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MAR 79 K S SEKHON, L A NELSON DAAK40-77-C-0242
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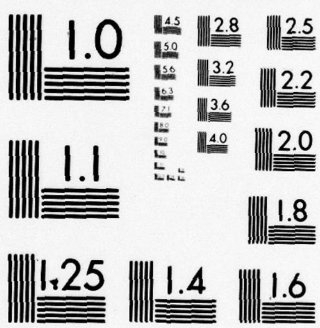

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METHODS FOR MANUFACTURING HEAT PIPES FOR CIRCUIT CARDS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Manufacturing processes to fabricate heat pipes for circuit cards were evaluated. These included shell and wick fabrication, shell and wick joining, and vacuum/fill and testing. Cost effective processes were selected to meet production requirements. A production facility was designed based on cost trade-offs. The results of the evaluation, selection of recommended manufacturing methods and the design of the production facility are presented.

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PREFACE

This final report documents the results obtained during the MM&T Program entitled "Methods for Manufacturing Heat Pipes for Circuit Cards." This report was prepared by Hughes Aircraft Company, Fullerton, California, under contract DAAK40-77-C-0242. The effort was sponsored by U.S. Army Missile Research and Development Command (MIRADCOM). The principal Hughes contributors were Dr. Kal Sekhon and Mr. Lloyd Nelson.

Results of the investigation clearly show that it is feasible to produce reliable, cost-effective heat pipe modules in a production environment.

The work covered by this report was performed between 30 September 1977 and 31 March 1979.

CONTENTS

SECTION S – SUMMARY

1. Design and Manufacturing Methods Analysis 6
2. Production System Analysis and Design 7
3. Conclusions and Recommendations 8

SECTION 1 – BACKGROUND AND OBJECTIVES

1. Need for Heat Pipes and Improved Heat Pipe Production Techniques ... 10
2. Attainment of the Project Objectives 12

SECTION 2 – DEVELOPMENT EFFORT

1. Approach to Meeting Design Requirements 16
2. Detailed Engineering Considerations for the Design and Manufacture of Circuit Card Heat Pipes 18

A – Design and Manufacturing Methods Analysis

1. Evaluation of Alternative Heat Pipe Design 22
2. Description of the Integrated Heat Pipe Module Design 24
3. Description of the Individual Heat Pipe Module Design 26
4. Evaluation of Wick Materials and Selection of Wicks for the Circuit Card Heat Pipe 28
5. Evaluation of Wick Fabrication and Attachment Techniques 30
6. Selection of Shell Materials 32
7. Evaluation of Shell Bonding Materials 34
8. Evaluation of Shell Manufacturing Techniques 36
9. Joining Method Selection Analysis 38
10. Evaluation of Heat Pipe Filling Techniques and Conceptual Design for the Vacuum Fill Station 40
11. Considerations for Attaching Heat Pipe to Circuit Card 42

B – Production System Analysis

1. Overview of the Heat Pipe Production Facility 44
2. Overview of Steps in the Production Process 46
3. Cost Analysis of the Production System 48
4. Design of a Test Station for Heat Pipe Performance Verification 52
5. Use of the Test Station in Measuring Heat Pipe Performance 54
6. Environmental Test of Heat Pipe Circuit Card 56

SECTION 3 – CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions Regarding Heat Pipe Performance 60
2. Recommendations for Future Effort 62

APPENDIX A – SURVEY OF HEAT PIPE MANUFACTURING METHODS A-1

APPENDIX B – DETAILED REQUIREMENTS FOR HEAT PIPE SLAB WICK THICKNESS AND FOR TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK B-1

APPENDIX C – DETAILED STEPS AND INSPECTIONS IN THE PRODUCTION PROCESS C-1

APPENDIX D – DETAILED COST ESTIMATES D-1

SECTION S
SUMMARY

1. Design and Manufacturing Methods Analysis 6
2. Production System Analysis and Design 7
3. Conclusions and Recommendations 8

Shell Materials, Wick Materials, and Heat Pipe Bonding Techniques Were Evaluated

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- Selection of Heat Pipe Materials
  - – Shell Material – Copper Alloy, Cartridge Brass, CDA 260
  - – Wick Material – Sintered Stainless Steel Fiber
    Thickness: 0.016 inch
    Recommended Type: Dynalloy No. X-11
- Selection of Braze Alloys
  - – Wicks to Cover and Base – Silver Braze
    Thickness: 0.0012 inch
    Recommended Type: Handy & Harman No. 505
  - – Cover to Base – Silver Braze
    Thickness: 0.005 inch
    Recommended Type: Handy & Harman No. 560
- Fill Fluid – Acetone

Alternative heat pipe materials and processes were analyzed for cost effectiveness. The analysis considered the reliability and effectiveness as well as the cost of manufacturing the complete heat pipe using the different materials and processes.

Shell Material – Analysis of candidate materials for fabrication of heat pipe shells indicates that copper alloys are the most suitable for the purpose. Cartridge brass, CDA 260, was chosen as the best material for the shells. The CDA 260 was machined and brazed in a production simulation test. The material, as expected, performed well, and the sample test showed excellent results.

Wick Material – The selected wick material, Dynalloy X-11, can be successfully cut, tack-welded in place, and brazed to the interior of the heat pipe. Experiments were run on bonding wicks to the heat pipe shell. The conclusion was that, with currently available materials and methods, thin mesh wicks could not be bonded to the heat pipe shell without completely filling the mesh with braze alloy. Because of this, the sintered stainless steel (SS) fiber wicks were selected.

Braze Alloy, Wicks to Cover and Base – HH Silver Braze foil No. 505, 0.0012 inch thick, gave adequate bonding performance without excessive blocking of the wick pores.

Braze Alloy, Cover to Base – The braze alloy must give a strong hermetic bond for the type T point without use of flux and must melt at a temperature significantly lower than the wick brazing alloy. HH Silver braze foil No. 560, 0.005 inch thick, used on a hydrogen furnace meets the requirements.

Fill Fluid – The final selection of the fill fluid is acetone. This has the best combination of thermal performance and compatibility as well as sufficiently high vapor pressure to assume operation over an extended temperature range.

The Production System Is Designed for Cost-Effective Operation

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- Production Line Design
  - Conceptualized plan for a 2500 sq ft production facility with 13 basic process areas
  - Production facility designed for a 4000 heat pipe per week capacity
  - EFS process designed for a production rate of over 50 heat pipes per hour
  - Semiautomatic equipment selected where possible to reduce labor cost
- Cost Analysis
  - Unit Cost:

	Labor cost/finished unit	$12.45
	Material cost/finished unit	35.06
	Total unit cost	$47.51

- Capital and Support Equipment:

Capital equipment	$533.2 K
Process support equipment	18.0 K
Tooling and expense equipment	9.3 K
Total	$560.5 K

The production line design features a state-of-the-art system capable of producing 4000 heat pipes per week on a 40 hour week (single shift). The production system has 13 basic process areas which are positioned for optimum flow of material and least interference to other adjacent processes. In addition, the process area is designed for the shortest distance of transportation between processes. This type of design is cost effective from the standpoint of reducing racking and packaging for transportation to the next operation. The configuration of the process room lends itself to easy supervision since the office area overviews most of the processes and consequently requires only one supervisor.

Semiautomatic equipment was selected where possible to reduce the labor and subsequently reduce the unit cost of the heat pipe.

The semiautomatic equipment may in some cases be modified to become fully automatic to further increase capacity and reduce the unit cost. The trade-off is the capital cost of the equipment. An industrial engineering analysis is required to determine if the cost is justified for the output gain.

The EFS process is designed for a multiple station operation and is easily adapted to add on more stations should there ever be a need for increased output. In addition, extra stations may serve as stand-by spares in the event that the valves become defective.

The unit cost is based on a manual-semiautomatic system. It is to be expected that the start-up cost may be several times the indicated cost due to the necessary learning and training required for a new process. The flow of material and efficiency or inefficiency factors will require effort on the part of supervision to establish clean and smooth flowing processes. The need for process engineers to solve flow problems will be higher in the start-up phase.

Conclusions and Recommendations

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- Major Conclusions
  - Integrated heat pipes give better performance than individual heat pipes with headers
  - Brazed evaporator condenser wicks improve heat transfer uniformity and reliability
- Recommendations
  - Further study is needed to find less expensive wick material
  - The feasibility of using a multiple head welder for tack welding should be investigated
  - Further investigation of plating techniques to enhance brazing of wicks and shells is needed

The most significant results are in the area of heat pipe design and production techniques. A major finding was that integrated heat pipes provide far better performance than do individual heat pipe modules. Since wicks brazed to the heat pipe walls provide improved uniformity and reliability of heat transfer, brazing was chosen as the wick bonding production technique. The brazing is best accomplished when sintered metal fiber wicks are used. However, the sintered stainless steel wick is the largest contributor to heat pipe unit cost. Further study is needed to find a less expensive wick material.

The most cost effective method for sealing the heat pipe shells to the covers is furnace brazing, which produces a heat pipe with superior mechanical strength. Another cost finding was that the most economical method of producing large numbers of heat pipe shells is stamping, but this technique requires expensive class A dies. Hughes recommends a combination of die casting and numerically controlled machining, depending upon the total quantity of heat pipes to be produced.

The production system uses a combination of manual and semiautomatic sequences to take full advantage of off-the-shelf equipment. Although expedient for start up, they are not necessarily the most desirable for full scale production. Hughes recommends additional studies in several areas to address the feasibility of process redesign to reduce labor, increase output capacity and decrease unit cost.

Major processes for further study include multiple head tack welding. Tack welding uses an off-the-shelf single head and single tip, a time consuming and costly process. If a multiple head welder is feasible, the resulting labor savings would significantly reduce heat pipe unit cost. Plating of the base and cover plates using either copper or nickel should be investigated as possible areas to improve brazing and sealing performance.

SECTION 1
BACKGROUND AND OBJECTIVES

1. **Need for Heat Pipes and Improved Heat Pipe Production Techniques 10**
2. **Attainment of the Project Objectives 12**

1. NEED FOR HEAT PIPES AND IMPROVED HEAT PIPE PRODUCTION TECHNIQUES

Increases in the sophistication of electronic systems have required denser packaging of electronic components with attendant increases in card power and density, but further growth cannot be met with conventional cooling techniques. Fortunately, given the development of a reliable manufacturing technology, heat pipes can remove this barrier to further sophistication and can increase system reliability.

The use of heat pipes to remove heat solves many electronics packaging problems, but the effectiveness of the concept has been demonstrated only with custom-made heat pipes. Thus, to enable more widespread and regular use, mass production techniques are required to reduce costs and to assure reliability. In this manufacturing-improvement project, the circuit card and heat pipe is configured as a card thermal mounting plate (see Figure 1), because most electronic equipment systems assemble electronic components in the form of a circuit card. Some of the heat pipe advantages made available are as follows.

Fewer Circuit Cards – Since there are many electrical interconnects within functional electronic units but relatively few interconnects between functional units, it is highly desirable to mount complete functional units on a single circuit card. Although there often is enough space on the card for the components, the total power dissipated is often too high for a conventional conduction-cooled card, and the circuit must be split between several cards. However, a circuit card heat pipe which utilizes the evaporation, condensation cycle of a fluid for heat transfer without high thermal resistance, will be able to handle the high power and thus allow the entire electronic functional unit to be mounted on a single card.

Optimized Component Layout – Optimal component layout for high frequency circuits dictates grouping the high power components on the center of the card. However, cooling limitations of conventional cards may require that the high power components be spread out over the entire card. However, optimal component layout can be used on cards cooled by the circuit card heat pipe since the local cooling capability of the heat pipe, which is dependent only on the thermal resistance of the evaporator, is equivalent regardless of component location on the heat pipe. The cooling capability of a circuit card heat pipe is not sensitive to component location, so optimal component layouts may be used.

Elimination of Special Spreader Plates – Single components with high local power densities require special spreader plates to lower the power density to the point where it can be handled by conventional cooling techniques. However, a circuit card heat pipe can accept very high local power densities with a low temperature rise because the thermal resistance of the evaporator is very low.

Enhancement of Reliability – Since failure rate of components is a log function with temperature, the reliability of electronic systems is seriously degraded by a few components operating at a higher than average temperature. Components mounted on the center of conventional conduction-cooled cards run at a higher temperature than those on the edge as they are further from the heat sink. However, a circuit card heat pipe provides uniform cooling regardless of component location, because the thermal resistance of the evaporator is low and the heat pipe vapor space is essentially isothermal.

Advancement to Higher Power Densities – Any extension of conventional cooling systems to higher power densities can be accomplished only by larger cross-sectional thermal plates with attendant increases in weight and space. A circuit card heat pipe can provide higher heat transfer capacity within existing weight and space restrictions.

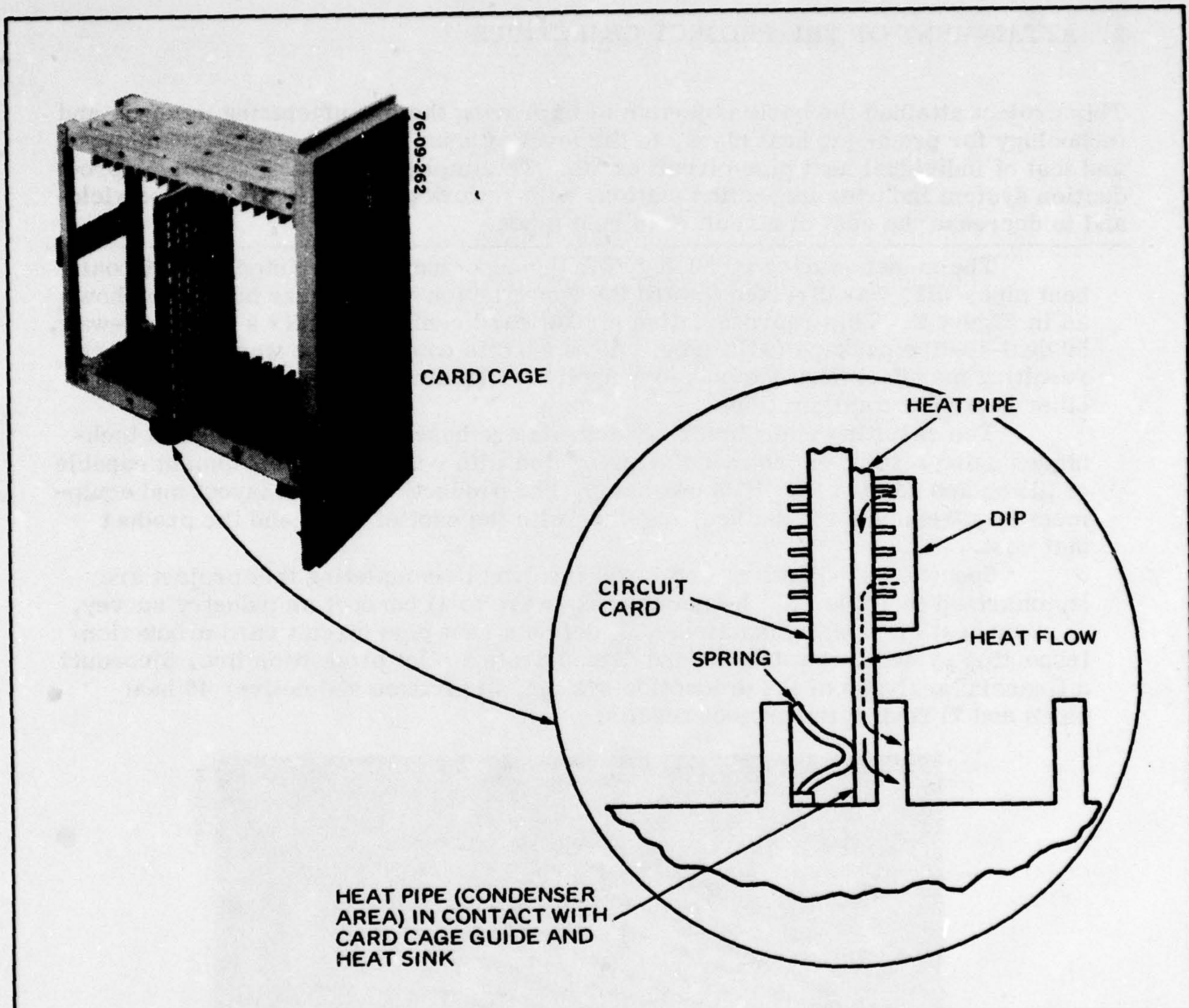

Figure 1. Representative Heat Pipe Circuit Card Application. Most electronic equipment systems mount and assemble the electronic components on cards as shown, to provide compact packaging, ease of access for test and maintenance, and for ease of cooling. High power systems use thermal mounting plates to conduct the heat energy dissipated by the components to a heat sink, in the manner shown here for a heat pipe.

2. ATTAINMENT OF THE PROJECT OBJECTIVES

This project attained the basic objective of improving the manufacturing methods and technology for producing heat pipes, to the level of actual manufacture, assembly, and test of individual heat pipe circuit cards. The implementing of a prototype production system includes inspection stations with rework provisions to increase yield and to decrease the cost of circuit card heat pipes.

The manufacturing technology for the construction of printed circuit board heat pipes (HP) was directed toward the construction of a ten-bar heat pipe shown as in Figure 2. This representative circuit card configuration is a 5 x 6, 50-watt, 50 dual-in-line package (DIP) type. Although this configuration was featured, the resulting manufacturing methodology applies to an almost unlimited number of other heat pipe configurations.

The resulting manufacturing methods are based on mass production techniques using a stand-alone manufacturing line with conventional equipment capable of filling and sealing fifty HPs per hour. The production system layout and equipment requirements are defined, together with the capital costs and the product unit cost.

Specific subobjectives and tasks involved in completing this project are summarized in Table 1. The major tasks were to 1) conduct an industry survey, 2) study heat dissipating manifolds, 3) define a heat pipe circuit card production/inspection system, 4) establish and demonstrate a pilot production line, 5)conduct a financial analyses of the production system, 6) produce and deliver 40 heat pipes and 7) review the project results.

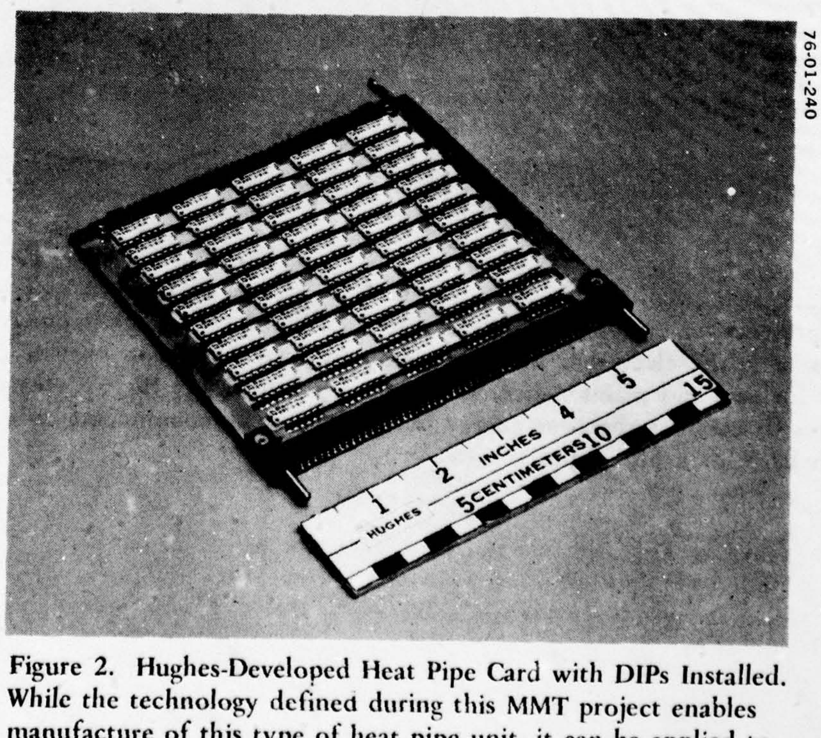

Figure 2. Hughes-Developed Heat Pipe Card with DIPs Installed. While the technology defined during this MMT project enables manufacture of this type of heat pipe unit, it can be applied to fabricate an indefinite variety of other configurations that would benefit from the advantages of heat pipe cooling.

TABLE 1. HEAT PIPE CIRCUIT CARD PRODUCTION TECHNIQUE PROJECT TASKS

Activity	Aims and Objectives
Conduct Industry Survey	• Identify useful methods, systems and controls for heat pipe fabrication
Study heat dissipating manifolds	• Determine the most cost-effective production methods

Define a heat pipe circuit card production/ inspection system	• Incorporate the following improvements/features
	– Reduced cost of work attachment, over present spot-weld techniques
	– Reduced cost of shell forming, over present chem mill techniques
	– A quantity production pipe shell bonding technique giving a life expectancy of 10 years
	– A reliable heat pipe sealing capability, including
	  – Production vacuum/fill techniques for 10-pipe batches
	  – Verification of pipe operation at rated power
	– Use of the most cost-effective material and process alternatives
	– A quantity production heat pipe attachment method that will not interfere with card circuitry

Establish and demonstrate a pilot production line	• Prove the system • Incorporate the production technology developed under this contract • Share the MMT advances with industry
Conduct a financial analysis of the resulting production system	• Provide a cost analysis
Produce and deliver 40 heat-pipe circuit cards	• Inspection and test by MIRADCOM
Review the MMT project results	• Provide recommendations for future effort

SECTION 2
DEVELOPMENT EFFORT

1. Approach to Meeting Design Requirements 16
2. Detailed Engineering Considerations for the Design and Manufacture of Circuit Card Heat Pipes 18

A – Design and Manufacturing Methods Analysis

1. Evaluation of Alternative Heat Pipe Designs 22
2. Description of the Integrated Heat Pipe Module Design 24
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5. Use of the Test Station in Measuring Heat Pipe Performance 54
6. Environmental Test of Heat Pipe Circuit Card 56

1. APPROACH TO MEETING DESIGN REQUIREMENTS

The Hughes approach to meeting project design requirements was based on extensive analysis and testing to determine the optimum manufacturing method for heat pipes for circuit cards.

The design of the heat pipe must be based on the particular circuit card and card cage design. The design shown in Figure 3 is a dual-in-line package (DIP) type required for use with a DIP circuit card. The heat pipe bars shown on the drawing represent an average geometry circuit card in the industry. The heat transfer requirements are based on typical military enclosure equipment used for air, sea, or ground support. These applications do not preclude the use of heat pipes for commercial use.

The heat pipe lateral bars are designed for a standard dual-in-line (DIP) integrated circuit shown in Section AA of Figure 3. This type of design will demonstrate the versatility of the heat pipe application to circuit boards.

The heat pipe must be constructed of non-magnetic material. The magnetic properties interfere with the signal responses of the circuit boards.

The heat pipe material must also be compatible with the requirements of the general processes used in the assembly of circuit cards per MIL-P-55110 and MIL-P-55640.

Performance Requirements – The heat pipe must be designed to enable the transfer of heat from the lateral bars carying the DIPs to the side condenser areas where the heat will be conducted to a card mounting guide. The parameters for the performance are shown in Table 2.

Heat Pipe Lifetime – The heat pipe must be constructed to have a 10 year performance lifetime capability.

Hughes Approach – The initial task in the project was to submit a questionnaire to various manufacturers of heat pipes in order to investigate the state of the art methodology for manufacturing of heat pipes. The intent was to utilize the available knowledge specifically for the development of manufacturing techniques of heat pipes for circuit cards.

The responses to questions regarding manufacturing techniques were general and no data was learned which would significantly affect the design of the heat pipe for circuit cards. Results of the survey are given in Appendix A.

An extensive analysis effort was required to determine the optimum materials and processes to be used. After selections were made, a testing and development program was conducted to determine the best production materials and production methods to use for the manufacturing of the heat pipes. In certain cases, a production test was considered not necessary for the selection of a material or process. An example of this is the case of the shell material selection. There is already in existence, a great deal of data regarding physical and manufacturing properties of all the material candidates selected. An exhaustive research exercise was conducted to determine the best candidates and a final choice was made for the actual production test.

TABLE 2. THERMAL PERFORMANCE REQUIREMENTS

Card Size	No. of Bars	Power Dissipation Capacity
3" x 3"	5	25
5" x 5"	5–10	50
12" x 12"	10	100

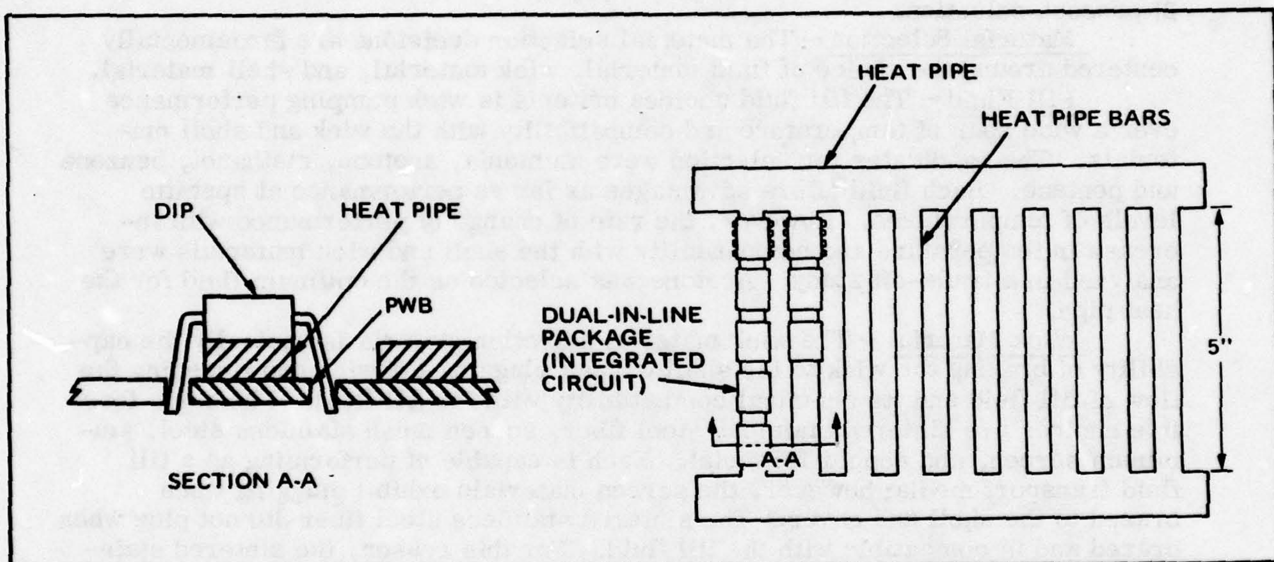

Figure 3. Placement of DIPs on Heat Pipe. The heat pipes are designed for a standard DIP circuit card.

2. DETAILED ENGINEERING CONSIDERATIONS FOR THE DESIGN AND MANUFACTURE OF CIRCUIT CARD HEAT PIPES

After extensive analysis and test, acetone was selected for the fill fluid, sintered stainless steel for the wick material and a copper alloy for the shell material. Manufacturing processes selected include stamping, tack welding, brazing, use of a multiple fill station and both the cold and hot weld pinch-off techniques.

The general engineering design considerations for the development of the heat pipe final design are shown graphically in the design chart, Figure 4, which summarizes the path of design evaluation. Basically the considerations are categorized by the following major design tasks: 1) material selection and 2) process selection.

Material Selection – The material selection decisions are fundamentally centered around the choice of fluid material, wick material, and shell material.

Fill Fluid – The fill fluid choices criteria is wick pumping performance over a wide span of temperature and compatibility with the wick and shell materials. The candidates for selection were ammonia, acetone, methanol, benzene and pentene. Each fluid offers advantages as far as performance at specific levels of temperatures. However, the rate of change of performance with increase in temperature and compatibility with the shell and wick materials were analyzed in a trade-off study. Acetone was selected as the optimum fluid for the heat pipe.

Wick Material – The wick material selection criteria is basically the capability of brazing the wick to the shell without plugging the wick and impeding the flow of fill fluid and its chemical compatibility with the fill fluid. The basic feasible choices are sintered stainless steel fiber, screen mesh stainless steel, aluminum screen, and copper feltmetal. Each is capable of performing as a fill fluid transport media; however, the screen materials exhibit plugging when brazed to the shell and cover. The sintered stainless steel fiber did not plug when brazed and is compatible with the fill fluid. For this reason, the sintered stainless fiber was chosen for the wick material.

Shell Material – The shell material selection criteria is based on thermal conductivity, formability, machinability, strength, compatibility to the fill fluid, bondability, non magnetic properties and commercial availability. The basic choices for selection were copper alloys, stainless steels and aluminum. The aluminum material was not selected due to its incompatibility with the fill fluid. The non-magnetic stainless steels were found to be acceptable even though the thermal conductivity in general is less than that of copper alloys. The copper alloys exhibit nearly all of the properties required with the exception of strength; however, this property is not a high priority attribute. The choice of the copper alloy is basically the selection of the optimum copper alloy which has the highest values of the criteria requirement. Copper alloy CDA 260 was selected as the material which has the highest qualification.

Manufacturing Processes – The various feasible manufacturing processes were analyzed to determine the most cost effective and viable approach to produce the heat pipe design. The Process selection is discussed on the following page.

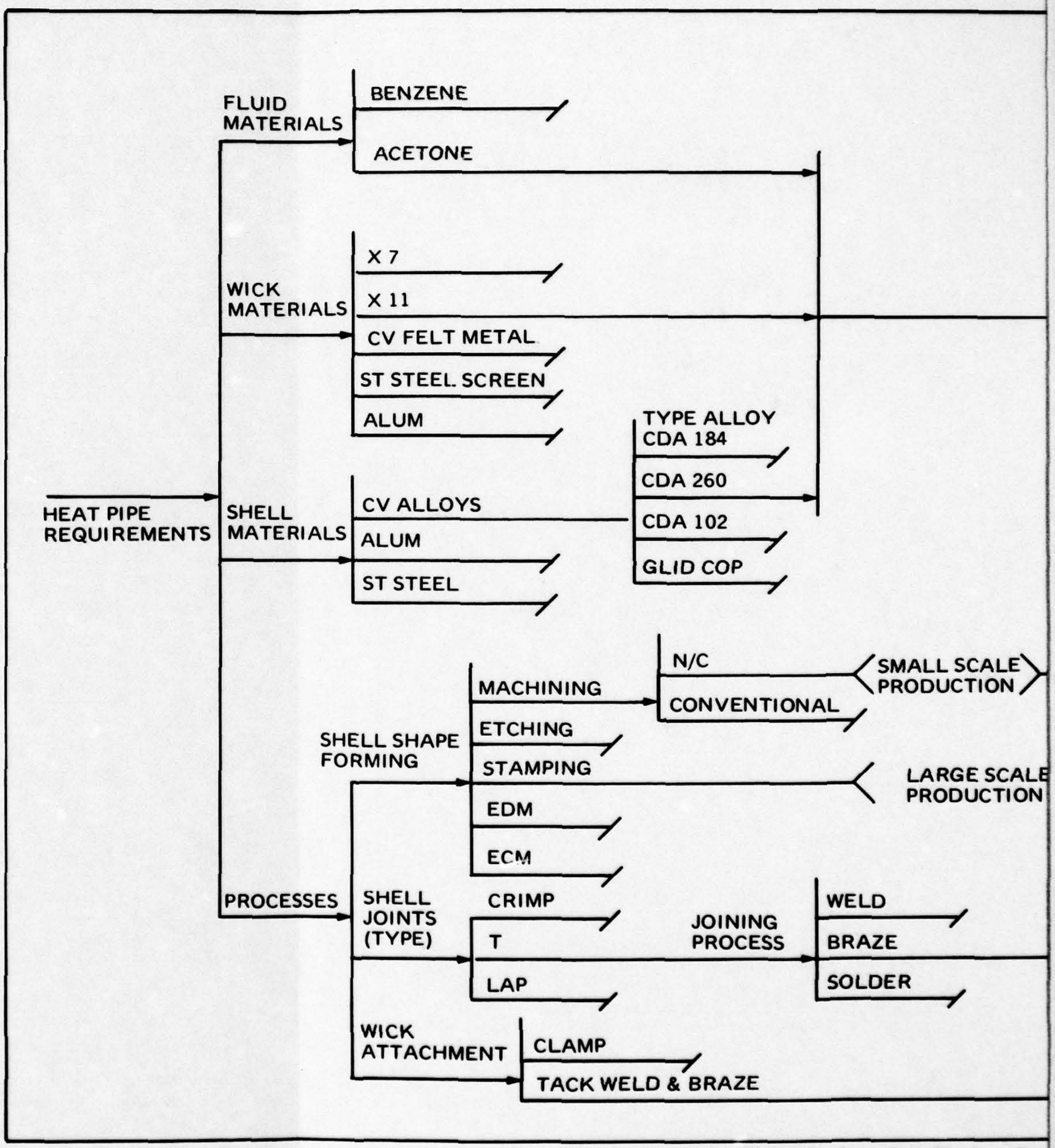

Figure 4. Heat Pipe Engineering Design Co
selection of the proper materials and manuf

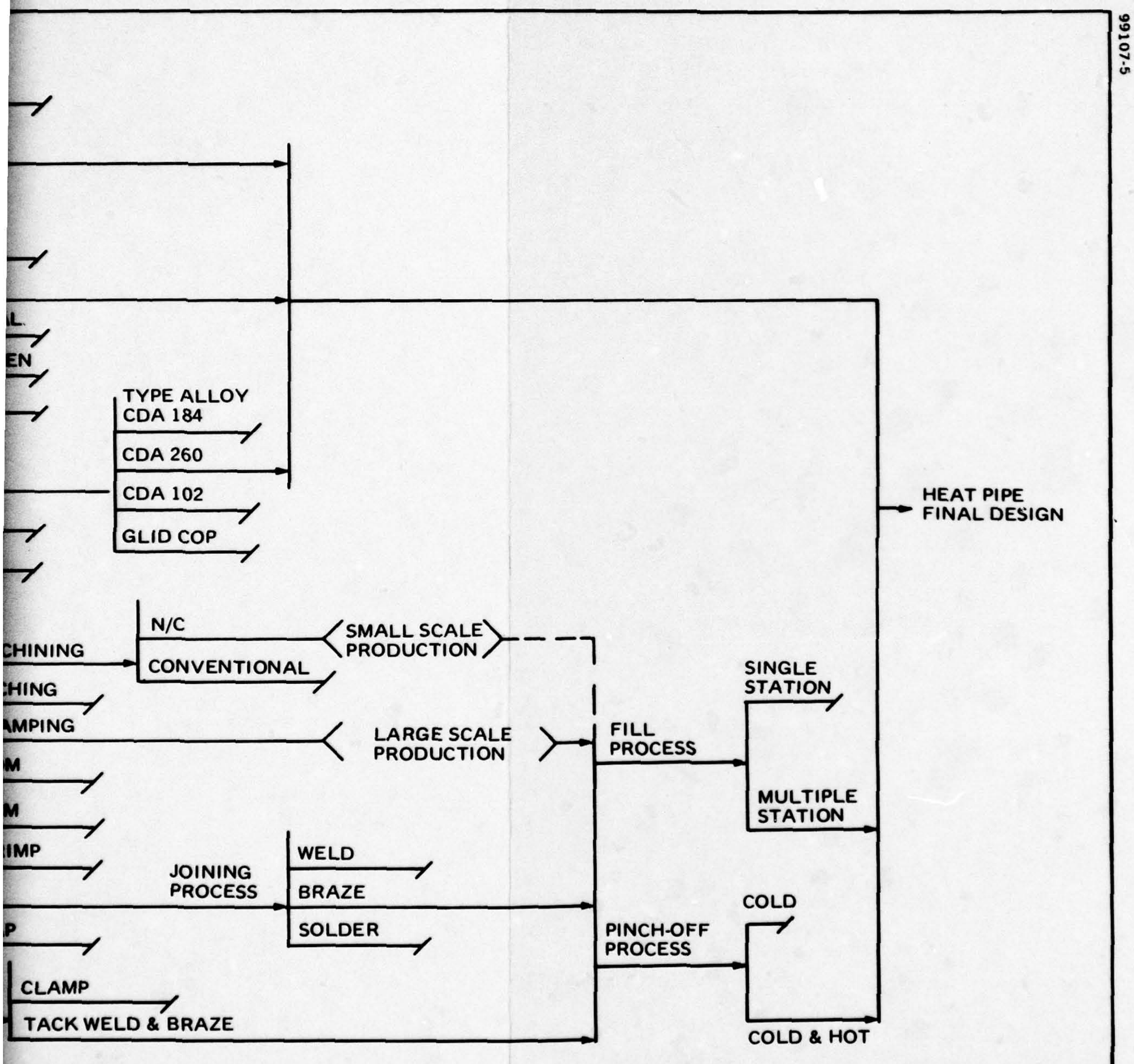

Figure 4. Heat Pipe Engineering Design Considerations and Decision Path. The major decisions were selection of the proper materials and manufacturing processes.

Forming – The forming processes considered were: machining (both conventional and numerical control), etching, stamping, EDM and ECM.

The stamping technique for the shell material (punch press) was determined to be the most cost effective and dimensionally repeatable approach to the forming process for a mass production environment. The numerical control machining process was found to be acceptable for small scale production or the manufacturing of a few parts of one part pattern. The machining technique eliminates the cost of a class A die which is used for stamping but the labor cost for machining is substantially higher than the labor cost for a stamping operation. The stamping technique must be used for cutting the wick material and braze preforms wherever possible. The alternatives of cutting the wicks and preforms are shearing (shear press), exacto knife and template and scissor and template. These alternatives produce the desired pattern, however, the labor cost is high and the dimension repeatability is not as high as with a small punch press.

Shell Joint Style – Considerations of the shell joint style are required to produce a strong and reliable joint. The joint style is especially important for the heat pipe base to the cover joint due to the complex shape and the high peripheral total joint length. The trade-off consideration is to produce a joint which is conventional and cost effective. The "T" joint was selected on the basis that the brazing operation would create a very strong bond in the material interface and crimping or lapping would not be necessary. The "T" joint is a standard joint which lends itself to design simplicity and cost effectiveness. The alternatives were crimp and lap.

Wick Attachment – The wick attachment processes which were considered are tack weld and braze. The brazing method was selected after various tests to assure bonding of the wick on the shell. The tack welding operation is required before the brazing to hold down the wick on the shell for brazing. This technique was tested and found to be suitable for the process.

Joining – The various feasible joining processes for the wick to the shell and cover plate to the base plate considered were welding, brazing and soldering. The brazing technique was selected as the optimum approach in design due to the mass production capability and low labor cost involved. The brazing joint was found to produce a highly reliable seal and strong joint. The soldering process was considered as a possible alternative; however, the problems of high labor cost and joint reliability were considered to be excessive.

Fluid Fill – The fluid fill process and pinch off process require design considerations to enable a uniform, reliable, and cost effective methodology. The alternatives considered for the fill process are single station and multiple station. In addition, the methodology considerations included plumbing and valving designs. The use of multiple vacuum pumps and three-way valves versus on-off bellows valves were part of the process design consideration analysis. The multiple fill station approach was selected as the most viable approach to the production process.

Pinch-Off – The fill tube, pinch-off process design considerations included both cold and hot weld processes. A cold weld process test was conducted and found to be adequate for a minimum tight temporary seal. A special copper tube cutter is used in the process and is simple to use; however, a stronger and longer life seal was considered to be required. A hot (spot weld) process was considered to be necessary after the cold weld and cut operation. The hot spot weld will enable the heat pipe to be handled and processed without fear of opening the cold weld.

1. EVALUATION OF ALTERNATIVE HEAT PIPE DESIGNS

The primary evaluation factors in selecting the heat pipe module design were thermal performance, size, weight, and adaptability to heat sink card slots. The design which meets these criteria best is the integrated module.

In order to evaluate the design options, a number of ground rules were established. The first of these was that evaluations would be based on the best heat pipe design for each configuration. The second was that consistent values of heat pipe parameters (e.g., evaporator or condenser thermal resistance) would be used. Third, an analysis of the effect of parameter changes (e.g., thermal resistance on heat pipe performance) would be made to determine how parameter changes affect the evaluation. Next, the primary evaluation factors would be thermal performance, size, weight, and adaptability to heat sink card slots. Finally, the secondary evaluation factors would be manufacturing complexity cost, processing and testing requirements, as well as life and reliability.

The two design configurations considered were the integrated heat pipe and the individual heat pipe. These configurations are discussed in greater detail in the next two topics.

Fluid Flow Parameter Study — A study of the fluid flow parameters was made for the competing heat pipe systems. The evaluation was based on the capability of the slab wick system to return the condensed heat pipe fluid from the condenser to the evaporator.

The characteristics of a high performance heat pipe fluid were used with several wick materials in calculating the required cross sectional area of the wick to provide the liquid flow path. The wick parameters are the pore size, which affects the pumping pressure, and the permeability, which is measure of the flow conductance through the wick. Manufacturers' data were used for these wick parameters and, although this may be a simplified case, the use of these data would give equivalent performance for either heat pipe system so an objective evaluation could be obtained.

The effect of gravity was also considered in the evaluation. The wick pore size was selected such that the wick would prime or remain primed if the heat pipe were vertical. In operation, the liquid flow in the heat pipe wicks is from the two ends (condensers) to the center. When operating vertically, the pumping pressure must be large enough to overcome the gravity force as well as fluid resistance. The pump pressure available for pumping fluid is the total pump pressure less the pressure requred to overcome the gravity to the center of the heat pipe (i.e., half the heat pipe length).

In the evaluation, it was assumed that the heat pipe component mounting bar would be 0.2 inch wide (suitable for mounting DIP packages) and the slab wick would be 0.050 inch wide. The wick thickness was calculated to give the required cross sectional area.

Operating the 12 in x 12 in circuit card heat pipe vertically places severe constraints on the selection of wicks and results in excessive wick cross sectional area requirements. It was felt, therefore, that operating at an angle (30 degrees) might present a better operating point on which to make a comparison between the two heat pipe concepts. It should be noted that the single heat pipes lengthened to provide more heat transfer area have a longer flow path, as well as a higher fluid gravity head, to overcome. Thus, larger slab wick dimensions will be required.

In reviewing the data for the wick thickness requirement, it can be concluded that: for the 3-in x 3-in, 25-watt card, comparatively thin wicks (i.e., small cross sectional area) are required. From a fluid flow standpoint, therefore, there is no particular advantage to either system. For the 5-in x 5-in, 50-watt card, adequate fluid flow performance can be obtained with thin wicks for either the 5 x 5 integrated heat pipe or the shorter, single heat pipes. However, for the longer single heat pipes, thicker wicks will be required. For the 12 x 12, 100-watt circuit card, thick wicks are required for any card that can operate vertically. Even at the 30 degree angle, wicks at least 0.100 inch thick are required. For this large a card, it may not be practical to use the 0.20 inch wide heat pipe bars.

Heat Transfer Parameter Study – A study of the thermal parameters was made for the competitive heat pipe systems. The overall temperature drop from the component mounting surface to the heat sink, including the temperature drop between the heat pipe and the heat sink, was calculated.

The thermal resistances include: the evaporator thermal resistance; the condenser thermal resistance; the thermal resistance between the heat pipe and the heat sink for the integrated module heat pipes; and the thermal resistance between the individual heat pipes and the spreader bar, and between the spreader bar and the heat sink for the individual heat pipe modules. Thermal resistances in the heat pipe shell and in the spreader bar were ignored because of the short distances and high thermal conductivity of the metals.

In addition to the nominal values for thermal resistance, values 100 percent higher and 50 percent lower than nominal were also used in the calculations to evaluate the effect of changes in those parameters on the temperature distribution. The nominal values used are shown below.

- Evaporator thermal resistance: $0.5^oC/watt/inch^2$
- Condenser thermal resistance: $0.5^oC/watt/inch^2$
- Joint thermal resistance: $1.0^oC/watt/inch^2$

In general, changes in the evaporator thermal resistance were not significant due to the low power density in the evaporator. Changes in the condenser and joint thermal resistances were significant, however, due to the higher power density.

For the 3-in x 3-in, 25-watt card, the integrated 3 x 4 module gave the best thermal performance. Only the thermal performance of the 3 x 6 module made of individual heat pipes approached the performance of the integrated module. Results were similar for the 5-in x 5-in, 50-watt card and the 12-in x 12-in, 100-watt card.

Selection of the Integrated Heat Pipe Design – The integrated heat pipe is definitely the best choice from the standpoint of heat transfer performance, size, weight, and compatibility with existing electronic equipment. It will be recognized that it will be more expensive to tool up for the integrated heat pipe and achieving a good hermetic seal over the long seal length will be a problem. However, based on the foregoing analysis, the integrated heat pipe configuration has been chosen for a further study of manufacturing methods and techniques.

The size of the component mounting bars and condenser section will depend on the heat pipe shell material, shell forming, and joining technique, as well as the thermal and flow parameters. Small (0.2 inch wide by 0.050 inch thick) component mounting bar size is possible only for small (3 x 4) heat pipe modules utilizing a shell thickness of 0.010 inch. For mid-size (5 x 6) modules, probable minimum conduction bar size is 0.2 inch wide by 0.080 inch thick. For the larger (12 x 13) modules, larger bar sizes will be required. Final bar size requirements will depend on the selection of heat pipe fluid, wicks, shell materials, and shell joining methods.

2. DESCRIPTION OF THE INTEGRATED HEAT PIPE MODULE DESIGN

The large thermal interface area afforded by the integrated heat pipe module design provides for effective heat transfer to the heat sink.

The integrated heat pipe module configuration is a flat heat pipe and is composed of parallel heat pipe conduction bars, manifolded together at each end. The electronic packages would be bonded directly to the top face of the bars, and the underside of the heat pipe array would be bonded to the top surface of the multilayer printed circuit card. As shown in Figure 5, the heat pipe manifolds project beyond the circuit card at each end to provide a large thermal interface area to transfer heat effectively to the heat sink.

The heat flow path in the heat pipe (Figure 6) starts at the interface where the heat dissipating component is bonded to the heat pipe. The heat flows through the heat pipe shell, and then through the evaporator wick-liquid matrix, to the liquid-vapor interface. The heat energy is absorbed in evaporation of the liquid. After this the vapor moves to the condenser where the heat energy is released by the condensing vapor. The heat flows through the condenser wick-liquid matrix and then through the heat pipe shell to the heat sink. The condensed vapor completes the cycle by flowing through the wicks to the evaporator where the cycle started.

The heat pipe bars to which the electronic components are mounted can be as small as 0.2 inch wide by 0.080 inch thick. Other sizes may be required to achieve effective overall thermal design requirements by matching the heat transfer surface areas of the components. The integrated circuit card heat pipe design is extremely flexible and can be configured with bars of different widths in the same assembly. In addition, non-constant width bars can also be utilized.

The heat pipe condenser manifolds assure uniform cooling of all components as the heat transfer from each component, regardless of location, is to the vapor space of the heat pipe. The vapor space, then, is used to transport the heat absorbed in vaporizing the fluid to the condenser manifold where it is released. Thus, all the components are equally coupled to the condensers.

The condenser manifolds are configured to fit into the card slots which constitute the heat sink for the heat pipe as well as provide structural support for the circuit card. The size and shape of the condenser manifolds can be varied to meet heat transfer requirements and electronic system structural requirements. The entire area of the card slot can be used for direct heat transfer from the heat pipe condenser to the heat sink, minimizing the temperature differentials in the heat pipe and between the heat pipe and the heat sink.

As required, typical rated power for the circuit card heat pipes is 100 watts for 12x12-inch card, 50 watts for a 5x5-inch card and 25 watts for a 3x3-inch card.

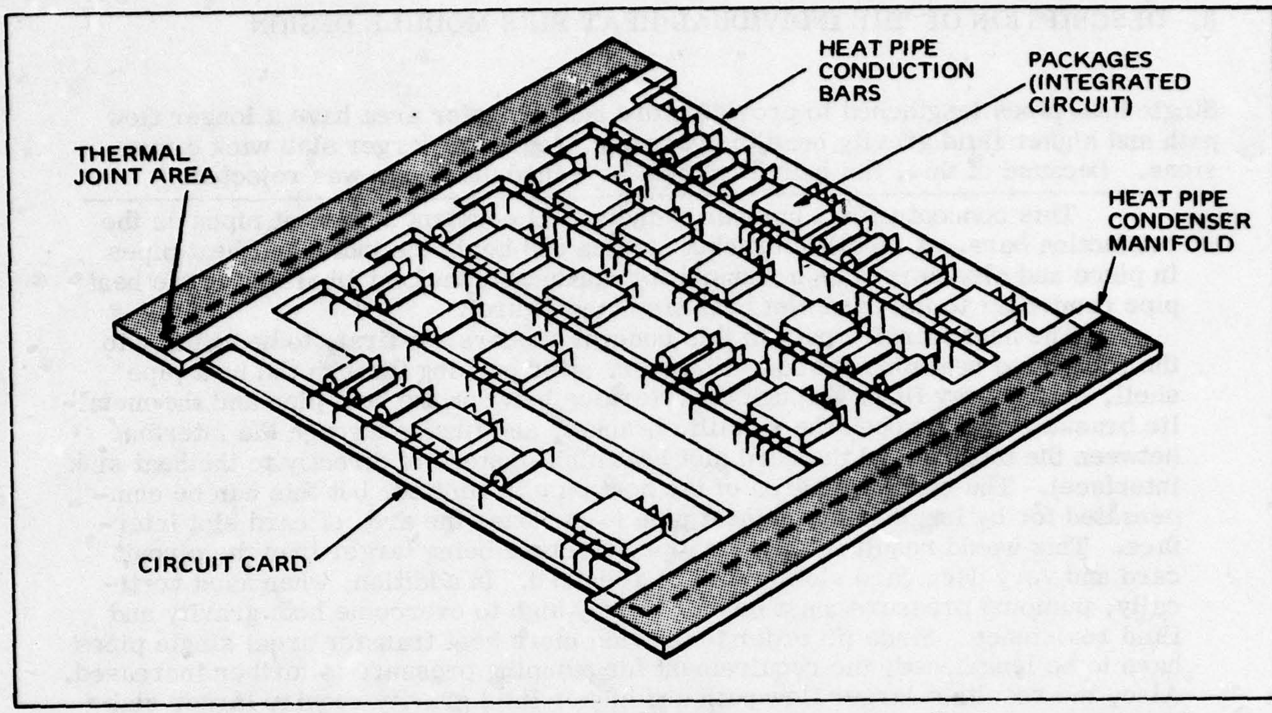

Figure 5. Integrated Circuit Card Heat Pipe Configuration. Since thin, flat heat pipes provide more surface area for conduction cooling than other configurations, the thermal resistance between the components and heat pipe interface is minimized.

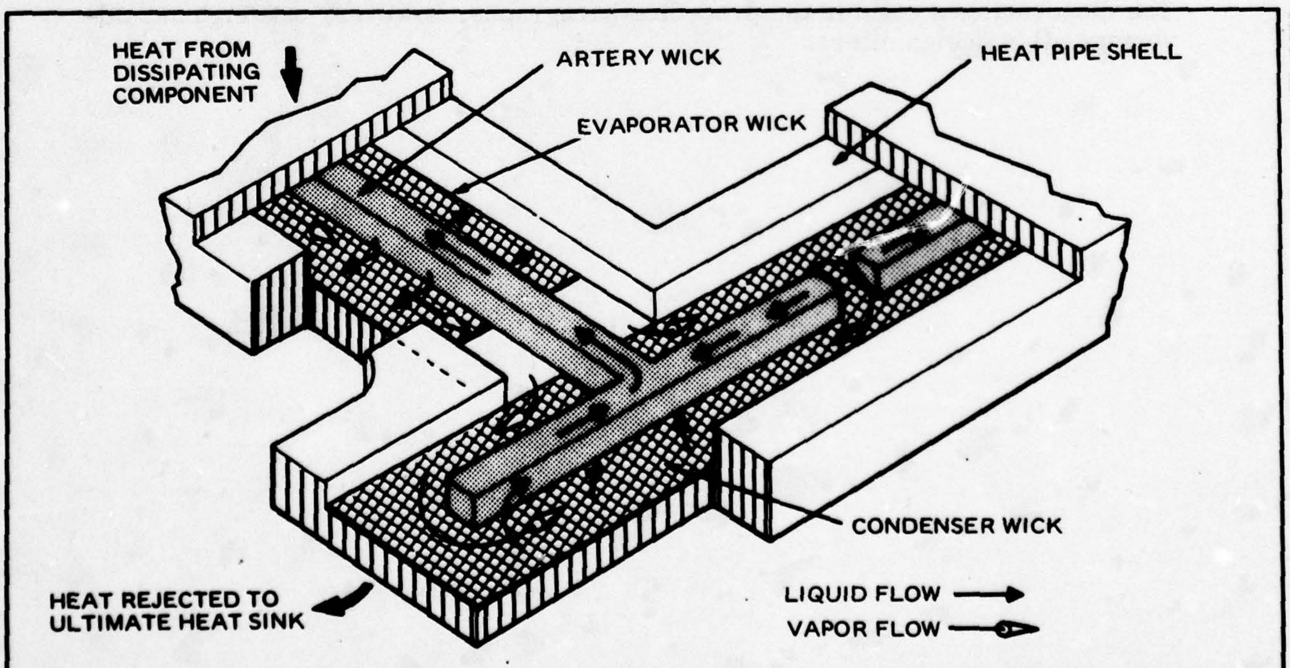

Figure 6. Flow Paths in the Integrated Circuit Card Heat Pipe Design. The integrated heat pipe circuit card cooling principle utilizes a combination of heat transfer and fluid flow techniques to move the heat from the dissipating component to the ultimate heat sink.

3. DESCRIPTION OF THE INDIVIDUAL HEAT PIPE MODULE DESIGN

Single heat pipes lengthened to provide more heat transfer area have a longer flow path and higher fluid gravity head to overcome, requiring larger slab wick dimensions. Because of this, the individual heat pipe module design was rejected.

This concept uses a number of individual constant area heat pipes as the conduction bars. A metallic bracket at each end holds the individual heat pipes in place and also serves as a channel for conducting the heat liberated in the heat pipe condenser to the card slot heat sink (see figure).

The heat transfer path in this concept appears, at first, to be similar to the integrated heat pipe design. However, after passing through the heat pipe shell, heat energy flows through the interface between the heat pipe and the metallic bracket, then through the metallic bracket, and finally through the interface between the bracket and the card slot heat sink (instead of directly to the heat sink interface). The condenser area of the heat pipe is limited, but this can be compensated for by lengthening the heat pipe to increase the area of card slot interface. This would result in the heat pipe structure being larger than the circuit card and very deep card slots would be required. In addition, when used vertically, pumping pressure must be sufficiently high to overcome both gravity and fluid resistance. Since (in order to provide more heat transfer area) single pipes have to be lengthened, the requirement for pumping pressure is further increased. Also, the resultant larger flow path and higher fluid gravity require larger slab wick dimensions.

The individual heat pipe module approach offers more flexibility than the integrated heat pipe module design. The number of individual heat pipes per circuit card and the spacing between them does not have to be specified beforehand. The disadvantages cited in the preceding paragraphs, however, outweigh any advantages this design offers.

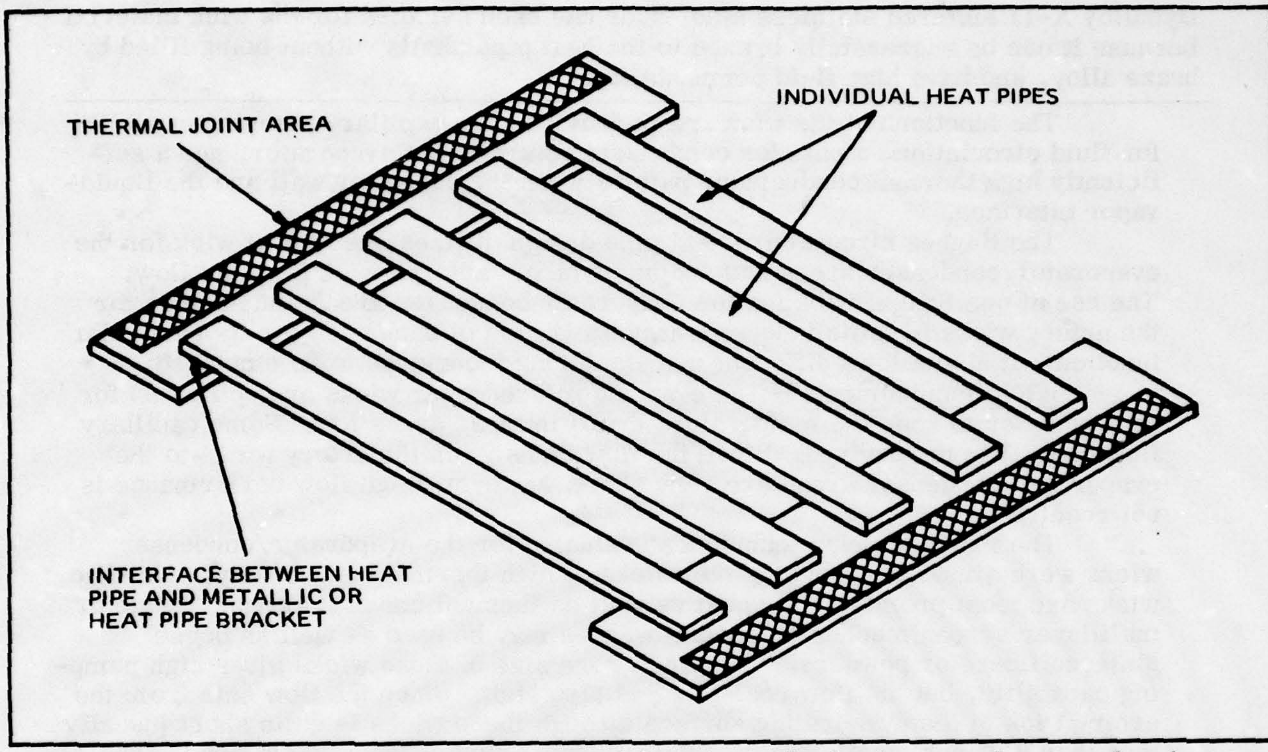

Figure 7. Individual Circuit Card Heat Pipe Module. A metallic header is used to interface between the individual heat pipes and the card slot heat sink.

4. EVALUATION OF WICK MATERIALS AND SELECTION OF WICKS FOR THE CIRCUIT CARD HEAT PIPE

Dynalloy X-11 sintered stainless steel fiber has been selected for the wick material because it can be successfully brazed to the heat pipe shells without being filled by braze alloy, and have high fluid permeability.

The functions of the wick are to provide: the capillary pumping capability for fluid circulation, a path for condensate return to the evaporator, and a sufficiently high thermal conductance path between the container wall and the liquid-vapor interface.

The Hughes circuit card heat pipe design utilizes one type of wick for the evaporator/condenser areas and another type of "artery" wick for fluid flow. The use of one type of wick for the evaporator condenser areas and another for the artery wicks permits independent optimization of each wick for its particular function. It also allows different manufacturing techniques to be employed.

Wick Requirements – The evaporator/condenser wicks are optimized for heat transfer to keep the temperature drops in these areas low. Some capillary flow capability is required. Since the flow paths from the artery wicks to the evaporator/condenser areas are very short, however, high flow performance is not required.

The manufacturing techniques evaluated for the evaporator/condenser wicks were aimed at producing thin wicks of high thermal conductivity. Metallic wicks are most promising for cost as well as thermal considerations. Single or multilayer screen meshes or special weaves may be used as well as dense sintered fibers or powders. The small pore size of these wicks gives high pumping capability, but the flow resistance is also high. Since the flow path from the artery wick to the evaporating surface through these wicks is quite short (usually less than 0.1 inch), satisfactory fluid transport performance is obtained. The Hughes Aircraft Company has used thin mesh wicks for the evaporator and condenser areas in circuit card heat pipes. These thin, relatively dense wicks give a very low temperature gradient across the evaporator and condenser.

Since artery wicks are used exclusively for fluid flow, they need not have the high thermal conductivity required of the evaporator and condenser wicks. The wick pore size, therefore, may be optimized for liquid transport. Decreasing the pore size increases the pumping capability and, simultaneously, increases the liquid flow resistance. Conversely, increasing pore sizes reduces the flow resistance and also reduces the pumping capability.

Because the selection of wick material must be made between commercially available materials, the pore size and permeability of these existing materials must be used in any trade-off studies. A number of materials can be used to fabricate the artery wicks. Sintered metal fibers or multilayers meshes can be fabricated with a variety of pore sizes and configurations.

Selection of Wick Materials – A preliminary investigation, based on design considerations, was made of various materials which could be used in wicks. The materials investigated and their acceptability are shown in Table 3.

Testing was then performed on certain materials accepted in the preliminary investigation. These materials were stainless steel screen and sintered stainless metals (fibers). The tests were conducted to choose a material which has good capillary pumping action for heat transfer and which would not be plugged by the brazing process (i.e., in certain materials, the molten braze material will fill and plug up the wick and prevent flow of the fill fluid).

The results of the tests were that stainless steel screen was unacceptable. The stainless steel screen test showed that the molten braze material crept into the voids and excessively plugged up the material, preventing fluid flow. This material, therefore, was not chosen. Although this type material did not perform satisfactorily, a different alloy or size screen might be found and tested which could improve the performance. (See recommendations section.) The stainless sintered fiber (X-7 and X-11) passed the test. In this test it was shown that the molten braze material did not fill the voids in the wick and did permit good pumping action of the fill fluid. The overall conclusion was that, for this heat pipe, the sintered stainless steel fiber gave the best performance. Dynalloy X-11 was selected for the artery wicks as well as the evaporator/condenser wicks. The specifications for using Dynalloy X-11 as a wick material are found in Table 4.

TABLE 3. MATERIALS INVESTIGATED AND THEIR ACCEPTABILITY

Material	Accepted/Rejected
Stainless steel screen	Accepted
Copper feltmetal	Accepted
Sintered stainless metals	Accepted
X-7, X-11 Dynalloy	
Aluminum screens	Rejected
Sintered stainless powder	Rejected

TABLE 4. SPECIFICATIONS OF DYNALLOY X-11 FOR USE AS A WICK MATERIAL

Sintered Metal Fibers	304 Stainless Steel
Thickness	0.016 inch
Porosity	67%
Density	0.096 lb/in^3
Mean Pore Diameter	22 microns
Permeability	0.14 x 10^{-9} ft^2

5. EVALUATION OF WICK FABRICATION AND ATTACHMENT TECHNIQUES

The selected wick material, Dynalloy X-11, can be successfully cut, tack-welded in place, and brazed to the interior of the heat pipe.

Wick fabrication requirements include cutting to the proper geometry, then attaching this shape into the shell, for subsequent brazing.

Wick Data — The Hughes circuit card heat pipe design utilizes one type of wick for the evaporator/condenser areas and another type of "artery" wick for fluid flow. The use of one type of wick for the evaporator condenser areas and another for the artery wicks permits independent optimization of each wick for its particular function. It also allows different manufacturing techniques to be employed.

Good thermal contact between the metallic wick and the heat pipe shell is essential. Even a very thin gap between the wick and shell, where the heat must be conducted by the low thermal conductivity heat pipe fluid, will introduce large thermal gradients. The method of attachment possible with a specific wick material, therefore, influenced wick material selection. Numerous bonding techniques for wick structures have been explored in previous Hughes studies. These include spot welding, diffusion bonding, brazing, sintering, adhesive bonding, and electroplating.

Attachment of the artery wick is less critical than that of the evaporator/condenser wicks and need only assure that the artery wick be in contact with the evaporator/condenser wicks to permit liquid transport.

As noted, Hughes has used thin mesh wicks for the evaporator and condenser areas in circuit card heat pipes. These wicks were usually spot welded in place. If the wicks were not perfectly flat when spot welded, however, there could be a gap between the wick and the heat pipe wall. This gap would be filled with the heat pipe fluid (which has a low thermal conductivity) and would present a significant thermal resistance. The net result would be inconsistent heat pipe performance and possible local hot spots. It was decided that the wicks needed to be metallurgically bonded to the heat pipe shell in order to assure consistent heat pipe thermal performance.

Wick Cutting Evaluations — A number of candidate approaches were evaluated. The most promising are laser and shearing. Laser technology for wick cutting requires further development. The approach selected is shearing. Table 5 results show no problems for any of the materials evaluated, thus the evaluations apply equally for the selected wick material, Dynalloy X-11.

Wick Fastening Evaluations — Among the different wick to shell attachment techniques, spot welding is the most frequently used within Hughes. It has been used successfully in several heat pipe projects. Table 6 data indicates the good results in spot welding the selected wick material, Dynalloy X-11. Therefore this technique is used for the tack welds of the artery wicks.

Evaluation of Bonding of Wicks — A number of experiments were run on bonding wicks to the heat pipe shell. The overall conclusion was that, with currently available materials and methods, the thin mesh wicks could not be bonded to the heat pipe shell without completely filling the mesh with braze alloy. Because of this, the sintered stainless steel (SS) fiber wicks were selected. These latter wicks can be successfully brazed to the heat pipe shells without being filled with braze alloy. They also help provide fluid flow capacity because they have high permeability.

TABLE 5. WICK SHEARING DATA*

Material	Thickness (In.)	Comments (**)
Brass Screen Mesh 200 Mesh (fine)	0.011	None
CU Screen Mesh 100 Mesh (coarse)	0.021	None
SS Screen Mesh (80x700)	0.010	None
SS Screen Mesh (200x1400)	0.006	None
Dynalloy X-13	0.025	0.0023
Dynalloy X-7	0.020	0.0005
Dynalloy X-12	0.021	0.0005
Felt Metal FM 1011	0.064	0.008
Felt Metal FM 702	0.060	0.005
Felt Metal FM 12	0.055	0.001
Felt Metal FM 1102	0.061	0.001
Felt Metal FM 1107	0.123	0.001

* Machine used: Peck, Stow & Wilcox Co.
Model 137 K (Foot Shear)
HAC No. 39110

**All sheared very well. This column indicates the amount of compression at pads, in inches.

TABLE 6. SPOT WELDING TESTS**

Shell	Wick		W/Section	Welding Tip Force NLB	Comments
BRASS	*SS	MESH 80x700	60	7	OK***
			30	2	OK***
	*SS	MESH 80x700	100	10	Larger Spot
	FM (1101)		100	6	Good
	FM (1101)		100	10	
BRASS	FM (1101)		100	2	Good
CU	*SS	MESH 80x700	100	2	Burned through
			30	2	Weaker
	*SS	MESH 80x700	70	2	Better – OK
CU	Phosphor Bronze	(200 Mesh)	70	7	No Good
BRASS			70	7	No Good – Poor
			70	7	Not too good
BRASS	Phosphor Bronze	(200 Mesh)	100	7	OK – Just sticks
SS	*SS	MESH 80x700	100	7	Good
			70	2	Good
SS	*SS	MESH 80x700	70	2	Good
SS	Phosphor Bronze (200 Mesh)		70	2	Good
	Phosphor Bronze (200 Mesh)		70	2	Good
SS	Dynalloy X-11		100	10	Good
BRASS	Dynalloy X-11		100	10	Good

* Twill Dutch Weave ***Strength about same

**Machine Used: Hughes VTW-30C HAC No. 176565

6. SELECTION OF SHELL MATERIALS

Investigation and test of candidate materials for fabrication of heat pipe shells indicates that copper alloys are the most suitable for the purpose, with stainless steel also having a potential use, in spite of its lower thermal conductivity. Cartridge brass was chosen as the best material for the shells.

A set of potential materials for constructing heat pipe shells was identified. The published specification properties were then compared, to select those with the best characteristics. This resulted in a group of five candidates which were then subjected to a weighted rating analysis. The selected material was then machined and brazed in a production simulation test, and performed excellently. The material selected is cartridge brass with alloy designation CDA 260 (Copper Development Association). Equipment ASTM specification materials are also identified.

Initial Group of Materials – Based upon potential suitable properties, the following candidate shell materials were identified for further analysis:

- Copper Alloys
  - CDA 102 (oxygen-free, high conductivity copper)
  - CDA 155 (zirconium copper)
  - CDA 172 (beryllium copper)
  - CDA 182-184 (chromium copper)
  - CDA 260 (cartridge brass)
  - CDA 260 (aluminum bronze)
  - CDA 725 (copper nickel)
  - GLID-COP AL-20 (proprietary alloy of Glidden Corporation)
- Aluminum Alloys
  - 5032 ("H14" hardness)
  - 6061 ("T0" softness)
  - 6951 (braze sheet)
- Stainless Steels
  - A1S1301
  - A1S1302
  - A1S1303
  - A1S1304
  - A1S1347

Potentially Acceptable Group of Materials – An analysis of specification characteristics indicated that the following materials would be acceptable as shell materials:

- Copper Alloys: CDA 102, CDA 182-184, CDA 260, GLID-COP AL-20
- Aluminum Alloys: 6061-T0, 6951
- Stainless Steels: 301, 302, 304, 347

Final Selection – As noted above, the group of potential materials further reduced to a group of five on the basis of apparent best suitability, was subjected to a weighted rating analysis as shown in Table 7. The specifications for the selected material, CDA 260, are provided in Table 8, with designators of acceptable alternatives throughout, materials were analyzed to find the one with the best set of the following properties:

1. High Thermal Conductivity
2. Brazing Ability
3. Structural strength and rigidity
4. Machinability
5. Chemical compatibility to the fill fluid
6. Commercially standard alloy and availability
7. Compatibility with circuit card assembly process

Shell Material Test Verification – The copper alloy selected for the shell material, CDA 260, was machined and brazed in a production simulation test. The material, as expected, performed well, and the sample test showed excellent results.

TABLE 7. SHELL MATERIAL WEIGHTED RATING SELECTION

Attribute	I_6	102 R	102 RxI	CDA 260 R	CDA 260 RxI	SS 303 R	SS 303 RxI	SS 347 R	SS 347 RxI	AL 6061 R	AL 6061 RxI
Thermal Conductivity	4	4	16	3	12	2	8	2	8	3	12
Brazeability	5	4	20	4	20	3	15	4	20	4	20
Strength	4	3	12	3	12	4	16	4	16	3	12
Mach & Stamp	3	2	6	3	9	4	12	3	9	4	12
Availability	4	3	12	4	16	4	16	3	12	4	16
Compat/Fill Fluid	3	4	12	4	12	4	12	4	12	1	3
Total Score			78		81		69		77		75

Notes: • I = Importance of attribute; R = Assigned Importance Rating; RxI = Product R and I
• Although 6061 has a high score of 75, its low chemical compatibility precludes its use.

TABLE 8. SPECIFICATIONS FOR CARTRIDGE BRASS, CDA 260

Chemistry

Composition	Nominal %	Min %	Max %
Copper	70	68.5	71.5
Lead			0.07
Iron			0.05
Zinc	30		Rest
Other Elements			0.15

Equivalent ASTM Specifications: B19, B36, B134

Physical Properties

Melting point (liquid)	1750°F
(solid)	1680°F
Density	0.308 lb/cu. in (68°F)
Coeff. thermal expansion	1.11 10-5 in/in/°F (68°-572°F)
Thermal conductivity	70 Btu/Hr/sq. ft./ft./°F (68°F)
Elect. resistivity	37 ohms (circ. Mils/ft)
Modulus of elasticity	16 10^6 PSI
Tensile strength	42 10^3 PSI
Modulus of rigidity	6 10^6 PSI
Yield strength	12 10^3 PSI
Elongation (2 inches, %)	52
Hardness	57 R_F

National Suppliers

- Anaconda
- Chase Brass & Copper
- Revere Copper and
- Scott Brass
- Olin Brass
- Bridgeport Brass

7. EVALUATION OF SHELL BONDING MATERIALS

Evaluation and test of candidate braze materials suitable for the in-process and final joining of heat pipe wick and shell components resulted in the selection of silver braze alloy as the most suitable.

Braze Requirements, Selection Criteria, and Tests – The close tolerance construction of the heat pipe and the shell material determines, to a large extent, what braze alloys may be used. Other factors which enter into the selection of the braze material are the flux requirement and compatibility with the fill fluid and wick. A hydrogen atmosphere is used in the brazing process to reduce metallic oxides.

The braze alloys tested were those which were most compatible for joining with the base and cover material, but which had a lower brazing temperature than the wick to shell and cover braze so these bonds would not melt during the base to cover braze. Various spot welding tests were also conducted to determine the best material to use. The criteria for spot welding were the quality, the flow, and the strength of the weld. Various thickness of materials were tested at various temperatures.

Candidate Materials – All of the following materials considered initially are shown with American Welding Specification (AWS) Code identifiers, except for the AMS, H&H, and Wesgo items:

- BCUP 1 and 2
- H&H 505, 560, and Litho 720
- BNi-2, -3 and -4
- AMS 4777, 4778 and 4779
- Al 4343 Braze Sheet Coating
- Wesgo Nicosil No. 3 and Incusil No. 15

"H&H" is the designator for Handy & Harmon, New York; "Wesgo" is the designator for Western Gold Corporation, Belmont, California.

Most Promising Brazes – Of the noted candidates, the following were considered acceptable: BCUP 2; H&H 505 and 560; BNi-2, -3 and -4; and the braze sheet coating.

Final Selection – Further evaluation resulted in the selection of H&H 560 for brazing the cover to base. Specifications for this braze is provided in Table 9.

To facilitate handling required in the wick, cover, and base brazing operations, temporary tack/spot welding is used to hold these elements in place. Of the various brazing materials tested in all of these processes, Handy and Harman HH560 was determined to be the most suitable.

TABLE 9. COVER TO BASE BRAZING ALLOY SPECIFICATIONS

Type:	**Silver Braze, BAg-7**
Vendor Alloy:	**Handy & Harman No. 560**
Composition	
Ag	**56%**
Cu	**22%**
Zn	**17%**
Sn	**5%**
Physical Characteristics	
Specific Gravity	**9.42 gm/cc**
Joint Color (as brazed)	**White**
Liquious (Flow Point)	**1205°F**
Solidus (Melt. Point)	**1145°F**
Other Equivalent Specifications	
AWS A5.8 - 76	**BAg-7**
ASME:	**BAg-7**
Material Suppliers	
Handy & Harman, New York, N.Y.	

8. EVALUATION OF SHELL MANUFACTURING TECHNIQUES

Evaluation of candidate fabrication techniques for the selected material identifies Die Stamping and Coining as the best method for fabricating heat pipe shells. However, other approaches are highly rated and could be employed by various manufacturers, based upon a management decision reflecting factors peculiar to a given company.

The advantages and disadvantages of the primary fabrication techniques considered for the selected Cartridge Brass material are reviewed below and the weighted rating selection criteria is presented in Table 10. **High energy rate forming is not shown, but is rated closely with the selected die forming method.** Its limitation is that only four firms in the U. S. have this highly rated skill, and its only other source is Japan.

Numerically Controlled Routing and Milling (NCRM) – In the numerical control (NC) method both the part outline and cavity are cut on a three-dimensional machine. Tooling costs consist of creating the tape that establishes the outline and the cavity.

- Advantages
  - – No capital cost of dies
  - – Tape control and repeatability
  - – Shape and cavity fab in one operation
  - – Reliability
  - – Excellent for short run jobs
- Disadvantages
  - – High capital cost for N/C machines
  - – Highly trained operator required
  - – Intermediate production labor cost
  - – Maintenance and down time of N/C machine
  - – Programming of N/C tape

Die Stamping and NC Milling (DSNCM) – In this, the part outline is die stamped and the cavity cut on an NC mill. Production rates would be increased over the previous method, but tooling cost would increase.

- Advantages
  - – The stamping of the outline of the part saves cost of labor
  - – Outline of part dimensionally repeatable
  - – Excellent for short run jobs
- Disadvantages
  - – Basically the same disadvantages of the above NCRM system
  - – Two operations required to produce part
  - – Precision indexing and registration of parts is required for two operations
  - – Two (2) step process requires added quality control and inspection

Die Stamping and Coining (DSC) – The part outline in this method is die stamped and the cavity formed by a coining die. This results in a higher production rate than the previous two methods but involves more expensive tooling for the coining die.

- Advantages
  - – Lowest labor cost to produce parts (for high volume production of one part style
  - – Outline and cavity of parts produced in one operation
  - – Dimensional repeatability
  - – No precision registration or indexing of parts required
  - – Quality Control problems and inspection significantly reduced

- Disadvantages
  - High cost of special tooling and dies
  - Development of tooling and dies
  - Not cost effective for short run jobs or for few parts

Chemical Milling (CM) – This is the present technique used for making thin prototype heat pipes. This method can be used for making the part as well as forming the cavity, but if used to form the outline, a final finishing operation would be required to remove irregularity at the edges. Accordingly, the following considers CM only for the cavity.

- Advantages
  - Easily processed by conveyor type chemical etcher machines
  - Low labor cost to etch
  - Cost of processing is not sensitive to quantity of parts. Good for high or low production
- Disadvantages
  - Cost of etching machine is high
  - Etch requires process and chemical control
  - Quality of parts and dimensional repeatability is questionable. Chemical etching quality greater for thinner parts. Cavity control on thicker parts may be a problem.
  - Requires greater quality control, inspection and cross sectional analysis to ensure consistency.

Discussion of Weighted Rating Selection Table Results – As may be noted, the die stamping and coining process has the highest weighted rating score and is selected as the most viable production process to fabricate the heat pipe shell.

The numerical controlled Routing and Milling and the Chemical Milling processes are highly rated and appears to be about equal in merit for attributes, thus may be considered as a possible alternatives. However, the advantages and disadvantages must be weighed by the individual manufacturing activities. Oftentimes this type of decision becomes a direct management decision based on policy or other management considerations.

TABLE 10. WEIGHTED RATING ANALYSIS OF CANDIDATE SHELL FABRICATION TECHNIQUES

Attribute	I (1-4)	NCRM R	NCRM RxI	DSNCM R	DSNCM RxI	DSC R	DSC RxI	CM R	CM RxI
Dimensional Control and Repeatability	4	4	16	3	12	4	16	3	12
Labor Cost	4	3	12	3	12	4	16	4	16
Simplicity	3	4	12	2	6	4	12	4	12
Process Control	3	4	12	2	6	4	12	3	9
Equipment or Tooling Cost	2	1	2	1	2	2	4	3	6
Total Score			54		38		60		55

Notes: I = Importance weight factor, values from 1 through 4.
R = Assigned evaluation rating of attribute for system (values from 1 through 4).
RxI = Product of assigned rating times importance weight, = score of attribute for system.

9. JOINING METHOD SELECTION ANALYSIS

Furnace brazing is selected as the most viable method of joining the heat pipe base and cover plates. Although the initial capital costs are high, the mass production capability afforded by this technique enables the process labor costs to be low, while providing joints with excellent strength and seal properties.

Various techniques for welding were considered including resistance welding which would provide an excellent quality and reliable seal. However, the special tooling and the configuration requirements does not lend resistance welding to state-of-the-art heat pipe production methods. The final contenders are shown in Table 11, and discussed briefly below.

Review of Welding Methods – A manually-operated TIG weld gun is too big to reach all surfaces of the pipe and produce an even weld bead. Only automatic control would be sufficiently precise to guide the heat source. Because of size, the heat source should be remote from the part. Laser or Electron Beam (E-B) can do this. Laser technology for this purpose is not commonly available. N/C E-B is the only feasible welding method. In sum, welding by any means other than Numerically/Controlled Electron-Beam (N/C E-B) entails time and skill levels that are either uneconomical or currently unavailable in U. S. technology.

Even so, there are unacceptable drawbacks to welding itself. These include the problems of joint design and parts production rates. In particular, an edge-flange weld-joint would be required, which dictates a hat-shaped pipe cross section. Also, high heat input to such a joint must come from the focused end of an energy beam (E-B). Then, the distortion and cool-down rates of each point about the circumference of the pipe pose many fixturing problems. Regardless of the desirability that N/C E-B may have, it cannot replace brazing of the wicks. Thus, capital equipment costs to adopt both methods would be doubled. Even further, consideration of the fact that over 117 inches of co-planar joint area must be sealed clearly points to the conclusion that the probability of successful welding is very small.

Diffusion Bonding – Diffusion bonding is a process highly dependent on ultra cleanliness, dimensional accuracy, and high-quality surface finish of the part. This means that parts must fit together far better than is necessary for any liquid-metal-bond method such as welding or brazing. It also means that the tolerances of manufacture of a part for diffusion bond joining must be extremely small, and the surfaces must be very smooth with almost no waviness. Further, since the bonding takes place on an inter-atomic level, the process is not rapid. Also, results are highly dependent on bond area size. For such reasons, diffusion bonding is ruled out.

Localized Sequential Brazing – The use of torch or induction brazing is eliminated because the former poses a skill problem, and both pose a heat distortion problem. In addition, the uniformity of the braze and repeatability using this process is highly questionable.

Broad Area Simultaneous Brazing – Liquid-metal-bonding (soldering or brazing) offers a better method than any of the above. Total time of exposure to temperature is less, the joint area sees a uniform temperature change during the process, and parts fitment need be no more precise than for welding. In practice, the difference between soldering and brazing depends on the temperature involved. Soldering is done below 800°F, brazing is done above.

Soldering – Soldering as a joining method could simplify the joining processes and ensure that the entire joint is sealed. This process was ruled out, however, due to the physical characteristics inherent in solder. The strength and temperature sensitivity of the soldered joints are not adequate for handling operations nor do they allow an assembly process which requires the heat pipe and circuit card to be subjected to elevated temperatures. In addition, the fluxes used in soldering may act as a contaminant and be harmful to the internal areas of the heat pipe.

Furnace Brazing – Furnace brazing the pipe joints is considered to be the most viable process to be used for the joining of heat pipes. The braze process lends itself to mass production techniques and the joint will have excellent strength and seal properties. The fusion of the metal and the grain structure of the joints produces a very reliable bond.

Pipe interior cleanliness and freedom from pipe fluid-reactive compounds are of prime importance. Therefore, fluxless joining is mandatory. In this respect, the use of a reducing atmosphere in a furnace provides the necessary cleaning action of a flux without residual slag. A dry hydrogen atmosphere was selected as the simplest with which to work.

The brazing process required a development program to determine the braze alloys to be used and a hydrogen retort furnace is required for this process. Fixturing and plate force loading techniques must be used to ensure that the plates are held down flat and in contact with the matching plate to ensure that the plates will be fused together. Although the capital cost of this process is high, the labor for the process and the mass production capability will enable the process labor cost to be low.

TABLE 11. SHELL JOINING PROCESS APPLICABILITY TO VARIOUS CANDIDATE SHELL MATERIALS

Joining Method	Shell Candidate Material Type			
	Brass	OFHC CU	SS	AL(4)
Welding, (N/C E-B)(1)	NR	NR	NR	NR
Diffusion bonding (2)	NR	NR	NR	NR
Torch brazing	OK	OK	OK	NR(3)
Furnace braze	OK	OK	OK	NR
Soldering	OK	OK	OK	NR

NOTES: NR – not recommended
(1) Lengthy process time
(2) Process beyond technical competence of general industry
(3) Requires highly-skilled operator, not generally available
(4) Oxides difficult to remove without flux

10. EVALUATION OF HEAT PIPE FILLING TECHNIQUES AND CONCEPTUAL DESIGN FOR THE VACUUM FILL STATION

An evaluation of all the feasible EFS techniques was performed to determine the most viable approach for a production-oriented system. Based on the evaluation, a modified 3-way valve system was selected.

A study was conducted to determine the most effective methods of filling and sealing the heat pipes. Tests were run on several different valving systems for the Heat Pipe Fill Station.

For all systems, the test procedure was the same. The ten sample heat pipes were weighted. Each heat pipe was attached to the fill station and pumped down. The pump down time and vacuum were recorded. The reservoir was maintained at approximately 150°F and the calibrated volume was maintained at approximately 110°F. One minute was allowed for the heat pipe to fill. After being filled, tape was placed on top of the fill tube to help prevent spillage and evaporative losses. After all the heat pipes were filled, they were weighed again on the same scale. The heat pipes were baked out overnight to remove the acetone.

The first system tested was a 3-way ball valve system shown in Figure 8. The best vacuum obtained using this system was approximately 70 microns, which was judged to be unsatisfactory, since a vacuum of at least 50 microns was desired. The 3-way valve was modified by adding two O-rings to the stem to improve the seal.

The modified 3-way valve system was tested next. The vacuum on this system was better than 30 microns and the pump down time was approximately 5 minutes.

The next system tested was the bellows valve system with the arrow pointing away from the heat pipe. Heat was added to this system in the same manner as the first system and the same temperatures were maintained. This system was able to maintain a vacuum better than 30 microns, but residual acetone vapor in the system caused the pump down time to be approximately 15 minutes. The schematic is shown in Figure 9 for comparison.

The last system to be tested was the bellows valve system with the arrows pointing towards the heat pipe. Again, the vacuum was good, less than 40 microns, but the pump down time was long, approximately 34 minutes.

The modified 3-way valve system performed the best of any systems tested. It had the lowest standard deviation as well as the quickest pump down time. The 3-way systems were easier for the operator to handle than the bellows valve systems since there were fewer valves to open and close. The 10 station EFS system was designed and built based on the modified 3-way valves. A schematic of the system is shown in Figure 10 and a photo of the console in Figure 11.

The table below summarizes the test results for the various systems examined.

TABLE 12. COMPARISON OF EFS TECHNIQUES

System	Ave. Size of Fill (Grams)	Standrd Deviation (Grams)	Average Vacuum (Microns)	Average Pump Down Time (Minutes)
Stock 3-way	1.6723	0.0358	74	4
Modified – 3-way	1.6313	0.0236	26	4
Bellows – Arrow Away	4.2666	0.3359	22	15
Bellows – Arrow Towards	1.1987	0.0569	34	34

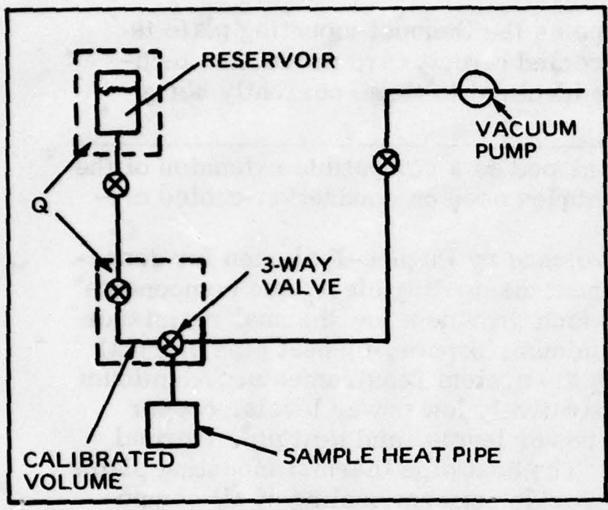

Figure 8. 3-Way Ball Valve System. This system, without modification, was unsatisfactory.

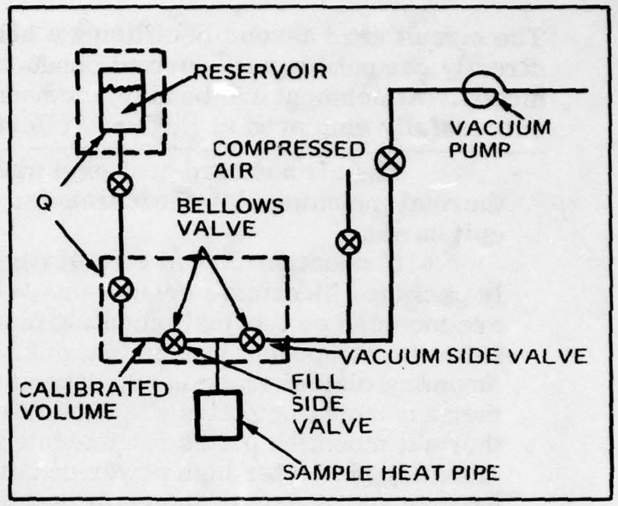

Figure 9. Bellows Valve System. This system exhibited extremely long down times.

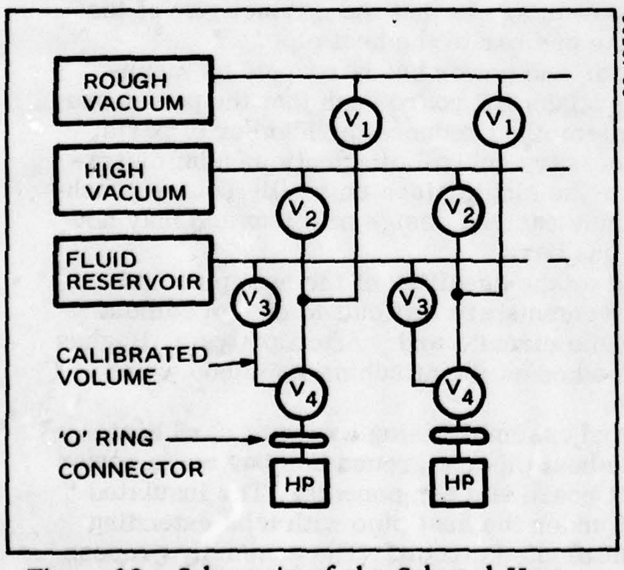

Figure 10. Schematic of the Selected Heat Pipe Fill Station (Using Modified 3-Way Valve System). Only 2 of the 10 parallel positions are shown.

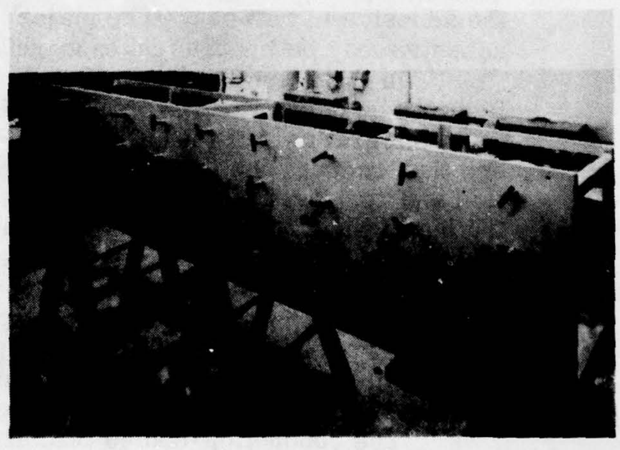

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Figure 11. Fill Station Console. From here the operator can evacuate, fill and seal.

11. CONSIDERATIONS FOR ATTACHING HEAT PIPE TO CIRCUIT CARD

The circuit card assembly utilizing a heat pipe as the thermal mounting plate is directly compatible with current conduction-cooled circuit card production techniques. Attachment and bonding methods are identical to those currently being successfully employed at Hughes-Fullerton.

The circuit card heat pipe was developed as a compatible extension of the thermal mounting plate heat transfer techniques used on conduction-cooled circuit cards.

Conduction-cooled circuit cards are used by Hughes-Fullerton for densely packaged electronic components. The heat dissipating electronic components are mounted on thermal mounting plates which provide a low thermal resistance from the component to the heat sink. Aluminum, copper, or heat pipe thermal mounting plates can be used, depending on the system requirements. Aluminum thermal mounting plates are used at comparatively low power levels, copper thermal mounting plates for intermediate power levels, and heat pipe thermal mounting plates for high power densities. The heat pipe thermal mounting plates have an additional advantage in that they provide uniform cooling of all components regardless of relative location on the thermal mounting plate.

As part of this project, two circuit card bonding methods were studied. In alternative 1, the circuit card is bonded to the ground bus bar by using a cold processed high conductive adhesive. Advantages of this method are: 1) the processing labor cost is substantially less; and 2) the soldering process is time consuming and requires special processing equipment whereas the adhesive requires only stamping out the adhesive and pressing the two parts together with the adhesive in between. The major disadvantage is that the conductivity of the adhesive may be insufficient to ground the bus bar to the heat pipe.

In the second method, the insulator and power bus bar would be manufactured by using a one-sided epoxy-fiberglass PC board such that the power bus is an integral part of the PC board. This method reduces the number of parts, and thus reduces the labor cost, and necessary control, inspection, administration and registration of parts. However, the single piece unit will require punching out of the center open areas. This may cause a design problem and may not be feasible for a complex design power bus bar.

Improvement alternatives depend on the specifics of the heat pipe and ground or power bus bar design. Improvements are difficult to design without the exact specifications of the heat pipe and circuit card. After analysis, Hughes selected the proven conduction-cooled method as the attachment method which will best service most heat pipe designs.

The conduction-cooled circuit card assembly using a circuit card heat pipe (see facing Figure 12), includes the heat pipe, a ground bus bar and a power bus bar in addition to the printed circuit board and components. The insulated ground and power bus bars are mounted under the heat pipe with tabs extending beyond the heat pipe for connection to the printed circuit. The assembly process for the conduction-cooled circuit card utilizing a heat pipe is as follows:

1. The ground bus bar (4 mil copper with 0.1 mil tin plate) is soldered to the heat pipe.
2. The power bus bar (4 mil copper with 0.1 mil tin plate) is bonded to the heat pipe with a Fiberglass-Epoxy insulator that also acts as the adhesive.

3. The heat pipe assembly is bonded to the printed circuit board by a Nomex-Acrylic adhesive that also acts as an insulator between the power bus bar and the printed circuit.
4. The electronic components are bonded to the heat pipe for heat sinking and mechanical strength. Flatpacks, dual in-line packs, or other component packages that have flat mounting surfaces are bonded to the heat pipe utilizing a filled epoxy film adhesive. Resistors are bonded to the thermal heat pipe with a high viscosity filled epoxy adhesive. Transistors in TO-5 or TO-18 cases are bonded to the heat pipe with an anerobic cyanoacrylate adhesive. After bonding the components to the heat pipe, the component leads are soldered to the printed circuit.

The conduction-cooled circuit card assembly may also be made without bus bars, in which case the heat pipe would be bonded directly to the printed wiring board using an insulating adhesive.

Alignment is accomplished using locating pins and the rivets used to attach the connector to the circuit card assembly.

The configuration of the circuit card heat pipe is not limited to the simplified geometry discussed herein, but can be tailored to accommodate various circuit card layouts. Hughes has assembled thousands of heat-sink circuit boards in the past years by utilizing the above described technique. This technique is cost effective, and it readily lends itself to single or multiple heat pipe circuit card assembly.

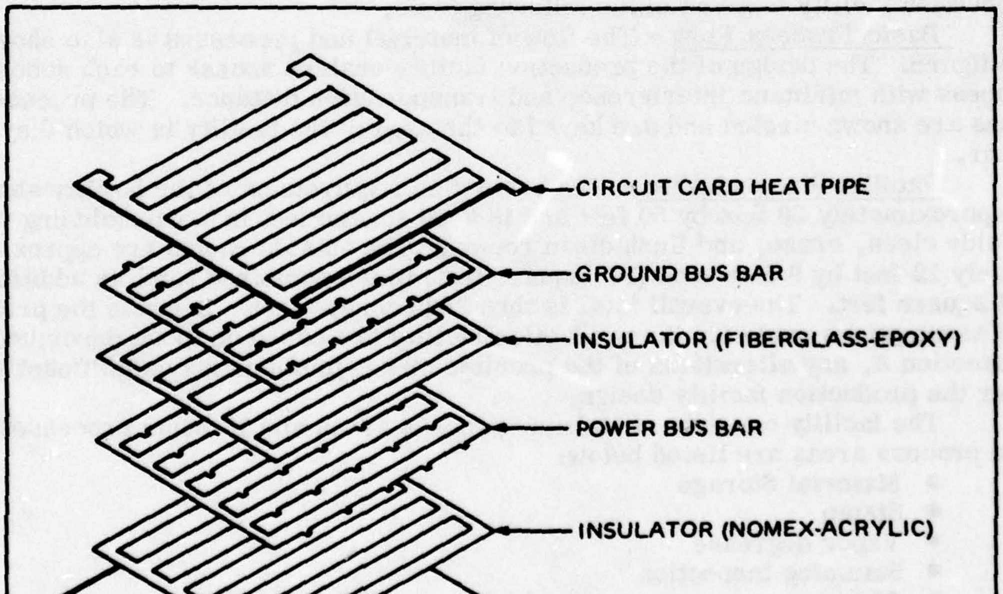

Figure 12. Elements of the Selected Conduction-Cooled Circuit Card Assembly. The circuit card heat pipe is one of six elements making up the circuit card assembly.

1. OVERVIEW OF THE HEAT PIPE PRODUCTION FACILITY

The Hughes designed heat pipe production facility can evacuate, fill and seal heat pipes at the rate of 50 per hour and can produce 4000 heat pipes per week, thus fully meeting the design requirements.

The heat pipe production system described in this Subsection is based on the materials and methods analyzed and selected in Subsection A. A production facility capable of performing all the necessary operations is shown in Figure 13. This facility represents a practical layout with the intent of showing the flow of material, area requirements, and labor force to produce heat pipes with the full scale production. The system shown has a capacity of producing 4000 heat pipes per week. The system shown is not the only layout possible and is only intended to depict a feasible system.

The manufacturing processes and methodology is based on mass production techniques. The basic goal of the system is to Evacuate, Fill, and Seal (EFS process) the heat pipe (integrated 10 bar design) at a rate of 50 heat pipes per hour. The alternate design concept was to produce individual heat pipe bars and to perform the EFS operation at a rate of 500 individual bars per hour. The final design concept is the integrated heat pipe which contains all 10 bars as one construction. Thus, the EFS process production rate required is 50/hr. since all 10 bars can be evacuated and filled at one time.

An overview of the actual process steps in relation to their location in the production facility is given in the following topic.

Basic Process Flow — The flow of material and processes is also shown in the figure. The design of the production facility enables access to each successive process with minimum interference and transportation distance. The process steps are shown circled and are keyed to the area of the facility in which they occur.

Facility Size and Area — The basic size requirement of the facility shown is approximately 50 feet by 50 feet and is 2500 square feet in area excluding the outside clean, braze, and flush clean rooms. The outside rooms are approximately 12 feet by 9 feet each (108 square feet) which combined total an additional 324 square feet. The overall total is then 2824 square feet. Because the premise and assumptions made for the production facility are based on those described in Subsection A, any alterations of the premise or assumptions may significantly alter the production facility design.

The facility consists of 13 basic process areas and 16 basic processes. The process areas are listed below:

- Material Storage
- Stamp
- Vapor degrease
- Stamping Inspection
- Clean
- Tack Weld
- Braze Prep
- Braze
- Braze Inspection
- Leak Test, Performance Test, EFS
- Flush Clean
- Final Inspection
- Packaging

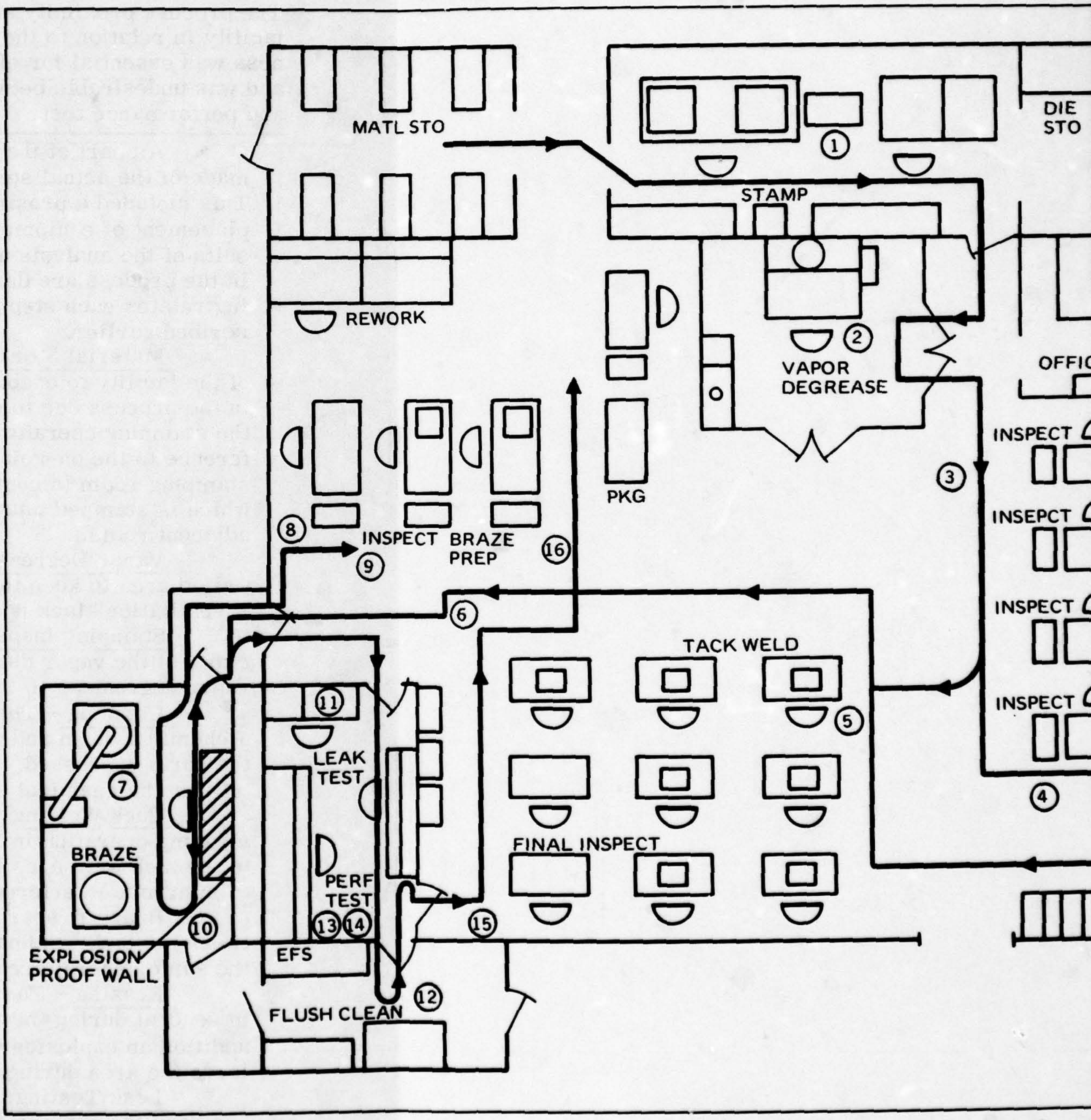

Figure 13. Heat Pipe Production Facility, B
is designed to manufacture 4000 heat pipes

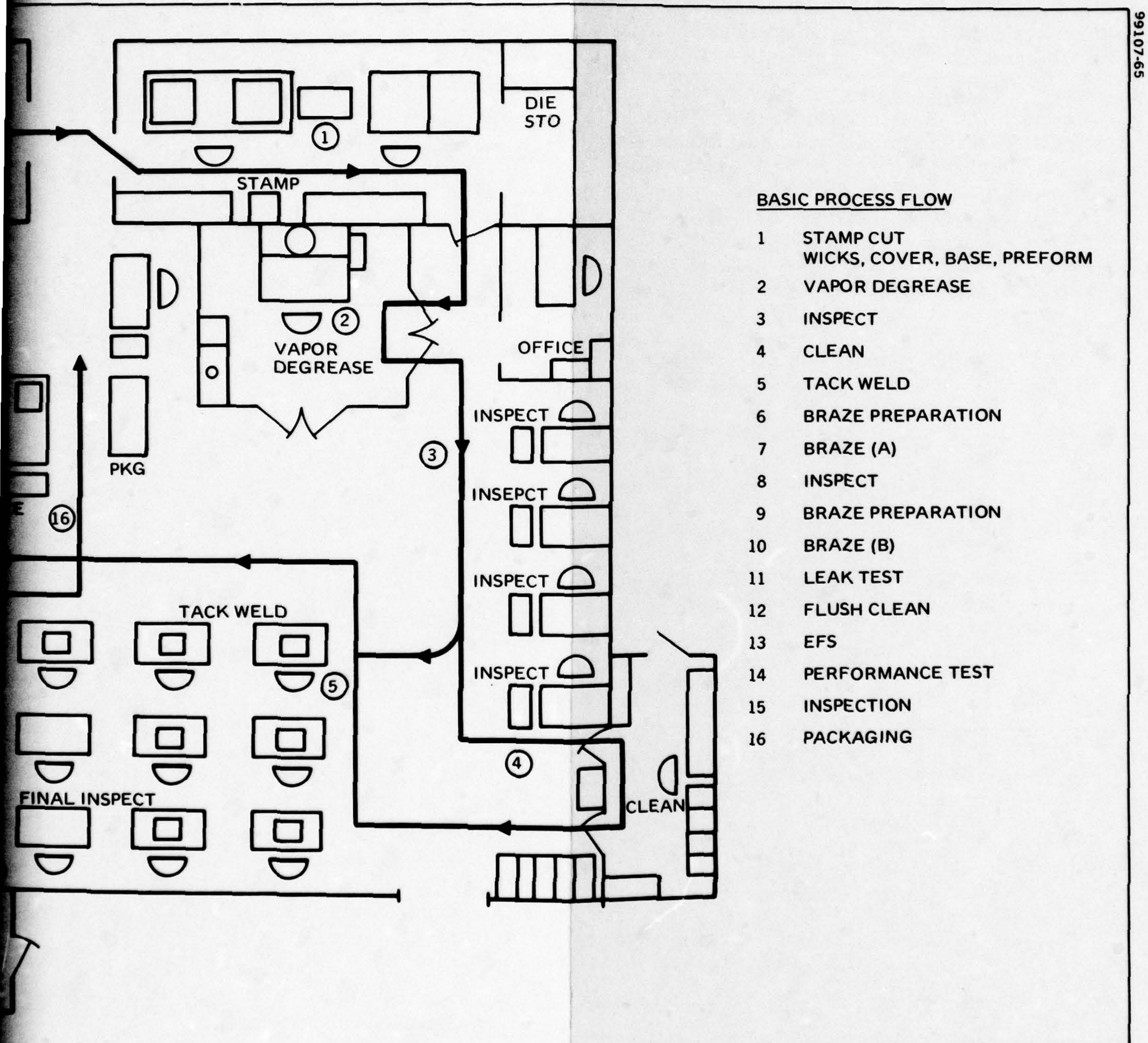

Figure 13. Heat Pipe Production Facility, Basic Process Flow (Relative Size 50' x 50'). This facility is designed to manufacture 4000 heat pipes per week.

2. OVERVIEW OF STEPS IN THE PRODUCTION PROCESS

The process proximity analysis was a driving factor in the design of the production facility in relation to the production steps. The analysis clearly showed that closeness was essential for efficient production of the stamping and vapor degrease steps, and was undesirable between the braze, and closely related leak test, EFS operation and performance test.

As part of the production facility analysis and design, an analysis was made of the actual steps to be accomplished in the manufacture of the heat pipes. This included a proximity analysis to determine the critical and non-critical placement of equipment for the most efficient accomplishment of each step. Results of the analysis are given in Figure 14 on the facing page. The actual steps in the process are described in more detail in Appendix C. The discussion following relates each step to its position in the Hughes-designed production facility described earlier.

Material Storage and Stamping – The material storage room is in a corner of the facility to enable re-supply of material with no interference to the workers in the process due to delivery of material. The material is easily accessed by the stamping operators directly across from the stamping operation with no interference to the on-going processes. The die storage room is in the vicinity of the stamping room to control and have easy access to the dies. Since all the material which is stamped must be vapor degreased, the vapor degreaser is located in the adjacent room.

Vapor Degrease – The vapor degrease operation is contained within a walled area to keep the vapor process away from the workers in the process room. A ventilation stack is needed for the vapor degreaser.

Stamping Inspection – The stamping inspection area is located in the vacinity of the vapor degreaser in order to reduce the transportation distance from vapor degreasing to inspection.

Cleaning – The next operation is the cleaning operation which consists of a chemical clean and an ultrasonic clean operation to remove oil and debris from the parts processed. The clean operation is located outside the main facility room to keep the chemical solutions and fumes away from the main process room.

Tack Welding – The welding operation is located directly adjacent to the cleaning operation in the main process room. The distance from the clean area to the tack weld area has been shortened to reduce the transportation of product to minimize interference with other process traffic.

Braze Preparation – The braze preparation area is located directly between the tack welding and the brazing operation, and the braze inspection is in the same general area as the braze prep area for convenience.

Brazing – The brazing process in general should not be close to workers in general during the firing process due to the nature of the braze process. In addition an explosion proof wall is shown for added protection. Workers must leave the area during the braze cycle except for loading and unloading.

Leak Testing, EFS and Performance Test – The leak testing, EFS process, and the performance test processes are located within the same room and are isolated from the other general processes in order to provide a more controlled and quiet atmosphere to conduct these operations and to eliminate general cross traffic of other operations.

Flush Clean – The flush clean operation is located directly outside of the EFS process room and in a separate room to keep chemical solutions and fumes away from the other processes areas.

Final Inspection – The final inspection area is located directly adjacent to the EFS process room since this is the next operation required and to reduce the transportation distance to the next operation.

Packaging – The packaging area is located directly adjacent to the final inspection area and near one of the main exits to the facility to enable easy flow of traffic from packaging to the next operation which may be card assembly. The heat pipes may also be packaged and stored for future use.

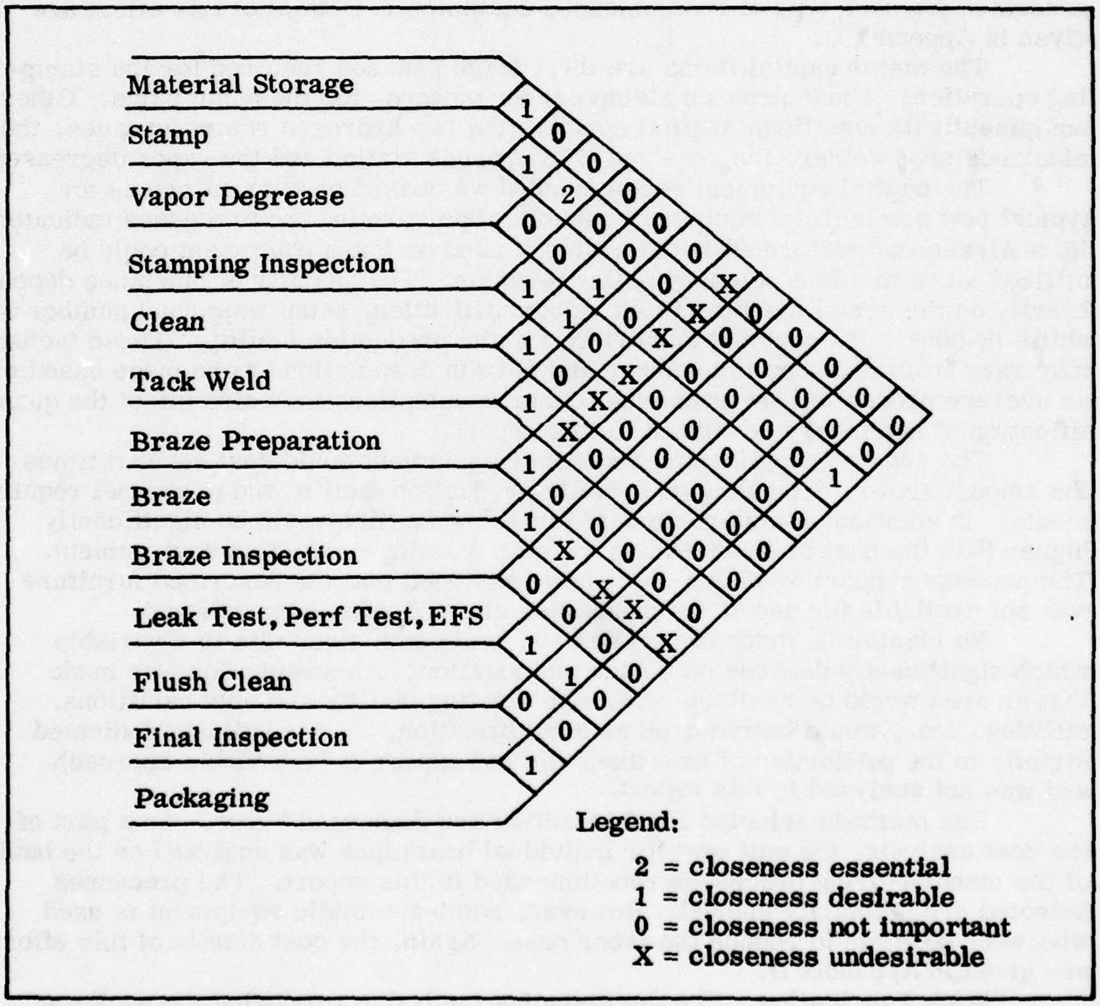

Figure 14. Process Proximity Analysis. The analysis shows the relative location requirements for a production environment.

3. COST ANALYSIS OF THE PRODUCTION SYSTEM

Die stamping (using a punch press) was selected as the wick fabrication method; stamp forming was selected as the shell fabrication method; and punch press stamping was selected as the braze preform method.

A major task of the project was to establish and demonstrate a pilot production line and to conduct a cost analysis of the resulting production system. To accomplish this, an analysis was made concerning the type of capital equipment required to establish such a facility. The facing figure shows the recommended equipment and its location in the facility. Additionally, cost figures were generated for each type of recommended equipment. Details of this effort are given in Appendix D.

The major capital items are the 2 large presses required for the stamping operation. These presses stamp out the patterns for the basic parts. Other equipment with significant capital cost are the two hydrogen retort furnaces, the electrode spot welder, the required EFS process station and the vapor degreaser.

The capital equipment recommended was based on current prices for typical new commercial equipment capable of performing the processes indicated. No analysis was performed to determine if used or lease equipment could be utilized since this is a company policy decision. The quantity of machines depends heavily on the actual machine rates, labor utilization, setup time, and number of shifts (8-hour work periods) authorized for the production facility. These factors may vary from one shop to another, and certain assumptions were made based on an average production environment. Other assumptions may also affect the quantification of machinery described in this report.

The support supplies and accessory equipment could cost several times the amount shown, depending on specific production facility and personnel requirements. In addition, the start-up cost for a new facility would be significantly higher than the cost of an add-on room to an existing production environment. The process support furniture cost shown assumed that the described furniture was not available for use at the production site and must be purchased.

No mention is made of building and land costs since this is a variable which significantly depends on design and location. An assumption was made that an area would be available within an existing facility and only partitions, utilities, etc., would be required as a modification. A new building dedicated strictly to the production of heat pipes did not appear to be a viable approach and was not analyzed in this report.

The methods selected for fabrication are discussed below. As a part of the cost analysis, the unit cost for individual heat pipes was analyzed on the basis of the manufacturing processes recommended in this report. The processes selected are primarily manual. However, semi-automatic equipment is used wherever possible to reduce the labor cost. Again, the cost details of this effort are given in Appendix D.

Wick Fabrication – The die stamping method of producing the wick was determined to be the most dimensionally repeatable, accurate, and low-cost technique. Alternative methods such as laser cutting were considered, but these were rejected due to the high capital cost and low speed of production. Testing of this operation was performed, and stamped wicks were used in the pilot production.

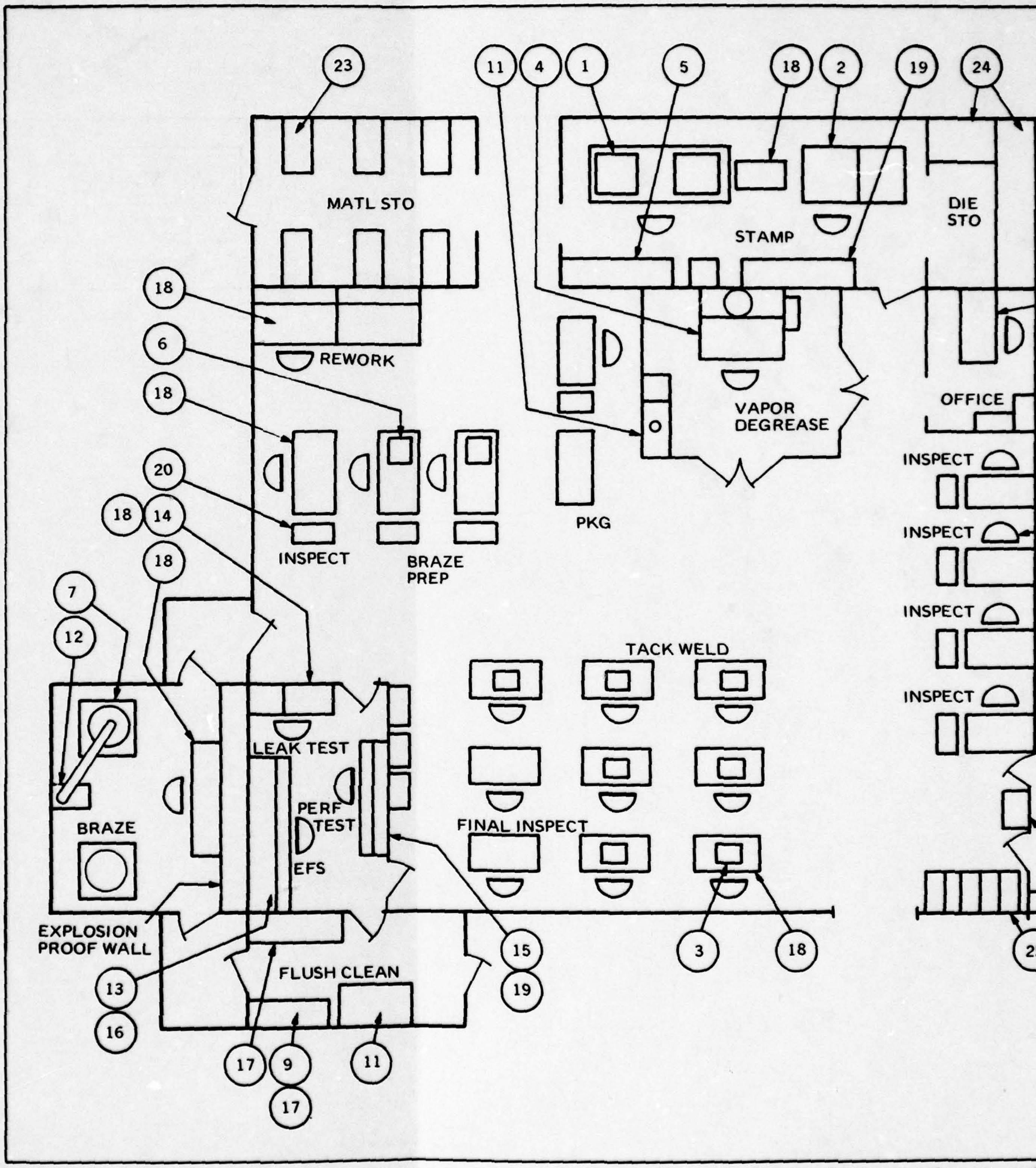

Figure 15. Heat Pipe Production Facility, Capital
Semiautomatic equipment is recommended where

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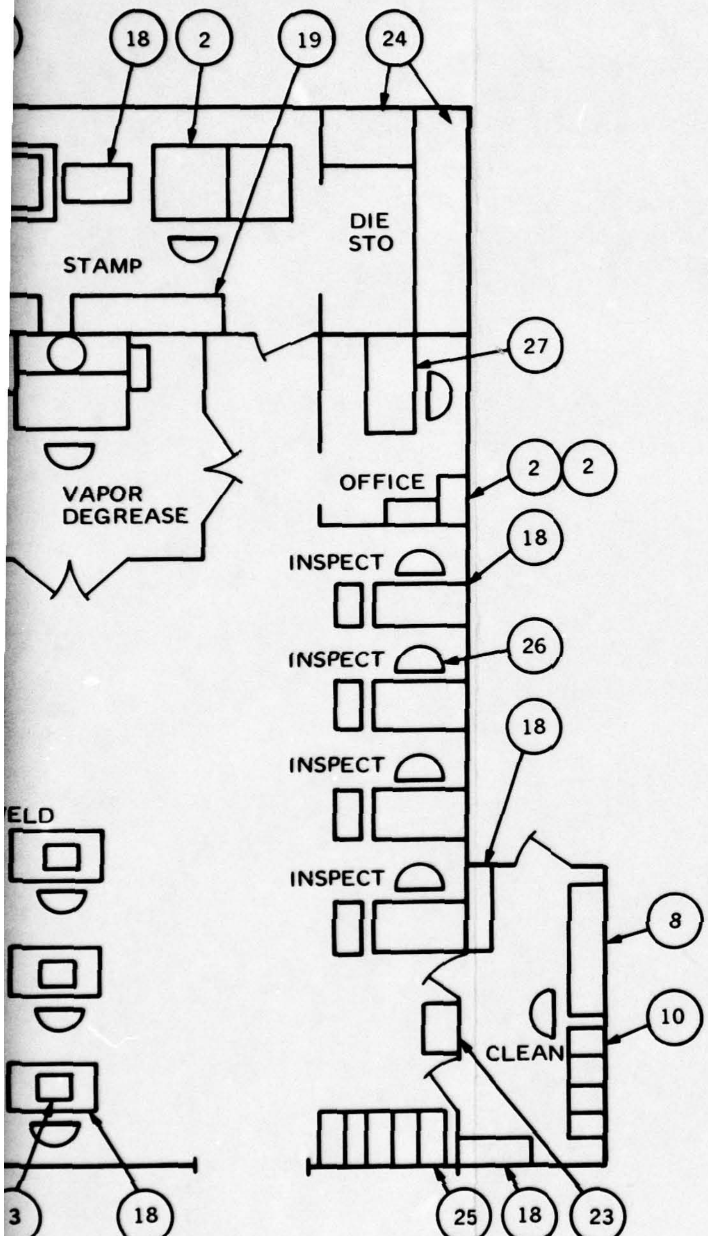

CAPITAL EQUIPMENT

ITEM	DESCRIPTION
1	SMALL PRESS
2	LARGE PRESS
3	SPOT WELDERS, SMALL
4	VAPOR DEGREASER
5	SHEAR PRESS
6	SPOT WELDER, LARGE
7	HYD RETORT FURNACE
8	CLEAN & SCRUB PROCESS
9	FLUSH PROCESS
10	CHEMICAL CLEAN PROCESS
11	OVEN, CONVERSION
12	CRANE, 2 1/2 T
13	EFS PROCESS
14	LEAK TESTER
15	PYROMETER TESTER
16	PELLET WELDER
17	ROUGHING PUMP

SUPPORT FURNITURE

ITEM	DESCRIPTION
18	WORK BENCH 5' x 2 1/2'
19	WORK BENCH 8' x 2 1/2'
20	CARTS 2' x 3'
21	INSPECTION LAMPS, 3X MAG
22	PACKAGE SEALER
23	CABINETS
24	RACKS
25	FILES
26	CHAIRS
27	DESK

Heat Pipe Production Facility, Capital & Support Equipment Location (Relative Size 50' x 50').
atic equipment is recommended where possible to reduce labor, and hence overall system cost.

Shell Fabrication – Several alternatives were considered for producing the shape and cavities of the shell. The N/C tape milling process was used to manufacture the test specimens and the process was found to be reliable and accurate. The cost of the operation, however, was sufficient to warrant further investigation of other mass production techniques. Conventional machining was ruled out due to the high cost of labor. Chemical milling was eliminated because it is expensive and slow. A stamp forming technique was determined to be the most viable for this operation. The stamp forming operations produce both the shape and the cavity for the wicks and fluid. The first operation is to cut out the shape of the heat pipe. This process was used for the heat pipe bases and covers used on the pilot production. The second operation is stamping out the cavities. The process was not tested. Similar parts for other components in industry, however, are fabricated in this manner with reliability and accuracy.

Braze Preform Fabrication – The braze preform fabrication method selected as the most viable was the stamping operation. A punch press is used for this operation and is considered to be the most cost-effective method to provide a dimensionally repeatable and accurate shape. A shear press may be used as an alternate approach. This method is considered to be more time consuming, however, and not nearly as repeatable as the stamp-out.

Other factors entering into the decision of the selection for the fabrication processes are summarized in the accompanying table.

TABLE 13. SELECTION OF FABRICATION PROCESSES

Material Study	Reason for Study
• Hardness	(1) Influences choice of process and type of equipment to be used
	(2) Tool life
• Machinability	(1) Producibility by machining
• Formability	(1) Producibility by stamping methods
• Strength	(1) Ability to withstand fabrication processes
	(2) Ability to withstand handling
	(3) Ability to withstand card assembly processes

4. DESIGN OF A TEST STATION FOR HEAT PIPE PERFORMANCE VERIFICATION

Following fabrication and filling, each heat pipe will be thermally tested to ensure acceptable operating performance, with only those units which pass certain test criteria continuing on through the manufacturing process. From a cost effectiveness standpoint, this is the preferable point in the cycle to uncover operation flaws.

A test pattern for circuit card performance evaluation under operating conditions has been designed. The primary design objectives were: quick heat pipe installation, testing, and removal; minimum heat loss; balanced heat loading and removal; and detection sensitivity. The analysis effort showed that the test station should be set up in the production facility to allow tests following the fabrication and fill operations.

The test station to be used for this operation is shown opposite (both in an exploded format (Figure 16) and an operating mode (Figure 17)). The test station is composed of two aluminum, water-cooled heat sinks and supports mounted on an aluminum plate for stability. Water cooling is accomplished with a one-pass, 1/4-inch channel through the full length of the sink. The capacity of the unit is such that 0.5 gpm of water is sufficient for operation, resulting in a less than 0.5°C water temperature gain. The proximity of the channels is within 1/2-inch of the heat pipe condensers.

The heat sinks are the control item in that everything else interfaces on their surfaces. The heat pipe sits on a recessed surface that has been accurately machined to achieve a flat base for maximized heat transfer. Further, the surface contains locator pins to assure accurate positioning and test repeatability. The undersurface of this protrusion grips the spring plate (by means of 3 screws) and is forced flat for even load distribution by a 1/4-inch thick aluminum retention bar. Additionally, a number of matched shims are used to vary the resistor load, ranging in thickness from 0.005 inch to 0.057 inch. These are fabricated from brass and mild steel. It is evident that the spring plate is unusual in configuration. This design was precipitated by the following factors: incompatibility between the size of the smallest commercially available, high quality wire-wound resistors, and the narrow bars and tight bar spacing requirements of the heat pipe; need for independently sprung heat sources; need for a readily deformable structure; and desire to have a single structure to maximize durability. Functionally, this item operates as a tension spring rather than the more conventional torsion or bending types and is very similar to a number of parallel cables. It is fabricated from beryllium copper and metallurgically age-hardened to a 1/4 HT condition to improve yield strength.

Ten Dale Model RH-5 50 (± 3%)-ohm wire-wound resistors (rated at 7 1/2 watts each) are mounted with screws to the center of the spring plate. To restrict heat transfer to the highly conductive spring structure, 0.036-inch glass cloth epoxy spacers are positioned between them. The resistors are wired in parallel with thin multiple-strand teflon-coated wire having generous bends to minimize the restraint effects between springs. Using a regulated DC power supply, 2.4 amps at 12.5 volts is required to attain 3 watts per resistor or 30 watts total.

Since the quality of interboundary heat transfer is a function of loading, among other things, the spring plate functions to press the resistor upper face into the center of the heat pipe bar. This reduces the contact resistance. The load can be varied by changing the amount of interference between the heat pipe and the static height of the resistors with the heat pipe removed. Of course, the heat pipe must be held down to overcome the spring load in order to contact the condenser surfaces. This is accomplished with the load plate and anchor-cam fasteners. The load plate is mild 1/8-inch thick steel with a rubber pad that contacts the upper surface of the condenser and applies the load. The three anchor-cams on each side supply the necessary load by means of an internal spring mechanism, and also allow for quick heat pipe removal by a 1/4-turn fingertip rotation. The support dimensions allow approximately 1/4 of the anchor-cam load to bear directly on the heat pipe condenser, or about 45 lbs per condenser.

79-01-322

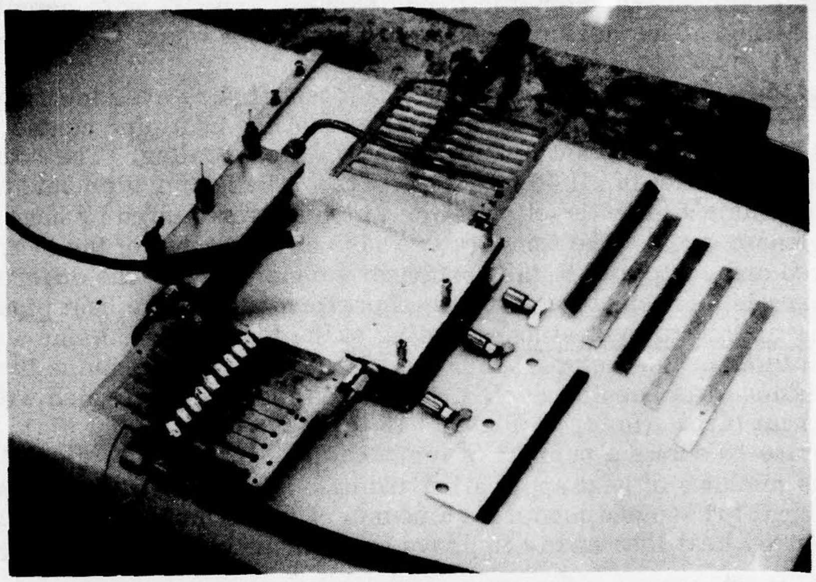

Figure 16. Exploded View of Heat Pipe Test Station. Two aluminum, water-cooled heat sinks and supports are mounted on an aluminum plate for stability.

79-01-319

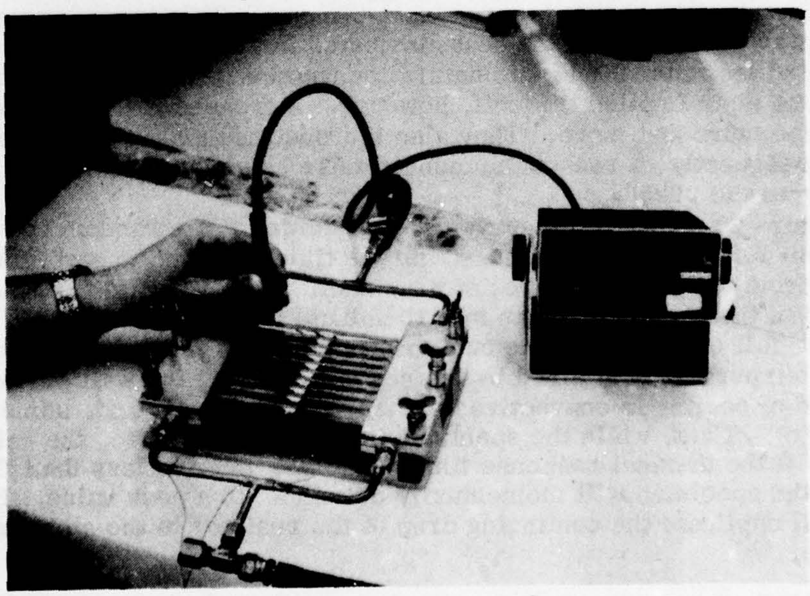

Figure 17. Test Station in Operation with Support Equipment. Less than a 0.5°C water temperature gain results when in operation at above 0.2 GPM.

5. USE OF THE TEST STATION IN MEASURING HEAT PIPE PERFORMANCE

A thermocouple method of temperature measurement was selected as the performance test process because it features a response time of 2 seconds and a temperature readout accuracy of 0.1°C.

An Omega Engineering surface temperature probe (Model 68007E) and a Doric digital readout thermometer (Model 400-A, Type T) were actually used for heat pipe testing. The thermocouple used in the tests was a Chromel-Constantan, Type E.

Method – The heat pipe is placed on a test fixture over locating pins and held down with cam fasteners. The condenser of the heat pipe contacts the heat sink which is held at constant temperature by water-cooling. The heater elements contact the underside of all 10 heat pipe bars. The heater elements are energized and produce a given level of power which is transferred by heat pipe action to the condenser area. The temperature rise of the center of the heat pipe bars is measured and compared to the condenser temperature. The difference of these temperatures is an indication of thermal performance of the heat pipe.

Characterization Testing – Testing of the test station, using a standard 0.062-inch thick brass thermal mounting plate (TMP) to determine the operating characteristics, has been conducted. Some testing was performed with a production MMT heat pipe. (Refer to Figures 18 through 20.)

Figure 18 shows a number of temperature drop curves, along the bars, for various methods of heat application and data spread. These data justified the use of thermal grease and moderate amounts of insulation. Both were used to minimize stray heat loss and to improve the balance of heat loading between heat pipe bars.

Figure 19 demonstrates the effect of resistor-to-heat pipe loading on the temperatures observed on the heat pipe. The bar center temperature curve shows that as shim is removed (i.e., the resistor loads increase), the temperature on the heat pipe directly above the resistor increases. This is analogous to stating that a greater percentage of the heat dissipated in the resistor is passing into the heat pipe and less in being lost to natural convection. This, of course, is desirable. There is an implied tradeoff, however. Increased loadings tend to deform the heat pipe more and more. They also increase the risk of damaging the spring plate. Consequently, a reasonable compromise has been selected, having a total shim thickness of .025".

Figure 20 shows three curves, representing three random condenser locations on a TMP. These demonstrate the time required to stabilize a test specimen from the moment of resistor contact. They indicate that a temperature within 1°C of the peak value seen in a 10-minute period is achieved in 1 to 3 minutes. The "fall off" that 2 of the curves experience is most probably due to the very high temperatures attained by the resistors during the wait period (when the only means of cooling is convective heat transfer to the air and, some, into the spring plate). Thus, while the specimen is rising to stabilize, the resistors are dropping. If the thermal response time of the specimen is less than that of the resistor, the specimen will momentarily overshoot to a peak value. Following this, it will duplicate the continuing drop of the resistor to the stabilization point of the latter.

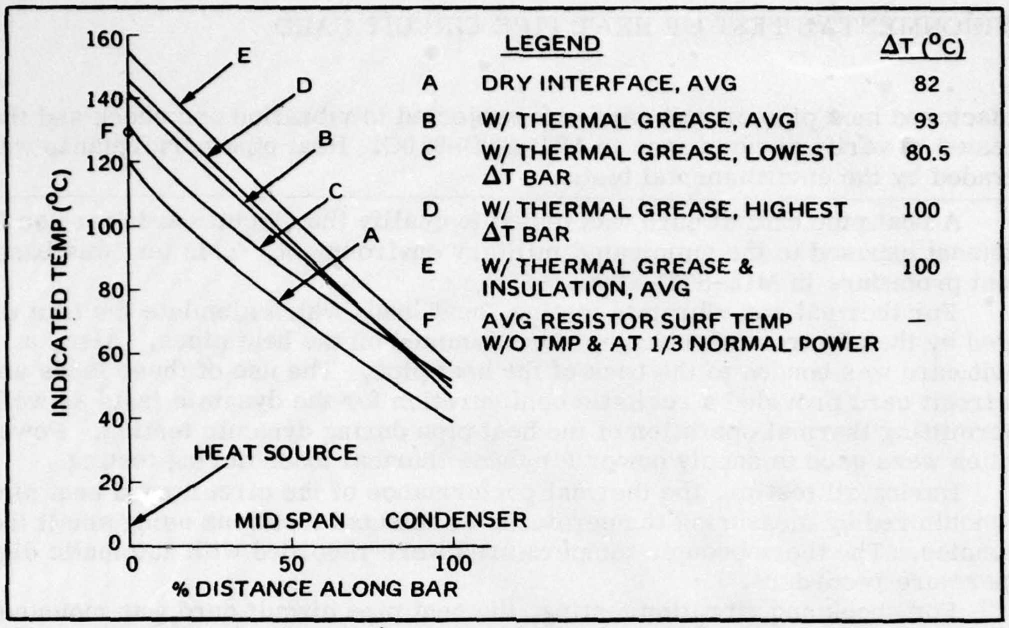

Figure 18. Heat Loading Performance of Test Station Using Metal TMP. Based on these data, thermal grease and moderate amounts of insulation were used in minimizing heat loss and improving the heat loading balance.

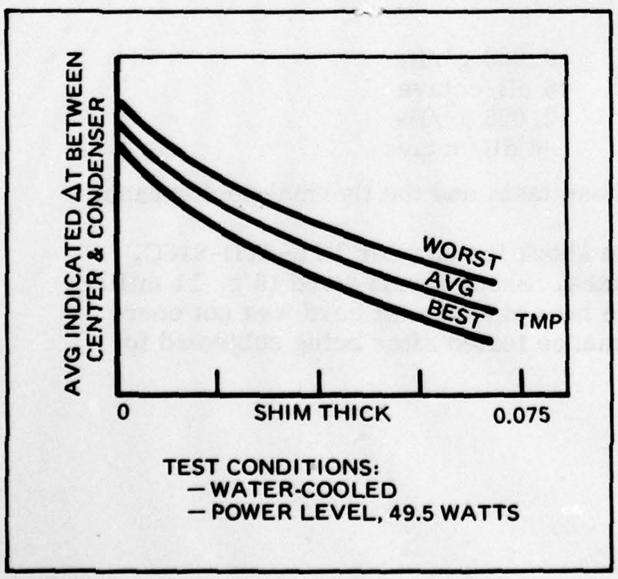

Figure 19. Heat Source Contact Resistance Performance. As shim is removed, the heat pipe temperature directly above the resistor increases.

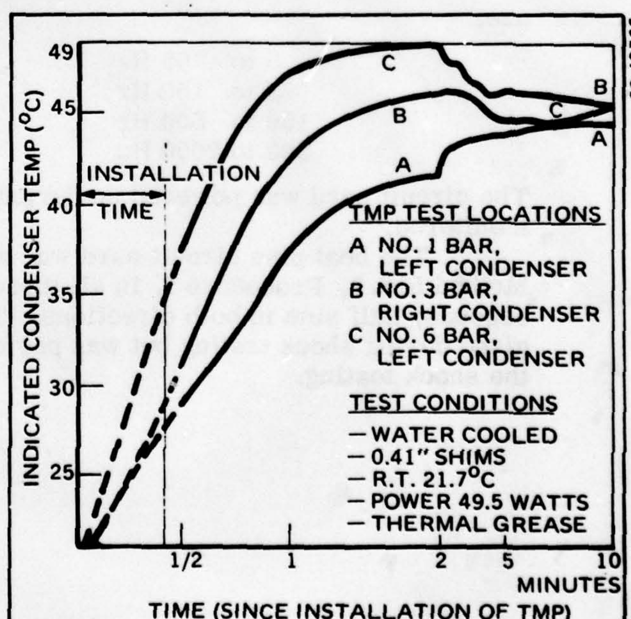

Figure 20. Test Stabilization Time. Temperature within 1°C of peak value is achieved in 1 to 3 minutes.

6. ENVIRONMENTAL TEST OF HEAT PIPE CIRCUIT CARD

A manufactured heat pipe circuit card was subjected to vibration and shock and thermally tested to verify performance in MIL-STD-810C. Heat pipe performance was not degraded by the environmental tests.

A heat pipe circuit card was tested to qualify the circuit cards for use in equipment exposed to the anticipated military environment. This test was based on test procedure in MIL-STD-810C.

For thermal and vibration testing, heat loads which simulate the heat dissipated by the electronics packages were mounted on the heat pipes. Also, a circuit card was bonded to the back of the heat pipe. The use of these loads and the circuit card provided a realistic configuration for the dynamic tests as well as permitting thermal operation of the heat pipe during dynamic testing. Power supplies were used to supply power for these thermal loads during testing.

During all testing, the thermal performance of the circuit card heat pipes was monitored by measuring temperatures at selected locations using small thermocouples. The thermocouple temperatures were recorded with automatic digital temperature recorders.

For shock and vibration testing, the heat pipe circuit card was mounted in a fixture which will simulate the actual mounting of a circuit card in an electronic equipment cabinet. Accelerometers used were mounted in appropriate places on the heat pipe circuit card and fixture. The circuit card heat pipe was subjected to random vibration in three mutually perpendicular axes per MIL-STD-810C, Method 514.2, Vibration, Procedure 1A. Results are depicted in Figure 21.

The anticipated power spectral density tolerances of applied vibration are:

5 to 65 Hz	0.005 g^2/Hz
65 to 150 Hz	6 dB/octave
150 to 500 Hz	0.025 g^2/Hz
500 to 2000 Hz	-6 dB/octave

The circuit card was powered up during these tests and the thermal performance monitored.

The heat pipe circuit card was also shock tested, per MIL-STD-810C, Method 516.2, Procedure I, in all three axes. Shock levels were 15 g, 11 milliseconds, half sine in both directions. The heat pipe circuit card was not energized during shock testing but was performance tested after being subjected to the shock testing.

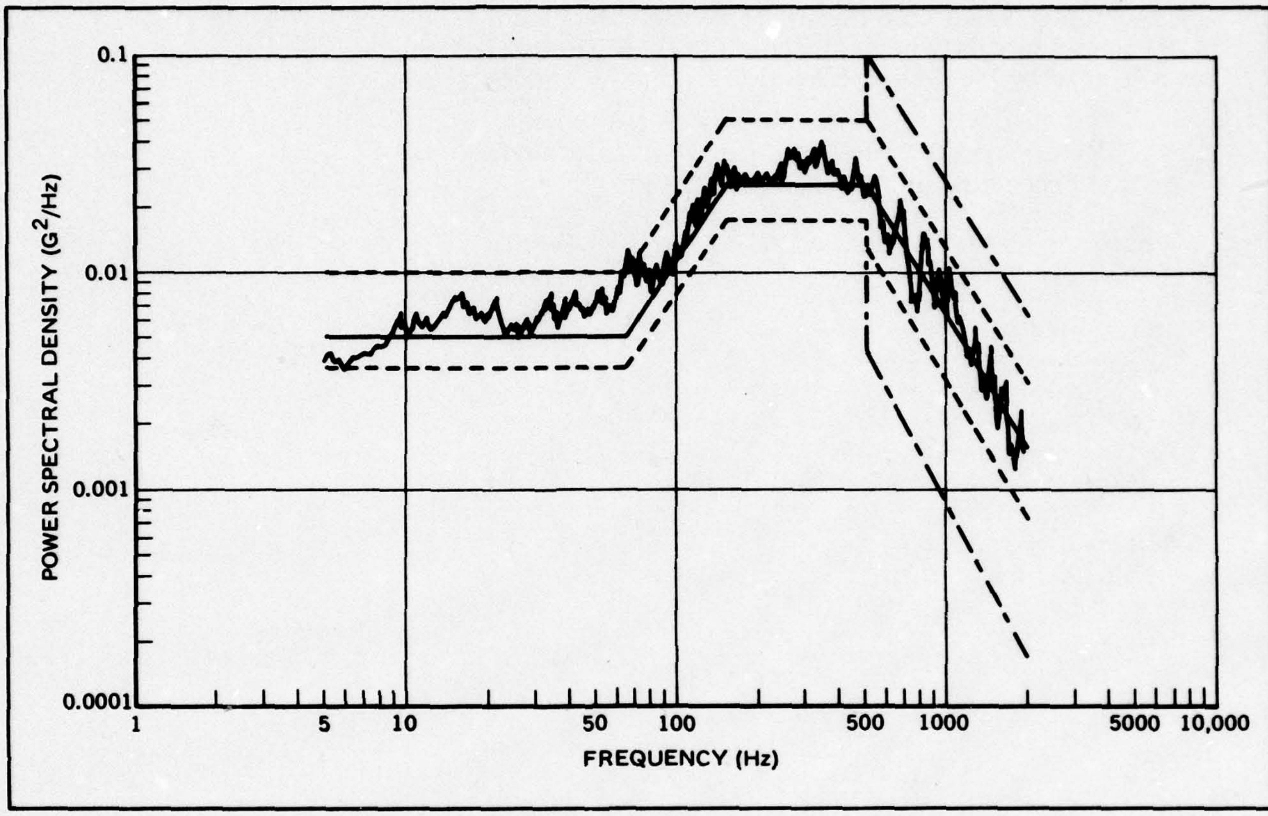

Figure 21. Power Spectral Density (G^2/Hz) vs Frequency (Hz) of Control Accelerometer During Test. No structural or functional damage was noted.

SECTION 3
CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions Regarding Heat Pipe Performance 60
2. Recommendations for Future Effort. 62

1. CONCLUSIONS REGARDING HEAT PIPE PERFORMANCE

This study demonstrated that reliable, cost effective heat pipes for circuit cards can be fabricated on a production basis.

A number of significant conclusions can be drawn from the study. These are listed opposite and discussed in more detail in the following paragraphs.

The integrated heat pipe concept gives better performance than a number of individual heat pipes attached to metallic headers. The additional thermal interfaces required by the individual heat pipes and high power density at the interfaces result in higher temperature gradients in the individual heat pipe modules. Although increasing the interface areas will lower the power density and temperature gradients, unacceptably large modules will be required to give adequate performance.

Brazed evaporater/condenser wicks will improve the uniformity and reliability of heat transfer in the heat pipe. The brazed-to-the-heat-pipe-wall wicks assure uniform high heat transfer rate from the wall to the wick fluid matrix by preventing formation of a gap between the wick and wall. This gap would be filled by the heat pipe fluid which has a much lower thermal conductivity than the wick, resulting in a low heat transfer rate in the areas where a gap has formed between the wick and the wall.

Brazing evaporator/condenser wicks to the heat pipe walls can be accomplished with sintered metal fiber wicks. Furnace brazing heat pipe wicks to the walls requires wicks with high porosity and careful control of the brazing parameters, i.e., braze alloy, alloy foil thickness, fixturing, braze temperature and time cycle. Conventional mesh wicks could not be brazed without filling the pores with braze alloy but the sintered metal fiber wicks with high porosity were successfully brazed without filling of the pores.

The most cost effective method for sealing the heat pipe shells to the covers is furnace brazing which produces a heat pipe with superior mechanical strength. Brazing of the heat pipe shells gives much better mechanical strength than soldering and is less expensive than any welding technique. Furnace brazing of the heat pipe shells to the covers requires close control of the brazing parameters and special fixturing to assure sealing over the entire length of the joint between the shell and cover.

The most cost effective method of producing large numbers of heat pipe shells is stamping, but expensive class A dies are required to meet the tight dimensional tolerances. Tight dimensional tolerances are required to assure proper alignment of the shell walls with the cover to meet the requirements for a strong, uniform brazed joint. Although stamping the heat pipes out has by far the lowest unit cost, the cost of the very expensive dies must be amortized over the life of the dies. For smaller production quantities a combination of die cast shells and numerically controlled machining will be more cost effective. For small production quantities, total numerical controlled machining is most cost effective.

TABLE 14. STUDY CONCLUSIONS

1. **An integrated heat pipe will give better performances than individual heat pipes with headers.**
2. **Stamping is the cheapest method of producing heat pipe shells but expensive Class A dies are required to meet dimensional tolerance requirements.**
3. **Brazed evaporater/condenser wicks will improve heat transfer uniformity and reliability. Brazing of wicks without plugging is possible for some wicks such as sintered metal fibers.**
4. **Furnace brazing with special fixtures and preforms is the best method of producing a good shell bond.**
5. **Copper base alloys (brasses) have the best combination of properties for shell fabrication.**
6. **Cold pinch-off techniques are sufficient for annealled copper, provided mechanical protection is provided. Otherwise resistance welded closures are required.**
7. **Major cost item in the heat pipe is the sintered metal fiber wicks.**

2. RECOMMENDATIONS FOR FUTURE EFFORT

The proposed Heat Pipe production system is based on processes which enable immediate shop start up. To improve yield and lower unit cost, additional studies in the areas of special equipment and materials are recommended.

The various manual and semiautomatic sequences of the proposed Heat Pipe production system utilize off-the-shelf machinery. Although expedient for shop start up, they are not necessarily the processes with the highest output capacity. Several of the processes selected could be redesigned to reduce labor, increase output capacity, and decrease unit cost. This could be accomplished by the use of special equipment, and possibly by substituting different materials for those already selected. The trade-off considerations are, of course, the design development cost, and the cost of the special equipment. The areas for possible future effort are shown in Table 15.

Tack Welding – The proposed braze preform tack welder utilizes an off-the-shelf single heat and single tip (one point weld). In addition to being time consuming and costly, several operators are required to maintain the production rate and schedule with this type of equipment. Therefore, it is recommended that the feasibility of a multiple head welder be investigated. Such a welder, with multiple tips, could be designed to produce several welds or possibly all welds at one time. A fixture could be designed to place the preforms in place and hold them down while the special multiple head welder is activated. The labor savings realized would significantly reduce the unit cost of the heat pipe.

Wick Material – The largest contributor to the proposed Heat Pipe unit cost is the sintered stainless steel fiber wick. The braze material, when used with this wick performed well, with very little evidence of material seepage into the wick. However, Hughes feels that a stainless steel screen wick material may be found which could perform adequately and which would not be blocked by the braze material, and therefore recommends additional research along these lines. Such a screen wick would cost about 25 percent of the present sintered stainless steel wick. If a suitable screen material can be found, the unit cost of the proposed Heat Pipe (with the exception of the wick) would be approximately $21.51 as opposed to the current estimated cost of $47.51. This represents a potential cost reduction of approximately 55 percent.

Performance Testing – The thermal performance tester developed for the testing operation permits only one heat pipe to be tested at a time. Hughes recommends developing a special test table with a cooling and heating manifold with a multiple tester and readout system to test several heat pipes at one time. This would reduce labor cost and increase the output capacity of the operation.

Leak Testing – The leak tester selected is a standard commercial unit with no special attachments which can test only one heat pipe at a time. Hughes recommends developing a special vacuum tight container manifolded and valved to test several heat pipes at one time. This would reduce labor time for testing and increase the output capacity. The cost of this improvement is minimal.

Wick Fabrication – Present die cutting process for producing wicks wastes a large portion of the wick material. Utilization of strips of wick instead of the die cut configuration would decrease wick costs markedly although labor costs would be increased.

Inspections – Hughes recommends the automation of various operations to reduce the amount of inspections required, and to subsequently reduce the support labor cost. In particular, the automation of the tack and spot welding operations would contribute greatly to the reduction of inspections.

Plating – Although plating of the base and cover plates is not discussed as a process in this report, a testing and development program is recommended to determine if plating with copper or nickel will enhance the brazing and sealing performance. Copper plating may enhance the bonding of the wicks to the cover and baseplate, while nickel plating may enhance the brazing and wear properties of the heat pipe.

TABLE 15. AREAS OF RECOMMENDED FUTURE EFFORT

Area	Potential Benefit			
	Material Cost	Labor Cost	Performance Improvement	Output Capacity
Tack Welding		X		X
Wick Material	X		X	
Performance Testing		X		X
Leak Testing		X		X
Inspections		X		X
Plating	X		X	

APPENDIX A
SURVEY OF HEAT PIPE MANUFACTURING METHODS

Appendix A

SURVEY OF HEAT PIPE MANUFACTURING METHODS

FORMAT OF LETTER SUBMITTED TO VENDORS – REQUEST TO RESPOND TO QUESTIONNAIRE

The U.S. Army Missile Research and Development Command is conducting an industry survey regarding heat pipe fabrication and production.

The purpose of the survey is to assess the current state of heat pipe manufacturing methods and production technology applicable to the production of heat pipes for cooling circuit card mounted electronics. In conducting the surveys, the attached questionnaire is being sent to all companies and government agencies involved in heat pipe development and production. The results of this survey will be summarized to provide a comprehensive view of current manufacturing methods without identifying the sources.

Your answers to these questions will be greatly appreciated. Please return the questionnaire to the Command before

Sincerely,

RESPONSES TO QUESTIONNAIRE

Vendor \ Description	Type of Heat Pipes Produced; Typical Design Interface w/Heat Sink	Heat Pipe Application	Heat Pipe Size Heat Transfer Rate (Transport Capacity)	Heat Pipe Operating Temperature Range	Heat Pipe Operating Environment	Heat Pipe Shell Material	Notes
A	1/4"-1/2" O.D. Bolted interface mode H. P.-S VCHP-S	Electronics, spacecraft, heat exchangers, space radiators, road/bridge de-icing, cryogenics	1/4"-1" O.D. – 8-3000 W-m 1" O.D. – 10,000 W-m	20-400°K 800-1400°K	Space (Tested in 1g)	Al, SS, Cu, CU-Ni, Kovar, Invar, Hastelloy, Inconel, Incoloy, Ti	
B	Tubular, flat, mini-flat, flexible, bendable, electrical buss-fex, transparent, curved, spherical, conical	Every area of electronics	DIA: .07, 1/8, 3/16, 1/4, 5/16, 3/8, 7/16, 1/2, 5/8, 3/4, 7/8, 1.0, 2.0 FLAT: .07 x 1/4, .08 x 1/4, .1 x 1/4, .125 x 1/4, .125 x 1/2, 3/16 x 5/8, 3/16 x 7/8, 1/4 x 3/4, 1 x 2	266-810°K (98-491°K some types)	Any operating environment	Cu, SS, Brass, Steel, Pyrex, Quartz, Ag, Au, Plastic, Cupon Ni, Moly, Dument, Ceramic	
C	Radiation heated/cooled, radiation/convection heated-direct contact cooled, radiation/convection heated-immersion cooled	Thermionic conv. emitter -0- -0- collector gas fired vacuum furnace glass melting, cooking griddle, commercial oven, deep fat fryer, RC receiver	4.5" DIA. 6 Ft Long – 20 KW 1" DIA. 6" Long – 500 W	263-2273°K	Vacuum, ambient combustion gases	T, Niobium, Mo, Inconel, SS, Al, Cu, Carbon Steel	
D	Isothermal H. P.-S Flexible -1- VCHP-S Diode H. P.-S Rotating H. P.-S	Spacecraft equipment thermal control, DOD and NASA infrared sensor cooling	1/16"-1-1/2" O.D. 4" to 5 ft length 1W-3000W	25-400°K	Space (0g) 1g (adverse tilt in 1g or 0 to 1-1/2 in	SS 300 Al (6061, 6063), Cu	
E	Variety of types for aerospace applications	Electronic cooling, spacecraft thermal control	1/8-2" O.D. (1/4"-5/8" O.D. usual)	25-420°K	Designed for 0g (operate at 1g)	Al, SS, Carbon Steel	

RESPONSES TO QUESTIONNAIRE (Continued)

Source / Description	Method of Heat Pipe Shell Fabrication	Method of Heat Pipe Shell Assembly	Wick Structure	Wick Materials	Wick Attachment Technique	Heat Transfer Fluid Used	Notes
A	Machining, stamping	Welding (Al, Steel) Brazing (Cu, Steel) Soldering (Cu)	Grooved; slab	Groove (.024"-.010") Slab (felt metal) Screen Mesh (100, 170, 250)	Machining, sintering mechanical attachment (spring loaded, swaging, crimping	H, N, Methane, Ethane Freon 11, 12, 14, 21; Propane, Ammonia Acetone, Methanol, H_2O, Dow 'A', Potassium Sodium, Li	
B	All metal forming (except explosive)	Almost all methods	28 different wick configurations	–	–	37 std. fluid systems	
C	Machining, roll and weld, swaging	Brazing, electron beam welding, tungsten inert arc welding, stick welding, sintering, diffusion bonding, high temp. and pressure bending	Mesh, microsphere wick, mesh arteries, grooved arteries	Woven meld mesh (80–400 mesh) Microsphere wick (200–400 mesh)	Brazing, diffusion bonding, sintering	Li, Sodium, Potassium, Cs, Hg, H_2O, Dow 'A', Dowanol, Methanol, Ethanol, Acetone, Ammonia, Methyl Chloride	
D	Extrusions, matching (turning on O.D., threading on I.D.) wire resistance weld	Welding/brazing (container), bonding/soldering (H.P. to surface) epoxy or polyurethane adhesives, thermal grease with clamps	Grooves, spiral arteries, special geometries*	SS 300 screen (30–250 mesh)	Spot welding, mechanical clamp type devices, natural reliance of screen	H 15–25°K Neon 30–40°K O 60–95°K Methane 95–150°K Etane 140–190°K Ammonia 200–300°K Methanol 270–330°K H_2O 300–400°K	*Proprietary
E	Cold drawn or extruded tube material	Welded	Arteries on slab wicks; graded porosity non-arterial, homogeneous slab	.060" arteries using 150 mesh SS screen; Al and SS non-arterial wicks with graded porosity	Wick is inserted in plastically deformed tube	Methanol, Ammonia, Freons, Methane, Ethane, Ne	

RESPONSES TO QUESTIONNAIRE (Continued)

Source / Description	Fluid Pre-Treatment (if applicable) and Fill Cycle	H. P. Sealing Technique Used	Material and Processing Standards Used	H. P. Inspection and Testing Methods	H. P. Life and Life Test Data	Availability of Brochures, Sketches	Notes
A	Commercial* Aerospace: Repeated freeze thaw cycling to remove non-condensable gases. Precise weighing of fill bottle before/after fill.	Commercial* Aerospace–chge tube (3/16" O. D. – 1/16" I. D.) double crimp and weld (braze) end closure	Mat'l Specs: MIL–HDBK–38 ASME boiler code for Mech. design factors. Cleaning specs and fluid purification treatments are co–researched production procedures.	X–Ray welds proof pressures test, leak test; chemically sensitive indicators, gas chronatograph, mass spectrometer, halogen leak detectors	2–5 years for Fluid — HP Mat'l Ammonia — Al, SS Freon–21 — Al H_2O — C_u Methanol — SS	–	*Proprietary
B	–	7 diff. method used	–	Std. testing methods. 100% pre and post age and performance test	10 years actual life testing, accelerated test to 152 years life. Life varies w/design and use.	–	
C	Vacuum degassing –0–distillation volumetric metering weighing	Cold weld pinch–off, hot weld pinch off high temp. melt–off. Electron beam welding Crimping and brazing	Vacuum outgass above operating temp.	H_e mass spectrometer leak chk., pressure chk., thermal gradient measurement under actual or simulated load	1,000–10,000 HRS depending on application	Available	
D	Freeze–thaw method for venting non–condensible gases. Vertical buring for soluble or condensiblec.	1/4" O. D. – 1/16" I. D. pinched and welded tube for large dia. pipes 1/16" to 1/8" O. D. Pinched tube for small dia. pipes.	Co. developed std. except for welding, machining, etc.	Visual–hardness, the leakage -10^{-9} cc/sec sensitivity, proof press. – 1.5 – 2 x thermal performance tests pressure transducer; weight	Life – 5 years for compatible fluid/metal pairs. Life data unavailable	IR&D brochures available	
E	Generally distilled. Filled by weight	Crimp or weld; resistance weld	Internal specs for mfg., Process, fill and test	Bubble point artery test, performance measurement of individual H. P.–S	5–10 years	–	

APPENDIX B
DETAILED REQUIREMENTS FOR HEAT PIPE SLAB WICK THICKNESS AND FOR TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK

Appendix B

DETAILED REQUIREMENTS FOR HEAT PIPE SLAB WICK THICKNESS AND FOR TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK

HEAT PIPE SLAB WICK THICKNESS REQUIREMENTS FOR A 3 INCH BY 3 INCH 25 WATT CIRCUIT CARD

Orientation	Wick Material	3 x 4	3 x 5	3 x 6
		Heat Pipe Type		
		3 x 4 Integrated 4 Inch Single	5 Inch Single	6 Inch Single
		Required Slab Wick Thickness – Inches		
Vertical	X-7	.025	.032	.039
	X-12	.035	.048	.062
	FM-1205	.026	.042	.069
Horizontal	X-7	.022	.028	.033
	X-12	.027	.033	.040
	FM-1205	.014	.017	.020

HEAT PIPE SLAB WICK THICKNESS REQUIREMENTS FOR A 5 INCH BY 5 INCH 50 WATT CIRCUIT CARD

Orientation	Wick Material	Module Size			
		5 x 6	5 x 7	5 x 8	5 x 9
		Heat Pipe Type			
		5 x 6 Integrated 6 Inch Single	7 Inch Single	8 Inch Single	9 Inch Single
		Required Slab Wick Thickness – Inches			
Vertical	X-7	0.049	0.059	0.070	0.081
	X-12	0.077	0.099	0.126	0.162
	1101	0.073	0.118	--	--
Horizontal	X-7	0.042	0.048	0.055	0.062
	X-12	0.050	0.058	0.066	0.074
	1101	0.027	0.031	--	--

HEAT PIPE SLAB THICKNESS REQUIREMENTS FOR A 12 INCH BY 12 INCH 100 WATT CIRCUIT CARD

		Module Size			
		12 x 13	12 x 14	12 x 15	12 x 16
		12 x 13 Integrated	Heat Pipe Type		
Orientation	Wick Material	13 Inch Single	14 Inch Single	15 Inch Single	16 Inch Single
		Required Slab Wick Thickness – Inches			
Vertical	X-7	0.135	0.151	--	0.190
	X-12	0.423	0.706	--	--
30^{o}	X-7	0.108	0.118	--	0.140
	X-12	0.176	0.198	--	0.255
Horizontal	X-7	0.089	0.096	--	0.111
	X-12	0.107	0.115	--	0.133

TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK 3 x 3 25 WATT CARD

Module Size	Low	$\Delta T^{o}C$ Normal	High
Evaporator Thermal Resistance	.25	.5	1.0
3 x 4 Integrated	14.25	16.0	19.47
3 x 4 Individual	41.25	43.0	46.47
3 x 5 Individual	21.50	23.25	26.75
3 x 6 Individual	15.93	16.66	20.16
Condenser Thermal Resistance	.25	.5	1.0
3 x 4 Integrated	13.90	16.0	20.17
3 x 4 Individual	37.8	43.0	53.4
3 x 5 Individual	20.65	23.25	28.45
3 x 6 Individual	14.9	16.66	20.1
Joint Thermal Resistance	0.5	1.0	2.0
3 x 4 Integrated	11.67	16.0	24.33
3 x 4 Individual	29.5	43.0	72.1
3 x 5 Individual	16.0	23.25	37.8
3 x 6 Individual	11.8	16.66	26.38

Effect of High & Low parameters on Normal

TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK 5 x 5 50 WATT CARD

Module Size	Low	ΔT°C Normal	High
Evaporator Thermal Resistance	0.25	.5	1.0
5 x 6 Integrated	16.25	17.5	20.0
5 x 6 Individual	48.75	50.0	52.5
5 x 7 Individual	25.0	26.25	28.75
5 x 8 Individual	17.08	18.33	20.83
Condenser Thermal Resistance	.25	.5	1.0
5 x 6 Integrated	15.0	17.5	22.5
5 x 6 Individual	43.25	50.0	62.5
5 x 7 Individual	23.1	26.25	34.5
5 x 8 Individual	16.25	18.33	22.5
Joint Thermal Resistance	0.5	1.0	2.0
5 x 6 Intcgrated	12.5	17.5	27.5
5 x 6 Individual	32.5	50.0	85.0
5 x 7 Individual	17.5	26.25	43.75
5 x 8 Individual	12.66	18.33	30.0

Effect of High & Low parameters on Normal.

TEMPERATURE GRADIENTS FROM COMPONENT MOUNTING SURFACE TO HEAT SINK 12 X 12 100 WATT CARD

	Low	ΔT°C Normal	High
Evaporator Thermal Resistance	.25	.5	1.0
12 x 13 Integrated	13.5	14.05	15.10
12 x 13 Individual	46.4	46.9	48.0
12 x 14 Individual	23.5	24.0	25.1
12 x 15 Individual	15.8	16.33	17.4
12 x 16 Individual	12.0	12.5	13.55
Condenser Thermal Resistance	.25	.5	1.0
12 x 13 Integrated	12.0	14.05	18.20
12 x 13 Individual	40.7	46.9	49.4
12 x 14 Individual	20.9	24.0	30.25
12 x 15 Individual	14.24	16.33	20.4
12 x 16 Individual	11.0	12.5	15.6
Joint Thermal Resistance	0.5	1.0	2.6
12 x 13 Integrated	9.87	14.05	22.4
12 x 13 Individual	30.2	46.88	80.2
12 x 14 Individual	19.66	24.0	40.66
12 x 15 Individual	10.83	16.33	27.33
12 x 16 Individual	8.17	12.5	20.8

APPENDIX C
DETAILED STEPS AND INSPECTIONS IN THE PRODUCTION PROCESS

Appendix C

DETAILED STEPS AND INSPECTIONS IN THE PRODUCTION PROCESS

The basic process for the production of heat pipes is shown in Figure C-1 following. Numbers on the figure correspond to the steps discussed below. The basic process consists of the following steps:

Basic Process Steps

- Heat pipe base and cover fabrication
- Preform and wick fabrication
- Braze preparation
- Braze
- Evacuate/Fill/Seal (EFS process)
- Performance Test

A generalized expanded description of the processes are described below.

DESCRIPTION OF PROCESSES

Material Stamp Cut – Steps 1A, 2A, 3A and 4A

A mechanical punch press is used for this operation to stamp cut the patterns for the basic parts. The dies required for this operation are not detailed within this report.

Vapor Degrease – Steps 1B, 2B, 3B and 4B

All parts which were stamp cut will be vapor degreased. This will remove any oil contaminants from the surfaces. Note, any oil on the faying surface of the basic parts will impede the brazing process and may produce a part failure.

All parts are loaded into a basket and dipped into the vapor degreaser (vapor zone) until dripping of solvent from the parts stop (approximately 1 minute). The parts should be loaded in such a manner that no fluid will be entrapped such as in the cavity of the base. Allow parts to cool after extraction.

NOTE: All wicks must be protected from dirt and dust by placing in containers.

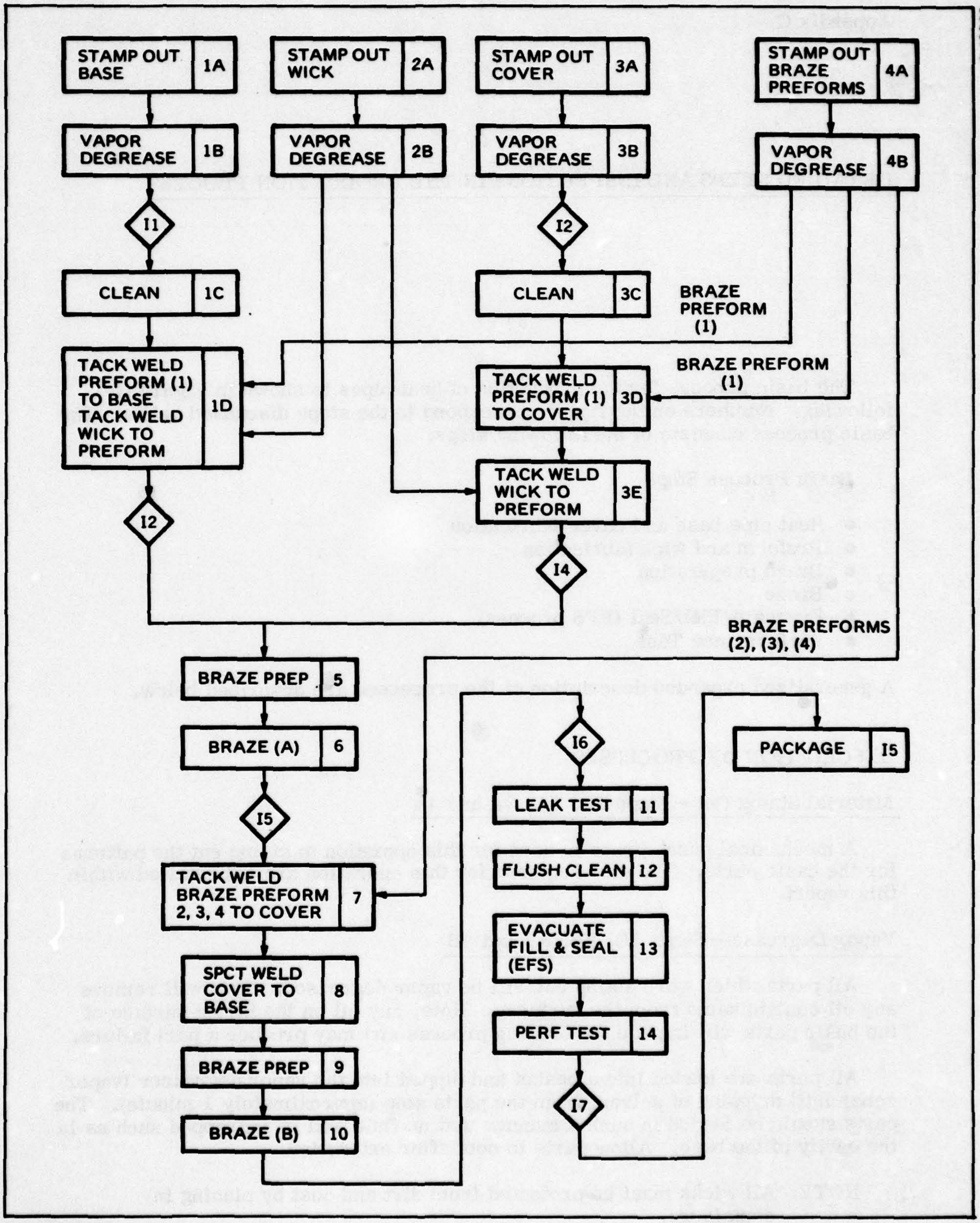

Figure C-1. Heat Pipe Production Process

Clean – Steps 1C and 3C

The heat pipe base and cover parts are loaded into a basket or rack in such a manner as to allow free flow of cleaning solution and water to flow in between each part without entrapment or pooling of solution.

PROCESS

Step	Solution (Dip)	Temperature	Time
(1)	Alkaline clean. (Oakite 26 or Equivalent)	120°F	3-5 minutes
(2)	Rinse, tap water, overflow Tank	Room	1 miniute
(3)	Rinse, tap water, overflow	Room	1 minute
(4)	Scale removal. 23% - 27% H_2SO4, 66° Be 11% - 13% Nitric, 42° Be Bal., tap water	Room	9-11 seconds (agitate)
(5)	Rinse, tap water, overflow	Room	30 seconds
(6)	Bright Dip, 58% - 62% H_2SO4 28% - 32% Nitric 0.2% - 0.3% Muriatic Bal. Tap water	Room	9-11 seconds (agitate)
(7)	Rinse, tap water, overflow	Room	30 seconds
(8)	Rinse, Deionized water	Room	30 seconds
(9)	Air Dry or Oven Dry		

NOTE: Scale Removal and Bright Dip may be substituted with a commercial equivalent process.

All parts should be stacked with paper slip sheets (with satin finish) in-between each part. White gloves are used in stacking. Parts are put in plastic bags to reduce the possibility of contamination.

Tack Weld – Step 1D (Braze Preform No. 1)

The braze preform and the wick are tack welded to the base simultaneously. The wick and the base are self-aligned. The tack weld should not be less than 12 places or more than 36 places. The least quantity is preferable. The tack welded parts are handled with white gloves during this process and are restacked with paper slip sheets for transportation to the next operation. See recommendations for automation of this process to reduce the labor content.

Tack Weld – Step 3D and 3E (Braze Preform No. 1)

This process is basically the same as Step 1D, except that the preform and wick are accurately positioned by an edge spacing tool during the tack welding. See recommendations for automation of this process in Section 3 of the Main report.

Braze Preparation – Step 5

(1) The first cover plate is loaded onto a furnace base fixture (not to be confused with the heat pipe base plate). The other nine cover plates are stacked (10 high, total) with graphite separators between each cover. The graphite separator should be 1/4" thick. Each stack of 10 is loaded onto the base fixture. A plate of 30 lbs is placed on the stack for preloading purposes and is thermally insulated from the stack.

(2) The base plate is loaded onto the base fixture. A top load plate is mounted on top of the stack as in (1) above.

The two groups (cover and base) with base fixtures are now prepared for brazing.

Braze (A) – Step 6

The groups of stacked covers (10 high) and stacked bases are inserted into the furnace and distributed evenly around the furnace by weight to prevent heat concentrations in a local area.

Thermocouples, T/C, are inserted into the appropriate base fixtures provided and into the graphite slip sheets.

The retort cover is assembled over the stack and locked down to the furnace base. The heating unit is placed over the retort and all T/C's are connected into the control panel. The T/C recorders are zeroed and the heat rate is set to 25°F/minute (minimum). An inert gas is used to purge the retort for 10 minutes and shut off. The hydrogen gas is turned on and flows within the retort. The exhaust is vented and burned into the atmosphere. The hydrogen gas quality must be at least -80°F dew point and the temperature setting is 1175°F. The load must remain set until all T/C's read steady state (approximately 10 minutes). The temperature on the controller is reset to 1400°F. The heat up rate to final temperature should be the highest rate possible. As soon as all T/C's come to steady state (-0°F, +25°F), this temperature is held for 5-10 minutes. All power is then shut down and allowed to cool to below 1200°F. The heating unit is then removed from the retort, and the retort is permitted to cool to 250°F at which time the retort is lifted off the fixture base. A crane is required to lift the heating coil and retort cover. The hydrogen gas is turned off according to normal safety specifications. The parts are left to cool to room temperature. Depending on the type of furnace, the parts may be unloaded onto a fixture table to air cool leaving the furnace free to be used again for production.

The parts are reloaded between paper slip sheets for the next operation. White gloves are used throughout this operation. Graphite stains on gloves are not harmful to the product and are acceptable.

It is very important that both the cover parts and the base parts be brazed in the same furnace at the same time. This will help to ensure that all parts see the same temperatures, heat up and cool down rates. This is necessary in order for all parts to have the same dimensional and physical control.

Tack Weld Braze Preform to Cover – Step 7 (Preforms No. 2, 3 and 4)

The preforms are tack welded first to the cover. Preform, Type 2 is welded to the cover followed by Types 3 and 4. The cover is placed back in between slip sheets if more than 10 minutes have elapsed before spot welding (Step 9). The objective is to preform the least amount of tack welds which will hold the braze preform in place. In no case do the preforms overlap. The tack welded parts are sonic degreaser cleaned in Freon to remove debris and oils.

Spot Weld Cover to Base – Step 8

The cover and base are assembled and pinned together by three alignment pins placed into the tooling holes provided in the cover and base. The assembled part is placed between the electrodes of the spot welder and a spot weld is made in opposite corners (the fill tube must be avoided). The alignment pins are removed, one at a time, after spot welding. The second and third pins are removed after the second spot weld.

The fill tube is inserted into the assembly and the preform ring is slipped over the tube. The fill tube preform ring is pushed firmly against the edge surface of the cover and base. There should be sufficient friction to prevent the preform ring from falling off the tube while in process.

Paper slip sheets are used to separate parts for transportation to next operation.

Braze Prep – Step 9

The base fixture is loaded with one assembly (cover down). The fixture may be sprayed with a braze inhibitor to prevent inadvertent brazing of the fixture to the parts. A graphite plate is placed over the assembly and another assembly is placed on top of the previous stack and the process repeated. A stack of 10 may be used. A greater number in a stack is not recommended due to the possibility of tilting or sliding. The orientation of the parts and slip sheets should be arranged such that the fill tubes are pointed in the same direction. The slip sheets should be oriented such that the vent hole patterns are congruent.

Braze (B) – Step 10

This process is basically the same as Step 6; however, the temperatures and times are different.

The initial temperature is 1100°F - 1125°F. The parts should remain at this temperature until steady state is attained plus 5 minutes. The heat rate is the same in both cases. The second temperature phase is 1275°F – 1300°F, maximum, and should remain for 1 minute. After this step, the power is shut down until the temperature reaches 1100°F. The heating unit is removed and the balance of the processes are the same.

Leak Test – Step 11

A helium leak test of all heat pipes (HP) is required to ensure that the H. P.'s will operate reliably indefinitely. The leak test will determine if all the brazed joints are completely sealed.

The heat pipes are placed in a closed container and the HP fill tubes are inserted into a sealed feedthrough. The container is closed and the HP fill tube protruding through the container wall is connected to a vacuum system. Helium in injected into the container, and the vacuum system is turned on. Each HP is connected to the vacuum separately and a vacuum of 10^{-6} torr is set. A leak rate of 3.2×10^{-9} cc/sec. (or 2.4×10^{-9} torr liter/sec) is the maximum permitted before rejection.

Flush Clean – Step 12

The heat pipes will be loaded on a rack in such a manner that the fill ports are all facing the same direction (vertical). A tube from a roughing pump is attached to each fill port long enough to achieve a partial vacuum of at least 28" of water. The tube from the roughing pump contains a 3-way valve, and the valve is turned to stop vacuum and admit acetone from a reservoir. The reservoir has a 24" head for permitting positive fill pressure. The heat pipes are placed in a rack with the fill ports vertical, and the rack is placed in a non-vented oven at 130°F for 24 hours. The oven is then turned up to 150°F for 2 hours.

The heat pipes are removed and stacked with paper slip sheets in between each unit.

Evacuate, Fill and Seal (EFS) – Step 13

Each heat pipe to be EFS processed is connected to a 3-way valve, using an O-Ring vacuum connector. Initially, the valve is positioned to the rough vacuum line. The heat pipe is first pumped down to a rough vacuum of approximately 80 millitorr and subsequently pumped down to a high vacuum of approximately 40 millitorr by shifting the valve to the high vacuum position. At 40 millitorr, essentially all the water vapor and air will be removed from the heat pipe (which is necessary for good heat pipe performance). After this operation, the heat pipe is ready to be filled with the working fluid.

A small calibrated tube is attached to the 3-way valve. The fluid supply line is kept at a slight positive pressure by keeping the fluid reservoir slightly above the boiling point of the working fluid. By keeping the reservoir above the boiling point and venting the vapor, the non-condensible gases in the fluid can be removed. By positioning the 3-way valve towards the calibrated volume, the fluid is dispensed into the heat pipe. To assure that all the fluid in the calibrated volume enters the heat pipe, the fill lines and valves are kept 10°F above ambient by heating the air inside the fill station. By this means, condensation of the fluid vapor will occur in the cooler heat pipe.

The final step is sealing off the heat pipe fill tube. Since the fill tube will be copper, a cold pinch-off will be used, followed by a spot weld to guarantee a seal. This technique employs a vise-like tool that cold welds and cuts the material. After pinch-off, the heat pipe fill tube is spot welded to further ensure that no leaks will occur. The excess tubing is cut off below the spot weld using a small tube shear.

EFS Process Expanded Process Description

SINGLE STATION OPERATION

Sub/ Step	Description	Valve No.	Std. Labor Time (Sec.)	Process Wait (Sec.)
1	Attach H. P. to Valve	–	30	–
2	Open Valve	1	5	240
3	Close Valve	1	5	120
4	Open Valve	2	5	–
5	Fill Std. Column (calibrated volume)	3	5	–
6	Close Valve	3	5	–
7	Close Valve	2	5	–
8	Turn Valve to Fill Position	4	5	60
9	Seal Fill Tube by Pinch Seal Tongs	–	5	–
10	Disconnect Heat Pipe	–	10	–
11	Reset Valve to Start Mode	–	5	–
			85	420 Sec.

Total: 85 + 420 = 595 sec, (0.14 Hrs.)

EFS Process, 1 Station Operation

Total standard cycle time for one station operation = 0.14 Hrs. Capacity = 7.1 units/hr.

EFS Process, 10 Station Operation

Standard cycle time for a ten station operation = .183 Hrs. Capacity = 10 units/.183 hrs. = 55 units/hr.

NOTE: In order to maintain the production capacity of the system shown in Figure C-1, an 18-station system is required.

Performance Test – Step 14

A performance test is performed by placing the finished heat pipe on a fixture specially designed to generate heat on the heat pipe bars and cool the condenser areas with a constant reference temperature heat sink. The performance of the heat pipe is measured as maximum temperature difference between the center of the heat pipe bar and the constant temperature heat sink.

INSPECTION CRITERIA

The inspection criteria described here represents the major critical items to be inspected and does not preclude other important facets which may be included by a particular manufacturer. In certain inspection operations, a particular tool may be necessary to check the alignment of wicks and preforms after tack welding. Various circuit card manufacturers require other criteria for circuit card components and, hence, the inspection criteria of the heat pipes may vary. Generally, the alignment of the preforms and wicks and the flatness are the two major items to be inspected. Fortunately, any number of go/no-go gages, both mechanical and/or optical, may be used for this purpose.

Inspection Operation, I1

The main items to be inspected are as follows:

(1) Flatness of base in general
(2) Heavy scratches
(3) Bent, jagged or warped walls
(4) Jagged edges
(5) Conformance to basic dimensions

Inspection Operation, I3

This operation is basically the same as I1, except the cover does not have cavity walls.

Inspection Operation, I2

(1) Ensure that edge dimensions and spacing of the preform and wick is maintained on the part.

(2) Ensure that the wicks are down flat against the surface.

(3) No wick tears, discontinuities, large voids (greater than 10% of the wick width), wick slivers, or contaminants are permitted on the material.

Inspection Operation, I4

This operation is basically the same as I2, except that the flatness of the wick and preform is very important.

Inspection Operation, I5

Inspect the cover and base plate for:

(1) Visible braze material on the top surface of the wick. The braze material which permeates through will inhibit action of the fill fluid. The spread of braze material should not approach the edge of the cover leaving less than a distance of .020 inches between the braze and the edge.

(2) Braze material creep up on side walls or over the top of wall.

(3) Excessive warping of parts.

(4) Flatness

Inspection Operation, I6

Inspect the completed assembly for:

(1) Braze joints. Each joint should be inspected for separation, or gaps.
(2) Misalignment (not greater than .005"/side).
(3) Fill tube proper braze flow.

Inspection Operation, I7 (Final)

The final inspection should consist of ensuring that the basic design requirements are maintained.

(1) Dimensional Conformity to Specification.

(2) Good workmanship, i.e.,

- Free of heavy scratches
- Flat
- Good quality brazing throughout
- Clean

Special Precautions

(1) It is very important that all parts be free of oil such as natural hand or hair oils.

(2) It is recommended that white gloves be used wherever possible after every clean or braze cycle and after assembly operations.

APPENDIX D
DETAILED COST ESTIMATES

Appendix D

DETAILED COST ESTIMATES

CAPITAL COST OF THE PRODUCTION SYSTEM

A cost analysis was done for the pilot production system. The list of capital equipment required and its associated cost is detailed below.

PROCESS EQUIPMENT AND CAPITAL COST

Item	Description	Qty.	Unit* Cost ($000)	Extended Cost ($000)
1	Small Press, 10 Ton	2	10	20.0
2	Large Press Open Side, C Frame 150 Ton	2	100	200.0
3	Electrical Spot Welders (1000 Watt)	7	10	70.0
4	Vapor degreaser 4' x 4' (60 gal.)	1	15.	15.0
5	Material Shear Machine (Manual)	1	5	5.0
6	Electrode Spot Welder (5000 Watt)	1	30	30.0
7	Hydrogen Retort Furnace	2	40	80.0
8	Special Clean (Ultrasonic Cleaner)	1	5	5.0
9	Flush Table (Modified work bench with acetone reservoir)	1	1.5	1.5
10	Chemical Cleaning Tanks	8	0.4	3.2
11	Oven, Convection (4' x 4')	2	6.0	12.0
12	Crance, 2-1/2 Tone	1	3.0	3.0
13	EFS Process Station	1	15.0	15.0
14	Leak Tester	1	8.0	8.0
15	Pyrometer Tester (Performance Test)	3	5.0	15.0
16	Miscellaneous Special Equipment			
	(a) Leak Tester Manifold System	1	–	50.0 (Est.)

PROCESS EQUIPMENT AND CAPITAL COST (Continued)

Item	Description	Qty.	Unit* Cost ($000)	Extended Cost ($000)
	(b) Perf. Test Multiple Station Syst.	1	—	
17	Roughing Pump	1	0.5	0.5
			Total	$533.2

PROCESS SUPPORT FURNITURE

Item	Description	Qty.	Unit* Cost ($000)	Extended Cost ($000)
18	Work Benches 5' x 2-1/2'	16	0.3	4.8
19	Work Benches 8' x 2-1/2'	4	0.5	2.0
20	Carts 2' x 3'	18	0.15	2.7
21	Inspection Magnifying Lamps (6" magnifiers)			
22	Packaging Sealer	2	0.3	0.6
23	Cabinets	12	0.3	3.6
24	Rack (die storage)	2	0.2	0.4
25	Files	7	.15	1.1
26	Chairs	25	.10	2.5
27	Desk	1	.3	0.3
			Total	$18.0

TOOLING AND EXPENSE

Description	Qty.	Unit* Cost ($000)	Extended Cost ($000)
(a) Cover Plate	1	2.5	2.5
(b) Base Plate for Item 1 and 2	1	2.5	2.5
(c) Wick	1	.8	.8
(d) Braze Preform	1	.8	.8
(e) Heater and Temp. Control (for Item 10)	1	1.5	1.5
(f) Vapor Degrease and Clean Process	6	0.2	1.2
		Total	$9.3

NOTE: Unit cost does not include tax, delivery or installation.

SHOP PARAMETERS ANALYSIS

1. **Production Rate, PR***

   PR = 50 H.P./Hr.

   *Assume that this is the key operation parameter and that the overall production requirement will be linearly extrapolated to a normal 40 hr. week.

2. **Weekly Output, WO**

   WO = PR x 40 hrs/wk. = 2000 H.P./Wk.

3. **Labor**

   Assume: 40 hours/week (production labor)
   1 shift (1 eight hour work period per day)

MACHINE QUANTITY ANALYSIS

1. **Punch Press, Small**

   Assume lot size = 500 units/part number

   Assume 2000 units/wk and 4 part numbers (distinct different configurations)

   Set ups: 4

   Set up time (SU) = 16 hrs.

   Mach. Rate = 250 U/Hr/Mach. (40-SU) x $\overline{U}$ = 5100 U/Wk/Mach.

   Q1 = Preforms = 8,000 units/wk
   Q2 = Wicks = 4,000 units/wk
   QT = 12,000 units/wk

   $$N = \frac{Q_T}{MR} = \frac{12,000 \text{ U/wk}}{5100 \text{ U/Wk/Mach}} = 2.3 \text{ machines}$$

   Assume 2 machines required.

2. **Punch Press, Large**

   Set ups: SU_1, 4 Set Ups Cover = 16 Hrs.

   SU_2, 4 Set Ups Base = 16 Hrs.

   SU_T = 32 Hrs.

   Q_1 = Covers = 2000 U/Wk

   Q_2 = Base = 2000 U/Wk

   Q_T = 4000 U/Wk

MR = 250 U/Hr/Mach $(40 - SU_T) \times \overline{U}$ = 1700 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{4000}{1700} = 2.35$$

Assume 2 machines required.

3. **Vapor Degreaser**

SU_T = 4 Hrs.

Q_T = 16,000 units/wk (total all parts)

MR = 500 U. Hr/Mach $(40 - SU_T)$ = 18,000 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{16,000}{18,000} = 0.89$$

Assume 1 machine required.

4. **Tack Welding Machines**

SU_T = 16 Hrs.

Q_1 = Step 1D = 2,000 units/wk

Q_2 = Step 3D = 2,000

Q_3 = Step 3E = 2,000

Q_4 = Step 7 = 6,000

Q_T = 12,000 U/Wk

MR = 71.5 U/Hr/Mach. $(40 - SU_T) \times \overline{U}$ = 1459/U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{12,000}{1,459} = 8.2$$

Assume 8 machines required

5. **Spot Welder**

SU_T = 8.0 Hrs.

Q_T = 2000 U/Wk

MR = 125 U/Hr Mach. $(40\ SU_T) \times \overline{U}$ = 3400 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{2,000}{3,400} = 0.58$$

Assume 1 machine required

6. Hydrogen Retort Furnance

SU_T = 24 Hrs.

Q_1 = Step 6 = 4000 units/wk

Q_2 = Step 10 = 2000 units/wk

Q_T = 6000 units/wk

MR = 250 U/Hr/Mach. (40 - SU) x $\overline{U}$ = 3400 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{6000}{3400} = 1.76$$

Assume 2 machines required

7. Evacuate, Fill and Seal (EFS)

SU_T = 6.0 Hrs.

Q_T = 2000 U/Wk

MR = 66 U/Hr/Mach (40 SU_T) x $\overline{U}$ = 1590 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{2000}{1590} = 1.25$$

Assume 1 machine with 10 stations is required.

NOTE: An EFS processor with 15 stations would serve to balance the 25% capacity deficit.

8. Leak Tester

SU_T = 4 Hrs.

Q_T = 2000 U/Wk

MR = 62 U/Hr/Mach (40 - SU_T) x $\overline{U}$ = 1897 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{2000}{1897} = 1.05$$

Assume 1 machine required.

9. Ovens

SU_T = 4.0 Hrs.

Q_T = 16,000 U/Wk

MR = 250 U/Hr/Mach (40 - SU_T) x $\overline{U}$ = 7650 U/Wk/Mach.

$$N = \frac{Q_T}{MR} = \frac{16,000}{7,650} = 2.09$$

Assume 2 machines required.

Maintenance and Downtime — It is anticipated that the equipment used in this operation will require regular inspection and maintenance in order to maintain the production rates, minimize downtime, and to maximize the lifetime of the equipment. A suggested rule is to ensure that each piece of equipment is maintained according to manufacturer's recommendations and a maintenance log system be used for all major equipment.

Downtime of equipment may be minimized by ensuring that all operators receive proper training in the use of each piece of equipment and that the equipment running conditions not be exceeded at any time. Care should be exercised to ensure that proper voltages are used with electrical equipment in order that the equipment will not be strained or overheated.

HEAT PIPE UNIT COST

The unit cost for the heat pipe is analyzed on the basis of the process described in previous sections of this report. The set up time shown is based on the type of equipment selected. The processes selected are generally manual; however, semi-automatic equipment is used wherever possible to reduce the labor cost.

Unit Cost Analysis (Assume 500 finished Units)

Total set up labor time, $T_s = 38.0$ hrs.

Total process manufacturing labor time, $T_p = 98.0$ hrs.

Basic Manufacturing labor time, $T_m = T_p + T_s = 136.0$ Hrs.

Utilization, $\overline{U} = .80$ (Defined as inefficiency and other factors which increases the time required to produce a run qty.)

Actual manufacturing time, $T_A = \frac{T_m}{\overline{U}} = \frac{136.0}{.80} = 17.0$ Hrs.

Equivalent manufacturing time/unit, T_E

$$T_E = \frac{T_A}{Qty/Run} = \frac{170.0}{500} \text{ hrs.} = .340 \text{ hrs/unit}$$

Yield (Assumed), Y = 85%

Manufacturing Direct Labor Time/Unit, T_{DL}

$$T_{DL} = \frac{T_E}{Y} = \frac{.34}{.85} = .40 \text{ hrs/unit}$$

Manufacturing Support Labor Time, T_S

Mfg. Engineering	T_0 =	5.0 Hrs.
Test	T_1 =	12.0 Hrs.
QC and Inspection	T_2 =	23.0 Hrs.
Support, Pkg.	T_3 =	4.0 Hrs.
Supervision	T_4 =	5.0 Hrs.
Total		49.0 Hrs.

T_S = 49.0/500 = .098 hrs/unit

Mfg. Cost (Labor), C_L

C_L = Mfg. Labor Rate X ($T_{DL} + T_S$)

Rate = $25.00 including overhead (Assumed value typical in electronics manufacturing)

$T_{DL} + T_S$ = .498 hrs/unit

C_L = $25.00/Hrs x .498 Hrs/Unit = $12.45/unit

Material Cost (Assume 500 finished units), C_M

Shell Material	$ 1,500	
Wick	14,500	(See recommendations for possible R&D
Braze Preform	1,000	Effort and cost reduction)
Acetone, 5 gal.	30	
Support Material Supplies	500	
	$17,530	

$$C_M = \frac{\$17,530}{500} = \$35.06/\text{Unit}$$

Total Unit Cost, Summary, $C_L + C_M$

Labor Cost, C_L	$12.45/unit
Material Cost, C_M	35.06/unit
Total Unit Cost	$47.51/Finished Unit