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TRANSIENT HEAT PIPE INVESTIGATIONS FOR SPACE POWER SYSTEMS

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ABSTRACT

A 4-meter long, high temperature, high power, molybdenum-lithium heat pipe has been fabricated and tested in transient and steady state operation at temperatures to 1500 K. Maximum power throughput during the tests was approximately 37 kW/cm^2 for the 1.4 cm diameter vapor space of the annular wick heat pipe. The evaporator flux density for the tests was 150.0 W/cm^2 over a length of 40 cm. Condenser length was approximately 3.0 m with radiant heat rejection from the condenser to a coaxial, water cooled radiation calorimeter. A variable radiation shield, controllable from the outside of the vacuum enclosure, was used to vary the load on the heat pipe during the tests.

INTRODUCTION

Present space nuclear power system designs employ high temperature heat pipes for primary heat transport, system start-up and thermal conditioning, decay heat transport, and for heat rejection. Operating characteristics of these high temperature, high performance heat pipes have been the subject of a continuing experimental program at Los Alamos National Laboratory. Recent developments in this on-going program include the performance characterization of a 4-meter long lithium heat pipe. This heat pipe has been tested in transient and steady-state operation at temperatures to 1500 K. Tests conducted include start-up from the solid state under load, shut-down from high temperature operation with continuous radiation loading, and high power steady-state operation. The intent of these tests was to resolve questions pertaining to the operation and performance characterization of high length to diameter ratio (L/D) heat pipes under conditions of high radiation loading. Start-up times and power handling capability, shut-down behavior with radiation sink temperatures below the freezing point of the working fluid, and accuracy of presently used performance models were specific questions that were addressed in the test program. It is hoped that the results of these investigations will be of value in space nuclear power system design and analysis.

DESCRIPTION OF TEST HARDWARE

A 4 m long heat pipe was fabricated from 1.9-cm outside diameter, low carbon arc cast molybdenum tubing having a wall thickness of 0.15 cm. End closures were machined from bar stock of the same material. A cross section of the heat pipe is shown in Fig. 1.

The screen wick was fabricated from a single piece of 400-mesh, plain square weave wire cloth woven from 0.025-mm diameter molybdenum-41 w/o rhenium wire. In fabricating the wick the screen was wrapped on a low carbon steel tube mandrel to form a structure 7.25 layers thick. A series of spot welds along the leading and trailing edge of the wrap were used to hold the edges in place during forming and processing. A sheath, also of low carbon steel, was fitted over the screen layers and the assembly drawn through a sizing die to compress the layers. The reduction in screen cross section was approximately 20%. The steel mandrel and sheath were then removed by dissolution with hydrochloric acid to leave a clean cylindrical wick. The wick was further treated by vacuum firing at 1700 K for 2 hours in order to sinter the screen layers into a monolithic structure and to remove volatile contaminants. Surface tension measurements of the completed wick indicated an effective pore diameter of less than 53 microns. The fluid annulus, which extended the length of the heat pipe, was formed between the container tube inside diameter and the slightly smaller tubular wick. This annulus served as a path for fluid return from the condenser to the evaporator during operation. A molybdenum plug was used to close the screen wick tube at the evaporator end. This plug closure ensured that the annulus pumping capability was established by the effective pore size of the screen wick rather than by the annulus dimensions. The wick outside diameter of 15.9 mm established a maximum dimension for the annulus of 1.16 mm when assembled in the 16.0-mm inside diameter container tube and in line contact with one surface. The cross sectional flow area of the resulting annulus was 28.0 mm. Vapor flow area for the heat pipe, based on the screen wick tube inside diameter was 1.6 cm^2.

The evaporator end of the screen wick was sealed with a molybdenum plug using a vacuum braze joint made with preplaced zirconium wire braze material. Two turns of 0.381-mm diameter zirconium wire were pressed into the wick. An interference fit of 0.051 mm was maintained between the plug and the bore of the screen wick tube. Brazing was accomplished by RF induction heating the joint in a quartz envelope that allowed visual observation of the braze material. In making the joint the RF power was slowly increased until the braze was observed to flow. The power and temperature were then immediately reduced and the joint brought to ambient temperature over a period of approximately one-half hour.

Hafnium and zirconium disks were placed inside each end of the heat pipe to serve as getters for carbon, nitrogen, and other trace contaminants during the operation. Closure of the heat pipe envelope was accomplished by electron beam welding a fill plug assembly in place after wick insertion. The fill plug assembly consisted of the tube closure preassembled to a fill tube of 6.35-mm molybdenum tubing with a niobium braze transition to stainless steel for fill system attachment. After completion of the weld the system was leak checked with a 9×10^{-11} atm cm^3/s leak detector. No leaks were disclosed.

FILLING AND PROCESSING OF THE HEAT PIPE

The lithium working fluid was placed in the heat pipe by distillation, using the apparatus shown schematically in Fig 2. The inner surfaces of the distillation pot were covered with multiple layers of 100 mesh stainless steel screen to ensure uniform temperatures and to increase the evaporation surface area. The distillation container was heated by RF induction at a level near the surface of the liquid lithium pool to minimize boiling or slugging of the liquid. Hafnium and zirconium getter materials were placed in the distillation pot prior to filling with the lithium charge. The getter materials were placed so as to remain below the surface of the lithium pool during distillation. A fill volume container was inserted in the fill line between the distillation pot and the heat pipe to establish the fill charge for the heat pipe. Water cooled chill blocks were used as valves on the fill lines during the fill operation.

The internal volume of the heat pipe was connected to a vacuum pumping system through the distillation lines as a means of degassing the system prior to distillation. This same pumping system was used to remove off gasses from the lithium during the fill process with a liquid trap providing for return of condensed lithium vapor to the distillation container.

During the vacuum bakeout and distillation processes the heat pipe exterior was protected from oxidation by a quartz envelope connected to a second vacuum system. Pressures were maintained below 10-4 torr throughout the fill process to reduce the possibility of hydrogen contamination by disassociation of atmospheric moisture on the heat pipe outer surface.

The heat pipe and fill apparatus was heated to 1050 K and held at temperature until the pressure levels internal to the system reached 10-6 torr. The charge volume was then cooled to 500 K and the lower fill line and heat pipe cooled to 300 K and the lower chill block indicated in the figure activated. The distillation pot temperature was then increased to 1150 K and then held while lithium vapor was condensed in the charge loading pot. When the charge pot had filled it was cooled to 900 K and the lower chill removed. The heat pipe and transfer tube were then heated to 500 K, the loading pot was heated to 800 K and the lithium was allowed to transfer into the heat pipe under the combined gravitational and vapor pressure head. At the end of this process the lower chill block was cooled to close off the heat pipe from the distillation apparatus. The heat pipe was then positioned horizontally for distribution and wet-in of the lithium charge. The heat pipe was heated to 1100 K with a full length RF coil and held at temperature for 5 hours to accomplish the internal surface wetting.

For initial performance verification the heat pipe was heated over a length of 127 cm and the length of the excess liquid pool determined. Final processing of the heat pipe prior to removal of the distillation system and capping consisted of operation under adverse gravity conditions for 4 hours at 1275 K with radiation loading to the laboratory environment.

TEST OPERATIONS

Power input to the heat pipe during the operational tests was provided by high frequency RF induction with a water cooled coaxial calorimeter used as a heat sink for radiation from the condenser as indicated in Fig. 3. An adjustable radiation shield was used to vary the loading on the heat pipe during start-up and shut down as shown in Fig. 4. Power throughput was determined from water flow and temperature change measurements at the calorimeter. Heat pipe temperature was measured by tungsten-rhenium thermocouples welded to the heat pipe at the evaporator exit area and at 50 cm intervals along the condenser. The tests were conducted in a vacuum chamber maintained at a pressure level of 10^{-6} torr throughout the test.

In the initial test the heat pipe was started by heating the evaporator with the radiation shields in the closed position. When the heat pipe reached steady state it was maintained at temperature overnight. The following day the heat pipe was increased in temperature to 1400 K for operational verification. Temperatures along the condenser length, liquid pool length and power throughput were recorded under steady-state operation at 1400 K with the radiation control shutters closed. The power input was then reduced slowly following the radiation coupling curve with the power input turned off once the heat pipe had reached sonic velocity limited operation. After cooling below the lithium solidification temperature over its entire length, the heat pipe was restarted with the chamber radiation shields in the closed position and brought to 1300 K. No operational anomalies were observed during the re-start. After again reaching steady state operating conditions the power input to the heat pipe was turned off instantaneously and the heat pipe again allowed to cool to below the lithium freezing point.

In the next test the radiation shields were opened and the heat pipe was brought to temperature at the same rate as in the previous test. The radiation shields were then closed with the heat pipe at temperature, the power instantaneously shut off and the heat pipe allowed to cool to laboratory ambient conditions. Re-start was accomplished without difficulty.

In a succeeding test the heat pipe was taken to a power throughput level of 10.4 kW at 1525 K and shut down under power with the shields open. Following this test the heat pipe was removed from the test chamber for x-ray and neutron radiography to determine the condition of the wick structure and the disposition of the lithium in the annulus. The neutron radiography showed the annulus region of the evaporator to be filled with lithium except for a region approximately 1 cm in diameter located approximately 16.5 cm from the end of the heat pipe. The screen wick was dewetted in this area. The x-ray examination did not show any damage to the screen structure in the dewetted region but did show slight buckling of the screen located about 32 cm from the evaporator end of the heat pipe. The buckling was assumed to be caused by expansion of the evaporator wick during start-up and was not extensive enough to affect heat pipe performance.

The heat pipe was then processed for increased emissivity of the outer surface over all but the evaporator region. This was accomplished by bead blasting the outer surface of the LCAC molybdenum tube and then DC plasma arc spraying zirconium diboride on the surface. Film thickness of the coating was approximately 0.08 mm with a coating density of about 85% of theoretical. An argon carrier gas was used for the plasma spray proces.

The heat pipe was then rewet at 1075 K for 20 hours in a horizontal vacuum furnace. Following the processing it was neutron radiographed and found to be completely wet in. After coating and wet-in the heat pipe was installed in the test chamber, re-instrumented, and operated to verify performance with the radiation shields closed. Peak power throughput during this test was 10.3 kW.

At this point in the test program the investigation of cooldown and restart limits was interrupted to perform a high rate start-up test duplicating the conditions of the heat pipe planned for lithium line melt in the thermoelectric system design for SP-100. For this test the radiation shutters were left open, and the evaporator region of the heat pipe brought to a temperature of 1350 K following a calculated temperature profile for the reactor temperature in the system. This temperature profile is given as Fig. 5. After bringing the evaporator temperature to 1350 K the temperature was held constant by increases in input power from the RF generator as the melt front progressed along the length of the condenser section. The resulting temperature history is shown in Fig. 6. Total time to bring the heat pipe to temperature over its 4-M length was approximately 3 hrs with a peak power throughput of 15 kW. At the end of this test the power input was shut off and the heat pipe allowed to cool from temperature with the radiation shutters open. Temperatures along the heat pipe were recorded throughout the cooldown. An axial temperature plot taken some minutes after power shutoff is sown in Fig. 7. The temperature profile shows that the lithium near the evaporator end of the condenser has reached the solidification point while the lithium in the evaporator section of the heat pipe is still more than 300 K above freezing. After complete solidification of the lithium a re-start was attempted with negative results.

The heat pipe was again removed from the test chamber and radiographed. The radiograph showed a lithium void in the annulus in the evaporator region. A decision was made at this point to ZrB_2 coat the entire heat pipe, including the evaporator region, in an attempt to provide a more uniform cooldown rate over the length of the heat pipe. It was felt that the formation of shrinkage voids in the evaporator during lithium solidification would be reduced by this technique because of the lower evaporator temperatures at the time that solidification first occurred in the annulus. The heat pipe was therefore reprocessed for full length coating, re-wet, and installed in the test chamber.

In the following test the heat pipe was brought to 1250 K evaporator exit temperature and 19.04 kW throughput and shut down with the radiation shutters open. The subsequent attempt at re-start was successful.

As final performance verification of the heat pipe the radiation shutter apparatus was removed from the test chamber and the heat pipe taken to its power limit with maximum radiation coupling. A temperature-power history for this test is given in Fig. 3. Peak power throughput achieved was 36.8 kW as measured at the calorimeter. Indicated heat pipe evaporator exit temperature at this power level was 1509 K based on corrected optical measurements. The corresponding vapor space power density achieved was 23 kW/cm^2.

INTERPRETATION AND CONCLUSIONS

Steady-state operation of the heat pipe resulted in temperature profiles in good agreement with the pressure recovery model developed by Busse (Ref. 1) and incorporated in the current Los Alamos heat pipe performance prediction code HTPIPE-A. As may be seen in Fig. 9 the predicted temperatures are bracketed by experimental data that has a total temperature scatter of less than 2%. This agreement is of interest because the high L/D ratio of the heat pipe is characteristic of the heat pipe configurations planned for use in space power system radiator applications.

Start-up and shut down of the radiation loaded heat pipe provided verification of the capability of high power, radiation coupled heat pipes to start under high load conditions, that is, with a high emissivity surface coating radiation to an ambient temperature black body calorimeter surface. The start-up demonstration that was conducted as verification of the performance of the lithium line melt-out heat pipe planned for the thermoelectric system was of particular interest because the evaporator temperature throughout the warmup was held at the temperatures predicted from the reactor core models and the results consequently established an upper bound for the behavior of a similar warm-up heat pipe radiation coupled to a lithium line. The data from this test has served as the basis for modeling of the SP-100 thermoelectric system start-up transient and is the basis for the current system start time predictions.

Shutdown investigations conducted with the 4-m heat pipe were also of interest although the results were not as simply interpreted as those for the start-up case. Primary interest in the shut down investigation was directed to the ability of the heat pipe to restart under normal loads following shutdown and freezing. Test results indicated that restart of the heat pipe without further conditioning following a shut down was dependent on both the radial power density in the condenser, controlled by the surface emissivity of the heat pipe, and on the relative radial power density of the evaporator and condenser regions of the heat pipe during cooldown. It appears that the critical issue is the axial location where freezing first occurs during the shutdown and the ability of the wick structure to accommodate shrinking of the fluid in the region of the heat pipe furthest from the condenser end liquid pool in the period following the establishment of the freeze plug. It appears that the prediction of restart capability for a given radiation coupled heat pipe design will be strongly dependent on the external geometry and thermal environment of a heat pipe as well as on the internal geometry of the heat pipe itself. It is hoped that the heat pipe transient analysis program presently under development by Los Alamos will be capable of this prediction under realistic system conditions.

The high power limit demonstrated in the tests of the 4-m heat pipe has served to advance the boundaries of heat pipe performance by more than 20% and may serve as the basis for the use of heat pipes in more advanced reactor designs.

REFERENCES

1. Pressure Drop in the Vapor Phase of Long Heat Pipes, C. A. Busse, 1967 Thermionic Conversion Specialist Conference, November 1967.

FIGURES

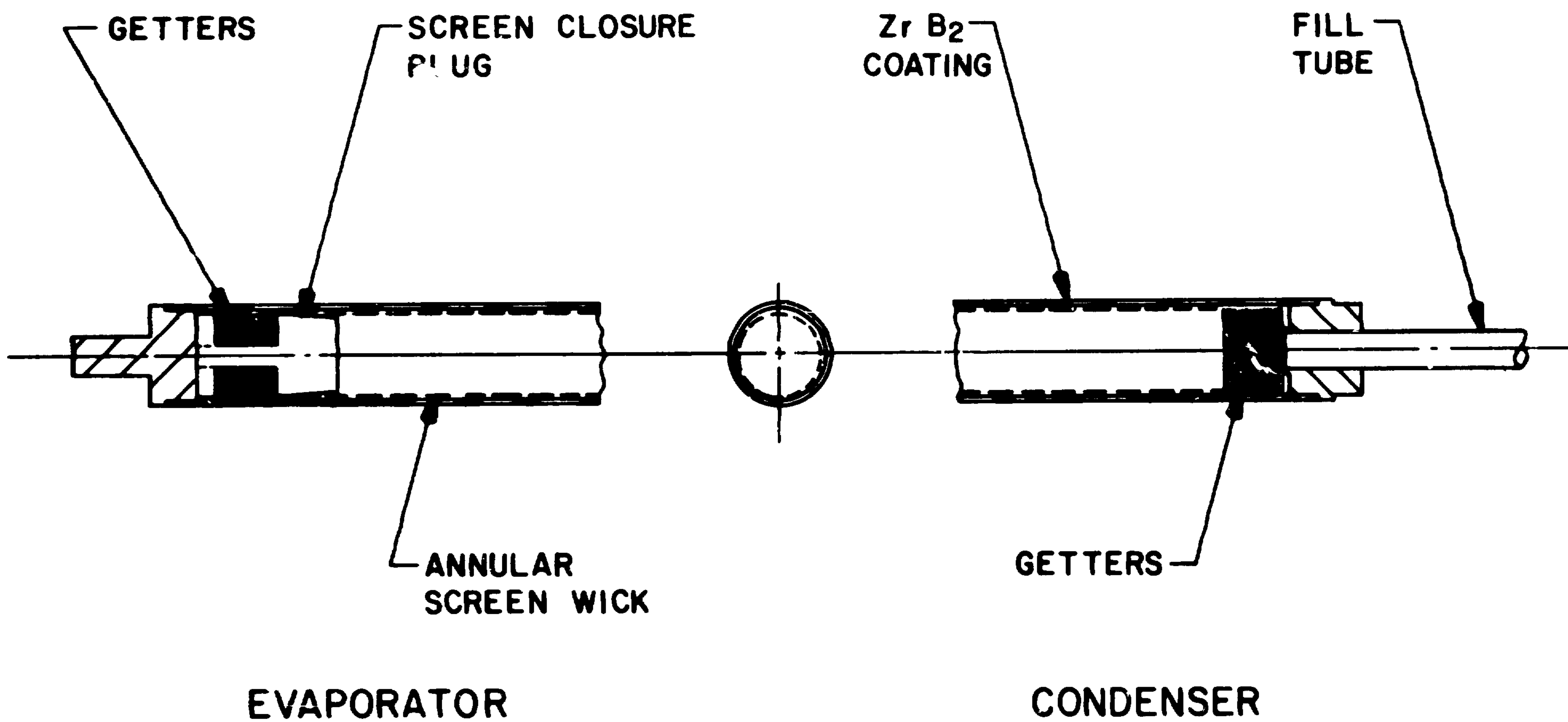


Fig. 1. Cross section of 4-M heat pipe.

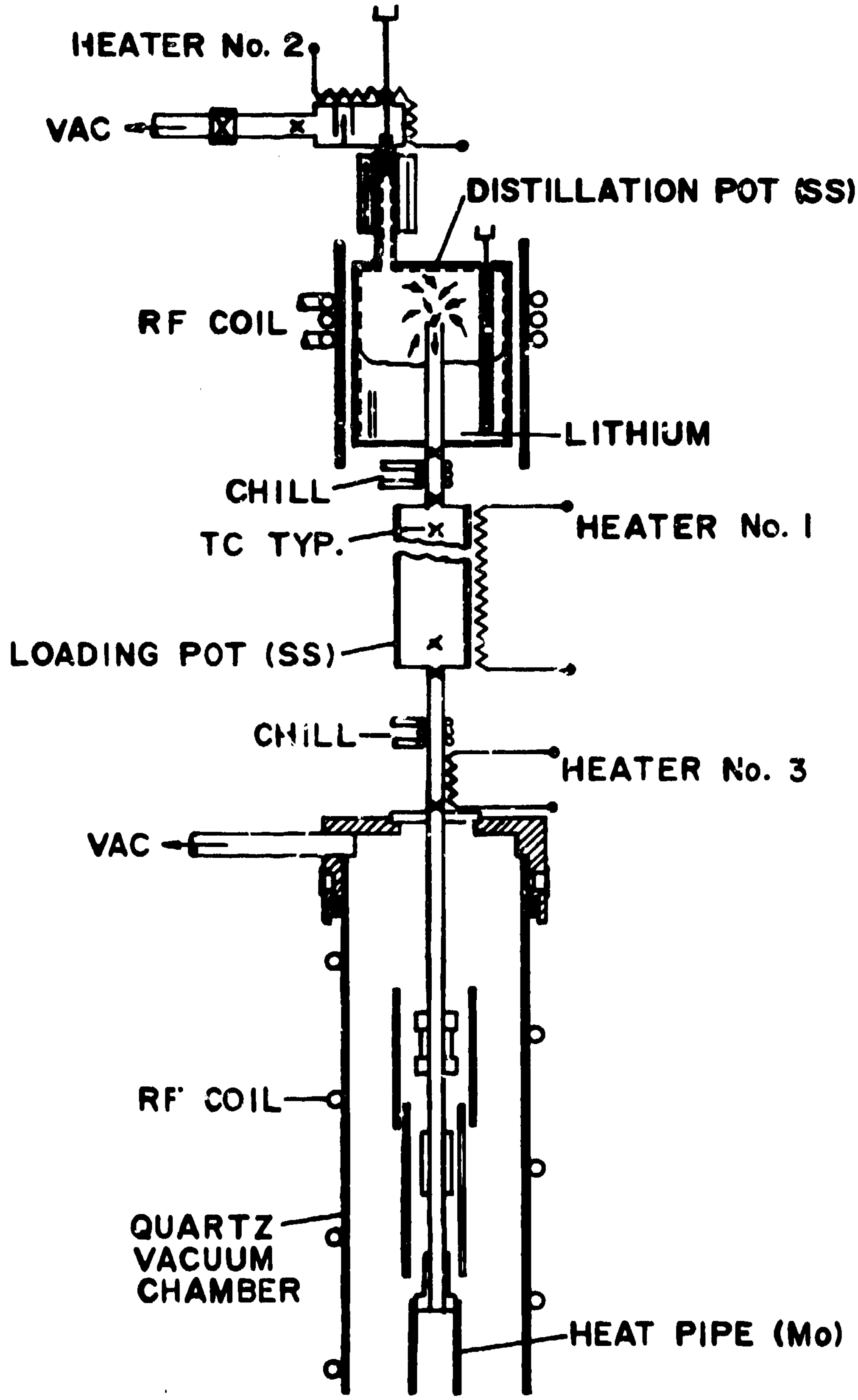


Fig. 2. Lithium distillation apparatus used for filling heat pipe.

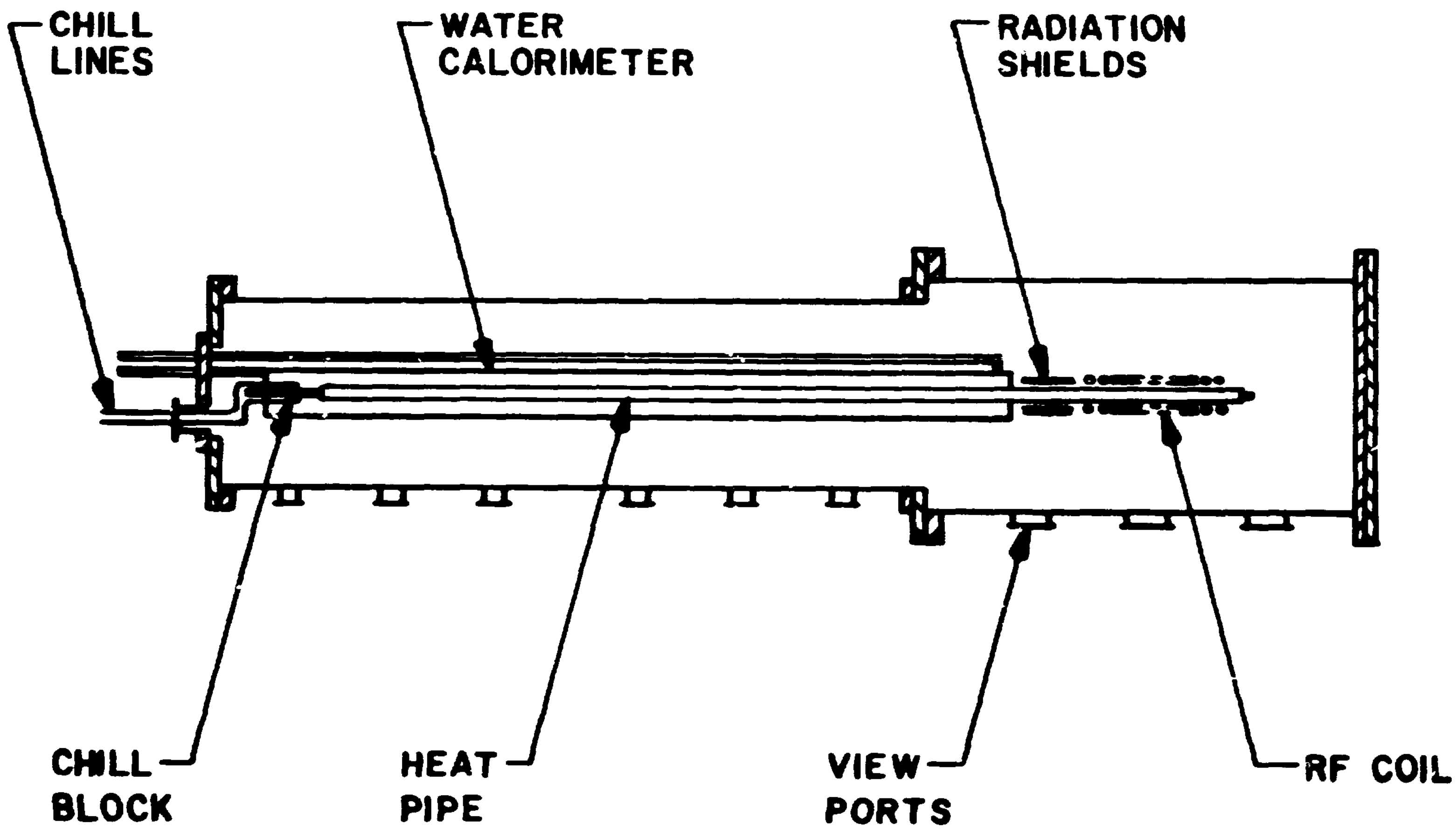
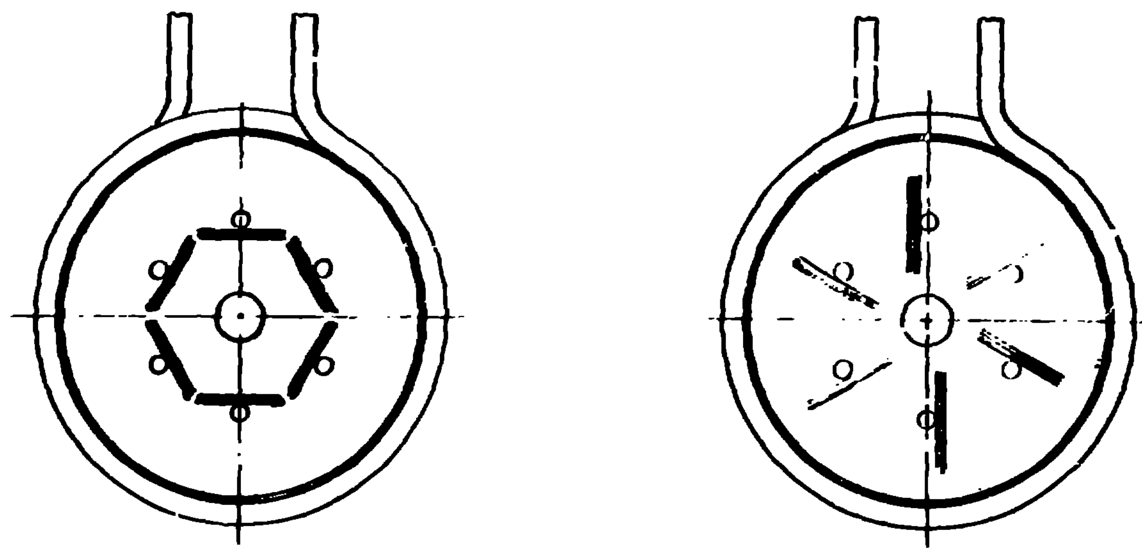


Fig. 3. Coaxial radiation calorimeter.



(a) (b)

Fig. 4. Adjustable radiation shields used for thermal control.

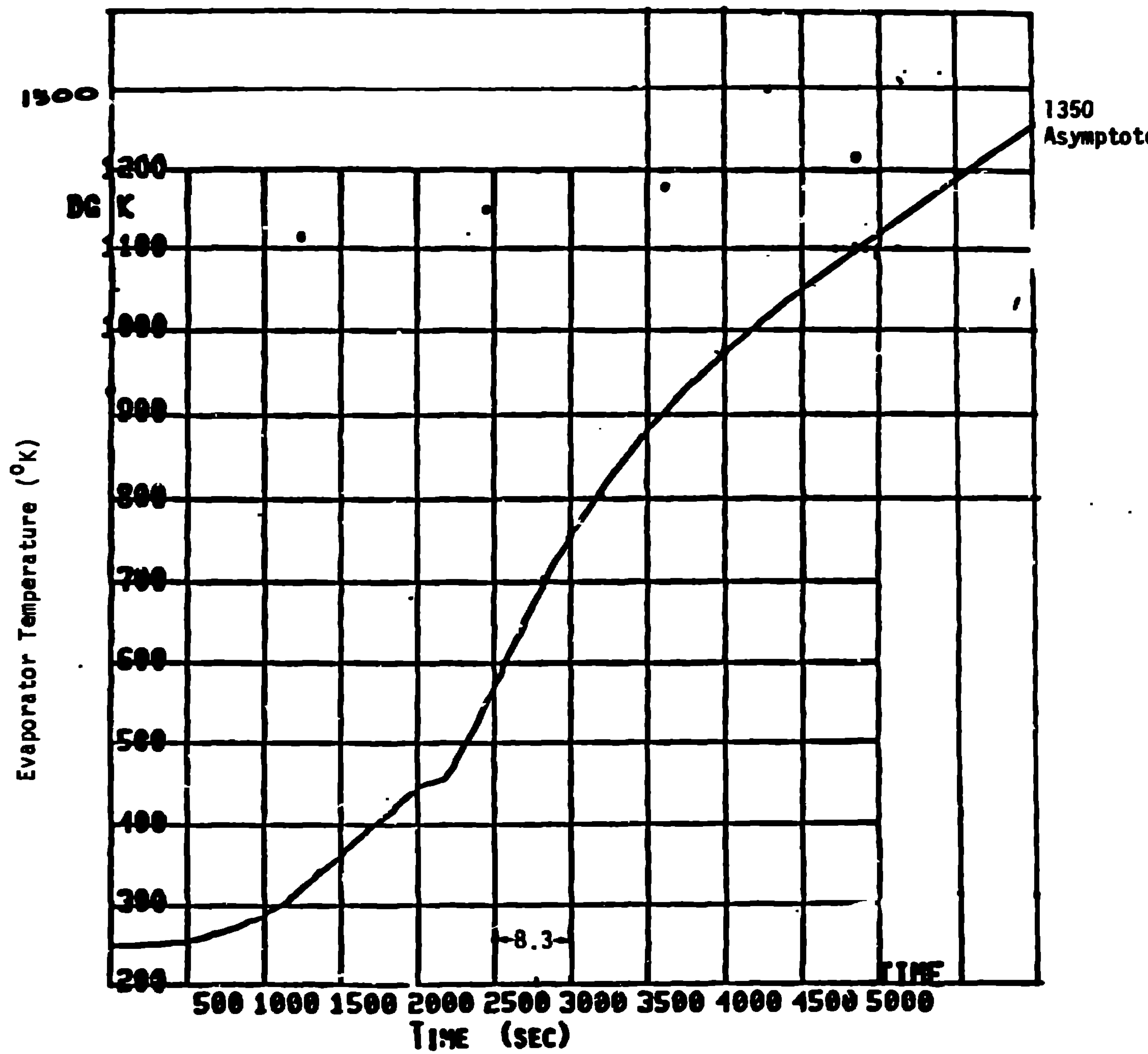


Fig. 5. Heat pipe input temperatures for simulated start test.

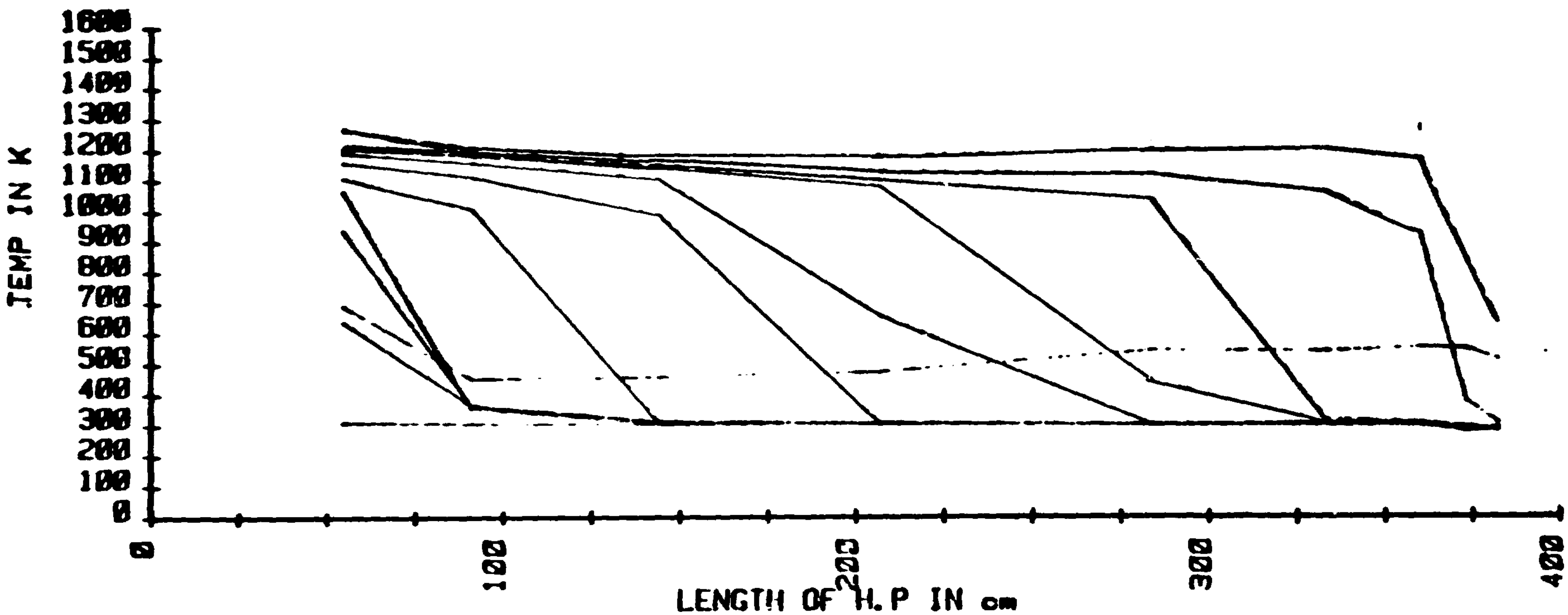


Fig. 6. Heat pipe temperatures versus time during start test.

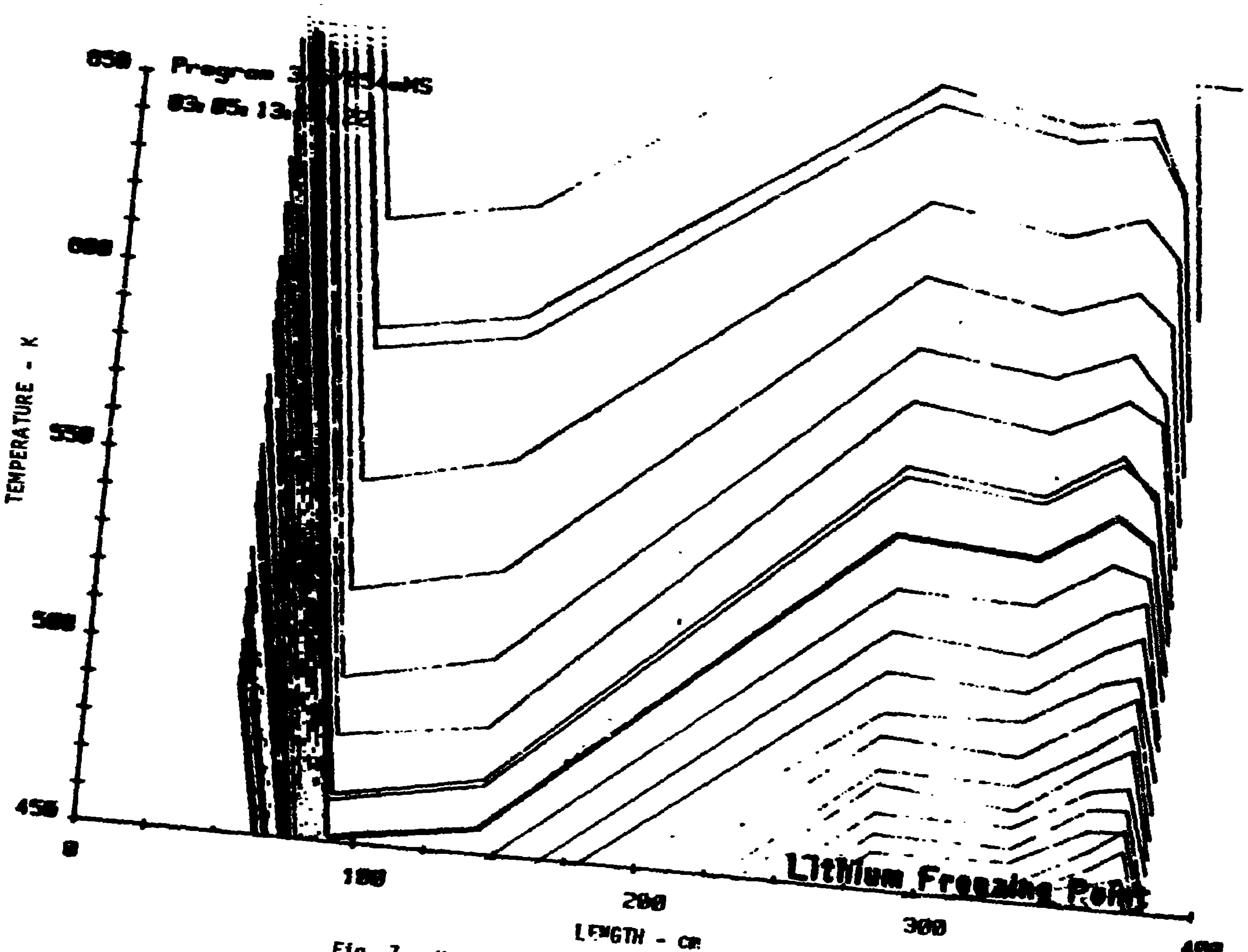


Fig. 7. Heat pipe temperatures during cooldown.

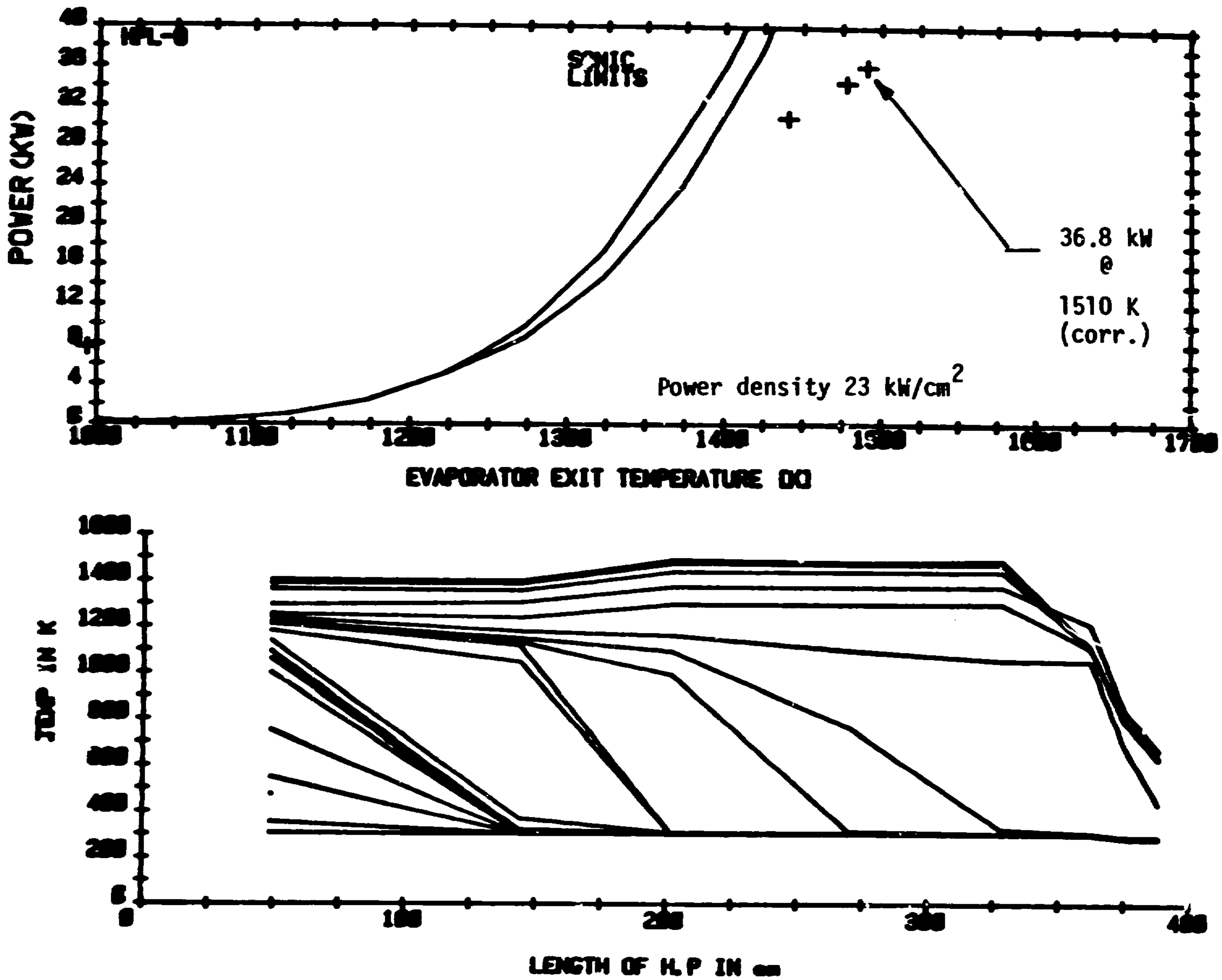


Fig. 8. High power test temperatures and power levels.

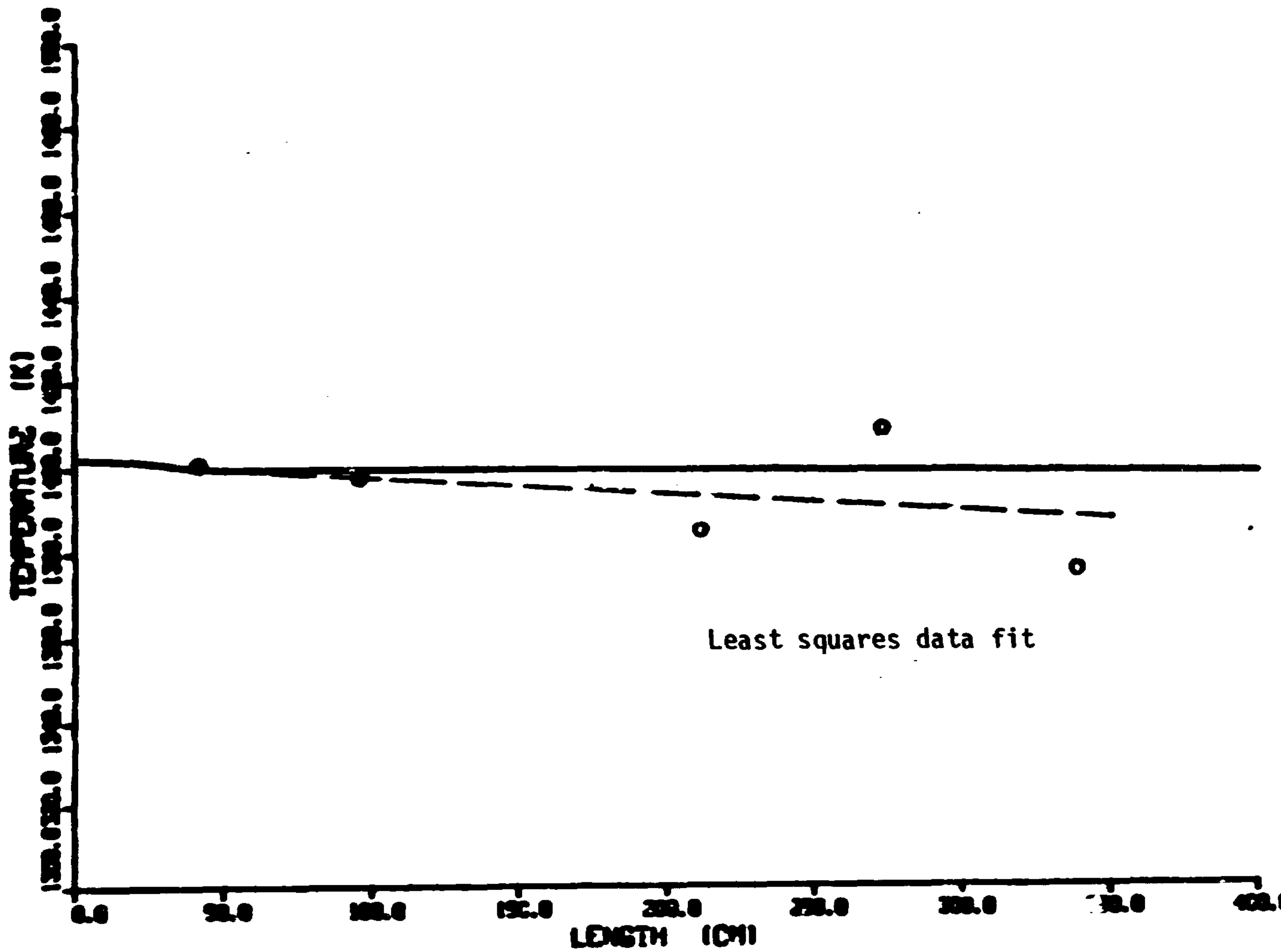


Fig. 9. Comparison of predicted and measured heat pipe temperatures.