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BDX-613-2039 (Rev.)

COOLING ALUMINUM MOLDS USING HEAT PIPES

By D. R. Hahn

Published December 1978

Final Report

Prepared for the United States Department of Energy
Under Contract Number DE-AC04-76-DP00613.

**Kansas City
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Printed in the United States of America

Available From the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Price:	Microfiche	\$3.00
	Paper Copy	\$4.50

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Final Report
D. R. Hahn, Project Leader

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A prime contractor with the United States
Department of Energy under Contract Number
DE-AC04-76-DP00613

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SUMMARY

This project was an initial investigation to develop a means of reducing shrinkage depressions in a molded-to-size polyurethane foam part used to house electrical components. The approach taken was to provide zone cooling for the mold using heat pipes. Bendix contracted with The University of New Mexico to modify a mold with heat pipes, and this contract has been fulfilled. Testing performed at the University indicated a much higher rate of heat removal from the mold after the modification, but it has not yet been determined if the shrinkage depression problem will be alleviated.

DISCUSSION

SCOPE AND PURPOSE

The intent of this project was to determine the feasibility of using heat pipes to reduce the formation of shrinkage depressions on a molded-to-size polyurethane foam part used to house electrical components. This part has a history of shrinkage depressions occurring at several locations on the part. These defects have been a major reason for low part yields of 10 to 60 percent, depending on the lot of material. Although some of the problem appeared to be associated with variations in material formulation, the locations of the depressions suggested that the problem might be related to uneven cooling between thin and thick sections. It was then decided to provide more isothermal cooling by inserting heat pipes into hotter sections of the mold. The extent of the project so far has been to procure heat pipes and have the mold modified to accept them.

ACTIVITY

A contract was placed with the University of New Mexico to design and fabricate a passive heat pipe cooling system for the mold. This work has been completed and the modified mold has been received by Bendix. A detailed final report was prepared by the University (Appendix).

ACCOMPLISHMENTS

Tests were performed on an individual heat pipe and on the mold with and without the heat pipes installed. Both exothermic foam heating and measured electrical internal heat generation were used. The test results indicated that heat removal with heat pipes and forced convection was four to six times as fast as cooling with no heat pipes in still air. In addition, the heat pipes tended to reduce hot spots and make the mold more isothermal.

Potential side benefits are faster heat-up of the mold for post-cure and faster initial mold pre-heat if the heat pipes are used during these phases of the production cycle.

FUTURE WORK

Although a system has been developed to provide zone cooling and more efficient heat removal from the mold, it still remains to be seen just how effective the heat pipes will be in controlling surface depressions. The modified mold will be tested to determine the validity of this approach. Comparison tests of parts manufactured with conventional tooling and with the modified mold under the same conditions and using the same material will be conducted. Extensive testing may be necessary to establish the validity of zone cooling.

Appendix

DEVELOPMENT OF PASSIVE HEAT PIPE COOLING
FOR A BENDIX INJECTION MOLD

FINAL REPORT

DEVELOPMENT OF PASSIVE HEAT PIPE
COOLING FOR A BENDIX INJECTION MOLD

TO

BENDIX CORPORATION
P. O. Box 1159
Kansas City, Missouri 64141

Attention: Dr. David Hahn

BY

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Date: April 10, 1978

Signed:

Karl Thomas Feldman, Jr.
Karl Thomas Feldman, Jr.

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ABSTRACT

A passive heat pipe cooling system was developed to cool a Bendix mold. The cooling system consists of ten copper-water heat pipes with cooling fins implanted into the aluminum mold and cooled by a domestic size fan blowing ambient air.

The number and location of the heat pipes was determined to provide the most effective cooling and mold isothermalization based on experimental measurements of mold temperatures during the exothermic foaming process and from practical considerations of the mold geometry and use.

Performance tests were conducted on an individual heat pipe and on the ten heat pipes implanted in the mold. Both exothermic foam heating and measured internal electrical heat input were used in the experiments.

The experimental test results indicate that the heat pipe cooling system with the fan is four to six times faster than free convection cooling of the mold with no heat pipes or fan and nearly twice as fast as cooling by the fan only. Similarly fast increases in mold heating time in the cure furnace could be realized if the heat pipes are used during this part of the production process. The heat pipes also cool hot spots in the mold and help isothermalize the mold so that better quality foam parts should be produced.

DEVELOPMENT OF PASSIVE HEAT PIPE
COOLING FOR A BENDIX INJECTION MOLD

I Introduction and Summary

The purpose of this project was to design, build, and test heat pipes for cooling a Bendix mold used in production molding of foam parts. This mold is made of aluminum and had a weight of 137.6 pounds and a volume displacement of 0.783 ft³. Photographs of the mold are shown later in the report.

After the mold was received and inspected, preliminary locations and sizes for the heat pipes were determined and discussed with Dr. Hahn. Using this preliminary data, theoretical calculations of heat pipe performance were conducted and finned copper tubing for the heat pipes was selected and ordered. Next a single water heat pipe was fabricated from the finned copper tubing. This heat pipe was then performance tested at several tilt angles with both free and forced convection cooling.

While the performance tests of the single heat pipe were being conducted, the mold was instrumented with thermocouples, and a foaming test was conducted. Based on the temperature vs. time data from the initial mold foaming test, the final location and number of heat pipes to go into the mold were determined. It was determined that ten heat pipes were needed and in order to avoid the existing holes and obstructions in the mold, six were placed in the top and four in the bottom

of the mold. A thermal grease was used to improve pipe-to-mold conductance.

Next a foaming test was conducted with the heat pipes in place and temperatures were recorded as a function of time. Based on the results of this second foaming test some modifications were made in the location of thermocouples and in the depth of the holes. Also an electric heater was placed in the mold cavity and then the third foaming test was conducted with the heat pipes in place. Eight additional thermal tests were conducted with internal heat supplied by an electric heater imbedded in the foam inside the mold. The exact thermal power input as a function of time could be determined by the wattmeter used with the electric heater. Both free convection and forced convection cooling with a fan were used.

II. Heat Pipe Design and Fabrication.

The heat pipe design begins with determination of the range of temperatures in which the heat pipe cooling system must operate. For this mold cooling application the heat pipes must operate from ambient temperature up to approximately 176.7 C (350° F). For this temperature range the best heat pipe working fluid is water. The most compatible pipe material with water is copper. Also copper is an excellent heat transfer material both for the pipe and the air cooled fins. Thus copper-water heat pipes with copper fins were selected as best for this application.

Examination of the space available in the mold indicated that 1/2 inch to 3/4 inch OD tubes could be used, with 5/8 inch OD heat pipe tubes being a logical choice. Also, when the various types of finned copper tubing were surveyed, a 5/8 inch OD, 1/2 inch ID integral finned copper tube with approximately 9 fins/inch of 1-5/16 inch OD, appeared to be a near optimum choice for good heat transfer, cost and availability. Further examination of the mold indicated that the average maximum length of the heat pipe that would be imbedded in the mold was 6 inches, thus the heated evaporator length of the heat pipes was taken to be 6 inches.

Considering the clearance space available around the mold the maximum length of the finned heat pipe section was determined to be approximately 8 inches, thus the finned condenser length of the heat pipes was taken to be 8 inches. In order

that the heat pipes be interchangeable, it was decided that they would all have the same dimensions, thus the 5/8 inch OD, 6-inch evaporator, 8-inch finned condenser with 9 fins per inch and 14-inch overall length was selected for all of the heat pipes.

In order to provide the most rapid cooling for the mold, as many heat pipes as possible and reasonable are needed. Careful inspection of the mold indicated places where ten 5/8 inch OD heat pipes could be placed to provide effective cooling. Thus it was decided to use ten finned heat pipes for the experimental tests.

Existing heat pipe design programs developed by the author at the University were used to predict the performance of the heat pipes. At 120 C (248° F) the 5/8 inch OD copper-water heat pipe was predicted to have a maximum heat transfer rate of 900 watts when operated in the horizontal orientation. Since this value was more than twice what was expected from the finned condenser, the heat pipe dimensions were considered to be sufficiently large.

Detailed heat transfer data on the chosen finned tube was requested but was never received so only experimental performance measurements were conducted on this finned tubing.

The internal wick design of the heat pipe was selected to provide a high conductance when operating in a horizontal orientation or tilted to provide gravity assist. An internal

screw thread or circumferential grooved wick was selected to provide the high conductance and minimal circumferential wicking requirements. A Standard, 20 threads per inch, tap was used to provide the internal screw thread. End caps were silver soldered on each end and a 1/8 inch OD copper capillary fill tube was silver soldered into the condenser end.

Each heat pipe was carefully cleaned, and filled with distilled water to approximately 25% full, by the boil-off fill technique. Air and other non-condensable gases were expelled from the heat pipes and finally the capillary fill tube was pinched off and sealed.

III. Tests of One Finned Heat Pipe

In order to predict the performance of the heat pipe cooling system, thermal performance tests were first conducted on a single finned heat pipe. Since the heat pipe would be cooled by ambient air in the actual mold cooling application, it was cooled by 20 C (70° F) ambient air in the performance tests. Both free convection and forced convection cooling with a small "muffin fan" were used. Three tilt angles were tested -- horizontal, 45°, and vertical, with the finned condenser up.

An electric resistance heater was wrapped over the 6 inch long evaporator section and carefully insulated with asbestos paper, fiberglass, and finally with a vacuum Dewar on the outside. This insulation was highly effective and allowed no more than 5% of the electric heat input to be lost. Five thermocouples were soldered or cemented with bond epoxy to the heat pipe. The thermocouples were located two at either end of the evaporator and three equally spaced on the pipe between fins in the condenser. Thermocouple output temperatures were measured by a high quality digital data logger in the Energy/Heat Pipe Laboratory. Electric power into the heater was measured by a high quality wattmeter and controlled by a variable transformer. A sketch of the heat pipe test apparatus is shown in Figure 1. Photographs of the actual test apparatus in operation with the fan off in the horizontal orientation and inclined at 45° are shown in Figures 2 and 3.

Figure 1. Sketch of Heat Pipe Performance Test Apparatus.

Thermocouple readings and wattmeter settings were recorded for each test after steady state conditions were reached. The test data are plotted in Figures 4 through 9 where temperatures at each measured point along the pipe are plotted versus pipe length for each power. These data indicated that only a few degrees temperature drop occurs along the heat pipe. The heat pipe temperature is decreased significantly by the fan.

In Figures 10 through 12 the power is plotted versus temperature difference to show the heat pipe conductance for each angle of inclination.

Figure 2. Heat Pipe Test Apparatus in Horizontal Orientation.

Figure 3. Heat Pipe Test Apparatus in 45° Inclined Orientation.

Figure 4. Horizontal Heat Pipe Performance
with free Convection Cooling of 21 C (70° F) Ambient Air

Figure 5. Horizontal Heat Pipe Performance with Fan on.

Figure 6. Heat Pipe Performance at 45° Inclination with Free Convection Cooling

Figure 7. Heat Pipe Performance at 45° Inclination
with Fan on.

Figure 8. Vertical Heat Pipe Performance
with Free Convection Cooling

Figure 9. Vertical Heat Pipe Performance with Fan on.

Figure 10. Horizontal Heat Pipe Conductance.

Figure 11. Heat Pipe Conductance at 45° Incline.

Figure 12. Vertical Heat Pipe Conductance.

IV. First Test Mold Foaming

In order to determine the temperature rise that occurs from the exothermic foaming process, the mold was instrumented with ten thermocouples and a foaming test was conducted. Five thermocouples, numbered 34-38, were cemented with bond epoxy to an internal aluminum mold block detail, as shown in Figure 13.

The remaining five thermocouples were suspended out in the foam one inch apart on a wooden support. A photograph showing some of these thermocouples is presented in Figure 14.

The foaming tests provided experience with handling the foam components and also provided data on the thermal response of the exothermic reaction. In the first test, the lid was not installed quickly enough and approximately 25% of the foam material escaped from the mold. Also, it was noticed after the foam part was removed that the mixing of the foam constituents was incomplete. However, the test data obtained from this first foaming test were used to help determine the location of the heat pipes needed for cooling the mold. The test data indicated that temperatures in the foam rose to an average of 80 C in 8 minutes after foaming began while the average temperatures on the aluminum surfaces rose to 59 C (138.2° F) during the same interval. The peak foam temperature was 119 C (249.2° F) which was reached after 7 minutes. The test data is plotted in Figure 16 along with data from two later foaming tests.

Figure 13. Sketch of Thermocouple Locations in the Foam Mold.

Figure 14. Thermocouples in the Foam Mold.

V. Heat Pipe Placement.

The locations for the heat pipes were selected so that:

1. The heat pipes would be as near as possible to the regions where the foam was thickest and hottest.
2. The heat pipes had to be located to avoid existing pins, screws, and guide holes in the aluminum mold.

Six 5/8 inch diameter holes were drilled in the top and four in the bottom to accommodate ten heat pipes. None of the holes were deeper than 6 inches. The location of the holes in the top of the mold is shown in Figure 15. No detailed drawings of the location of the holes was made since they can be observed on the mold itself.

Figure 15. Top Side of the Mold
Showing the Six Heat Pipes Located There.

VI. Second Foaming Test.

Nine additional heat pipes were fabricated just like the first one and the mold was reinstrumented in preparation for the second foaming test. The 6-inch long evaporator sections of each heat pipe were smeared with thermal grease and thermocouples were cemented to the condenser ends of four of the heat pipes.

For this test the foam constituents were thoroughly mixed, the mold was preheated to 51 C (123.8° F) with heat lamps, the foam was carefully poured into the mold and bolted down. However, about 10% of the foam leaked out through two access holes that were unplugged. Approximately six minutes elapsed from the time the pouring was begun until the lid was installed and the heat pipes inserted. For this test, the mold was mounted on its support dolly, and after the lid was installed, the mold was tilted 90° so that the heat pipes were in the horizontal orientation. No fan was used; only free convection cooling of the heat pipes was used in the second foaming test.

The test data indicate that the temperatures in the foam rose to an average of 120 C (248° F) after 11 minutes, while the average temperature on the aluminum surfaces rose to 60 C (140° F) after 4 minutes and then cooled off slowly. The peak temperature recorded in the foam was 139 C (282.2° F) at 8 minutes after foaming began. The test data is plotted in Figure 16, along with data from the two other foaming tests.

It appeared that the relatively lower temperatures that occurred during the first foaming test were due to the extra loss of foam and the less complete mixing than occurred in the second test. However, due to the difficulty of getting reproducible exothermic foaming tests it was decided that subsequent tests would use an internal electric heater to provide the heat.

Also, in order to provide better cooling, one heat pipe hole was drilled deeper so that the pipe extended through the top and into the bottom part of the mold. Three additional thermocouples were mounted on the heat pipes and two additional thermocouples were mounted on the wooden support to measure foam temperature.

VII. Third Foaming Test.

Before the third foaming test, an 8-foot long insulated electric resistance heater was placed in the mold cavity. The heater was wound around the entire cavity to give relatively uniform heating. The heater was connected to a wattmeter and a variable transformer so that a known and reproducible amount of internal heat could be provided in the mold for later tests. After the new thermocouples were mounted in the mold the third foaming test was conducted.

For the third foaming test the foam constituents were carefully mixed and no foam was lost during the test. About 4.5 minutes elapsed from the time the foam was poured until the lid was in place and the heat pipes inserted. Again, the mold was rotated after the lid was in place so that the heat pipes were horizontal. No electric heater power was used at this time. Two small muffin fans were used to provide some modest amount of forced convection cooling for the heat pipes.

The test data indicate that the average temperature in the foam rose to only 71 C (159.8° F) after 15 minutes while the average temperature in the aluminum mold remained very near the 46 C (114.8° F) preheat temperature. The peak temperature in the foam rose to 128 C (262.4° F) after 13 minutes. The test data is plotted in Figure 16.

The curves marked "A" give the average temperature of the five thermocouples attached to the aluminum mold as was shown in Figure 13. Thus, the "A" curves give an indication

Figure 16. Exothermic Foaming Tests in Mold for Three Types of Cooling.

of the average interior aluminum mold temperature. The curves marked "B" are the average of the five thermocouples supported in the foam. The curves marked "C" give the highest temperature recorded in the foam. The curves marked "D" give the highest temperature, #36, of the thermocouples attached to the aluminum mold surface.

Thus, even though the heat released during each of the three foaming tests was not the same due to poor mixing or foam losses, the beneficial cooling effect of the heat pipes was readily apparent. All of the subsequent tests were conducted with internal heat provided by the electric heater.

VIII. Tests with Internal Electric Heating.

Eight additional tests of the heat pipe cooling system were conducted on the mold. A summary of the various tests conducted with electric heating is given in Table 1. Two preliminary tests were conducted, starting at low power input of 30 watts and increasing to 160 watts. Temperatures were observed but not recorded in these two exploratory tests. Photographs of the experimental test apparatus are shown in Figures 17 and 18.

Test #6 was conducted at 160 watts input and data recorded. The mold was heated to 48 C (118.4° F), the power was cut off and the heat pipes inserted. A large domestic type fan was used to improve the cooling of the heat pipes, as is shown in Figures 17 and 18. Test #7 was a repeat of test #6, but with a heater power of 330 watts, and the mold was heated to 66.5 C (151.7° F).

Table 1. Summary of Test Conditions

<u>Test No.</u>	<u>Power Input Watts</u>	<u>Heating Mode Duration Min.</u>	<u>Mold * Initial Temp. C</u>	<u>Heat Pipes Used</u>	<u>Fan Used</u>
6	160	continuous	48 C	yes	yes
7	330	continuous	66.5 C	yes	yes
8	330 final	power varied	58.1	no	no
9	330	184	63.4	yes	yes
10	490	39	44.2	yes	yes
11	509	57	54.5	yes	yes
12	490	70	58.4	no	no
13	385 final	power varied	113.3	yes	yes
14	415	157	85.4	no	yes
15	530	82	61.4	no	yes

* Internal aluminum mold average temperature prior to cooling.

Figure 17. Heat Pipe Mold Cooling with Fan in Operation.

Figure 18. Another View of Heat Pipe Mold Cooling with Fan in Operation.

Tests #8 and #12 were similar to #6 and #7 but the mold was allowed to cool without heat pipes or the fan. Test #9 had a power input of 330 watts and both the heat pipes and fan were used in cooling.

Tests #10 and #11 were also repeats of #6 and #7 with heat pipes and fan. Test #13 was a heat up with insulation on the mold and cool down with fan and heat pipes but no insulation. And Tests #14 and #15 were conducted with insulation around the mold during heating and a cool down with fan but no heat pipes and no insulation.

Thus, the three major catagories of tests were:

1. Heating and cooling without heat pipes or fan. Tests #8, #12
2. Heating and cooling without heat pipes but with fan. Test #15.
3. Heating and cooling with heat pipes and fan. Tests #6, #7, #9, #10, #11, #13

IX. Test Results.

The results of these three categories of tests are given in Figure 19, where the average mold interior temperature as a percent of the initial mold temperature (60 C, 140° F) is plotted versus time. The data in Figure 19 indicates that without the heat pipes or the fan the interior temperature is down to 75% of its initial temperature in one hour. With only the fan operating, this same amount of cooling is obtained in 24 minutes. With the heat pipes and the fan working, this same amount of cooling is obtained in 14 minutes.

In Figure 20 average mold interior temperature is plotted versus time for categories 1 and 3 of tests conducted. It is apparent from these data that the heat pipe cooling is particularly effective for high initial mold temperatures.

In Figure 21, overall system thermal response is shown for both heating and cooling. During Tests #9, #10 and #11 the first 60 minutes were allowed for heating and the remaining 60 minutes were used for cooling. The curves with upward pointing arrows indicate the heating process while the downward pointing arrows indicate cooling. The upper most curve describes the mold cooling process with no heat pipes or fan. The initial temperature rise after the power was cut off indicates that heat stored in the foam was released to the aluminum during the first few minutes. The power input of 330 watts was applied for 60 minutes until the mold reached 57 C (134.6° F) the power was turned off and the mold allowed to cool. After

Figure 19. Cool Down Rate as Percent of Initial Mold Temperature.

Figure 21. Mold Heating and Cooling Rates with and without the heat pipe cooling system.

60 minutes of cooling without the heat pipes or fan the mold had cooled 46 C (114.8° F). With the heat pipes and fan the mold cools to 46 C (114.8° F) after only nine minutes and to 24 C (75.2° F) after 60 minutes.

In addition to providing very rapid cooling of the mold, the heat pipes are located where they will cool mold hot spots and help isothermalize the mold.

X. Conclusions.

Based on the experimental test results described in the previous section, it is apparent that the cooling system composed of ten finned heat pipes and a fan provide exceptionally effective cooling for the Bendix Mold. As was shown in Figure 19 the heat pipe cooling system was four times faster than free convection cooling with ambient air (and no heat pipes) and nearly twice as fast as cooling by the fan only. The data shown in Figure 21 show that the heat pipe cooling system was better than six times faster than free convection cooling with no heat pipes. Similarly, fast heating of the mold in the curing furnace could be realized if the heat pipes could remain in the mold. The use of a thermal grease is important to obtain the best possible pipe-to-mold conductance. Only modest fan power and air velocity from a domestic size fan are needed to obtain rapid mold cooling rates with the heat pipe cooling system.

The factor of 4 to 6 increase in mold cooling time and similar increases in mold heating time in the cure furnace will allow significant increases in mold production rate. Also the cooling of mold hot spots and more nearly isothermal mold temperatures should help the mold produce better quality foam parts.

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BDX-613-2039 (Rev.)

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MECHANICAL: Mold Cooling

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