PERFORMANCE TEST PLAN
FOR
A SPACE STATION TOLUENE HEATER TUBE

CONTRACT NO. 9-X6H-8102L-1

PREPARED FOR
LOS ALAMOS NATIONAL LABORATORY
LOS ALAMOS, NEW MEXICO

BY
SUNDSTRAND ENERGY SYSTEMS
4747 HARRISON AVENUE
ROCKFORD, ILLINOIS

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MASTER

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APPROVAL SHEET

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(CONTRACT NO: 9-X6H-8102L-1)

PREPARED BY

(M.B. PAREKH)

DATE Oct. 05, 87

APPROVED BY

(G. HEIDENREICH)

DATE 10-14-87

APPROVED BY

(G. HILL)

DATE 10/15/87

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1.0 Introduction

This test plan describes the Sundstrand portion of Task 4 of Los Alamos National Laboratory (LANL) contract 9-X6H-8102L-1.

Sundstrand Energy Systems was awarded a contract to investigate the performance capabilities of a toluene heater tube integral to a heat pipe as applied to the Organic Rankine Cycle (ORC) solar dynamic power system for the Space Station.

This heat pipe is a subassembly of the heat receiver shown in Figure 1. The heat receiver, the heat absorption component of the ORC solar dynamic power system, consists of forty liquid metal heat pipes located circumferentially around the heat receiver's outside diameter. As shown in Figure 1, each heat pipe contains a toluene heater tube, two thermal energy storage (TES) canisters and potassium.

The function of the heater tube is to heat the supercritical toluene to the required turbine inlet temperature. During the orbit of the space station, the heat receiver and thereby the heat pipe and heater tube will be subjected to variable heat input. The design of the heater must be such that it can accommodate the thermal and hydraulic variations that will be imposed upon it.

2.0 Technical Objectives

The following represent the technical objectives for Task 4:

- o To determine the hydraulic and thermal performance characteristics of the toluene heater tube (THT) with heat input simulating that from a heat pipe.
- o To verify the design techniques used to predict the thermal performance characteristics of the heater tube. The following two space station conditions are planned to be simulated:
 - a. Maximum input power
 - b. Minimum input power

3.0 Design Requirements

The following form the basis for the design of the test loop and test hardware:

- o Simulate thermal and hydraulic aspects of the space station heater tube (Described in section 5.0)
- o Maximum input power to the working fluid 3.85 KW_t
- o Toluene working fluid (Conditions defined in Table III)
- o Constant flow rate for all conditions (54.35 lbm/hr for maximum power and 39.25 lbm/hr for minimum power)
- o Supercritical cycle
- o Fluidized bed as a heat source to simulate isothermal heat input to heater tube
- o Detailed cleaning and purging procedures similar to that used under the NAS3-24663 Toluene Stability Program

4.0 Test Loop and Hardware Description

Descriptions are given for the test loop and test hardware in this section.

4.1 Test Loop Description

The toluene heater tube (THT) thermal and hydraulic performance tests will be conducted in Sundstrand test cell 62 using the toluene stability loop which is specifically modified for these tests. The toluene stability test loop was originally designed and built under the separate government funded program (NAS3-24663) for the measurement of toluene degradation rate while simulating the ORC turbine inlet/outlet conditions. Figure 2 shows the modified toluene test facility schematic for testing the toluene heater tube. Test loop cleaning and toluene handling procedures are briefly described in Paragraph 7.0. The toluene inlet mass flow will be adjusted to the desired value by the control valve shown on Figure 2. The toluene inlet temperature will be controlled by adjusting the heat rejected in the water cooled condenser. This is done with valve VI shown on Figure 2. The temperature of fluidized bed, which is a heat source for this test, will be maintained at the desired value by controlling the power input to the electrical heaters. Figure 3 shows the test article submerged in the fluidized bed. General engineering features of the fluidized bed are shown in Figure 4.

Instrumentation (as listed in Table I) will be provided to measure the inlet mass flow, pressure and temperature for the toluene heater tube. The outlet temperature and the pressure drop across the toluene heater tube inlet and outlet ports will also be measured. Additional thermocouples will be located on the thermal stand-off sections of the heater tube. The fluidized bed temperature and the heater tube external skin temperature will be monitored. Figures 2 and 5 show the pressure and temperature probe locations. An automatic computer data acquisition system will be used to monitor and record the test data. The red line parameters will also be identified to shut down the test system in case of the system operating beyond a safe limit. The shutdown may be automatic and/or manual. Table I describes the instrumentation that will be used to monitor the thermal performance of the toluene heater tube.

4.2 Toluene Heater Tube

The organic Rankine cycle solar dynamic power system (ORC-SDPS) converts concentrated solar energy into the thermal energy required to generate electric power. Heat pipes, with integral thermal energy storage canisters and

heater tubes, form the cavity inside wall of the solar receiver. They absorb solar energy and transform it into a uniform source temperature for the ORC working fluid (toluene). The bayonet style toluene heater tube (THT), integral to the heat pipe, provides an interface between the heat pipe potassium vapor and the toluene working fluid. A constant heat flux THT design ensures a gradual toluene temperature increase throughout the heater tube length, thereby minimizing toluene degradation for a given outlet temperature.

Constant heat flux to the toluene working fluid from a uniform source temperature can be accomplished by incorporating thermal standoffs in the THT design. One such design provides disk fins with axially varying cross-section as the thermal standoffs between the heat pipe/heater tube interface (outer tube) and the inner toluene working fluid tube (inner tube). Thermal standoffs with radially low conductance at the toluene annulus inlet linearly increasing to radially high conductance at the toluene annulus exit provide an axially uniform heat flux to the toluene.

The disk fin constant heat flux heater tube developed and fabricated under Los Alamos contract no. 9-X6H-8102L-1, shown in Figure 6. The heater tube is fabricated from 300 series stainless steel, which is compatible with toluene.

5.0 Performance Predictions

The heater tube was designed for supercritical toluene flow. Therefore, any boiling phenomena is avoided. A thermal math model was developed to analyze the design and determine how closely it meets the SD-ORC performance requirements. The minimum power input occurs during the nominal insolation orbit (solar constant 1.323 kW/m^2) at the end of the eclipse period. Maximum power input occurs during the maximum insolation orbit (solar constant 1.419 kW/m^2) at the end of the insolation period. The design parameters and accompanying pressure-enthalpy (P-H) diagram are summarized in Table II. The thermal model results based on the two design points are shown in Figures 7 and 8. The minimum design point is identified as a "min-insolation" and the maximum design point is identified as "max-insolation." The model predicts that the design will adequately meet the SD-ORC performance requirements. The predicted outlet temperatures are shown in Table II. The maximum pressure drop across the THT is calculated to be 8.8 psi.

6.0 Planned Tests

Steady-State Thermal Performance Test

The series of tests are planned to determine the steady-state performance characteristics of the toluene heater tube. A minimum of two steady-state thermal and hydraulic performance tests are planned which will permit the various combinations of the inlet toluene mass flow, pressure and temperature conditions to be investigated. The test conditions are based upon the toluene heater tube design parameters derived from the ORC solar dynamic power system performance requirements for the Space Station, and are shown on Table III.

7.0 Procedures

The test loop cleaning and toluene handling procedures that will be conducted prior to testing are listed below:

Loop Construction

1. Cleaning Piece Parts and Subassemblies

- o CP14.57-01
General precision cleaning
KIPS (See Appendix G)
- o Summary of CP14.57-01
 - o NVR < 10 ppm
 - o

<u>Particle Size</u> (μm)	<u>Particle Count</u>
5-15	8000
16-25	1425
26-50	253
51-100	45
>100	8
- o Basic procedure defined in CP14.57-01
 - o Flush with freon
 - o Blow dry with GN_2
 - o Vapor decrease in freon
 - o Ultrasonic clean
 - o Rinse
 - o Sample flushing liquid, must comply with above
 - o Blow dry with GN_2
 - o Vacuum bake
 - o Bag and seal

2. Leak Checks

- o Helium mass spectrometer leak check on subassemblies and system
- o Evacuate interior to 1×10^{-4} torr
- o Max. allowable leakage rate 1×10^{-6} scc/sec

3. Toluene Preparation

- o Deaerate charge of toluene
 - o Freeze under vacuum using liquid nitrogen
 - o Repeat twice
- o Load deaerated toluene into clean, evacuated system

4. Flushing

- o Charge evacuated circuit with deaerated toluene
- o Heat fluidized bed
- o Circulate toluene
- o Analyze sample for:
 - 1. Particulates per NAS1638, Class 5
 - 2. Nonvolatile residue shall not exceed 10 ppm per 100 ml of fluid
 - 3. Volatile contaminants shall not exceed amounts in original toluene sample
- o Continue flushing until acceptable

8.0 Data Acquisition System

An existing Analog Devices MACSYM automatic data acquisition system will be used to monitor and record the temperature, pressure and mass flow data. The critical parameters will also be recorded on the 8-channel brush recorder. Table I describes the type of recording device used for monitoring such parameters. The daily record of testing, including any anomalies, will be logged in the THT test log book. The inlet/outlet test parameters will be recorded in the test data sheet shown in Table IV. Test anomalies, if any identified, will be evaluated for their impact on future testing. The appropriate corrective actions will be taken to minimize the impact due to anomalies on further testing.

9.0 Report

A test report describing the test objectives, test results and correlation with the analytical data, and conclusions will be prepared and submitted as part of meeting the contractual requirements.

TABLE I

TOLUENE HEATER TUBE INSTRUMENTATION

<u>No.</u>	<u>Parameters</u>	<u>Unit</u>	<u>Range</u>	<u>Device</u> *
1	Inlet Mass Flow	Lb/hr	0-72	X, Y
2	Inlet Temp (A)	°F	RT-600	X, Y
3	Inlet Temp (B)	°F	RT-600	Y
4	Inlet Pressure	Psig	0-1000	X, Y
5	Outlet Temp (A)	°F	400-1000	X, Y
6	Outlet Temp (B)	°F	400-1000	Y
7	P (Pressure Drop)	Psi	0-200	X, Y
8	Fluidized Bed Temp (A)	°F	RT-1200	Y
9	Fluidized Bed Temp (B)	°F	RT-1200	X, Y
10	Fluidized Bed Temp (C)	°F	RT-1200	Y
11	Thermal Standoff Temp (1)	°F	RT-1200	X, Y
12	Thermal Standoff Temp (2)	°F	RT-1200	Y
13	Thermal Standoff Temp (3)	°F	RT-1200	Y
14	Thermal Standoff Temp (4)	°F	RT-1200	Y
15	Thermal Standoff Temp (5)	°F	RT-1200	Y
16	Thermal Standoff Temp (6)	°F	RT-1200	Y
17	Thermal Standoff Temp (7)	°F	RT-1200	Y
18	Heater Tube Outer Skin Temp (1)	°F	RT-1200	Y
19	Heater Tube Outer Skin Temp (2)	°F	RT-1200	Y
20	Heater Tube Outer Skin Temp (3)	°F	RT-1200	Y

* NOTE: X - Brush Recorder
Y - Digital Display

TABLE II
SD-ORC HEATER TUBE DESIGN POINTS

Minimum Power Input
(○ — ○)

Heat Pipe Vapor Temperature	852°F
Toluene Inlet Temperature	424°F
Toluene Mass Flow Rate Per Heater Tube	39.25 lbm/hr
Toluene Inlet Pressure	614 psia
Required Toluene Outlet Temperature	725°F
Model Predicted Toluene Outlet Temperature	722°F

Maximum Power Input
(□ — □)

Heat Pipe Vapor Temperature	893°F
Toluene Inlet Temperature	375.3°F
Toluene Mass Flow Rate Per Heater Tube	54.35 lbm/hr
Toluene Inlet Pressure	731 psia
Required Toluene Outlet Temperature	687°F
Model Predicted Toluene Outlet Temperature	707°F

P-H DIAGRAM, TOLUENE

TABLE III
TOLUENE HEATER TUBE TEST CONDITIONS

Test No.	Bed Temp (°F)	Toluene Flow lb/hr	Inlet Temp (°F)	Inlet Pressure (psia)	Solar Dynamic Power System Operating Condition
1	893	54.35	375	731	Maximum Input Power
2	852	39.25	424	614	Nominal Input Power

TABLE IV
TOLUENE HEATER TUBE TEST DATA

Test Run _____

Date _____

TEST NO.	INLET TEMP. °F	INLET PRESS. Psi	INLET MASS FLOW lb/Hr	OUTLET TEMP. °F	PRESSURE DROP Psi	FLUIDIZED BATH TEMP °F	THERMAL STAND-OFF TEMP °F	REMARKS
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Engineer: _____

Date: _____

FIGURE 1

ORC Heat Pipe Receiver

FIGURE 2

FIGURE 3

A SCHEMATIC OF TOLUENE HEATER TUBE
SUBMERGED IN FLUIDIZED BED

Top View Furnace

Front Elevation Furnace

1. 40 Kw capacity
2. 6 watlow radiant heaters, 7-1/2 kw, 480V, 3Ø
3. Max. temp 1450°F
4. Air blower 1500 CFH
5. Al₂O₃ extra fine mesh 120
6. Ceramic insulation
7. Overall dimensions 110" x 32" x 50"
(retort) 92" x 12" x 24")
8. +/-10°F
9. Fluidtherm Corp., Michigan

FIGURE 5
DISC FIN TOLUENE HEATER TUBE INSTRUMENTATION

NOTE: INLET/OUTLET INSTRUMENTATION IS SHOWN IN FIGURE 2

FIGURE 6
DISC FIN TOLUENE HEATER TUBE

THT TEMPERATURE VS LENGTH

DATE 10/1/87

THT CUMULATIVE Q ABSORBED VS LENGTH

DATE 10/1/87

THT MATERIAL IS SS316L
THT OD = 1.00" THK = .035"
THT ID = .900" THK = .035"
CB OD = .375" THK = .035"

FIN THK = .04, .06, .07, .07 TO .1" 250 FINS
FIN GAP = .195"
K = 0.89-11.0
.000" THK CU LAYER
7 SEGMENTS

T_{in} = 424.0 F
T_{out} = 852.0 F
P_{in} = 614 psia
MDOT = 39.25 LBM/HR

FIGURE 7

HEATER TUBE PERFORMANCE PREDICTION
(NOMINAL INSULATION)

THT TEMPERATURE VS LENGTH

DATE 10/1/87

THT CUMULATIVE Q ABSORBED VS LENGTH

DATE 10/1/87

THT MATERIAL IS SS316L
THT OD = 1.00" THK = .035"
THT ID = .500" THK = .035"
CB OD = .375" THK = .035"

FIN THK = .04-.06-.07 TO .1" 250 FINS
FIN GAP = .105"
K = 0.89-11.0
.000" THK Co LAYER
7 SEGMENTS

T_o = 375.3 F
T_o = 893.0 F
P_o = 731 psia
MDOT = 84.35 LBM/HR

FIGURE 8

HEATER TUBE PERFORMANCE PREDICTION
(MAXIMUM INSOLATION)