7-18-95

SANDIA REPORT

SAND92-1449 • UC-1302

Unlimited Release

Printed May 1995

Design, Fabrication, and Testing of a Sodium Evaporator for the STM4-120 Kinematic Stirling Engine

K. Scott Rawlinson, Douglas R. Adkins

Prepared by

Sandia National Laboratories

Albuquerque, New Mexico 87185 and Livermore, California 94550

for the United States Department of Energy

under Contract DE-AC04-94AL85000

Approved for public release; distribution is unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A06
Microfiche copy: A01

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Distribution
Category UC-1302

SAND92-1449
Unlimited Release
Printed May 1995

**DESIGN, FABRICATION, AND TESTING
OF A SODIUM EVAPORATOR
FOR THE STM4-120 KINEMATIC STIRLING ENGINE**

**K. Scott Rawlinson
Douglas R. Adkins**

**National Solar Thermal Test Facility
Sandia National Laboratories**

ABSTRACT

This report describes the development and testing of a compact heat-pipe heat exchanger that is designed to transfer thermal energy from hot combustion gases to the heater tubes of a 25-kW_e Stirling engine. In this system, sodium evaporates from a surface that is heated by a stream of hot gases. The liquid metal then condenses on the heater tubes of a Stirling engine, where energy is transferred to the engine's helium working fluid. Tests on a prototype unit illustrated that a compact (8 cm x 13 cm x 16 cm) sodium evaporator can routinely transfer 15 kW_e of energy at an operating vapor temperature of 760°C. Four of these prototype units were eventually used to power a 25-kW_e Stirling engine system. Design details and test results from the prototype unit are presented in this report.

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DLC

Contents

I. INTRODUCTION.....	7
II. DESIGN CONSIDERATIONS	8
Fluid Properties Calculations.....	8
Heat Transfer Calculations.....	8
Pressure Drop Calculations	11
Computer Code.....	11
Engine Power Requirements.....	11
Heat Transfer Results.....	13
Validity of Heat Transfer Calculation.....	13
Heat Transfer Comparison with an Alternate Correlation.....	18
Stress Analysis.....	18
Summary of FEA Results	21
Wick Design	27
Condenser Design and Liquid Entrainment.....	27
III. FABRICATION.....	30
Prototype Variations.....	30
Materials.....	30
Joining.....	30
Component Construction.....	31
Cleaning	32
Bakeout and Fill Operations.....	32
Vacuum bakeout.....	32
Sodium filling	32
IV. TEST PREPARATION.....	34
Test Setup	34
Temperature.....	34
Volumetric Flowrate.....	34
Mass Flowrate	37
Pressure.....	37
V. TEST RESULTS.....	38
Unit 1.....	38
Summary.....	38
Details.....	38
Conclusions from Unit 1 Test.....	40
Unit 2.....	40
Summary.....	40
Details.....	44
Failure Analysis of Unit 2.....	47
Conclusions from Unit 2 Test.....	47
Unit 3.....	47
VI. SUMMARY AND CONCLUSIONS	56
Acknowledgments.....	57
REFERENCES	58
Appendix I. Conceptual Designs for a New Evaporator.....	61
Appendix IIA. Detailed Combustion Product Thermodynamic Property Analysis.....	67
Appendix IIB Start-Up Temperature Distribution in the Evaporator Tube Bank.....	73
Appendix III Heat Transfer Code and Sample Output.....	75
Appendix IV Testing Summary by Date for Evaporator Units 1, 2, and 3.....	89
Appendix V. Wick Sampler Tests.....	99
Appendix VI. Uncertainty Analysis	107

FIGURES

1.	Construction of STM evaporator	7
2.	Gas-fired sodium evaporator illustration.....	9
3.	Flowchart for fluid property data and heat transfer code.....	12
4.	Tube configurations considered for final design.....	14
5.	Effect of combustion gas mass flowrate on power input.....	15
6.	Effect of sodium vapor temperature on power input.....	16
7.	Effect of air/fuel ratio on power input.....	17
8.	Finite element model—resultant temperature profile (no preheat)	19
9.	Finite element model—resultant displacements (no preheat)	19
10.	Finite element model—Von Mises Stresses, upper isometric view (no preheat)	20
11.	Finite element model—Von Mises Stresses, lower isometric view (no preheat).....	20
12.	Finite element model—Von Mises Stresses, close-up of front row/upper manifold interface (no preheat)	22
13.	Finite element model—Von Mises Stresses, close-up of front five rows/lower manifold interface (no preheat)	22
14.	Finite element model—resultant temperature profile (preheat to 300°C)	23
15.	Finite element model—resultant displacements (preheat to 300°C)	23
16.	Finite element model—Von Mises Stresses, upper isometric view (preheat to 300°C)	24
17.	Finite element model—Von Mises Stresses, lower isometric view (preheat to 300°C).....	24
18.	Finite element model—Von Mises Stresses, close-up of front row/upper manifold interface (preheat to 300°C).....	25
19.	Finite element model—Von Mises Stresses, close-up of front five rows/lower manifold interface (preheat to 300°C).....	25
20.	Wick structure in the evaporator tubes.....	28
21.	Flooding limit in the condenser section of the heat pipe if no vapor duct is used.....	29
22.	Bakeout and fill operation setup	33
23.	Piping and instrumentation diagram for test setup.....	35
24.	Photo of evaporator being weighed after sodium fill operation.....	36
25a.	Evaporator temperatures during a period of unstable operation.....	39
25b.	Video images of evaporator during unstable operation.....	41
26.	Location of current probes.....	42
27.	Current probe resistances during operation.....	43
28.	Unit 2 data plots illustrating instability due to excess sodium inventory.....	45
29.	Typical Unit 2 data plots after excess sodium inventory removal and installation of condenser heaters to remove hydrogen.....	46
30.	Sodium evaporator actual and predicted performance at $A/F = 23.5$	48

FIGURES (Continued)

31.	Sodium evaporator actual and predicted performance at $A/F = 22.0$	49
32.	Sodium evaporator actual and predicted performance at $A/F = 21.0$	50
33.	Sodium evaporator actual and predicted efficiency at $A/F = 23.5$	51
34.	Sodium evaporator actual and predicted efficiency at $A/F = 22.0$	52
35.	Sodium evaporator actual and predicted efficiency at $A/F = 21.0$	53
A-V-1.	Schematic of the four-tube evaporator-wick sampler system	100
A-V-2.	Wick structures tested in the evaporator tube wick sampler experiment	101
A-V-3.	Test system for the wick sampler.....	102
A-V-4.	Wick sampler temperature plots illustrating wick dryouts.....	103
A-V-5.	Wick sampler current probe plots illustrating wick dryouts.....	104

TABLES

I.	Property Data for SS321.....	26
II.	Performance Map Data.....	55
IIA-I.	Comparison of Calculated Property Data vs. Tabular Data	72
VI-I.	Uncertainty Analysis Results.....	110

EXECUTIVE SUMMARY

The solar thermal electric program undertook performance testing of a STM4-120 engine with thermal input from propane combustion in preparation for testing a complete engine-receiver-generator system on a solar concentrator. Propane-fired evaporators simulated the delivery of hot sodium vapor to the heater tubes of the engine that would be produced in solar testing by a reflux solar receiver. The evaporators supplied by STM proved to have short lifetimes. Sandia undertook development of a replacement evaporator based on a tube-and-shell approach.

Tests on a prototype unit illustrated that a compact (8 cm x 13 cm x 16 cm) sodium evaporator can routinely transfer 15-kW_t of energy at an operating vapor temperature of 760°C. Design details and test results from the prototype unit are presented in this report.

The first evaporator constructed displayed unstable temperatures during operation due to poor liquid distribution. Detailed diagnostics indicated that changes were needed in the wick structure. These changes were incorporated into a second unit, which performed flawlessly until a leak occurred that was unrelated to the evaporator design. A third unit was fabricated and used to performance map the evaporator. The desired power throughput, 15 kW, was achieved on a routine basis. A U.S. patent on this design was applied for and granted.

Eight evaporators based on UNIT 2/3 design were fabricated from SS321. Four of these units were interfaced with the STM heater heads and engine testing resumed. The evaporators proved to be much more reliable and durable than the STM evaporators. The only problems that occurred during testing were traced back to liquid entrainment problems in the heater heads (opposite end from the evaporator) at high power levels. Future work could include fabricating four units from Haynes 230. While we are confident that the 321 stainless units will be satisfactory, Haynes 230 has superior properties with respect to strength, lower coefficient of expansion (lower thermal stresses during startup), and external oxidation resistance. In addition, endurance testing using 24-hour operation would be needed to prove long-term durability.

It should be noted that this evaporator is not limited to Stirling engine testing. These units could be used to provide thermal energy to many other devices requiring a uniform temperature distribution. Examples include extrusion dies, heat recovery systems, and isothermal ovens.

I. INTRODUCTION

A primary objective of the solar thermal program is to develop systems to produce electrical power that can compete in cost with electricity produced by gas and coal-fired generators. The Dish-Stirling system has high potential for meeting the program's goals for efficiency, reliability, and installed cost. The high potential is mainly due to the high thermodynamic efficiency of the Stirling cycle. Sandia is in the process of evaluating the STM4-120, a 25-kW Stirling cycle engine manufactured by Stirling Thermal Motors (STM). Details of the engine results can be found in [1].

Considering that the STM engine is in development, there have been relatively few problems with the engine itself. However, many failures occurred in the heat pipes originally supplied with the engine. There are four heat pipes for the engine; one for each cylinder. Each heat pipe consists of an evaporator, a heat pipe, a heater tube bundle, a cylinder housing, and a regenerator housing. Most of the heat pipe failures have occurred in the evaporator section. A schematic of STM's evaporator is shown in Figure 1. The design consists of 10 fins, each fin containing an internal wick structure. The primary advantage of the design is that it offers a very large heat transfer area in a small package. However, each fin requires welding along three edges. A significant part of this weld is exposed to high fluxes; in fact, the weldment along the leading edge is directly exposed to the flame. Sandia analyzed the failed evaporators and determined that the failures occurred because of the design along this leading edge. Other areas of concern include: (1) the leading edge is crimped and welded, and the impact on the wick structure from these operations is unknown and non-inspectable, (2) the heat flux along the leading edge is very large, and (3) dryouts occurred at higher power levels, possibly due to the lack of a reservoir for excess sodium.

The primary interest of the program was in completing performance mapping of the engine with thermal input from propane before initiating solar testing of an engine-receiver-generator package. The evaporators provided a method of transferring heat of combustion to the heater tubes in a manner simulating thermal input from a reflux receiver. However, each time a failure occurred, it was necessary to disassemble the heater, package the heat pipe, send it to STM for repair, and install a new heat pipe. Of course, engine testing ceased during these downtimes. To eliminate these problems, Sandia decided to design another evaporator (STM had plans to upgrade their design, but no external funds were available). The

design requirements called for reliability, efficient heat transfer, acceptable stresses, ease of fabrication, and acceptable pressure drop. The design aspects are discussed in the next section.

Figure 1. Construction of STM evaporator.

II. DESIGN CONSIDERATIONS

To correct the previously described evaporator issues, several different evaporator concepts were considered. These concepts included:

- (1) Tube-and-shell heat exchanger
- (2) Pool boiler with an external concentric burner
- (3) Pool boiler with an internal fire tube
- (4) Pool boiler with an immersion heater
- (5) Pool boiler with an external electrical heater

A diagram of each of these concepts with their associated advantages and disadvantages can be found in Appendix I. The tube-and-shell heat exchanger was chosen for the following reasons:

- (1) The heat exchanger "footprint" would be most adaptable to the present test set-up. The existing burners and combustion chambers could be used.
- (2) All welds could be made on the sodium side of the heat exchanger. No crevices for sodium oxide corrosion would exist.
- (3) All welds are simple tube-to-plate welds.
- (4) No welds exist in the very high heat flux area.
- (5) A sodium reservoir is provided outside the high flux region (the reservoir provides a supply of sodium to the wick yet the liquid pool does not interfere with evaporation from the heated surface).
- (6) The design is relatively simple to fabricate.

The tube-and-shell gas-fired sodium evaporator is illustrated in Figure 2. In this system, hot gases from a propane burner are forced to flow between the 40 evaporator tubes. Liquid sodium on the inner surface of the evaporator tubes vaporizes and removes heat from the tube walls. The sodium vapor then travels to the condenser end of the heat pipe where heat is removed and measured using a gas-gap calorimeter. Under the influence of gravity, the condensed sodium flows down the condenser walls and into a gutter at the bottom of the condenser tube. A drain in the gutter directs the condensed sodium into the upper manifold of the evaporator. After the liquid sodium enters the upper manifold, it flows along the manifold and spills into the evaporator tubes. Sodium that spills down the evaporator tubes either evaporates from the tube walls or is collected in the bottom manifold. A wick structure on the inner walls of the evaporator tubes distributes the liquid sodium over the evaporator tube walls.

There are many things to consider when designing a heat exchanger. The heat transfer rate depends on mass flowrate, tube temperature, tube spacing and area, flame temperature, and fluid properties. The calculations for evaluating these parameters are discussed in the following sections and in Appendix IIA.

Fluid Properties Calculations

The heat transfer coefficient is dependent on many conditions, such as fluid properties, tube surface temperature, freestream temperature, and the tube configuration. In this case, accurate calculations of fluid properties are difficult because the gas is not a single component but is a mixture of several gases. To reduce hydrogen generation, which can diffuse into the heat pipes and prevent sodium from reaching the condenser, the fuel is typically run with excess air. The fuel used at the National Solar Thermal Test Facility (NSTTF) is propane. When propane reacts with excess air, the major combustion products are carbon dioxide, oxygen, nitrogen, and water. The proportions of these components depend on the air/fuel ratio. Mixture properties needed for heat transfer and pressure drop calculations are viscosity, thermal conductivity, specific heat, and density. Details of the computing the properties of the combustion gases can be found in Appendix IIA.

Heat Transfer Calculations

The evaporator is essentially a tube-and-shell heat exchanger—therefore the heat transfer from the combustion gases to the tubes was treated as flow through a bank of tubes. The steady-state heat transferred to each tube is given by

$$q = \frac{T_{\infty} - T_m}{R_{tot}} \quad (1)$$

where q = heat transfer into tube, [W]
 T_{∞} = gas bulk temperature, [K]
 T_m = sodium temperature inside tube, [K]
 R_{tot} = total thermal resistance from gas to inner tube, [K/W].

Thermal resistance from the flue gases to the sodium inside the tube is the sum of the resistance from the flue gas to the outer surface plus the resistance through the tube plus the resistance from the inner tube surface to the sodium:

Figure 2. Gas-fired sodium evaporator illustration.

$$R_{tot} = \frac{1}{2\pi r_o L h_o} + \frac{\ln(r_o / r_i)}{2\pi k L} + \frac{1}{2\pi r_i L h_i} \quad (2)$$

where r_i = tube inner radius, [m]
 r_o = tube outer radius, [m]
 h_i = heat transfer coefficient on inner tube surface, [W/m²-K]
 h_o = heat transfer coefficient on outer tube surface, [W/m²-K]
 k = thermal conductivity of tube material, [W/m-K]
 L = length of tube, [m]

The heat transfer coefficient on the flue gas side of the heat exchanger governs the heat transfer into the evaporator. This convection coefficient can be obtained with empirical correlations developed for flow past tube banks. A correlation that fits the data quite well is given by Zhukauskas [2] as:

$$Nu_D = \frac{\bar{h}D}{k} = C Re_D^m Pr^{0.36} (Pr_\infty / Pr_s)^{1/2} \quad (3)$$

for $0.7 < Pr < 500$

$1000 < Re_{D,max} < 2 \times 10^6$

where Nu_D = average Nusselt number,

$\bar{h}$ = average convection coefficient, [W/m²-K]

D = tube diameter, [m]

k = thermal conductivity of gas, [W/m-K]

$Re_{D,max}$ = Reynolds number based on maximum velocity of combustion gas,

Pr_∞ = Prandtl number at fluid temperature,

Pr_s = Prandtl number at tube surface temperature,

C, m = constants dependent on tube configuration,

Note the Reynolds number is based on the maximum velocity of the gas. The maximum velocity depends on the tube configuration and can occur at either the transverse or diagonal plane. The maximum velocity occurs at the diagonal plane if

$$S_D = \left[S_1^2 + (S_t / 2)^2 \right]^{1/2} < (S_t + D) / 2 \quad (4)$$

where S_t = transverse pitch, [m]
 S_1 = longitudinal pitch, [m]

Then the maximum velocity is computed from

$$V_{max} = \frac{S_t}{2(S_D - D)} V \quad (5)$$

where V = upstream average velocity (m/sec)

If equation (4) is false, the maximum velocity occurs at the transverse plane and is calculated as

$$V_{max} = \frac{S_t}{S_t - D} V \quad (6)$$

For the designs considered, the ratio of the transverse to the longitudinal pitch is less than two, and the Reynolds numbers are between 1000 and 2×10^5 . For these conditions, the coefficients in Equation (3) are

$$C = 0.35 (S_t / S_1)^{1/5} \quad (7)$$

and

$$m = 0.6$$

Since the heat transfer coefficient on the sodium side is at least two orders of magnitude larger than the heat transfer coefficient on the flue gas side, the last term in Equation (2) can be neglected. The fluid temperature, T_∞ , drops as the gas passes through each row of tubes, transferring some heat to the sodium. The bulk combustion gas temperature for the next row of tubes is then calculated by applying an energy balance to the combustion chamber:

$$\dot{Q} + \dot{W} = \frac{\partial}{\partial t} \int_{cv} e \rho dV + \int_{cs} \left\{ h + \frac{V^2}{2} + gz \right\} \rho \vec{V} \cdot d\vec{A} \quad (8)$$

Assuming:

- steady state conditions
- ideal gas
- no change in potential or kinetic energy
- no shaft work

then the above equation can be solved for the downstream temperature:

$$T_{down} = T_{up} - \frac{|\dot{Q}|}{\dot{m} c_p} \quad (9)$$

where T_{down} = downstream temperature, [K]

T_{up} = upstream temperature, [K]
 $\dot{m}$ = mass flowrate, [kg/sec]
 c_p = constant pressure specific heat, [J/kg-K]

Effect of Radiation:

The effect of radiation was considered initially. The radiation from the gas to the tube surface is

$$q_r = \varepsilon \sigma A_s (T_\infty^4 - T_s^4) \quad (10)$$

where q_r = heat transfer from radiation, [W]
 ε = emissivity of gas,
 σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/m²-K⁴
 A_s = surface area, [m²]
 T_∞ = bulk temperature, [K]
 T_s = tube surface temperature, [K]

The emissivity of a gas depends on the gas composition, the gas temperature and a characteristic "beam" length that is a function of the tube bundle and combustion chamber geometry. Based on correlations provided in Siegel and Howell [3], the largest mean beam length for our system was on the order of 0.15 meters. Using this beam length and the mole fractions of the combustion gases, the Sandia fire code RADIAT predicted an emissivity of between 0.05 and 0.1 using Edward's wide-band model [3].

Upper bounds of the benefit of radiation heat transfer were estimated. Total heat transfer into the tube bundle increased less than 0.5 kW, and even this estimate is high because the effect of the radiation heat transfer dropping the bulk temperature slightly and thus reducing the convection heat transfer was neglected. Therefore, because the effect is small, the complexity of the computer program would be greatly increased, and the error will be on the conservative side, radiation effects were neglected.

Pressure Drop Calculations

The most recent and reliable results for pressure drop across a bank of tubes comes from Incropera and DeWitt [4] and is given by the equation:

$$\Delta p = N \chi \frac{\rho V_{\max}^2}{2} f \quad (11)$$

where Δp = pressure drop through tube bundle, [Pa]

N = number of rows of tubes,
 χ = correction factor dependent on tube arrangement,
 ρ = density of gas, [kg/m³]
 $V_{\max}$ = maximum velocity of gas (see heat transfer section), [m/sec]
 f = friction factor,

The friction factor is a function of the Reynolds number and the tube bank arrangement. The friction factor was calculated by curve-fitting data given in [4]. The correction factor is unity for the arrangement of interest.

Computer Code

A computer program was written to automate all of the computations described above so that many different tube arrangements, air/fuel ratios, sodium temperatures, and mass flowrates could be analyzed quickly. A flowchart of the program is shown in Figure 3. After the tube configuration, combustion chamber dimensions, sodium temperature, and air/fuel ratios are set, the fluid properties (based on the flame temperature) are calculated. Then the gas-side convection coefficient is determined. Next, the program calculates the heat transferred into a row of tubes, and computes the new gas temperature for the next tube row. After stepping through each row of tubes, the results (fluid properties, heat transfer, pressure drop) are displayed. The program then averages the flame temperature and the exhaust temperature and calculates new fluid properties based on this average bulk temperature. This entire process is repeated until the average bulk temperature converges.

The heat transfer code and a sample output can be found in Appendix III.

Engine Power Requirements

The STM4-120 Stirling engine is designed to produce 25 kW of shaft power at an efficiency of about 40% (thermal input to shaft out). There are four heat pipes on the engine, and therefore each evaporator needs to produce one-fourth of the total power required. At 40% efficiency, the power requirement is 15.6 kW from each evaporator. When the evaporator was initially designed, the engine efficiency had peaked at 35-36% at half power. To be conservative, we assumed 35% minimum efficiency. At that efficiency, the power requirement was 17.9 kW. Based on the higher power requirement, the evaporator design goal was 18 kW. Since that time, we increased the power slightly and achieved efficiencies of 39-40%, and expected about 42% at full power. With an

Figure 3. Flowchart for fluid property data and heat transfer code.

efficiency of 42%, the required throughput for each evaporator drops to 14.9 kW. Therefore our design point was 15 kW.

Heat Transfer Results

Many different tube arrangements were considered. The six configurations with the most merit are shown in Figure 4. The power, pressure drop, and heat transfer efficiency are also shown in this figure. The heat transfer efficiency is the percentage of heat that is transferred based on the heat available for heat transfer, given the flame temperature and the sodium vapor temperature. Configurations 1 and 3 have the highest power levels, but have unacceptable pressure drops, which imply a larger blower. Configurations 4, 5, and 6 had acceptable pressure drops, but the predicted heat transfer is slightly low. The best compromise that fit the space constraints was configuration #2. This was the layout chosen for the new design.

As mentioned above, the heat transfer is affected by many variables. Sensitivities for the most important parameters were done for the chosen tube configuration.

The first sensitivity performed was power throughput as a function as combustion gas mass flowrate. The results presented in Figure 5 shows that power is a linear function of mass flowrate.

The next sensitivity performed was the effect of the sodium vapor temperature on power throughput. As Figure 6 indicates, power increases with decreasing vapor temperature. This is because the differential temperature between the flue gas and the sodium is the driving force. However, the engine efficiency increases with increasing vapor temperature. Engine performance mapping determines the optimum system efficiency in this particular tradeoff.

The final sensitivity presented is the effect of the air/fuel ratio on power throughput (see Figure 7). Power increases dramatically as the air/fuel ratio decreases from 50% excess air towards the stoichiometric ratio. This is because the flame temperature peaks at the stoichiometric air/fuel ratio. We chose to run at 50% excess for two reasons: (1) hydrogen diffusion into the heat pipe is much lower at high air/fuel ratios, and (2) tube surface temperatures towards the front of the evaporator are lower.

Validity of Heat Transfer Calculation

During the design, several questions with regard to the convective heat transfer calculations arose. Each of these is discussed below:

Using "local" bulk temperatures:

None of the references for heat exchanger design contained enough detail to decipher how the experiments were conducted. Most of the experiments were performed for modest fluid temperature changes, defining the fluid temperature fairly well. In our case, the bulk fluid temperature changes from about 1800K to 1200K as flue gases pass through the tube bundle. We used the average convection coefficient for the entire tube bundle, but in the heat transfer calculation through each row of tube, we varied the bulk temperature as heat was extracted from each tube row. However, fluid properties used to calculate the convection coefficient change for such a large temperature change. To improve on the prediction, fluid properties were calculated based on an average bulk temperature, defined as the average between the flame temperature and the exhaust temperature. The process was continued until convergence was reached. These assumptions appeared to be a reasonable way to approach the problem. Helping to confirm these assumptions, the correlations for a tube bundle are very similar to that of a single tube in cross-flow—therefore the calculations using a "local" bulk temperature appear valid.

Closely spaced tube arrangements:

The small required footprint of the evaporator demanded a closely packed tube bank, defined as tube clearances of less than 0.4-0.5 tube diameters. The chosen design had clearances below this limit. Kays & London [5] presents results on closely spaced tube banks. The results, as compared to more open arrangements, vary somewhat, but in general the correlations under-predict the actual heat transfer into closely spaced tube banks. Again, the results should err on the conservative side.

High temperature:

Zhukauskas [2] states that the correlations do not apply for convective heat transfer at high temperature or in the presence of chemical reactions. The flame temperature is more than 1800K, which is probably considered high temperature. Zhukauskas does not place a number on "high temperature." Other references do not state a temperature limitation. In any event, the correlations used are the most recent and are the best we have available.

Figure 5. Effect of combustion gas mass flowrate on power input.

Figure 6. Effect of sodium vapor temperature on power input.

Figure 7. Effect of air/fuel ratio on power input.

Number of rows:

The heat transfer correlations are developed for tube banks with many rows of tubes. The actual heat transfer for smaller bundles decreases somewhat because the first few rows see less turbulent flow and act as turbulence generators for downstream tube rows. Therefore, the actual heat transfer coefficient increases as the gas passes from the front rows to the back rows. The chosen design contains ten rows of tubes. The correction factor for the heat transfer coefficient is about 0.98.

Heat Transfer Comparison with an Alternate Correlation

The evaporator heat transfer coefficient was calculated as described in this report. Comparison was made with a second correlation [5] and the results were similar. Using the same input parameters, the coefficient using the method described above was $254 \text{ W/m}^2\text{-K}$, while the coefficient using [5] was $235 \text{ W/m}^2\text{-K}$.

Stress Analysis

Several finite element models for the gas-fired sodium evaporator were developed to estimate the stresses that would result from the uneven temperature distribution during startup. The uneven distribution is due to the flue gas dropping in temperature as it flows through the tube bank. Therefore, during startup, the front rows of tubes would expand at a greater rate than the back rows of tubes. The temperature gradient eventually evens out at about 500°C , when the sodium vapor pressure is high enough to provide isothermal operation. These finite element models ranged from conservative and simple to complex and more representative. Because the simpler models predicted unacceptable stresses during the startup phase, more accurate models were developed. One of the more advanced models consisted of accurately modeled upper and lower manifolds, but used only 2-noded "PIPE" elements to represent each tube. The results of the analysis for that model indicated that stresses were too high during startup, assuming that the predicted temperature profile was fairly accurate. The areas of high stress occurred where the PIPE elements meshed with the upper and lower manifolds.

A more accurate model was needed to determine if the high stresses were real or were due to point loading of the PIPE elements on the manifolds. The finite element model was upgraded by modeling each of the 40 tubes with shell elements in place of single 2-noded elements. Although this model was completed, it was too large to analyze on a personal computer. To solve this problem,

the complexity of the model was cut down somewhat. The first 5 tube rows were fully modeled, while the last 5 tube rows were modeled with PIPE elements. This model provided reasonable results since the steepest temperature gradient (and resultant high stresses) exists toward the front of the evaporator.

The model presented here includes modifications that were incorporated into the second design (see fabrication section for a description of the modifications between the two designs). A summary of the model is given below:

- Program name: COSMOS/M
- Program version: 1.65X
- Element type (for manifolds, first 20 tubes, vapor exit tube): Linear 4-node thin shell, "SHELL4"
- Element type (for last 20 tubes): 2-noded "PIPE"
- Force/pressure boundary conditions: None
- Temperature boundary conditions: [See Appendix IIB]

Row #1:	380°C
Row #2:	290°C
Row #3:	221°C
Row #4:	170°C
Row #5:	132°C
Row #6:	103°C
Row #7:	81°C
Row #8:	64°C
Row #9:	52°C
Row #10:	43°C

Note: Nodal temperatures specified only on the front surface of each tube for the first 20 tubes.

- Displacement boundary conditions: Zero displacement in y direction along upper curve of vapor tube, fixed in all directions at one node on upper curve of vapor tube, fixed in z direction at one point on upper curve of vapor tube
- Modulus of elasticity: $190,000 \text{ N/mm}^2$
- Poisson's ratio: 0.3
- Thermal conductivity: 0.0242 W/mm-K
- Coefficient of thermal expansion: $17.3 \times 10^{-6} \text{ m/m-K}$

Figure 8. Finite element model—resultant temperature profile (no preheat).

Figure 9. Finite element model—resultant displacements (no preheat).

Figure 10. Finite element model—Von Mises Stresses, upper isometric view (no preheat).

Figure 11. Finite element model—Von Mises Stresses, lower isometric view (no preheat).

Note: Material properties are for Stainless Steel 321 (SS321).

Temperature boundary conditions were estimated using a lumped-mass thermal analysis which is discussed in Appendix IIB.

The results of the stress analysis are shown in Figures 8 through 13. All stresses discussed below are Von-Mises stresses, a common stress criteria used to predict failure. The maximum stress of 266 MPa occurs at the back row. This is not a problem area because the resultant stress is due to the FEA model -- the high stress results from the point load applied by the 2-noded pipe element. Examining Figure 12, high stresses occur where the first tube meets the upper manifold (150 MPa) and where the outer tube on the second row meets the upper manifold (175 MPa). Referring to Figure 13, stresses of 190 MPa occur where the outer tube in the second row joins the lower manifold, and high stresses occur in the outer tubes in the third and fifth row (181 MPa and 215 MPa). All of these stresses exceed the yield strength of the material at their respective temperatures. The yield, ultimate, and creep strengths of SS321 at various temperatures from two sources are listed in Table I.

Contrasting these results to UNIT 1 model results (which had shallow manifolds), similar stresses occur in areas near the inner tubes. However with the deeper manifolds, higher stresses develop along the outer tubes/manifolds interface. This is caused by the deeper manifolds -- the increased depth increases the stiffness of the structure, i.e., the "web" of the "beam" is increased. The increased stiffness results in higher stresses.

Since the finite element model predicted high stresses, we were able to use this information in our startup procedure. The evaporator was preheated to at least 300°C before the burner was ignited. This procedure resulted in a much more uniform temperature profile since the internal sodium vapor flow equalizes temperatures in the 500-550°C range.

Finally, we examined actual measured data and found a point where the highest temperature gradient existed during startup. This data was then used as input data to the FEA model. The temperature profile used in the FEA model was:

Row #1:	517°C
Row #2:	506°C
Row #3:	494°C
Row #4:	482°C

Row #5:	470°C
Row #6:	458°C
Row #7:	446°C
Row #8:	435°C
Row #9:	423°C
Row #10:	411°C

The results are illustrated in Figures 14 through 19. Although the stress patterns are similar, the magnitude of the stresses are much lower -- a peak stress of 27 MPa is predicted with this model. This value is much less than the yield strength of the SS321.

It should be noted that the predicted peak stresses probably exceed the actual stresses. In the FEA model, the circular tubes are represented by octagon-shaped tubes. Therefore stress risers are created by this non-smooth geometry. We attempted to modify the model by changing the associated elements to second-order elements, which would represent the circular tubes more accurately. Unfortunately, the code does not support thermal loading for this element type.

Summary of FEA Results

The most detailed FEA model provides a tool to predict stresses during the non-isothermal startup phase. The model was updated to reflect the newer evaporator design with deeper manifolds. The model predicted unacceptable stress levels using the calculated non-uniform temperature profile. In order to reduce these stresses, the startup procedure called for preheating the entire evaporator to at least 300°C. Next, the maximum temperature gradient measured during actual operation was used as input data for the FEA program. The predicted stresses confirmed that preheating the unit results in very low startup stresses. Note that these models were run with SS321 material properties. The stresses for any evaporators made from Haynes 230 would be even lower since the coefficient of thermal expansion is much less than that of SS321. In addition, the yield strength of Haynes 230 is much higher.

The intended follow-up work with the FEA model called for measuring the temperature profile with preheating the evaporator to only 100°C, the melting point of sodium. This amount of preheating would result in lower stresses than starting the unit from ambient temperature, but is less conservative than a preheat to 300°C. Unfortunately, UNIT 2 developed a leak in the condenser section (away from the evaporator section) and ruined the evaporator before this test could be completed. Therefore, the FEA model could not be run with this more severe temperature

Figure 12. Finite element model—Von Mises Stresses, close-up of front row/upper manifold interface (no preheat).

Figure 13. Finite element model—Von Mises Stresses, close-up of front five rows/lower manifold interface (no preheat).

Figure 14. Finite element model—resultant temperature profile (preheat to 300°C).

Figure 15. Finite element model—resultant displacements (preheat to 300°C).

Figure 16. Finite element model—Von Mises Stresses, upper isometric view (preheat to 300°C).

Figure 17. Finite element model—Von Mises Stresses, lower isometric view (preheat to 300°C).

Figure 18. Finite element model—Von Mises Stresses, close-up of front row/upper manifold interface (preheat to 300°C).

Figure 19. Finite element model—Von Mises Stresses, close-up of front five rows/lower manifold interface (preheat to 300°C).

Table I. Property Data for SS321
Units = MPa (ksi)

<u>Aerospace Structural Metal Handbook [6]</u>			<u>Engineering Properties of Steel</u>		
<u>Bar, annealed, heat treat not specified</u>			<u>6mm rod, annealed at 1040°C for 1/2 hr., water-quenched</u>		
	<u>Su</u>	<u>Sy</u>		<u>Su</u>	<u>Sy</u>
~24°C	538-690 (78-100)	207-448 (30-65)	21°C	569 (83)	207 (30)
205°C	483-620 (70-90)	172-427 (25-62)	205°C	421 (61)	145 (21)
425°C	393-517 (57-75)	145-379 (21-55)	425°C	400 (58)	121 (18)
540°C	344-448 (50-65)	131-345 (19-50)	540°C	379 (55)	124 (18)
760°C	172-276 (25-40)	103-241 (15-35)	760°C	210 (31)	114 (17)
<u>Sheet, annealed, heat treat not specified</u>			<u>Creep rate (form not specified)</u>		
	<u>Su</u>	<u>Sy</u>		<u>1% in 10K hr.</u>	<u>Rupture in 10K hr.</u>
24°C	586 (85)	241 (35)	760°C	17 (2.5)	25 (3.5)
205°C	448 (65)	172 (25)	815°C	10 (1.5)	15 (2.0)
425°C	448 (65)	138 (20)			
540°C	434 (63)	131 (19)			
760°C	241 (35)	124 (18)			
<u>Creep rupture in 10K hr., (form not specified)</u>					
760°C	28 (4)				
815°C	14 (2+)				
<u>Creep rupture in 1K hr.</u>					
760°C	48 (7)				
815°C	28 (4)				

gradient (UNIT 3 was not risked because of possible future performance/durability tests). However, the results indicated that we could be confident that our startup procedure significantly reduced stresses. This start-up procedure was followed in all tests involving the STM engine.

Wick Design

A wick structure in each evaporator tube transports liquid sodium over the heated tube walls. The tubular wick structure is made of eight layers of a 200-mesh stainless steel screen that lines the inner wall of the evaporator tubes and extends into both the upper and lower manifolds (see Figure 20). The bottom extension of the wick allows liquid sodium to travel up from the lower manifold through capillary pumping, and the top wick extension allows liquid to enter the wick structure from the top without encountering high vapor velocities.

For the evaporator tube wick to function properly, the capillary pumping capabilities of the wick must exceed the hydrostatic and frictional pressure drops. The most severe design load on the wick structure will occur when heat is being applied to the evaporator and condensed liquid has not started to flow back into the top manifold. In this situation, all of the liquid that cools the heated evaporator tube must come from the lower manifold. If it is assumed that the flux across the evaporator tube is uniform, then the maximum pressure drop in wick structure is given by the expression,

$$\Delta P_W = \rho_l g L + v_l q L^2 / (2 h_{fg} \delta_w \kappa_w), \quad (4)$$

where L is the length of the evaporator tube (m), ρ_l is the liquid density (kg/m^3), v_l is the liquid viscosity (m^2/s), q is the heat flux (W/m^2), h_{fg} is the latent heat of evaporation (kJ/kg), δ_w is the wick thickness (m), and κ_w is the Darcy permeability of the wick (m^2). The capillary pumping that must overcome this pressure drop is given by the expression,

$$P_{cap} = 2 \sigma / r_e, \quad (5)$$

where σ is the surface tension of sodium (N/m) and r_e is the effective pore radius (m).

For eight layers of 200-mesh screen, the effective pore radius is approximately $45 \mu\text{m}$, the thickness is 0.73 mm , and the permeability is roughly $80 \times 10^{-12} \text{ m}^2$ [7]. Even though the pressure drop in the wick decreases as the operating temperature increases, fluid properties should

be computed at the maximum operating temperature; the drop in surface tension with increasing temperature places the greatest limits on the wick system. Properties of sodium are given in Dunn and Reay [8]. At 800°C , the surface tension of sodium is 0.122 N/m , the density is 761 kg/m^3 , the viscosity is $2.2 \times 10^{-7} \text{ m}^2/\text{s}$, and the latent heat is 3968 kJ/kg . By combining EQs (4) and (5) and solving for q , the maximum allowable flux on the evaporator tubes is 155 W/cm^2 . This value is well above the predicted maximum for the tube bank, so it is unlikely that the wick will dry out when liquid is present in the lower manifold.

Liquid in the wick is usually in a superheated state because of two phenomena; first, the heat flux through the saturated wick makes the liquid temperature in the wick higher than the vapor temperature; and second, hydrostatic and frictional pressure drops make the pressure in the wick lower than the vapor pressure. With a sodium saturated wick made of 200-mesh stainless steel screen, the effective conductivity is roughly $30 \text{ W/m}^\circ\text{C}$. The temperature drop across the 0.73-mm thick wick is only 15°C when the flux is 60 W/cm^2 , and at this same flux level, the minimum local pressure is found using EQ (4) to be roughly 3-kPa below the vapor pressure. At normal operating vapor temperatures, the liquid superheat will be on the order of 20°C which is within the demonstrated tolerance levels for sodium heat pipe systems [8].

Condenser Design and Liquid Entrainment

In the engine/evaporator system, the heater tubes of the engine serve as the condenser for the sodium vapor. To test the prototype units, however, heat was removed by a water-cooled calorimeter. The condenser section for the prototype units was a 50.8 mm (2") diameter tube that slips into the calorimeter. At lower operating temperatures ($<650^\circ\text{C}$), velocities in the condenser can be high enough to sweep liquid up the walls of the condenser. This liquid entrainment problem can also occur in the evaporator tubes.

On the first prototype gas-fired evaporator, it was discovered that liquid was collecting in the upper manifold and possibly in the condenser tube during startup periods. With a flux of only 10 W/cm^2 , the vapor velocity exiting the evaporator tubes is about 80 m/s when the vapor temperature is only 600°C . This velocity can theoretically suspend liquid roughly 6-mm above the top edge of the evaporator tube, and it could cause liquid to collect in the upper manifold. This problem was

Figure 20. Wick structure in the evaporator tubes.

avoided in subsequent units by extending the evaporator wick into the upper manifold so liquid can enter the wick structure without being subjected to the vapor flow.

Entrainment in the condenser is primarily an artifact of the calorimeter that is used to remove the heat from the system. The water cooled calorimeter removes an excessive amount of heat during the startup phase and therefore high vapor velocities are developed in the condenser. It is possible that the high vapor velocity could entrain the liquid on the condenser wall and prevent it from returning to the evaporator. This entrainment phenomenon is referred to as flooding.

Originally, the flooding limit in the condenser was calculated using correlations developed by Wallis [9]. However, the results overestimated the level of heat removal where flooding could occur. A more conservative estimate of the flooding limit was obtained using the Kutateladze criteria as interpreted by Tien and Chung [10]. This criteria states that the limiting heat flux through the condenser tube cross-section is

$$Q/A = 3.2 \xi^{-1/4} (D g \rho_l \rho_v)^{1/2} h_{fg} \tanh^2(0.5 \xi^{1/2}), \quad (6)$$

where Q/A is the heat flux through the cross-section of the evaporator, D is the tube inner diameter (m), ρ_l and ρ_v are respectively the liquid and vapor densities (kg/m^3), h_{fg} is the latent heat of vaporization (J/kg), and ξ is the flooding correlation factor, $\xi = D^2 g \rho_l / \sigma$. For heat fluxes less than this level, liquid will flow down the condenser wall, and for fluxes greater than this level, liquid is swept up the condenser wall.

A plot of the flooding limit as a function of the vapor temperature is given in Figure 21. Also shown in this figure is the measured minimum heat removed by the calorimeter as a function of the condenser wall temperature. The minimum power that is removed by the calorimeter is less than the computed flooding limit, so flooding should not be a problem with this system. Taking extra precautions was deemed necessary, however, because of the uncertainties in the flooding correlation.

Figure 21. Flooding limit in the condenser section of the heat pipe if no vapor duct is used.

To reduce the possibility of flooding, a vapor duct was placed in the middle of the condenser tube. The duct directs the flow of vapor through the center of the condenser tube to within 5 cm of the top. After passing

through the duct, the vapor flow turns and flows through the annular gap between the duct and the condenser wall. With this duct system, liquid will be swept down the condenser wall by the flow of vapor.

III. FABRICATION

Prototype Variations

A total of three prototypes were built and tested in this program. The units were built sequentially, so improvements were incorporated in each successive generation. Each unit used the same tube and manifold arrangement; however, changes were made in the joining of the evaporator tubes to the manifolds, the liquid sodium distribution system, and the condenser construction. The major differences in the units are summarized as follows:

- UNIT 1. Evaporator tubes were brazed into the manifolds. The wick structure was roughly flush with the upper manifold plate, so liquid could not enter the wick without opposing the flow of vapor. This unit had no overflow tubes (see Figure 20) and no vapor duct was used in the condenser.
- UNIT 2. Evaporator tubes were electron-beam welded into the manifolds and a vapor duct was added to the condenser to prevent liquid entrainment. Evaporator wicks extended into the top manifold and overflow tubes were also provided on ten of the evaporator tubes. Short slotted tubes slid over the wick extension in the lower manifold to provide mechanical support.
- UNIT 3. This unit was similar to UNIT 2, except that the evaporator tubes were brazed into the upper and lower manifolds. The screen evaporator wicks in UNIT 3 were not sintered into place as they were in the first two units, and the wick extensions in the lower manifold were supported by a tube that slid inside of the extension. Two holes in the bottom support tube allowed liquid and vapor to move in and out of the lower manifold.

The following sections primarily describe the construction of UNIT 2, which was the first successful design.

Materials

The evaporator tubes and the manifolds were made of 321 stainless steel and the condenser tube was made of 304 stainless steel. At an operating temperature of 800°C, high-nickel alloys such as Haynes 230 or Inconel 617 may be a better choice of material with respect to

strength and air-side corrosion, but the higher costs and reduced availability of these alloys pushed the design towards stainless steel. Both 304 and 321 stainless steels (SS) are acceptable materials for sodium heat pipes, and 321-SS is noted for its durability in corrosive combustion atmospheres. A trace amount of titanium in 321-SS forms stable carbides that are distributed throughout the grain structure. This prevents the precipitation of chromium carbides at the grain boundaries, and therefore avoids intergranular corrosion problems [6].

Joining

In joining materials for high temperature liquid metal heat pipe systems there are a few rules that should be followed to reduce possible corrosion problems. In general, it is better to weld the joint on the side that will be exposed to sodium. Placing the welds on the sodium side avoids the creation of crevices where the sodium oxides could be trapped and corrosion could be accelerated. It is also better to purge the inside of sodium containment vessels with Argon during gas-tungsten-arc (GTA) welding procedures. This practice will reduce the thickness of oxide layers developed during the welding process.

Both electron-beam welding and brazing were considered for the tube-to-manifold plate joint. The advantage of welding is that no other material is added to the evaporator that could possibly react with the sodium at high temperature. With a welded system, it is also possible to sinter screens into the evaporator tubes after the tubes are joined to the manifold. (Sintering is generally performed at 1050°C and brazing with BNi series brazes is usually performed at temperatures between 940 and 970°C.) The disadvantage of welding is that performing 80 tube welds on each evaporator was time consuming for the numerically controlled electron-beam welder.

With brazing, several units could be brazed in one oven run, but the service life of brazes in sodium environments at the operating temperatures of these systems is not well understood. A review of braze materials by Cole [11] states that BNi-2 and BNi-5 performed well when tested in liquid sodium at temperatures up to 700°C, and BNi-3 was also found to perform well in a liquid sodium environment at 650°C. If a braze is used to join the tubes to the manifold, it is also not possible to perform a high temperature sinter operation to join the wick to the inner evaporator tube wall.

Thermal expansion differences between the front and back tubes of the evaporator unit stress the manifold to the evaporator tube joint. To determine the strength of both options, pull tests were performed on BNi-5 brazed and welded specimens made of a single evaporator tube in a small plate of the manifold material. In the pull test, the maximum load for the weld was 9083N, and the maximum load for the braze joint was 16,116N. The braze joint withstood a higher load; however, the joint began to deform significantly at loads above 7100N. Based on the pull tests, both joining options provided acceptable strength.

Component Construction

The manifold pans were formed by notching the corners of a 1.57-mm thick sheet of 321-SS and then folding the edges over to form the sides. Gas-tungsten-arc (GTA) welding was used to close the corners. The staggered hole pattern for the evaporator tubes was stamped in the manifold pans with a numerically controlled punch. A slight taper on the both ends of the evaporator tubes allowed the tubes to be positioned in the manifold plates for welding. All 40 evaporator tubes were then electron-beam welded into the pans. After the tubes were welded into the manifold pans, the tubes and the pans were cleaned and then treated in a passivating solution to reduce the buildup of oxides on the stainless steel surfaces (see cleaning section).

The wick structure for each evaporator tube was formed by rolling a 23-cm by 12-cm sheet of 200-mesh, 316-SS screen around a dowel to form a 12-cm long tube. Screen-wick tubes were then inserted into the evaporator tubes in the tube bank, and a 9.5-mm diameter mandrel was pushed through the middle of each screen wick to press the screens tightly against the tube wall. A 302-SS spring was slipped into the screen tube to maintain the contact between the wick and the evaporator tube wall. Support rings that were made of 9.5-mm diameter 316-SS tubing were then inserted into the portion of the evaporator wick that extends into the top manifold (see Figure 20). Slotted rings were placed around the wick extensions in the bottom manifold to provide support for the screens. Once the evaporator tube wicks were in place, the tube bank was put in a hydrogen furnace and heated for two hours at 1050°C to sinter the screens. After the system was removed from the oven, slots were cut in the bottom wick extensions to provide a passage for vapor to escape from the lower manifold. The slots also allow liquid to flow more readily into the lower manifold.

In each row of the tube bank, a liquid overflow tube was installed in the evaporator tube nearest the manifold edge. These 10 overflow tubes were made by brazing a 4.76-mm tube into the 9.5-mm support rings with a BNi-5 braze alloy. A hole in the side of the overflow tube and the support ring allows liquid to drain from the top manifold without running directly onto the evaporator wick (see Figure 20). The support tubes with overflow tubes were not installed in the system until after the sintering operation was completed.

The condenser section of the heat pipe was made from a 50.8-mm diameter, 740-mm long tube with a wall thickness of 1.24-mm. This tube was GTA welded to the top manifold pan and two stubs (6.35-mm and 12.7-mm O.D.) were welded to the side of the condenser tube for the fill and vacuum valves (see Figure 2). Five 3.18-mm diameter tubes with sealed ends were also welded into the top manifold pan to form thermowells for measuring vapor temperatures in the evaporator tubes and the pool temperature. Just below the valve stubs, a tilted disk with one 28-mm hole in the middle and one 9.5-mm hole on the lowest side was installed inside the condenser pipe to form a gutter that directed the condensate flow to a 9.5-mm drain tube. A 28.0-mm diameter, 690-mm long tube slipped through the center of the gutter disk to form the vapor duct. The gutter disk, the drain tube and the vapor duct were all brazed in place with a BNi-5 braze alloy.

Because the manifold pans that are attached to the evaporator tubes are subjected to the hot combustion gases, the surface between the tubes in both manifolds was lined with four layers of 200-mesh screen. Holes were cut in the screens so they would fit over the evaporator-tube wick extensions, and the stack of screens were then resistance welded to the inner surface of the pan. Four screen tabs were also installed in the lower manifold to help transport liquid up the screens lining the lower manifold pan. The top pan of the upper manifold was lined with four layers of 56-mesh screen to help distribute liquid sodium returning from the condenser. The drain tube from the condenser discharged into a shallow trough in the upper manifold; the trough diverted liquid onto the 56-mesh screens rather than allowing it to spill directly into the evaporator tubes.

A GTA fusion weld was used to join the two halves of the upper and lower manifolds. Before the system was sealed, however, a pleated 7.5 by 15-cm strip of zirconium was placed in the lower manifold pan. The zirconium served as a getter to remove oxygen from the sodium, and thereby reduce the possibility of corrosion. Thermocouples were vacuum brazed onto seven of the

evaporator tubes with a BNi-3 braze alloy after the condenser and evaporator sections were GTA welded together. Three thermowells were welded into the 2.8-mm thick condenser endcap; two of the thermowells were angled to contact with the condenser walls 10-cm and 30-cm below the top, and the third thermowell extended 30-cm down the middle of the vapor duct. One thermowell was also placed in the annular gap between vapor duct and the condenser wall near the drain gutter, and another thermowell was placed in the entrance of the vapor duct. The last step of the assembly was to GTA weld high temperature bellows valves to the fill and vacuum stubs on the condenser.

Cleaning

Throughout the construction of this system, measures were taken to ensure the cleanliness of the components. All of the parts were cleaned inside and out with acetone and rinsed with alcohol prior to assembly. The evaporator tube bank, the manifold pans and the condenser tube were treated in a passivation bath to reduce the amount of oxides on the surfaces. As a rule, the passivation was done after parts were welded together, but the passivation treatment was not performed on brazed parts or on parts with screens. All of the final closure welds were performed while the system was purged with argon to minimize the formation of oxides inside of the heat pipe.

Bakeout and Fill Operations

Quality vacuum bakeout and fill operations are critical when using alkali metal heat pipes. Improper procedures can lead to sodium contamination (creating corrosive oxides) and condenser blanketing from non-condensable gas formation. These two operations are discussed below.

Vacuum bakeout

A diagram of the bakeout and filling operation is shown in Figure 22. All associated plumbing was stainless steel. The sodium vessel was manifolded to the heat pipe, an argon supply, a vacuum pump, and a residual gas analyzer. A defined volume, corresponding to the amount of desired sodium, was placed between the sodium vessel and the heat pipe to be filled. Next, the entire system was instrumented, heat-traced and insulated. Each heat-trace was controlled with an ON/OFF controller via thermocouples.

During the bakeout, the manifold was vacuum baked at 150°C, the defined volume (fill canister) was baked at 200°C, and the heat pipe was baked out at 600°C. The vacuum bakeout drove the water and other contaminants out of the walls of the heat pipe and plumbing. The time required for bakeout varies with the temperature and the surface area. Since the evaporator contains much surface area and many screens, bakeout typically took 2-3 days. When the vacuum bakeout was completed, the total pressure in the system was in the high 10^{-7} torr range, while the partial pressure of water was less than 1.0×10^{-7} torr range with the heat pipe and plumbing at temperature. (These measurements were made at the manifold to the vacuum pump; the pressure in the actual vessel was roughly 2 orders of magnitude higher.)

Sodium filling

After vacuum bakeout was completed, the heat pipe temperatures were reduced to about 200°C. The head space in the sodium vessel was charged with about 35 kPa (5 psig) of argon. Next, the fill valve on the sodium vessel was opened and sodium was allowed to enter the defined volume. Pressure was kept on the system to allow sodium flow for 5 minutes, although filling is usually complete in less than one minute. Sodium was detected in the fill volume in two different ways. Thermocouples were attached at two or three different levels on the fill container. A drop in temperature occurs as the 150-160°C sodium enters the 200°C container. In addition, 4-wire current probes can be attached to the fill canister. Five amps of current are passed through the container while monitoring the voltage drop. Because sodium is conductive, the voltage drop decreases as sodium fills the container. Next, argon pressure is applied to valves #5 and #7. The heat pipe valve (# 9) was then opened. Finally, valve #8 was opened to break the vacuum and sodium flowed into the heat pipe. After the heat pipe was filled, the argon was pumped out of the pipe.

By weighing the heat pipe before and after the fill operation, the amount of sodium transferred to the heat-pipe evaporator was determined.

Figure 22. Bakeout and fill operation setup.

IV. TEST PREPARATION

Test Setup

The piping and instrumentation diagram for testing the gas-fired sodium evaporator is illustrated in Figure 23, and a photograph of the heat-pipe assembly is shown in Figure 24. In this system, hot gases from a propane burner are forced to flow between the 40 evaporator tubes. Liquid sodium on the inner surface of the evaporator tubes vaporizes and removes heat from the tube walls. The sodium vapor then travels to the condenser end of the heat pipe where heat is removed and measured using a gas-gap calorimeter.

The combustion chamber used was built by STM for the use on their evaporator assemblies. It consisted of a single-pass preheater with a swirl mixer at the gas combustor nozzle. The evaporator test chamber was located at the discharge of the combustion chamber. A window was located toward the front of the combustion chamber which allowed viewing of the front evaporator tubes. A window was also located in the wall of the evaporator test chamber to allow viewing the entire length of the right side of the evaporator. Video cameras allowed test personnel to view the front tube row and one entire side of the evaporator from the control room. Video images were recorded on an 8-mm VCR.

Power was extracted and measured with a gas-gap calorimeter mounted around the condenser section. A mixture of helium and argon flows between the heat-pipe wall and the inner surface of the calorimeter. The ratio of the gases changes the conduction and therefore controls the rate of heat extraction. Power is calculated based on ΔT and the flowrate of the water. The calorimeter was designed to extract a maximum of 25 kW.

Thermocouples were brazed to the surface of seven of the 40 evaporator tubes, and thermowells were located in four of the tubes. One thermowell was also located in the bottom manifold to measure the sodium pool temperature. Two more thermowells were located in the condenser section and one was placed in the vapor space near the gutter. Thermocouples were also located on the vacuum and fill valves to ensure temperatures did not exceed the manufacturer's operating limits.

Electrical current probes were attached to external surfaces of the evaporator. These current probes allowed the liquid levels to be monitored in the upper manifold, lower manifold, and above the gutter section. All

transducer signals were measured and stored on an HP3852/HP320 data acquisition system (DAS) system, and an independent HP3497A/HP DAS system monitored most of the transducer signals and issued a shutdown signal to the propane valve if any parameter exceeded preset limits.

Before results for each evaporator is presented, the type and accuracy of the instrumentation will be discussed.

Temperature

All heat pipe vapor and tube temperatures, flue gas temperatures, and propane gas temperatures were measured with sheathed Type K thermocouples. Sheath diameters were 1.6-mm (1/16"), except for the propane and flue gas thermocouples, which were 3.2-mm (1/8").

Absorbed power is calculated by the product of mass flowrate, specific heat, and temperature rise through the gas-gap calorimeter. Since calculated power is a critical measurement, the ΔT through the calorimeter is measured with a matched pair of sheathed Type T thermocouples.

Accuracies of Type K thermocouples are $\pm 2.8^\circ\text{C}$ in the 0°C to 349°C range, and $\pm 0.75\%$ in the 350°C to 1260°C range. Accuracies of Type T thermocouples are $\pm 0.5\%$ or $\pm 0.8^\circ\text{C}$ (whichever is greater) in the -59°C to 93°C range, and $\pm 0.75\%$ in the 94°C to 371°C range [15]. Previous experience on other projects has indicated that accuracies of ΔT measurements with a matched pair of Type T thermocouples are typically $\pm 0.1^\circ\text{C}$.

Volumetric Flowrate

Mass flowrate of water through the gas-gap calorimeter is determined from the product of density and volumetric flowrate. Density is well-known for pure water. Volumetric flowrate was measured with a Flowtech turbine flowmeter. The magnetic pulses from the turbine meter are input to a pulse rate converter, which measures the number of pulses in a given time frame, and converts the signal to a 4-20 mA output. The accuracy of the flowmeter, according to the manufacturer, is 0.60% of reading, which is a combination of 0.50% linearity, 0.05% repeatability, and 0.05% flow calibration standard.

Figure 23. Piping and instrumentation diagram for test setup.

Figure 24. Photo of evaporator being weighed after sodium fill operation.

Mass Flowrate

The mass flowrate of propane was measured with a Kurz 505 true mass flowmeter, in which the amount of current required to maintain the sensing probe at a set temperature above ambient temperature is proportional to the mass flowrate. The manufacturer's published accuracy is $\pm(2\%$ of reading + $1/2\%$ of full scale) (50 SLPM propane).

Pressure

Propane pressure was measured with a Rosemount pressure transducer, and helium/argon pressures were measured with Square D pressure transducers. Since these transducers were installed to monitor only the presence of adequate pressure, their accuracies are irrelevant for power and efficiency calculations.

V. TEST RESULTS

Unit 1

Summary

Testing of the first unit began on 12/11/90 and was completed on 2/19/91. The system's performance was less than satisfactory. However, with extensive testing and some first order calculations, we were able to pinpoint liquid entrainment as the cause of system instability. When the system was operated at temperatures below 650°C, the liquid sodium appeared to become entrained in the high velocity vapor flow. The entrained liquid sodium becomes suspended at the top of the evaporator tubes and is prevented from reaching the heated tube surfaces. We concluded that it would be possible to prevent liquid entrainment with a minor design modification, which was subsequently used in Unit 2. A detailed description of the first unit's test results follows.

Details

After the gas-fired evaporator was assembled, it was baked-out under a high vacuum for two days at 650°C. The system was then filled by pushing a 180-gm charge of high purity sodium from a fixed-volume container into the heat pipe. This amount of sodium should have almost filled the lower manifold at the 800°C design operating temperature. Preliminary tests, however, indicated that an insufficient charge of sodium was placed in the system, and X-ray photos indicated that only about 75-gm was located in the lower manifold. A second 180-gm charge of sodium was put into the system before the main series of tests was initiated. Weight measurements that were taken during the second filling indicated that the fixed-volume procedure used during the first filling was satisfactory and a full 180-gm charge was probably delivered to the system. (It is suspected that the missing sodium was plated in a thin layer along the surface of the condenser tube.)

Our first attempt to run the gas-fired sodium evaporator was on December 11, 1990 (a detailed summary of the evaporator preparation, fill, and test operations can be found in Appendix IV). Our system had significantly lower back pressures than earlier evaporator systems supplied by Stirling Thermal Motors, so it was necessary to adjust the air/fuel ratio of the propane combustion system. When the system was started, two tubes on the front row and one tube on the second row overheated. X-rays of the evaporator indicated that there was an

insufficient supply of sodium in the lower manifold. After the system was visually inspected for damage and leak tested, the second 180-g charge of sodium was added to the system on January 21, 1991.

The system was started for a second time on January 28, 1991. During these tests, severe temperature cycles were observed on several evaporator tubes. Overheat conditions on two evaporator tubes were visually observed through a window in the combustion chamber. Similar events were measured on a few of the instrumented tubes. The temperature excursions were worse near the front of the evaporator and the cycling was almost negligible in the back tubes. In the largest excursions of the instrumented tubes, the temperature fluctuated over 60°C in a period of about 15-20 seconds. These results are shown in Figure 25a.

After the tests were completed on January 28, we met with other Sandia personnel with sodium heat pipe and pool boiler experience. The possibilities of sonic limits, boiling, and liquid return problems were discussed, but no exact cause for the instabilities was determined in this meeting. It was postulated, however, that the stability may increase if the system was operated at a lower power or a higher temperature. At higher temperatures, the vapor density increases and vapor velocities in the evaporator tubes decrease.

During the next series of tests, the calorimeter was repositioned to cover less of the condenser tube so that less power would be extracted from the heat pipe, and it would be possible to operate at a higher temperature at lower input power levels. A microphone was also strapped to a valve on the gas-fired evaporator during most of these tests. The attempt to operate at a higher temperature in these tests was not successful. Before we could reach a higher temperature, the system again became unstable so the tests were terminated. These tests, however, did provide some insight into what was occurring inside the heat pipe. By carefully correlating the soundtrack with the video, it appeared that the tubes were being quenched by sodium falling from the upper manifold rather than by sodium wicking up from the bottom manifold. The sound in the system was amplified through the steel evaporator structure, so the movement of sodium and the subsequent quenching of the tubes was clearly audible.

Several other tests were also conducted to gain a better understanding of the sodium movement in the gas-fired evaporator. On February 1, the heat pipe was tilted slightly towards the front evaporator to force more sodium to travel toward the front tubes. This change had

Figure 25a. Evaporator temperatures during a period of unstable operation.

little influence on the systems performance, and, when the evaporator was tilted backwards, the results were about the same. An attempt was also made to preheat the system to temperatures above 700°C, but the heater was unable to bring the evaporator up to that temperature with the calorimeter in place. (The system cannot be operated with the gas-fired burner if the calorimeter is off.)

The viewport on the front of the evaporator was invaluable, but it was obvious from the data and the video/audio recording that we were not seeing the whole

picture. At this point, we decided it would be useful to have a viewport along the entire length of the evaporator. A piece of quartz glass, machined to maintain proper tube-to-chamber spacing, was used in place of the insulation along one side of the evaporator. One side of the combustion chamber was removed and the glass was inserted. A camera focused on the side tubes showed that on many occasions several tubes would begin overheating at roughly the same time. After a slug of sodium would fall down one of the overheated tubes (clearly visible on video), a tapping and subsequent sizzling noise could be heard, and then a few seconds later the adjacent

overheated tubes would quench from the bottom up. Apparently, the excess sodium would start filling the lower manifold and begin to feed the adjacent tubes. It is also possible that the sound was caused by the explosive evaporation of the liquid sodium as it hit the hot walls of the evaporator tube. The observation that adjacent tubes were quenched from the bottom up indicated that the wicks would work properly if a supply of liquid sodium was available in the lower manifold. Figure 25b shows images taken from the actual video viewed through quartz windows at the front row of tubes.

Assuming that the average flux on tubes near the front is about 10 W/cm^2 , the vapor velocity in the tubes is about 80 m/sec at an operating temperature of 600°C . Simple calculations have indicated that the high-velocity vapor exiting the evaporator tube could suspend sodium about 6-mm above the top edge of the tube. When this is added to the 3-mm that the tube protrudes into the top manifold, it is apparent that a significant quantity of sodium could be trapped in the top manifold and prevented from reaching the wick in the evaporator tubes. The trapped liquid sodium eventually falls into the evaporator tube either because the hydrostatic head overcomes the vapor's dynamic pressure or the tube begins to dry out as it overheats and the vapor velocity decreases. While these conclusions are somewhat speculative, they do fit the patterns observed in the tests.

One attempt was made to provide a path for the liquid sodium to reach the bottom manifold. Two of the evaporator tubes, one in the fourth row from the front and one in the back row, were insulated to reduce the heat flux on the tubes. This procedure should have reduced the vapor velocity in the two tubes and allowed sodium to spill more easily into the bottom manifold. The performance of the system did improve during this test, but we were still unable to reach a temperature where entrainment was not a problem.

Another final set of tests was performed to further prove the entrainment theory. It was suggested that current probes could be used to measure the liquid level. The test consists of running a current source through the part in question. Since sodium is an excellent electrical conductor, a part filled with sodium will conduct electricity better than a part not filled with sodium. The voltage drop measured indicates the relative amount of sodium in the part.

Nichrome wire was tacked to opposite ends of the lower manifold and opposite ends of the upper manifold (see Figure 26). In the final test, another set of wires was attached to the vapor tube in the liquid return area. Five

amps were passed through each set of probes during the experiment while the corresponding voltage drops were recorded with the data acquisition system. The results were conclusive (see Figure 27). As soon as the propane valve was opened and combustion began, the resistance on the lower manifold ("pool probe") increased rapidly. This is because the flux is the driving force, causing the liquid to wick up the tube walls, as it should. At the same time, the resistance in the upper manifold ("top probe") falls rapidly, indicating the sodium is pooling above the tubes. The probe in the liquid return area ("liquid probe") was erratic, but generally indicated a sodium buildup. The plot also illustrates that immediately after the propane valve is shut, liquid sodium drains from the liquid return area in the condenser and falls into the upper manifold. Finally, the sodium drains into the lower manifold.

Conclusions from Unit 1 Test

The main conclusion from this series of tests was that liquid sodium was becoming entrained in the vapor flow and was prevented from reaching the heated evaporator tube surfaces. First order computations along with extensive testing and video/audio recordings support this conclusion. Entrainment causes temperatures on the tubes to cycle as they overheat and rapidly quench. Operating in this manner is not acceptable for engine testing.

Results from this test lead to the redesign of the evaporator wick structure. To study the impact of possible design modifications on a full-scale evaporator, a small heat pipe with four evaporator tubes was fabricated and then tested at our Engine Test Facility. A different wick structure was installed in each of the four evaporator tubes. Tests on this small heat pipe demonstrated that the instabilities due to dryouts could be eliminated by extending the evaporator tube wick into the upper manifold and providing drain tubes from the upper manifold to the lower manifold. Results from this wick sampler system can be found in Appendix V.

Unit 2

Summary

Testing on UNIT 2 began on 11/05/91 and was completed on 1/27/92. The results indicated that extending the evaporator tube wicks and providing overflow tubes eliminated the instabilities that were encountered with UNIT 1. As a precautionary measure, the depth of the lower manifold was also increased to

Figure 25b. Video images of evaporator during unstable operation.

Figure 26. Location of current probes.

Resistance Probes, Pool and Vapor Tube Temperatures

Figure 27. Current probe resistances during operation.

provide a larger sodium inventory. A larger volume of sodium should ensure that no dryouts occur, especially at lower temperatures ($<600^{\circ}\text{C}$) when the vapor velocity is relatively high. In addition to these measures, a duct was placed inside of the condenser tube to separate the upcoming vapor flow from the returning condensed sodium. This change makes the vapor sweep the condensed liquid to the evaporator section of the heat pipe, and thereby reduces the possibility of entrainment.

A total of 76.7 hours of operation were accumulated on the system, with 17.6 of the operating hours at power levels of 14 kW or above. Near isothermal operation was demonstrated at vapor temperatures from 650°C to 780°C . Instabilities that were observed in previous gas-fired evaporator tests were not encountered with this system.

After 71 hours of operation, a leak developed near a thermowell in the condenser section and air entered the heat pipe. The leak was repaired, but sodium in the pipe was heavily contaminated by oxygen in the air. The repaired heat pipe continued to run for 5 hours before a hole developed in an evaporator tube, caused by oxygen contamination from the condenser leak. The thermowell was not critical to the operation of this system and no problems resulted from eliminating it in future evaporator systems.

The following section discusses the tests on the second gas-fired evaporator, and results from an analysis of the system's failure are also provided.

Details

The second gas-fired evaporator was vacuum-baked at 600°C and then filled with 370 grams of sodium. The required sodium charge was determined by combining the amount needed to fill the lower pan plus the amount of sodium that deposits on all the inner surfaces. This plating thickness was determined by calculating the inventory lost (inventory that did not remain in the pool in the lower manifold) after running the first evaporator unit and the wick sampler heat pipe.

Testing on the second unit began in November 1991. Unstable operation was observed in this unit (see Figure 28), although the temperature oscillations were not as severe as the oscillations in the first unit. In addition, current probe measurements indicated that sodium was returning to the lower manifold, eliminating the entrainment problem observed in Unit 1.

A detailed investigation of the data indicated that the instability could have been caused by excess sodium in the heat pipe. A gamma-beam source/detector system showed that the pool of sodium extended into the evaporator tubes. At an operating temperature of 800°C the liquid sodium would be 46-mm above the lower manifold. Temperatures became unstable in this system when the excess liquid superheated and explosively boiled. In December, 112 grams of sodium were removed and the boiling problems were eliminated.

The accumulation of hydrogen in the heat pipe was another problem encountered in our initial tests of the second gas-fired evaporator. Hydrogen, which was produced in the combustion of propane, diffused through the high temperature evaporator surfaces and collected in the heat pipe. Residual gas analysis of the heat pipe indicated high levels of hydrogen after less than an hour of operation. STM solved this problem with their heat pipes by installing hydrogen diffusers. In an attempt to eliminate the need to refabricate a unit with a hydrogen diffuser, a heater was wrapped around the condenser end of the heat pipe to create a hot region or "window" where hydrogen could exit the heat pipe -- higher wall temperatures enhance the diffusion of hydrogen through metals. The air-fuel ratio was also increased to reduce the amount of hydrogen in the combustion products.

Testing was resumed in late December after the excess sodium was removed. The operation of the evaporator proved to be completely stable. Although we had some trouble with the degradation of the surrounding insulation at the high temperatures and flue gas flow rates, the evaporator operated flawlessly. Startups were very smooth with no dryouts. Power levels in excess of 15 kW (as measured with the calorimeter) were achieved with absolutely stable tube surface and vapor temperatures. Figure 29 is a plot of the surface temperatures on a typical test.

After 71 hours of operation, a leak developed near a thermowell just below the condenser section of the heat pipe. The calorimeter was improperly supported during the first part of the testing program, and as a result of the loading, the calorimeter placed on the condenser section of the heat pipe, unanticipated stresses were induced upon the area where the leak eventually developed. Unfortunately, the system continued to operate at 800°C for over two hours after the leak occurred (but before an overtemperature limit caused a system shutdown), causing sodium in the heat pipe to become heavily contaminated.

Figure 28. Unit 2 data plots illustrating instability due to excess sodium inventory.

Figure 29. Typical Unit 2 data plots after excess sodium inventory removal and installation of condenser heaters to remove hydrogen.

The unit was backfilled with argon and the leak was repaired by removing the thermocouple, cleaning the area mechanically (we did not want to leak alcohol into the heat pipe), and inserting a piece of SS309 welding rod into the thermowell. The thermowell was then welded closed while argon was purged through the system. The heat pipe was then re-evacuated and reinstalled in the combustion evaporator test chamber. After about five hours of operation, a failure occurred in an evaporator tube. This failure was anticipated; sodium oxide that developed in the heat pipe after the first leak was most likely attacking the inner walls and wick structure in the evaporator. The heat pipe was cut open in an argon atmosphere, and the sodium was drained from the evaporator section in the glove box. The evaporator was decontaminated with propanol and water, and taken to Robert Sorenson (Sandia Organization 1834) for a failure analysis.

Failure Analysis of Unit 2

A failure analysis of the evaporator was performed by Robert Sorenson in the Corrosion, Cleaning, and Thin-Film Technology Division at Sandia National Laboratories. Sorenson's investigation determined that the corrosion started inside of the evaporator tube and worked its way through the tube wall. Evidence of corrosion was visible in the screen wicks of several evaporator tubes. Corrosion was concentrated around the area of failure rather than along the entire wick/tube structure. This is common in corrosion failures. Localized high fluxes and the corresponding high temperatures probably accelerated the corrosive action of the oxides.

No evidence of degradation was detected in any weld or braze joints. The braze on one overflow tube did break when the evaporator was cut open, but this failure was apparently caused by a poor initial braze, and not corrosion. Sorenson also noted that the external surface of the evaporator tubes appeared to be in fairly good condition.

To summarize, based on the results of the failure analysis, it appears that neither internal nor external corrosion will be a problem with these evaporators. The strength of the stainless is acceptable at these temperatures since the evaporators will be preheated before operation.

Conclusions from Unit 2 Test

Based on the test results of the second gas-fired evaporator, we were confident with the sodium evaporator's design. Instabilities that were encountered with the first gas-fired evaporator were eliminated with the new wick and condenser design, and the origin of the earlier problems were largely identified by tests on the wick sampler heat pipe.

Even though the evaporator did fail during the test program, the hole in the evaporator was solely a result of sodium contamination that occurred when a leak developed around a stressed thermowell in the condenser. A post-failure inspection of the evaporator indicated that external corrosion will not be a major problem, and all weld and braze joints appeared to be in good condition.

Unit 3

A third prototype evaporator was constructed to fulfill the test plan for the second unit, including performance mapping and the evaluation of different combustion chamber insulating materials. A few modifications were made to the third unit which simplified the fabrication—evaporator tubes were brazed in a single operation rather than welded, screens were not sintered to the tubes, and the screens were supported by tube inserts rather than external rings. These changes have no effect on the internal liquid and vapor flow inside of the evaporator. The bakeout and fill operations were performed in April 1992. Learning from the previous evaporators and the wick sampler, the unit was charged with 258 grams of sodium.

This unit also performed flawlessly with the exception of some external combustion chamber insulation degradation. The evaporator was performance mapped as a function of mass flow rate, sodium vapor temperature, and air/fuel ratio.

The power and efficiency test results are presented in Table II and Figures 30 through 35. Table II data contains the operational parameters along with the resultant power and efficiency. Note that there are two columns for power and efficiency—original data stored in the DAS files, and adjusted results. Power and efficiency numbers were adjusted slightly because the original DAS calculations were based on an estimated water density of 990 kg/m^3 and a specific heat of $4177 \text{ J/kg-}^\circ\text{C}$. In the actual temperature range in which data was taken, the density is 998 kg/m^3 and the specific heat is $4181 \text{ kJ/kg-}^\circ\text{C}$. Therefore the original DAS power are

Figure 30. Sodium evaporator actual and predicted performance at $A/F = 23.5$.

Figure 31. Sodium evaporator actual and predicted performance at $A/F = 22.0$.

Figure 32. Sodium evaporator actual and predicted performance at A/F = 21.0.

Figure 33. Sodium evaporator actual and predicted efficiency at $A/F = 23.5$.

Figure 34. Sodium evaporator actual and predicted efficiency at A/F = 22.0.

Figure 35. Sodium evaporator actual and predicted efficiency at $A/F = 21.0$.

efficiency numbers are multiplied by the ratios (998/990) and (4181/4177). For each measured or calculated parameter, the statistical average and standard deviation are recorded. Each data point was taken over a steady-state three-minute interval at a scan rate of five seconds. Figures 30 through 32 indicate a linear power input with mass flowrate, as expected. Power extracted increases with decreasing vapor temperature because of an increasing temperature difference between the flue gas and the sodium vapor space. Finally, the air/fuel ratio has a large effect on the power throughput. This is a result of the resultant large change in flame temperature with the air/fuel ratio.

It should be noted that the power and efficiency numbers are sensitive to the quality of the insulation package surrounding the evaporator. Flue gas leaks developed on several occasions. These flue gas leaks can be detected by a loss in power and efficiency.

Note that the system efficiency is fairly low. This is primarily due to the fact that none of the exhaust gas is used to preheat the incoming air, which would greatly improve the efficiency. In this test program, the goal was to performance map the engine for solar use and not maximize evaporator efficiency. Therefore, the existing STM combustion chambers were used; no effort was made to redesign a new chamber.

Finally, the accuracy limits need to be addressed. Absorbed power and efficiency uncertainties were estimated using the root-sum square method discussed in detail in Appendix VI. Typical uncertainties for power were 150-200 W while uncertainties on efficiency were about 2-3%.

A testing summary by date for all three test units can be found in Appendix IV.

Table II. Performance Map Data

Run Order	Nominal A/F	Nominal mp (g/sec)	Nominal T _{vap} (C)	Date	Time Begin	Time End	Actual A/F	Actual mp (g/sec)	Actual T _{vap} (C)	Temp #1 L (C)	Temp #1 R (C)	Power Calc (kW)	Eff Calc (%)	Power Adj (kW)	Eff Adj (%)
0*	23.5	0.92	760	11/20/92	10:58:56	11:01:56	23.38 ± 14	.917 ± 001	759.7 ± 07	801.0 ± 2	800.4 ± 3	13.01 ± 055	30.62 ± 13	13.13	30.90
1	23.5	0.55	720	11/20/92	15:56:06	15:59:06	23.57 ± 09	.547 ± 001	719.5 ± 21	758.4 ± 3	750.5 ± 3	8.63 ± 077	33.99 ± 30	8.71	34.30
2	23.5	0.55	750	11/20/92	15:50:01	15:53:01	23.61 ± 10	.547 ± 001	749.6 ± 07	785.8 ± 2	778.8 ± 3	8.19 ± 029	32.29 ± 13	8.26	32.58
3	23.5	0.60	775	11/20/92	15:43:41	15:46:41	23.34 ± 08	.598 ± 001	774.6 ± 04	811.1 ± 2	804.8 ± 2	8.66 ± 027	31.19 ± 10	8.74	31.47
4	23.5	0.70	720	11/20/92	15:06:31	15:09:31	23.60 ± 09	.695 ± 001	719.6 ± 05	763.8 ± 2	757.3 ± 2	11.09 ± 033	34.44 ± 11	11.19	34.75
5	23.5	0.70	750	11/20/92	15:28:11	15:31:11	23.26 ± 08	.701 ± 001	749.6 ± 09	791.8 ± 2	785.1 ± 3	10.44 ± 068	32.10 ± 21	10.53	32.39
6	23.5	0.70	775	11/20/92	15:35:36	15:38:36	23.61 ± 09	.700 ± 001	774.6 ± 08	813.4 ± 2	808.0 ± 2	10.04 ± 041	30.94 ± 14	10.13	31.22
7	23.5	0.92	720	11/20/92	14:59:56	15:02:56	23.49 ± 12	.917 ± 001	719.6 ± 07	764.2 ± 2	762.2 ± 3	13.84 ± 046	32.55 ± 13	13.96	32.84
8	23.5	0.92	750	11/20/92	14:53:56	14:56:56	23.42 ± 13	.917 ± 002	749.6 ± 05	791.4 ± 2	789.5 ± 3	13.23 ± 059	31.14 ± 14	13.35	31.42
9	23.5	0.92	775	11/20/92	14:48:21	14:51:21	23.33 ± 11	.916 ± 001	774.6 ± 04	814.4 ± 2	812.9 ± 3	12.74 ± 035	30.01 ± 09	12.85	30.28
10	22.0	0.55	720	11/20/92	13:19:51	13:22:51	22.10 ± 10	.543 ± 001	719.6 ± 13	761.5 ± 3	752.7 ± 4	8.81 ± 045	35.02 ± 18	8.89	35.34
11	22.0	0.55	750	11/20/92	13:27:41	13:30:41	22.14 ± 08	.542 ± 001	749.7 ± 05	788.6 ± 2	780.8 ± 2	8.35 ± 044	33.22 ± 19	8.43	33.52
12	22.0	0.60	775	11/20/92	13:37:56	13:40:56	21.89 ± 09	.600 ± 001	774.7 ± 05	814.2 ± 2	807.2 ± 2	9.01 ± 039	32.39 ± 14	9.09	32.68
13	22.0	0.70	720	11/20/92	14:20:06	14:23:06	21.93 ± 09	.704 ± 001	719.6 ± 06	770.7 ± 2	761.2 ± 2	11.62 ± 036	35.59 ± 13	11.72	35.91
14	22.0	0.70	750	11/20/92	14:13:26	14:16:26	21.94 ± 09	.703 ± 001	749.6 ± 09	797.4 ± 2	789.1 ± 3	11.21 ± 092	34.39 ± 29	11.31	34.70
15	22.0	0.70	775	11/20/92	14:05:41	14:08:41	22.07 ± 09	.697 ± 001	774.7 ± 05	818.9 ± 2	811.5 ± 3	10.56 ± 065	32.68 ± 21	10.66	32.97
16	22.0	0.92	720	11/20/92	14:29:06	14:32:06	22.00 ± 09	.915 ± 001	719.7 ± 07	775.0 ± 2	767.8 ± 2	14.95 ± 046	35.25 ± 12	15.08	35.57
17	22.0	0.92	750	11/20/92	14:34:41	14:37:41	22.08 ± 08	.913 ± 001	749.7 ± 05	801.2 ± 2	795.0 ± 3	14.44 ± 057	34.10 ± 13	14.57	34.41
18	22.0	0.92	765	11/20/92	14:40:26	14:43:26	22.18 ± 08	.912 ± 001	764.7 ± 09	814.0 ± 2	808.5 ± 3	14.06 ± 038	33.26 ± 09	14.19	33.56
19	21.0	0.55	720	11/20/92	13:09:36	13:12:36	21.10 ± 09	.546 ± 001	719.6 ± 14	764.4 ± 3	754.4 ± 3	9.19 ± 048	36.32 ± 20	9.27	36.65
20	21.0	0.55	750	11/20/92	13:00:56	13:03:56	21.13 ± 07	.546 ± 001	749.6 ± 04	791.6 ± 2	782.6 ± 2	8.79 ± 045	34.73 ± 20	8.87	35.04
21	21.0	0.60	775	11/20/92	12:49:46	12:52:46	21.01 ± 08	.598 ± 001	774.6 ± 12	816.3 ± 3	808.2 ± 3	9.28 ± 034	33.48 ± 13	9.36	33.78
22	21.0	0.70	720	11/20/92	12:20:56	12:23:56	20.89 ± 07	.697 ± 001	719.7 ± 06	772.1 ± 2	762.6 ± 3	12.09 ± 040	37.39 ± 13	12.20	33.69
23	21.0	0.70	750	11/20/92	12:31:11	12:34:11	20.81 ± 10	.697 ± 001	749.7 ± 04	799.4 ± 2	790.6 ± 3	11.61 ± 052	35.94 ± 18	11.71	36.26
24	21.0	0.70	775	11/20/92	12:39:31	12:42:31	20.75 ± 07	.697 ± 001	774.7 ± 06	822.0 ± 2	814.1 ± 2	11.21 ± 063	34.67 ± 20	11.31	34.98
25	21.0	0.92	730	11/20/92	12:08:31	12:11:31	20.75 ± 06	.928 ± 001	729.7 ± 07	789.1 ± 3	781.0 ± 3	15.99 ± 064	37.17 ± 15	16.13	37.50
26	21.0	0.92	750	11/20/92	11:59:56	12:02:56	20.80 ± 08	.926 ± 001	749.7 ± 04	806.9 ± 2	799.6 ± 3	15.58 ± 050	36.28 ± 14	15.72	36.61
27	21.0	0.92	765	11/20/92	11:53:21	11:56:21	20.86 ± 05	.925 ± 001	764.7 ± 04	820.1 ± 2	813.2 ± 3	15.19 ± 042	35.44 ± 11	15.33	35.76
28*	23.5	0.92	760	11/20/92	16:10:06	16:13:06	23.51 ± 10	.918 ± 001	759.6 ± 04	800.0 ± 2	798.3 ± 2	12.86 ± 055	30.22 ± 13	12.98	30.49

* Used to check against previous mapping on 5/19/92, Power = 12.4 kW, Efficiency = 29.0%

Note: Actual surface temperatures #1L and #1R are reversed from what is tabulated in last two columns (data directly from DAS files).

Unit #3 is a mirror image of unit #2, but DAS was not changed so that files between the different evaporators remain the same.

VI. SUMMARY AND CONCLUSIONS

Three gas-fired sodium evaporators were designed, built and tested to develop a reliable system for delivering power to a 25-kWe Stirling engine. Each prototype evaporator consisted of a bank of 40 tubes with common plenums (or reservoirs) at the top and bottom. Hot gases pass over the outside of the bank of tubes, and heat is removed by the evaporation of liquid sodium on the inner walls of the tubes. A wick structure in each tube transfers liquid sodium across the heated tube surface.

In the first prototype unit, the evaporator wicks only extended into the lower manifold. From tests on the first unit, it was determined that the liquid in the top manifold must be given a route to enter the wick structure that is isolated from the flow of vapor. By extending the evaporator wicks into the top manifold, an isolated path was provided for the liquid to enter the wick. Overflow tubes were also provided in one quarter of the tubes to prevent excess liquid from accumulating in the upper manifold. A U.S. patent (No. 5,275,232) was granted on the improved wick design.

The improved wick structure was incorporated into the second and third prototype evaporators. The improved wick structure performed flawlessly in these two units. Performance mapping and durability tests were performed on these two evaporators. The desired power throughput of 15 kW was achieved on a routine basis with the third unit.

The final (and recommended) wick configuration that was used on UNIT 3 is illustrated in Figure 20. The wick is made of nine layers of 200-mesh stainless steel screen (316L grade) which is held against the inner surface of the evaporator tube by a stainless steel screen. It was not necessary to sinter the screen in place, so the wicks can be installed after the tubes are brazed or welded into the manifolds. The wick extends into both the top and the bottom manifold, and short tubes are pressed into the extended portions for support. Holes in the lower extensions and support tubes allow vapor to vent from the lower manifold. Ten of the 40 evaporator tubes are equipped with a overflow tube that allows liquid to drain from the top manifold without flowing over the heated wick surfaces.

Eight evaporators based on UNIT 3 design were fabricated from SS321. Four of these units were interfaced with the STM heater heads and engine testing resumed. The evaporators proved to be much more reliable and durable than the STM evaporators. The only

instabilities that occurred were traced back to liquid entrainment in the engine heater heads at high power levels. Future work could include fabricating four units from Haynes 230. While we are confident that the 321 stainless units will be satisfactory, Haynes 230 has superior properties with respect to strength, lower coefficient of expansion (lower thermal stresses during startup), and external oxidation resistance. In addition, endurance testing using 24-hour operation would be needed to prove long-term durability.

It should be noted that this evaporator is not limited to Stirling engine testing. These units could be used to provide thermal energy to many other devices requiring a uniform temperature distribution. Examples include extrusion dies, isothermal ovens, and heat recovery systems.

Acknowledgments

Several people contributed to the success of this project and they deserve recognition. We would like to acknowledge the work of Ron Dykhuizen in helping us find the level of sodium in the heat pipe, and we also want to recognize Walt Einhorn and Daniel Ray for the many hours they spent preparing the facility for the heat pipe tests. In addition, we would like to thank the personnel who assisted in the operation of the pipe on overnight runs. Finally, we would like to thank Phyllis Blair for assisting us in preparing this report.

REFERENCES

1. Linker, K.L., K.S. Rawlinson, and G.A. Smith, *Finite Element Analysis, Test Description and Preliminary Test Results of the STM4-120 Kinematic Stirling Engine*, SAND90-1162, Albuquerque: Sandia National Laboratories, October 1990.
2. Zhukauskas, A., "Heat Transfer from tubes in Cross Flow" in J. P. Hartnett and T. F. Irvine, Jr. Eds., *Advances in Heat Transfer*, Vol. 8, Academic Press, New York, 1972.
3. Siegel, R. and J. R. Howell, *Thermal Radiation Heat Transfer*, 2nd ed., McGraw-Hill Book Company, NY, 1981.
4. Incropera, Frank P., Dewitt, David P., *Fundamentals of Heat Transfer*, John Wiley & Sons, New York, 1981.
5. Kays, W. M., and A. L. London, *Compact Heat Exchangers*, 2nd ed., McGraw-Hill, NY, 1964.
6. Kattus, J. R., "Aerospace Structural Metals Handbook," code 1308, 1976.
7. Adkins, D.R., and Moss, T.A., "Measuring Flow Properties of Wicks for Heat-Pipe Solar Receivers," Proceedings of the 12th Annual Solar Energy Conference, pp. 103-108, April 1-4, 1990, Miami, FL.
8. Dunn, P.D., and Reay, D.A., *Heat Pipes*, 3rd edition, Pergamon Press, Oxford, UK, 1982.
9. Wallis, G.B., *One Dimensional Two Phase Flow*, McGraw-Hill, 1969.
10. Tien, C.L., and Chung, K.S., "Entrainment Limits in Heat Pipes," AIAA Paper 78-382, Proceedings of the Third International Heat Pipe Conference, Palo Alto, CA, 1978.
11. Cole, N. C., "Corrosion Resistance of Brazed Joints," Welding Research Council Bulletin 247, United Engineering Center, New York, April 1979.
12. Reid, Robert C., Prausnitz, John M., Sherwood, Thomas K., *The Properties of Gases and Liquids*, McGraw-Hill, New York, 1977.
13. Ibid.
14. Gijsbers, F., J. C. Wilhelmus, H. H. Otto, and O. H. Uhlemann, 1976, "Apparatus for Evaporating Liquids," U.S. Patent 3,977,364 assigned to U.S. Philips Corporation, August 31, 1976.
15. Doebelin, E.O., *Measurement Systems*, McGraw-Hill Publishing Company, New York, NY, 1983.

APPENDIX I

Conceptual Designs for a New Evaporator

APPENDIX I

Conceptual Designs for a New Evaporator

Wicked multiple heat pipe tubes / sodium pool.

Advantages

Na pool to eliminate dryout
Use existing burners

Disadvantages

Same high flux problems on leading edge.

Pool boiler - external electrical heater

Advantages

No internal immersion heater -no additional welds

Disadvantages

Need insulated box for each evap

Need air cooling for fast drop in control temp and during shutdown

Pool boiler - immersion heater

Advantages

No propane system needed

Disadvantages

Need to machine pits in heater element (boiling initiators)

Have to install element in vessel

Pool boiler - internal fire tube

Advantages

If used four, could use existing combustion skid for fuel/air mixture, control

Disadvantages

Internal vessel harder to fabricate (more welds)

Pool boiler with external concentric propane-fired burner

Advantages

Use existing propane control skid

Disadvantages

Need to purchase or design/fabricate concentric burner

APPENDIX IIA.

Detailed Combustion Product
Thermodynamic Property AnalysisFluid Properties:

The heat transfer coefficient is dependent on many conditions, such as fluid properties, tube surface temperature, freestream temperature, and the tube configuration. In this case, accurate calculations of fluid properties are difficult because the gas is not a single component but is a mixture of several gases. To reduce hydrogen generation, which can diffuse into the heat pipes and prevent sodium from reaching the condenser, the fuel is typically run with excess air. The fuel used at the NSTTF is propane. When propane reacts with excess air, the major combustion products are carbon dioxide, oxygen, nitrogen, and water. The proportions of these components depend on the air/fuel ratio. Mixture properties needed are viscosity, thermal conductivity, specific heat, and density. Each of these are now discussed.

Dynamic Viscosity:

The dynamic viscosity of a gas mixture at low pressure can be calculated by an approximation to the kinetic theory of Chapman-Enskog [12]. The mixture viscosity is

$$\mu_m = \frac{\sum_{i=1}^n y_i \mu_i}{\sum_{j=1}^n y_j \phi_{ij}} \quad (1)$$

where μ_m = viscosity of mixture, [N-sec/m²]
 y_i = mole fraction of component i,
 μ_i = viscosity of component i, [N-sec/m²]
 ϕ_{ij} = parameter to be defined later,

The viscosity of an individual gas component can be found using the equation

$$\mu_i = 26.69 \frac{\sqrt{M_i T}}{\sigma^2 \Omega_v} \quad (2)$$

where μ_i = viscosity of the component, [micropoise]
 M_i = molar mass of the component, [kg/kg-mole]
 T = gas temperature, [K]
 σ = hard-sphere diameter, [angstroms]
 Ω_v = collision integral

The collision integral, Ω_v , is given as

$$\Omega_v = \frac{A}{T^{*B}} + \frac{C}{e^{DT^*}} + \frac{E}{e^{FT^*}} + \frac{0.2\delta^2}{T^*} \quad (3)$$

for $0.3 \leq T^* \leq 100$

where T^* = dimensionless temperature
 $A = 1.16145$

$$\begin{aligned} B &= 0.14874 \\ C &= 0.52487 \\ D &= 0.77320 \\ E &= 2.16178 \\ F &= 2.43787 \\ \delta &= \text{polar parameter} \end{aligned}$$

The polar parameters, which represent the dipole-dipole interactions between the molecules, are tabulated in [12], and are zero unless the molecule is polar—in this case, water vapor.

The dimensionless temperature is defined as

$$T^* = \frac{kT}{\varepsilon} \quad (4)$$

where T = gas mixture temperature [K]
 k = Boltzmann's constant [J/K]
 ε = characteristic energy [J]

Values of ε/k are tabulated in [12].

The next step is to determine the parameter ϕ_{ij} . The flue gases contain water vapor, which is a polar molecule. For polar-non-polar mixtures, Browkaw's approximation provides the most accurate method [12] of obtaining ϕ_{ij} :

$$\phi_{ij} = \left\{ \frac{\mu_i}{\mu_j} \right\}^{1/2} S_{ij} A_{ij} \quad (5)$$

The parameter A_{ij} is a function of the molecular-weight ratios and is given as

$$A_{ij} = m_{ij} M_{ij}^{-1/2} \left[1 + \frac{M_{ij} - M_{ij}^{0.45}}{2(1 + M_{ij}) + \frac{(1 + M_{ij}^{0.45})m_{ij}^{-1/2}}{1 + m_{ij}}} \right] \quad (6)$$

with m_{ij} as

$$m_{ij} = \left[\frac{4}{(1 + M_{ij}^{-1})(1 + M_{ij})} \right]^{0.25} \quad (7)$$

and

$$M_{ij} = \frac{M_i}{M_j} \quad (8)$$

The parameter S_{ij} is calculated from

$$S_{ij} = S_{ji} = \frac{1 + (T_i^* T_j^*)^{1/2} + (\delta_i \delta_j / 4)}{\left[1 + T_i^* + (\delta_i^2 / 4)\right]^{1/2} \left[1 + T_j^* + (\delta_j^2 / 4)\right]^{1/2}} \quad (9)$$

The polar parameters δ_i and δ_j are used only if either is greater than 0.1. Otherwise, $S_{ij} = S_{ji} = 1.0$.

After equations (5) through (9) are evaluated, the numbers are finally substituted into equation (1) to obtain the dynamic viscosity of the mixture.

The estimated error for the viscosity is less than 4% for polar-non-polar mixtures [12].

Specific Heat at Constant Pressure:

The molar specific heats at constant pressure are easily calculated for the gas components with the following polynomials [12] (units are cal/g-mole-K):

$$\text{CO}_2: \quad \bar{c}_p = -0.89286 + 7.2967\theta^{0.5} - 0.98074\theta + 5.7835 \times 10^{-3}\theta^2 \quad (10)$$

$$\text{N}_2: \quad \bar{c}_p = 9.3355 - 122.56\theta^{-1.5} + 256.38\theta^{-2} - 196.08\theta^{-3} \quad (11)$$

$$\text{O}_2: \quad \bar{c}_p = 8.9465 + 4.8044 \times 10^{-3}\theta^{1.5} - 42.679\theta^{-1.5} + 56.615\theta^{-5} \quad (12)$$

$$\text{H}_2\text{O}: \quad \bar{c}_p = 34.190 - 43.868\theta^{0.25} + 19.778\theta^{-0.5} - 88407\theta \quad (13)$$

where $\theta = T/100$,
 $T = \text{temperature of gas, [K]}$

The errors are less than 0.5% for the components of interest.

The molar specific heat for the mixture is calculated by weighting the component specific heats with their corresponding mole fractions:

$$\bar{c}_{p,m} = y_i \bar{c}_{p,i} \quad (14)$$

where $\bar{c}_{p,m}$ = molecular specific heat of mixture, [cal/g-mole-K]
 y_i = mole fraction of component i,
 $\bar{c}_{p,i}$ = molecular specific heat of component i, [cal/g-mole-K]

In a similar fashion, the apparent molecular mass of the mixture is weighted by multiplying the component molecular weights with the appropriate mole fractions:

$$M_m = y_i M_i \quad (15)$$

where M_m = apparent molecular weight of mixture, [g/g-mole]
 M_i = molecular weight of component i, [g/g-mole]

Finally, the mass-specific heat of the mixture can be obtained by the following:

$$c_{p,m} = \frac{\bar{c}_{p,m}}{M_m} \quad (16)$$

where $c_{p,m}$ = mass specific heat of mixture, [cal/g-K]
 $\bar{c}_{p,m}$ = molar specific heat of mixture, [cal/g-mole-K]

Thermal Conductivity:

The thermal conductivity of a low-pressure gas mixture is approximated with the Wassiljewa equation [13]:

$$\lambda_m = \sum_{i=1}^n \frac{y_i \lambda_i}{\sum_{j=1}^n y_j A_{ij}} \quad (17)$$

where λ_m = thermal conductivity of mixture [cal/cm-sec-K]
 λ_i = thermal conductivity of component i [cal/cm-sec-K]
 y_i, y_j = mole fractions of components i and j
 A_{ij} = function defined below,

The function A_{ij} is approximated using the Mason and Saxena relation [13]:

$$A_{ij} = \kappa \left[\frac{\left[1 + (\lambda_{tri} / \lambda_{trj})^{1/2} (M_i / M_j)^{1/2} \right]^2}{\left[8(1 + M_i / M_j) \right]^{1/2}} \right] \quad (18)$$

where M_i, M_j = molecular weight of components i and j [kg/kg-mole]
 λ_{tri} = monotomic value of thermal conductivity [cal/cm-sec-K]
 κ = numerical constant = 1.0

The monotomic thermal conductivity ratio above is obtained from

$$\frac{\lambda_{tri}}{\lambda_{trj}} = \frac{\mu_i}{\mu_j} \frac{M_j}{M_i} \quad (19)$$

where μ_i, μ_j = dynamic viscosity from previous section

Next, the individual thermal conductivities are needed. The conductivities are evaluated from the Eucken correlation for polytomic gases [13]:

$$\frac{\lambda_i M_i}{\mu_i} = \bar{c}_v + 4.47 \quad (20)$$

where λ_i = thermal conductivity of component i, [cal/cm-sec-K]
 $\bar{c}_v$ = molar specific heat at constant volume of component i, [cal/g-mole-K]

The molar specific heats at constant volume are calculated from the following:

$$\bar{c}_v = \bar{c}_p - R \quad (21)$$

where $\bar{c}_p$ = molar specific heat at constant pressure, [cal/g-mole-K]
 R = universal gas constant = 1.987 cal/g-mole-K

The constant pressure specific heats are calculated using the method outlined in the previous section.

After equations (18) through (21) are evaluated, the thermal conductivity can be obtained by substituting into equation (17).

The errors associated with thermal conductivity are higher than for viscosity, but are generally within 10%.

Prandtl Number:

The Prandtl number is a ratio of molecular momentum to thermal diffusivity. For the gas mixture, the Prandtl number is

$$Pr = \frac{c_{p,m} \mu_m}{\lambda_m} \quad (22)$$

The properties in the equation are obtained from the previous sections.

Density:

The density of the mixture was calculated by using the ideal gas law, quite valid since the gas is at high temperature and low pressure. Thus

$$\rho_m = \frac{P}{R_m T} \quad (23)$$

where ρ_m = density of mixture, [kg/m³]
 P = gas pressure, [Pa]
 R_m = gas constant for mixture, [J/kg-K]
 T = temperature of gas, [K]

The gas constant for the mixture is obtained by using the universal gas constant and the apparent molecular weight for the mixture:

$$R_m = R_u / M_m \quad (24)$$

where R_u = universal gas constant, [8315 J/kg-mole-K]
 M_m = apparent molecular mass of mixture, [kg/kg-mole]

Property Data Results:

The calculated property data for the components of interest are compared to tabular data from references [2] and [4]. The results are presented in Table II.A-I.

Calculated values of viscosity are, in general, within their advertised error limits of 4%. The only exception is water vapor, which is approximately 8.6% low.

As stated in [13], the thermal conductivity accuracies for polar-non-polar gas mixtures vary significantly, and are not as accurate as viscosity correlations. The errors for conductivity ranged from 1% to 17%, the 17% error for water vapor.

The overall accuracy of property data is considered to be sufficient for evaporator design. The methods presented here are better than assuming a single component gas. In addition, the evaporator testing will be performed near 50% excess air. With the air/fuel ratio in this range, the property data are heavily weighted by the nitrogen mole fraction. The results for nitrogen are quite accurate.

Appendix IIA. Detailed Combustion Product Thermodynamic Property Analysis

Table IIA-I. Comparison of Calculated Property Data vs. Tabular Data

Vis x 10 ⁷ {N-sec/m ² }						k x 10 ³ {W/m-K}					c _p {J/kg-K}				
Calculated	Tabular(1)	% Error(1)	Tabular(2)	% Error(2)		Calculated	Tabular(1)	% Error(1)	Tabular(2)	% Error(2)	Calculated	Tabular(1)	% Error(1)	Tabular(2)	% Error(2)
800K															
CO ₂	335	337	0.6%	339	1.2%	47	55	14.5%	56	16.0%	1167	1170	0.25%	1168	0.08%
H ₂ O	255	279	8.6%	N/A	-	69	59	-17.0%	N/A	-	2157	2152	-0.23%	N/A	-
O ₂	412	415	0.72%	421	2.1%	57	59	3.4%	60	5.0%	1053	1054	0.09%	1054	0.09%
N ₂	342	349	2.0%	352	2.9%	51	55	7.3%	54	5.5%	1127	1122	-0.44%	1122	-0.44%
1300K															
CO ₂	468	N/A	-	474	1.3%	72	N/A	-	83	13.2%	1297	N/A	-	1298	0.08%
H ₂ O	418	N/A	-	N/A	-	128	N/A	-	N/A	-	2489	N/A	-	N/A	-
O ₂	566	588	3.7%	567	0.18%	82	87	5.8%	87	5.8%	1124	1125	0.09%	1125	0.09%
N ₂	468	466	0.43%	471	0.64%	74	81	8.6%	75	1.3%	1218	1219	0.08%	1219	0.08%

1. Data from Fundamentals of Heat Transfer [4]
2. Data from Compact Heat Exchangers [5]
3. Method of calculation from The Properties of Gases and Liquids [12]

Results:

- Viscosity quite accurate, worst case is H₂O, but <10% error. In line with Ref [12], stated within 4%.
- Conductivity 3-18% error, in line with correlation accuracy stated in Ref [12], stating ~10%.
- Overall properties should be accurate in our case, since N₂ has the largest mole fraction, and properties for N₂ are accurately predicted.

APPENDIX IIB

Start-Up Temperature Distribution in the Evaporator Tube Bank

The evaporator system was generally preheated up to a tube temperature of 100°C or higher to melt the sodium before the combustor was ignited. After ignition, however, very little heat will be transferred from the evaporator tubes until the vapor temperature exceeds about 600°C. (At lower temperatures, evaporation rates are too small to efficiently remove heat from the tubes.) During this startup period, the front row of tubes will be much hotter than the rear row of tubes because of the higher gas temperatures in the front row.

The temperature distribution in the tube bank was estimated using a simple lumped-mass heat transfer model. Figure II.B.1 illustrates the combustion gas flow through the bank of tubes. As the gases pass from row 1 to row 2, energy is delivered to the tubes and the gas temperature drops in accordance with the relationship,

$$\dot{m}_g C_{pg} (T_{gA} - T_{gB}) = N_T S_T h_T (T_{gA} - T_{T2}) = 4 Q_{TUBE2} ,$$

where the term on the left is the change in enthalpy of the gas, $N_T S_T$ is the surface area of N_T tubes, h_T is the heat transfer coefficient between the gas and the tubes, and $(T_{gA} - T_{T2})$ is the temperature difference between the gas and the outer surface of the tube.

Figure II.B.2 illustrates the heat transfer to the tube and the wick. This energy transfer can be expressed as a coupled pair of equations,

$$\delta_T S_T \rho_T C_T \frac{dT_T}{dt} = Q_{TUBE} - Q_{WICK}$$

and

$$\delta_W S_W \rho_W C_W \frac{dT_W}{dt} = Q_{WICK} - Q_{VAPOR} .$$

The left side of the first equation represents of the rate of increase of sensible energy in the tube and the left side of the second equation represents the rate of increase of energy stored in the wick. Q_{VAPOR} is the energy removed from the tube by the evaporation of liquid sodium. It was assumed that Q_{VAPOR} could be ignored at temperatures below 500°C. Q_{WICK} is the energy that is transferred from the wall of the evaporator tube to the saturated wick structure. This energy transfer to the wick can be treated as simple conduction problem. However, to obtain an estimate of the maximum temperature gradient through the tube bank, the tube wall and the wick structure were lumped together. With these simplifying assumptions, the above equations can be solved for the temperature of each row of tubes and the gas temperature drop across each row of tubes.

For an upstream gas temperature of T_{gi} , the temperature of the i^{th} row of tubes is

$$T_{Ti} - T_{gi} = (T_0 - T_{gi}) e^{-t/\tau_c} ,$$

where $\tau_c = \delta_T \rho_T C_T / h_T$ and T_0 is the initial temperature of the temperature of the tube bank. The gas temperature drop across each tube row is

$$T_{gi+1} - T_{gi} = \alpha_c (T_{Ti} - T_{gi}) ,$$

Figure II.B.1. Heat transfer in tube bank.

Figure II.B.2. Heat transfer in evaporator tube.

where $\alpha_c = N_T S_T h_T / n C_{pg}$. Based on the evaporator heat transfer model, the combustion gas was estimated to have a typical mass flow rate of 5 g/s during startup with $h_T = 165 \text{ W/m}^2\text{K}$ and $C_{pg} = 1330 \text{ J/kgK}$. The time constant τ_c will be on the order of 20 seconds for the tube rows and the thermal diffusivity α_c is approximately 0.33.

With a combustion gas temperature of 1814K (1541°C) and an initial tube temperature of 25°C, the maximum temperature variation across the ten rows of tubes would be as follows:

Row #1:	380°C
Row #2:	290°C
Row #3:	221°C
Row #4:	170°C
Row #5:	132°C
Row #6:	103°C
Row #7:	81°C
Row #8:	64°C
Row #9:	52°C
Row #10:	43°C

In reality, the thermal gradient will be less severe than this prediction because the tube-bank will be preheated before gases in the combustion chamber are ignited. These predicted temperatures were used, however, to determine the maximum possible startup stress on the evaporator.

APPENDIX III

Heat Transfer Code and Sample Output

```

10  ! *****
20  ! *
30  ! *           Heat Transfer Calculations           *
40  ! *
50  ! *
60  ! *   Filename:  TUBEBANK           Revised:  25 July 90   *
70  ! *
80  ! *
90  ! *
100 ! *           Written for HP 9845 by KSR, 6215, 3/90       *
110 ! *
120 ! *           Conversion to HP 9000/340, BASIC 5.1, 7/23/90   *
130 ! *
140 ! *****
150 !
160 !
170 !   Heat xfer program for calculating heat transfer coefficients
180 !   and total heat xfer across tube banks.
190 !
200 !   Assumes staggered configuration.
210 !   See "Fundamentals of Heat Transfer", 353-358 for details.
220 !
230 !   Gas properties are calculated assuming combustion of propane
240 !   and air, using 50% excess air. The correlations for dynamic
250 !   viscosities and thermal conductivities, and these properties
260 !   as a mixture are taken from "The Properties of Gases and Liquids",
270 !   by Reid, Prausnitz, and Sherwood.
280 !
290 !   The properties for specific heat at constant pressure are
300 !   taken from "           ", Table A.9
310 !
320 !
330 !   DIM Comp_name$(1:4)[18]
340 !   DIM M(1:4),N_mole(1:4),Epsk(1:4),Sigma(1:4),Delta(1:4)
350 !   DIM Y(1:4),T_star(1:4),Vis(1:4),Cp_molar(1:4),Cond(1:4)
360 !   DIM N_tubes(1:10)
370 !
380 !   COM Init$(10)           !   Program variable initialization flag
390 !   COM Hard_copy$(4)       !   Hard copy printer flag
400 !   COM T_flame             !   Flame temperature
410 !   COM T_prop              !   Temperature for gas properties
420 !   COM Flow                !   Gas mass flowrate
430 !   COM Prop_kbd$(4)        !   Keyboard data input flag
440 !   COM Den                 !   Density
450 !   COM Cp                  !   Specific heat
460 !   COM Vis_d               !   Dynamic viscosity
470 !   COM K_fluid             !   Thermal conductivity
480 !   COM Pr_infin            !   Prandtl number
490 !   COM Prs                 !   Prandtl number, surface
500 !
510 !
520 !   CLEAR SCREEN
530 !   KEY LABELS OFF
540 !   USER 1 KEYS
550 !
560 !   Printer=9           !   Address of hard copy printer
570 !
580 !
590 !
600 !   Combustion products and gas correlation constants

```

Appendix III. Heat Transfer Code and Sample Output

```

620  !
630  !
640  !   Subscripts:
650  !     i=1: CO2
660  !     i=2: H2O
670  !     i=3: O2
680  !     i=4: N2
690  !
700  N_gas=4           ! Number of gases in mixture
710  Comp_name$(1)="CO2"! Name of component
720  Comp_name$(2)="H2O"
730  Comp_name$(3)="O2"
740  Comp_name$(4)="N2"
750  M(1)=44          ! Molar mass of each component
760  M(2)=18
770  M(3)=32
780  M(4)=28
790  N_mole(1)=3       ! Number of moles of each combustion product
800  N_mole(2)=4
810  N_mole(3)=2.5
820  N_mole(4)=28.2
830  Epsk(1)=195.2     ! Characteristic energy/Boltzmann's constant
840  Epsk(2)=809.1
850  Epsk(3)=106.7
860  Epsk(4)=71.4
870  Sigma(1)=3.941    ! Sphere diameter
880  Sigma(2)=2.641
890  Sigma(3)=3.467
900  Sigma(4)=3.798
910  Delta(1)=0        ! Polar parameter (water molecule is polar)
920  Delta(2)=1
930  Delta(3)=0
940  Delta(4)=0
950  Pressure_gas=101300 ! Gas pressure of mixture (N/m^2)
960  !
970  !
980  !   Heat exchanger parameters
990  !
1000 !
1010 !
1020 T_na=1053         ! Sodium temp inside tubes (K)
1030 Height=.083       ! Chamber height (m)
1040 Wide=.072         ! Chamber width (m)
1050 H_na=1.E+99       ! Film coeff for sodium (W/m^2-K)
1060 N_rows=10         ! Number of rows of tubes
1070 N_tubes(1)=4       ! Number of tubes in row 1
1080 N_tubes(2)=4
1090 N_tubes(3)=4
1100 N_tubes(4)=4
1110 N_tubes(5)=4
1120 N_tubes(6)=4
1130 N_tubes(7)=4
1140 N_tubes(8)=4
1150 N_tubes(9)=4
1160 N_tubes(10)=4
1170 L_tube=Height     ! Length of tube (m)
1180 D_tube=.0127      ! Tube OD (m)
1190 Wall=.030*.0254   ! Wall thickness (m)
1200 K_tube=24         ! Conductivity of wall (W/m-K)

```

```

1220 S1=.015      ! Tube spacing longitudinal direction (m)
1230 !
1240 !
1250 !      Other initial values
1260 !
1270 !
1280 !
1290 IF Init$="TUBE BANK" THEN Begin
1300 !
1310 Hard_copy$="N"      ! Hard copy printer flag
1320 T_flame=2000      ! Flame temperature (K)
1330 T_prop=1000      ! Operating temperature (K)
1340 Flow=20      ! Gas flowrate (g/sec)
1350 Prop_keybd$="N"      ! Keyboard input flag
1360 Vis_d=5.00E-5      ! Dynamic viscosity (N-sec/m)
1370 K_fluid=.085      ! Thermal conductivity (W/m-K)
1380 Pr_infin=.7      ! Prandtl number
1390 Prs=.70      ! Prandtl number, surface
1400 Den=.235      ! Density (kg/m^3)
1410 Cp=1300      ! Specific heat (J/kg-K)
1420 Init$="TUBE BANK"      ! Variable initialization flag
1430 !
1440 Begin: CALL Title      ! Print opening CRT screen
1450 !
1460 !
1470 Iteration=1
1480 OUTPUT KBD;Hard_copy$;
1490 DISP " Do you want a hard copy of results ? (Y/N) ";
1500 LINPUT "(Default = NO ) ",Hard_copy$
1510 OUTPUT KBD;T_flame;
1520 INPUT "Enter T_flame (K) ",T_flame
1530 OUTPUT KBD;T_prop;
1540 INPUT " Enter temp at which to evaluate properties (K) ",T_prop
1550 OUTPUT KBD;Flow;
1560 INPUT "Enter flowrate of mixture (g/sec) ",Flow
1570 Mdot=Flow/1000
1580 DISP " Do you want to input gas properties ? (Y/N) ";
1590 OUTPUT KBD;Prop_keybd$;
1600 INPUT "(Default = N ) ",Prop_keybd$
1610 IF UPC$(Prop_keybd$)="Y" THEN
1620     DISP " NOTE: All properties (except Pr number on tube) are at T_infin "
1630     OUTPUT KBD;Vis_d;
1640     INPUT "Enter dynamic viscosity (N-sec/m) ",Vis_d
1650     OUTPUT KBD;K_fluid;
1660     INPUT "Enter thermal conductivity (W/m-K) ",K_fluid
1670     OUTPUT KBD;Pr_infin;
1680     INPUT "Enter Prandtl number ",Pr_infin
1690     IF (Pr_infin<.65) OR (Pr_infin>500) THEN
1700         PRINT " ** Prandtl number out-of-range, try again ** "
1710         GOTO 1680
1720     END IF
1730     OUTPUT KBD;Prs;
1740     INPUT "Enter Prandtl number on tube surface ",Prs
1750     IF (Prs<.65) OR (Prs>500) THEN
1760         PRINT " ** Prandtl number out-of-range, try again ** "
1770         GOTO 1740
1780     END IF
1790     OUTPUT KBD;Den;
1800     INPUT "Enter density (kg/m^3) ",Den

```

Appendix III. Heat Transfer Code and Sample Output

```
1820     INPUT "Enter specific heat heat (J/kg-K) ",Cp
1830 END IF
1840 !
1850 !
1860 !
1870 !   Find gas properties of mixture if not input from keyboard.
1880 !
1890 !
1900 !
1910 IF UPC$(Prop_keybd$)="Y" THEN
1920     CLEAR SCREEN
1930     GOTO 2250
1940 END IF
1950 !
1960 !
1970 !   Find Prandtl number at tube surface
1980 !
1990 !
2000 !
2010 Temp=T_na
2020 GOSUB Mole_fraction
2030 GOSUB Viscosity_d
2040 GOSUB Specific_heat
2050 GOSUB Conductivity
2060 GOSUB Prandtl
2070 Prs=Pr
2080 CLEAR SCREEN
2090 !
2100 !
2110 !
2120 Prop: !   Find properties at T_prop.
2130 !
2140 !
2150 !
2160 Temp=T_prop
2170 GOSUB Viscosity_d
2180 GOSUB Specific_heat
2190 GOSUB Conductivity
2200 GOSUB Prandtl
2210 Pr_infin=Pr
2220 GOSUB Density
2230 !
2240 !
2250 IF UPC$(Hard_copy$)="Y" THEN PRINTER IS Printer;WIDTH 120
2260 IF UPC$(Prop_keybd$)="Y" THEN
2270     GOSUB Print_prop_sing
2280 ELSE
2290     GOSUB Print_prop_mult
2300 END IF
2310 GOSUB Heat_xfer
2320 IF UPC$(Prop_keybd$)="Y" THEN 2380
2330 IF ABS(T_prop-(T_flame+T_down)/2)>2 THEN
2340     T_prop=(T_flame+T_down)/2
2350     Iteration=Iteration+1
2360     GOTO Prop
2370 END IF
2380 PRINTER IS CRT
2390 PRINT
2400 DISP TAB(35);" TUBEBANK Finished "
```

```

2420  !
2430  !
2440  !
2450  ! SUBROUTINE *****
2460  !
2470  !
2480  !
2490  Heat_xfer:  ! Calculate film coeff and heat xfer into tube bank.
2500  !
2510  !
2520  !
2530  IF (Pr_infin<.65) OR (Pr_infin>500) THEN
2540      PRINT " ** WARNING - Prandtl number at T_infin out-of-range ** "
2550      PRINT USING "K,DD.DDD";" Prandtl number at T_infin = ";Pr
2560  END IF
2570  IF (Prs<.65) OR (Prs>500) THEN
2580      PRINT " ** WARNING - Prandtl number at Ts is out-of-range ** "
2590      PRINT USING "K,DD.DDD";" Prandtl number at Ts = ";Prs
2600  END IF
2610  Vis_k=Vis_d/Den
2620  Sd=SQR(S1^2+(St/2)^2)
2630  Vavg=Mdot/(Den*Height*Wide)
2640  IF Sd<(St+D_tube)/2 THEN
2650      Vmax=St*Vavg/(2*(Sd-D_tube))
2660  ELSE
2670      Vmax=Vavg*St/(St-D_tube)
2680  END IF
2690  Redmax=Vmax*D_tube/Vis_k
2700  IF (Redmax<1000) OR (Redmax>2.E+5) THEN
2710      PRINT " ** Reynolds number is out-of-range for this St/S1 ** "
2720      PRINT " Redmax = ",Redmax
2730      CALL Super_beep
2740      STOP
2750  END IF
2760  IF St/S1<2 THEN
2770      C_nu=.35*(St/S1)^.2
2780      M_nu=.6
2790  ELSE
2800      C_nu=.40
2810      M_nu=.6
2820  END IF
2830  Nu_d=C_nu*Redmax^M_nu*Pr_infin^.36*(Pr_infin/Prs)^.25
2840  H_gas=K_fluid/D_tube*Nu_d      ! Film coeff (W/m^2-K)
2850  A_tube=PI*D_tube*L_tube      ! Surface area of tubes
2860  !
2870  !
2880  ! Calculate thermal resistance from gas side to sodium side
2890  !
2900  !
2910  !
2920  Ro=D_tube/2
2930  Ri=Ro-Wall
2940  Res1=1/(2*PI*Ri*L_tube*H_na)
2950  Res2=LOG(Ro/Ri)/(2*PI*K_tube*L_tube)
2960  Res3=1/(2*PI*Ro*L_tube*H_gas)
2970  R_tot=Res1+Res2+Res3
2980  !
2990  !
3000  ! Calculate convective heat xfer into Na as pass thru each row of tubes

```

Appendix III. Heat Transfer Code and Sample Output

```

3020 !
3030 !
3040 PRINT " "
3050 PRINT " HEAT XFER DATA:"
3060 PRINT " "
3070 PRINT " Calculations for the following chamber and tube configuration:"
3080 PRINT USING "K,4D.D,K,4D.D,K";" Chamber dims: ";Wide*1000;" mm wide x ";Height*1000;" m
m high"
3090 PRINT USING "K,3D.DD";" Tube diameter (mm) = ";D_tube*1000
3100 PRINT USING "K,3D.D,K,3D.D,K";" Staggered tube spacing (St x S1) = ";St*1000;" mm X ";S
1*1000;" mm"
3110 PRINT USING "K,3D.D";" Clearance between adjacent tubes (mm) = ";(St-D_tube)*1000
3120 PRINT " "
3130 PRINT " Calculated convective heat transfer and pressure drop data:"
3140 PRINT USING "K,DDD.DD";" Mass flowrate of air (g/sec) ",Mdot*1000
3150 PRINT USING "K,DDD.D";" Average velocity (m/sec) = ",Vavg
3160 PRINT USING "K,6D";" Reynolds number = ";Redmax
3170 PRINT USING "K,4D.D";" Flue gas film coefficient (W/m^2-K) = ";H_gas
3180 PRINT USING "K,4D";" Flame temp (K) = ";T_flame
3190 PRINT USING "K,4D";" Sodium temp (K) = ";T_na
3200 PRINT USING "K,DD.DDD";" Total thermal resistance (K/W) = ";R_tot
3210 PRINT " "
3220 PRINT " Row #      T_infin (K)      q (W)      q_flux (W/cm^2)      T_down (K)"
3230 !
3240 T_infin=T_flame
3250 Q_sum_conv=0
3260 FOR I=1 TO N_rows
3270     Q=N_tubes(I)*(T_infin-T_na)/R_tot
3280     Q_sum_conv=Q_sum_conv+Q
3290     Q_flux=Q/(N_tubes(I)*A_tube)/100^2
3300     T_down=T_infin-Q/(Mdot*Cp)
3310     PRINT USING "2X,DD,10X,4D,7X,5D,8X,DDD.D,12X,4D";I,T_infin,Q,Q_flux,T_down
3320     T_infin=T_down
3330 NEXT I
3340 Q_max=Mdot*Cp*(T_flame-T_na)
3350 Eff_ht=Q_sum_conv/Q_max*100
3360 PRINT " "
3370 PRINT USING "K,DDD.D";" Total convective heat transfer thru tubes (kW) = ",Q_sum_conv/1
000
3380 PRINT USING "K,4D";" Final exhaust temp (K) = ",T_down
3390 PRINT USING "K,DDD.D";" Maximum heat transfer available to sodium (kW) = ",Q_max/1000
3400 PRINT USING "K,DDD.D,K";" Heat transfer efficiency = ";Eff_ht;" %"
3410 !
3420 !
3430 !
3440 ! Calculate pressure drop thru tube bundle
3450 !
3460 !
3470 !
3480 ! See "Fundamentals of Heat Transfer", pp 357-358 for details.
3490 ! Figure 7.12 was curve-fit for staggered arrangement.
3500 !
3510 !
3520 !
3530 Chi=1      ! Valid if Pt/P1 =1.0. If not, refer to Figure 7.12,
3540 !           "Fundamentals of Heat Transfer"
3550 !
3560 P1=S1/D_tube
3570 Pt=St/D_tube
3580 IF (Pt/P1 > 0.95) OR (Pt/P1 < 0.5) THEN

```


Appendix III. Heat Transfer Code and Sample Output

```

4180      END IF
4190      Omega=A/T_star(I)^B+C/EXP(D*T_star(I))+E/EXP(F*T_star(I))+.2*Delta(I)^2/T_star(I)
4200      Vis(I)=26.69*SQR(M(I)*Temp)/(Sigma(I)^2*Omega)
4210      Vis(I)=Vis(I)/1.E+7      ! Viscosity in N-sec/m^2
4220  NEXT I
4230  !
4240  !
4250  ! Calculate dynamic viscosity for the mixture.
4260  !
4270  !
4280  !
4290  Vis_mix=0
4300  FOR I=1 TO N_gas
4310      Sum_y_phii_j=0
4320      FOR J=1 TO N_gas
4330          Mrat=M(I)/M(J)
4340          Mij=(4/((1+1/Mrat)*(1+Mrat)))^25
4350          Top=Mrat-Mrat^45
4360          Bottom=2*(1+Mrat)+(1+Mrat^45)/(SQR(Mij)*(1+Mij))
4370          Aij=Mij/SQR(Mrat)*(1+Top/Bottom)
4380          IF (Delta(I)=0) AND (Delta(J)=0) THEN
4390              Sij=1
4400              GOTO 4450
4410          END IF
4420          Top=1+SQR(T_star(I)*T_star(J))+Delta(I)*Delta(J)/4
4430          Bottom=SQR(1+T_star(I)+Delta(I)^2/4)*SQR(1+T_star(J)+Delta(J)^2/4)
4440          Sij=Top/Bottom
4450          Phii_j=SQR(Vis(I)/Vis(J))*Sij*Aij
4460          Sum_y_phii_j=Sum_y_phii_j+Y(J)*Phii_j
4470      NEXT J
4480      Vis_mix=Vis_mix+Y(I)*Vis(I)/Sum_y_phii_j
4490  NEXT I
4500  Vis_d=Vis_mix
4510  RETURN
4520  !
4530  !
4540  ! SUBROUTINE *****
4550  !
4560  !
4570  !
4580  Specific_heat:      ! Calculate specific heat (const press) of mixture.
4590  !
4600  !
4610  !
4620  !
4630  ! Calculate molar specific heats (cal/g-mole-K)
4640  !
4650  !
4660  Trat=Temp/100
4670  Cp_molar(1)=-.89286+7.2967*SQR(Trat)-.98074*Trat+5.7835/1000*Trat^2
4680  Cp_molar(2)=34.19-43.868*Trat^25+19.778*SQR(Trat)-.88407*Trat
4690  Cp_molar(3)=8.9465+4.8044/1000*Trat^1.5-42.679/Trat^1.5+56.615/Trat^2
4700  Cp_molar(4)=9.3355-122.56/Trat^1.5+256.38/Trat^2-196.08/Trat^3
4710  !
4720  Cp_mix_molar=0
4730  M_mix=0
4740  FOR I=1 TO N_gas
4750      Cp_mix_molar=Cp_mix_molar+Y(I)*Cp_molar(I)
4760      M_mix=M_mix+Y(I)*M(I)
4770  NEXT I

```

```

4780  Cp_mix=Cp_mix_molar/M_mix      ! Units are cal/g-K
4790  Cp_mix=Cp_mix*1055/252.16*1000 ! Convert to J/kg-K
4800  Cp=Cp_mix
4810  RETURN
4820  !
4830  !
4840  !
4850  ! SUBROUTINE *****
4860  !
4870  !
4880  Conductivity:  ! Calculate thermal conductivity of mixture.
4890  !
4900  !
4910  !
4920  Ru=8.315*252.16/1055 ! Universal gas constant in cal/g-mole-K
4930  FOR I=1 TO N_gas
4940      Cv_molar=Cp_molar(I)-Ru
4950      Cond(I)=Vis(I)*10/M(I)*(Cv_molar+4.47) ! k in cal/cm-sec-K.
4960      Cond(I)=Cond(I)*1055/252.16*100 ! Converted to W/m-K
4970  NEXT I
4980  !
4990  !
5000  ! Now calculate conductivity of gas mixture.
5010  !
5020  !
5030  !
5040  Kappa=1
5050  K_mix=0
5060  FOR I=1 TO N_gas
5070      Sum_y_aij=0
5080      FOR J=1 TO N_gas
5090          Krat=Vis(I)/Vis(J)*(M(J)/M(I))
5100          Top=Kappa*(1+SQR(Krat)*(M(I)/M(J))^2.25)^2
5110          Bottom=SQR(8*(1+M(I)/M(J)))
5120          Aij=Top/Bottom
5130          Sum_y_aij=Sum_y_aij+Y(J)*Aij
5140      NEXT J
5150      K_mix=K_mix+Y(I)*Cond(I)/Sum_y_aij
5160  NEXT I
5170  K_fluid=K_mix
5180  RETURN
5190  !
5200  !
5210  ! SUBROUTINE *****
5220  !
5230  !
5240  Prandtl:  ! Calculate Prandtl number of the mixture.
5250  !
5260  !
5270  !
5280  Pr=Cp_mix*Vis_mix/K_mix
5290  RETURN
5300  !
5310  !
5320  !
5330  ! SUBROUTINE *****
5340  !
5350  !
5360  Density:  ! Calculate density of the mixture.
5370  !

```

```

5380  !
5390  !
5400  Ru=8315      ! Universal gas constant in J/kg-mole-K
5410  R_mix=Ru/M_mix
5420  Density_mix=Pressure_gas/(R_mix*Temp) ! Density in kg/m^3
5430  Den=Density_mix
5440  RETURN .
5450  !
5460  !
5470  !
5480  ! SUBROUTINE *****
5490  !
5500  !
5510  Print_prop_sing:  ! Print results for single component gas.
5520  !
5530  !
5540  !
5550  PRINT " PROPERTY DATA: "
5560  PRINT USING "K,4D";" T_flame (K) = ",T_flame
5570  PRINT USING "K,DDD.D";" Dynamic viscosity * 10^7 (N-sec/m) ",Vis_d*1.E+7
5580  PRINT USING "K,4D.D";" Specific heat heat (J/kg-K) ",Cp
5590  PRINT USING "K,DDD.D";" Thermal conductivity * 10^3 (W/m-K) ",K_fluid*1000
5600  PRINT USING "K,D.DDD";" Prandtl number ",Pr_infin
5610  PRINT USING "K,D.DDD";" Prandtl number on tube surface ",Prs
5620  PRINT USING "K,D.DDD";" Density (kg/m^3) ",Den
5630  RETURN
5640  !
5650  !
5660  !
5670  ! SUBROUTINE *****
5680  !
5690  !
5700  !
5710  Print_prop_mult:  ! Print results for multi-component gas.
5720  !
5730  !
5740  !
5750  PRINT
5760  PRINT
5770  PRINT " DATA FOR ITERATION #";Iteration;" "
5780  PRINT USING "K,4D";" Property data evaluated at (K) ";T_prop
5790  PRINT " "
5800  PRINT " Component   N frac   vis*10^7 (N-s/m^2)  k*10^3 (W/m^2-K)  cp (J/kg-K)"
5810  FOR I=1 TO N_gas
5820      PRINT USING "2X,4A,6X,D.4D,8X,DDD.D,15X,DDD.D,10X,5D.D";Comp_name$(I),Y(I),Vis(I)*1.E+
7,Cond(I)*1000,Cp_molar(I)/M(I)*1055/252.16*1000
5830  NEXT I
5840  PRINT " "
5850  PRINT " Mixture data:"
5860  PRINT USING "K,DDD.D";" Dynamic viscosity * 10^7 (N-sec/m) ",Vis_d*1.E+7
5870  PRINT USING "K,4D.D";" Specific heat heat (J/kg-K) ",Cp
5880  PRINT USING "K,DDD.D";" Thermal conductivity * 10^3 (W/m-K) ",K_fluid*1000
5890  PRINT USING "K,D.DDD";" Prandtl number ",Pr_infin
5900  PRINT USING "K,D.DDD";" Prandtl number on tube surface ",Prs
5910  PRINT USING "K,D.DDD";" Density (kg/m^3) ",Den
5920  RETURN
5930  !
5940  !
5950  END
5960  !

```

```

5970  !
5980  !
5990  !
6000  !  SUBPROGRAM  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
6010      !
6020      !
6030      !
6040  SUB Title
6050      !
6060      !
6070      !
6080      !
6090 Title:  !  Fancy Graphics title for opening screen
6100      !
6110      !
6120      !
6130      !
6140      PDIR 0
6150      VIEWPORT 0,133.377,0,100
6160      WINDOW 1,128,41,1
6170      GRAPHICS ON
6180      AREA COLOR 1,1,1
6190      CSIZE 4
6200      LORG 3
6210      MOVE 6,4*.86
6220      RECTANGLE 120,5,FILL
6230      PEN -1
6240      FOR Y=0 TO .10 STEP .05
6250          FOR X=0 TO .3 STEP .1
6260              MOVE 10+X,5+Y
6270              LABEL " T U B E   B A N K   H E A T   T R A N S F E R "
6280          NEXT X
6290      NEXT Y
6300      MOVE 8,4.5*.86
6310      RECTANGLE 115,4.2
6320      MOVE 25,15
6330      PEN 1
6340      GRAPHICS OFF
6350      !
6360  SUBEND
6370      !
6380      !
6390      !
6400  !  SUBPROGRAM  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
6410      !
6420      !
6430      !
6440  SUB Super_beep
6450      !
6460      !
6470      !
6480 Super_beep:  !
6490      !
6500      !
6510      !
6520      FOR I=1000 TO 100 STEP -100
6530          BEEP I,.050
6540      NEXT I
6550  SUBEND

```

DATA FOR ITERATION # 1

Component	N frac	$v_{is} \times 10^7$ (N-s/m ²)	$k \times 10^3$ (W/m ² -K)	c_p (J/kg-K)
CO2	.0796	579.1	92.3	1358.3
H2O	.1061	562.4	187.1	2749.7
O2	.0663	698.5	104.2	1167.5
N2	.7480	578.0	94.8	1268.4

```
Dynamic viscosity * 10^7 (N-sec/m) 596.6
Specific heat heat (J/kg-K) 1371.2
Thermal conductivity * 10^3 (W/m-K) 103.5
Prandtl number .790
Prandtl number on tube surface .785
Density (kg/m^3) .193
```

Chamber dims: 72.0 mm wide x 83.0 mm high
Tube diameter (mm) = 12.70
Staggered tube spacing (St x S1) = 15.0 mm X 15.0 mm
Clearance between adjacent tubes (mm) = 2.3

Mass flowrate of air (g/sec) = 18.90
Average velocity (m/sec) = 16.4
Reynolds number = 4391
Flue gas film coefficient (W/m^2-K) = 402.4
Flame temp (K) = 1814
Sodium temp (K) = 1053
Total thermal resistance (K/W) = .761

Total convective heat transfer thru tubes (kW) = 17.7
Final exhaust temp (K) = 1132
Maximum heat transfer available to sodium (kW) = 19.7
Heat transfer efficiency = 89.6 %

```
Friction factor (staggered config, Pt=1.25) = .59
Pressure drop thru tube bundle (Pa) = 6457
```

DATA FOR ITERATION # 2

Component	N frac	vis*10 ⁷ (N-s/m ²)	k*10 ³ (W/m ² -K)	cp (J/kg-K)
CO2	.0796	507.8	79.2	1323.6
H2O	.1061	469.8	148.7	2588.0
O2	.0663	613.3	89.9	1140.6
N2	.7480	507.5	81.7	1238.4

88

```
Dynamic viscosity * 10^7 (N-sec/m) 522.7
Specific heat heat (J/kg-K) 1332.1
Thermal conductivity * 10^3 (W/m-K) 88.3
Prandtl number .789
Prandtl number on tube surface .785
Density (kg/m^3) .236
```

HEAT XFER DATA:

Calculations for the following chamber and tube configuration:

Chamber dims: 72.0 mm wide x 83.0 mm high
 Tube diameter (mm) = 12.70
 Staggered tube spacing (St x S1) = 15.0 mm X 15.0 mm
 Clearance between adjacent tubes (mm) = 2.3

Calculated convective heat transfer and pressure drop data:

Mass flowrate of air (g/sec) 18.90
Average velocity (m/sec) = 13.4
Reynolds number = 5011
Flue gas film coefficient (W/m^2-K) = 371.0
Flame temp (K) = 1814
Sodium temp (K) = 1053
Total thermal resistance (K/W) = .824

Row #	T infin (K)	q (W)	q flux (W/cm^2)	T down (K)
1	1814	3694	27.9	1667
2	1667	2982	22.5	1549
3	1549	2407	18.2	1453
4	1453	1943	14.7	1376
5	1376	1568	11.8	1314
6	1314	1266	9.6	1264
7	1264	1022	7.7	1223
8	1223	825	6.2	1190
9	1190	666	5.0	1164
10	1164	537	4.1	1142

Total convective heat transfer thru tubes (kW) = 16.9
Final exhaust temp (K) = 1142
Maximum heat transfer available to sodium (kW) = 19.2
Heat transfer efficiency = 88.3 %

```
** WARNING - Pt not close to 1.25, friction factor and dP may not be accurate **
Pt = 1.18
```

Friction factor (staggered config, $Pt=1.25$) = .57

Pressure drop thru tube bundle (Pa) = 5112

[illegible]

DATA FOR ITERATION # 3

Property data evaluated at (K) 1478

Component	N frac	vis*10 ⁷ (N-s/m ²)	k*10 ³ (W/m ² -K)	cp (J/kg-K)
CO2	.0796	509.0	79.4	1324.3
H2O	.1061	471.3	149.3	2590.8
O2	.0663	614.7	90.1	1141.1
N2	.7480	508.7	81.9	1239.0

Mixture data:

```
Dynamic viscosity * 10^7 (N-sec/m) 524.0
Specific heat heat (J/kg-K) 1332.8
Thermal conductivity * 10^3 (W/m-K) 88.5
Prandtl number .789
Prandtl number on tube surface .785
Density (kg/m^3) .235
```

HEAT XFER DATA:

90

APPENDIX IV

Testing Summary by Date for Evaporator Units 1, 2, and 3

UNIT 1

- 12/11/90 First startup. The back-pressure on our evaporator is less than STM's evaporator. The air flow was much too high - had to install a gate valve (only valve available in that size) to restrict the flow.
- Had dryouts on 2 tubes on row #1, and the 4th tube on row #2 dried out.
- In the next startup, only the 3rd tube in row #1 and the 4th tube in row #2 had dryouts. Some sodium contacted the other too, but not all the tubes.
- Conclusion: Not enough sodium in heat pipe.
- 12/91 Attempted to measure sodium quantity in horizontal position. X-rays indicated 75 grams of free sodium (desired about 180 grams).
- 12/91 Measured sodium in normal operating position. X-rays indicated the lower manifold was only 1/2 full, or about 75 grams of sodium (consistent with other measurement).
- 1/02/91 Tried to force sodium in condenser by heating evaporator in inverted position. This attempt did not work. The sodium remained in the evaporator.
- Conclusion: Although heat pipe was not weighed before filling, there were many indications that sodium entered the heat pipe and much time was allowed to fill the canister. Also, the second fill was done in the same way, and all sodium entered the heat pipe. Therefore, out of the 180 grams desired, 75 grams was available, while the remainder plated out on the many surfaces.
- Suspected we might have overheated the fill valve on the inverted bakeout.
- 1/09/91 Attached heat pipe to RGA and baked out plumbing.
- 1/16/91 Eliminated all leaks in plumbing. Leak tested evaporator and leak tested the fill valve. Both were leak-tight.
- 1/17/91 Started heating sodium vessel so that all oxides could equalize throughout the sodium container. The vessel was at 150°C for the entire weekend.
- 1/21/91 Added another canister (approximately 180 grams) of sodium to the evaporator.
- 1/22/91 Drove sodium out of plumbing and into the fill canister.
- 1/23/91 Heated evaporator in normal operating position in preparation to observe level with x-rays.
- 1/24/91 X-rays indicated sodium filled the lower manifold and into the tubes. How far into the tubes was not visible since we were shooting through four tubes. Weight confirmed 177 grams of sodium entered the heat pipe.
- 1/28/91 Last couple of days spent preparing to run evaporator again.
- Today, the air valve was re-tuned to allow us to run the evaporator. The gate valve used for restriction did not allow the proper A/F ratio throughout the valve travel.

- Ran evaporator - had intermediate dryouts on 3rd tube in row #1 and in 4th tube in row #2. Note these two tubes were severely overheated in the first run.
- 1/29/91 Met with Moreno, Andraka, and Moss. No new ideas or obvious solutions - the possibilities of boiling, liquid return problems, sonic velocity limits, and non-condensable gases were discussed.
- 1/30/91 Ran evaporator - Calorimeter was moved up to allow higher temperatures to be obtained at the same gas flowrate. Dryouts occurred in 3rd tube in row #1 and in 4th tube in row #2. Temperatures still unstable.
- 1/31/91 Strapped microphone to valve on heat pipe and tried operating again. There was a definite correlation between the sounds we heard and the dryout and re-wetting on several tubes.
- Best guess: Sodium is pooling in upper manifold (tubes stick 3-mm above manifold surface), then surface tension finally breaks, and a slug of sodium flows down tube (hear the noises). Then the sodium is wicked up the tube and the dryout condition disappears.
- 2/01/91 Tilted evaporator about 1 degree forward to try to force the sodium to flow more toward the front of the evaporator.
- Also, a window was cut in the insulation near the liquid return so that we could observe any sodium was pooling up in the liquid return area.
- Results: If anything, it was worse. Possibly due to more sodium sticking toward the front of the evaporator, but in the upper (rather than the lower) chamber.
- 2/05/91 Adkins performed calculations and we developed the entrainment theory. Velocities of 57 m/sec occur at 600°C!
- Tried to bring the entire heat pipe to 700°C with bottom heater to get over the entrainment "hump." No success since the calorimeter starts to extract heat (as well as high convective losses in combustion chamber).
- Tried to start up anyway - same results as before.
- 2/06/91 Tilted evaporator back 1 degree to force sodium down the rear tubes. Same results as before.
- 2/07/91 Tilted evaporator back 2 degrees. Tilts too much. Results, if anything, are worse than before.
- 2/11/91 Installed a quartz glass window along the side of the combustion chamber - able to observe all the way to row #9. Although not as severe, the same type of dryout and quench cycles are present to at least row #5.
- Learned quite a bit combining what we saw today with other observations throughout the month. On several occasions, several tubes would start to dry out. Then a slug of sodium would fall into one tube (no sodium vapor to keep it on top). The excess sodium could be heard hitting the lower chamber (a microphone was mounted on the heat pipe). A few seconds later the adjacent tubes would start wicking upward. Apparently, the excess sodium would start filling the pan and begin to feed the adjacent tubes.
- 2/12/91 Started up again to let Adkins observe first hand.

Rawlinson also did some more accurate calculations to confirm the entrainment theory. The velocity of the sodium at 600°C is 82 m/sec! At this velocity, the static pressure is high enough to support a liquid sodium column of 5.6 mm. Considering the tubes protrude 2-4 mm through the manifold, it appears that nearly the entire upper chamber could be filled with sodium! That explains the dryouts.

2/13/91 Two tubes (outer tubes on row #4 and row #10) were insulated. The idea here was to cut off the flux in two tubes so that the vapor velocities would be much lower and perhaps act as liquid return tubes.

Results: Achieved somewhat higher temperatures, but still had dryouts. Some insulation torn away by flue gas.

2/14/91 Re-insulated tubes with Refrasil cloth-type insulation. Same results as 2/13/91.

2/18/91 Attached probes to upper and lower manifolds and passed 5 amps through each during operation.

Results: Proved bottom pan dries out while upper pan collects sodium. Consistent with entrainment theory.

2/19/91 Same probes as 2/18/91 plus attached another set in liquid return area.

Results: Sodium appears to be collecting in liquid return area as well as in the upper pan.

7/10/91 Retested evaporator following wick "sampler" testing. Learned from sampler that if vapor temps > 600°C, system stable. Tried this on 2/05/91, but vapor temps only 450°C. Removed calorimeter and added guard heating condenser.

Results: Same dryout and quench sequence even though vapors temps > 650°C. Same conclusion as before.

<End of Unit 1>

UNIT 2

7/91 - Fabrication of second evap (larger pool, exposed screens, overflow tubes). Also added more DAS channels, updated DAS/ECU programs, installed new mass flowmeters (sent flowmeters for STM test out for calibration).

10/22/91

10/23/91 Preparing for fill operation: TCs, TCs tacked to evap, new heater bent/installed, weighed heat pipe, end-to-end DAS check, leak-checked system, heat-traced everything, started insulating.

10/24/91 Finished insulating, started bakeout of heat pipe, plumbing.

10/25/91 Started heating sodium vessel, continued bakeout.

10/26/91 Continued bakeout. TC failure set off auto-dialer at midnight!

10/27/91 Vacuum pump turbo crashed. Bakeout will have to start from scratch.

10/28/91 Turbo replaced, associated plumbing cleaned, solenoid valve replaced.

10/29/91 Performed another leak-check on heat pipe since turbo crashed. Replaced Piranni gage. Restarted bakeout.

10/30/91 Finished bakeout. Performed fill operation.

10/31/91	Performed wick saturation operation.
11/01/91	Re-weighed heat pipe (370 grams of Na).
11/01-05	Performed end-to-end DAS check, installed evap, insulated, set up cameras, current probes, moved 250 ohm resistors to test cell. First start-up attempt. Propane mass flowmeter failed. Did see some oscillations in tube surface temps.
11/06/91	First extended startup. Fairly smooth operation initially, then oscillations slowly grew after about 1 hour of operation. Conclusions: A/F ratio about 16. Possibly H ₂ buildup.
11/08/91	More data reduction from 11/6. Conclusions: Mole fraction of H ₂ 89 times higher at stoich than at A/F = 23.5. Also checked flux at A/F = 16 with TUBE BANK program—should not be a problem. In addition, tubes in the rear also oscillated, where the flux is very low. Finally, compared pool probe readings to Unit 1. Although magnitude different, relative changes indicate pool is not drying out. Began to doubt dT meter.
11/11/91	Setup vacuum system to perform RGA on heat pipe.
11/12/91	Performed RGA. Results: Total pressure in 10 ⁻⁶ torr range, almost all H ₂ . A/F ratio probably accountable. No N ₂ --> no leak.
11/13/91	Re-ran evap after pumping out H ₂ . Results: Started smooth, then oscillations began to grow again after about 20 minutes. Also began to suspect boiling after plotting data (condenser fluctuations out-of phase with surface temps). Looked into heat pipe w/ RGA again. About 1 torr of H ₂ again. Also leak-checked evaporator—no problem.
11/14/91	Pumped out H ₂ for 3rd time. Ran again, then pumped out another torr of H ₂ . Results: More of the same—gradual decrease in stability. More talk about boiling. Some data suggest boiling, some does not (sometimes tube surfaces and vapors are in-phase, sometimes out-of-phase). However, pool never dries out, which is consistent with boiling. 11/15-11/20 Dynatherm work.
11/20/91	Performed level check with gamma ray source/detector system (1513). Results: Sodium level between 15 and 35-mm into tube, but exact level hard to determine since sodium froze at different levels in different tubes (but definitely too much inventory).
11/22/91	Built a better fixture for gamma ray measurement and re-performed test with molten sodium so levels are equal.

Results: Sodium level at 26-mm into tubes at 150°C.

Performed calculations. Sodium level at 46-mm at 800°C! This led us to believe we definitely have boiling. Determined we needed to remove 112g of Na.

11/26/91 Moss and Rawlinson replaced turbo pump (the one we replaced for the fill operation was borrowed).

11/27/91 Ray built rotatable fixture for drain operation.

11/28-12/2/91 Thanksgiving break, Dynatherm work.

12/3/91 Mounted evap on fixture, heat-traced, insulated. Melted sodium, inverted heat pipe and froze sodium at 3-4 degree tilt.

12/04/91 Daniel decontaminated bellows valve, but too much sodium present.

12/05/91 We hooked up a trap system and evaporated sodium from bellows valve.

12/06/91 Finished bakeout and cleaning bellows valve. Plumbed remainder of system.

12/09/91 Bakeout of drain system.

12/10/91 Performed drain operation.

Results: By probe data, it looks like we removed only a trace of sodium.

12/11/91 Weighed heat pipe.

Results: Removed only 8 grams of sodium.

Determined problem -- vapor tube is spliced -- sodium probably had time to drain through splice and back into evaporator since the unit was at a 3-4 degree angle.

12/12/91 Meeting to discuss problem. Decided to use an exact sized drain container. Also decided to leak-check evaporator again to assure that there was not a failure.

12/13/91 Heat-traced vacuum lines and fill/vacuum lines on heat pipe. Started bakeout.

12/16/91 Leak-checked evaporator.

Results: No leak.

Let Moss/Moreno have vacuum system to start their NaK drain operation.

12/17/91 Heat-traced heat pipe, inverted, and cooled in horizontal position. Baked out everything up to drain vessel, which was delayed in the shops.

12/18/91 Installed drain canister and continued bakeout.

12/19/91 Performed drain operation (2nd time).

Appendix IV. Testing Summary by Date for Evaporator Units 1, 2, and 3

	Results: Probed indicated we filled canister. Reweighed heat pipe. Removed the amount we wanted: 104 grams. Total amount removed with both operation = $8 + 104 = 112$ grams.
12/20/91	Attached new pool heater, reweighed heat pipe. Reinstalled heat pipe, checked all data lines. Noticed that pool probe was higher than expected. Also installed condenser heater.
12/23/91	Re-ran unit for the first time since drain operation. Results: Stable operation. Achieved 8 kW power. Shutdown due to TC failure. Noticed during last startup (several shutdowns due to low pressure trips), pool and top probes reversed. The overflow tubes probably primed. Video showed a few oscillations on tube #8 at bottom, but not indicated on TC. Need to re-insulate at top - TC leads around upper manifold red-hot.
1/06/92	Re-insulated around upper manifold, repaired TE471. Results: Stable operation, reached 8 kW (dT) or 10 kW (TCs). Noticed problem with dT meter.
1/07/92	To try to increase power, insulated combustor box. Used TCs for power calculations. Results: Power up to 10.5 kW at 760°C, about 12 kW at 720°C. The dT meter failed, and the pool probe was erratic.
1/08/92	Removed quartz glass window, chamber more heavily insulated. Pool probe repaired. Results: Power up to 12.1 kW at 760°C (up about 1.5 kW). Decreased A/F to about 21—achieved almost 15 kW, then condenser heater failed (noticed power dropped about 0.5 kW).
1/09/92	Decided that although fine at lower A/F ratio, surface temps on row #1 were almost 800°C. Decided to increase mass flow and keep A/F at 23.5. The air valve was tuned again to allow for higher flow rates.
1/10/92	Fine-tuned air valve while running engine. Results: No major problems.
1/14/92	Filled gaps around evaporator and insulation w/ moldable Fiberfrax. Results: No problems. Ran 14-15 kW.
1/15/92	Checked combustion box for leaks (CNN, DOE visiting -- decided to check everything).
1/16/92	No changes. Results: No problems, ran 13 kW in day, 10 kW at night.
1/17/92	No changes. Results: No problems except front piece of insulation broke and started falling down. Had to shut down.
1/20/92	Tried Zirconia board -- too brittle. Used 17C board again. No run time.
1/21/92	Ran w/ new insulation.

Results: No problems. Ran at 13-15 kW in day, 10 kW at night (ran into 1/22 a.m. when Argon supply exhausted).

1/22/92 No changes.

Results: No problems until nighttime. Heat pipe ran for over 2 hours with a leak developing.

1/23/92 Discovered leak in TE474 thermowell -- no problems with evaporator. Started bakeout of HP vacuum line.

1/24/92 RGA on heat pipe -- initial press > 1 torr. Repaired leak in the thermowell (welding rod inserted and welded w/ SS309).

1/25/92 (Sat) Reinstalled evaporator. Pulled on heat pipe, then melted sodium -- much gas entrained in sodium. Ran heat pipe.

Results: Rough start because of H₂ remaining. Heat pipe stable as temperature increased. Looked very good for last 1/2 of run.

1/27/92 Ran at 10 kW. Running very smoothly when overtemped suddenly. Sodium leak on tube row #2, fourth tube.

1/28/92 Heat pipe cut open and put in glove box until we can decontaminate (peer reviews).

2/03/92 Top manifold cut off.

Results: Oxidation on rows 1-3.

2/04/92 Photographed, then set up and drained evaporator. Waiting to get approval to clean w/ propanol and water.

2/92 Cleaned w/ propanol and water. Sent to Robert Sorenson for analysis. Results indicated oxygen contamination from leak, concentrated around area of leak, but also contamination elsewhere. No degradation on any other weld or braze joints. No measurable change in tube diameter from flue gas oxidation.

<End of Unit 2>

UNIT 3

2-4/92 Adkins had the original tube bank, which was essentially a bank used to try the brazing assembly, fabrication completed.

4/17/92 Setup for bake and fill, weigh heat pipe, etc. Started bakeout.

4/21/92 Charged heat pipe w/ 258 grams of sodium.

4/23/92 Heat-soaked heat pipe at 500°C for about 5 hours.

4/23/92-4/27/92 Cut insulation pieces for chamber, installed, check-out. Also measured current and voltage on pre-heater so we could run a more appropriately sized heaters on units destined for engine testing (470W).

4/28/92 Ran for first time. Baseline hours = 81.1.

Appendix IV. Testing Summary by Date for Evaporator Units 1, 2, and 3

- No problems, reached 12 kW. Shutdown for meeting and STM trip. Hours = 81.7.
- 5/05/92 Had problems with TE440, tied into TE460.
- Results: No problems at all. Hours = 86.2.
- 5/06/92 Ray moved propane valves up so that the two valves could not bind (since now they can move independently). We also retuned the air valve for more air (previously set for STM evaps).
- 5/07/92 Ran evap again.
- Results: No problems, ran mostly at 10 kW. Hours = 89.5.
- 5/08/92 No changes, ran again.
- Results: Reached about 13.8 kW at A/F = 21.0. Increased air flow while running -- flows lower at temperature. Started to see degradation of front piece of SALI-2 board. No problems with evaporator. Hours = 93.5. Adjusted air flow to 25.0 g/sec cold, which is about 21.5 g/sec at temperature.
- 5/12/92 No changes, ran again.
- Results: Piece of SALI-2 board on front insulation broke off. Shutdown in case manifolds were unprotected. Hours = 93.9. Hours on SALI-2 board = 93.9 - 81.1 = 12.8.
- 5/12/92 Pulled evap to replace front piece. Side pieces in good shape, except for a small piece towards the back which broke on removal.
- 5/15/92 Replaced front insulation piece with rigidized zirconia board. Reinstalled evaporator and another end-to-end check.
- 5/18/92 Attempted to run.
- Results: Had problem with A/F controller -- affected propane reading on DAS.
- 5/19/92 Performance mapped evaporator with respect to mass flowrate, vapor temperature, and air/fuel ratio.
- Results: Acquired good data because manually locked air and fuel flows, no condenser heater needed. Achieved about 14.6 kW. Hours = 98.0.
- 11/11/92 Decided to remap to obtain a map through a rectangular space instead of a "cross," i.e., varying one variable at a time.
- Results: Poor data -- TC insulation on cooling water melted and shorted.
- 11/12/92 Attempt to remap.
- Results: Cooling water TC inlet bad, installed another matched pair. Also had flue gas leak -- need to re-insulate.
- 11/16/92 Replaced insulation on top of evaporator, attempt to remap.
- Results: Data points not matching up well. A/F of 21.0 too close to A/F = 22.0. Electronics too warm from running with door closed?

11/17/92 Attempt to remap.

Results: Point #0 lines up. Will remap tomorrow.

11/18/92 Resume performance mapping.

Results: Mapped through point #24. Power down 0.4 kW as compared to point #0 11/17/92.

11/20/92 Resumed performance mapping.

Results: Started to remap $A/F = 21.0$. Power and efficiency more as expected. Continued to map entire space to recheck data. Resulted in most consistent data.

<End of testing to date on unit 3>

APPENDIX V

Wick Sampler Tests

The construction of the wick sampler system is illustrated in Figure A-V-1 and the structure of the wick inside each evaporator tube is shown in Figure A-V-2. The first two evaporator tubes had a screen wick that extended into the top manifold and a short tube inside of the wick extension that provides support. With this wick structure, liquid can enter the evaporator wick without being subjected to the high velocity vapor exiting the evaporator tube. The 1/8" tube that is located in the second evaporator tube acted as an overflow to prevent excess liquid from accumulating in the upper manifold.

In the third evaporator tube, the wall of the evaporator tube extends into the upper manifold to prevent liquid from entering the screens from the top. This evaporator tube was used to verify that capillary pumping alone could transport liquid sodium across the heated tube surface from the bottom manifold. All four of the evaporator tubes extended into the lower manifold to allow the screen wicks to access liquid in the bottom pool.

The last evaporator tube in the sampler system was used to examine the operation of a wick design that was proposed in a Philips patent [14]. With this system, the evaporator tube extends into the top manifold and the wick system is brought up and over the top of the tube extension and then bent back into the upper manifold. In the Philips patent, it was claimed that this wick structure would prevent excess liquid from flowing down the heated evaporator surface. Excess liquid on the heated surface could cause temperature fluctuations along the tube walls.

A schematic of the system that was used to test the wick sampler is shown in Figure A-V-3. In the first round of tests, one tube at a time was heated with the quartz halogen lamps, and fiberboard insulation was used to insulate the manifold surfaces and the other three evaporator tubes. In a later series of tests, insulation was removed to allow all four evaporator tubes to be heated at the same time.

When four tubes were heated simultaneously, power was removed from the sampler heat pipe with a gas-gap calorimeter. The vapor temperature in the heat pipe was maintained at 780°C by controlling the rate at which power was extracted with the calorimeter. When individual evaporator tubes were tested, however, the calorimeter had to be removed to achieve a 780°C operating temperature. When the heat pipe was operated without the calorimeter, the vapor temperature was controlled by adjusting the incident flux. Tests with a flux gauge indicated that the maximum incident flux on the evaporator tubes was on the order of 40 W/cm².

Each tube was tested in a vertical orientation and ± 2 degrees from vertical to determine the system's sensitivity to slight changes in orientation. In general, the four tubes functioned properly when heat was applied to one evaporator tube at a time. The only exception was that 50°C temperature oscillations were observed on the surface of tube #1 the first two times it was tested. These oscillations began when the vapor temperature reached 450°C and ended when the vapor temperature exceeded 600°C. In subsequent tests, the oscillations were not repeated, so it is speculated that the problem may have been associated with the functioning of the drain tube in the early part of the testing program.

After individual tubes were tested, all four tubes were exposed to the incident flux simultaneously. Instabilities occurred in these tests that were very similar to the instabilities observed with the full-scale unit. In fact, the first tube to dryout was tube #3, which had a wick structure similar to the structure used in the original gas-fired evaporator design. As noted above, this wick is not exposed to sodium in the upper manifold and must rely on wicking from the lower manifold. Surface temperatures on tubes #3, #4, and then #1 would oscillate more than 50°C and then stabilize after vapor temperatures reached 600°C. The most stable temperature was on tube #2, the design with a liquid return line. Possibly, liquid sodium would return to the wick in tube #2 first because it was closest to the liquid return tube.

To determine the location of liquid sodium in the sampler heat pipe, current probes were attached to the upper and lower manifolds, and another set of probes were placed on the condenser just above the liquid return gutter. Figures A-V-4 & A-V-5 show typical results that were obtained during a test when all of the evaporator tubes were heated. When the incident flux was increased from 20 to 35 W/cm², the temperature increased rapidly on tubes #3 and #4, and the voltage drop across the lower manifold began to rise. The voltage rise indicated that liquid was leaving the lower manifold, and the rapid

Figure A-V-1. Schematic of the four-tube evaporator-wick sampler system.

Figure A-V-2. Wick structures tested in the evaporator tube wick sampler experiment.

Test Configuration

Figure A-V-3. Test system for the wick sampler.

Surface and Pool Temperatures

Figure A-V-4. Wick sampler temperature plots illustrating wick dryouts.

Resistance Probe Voltage Drops and SCR Control Voltage

Figure A-V-5. Wick sampler current probe plots illustrating wick dryouts.

increase in temperatures on tube #3 and #4 indicated that the liquid in the lower manifold dropped below the level of the wicks. As the temperature increased on tubes #3 and #4, liquid sodium slowly started to return to the lower manifold. Once the liquid reached the evaporator tube wicks in the lower manifold, tubes #3 and #4 were quenched and the temperatures dropped. The quenching may have removed enough liquid from the lower manifold to cause a brief temperature jump in all four evaporator tubes. It appeared that liquid sodium started to collect in the upper manifold gradually, and then began to collect in the liquid return gutter. At the same time the liquid return gutter dumped some of its inventory, sodium would enter the upper manifold and the tubes would be immediately quenched. After the surface temperatures returned to the vapor temperatures, sodium began to return to the lower manifold.

The wick structure that was used in configuration #1 was selected for the final design of the full-scale evaporator unit. The overflow tube arrangement that was used in the #2 configuration was also chosen for 10 of the 40 tubes in the final evaporator system design. The overflow tube allows excess liquid sodium to drain from the upper to the lower manifold with out flowing onto the heated wick surface.

APPENDIX VI

Uncertainty Analysis

Introduction

An uncertainty analysis was carried out for the calculations of absorbed power and system efficiency. As mentioned earlier, the published power and efficiency figures listed in Table II are 3-minute averages of data at a 5-second scan rate when the system was stable (steady-state). Random errors are averaged out over this time period. However, uncertainty exists from bias or calibration uncertainties in the instruments. When uncertainties are involved, it can be shown [15] that the common method of combining such uncertainties is according to the root-sum-square (rss) formula:

$$E_{rss} = \sqrt{\left(\Delta u_1 \frac{\partial f}{\partial u_1}\right)^2 + \left(\Delta u_2 \frac{\partial f}{\partial u_2}\right)^2 + \dots + \left(\Delta u_n \frac{\partial f}{\partial u_n}\right)^2} \quad (1)$$

where E_{rss} = root-sum-square uncertainty
 u_i = measured quantity
 Δu_i = uncertainty in measured quantity
 $\partial f / \partial u_i$ = partial derivative of the calculated function

This equation can be used to predict the uncertainty limits in which 99.7% of the data will fall.

Heat Gain Uncertainty

The following equation was used in calculating the steady-state heat gain using the gas-gap calorimeter:

$$\dot{Q} = \rho \dot{V} c_p dT \quad (2)$$

where $\dot{Q}$ = absorbed power, [W]
 ρ = density of water, [kg/m³]
 $\dot{V}$ = volumetric flowrate of water, [m³/sec]
 c_p = specific heat of water at constant pressure, [J/kg-°C]
 dT = temperature rise through calorimeter, [°C]

For the uncertainty associated with the absorbed power measurement, equation (1) becomes:

$$E_{rss} = \sqrt{\left(\Delta \rho \frac{\partial \dot{Q}}{\partial \rho}\right)^2 + \left(\Delta \dot{V} \frac{\partial \dot{Q}}{\partial \dot{V}}\right)^2 + \left(\Delta c_p \frac{\partial \dot{Q}}{\partial c_p}\right)^2 + \left(\Delta dT \frac{\partial \dot{Q}}{\partial dT}\right)^2} \quad (3)$$

In this test, the density of water was input at a constant 998 kg/m³ at an average temperature of 19°C. The temperature range was 13°C to 24°C, resulting in a maximum uncertainty of $\Delta \rho = 2$ kg/m³.

The volumetric flowrate uncertainty is 0.6% of reading.

The specific heat of water was assumed to be constant at 4181 J/kg-°C in the data program. In the range of 300-320K, which is the temperature range of operation, the maximum uncertainty is 3 J/kg-°C.

For accurate measurements of water temperature ΔT , we used a matched pair of Type T thermocouples. From previous experience in other test programs, accuracies of 0.1 °C in ΔT can be expected.

Efficiency Uncertainties

Efficiency for this system was defined as the ratio of absorbed power to heat available by the combustion of propane:

$$\eta = \frac{\dot{Q}_{abs}}{\dot{Q}_p} = \frac{\rho \dot{V} c_p dT}{\dot{m}_p HV} \quad (4)$$

where $\dot{m}_p$ = mass flowrate of propane, [kg/sec]

HV = heat rate of propane, [kJ/kg]

(other variables defined in previous section)

Using equations (1) and (4), the uncertainty in the efficiency measurement becomes:

$$E_{rss} = \sqrt{\left(\Delta \rho \frac{\partial \eta}{\partial \rho}\right)^2 + \left(\Delta \dot{V} \frac{\partial \eta}{\partial \dot{V}}\right)^2 + \left(\Delta c_p \frac{\partial \eta}{\partial c_p}\right)^2 + \left(\Delta dT \frac{\partial \eta}{\partial dT}\right)^2 + \left(\Delta \dot{m}_p \frac{\partial \eta}{\partial \dot{m}_p}\right)^2 + \left(\Delta HV \frac{\partial \eta}{\partial HV}\right)^2} \quad (5)$$

The uncertainty in the mass flowrate measurement is $\pm(2\% + 1/2\% \text{ full scale})$ (g/sec).

We used a heating value of 46,359 kJ/kg. This is based on calculating the enthalpy of combustion for propane. This assumes that water appears as a gas in the products of combustion—certainly the case in this test.

Example:

Referring back to data point #0 in Table II, the following uncertainties are associated with the absorbed power and system efficiency. Data from both Table II and the following values are based on 3-minute averages taken at a 5-second scan rate. The uncertainty in each measurement were discussed in the previous two sections of this Appendix.

$$\begin{aligned} \rho &= 998 \text{ kg/m}^3 = \text{constant} \\ \Delta \rho &= 2 \text{ kg/m}^3 \\ \dot{V} &= 20.24 \text{ l/min} = 20.24/60,000 \text{ m}^3/\text{sec} \\ \Delta \dot{V} &= 0.006(\dot{\hat{V}}) = 2.024 \times 10^{-6} \text{ m}^3/\text{sec} \\ c_p &= 4181 \text{ J/kg-}^\circ\text{C} = \text{constant} \\ \Delta c_p &= 3 \text{ J/kg-}^\circ\text{C} \\ dT &= 9.33 \text{ }^\circ\text{C} \\ \Delta dT &= 0.1 \text{ }^\circ\text{C} \\ \dot{m}_p &= 0.917 \text{ g/sec} \\ \Delta \dot{m}_p &= 0.02 (0.917 \text{ g/sec}) + .005(1.5 \text{ g/sec}) = 2.584 \times 10^{-5} \text{ kg/sec} \\ HV &= 46,359 \text{ kJ/kg} \\ \Delta HV &= 4044 \text{ kJ/kg} \end{aligned}$$

Substituting these values into equations (3) and (5), the power throughput and thermal efficiency with their associated uncertainties are:

$$\begin{aligned} \text{Power} &= 13.13 \pm 0.16 \text{ kW} \\ \text{Efficiency} &= 30.90 \pm 2.85\% \end{aligned}$$

Table VI-I contains the results from the uncertainty analysis. The columns labeled "TERMxQ" and "TERMxEFF" refer to each term in equation (3) and (5). Note some uncertainty completely overshadow other errors. Remember each term in the uncertainty equation is squared. Uncertainties in power calculations are dominated by the ΔT measurement, and the assumed uncertainty was based on a matched pair of thermocouples. If unmatched thermocouples were used, the uncertainty would be much larger. The efficiency measurement error is dominated by the possible uncertainty in heating value. This is due to the large difference between the higher and lower heating values of propane.

Appendix VI. Uncertainty Analysis

Table VI-I. Uncertainty Analysis Results

Run Order	Nominal A/F	Nominal mp (g/sec)	Nominal T _{evap} (°C)	Date	Time Begin	Time End	Power Adj (kW)	Eff Adj (%)	Density (kg/m ³)	Water Flowrate (l/min)	Spec Heat (J/kg·°C)	dT (°C)	Propane MFlow (g/sec)	Heat Rate (kJ/kg)	Error Density (kg/m ³)	Error Water Flowrate (l/min)	Error Spec Heat (J/kg·°C)
0*	23.5	0.92	760	11/20/92	10:58:56	11:01:56	13.13	30.90	998	20.24	4181	9.33	0.917	46,359	2	0.12	3
1	23.5	0.55	720	11/20/92	15:56:06	15:59:06	8.71	34.30	998	20.58	4181	6.08	0.547	46,359	2	0.12	3
2	23.5	0.55	750	11/20/92	15:50:01	15:53:01	8.26	32.58	998	20.57	4181	5.78	0.547	46,359	2	0.12	3
3	23.5	0.60	775	11/20/92	15:43:41	15:46:41	8.74	31.47	998	20.56	4181	6.11	0.598	46,359	2	0.12	3
4	23.5	0.70	720	11/20/92	15:06:31	15:09:31	11.19	34.75	998	20.53	4181	7.84	0.695	46,359	2	0.12	3
5	23.5	0.70	750	11/20/92	15:28:11	15:31:11	10.53	32.39	998	20.55	4181	7.37	0.701	46,359	2	0.12	3
6	23.5	0.70	775	11/20/92	15:35:36	15:38:36	10.13	31.22	998	20.56	4181	7.08	0.700	46,359	2	0.12	3
7	23.5	0.92	720	11/20/92	14:59:56	15:02:56	13.96	32.84	998	20.54	4181	9.78	0.917	46,359	2	0.12	3
8	23.5	0.92	750	11/20/92	14:53:56	14:56:56	13.35	31.42	998	20.53	4181	9.35	0.917	46,359	2	0.12	3
9	23.5	0.92	775	11/20/92	14:48:21	14:51:21	12.85	30.28	998	20.52	4181	9.01	0.916	46,359	2	0.12	3
10	22.0	0.55	720	11/20/92	13:19:51	13:22:51	8.89	35.34	998	20.39	4181	6.27	0.543	46,359	2	0.12	3
11	22.0	0.55	750	11/20/92	13:27:41	13:30:41	8.43	33.52	998	20.40	4181	5.94	0.542	46,359	2	0.12	3
12	22.0	0.60	775	11/20/92	13:37:56	13:40:56	9.09	32.68	998	20.42	4181	6.40	0.600	46,359	2	0.12	3
13	22.0	0.70	720	11/20/92	14:20:06	14:23:06	11.72	35.91	998	20.48	4181	8.23	0.704	46,359	2	0.12	3
14	22.0	0.70	750	11/20/92	14:13:26	14:16:26	11.31	34.70	998	20.48	4181	7.94	0.703	46,359	2	0.12	3
15	22.0	0.70	775	11/20/92	14:05:41	14:08:41	10.66	32.97	998	20.46	4181	7.49	0.697	46,359	2	0.12	3
16	22.0	0.92	720	11/20/92	14:29:06	14:32:06	15.08	35.57	998	20.51	4181	10.58	0.915	46,359	2	0.12	3
17	22.0	0.92	750	11/20/92	14:34:41	14:37:41	14.57	34.41	998	20.50	4181	10.22	0.913	46,359	2	0.12	3
18	22.0	0.92	765	11/20/92	14:40:26	14:43:26	14.19	33.56	998	20.51	4181	9.95	0.912	46,359	2	0.12	3
19	21.0	0.55	720	11/20/92	13:09:36	13:12:36	9.27	36.65	998	20.37	4181	6.55	0.546	46,359	2	0.12	3
20	21.0	0.55	750	11/20/92	13:00:56	13:03:56	8.87	35.04	998	20.37	4181	6.26	0.546	46,359	2	0.12	3
21	21.0	0.60	775	11/20/92	12:49:46	12:52:46	9.36	33.78	998	20.37	4181	6.61	0.598	46,359	2	0.12	3
22	21.0	0.70	720	11/20/92	12:20:56	12:23:56	12.20	33.69	998	20.18	4181	8.69	0.697	46,359	2	0.12	3
23	21.0	0.70	750	11/20/92	12:31:11	12:34:11	11.71	36.26	998	20.19	4181	8.35	0.697	46,359	2	0.12	3
24	21.0	0.70	775	11/20/92	12:39:31	12:42:31	11.31	34.98	998	20.17	4181	8.06	0.697	46,359	2	0.12	3
25	21.0	0.92	730	11/20/92	12:08:31	12:11:31	16.13	37.50	998	20.22	4181	11.48	0.928	46,359	2	0.12	3
26	21.0	0.92	750	11/20/92	11:59:56	12:02:56	15.72	36.61	998	20.22	4181	11.18	0.926	46,359	2	0.12	3
27	21.0	0.92	765	11/20/92	11:53:21	11:56:21	15.33	35.76	998	20.22	4181	10.90	0.925	46,359	2	0.12	3
28*	23.5	0.92	760	11/20/92	16:10:06	16:13:06	12.98	30.49	998	20.46	4181	9.12	0.918	46,359	2	0.12	3

* Used to check against previous mapping on 5/19/92, Power = 12.4 kW, Efficiency = 29.0%

Note: Actual surface temperatures #1L and #1R are reversed from what is tabulated in last two columns (data directly from DAS files).

Unit #3 is a mirror image of unit #2, but DAS was not changed so that files between the different evaporators remain the same.

Run	Error	Propane	Error	Heat Rate	Error	TERMA10	TERMA20	TERMA30	TERMA40	TERMI1RF	TERMI2RF	TERMI3RF	TERMI4RF	TERMI5RF	TERMI6RF	TERMI7RF	TERMI8RF	TERMI9RF	TERMI10RF	TERMI11RF	TERMI12RF	TERMI13RF	TERMI14RF	TERMI15RF	TERMI16RF	TERMI17RF	TERMI18RF	TERMI19RF	TERMI20RF	TERMI21RF	TERMI22RF	TERMI23RF	TERMI24RF	TERMI25RF	TERMI26RF	TERMI27RF	TERMI28RF	TERMI29RF	TERMI30RF	TERMI31RF	TERMI32RF	TERMI33RF	TERMI34RF	TERMI35RF	TERMI36RF	TERMI37RF	TERMI38RF	TERMI39RF	TERMI40RF	TERMI41RF	TERMI42RF	TERMI43RF	TERMI44RF	TERMI45RF	TERMI46RF	TERMI47RF	TERMI48RF	TERMI49RF	TERMI50RF	TERMI51RF	TERMI52RF	TERMI53RF	TERMI54RF	TERMI55RF	TERMI56RF	TERMI57RF	TERMI58RF	TERMI59RF	TERMI60RF	TERMI61RF	TERMI62RF	TERMI63RF	TERMI64RF	TERMI65RF	TERMI66RF	TERMI67RF	TERMI68RF	TERMI69RF	TERMI70RF	TERMI71RF	TERMI72RF	TERMI73RF	TERMI74RF	TERMI75RF	TERMI76RF	TERMI77RF	TERMI78RF	TERMI79RF	TERMI80RF	TERMI81RF	TERMI82RF	TERMI83RF	TERMI84RF	TERMI85RF	TERMI86RF	TERMI87RF	TERMI88RF	TERMI89RF	TERMI90RF	TERMI91RF	TERMI92RF	TERMI93RF	TERMI94RF	TERMI95RF	TERMI96RF	TERMI97RF	TERMI98RF	TERMI99RF	TERMI100RF	TERMI101RF	TERMI102RF	TERMI103RF	TERMI104RF	TERMI105RF	TERMI106RF	TERMI107RF	TERMI108RF	TERMI109RF	TERMI110RF	TERMI111RF	TERMI112RF	TERMI113RF	TERMI114RF	TERMI115RF	TERMI116RF	TERMI117RF	TERMI118RF	TERMI119RF	TERMI120RF	TERMI121RF	TERMI122RF	TERMI123RF	TERMI124RF	TERMI125RF	TERMI126RF	TERMI127RF	TERMI128RF	TERMI129RF	TERMI130RF	TERMI131RF	TERMI132RF	TERMI133RF	TERMI134RF	TERMI135RF	TERMI136RF	TERMI137RF	TERMI138RF	TERMI139RF	TERMI140RF	TERMI141RF	TERMI142RF	TERMI143RF	TERMI144RF	TERMI145RF	TERMI146RF	TERMI147RF	TERMI148RF	TERMI149RF	TERMI150RF	TERMI151RF	TERMI152RF	TERMI153RF	TERMI154RF	TERMI155RF	TERMI156RF	TERMI157RF	TERMI158RF	TERMI159RF	TERMI160RF	TERMI161RF	TERMI162RF	TERMI163RF	TERMI164RF	TERMI165RF	TERMI166RF	TERMI167RF	TERMI168RF	TERMI169RF	TERMI170RF	TERMI171RF	TERMI172RF	TERMI173RF	TERMI174RF	TERMI175RF	TERMI176RF	TERMI177RF	TERMI178RF	TERMI179RF	TERMI180RF	TERMI181RF	TERMI182RF	TERMI183RF	TERMI184RF	TERMI185RF	TERMI186RF	TERMI187RF	TERMI188RF	TERMI189RF	TERMI190RF	TERMI191RF	TERMI192RF	TERMI193RF	TERMI194RF	TERMI195RF	TERMI196RF	TERMI197RF	TERMI198RF	TERMI199RF	TERMI200RF	TERMI201RF	TERMI202RF	TERMI203RF	TERMI204RF	TERMI205RF	TERMI206RF	TERMI207RF	TERMI208RF	TERMI209RF	TERMI210RF	TERMI211RF	TERMI212RF	TERMI213RF	TERMI214RF	TERMI215RF	TERMI216RF	TERMI217RF	TERMI218RF	TERMI219RF	TERMI220RF	TERMI221RF	TERMI222RF	TERMI223RF	TERMI224RF	TERMI225RF	TERMI226RF	TERMI227RF	TERMI228RF	TERMI229RF	TERMI230RF	TERMI231RF	TERMI232RF	TERMI233RF	TERMI234RF	TERMI235RF	TERMI236RF	TERMI237RF	TERMI238RF	TERMI239RF	TERMI240RF	TERMI241RF	TERMI242RF	TERMI243RF	TERMI244RF	TERMI245RF	TERMI246RF	TERMI247RF	TERMI248RF	TERMI249RF	TERMI250RF	TERMI251RF	TERMI252RF	TERMI253RF	TERMI254RF	TERMI255RF	TERMI256RF	TERMI257RF	TERMI258RF	TERMI259RF	TERMI260RF	TERMI261RF	TERMI262RF	TERMI263RF	TERMI264RF	TERMI265RF	TERMI266RF	TERMI267RF	TERMI268RF	TERMI269RF	TERMI270RF	TERMI271RF	TERMI272RF	TERMI273RF	TERMI274RF	TERMI275RF	TERMI276RF	TERMI277RF	TERMI278RF	TERMI279RF	TERMI280RF	TERMI281RF	TERMI282RF	TERMI283RF	TERMI284RF	TERMI285RF	TERMI286RF	TERMI287RF	TERMI288RF	TERMI289RF	TERMI290RF	TERMI291RF	TERMI292RF	TERMI293RF	TERMI294RF	TERMI295RF	TERMI296RF	TERMI297RF	TERMI298RF	TERMI299RF	TERMI300RF	TERMI301RF	TERMI302RF	TERMI303RF	TERMI304RF	TERMI305RF	TERMI306RF	TERMI307RF	TERMI308RF	TERMI309RF	TERMI310RF	TERMI311RF	TERMI312RF	TERMI313RF	TERMI314RF	TERMI315RF	TERMI316RF	TERMI317RF	TERMI318RF	TERMI319RF	TERMI320RF	TERMI321RF	TERMI322RF	TERMI323RF	TERMI324RF	TERMI325RF	TERMI326RF	TERMI327RF	TERMI328RF	TERMI329RF	TERMI330RF	TERMI331RF	TERMI332RF	TERMI333RF	TERMI334RF	TERMI335RF	TERMI336RF	TERMI337RF	TERMI338RF	TERMI339RF	TERMI340RF	TERMI341RF	TERMI342RF	TERMI343RF	TERMI344RF	TERMI345RF	TERMI346RF	TERMI347RF	TERMI348RF	TERMI349RF	TERMI350RF	TERMI351RF	TERMI352RF	TERMI353RF	TERMI354RF	TERMI355RF	TERMI356RF	TERMI357RF	TERMI358RF	TERMI359RF	TERMI360RF	TERMI361RF	TERMI362RF	TERMI363RF	TERMI364RF	TERMI365RF	TERMI366RF	TERMI367RF	TERMI368RF	TERMI369RF	TERMI370RF	TERMI371RF	TERMI372RF	TERMI373RF	TERMI374RF	TERMI375RF	TERMI376RF	TERMI377RF	TERMI378RF	TERMI379RF	TERMI380RF	TERMI381RF	TERMI382RF	TERMI383RF	TERMI384RF	TERMI385RF	TERMI386RF	TERMI387RF	TERMI388RF	TERMI389RF	TERMI390RF	TERMI391RF	TERMI392RF	TERMI393RF	TERMI394RF	TERMI395RF	TERMI396RF	TERMI397RF	TERMI398RF	TERMI399RF	TERMI400RF	TERMI401RF	TERMI402RF	TERMI403RF	TERMI404RF	TERMI405RF	TERMI406RF	TERMI407RF	TERMI408RF	TERMI409RF	TERMI410RF	TERMI411RF	TERMI412RF	TERMI413RF	TERMI414RF	TERMI415RF	TERMI416RF	TERMI417RF	TERMI418RF	TERMI419RF	TERMI420RF	TERMI421RF	TERMI422RF	TERMI423RF	TERMI424RF	TERMI425RF	TERMI426RF	TERMI427RF	TERMI428RF	TERMI429RF	TERMI430RF	TERMI431RF	TERMI432RF	TERMI433RF	TERMI434RF	TERMI435RF	TERMI436RF	TERMI437RF	TERMI438RF	TERMI439RF	TERMI440RF	TERMI441RF	TERMI442RF	TERMI443RF	TERMI444RF	TERMI445RF	TERMI446RF	TERMI447RF	TERMI448RF	TERMI449RF	TERMI450RF	TERMI451RF	TERMI452RF	TERMI453RF	TERMI454RF	TERMI455RF	TERMI456RF	TERMI457RF	TERMI458RF	TERMI459RF	TERMI460RF	TERMI461RF	TERMI462RF	TERMI463RF	TERMI464RF	TERMI465RF	TERMI466RF	TERMI467RF	TERMI468RF	TERMI469RF	TERMI470RF	TERMI471RF	TERMI472RF	TERMI473RF	TERMI474RF	TERMI475RF	TERMI476RF	TERMI477RF	TERMI478RF	TERMI479RF	TERMI480RF	TERMI481RF	TERMI482RF	TERMI483RF	TERMI484RF	TERMI485RF	TERMI486RF	TERMI487RF	TERMI488RF	TERMI489RF	TERMI490RF	TERMI491RF	TERMI492RF	TERMI493RF	TERMI494RF	TERMI495RF	TERMI496RF	TERMI497RF	TERMI498RF	TERMI499RF	TERMI500RF	TERMI501RF	TERMI502RF	TERMI503RF	TERMI504RF	TERMI505RF	TERMI506RF	TERMI507RF	TERMI508RF	TERMI509RF	TERMI510RF	TERMI511RF	TERMI512RF	TERMI513RF	TERMI514RF	TERMI515RF	TERMI516RF	TERMI517RF	TERMI518RF	TERMI519RF	TERMI520RF	TERMI521RF	TERMI522RF	TERMI523RF	TERMI524RF	TERMI525RF	TERMI526RF	TERMI527RF	TERMI528RF	TERMI529RF	TERMI530RF	TERMI531RF	TERMI532RF	TERMI533RF	TERMI534RF	TERMI535RF	TERMI536RF	TERMI537RF	TERMI538RF	TERMI539RF	TERMI540RF	TERMI541RF	TERMI542RF	TERMI543RF	TERMI544RF	TERMI545RF	TERMI546RF	TERMI547RF	TERMI548RF	TERMI549RF	TERMI550RF	TERMI551RF	TERMI552RF	TERMI553RF	TERMI554RF	TERMI555RF	TERMI556RF	TERMI557RF	TERMI558RF	TERMI559RF	TERMI560RF	TERMI561RF	TERMI562RF	TERMI563RF	TERMI564RF	TERMI565RF	TERMI566RF	TERMI567RF	TERMI568RF	TERMI569RF	TERMI570RF	TERMI571RF	TERMI572RF	TERMI573RF	TERMI574RF	TERMI575RF	TERMI576RF	TERMI577RF	TERMI578RF	TERMI579RF	TERMI580RF	TERMI581RF	TERMI582RF	TERMI583RF	TERMI584RF	TERMI585RF	TERMI586RF	TERMI587RF	TERMI588RF	TERMI589RF	TERMI590RF	TERMI591RF	TERMI592RF	TERMI593RF	TERMI594RF	TERMI595RF	TERMI596RF	TERMI597RF	TERMI598RF	TERMI599RF	TERMI600RF	TERMI601RF	TERMI602RF	TERMI603RF	TERMI604RF	TERMI605RF	TERMI606RF	TERMI607RF	TERMI608RF	TERMI609RF	TERMI610RF	TERMI611RF	TERMI612RF	TERMI613RF	TERMI614RF	TERMI615RF	TERMI616RF	TERMI617RF	TERMI618RF	TERMI619RF	TERMI620RF	TERMI621RF	TERMI622RF	TERMI623RF	TERMI624RF	TERMI625RF	TERMI626RF	TERMI627RF	TERMI628RF	TERMI629RF	TERMI630RF	TERMI631RF	TERMI632RF	TERMI633RF	TERMI634RF	TERMI635RF	TERMI636RF	TERMI637RF	TERMI638RF	TERMI639RF	TERMI640RF	TERMI641RF	TERMI642RF	TERMI643RF	TERMI644RF	TERMI645RF	TERMI646RF	TERMI647RF	TERMI648RF	TERMI649RF	TERMI650RF	TERMI651RF	TERMI652RF	TERMI653RF	TERMI654RF	TERMI655RF	TERMI656RF	TERMI657RF	TERMI658RF	TERMI659RF	TERMI660RF	TERMI661RF	TERMI662RF	TERMI663RF	TERMI664RF	TERMI665RF	TERMI666RF	TERMI667RF	TERMI668RF	TERMI669RF	TERMI670RF	TERMI671RF	TERMI672RF	TERMI673RF	TERMI674RF	TERMI675RF	TERMI676RF	TERMI677RF	TERMI678RF	TERMI679RF	TERMI680RF	TERMI681RF	TERMI682RF	TERMI683RF	TERMI684RF	TERMI685RF	TERMI686RF	TERMI687RF	TERMI688RF	TERMI689RF	TERMI690RF	TERMI691RF	TERMI692RF	TERMI693RF	TERMI694RF	TERMI695RF	TERMI696RF	TERMI697RF	TERMI698RF	TERMI699RF	TERMI700RF	TERMI701RF	TERMI702RF	TERMI703RF	TERMI704RF	TERMI705RF	TERMI706RF	TERMI707RF	TERMI708RF	TERMI709RF	TERMI710RF	TERMI711RF	TERMI712RF	TERMI713RF	TERMI714RF	TERMI715RF	TERMI716RF	TERMI717RF	TERMI718RF	TERMI719RF	TERMI720RF	TERMI721RF	TERMI722RF	TERMI723RF	TERMI724RF	TERMI725RF	TERMI726RF	TERMI727RF	TERMI728RF	TERMI729RF	TERMI730RF	TERMI731RF	TERMI732RF	TERMI733RF	TERMI734RF	TERMI735RF	TERMI736RF	TERMI737RF	TERMI738RF	TERMI739RF	TERMI740RF	TERMI741RF	TERMI742RF	TERMI743RF	TERMI744RF	TERMI745RF	TERMI746RF	TERMI747RF	TERMI748RF	TERMI749RF	TERMI750RF	TERMI751RF	TERMI752RF	TERMI753RF	TERMI754RF	TERMI755RF	TERMI756RF	TERMI757RF	TERMI758RF	TERMI759RF	TERMI760RF	TERMI761RF	TERMI762RF	TERMI763RF	TERMI764RF	TERMI765RF	TERMI766RF	TERMI767RF	TERMI768RF	TERMI769RF	TERMI770RF	TERMI771RF	TERMI772RF	TERMI773RF	TERMI774RF	TERMI775RF	TERMI776RF	TERMI777RF	TERMI778RF	TERMI779RF	TERMI780RF	TERMI781RF	TERMI782RF	TERMI783RF	TERMI784RF	TERMI785RF	TERMI786RF	TERMI787RF	TERMI788RF	TERMI789RF	TERMI790RF	TERMI791RF	TERMI792RF	TERMI793RF	TERMI794RF	TERMI795RF	TERMI796RF	TERMI797RF	TERMI798RF	TERMI799RF	TERMI800RF	TERMI801RF	TERMI802RF	TERMI803RF	TERMI804RF	TERMI805RF	TERMI806RF	TERMI807RF	TERMI808RF	TERMI809RF	TERMI810RF	TERMI811RF	TERMI812RF	TERMI813RF	TERMI814RF	TERMI815RF	TERMI816RF	TERMI817RF	TERMI818RF	TERMI819RF	TERMI820RF	TERMI821RF	TERMI822RF	TERMI823RF	TERMI824RF	TERMI825RF	TERMI826RF	TERMI827RF	TERMI828RF	TERMI829RF	TERMI830RF	TERMI831RF	TERMI832RF	TERMI833RF	TERMI834RF	TERMI835RF	TERMI836RF	TERMI837RF	TERMI838RF	TERMI839RF	TERMI840RF	TERMI841RF	TERMI842RF	TERMI843RF	TERMI844RF	TERMI845RF	TERMI846RF	TERMI847RF	TERMI848RF	TERMI849RF	TERMI850RF	TERMI851RF	TERMI852RF	TERMI853RF	TERMI854RF	TERMI855RF	TERMI856RF	TERMI857RF	TERMI858RF	TERMI859RF	TERMI860RF	TERMI861RF	TERMI862RF	TERMI863RF	TERMI864RF	TERMI865RF	TERMI866RF	TERMI867RF	TERMI868RF	TERMI869RF	TERMI870RF	TERMI871RF	TERMI872RF	TERMI873RF	TERMI874RF	TERMI875RF	TERMI876RF	TERMI877RF	TERMI878RF	TERMI879RF	TERMI880RF	TERMI881RF	TERMI882RF	TERMI883RF	TERMI884RF	TERMI885RF	TERMI886RF	TERMI887RF	TERMI888RF	TERMI889RF	TERMI890RF	TERMI891RF	TERMI892RF	TERMI893RF	TERMI894RF	TERMI895RF	TERMI896RF	TERMI897RF	TERMI898RF	TERMI899RF	TERMI900RF	TERMI901RF	TERMI902RF	TERMI903RF	TERMI904RF	TERMI905RF	TERMI906RF	TERMI907RF	TERMI908RF	TERMI909RF	TERMI910RF	TERMI911RF	TERMI912RF	TERMI913RF	TERMI914RF	TERMI915RF	TERMI916RF	TERMI917RF	TERMI918RF	TERMI919RF	TERMI920RF	TERMI921RF	TERMI922RF	TERMI923RF	TERMI924RF	TERMI925RF	TERMI926RF	TERMI927RF	TERMI928RF	TERMI929RF	TERMI930RF	TERMI931RF	TERMI932RF	TERMI933RF	TERMI934RF	TERMI935RF	TERMI936RF	TERMI937RF	TERMI938RF	TERMI939RF	TERMI940RF	TERMI941RF	TERMI942RF	TERMI943RF	TERMI944RF	TERMI945RF	TERMI946RF	TERMI947RF	TERMI948RF	TERMI949RF	TERMI950RF	TERMI951RF	TERMI952RF	TERMI953RF	TERMI954RF	TERMI955RF	TERMI956RF	TERMI957RF	TERMI958RF	TERMI959RF	TERMI960RF	TERMI961RF	TERMI962RF	TERMI963RF	TERMI964RF	TERMI965RF	TERMI966RF	TERMI967RF	TERMI968RF	TERMI969RF	TERMI970RF	TERMI971RF	TERMI972RF	TERMI973RF	TERMI974RF	TERMI975RF	TERMI976RF	TERMI977RF	TERMI978RF	TERMI979RF	TERMI980RF	TERMI981RF	TERMI982RF	TERMI983RF	TERMI984RF	TERMI985RF	TERMI986RF	TERMI987RF	TERMI988RF	TERMI989RF	TERMI990RF	TERMI991RF	TERMI992RF	TERMI993RF	TERMI994RF	TERMI995RF	TERMI996RF	TERMI997RF	TERMI998RF	TERMI999RF	TERMI1000RF	TERMI1001RF	TERMI1002RF	TERMI1003RF	TERMI1004RF	TERMI1005RF	TERMI1006RF	TERMI1007RF	TERMI1008RF	TERMI1009RF	TERMI1010RF	TERMI1011RF	TERMI1012RF	TERMI1013RF	TERMI1014RF	TERMI1015RF	TERMI1016RF	TERMI1017RF	TERMI1018RF	TERMI1019RF	TERMI1020RF	TERMI1021RF	TERMI1022RF	TERMI1023RF	TERMI1024RF	TERMI1025RF	TERMI1026RF	TERMI1027RF	TERMI1028RF	TERMI1029RF	TERMI1030RF	TERMI1031RF	TERMI1032RF	TERMI1033RF	TERMI1034RF	TERMI1035RF	TERMI1036RF	TERMI1037RF	TERMI1038RF	TERMI1039RF	TERMI1040RF	TERMI1041RF	TERMI1042RF	TERMI1043RF	TERMI1044RF	TERMI1045RF	TERMI1046RF	TERMI1047RF	TERMI1048RF	TERMI1049RF	TERMI1050RF	TERMI1051RF	TERMI1052RF	TERMI1053RF	TERMI1054RF	TERMI1055RF	TERMI1056RF	TERMI1057RF	TERMI1058RF	TERMI1059RF	TERMI1060RF	TERMI1061RF	TERMI1062RF	TERMI1063RF	TERMI1064RF	TERMI1065RF	TERMI1066RF	TERMI1067RF	TERMI1068RF	TERMI1069RF	TERMI1070RF	TERMI1071RF	TERMI1072RF	TERMI1073RF	TERMI1074RF	TERMI1075RF	TERMI1076RF	TERMI1077RF	TERMI1078RF	TERMI1079RF	TERMI1080RF	TERMI1081RF	TERMI1082RF	TERMI1083RF	TERMI1084RF	TERMI1085RF	TERMI1086RF	TERMI1087RF	TERMI1088RF	TERMI1089RF	TERMI1090RF	TERMI1091RF	TERMI1092RF	TERMI1093RF	TERMI1094RF	TERMI1095RF	TERMI1096RF	TERMI1097RF	TERMI1098RF	TERMI1099RF	TERMI1100RF	TERMI1101RF	TERMI1102RF	TERMI1103RF	TERMI1104RF	TERMI1105RF	TERMI1106RF	TERMI1107RF	TERMI1108RF	TERMI1109RF	TERMI1110RF	TERMI1111RF	TERMI1112RF	TERMI1113RF	TERMI1114RF	TERMI1115RF	TERMI1116RF	TERMI1117RF	TERMI1118RF
-----	-------	---------	-------	-----------	-------	---------	---------	---------	---------	----------	----------	----------	----------	----------	----------	----------	----------	----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------	-------------

Attn: Karl Thomas Feldman, Jr.
Mechanical Engineering Consultant
1704 Stanford Drive NE
Albuquerque, NM 87106

Attn: David Hagen
134 Kitchener Street
Garran, ACT 2605, AUSTRALIA

Attn: Carlo LaPorta
2201 Wisconsin Avenue, NE
Washington, DC 20007

3M - Energy Control Products
Attn: R. Dahlen
201-1W 3M Center
St. Paul, MN 55144-1000

3M - Solar Optics Program
Attn: Paul Jaster
3M Center
Building 225-2N-06
St. Paul, MN 55144-1000

Acurex Corporation
Attn: Hans Dehne
555 Clyde Avenue
Mountain View, CA 94039

Acurex Corporation
Attn: John Schaeffer
555 Clyde Avenue
Mountain View, CA 94039

American Hydrogen Assoc.
Attn: Roy McCalister
216 S. Clark, MS-103
Tempe, AZ 85281

Arizona Public Service Co.
Attn: Scott McLellan
P.O. Box 53999
MS 1424
Phoenix, AZ 85072-3999

Arizona Solar Energy Office
Attn: Jack Haenichen
Department of Commerce
3800 N. Central
Suite 1200
Phoenix, AZ 85012

Arizona Solar Energy Office
Attn: Frank P. Mancini, Ph.D.
Department of Commerce
3800 N. Central
Suite 1200
Phoenix, AZ 85012

AT&T
Attn: Gregory P. Robertson, P.E.
P.O. Box 13369
Phoenix, AZ 85002

Australian National University
Attn: K. Inall (2)
R.S. Phy. Sc.
Energy Research Center
Canberra, ACT 2601, AUSTRALIA

Australian National University
Attn: Stephen Kaneff
Dept. of Engineering Physics
P.O. Box 4
Canberra, ACT 2600, AUSTRALIA

Barber-Nichols Engineering
Attn: Robert Barber
6325 W. 55th Avenue
Arvada, CO 80002

Battelle Pacific Northwest Laboratory
Attn: K. Drumheller (2)
P.O. Box 999
Richland, WA 99352

Bomin Solar
Attn: H.J. Kleinwachter
Industriestr. 8-10
D-7850
Lorrach-Haagen 6, GERMANY

California Energy Commission
Attn: Alec Jenkins
Energy Technology Development Div. R&D
Office
1516 9th Street
MS-43
Sacramento, CA 95814-5512

California Polytechnic State University
Attn: William B. Stine
Department of Mechanical Engineering
3801 West Temple Avenue
Pomona, CA 91768-4062

Central and South West Services, Inc.
Attn: E.L. Gastineau
1616 Woodall Rogers Freeway
MS 7RES
Dallas, TX 75202

Central and South West Services, Inc.
Attn: Ward Marshall
P. O. Box 660164
Dallas, TX 75266-0164

Central and South West Services, Inc.
Attn: Rick Walker
P.O. Box 21928
Tulsa, OK 74121-1928

Centro Investigaciones Energeticas
Attn: M. Macias
Medioambientales y Tecnologicas
Instituto de Energias Renovables
Avda. Complutense, 22
28040 Madrid, SPAIN

Centro Investigaciones Energeticas
Attn: M. Romero
Medioambientales y Tecnologicas
Instituto de Energias Renovables
Avda. Complutense, 22
28040 Madrid, SPAIN

Clarkson University
Attn: Eric F. Thacher
Department of Mechanical & Aeronautical
Engineer
Potsdam, NY 13699-5725

Clever Fellows
Attn: John A. Corey, P.E.
Innovation Consortium, Inc.
R.D. 1, Box 410, River Road
Melrose, NY 12121

Conservation and Renewable Energy System
Attn: Ben Wolff
6918 N.E. Fourth Plain Blvd., Suite B
Vancouver, WA 98661

Cummins Power Generation
Attn: John Bean
Mail Code 50179
P.O. Box 3005
500 Jackson Street
Columbus, IN 47202-3005

Cummins Power Generation
Attn: John Christianson
Mail Code 50179
P.O. Box 3005
500 Jackson Street
Columbus, IN 47202-3005

Cummins Power Generation
Attn: Isoroku (Rocky) Kubo (2)
Mail Code 60125
P.O. Box 3005
500 Jackson Street
Columbus, IN 47202-3005

Cummins Power Generation South
Attn: Monte McGlaun
150 Tannehill Drive
Abilene, TX 79602

Cummins Power Generation, Inc.
Attn: Jerome Davis
Mail Code 60125
P.O. Box 3005
500 Jackson Street
Columbus, IN 47202-3005

DLR
Attn: Reiner Buck
Pfaffenwaldring 38-40
7000 Stuttgart 80, GERMANY

Dynatherm Corporation
Attn: W. Bienert
1 Beaver Court
P.O. Box 398
Cockeyville, MD 21030

Dynatherm Corporation
Attn: D. Wolf
1 Beaver Court
P.O. Box 398
Cockeyville, MD 21030

Electric Power Research Institute
Attn: J. Schaeffer
P.O. Box 10412
3412 Hillview Avenue
Palo Alto, CA 94303

ENTECH, Inc.
Attn: Mark O'Neill
P.O. Box 612246
DFW Airport, TX 75121

ENTECH, Inc.
Attn: R. Walters
P.O. Box 612246
DFW Airport, TX 75121

Environmental Enterprise Institute
Attn: John Thompson
2066 Westwood Circle
Smyrna, GA 30080

Flachglas Solartechnik GmbH
Attn: M. Geyer
Theodor-Heuss-Ring 1
5000 Koln 1, GERMANY

Florida Solar Energy Center
Attn: Library
300 State Road, Suite 401
Cape Canaveral, FL 32920-4099

Georgia Power Co.
Attn: W. Rosskist
7 Solar Circle
Shenandoah, GA 30265

Harris Corporation
Attn: K. Schumacher
Government Aerospace Systems Division
P.O. Box 9400
Melbourne, FL 32902

HMG & Associates
Attn: Edwin Mole
3508 Far West Blvd.
Suite 350
Austin, TX 78731

Innovation Consortium, Inc.
Attn: John Cory (3)
R. D. 1, Box 410, River Road
Melrose, NY 12121

Institute of Gas Technology
Attn: Library
34245 State Street
Chicago, IL 60616

Jet Propulsion Laboratory
Attn: M. Alper
4800 Oak Grove Drive
Pasadena, CA 91109

Kearney & Associates
Attn: David W. Kearney
14022 Condessa Drive
Del Mar, CA 92014

Lawrence Berkeley Laboratory
Attn: Arlon Hunt
University of California
MS 90-2024
One Cyclotron Road
Berkeley, CA 94720

Los Alamos National Laboratory
Attn: M. Merrigan
P.O. Box 1663
MS-E13
Los Alamos, NM 87545

McDonnell-Douglas Astronautics Co.
Attn: Bob Drubka (3)
5301 Bolsa Avenue
Huntington Beach, CA 92647-2048

McDonnell-Douglas Astronautics Co.
Attn: J. Rogan (3)
5301 Bolsa Avenue
Huntington Beach, CA 92647

McDonnell-Douglas Astronautics Co.
Attn: D. Steinmeyer (3)
5301 Bolsa Avenue
Huntington Beach, CA 92647

Mechanical Technologies, Inc.
Attn: G.R. Dochat
968 Albany Shaker Road
Latham, NY 12110

Mechanical Technologies, Inc.
Attn: J. Wagner (2)
968 Albany Shaker Road
Latham, NY 12110

NASA/Lewis Research Center
Attn: Jim Calogeras
21000 Brook Park Road
Cleveland, OH 44135

NASA/Lewis Research Center
Attn: J. Schrieber
21000 Brook Park Road
Cleveland, OH 44135

NASA/Lewis Research Center
Attn: R. Shaltens (4)
21000 Brook Park Road
Cleveland, OH 44135

National Renewable Energy Laboratory
Attn: Mark Bohn
1617 Cole Blvd.
Golden, CO 80401-3393

National Renewable Energy Laboratory
Attn: Gary Jorgensen
1617 Cole Blvd.
Golden, CO 80401-3393

National Renewable Energy Laboratory
Attn: A. Lewandowski
1617 Cole Blvd.
Golden, CO 80401-3393

National Renewable Energy Laboratory
Attn: L.M. Murphy
1617 Cole Blvd.
Golden, CO 80401-3393

National Renewable Energy Laboratory
Attn: Tim Wendelin
1617 Cole Blvd.
Golden, CO 80401-3393

National Renewable Energy Laboratory
Attn: Tom Williams (6)
1617 Cole Blvd.
Golden, CO 80401-3393

Northern Research & Engineering Corp.
Attn: James B. Kesseli
39 Olympia Avenue
Woburn, MA 01801-2073

Pacific Power
Attn: Stephen Schuck
Park and Elizabeth Streets
GPO Box 5257
Sydney
New South Wales, 2001 AUSTRALIA

Power Kinetics, Inc.
Attn: W.E. Rogers (2)
415 River Street
Troy, NY 12180-2822

Renewable Energy Training Institute
Attn: Kevin Porter
122 C St. NW, Suite 520
Washington, DC 20001

Research International
Attn: E. Saaski
18706 142nd Avenue, NE
Woodinville, WA 98072

Rockwell International Corp.
Attn: William Bigelow
Energy Technology Engineering Center
P.O. Box 1449
Canoga Park, CA 91304

Rockwell International Corp.
Attn: R. LeChevalier
Energy Technology Engineering Center
P.O. Box 1449
Canoga Park, CA 91304

Rockwell International Corp.
Attn: W. Marlatt
Rocketdyne Division
P.O. Box 7922
6633 Canoga Avenue
Canoga Park, CA 91309-7922

Rockwell International Corp.
Attn: Bob Musica
Energy Technology Engineering Center
P.O. Box 1449
Canoga Park, CA 91304

Sacramento Municipal Utility District
Attn: Don Osborne
Generation Systems Planning
Power Systems Dept.
6201 'S' St.
P.O. Box 15830
Sacramento, CA 95852-1830

Schlaich, Bergermann & Partner
Attn: W. Schiel
Hohenzollernstr. 1
D-7000 Stuttgart 1, GERMANY

Science Applications International Corp.
Attn: Kelly Beninga
15000 W. 6th Avenue
Suite 202
Golden, CO 80401

Science Applications International Corp.
Attn: Bill Bruninga
15000 W. 6th Avenue
Suite 202
Golden, CO 80401

Science Applications International Corp.
Attn: Barry L. Butler
Room 2043, M/S C2J
10260 Campus Point Dr.
San Diego, CA 92121

Science Applications International Corp.
Attn: Roger L. Davenport
15000 W. 6th Avenue
Suite 202
Division 448
Golden, CO 80401

Science Applications International Corp.
Attn: Neil Otto
10260 Campus Point Dr.
Mail Stop 32
San Diego, CA 92121

Solar Energy Industries Association
Attn: Linda Ladas
122 C Street, NW
4th Floor
Washington, DC 20001-2109

Solar Energy Industries Association
Attn: Ken Sheinkopf (2)
122 C Street, NW
4th Floor
Washington, DC 20001-2109

Solar Energy Industries Association
Attn: Scott Sklar (2)
122 C Street., NW
4th Floor
Washington, DC 20001-2109

Solar Kinetics, Inc.
Attn: Gus Hutchison (2)
10635 King William Drive
P.O. Box 540636
Dallas, TX 75354-0636

Solar Kinetics, Inc.
Attn: D. White
10635 King William Drive
P.O. Box 540636
Dallas, TX 75354-0636

South Coast AQMD
Attn: Ranji George
21865 Copley Drive
Diamond Bar, CA 91765

Southern California Edison Co.
Attn: Mark Skowronski
P.O. Box 800
2244 Walnut Grove Avenue
Rosemead, CA 91770

Stirling Machine World
Attn: B. Ross
1823 Hummingbird Court
West Richland, WA 99352-9542

Stirling Technology Co.
Attn: Jack Noble
2952 George Washington Way
Richland, WA 99352

Stirling Technology Co.
Attn: Maurice A. White
2952 George Washington Way
Richland, WA 99352

Stirling Thermal Motors
Attn: Ted Goddett
275 Metty Drive
Ann Arbor, MI 48103

Stirling Thermal Motors
Attn: Stefan Johansson
275 Metty Drive
Ann Arbor, MI 48103

Stirling Thermal Motors
Attn: Lennart Johansson (2)
275 Metty Drive
Ann Arbor, MI 48103

Stirling Thermal Motors
Attn: Ben Ziph
275 Metty Drive
Ann Arbor, MI 48103

Sunpower, Inc.
Attn: W. Beale
6 Byard Street
Athens, OH 45701

Tech Reps, Inc.
Attn: Faith Putter
5000 Marble NE, Suite 222
Albuquerque, NM 87110

Tech Reps, Inc.
Attn: Dan Scott
5000 Marble NE, Suite 222
Albuquerque, NM 87110

Technology Properties Limited
Attn: Janet Neal
4010 Moorpark Avenue, Suite 215
San Jose, CA 95117

The Solar Letter
Attn: Allan L. Frank
9124 Bradford Road
Silver Spring, MD 20901-4918

Thermacore Inc.
Attn: Bill Anderson
780 Eden Road
Lancaster, PA 17601

Thermacore, Inc.
Attn: Pete Dussinger
780 Eden Road
Lancaster, PA 17601

Thermacore, Inc.
Attn: Donald Ernst
780 Eden Road
Lancaster, PA 17601

U.S. Department of Energy
Attn: R. (Bud) Annan (2)
Code EE-13
Forrestal Building
1000 Independence Ave. SW
Washington, DC 20585

U.S. Department of Energy
Attn: Gary Burch (5)
Code EE-132
Forrestal Building
1000 Independence Avenue, SW
Washington, DC 20585

U.S. Department of Energy
Attn: R. Hughey
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612

U.S. Department of Energy
Attn: D.A. Sanchez (2)
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87115

United Solar Technologies, Inc.
Attn: Richard Kelly
3434 Martin Way
Suite One
Olympia, WA 98506

University of Chicago
Attn: J. O'Gallagher
Enrico Fermi Institute
5640 Ellis Avenue
Chicago, IL 60637

University of Houston
Attn: James Richardson (2)
Solar Energy Laboratory
4800 Calhoun Road
Houston, TX 77704

University of Minnesota
Attn: E.A. Fletcher
1111 Church Street, SE
Dept. of Mech. Engr.
Minneapolis, MN 55455

W.G. Associates
Attn: Vern Goldberg
6607 Stonebrook Circle
Dallas, TX 75240

Internal Distribution:

MS 0100 Document Proc. for DOE/OSTI, 7613-2 (2)
MS 0619 Technical Publications, 12613
MS 0703 C.E. Andraka, 6216
MS 0703 R.B. Diver, 6216
MS 0703 D.R. Gallup, 6216
MS 0703 T.R. Mancini, 6216
MS 0703 J.B. Moreno, 6216
MS 0703 T.A. Moss, 6216
MS 0703 C.E. Tyner, 6216
MS 0835 D.R. Adkins, 1513 (10)
MS 0835 R.D. Skocypec, 1513
MS 0899 Technical Library, 13414 (5)
MS 1127 J.M. Chavez, 6215
MS 1127 Library, 6215 (5)
MS 1127 K.S. Rawlinson, 6215 (10)
MS 9018 Central Technical Files, 8523-2