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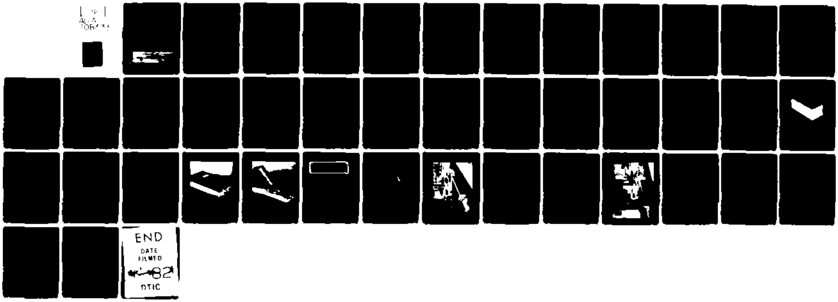

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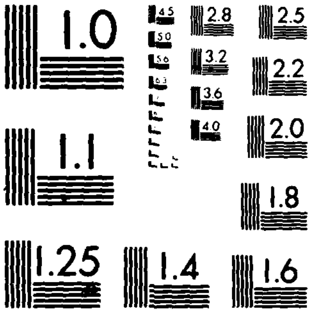

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Development of Heat Pipe Module for Power Semiconductor Cooling

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

Application of heat pipe technology to cooling problems is an efficient means to reduce hot spot temperatures; overall thermal conductance is significanty improved as compared to conduction through a solid. This effort was focussed on the design and development of a heat pipe module which could be used to retrofit an efficient cooling system to an existing Integrated Power Switch (IPS) module. The design selected maximized the thermal performance of the heat exchange system by eliminating a dielectric barrier between the IPS power strip and the heat sink. This necessitated the use of isolation between the two power strips of the IPS to

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)* maintain normal circuit insertion capability; the overall package was also electrically insulated.

At constant air flow pressure drop (different flow rates) the heat pipe module provided a reduction in component temperature rise by about a factor of three (3) at equal input power, or could handle approximately three (3) times the power of the conventional IPS thermal system for equivalent temperatute rise. Measured thermal resistances of .17 and .51 °C/watt were obtained for the heat pipe heat exchange system and the original IPS conduction heat sink, respectively, at a pressure drop of 0.60 inches of water.

DEVELOPMENT OF HEAT PIPE MODULE FOR POWER SEMICONDUCTOR COOLING

BY

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FOREWORD

This report summarizes the results of a research and development program to construct a high performance heat pipe and heat exchanger system to improve the cooling of an Integrated Power Switch (IPS) module. The IPS module is a component of a power conditioning system which is used to switch high power systems and provides protection against overload conditions. The power dissipation in the IPS module is relatively high and requires adequate cooling in order to maintain a high reliability and life of the system.

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LIST OF ILLUSTRATIONS

SCOPE

This research and development program shall consider the problem of transferring the thermal heat load from the power terminal strips of the integrated power switch to a finned heat exchanger and removing the heat by air convection through a heat exchanger. The final design shall contain a heat pipe as the principal source of spreading and reducing the temperature at the base plate. The mechanical design of the improved heat exchanger module shall also be constructed to be interchangeable with the MERDC IPS system for testing purposes. The materials and processes used for fabrication shall be considered to optimize the heat transfer from the power terminal to the heat exchanger.

SECTION 1
INTRODUCTION AND SUMMARY

SECTION 1. INTRODUCTION

A. INTRODUCTION

The U.S. Army Mobility Equipment Research and Development Center (USAMERDC) at Fort Belvoir, Virginia has been conducting research and development in the area of power supplies with the goal of improving the efficiency and reducing the size, weight and bulk of power-conditioning equipment. The research includes development of the Integrated Power Switch (IPS) assembly which is a solid state power control. The IPS can control relatively high power systems and provides protection against overload with transistors which have ideal switching characteristics. Each half of the IPS is electrically isolated from the signal input and modern printed circuit board and thick film technology is used. The IPS is cooled by forced-air convection over a finned heat sink which is the base plate for the IPS. The heat sink is approximately 7 in. x 3.5 in. in surface size and is electrically isolated from the power terminals. The IPS base plates are isolated by use of high temperature insulation film between the terminal strips and the base plate. This strip also inadvertently acts as a thermal insulation strip since electrical resistance is directly proportional to thermal resistance for most engineering materials.

The temperature rise in the IPS unit and the base plate is relatively high since there is a significant thermal resistance between the base plate (heat sink) and the terminal strips (heat source). Approximately 400 watts of power (200 watts per side) is dissipated in the IPS system and must be transferred directly to the finned heat sink which is cooled by forced-air convection. The heat sink fins are approximately 1/2 in. height x 7 in. long and are spaced 1/4 in. apart.

The Hughes Aircraft Company was tasked to develop an improved heat transfer system to reduce the case temperature which would enable the IPS to have a higher power dissipation capacity. A heat pipe in direct contact between the power strip and the heat exchanger was selected as the device for optimizing the heat transfer to the heat exchanger.

B. STATEMENT OF THE PROBLEM

The existing MERDC Integrated Power Switch (IPS) assembly operates at a base plate temperature in excess of desired limits. The high internal housing temperature causes electrical malfunctions and affects the overall system reliability. It is desired that a heat exchanger system be designed to reduce the base plate temperature for the same amount of power dissipation.

C. SUMMARY

The Hughes Improved Heat Exchanger (HIHE) consists of the elements of the Integrated Power Switch (IPS) mounted directly to a heat pipe developed specifically for this application. The heat pipe is designed to absorb the heat energy of the IPS power strips and to distribute the heat over a large area. In addition the temperature across the heat pipe is equalized across the length of the pipe thus lowering the terminal strip hot spots. The IPS terminal strips are mounted directly to the Hughes heat pipe and a thermal compound is used as a filler in between the contact surface to improve the heat transfer to the heat exchanger.

The flow path in HIHE starts at the terminal power strip and proceeds through the heat pipe cover and through an evaporator wick-liquid matrix to the liquid vapor interface. The liquid in the evaporator flashes into vapor and recondenses down stream at the condenser wick-liquid matrix end of the heat pipe. The cycle is completed by the condensed liquid flowing through an artery wick by capillary action to the evaporator section where the process is repeated ad-infinitum. The heat transferred through the heat pipe proceeds to the enclosed and corrugated finned heat exchanger. Air flowing through the heat exchanger removes the heat from the HIHE.

Test results indicate that the HIHE provides approximately 2 times the thermal efficiency compared to that of the MERDC standard finned heat exchanger. The power dissipation capacity is higher for the HIHE compared to the MERDC unit for the same air pressure drop which was a critical design criteria for the HAC system. One design objective of the HIHE was to reduce the base plate interface temperature for the same power dissipation as the MERDC system. This objective was achieved. The base plate interface of the MERDC system measured well over 120°C while the HIHE terminal strip to heat pipe interface measured approximately 85°C for 400 watts of heat energy input.

SECTION 2
TECHNICAL DISCUSSION

SECTION 2. TECHNICAL DISCUSSION

An improved heat exchanger system using a heat pipe was developed to replace the MERDC base plate and triangular fin heat exchanger system. The Hughes heat pipe was designed to be used as the interface component between the MERDC terminal power strips and the heat exchanger to reduce the base plate interface temperature and to spread the thermal energy input to the heat exchanger over a wider area. The heat pipe and heat exchanger assembly is shown in Figure 1. Performance tests were conducted to compare the thermal efficiency and interface temperatures for the MERDC and HAC heat exchanger systems. The materials and fabrication processes were selected on the basis of providing the maximum efficiency and a lower interface temperature for 400 watts total input power (200 watts per side). An important parameter which was a key to the design of the improved system was the total air flow pressure drop across the convolution finned heat exchanger.

A. GOALS

The following goals and constraints were stipulated by Mobility Equipment R&D Center for the research and development of an improved heat exchanger for the MERDC Integrated Power Switch system.

(1) The heat pipe module shall have a minimum thermal power transport capability of 400 watts total (200 watts per side) steady state.

(2) The heat pipe – thermal strip interface temperature shall be designed not to exceed 85°C at 400 watts thermal power input to the heat pipes.

(3) The size and shape of the heat pipe and heat exchanger assembly shall be 7 in. long by not more than 3-3/4 in. wide.

(4) The mounting hole patterns in the existing IPS shall be duplicated in the HAC HIHE unless deviations are requested by HAC and approved by MERDC.

(5) The design of the heat exchanger shall be based on minimizing the overall air flow pressure drop through the corrugated fins; however, the 400 watts thermal power transport capability shall be the primary consideration.

(6) The heat pipe – terminal power strip interface shall not contain an electrical insulator film i.e., the terminal strip shall be in direct metal to metal contact with the heat pipe.

(7) Each heat pipe/heat exchanger unit shall be separated electrically from each other i.e., each system is composed of two heat pipes and two heat exchangers. Each set will be electrically isolated.

B. PROGRAM PLAN

A 5 phase program plan was conceived to develop and produce the final version of a Hughes Improved Heat Exchanger (HIHE) module. The phases are summarized below:

Phase I – Conceptual Design

(1) Review the basic design and functional requirements and produce two (2) basic conceptual schemes for the HIHE module.

(2) Select one design and determine basic size and shape factors.

Phase II – Material and Process Analysis

(1) Analyze the specific requirements for materials based on temperature, thermal power load, electrical factors, and compatibility.

(2) Perform a materials search to find materials required from (1) above.

(3) Determine fabrication processes best suited for design and materials selected.

(4) Determine heat pipe processes required.

Phase III – Prototype Heat Pipe Construction and Test

(1) Design a prototype heat pipe based on the preliminary conceptual design and heat pipe requirements.

(2) Fabricate prototype heat pipe.

(3) Test prototype heat pipe.

(4) Evaluate results and determine the changes (if any) required in the final design of the heat pipe.

Phase IV – Final Design and Fabrication of Hughes Improved Heat Exchanger Module

(1) Lay out assembly of MERDC IPS and HIHE final design.

(2) Detail all heat pipe and heat exchanger module parts.

(3) Fabricate all detailed parts.

(4) Nickel plate heat pipe cover and shell, assemble heat pipe with wicks and screens, spot weld, braze, fill, and leak test.

(5) Assemble all components.

Phase V – Performance Test

(1) Fabricate thermal load plate to simulate MERDC IPS terminal power strip.

(2) Set up test bench with all required instruments.

(3) Assemble the HIHE and simulated load package for test.

(4) Performance test the HIHE module and the MERDC fin heat exchanger and compare results.

C. PROJECT PHASES (I – V)

1. Phase I – Conceptual Design

The MERDC IPS shape and size requirements were analyzed, and envelope dimensions were determined. The two (2) conceptual designs were evaluated and a tentative final design was selected. The design shown in Figure 2 shows the basic concept of one side of the complete module. The heat path is shown in Figure 3 for the MERDC system and Figure 4 for the HIHE. The HIHE module is an improvement over the basic system shown in Figures 5 and 6 in that the electrical insulation was eliminated which permits the IPS thermal power to be transported directly to the heat pipe and heat exchanger. The IPS electrical insulation film represents a high thermal resistance for the heat. Another improvement in the design is the heat pipe which reduces the peak temperature at the power strip and spreads the heat load over a larger area and helps the temperature distribution curve to flatten over the length of the heat pipe. Another improvement is the computer optimized heat exchanger. A computer program was written to assist in the development and selection of the heat exchanger design parameters. The program considers the pressure drop through the system (which was a critical factor to MERDC), the mass flow of air, velocity, thermal load, and size parameters of the heat exchanger fin convolutions. The results were used in the final design of the HIHE.

The HIHE module was designed to enable the IPS cover and all the electrical components to be assembled interchangeably with the original MERDC IPS module.

2. Phase II – Material and Process Analysis

The materials used for the HIHE module enclosure were selected after an exhaustive study to determine the options based on high working temperature capability, electrical resistance, fabrication properties, strength, dielectric strength, cost, esthetics, and availability. Several materials were compared for the above factors. The principle options were: glass filled nylon, linen filled phenolic, G-10 and G-11 fiber glass epoxies (such as that used for circuit boards), and glass filled Poly Phenylene Sulfide (PPS). Poly Phenylene Sulfide was selected as the material for the enclosure. The operating temperature is above 500°F, and the thermal and electrical properties are excellent for the application. The glass fill enhances the strength of the material, and a 30% glass fill was selected.

The heat pipe shell and cover candidate materials were considered; however, it was established almost immediately that an oxygen free copper would be used for this application due to the overpowering high coefficient of conductivity. Brasses and steels were considered for the ease of fabrication and brazing; however, the loss of conductivity far outweighed the advantage of fabrication. Copper type 101 OFHC was selected as the final choice for the heat pipe shell and cover. A hydrogen retort furnace braze operation is required to braze type 101 OFHC copper since no flux may be used in the brazing process. The possibility existed that the elements of the brazing flux could adversely contaminate and affect the screen, wick and fill fluid materials. The hydrogen furnace process does not require a flux as an activation medium since the hydrogen atomically cleans the surfaces to be brazed and permits the braze filler to flow and seal all openings.

A BAg-8 braze material was selected as the braze element to use with the 101 copper since this material has good flow properties and the melting point is under the melting point of 101 copper.

The heat pipe screen and wick materials were selected based on the requirements for compatibility with the fill fluid and copper material used in the cover and shell. A sintered (fiberous) stainless steel mat material (0.015 in. thick) was used as the artery wick material and a 304 stainless steel 200 x 1400 mesh screen (0.006 in. thick) was used as the spreader screen. These materials were spot welded to the shell and cover after nickel plating (the shell and cover).

A nickel sulfamate plating process was used to coat the cover plate and shell body. The nickel plating is used to improve the spot welding and brazing process.

The spot welding process used to spot weld the wick and screen to the shell and cover consisted of using an electrode resistance welder set at 20 – 50 amp seconds.

The fill fluid selected for the application was hexane. This material was selected based on experience and results from the prototype tests. Approximately 6.5 cc's was used per heat pipe. The final amount of fill fluid is based on performance test results.

3. Phase III – Prototype Heat Pipe Construction and Test

The prototype heat pipe (see Figure 7) was designed and constructed based on the criteria of materials and processes selected for the HIHE heat pipe (see Section 2, C1 and C2). The steps used in the construction are summarized below.

- Design envelope and details for fabrication
- Specify and procure materials based on material analysis and final selection
- Fabricate parts
- Nickel plate shell and cover
- Fabricate wick and screens
- Spot weld wick and screens to shell and cover
- Braze shell and cover together
- Leak test

- Fill heat pipe with hexane after vacuum purge. The volume of hexane is approximately equal to the volume of the sintered stainless steel wick material.

The test results of the prototype indicate that all the basic materials perform satisfactorily and only the determination of the fill fluid volume would be left to experimentation on the final assembly by trial and error. A few problems occurred during the test phase which were not catastrophic but were helpful in highlighting areas where care must be taken in the final HIHE heat pipe design. Some of the areas for care and improvement which were learned from the prototype test phase are:

(1) Ensure that the structural support pads within the heat pipe are properly brazed to the cover for structural support of the cover and shell when under positive pressure as result of thermal bond and fill fluid vapor pressure.

(2) Provide less (not more) clearance between the cover and shell. A large clearance does not permit the braze material to wedge properly. A smaller clearance is helpful for braze filler material support as well as for the improvement of braze material flow characteristics.

(3) Ensure that the sulfamate nickel plating bath is free of harmful contamination elements. The contamination inhibits the spot welding of the wick and screen to the plated cover and shell.

(4) The fill fluid volume must be determined by trial and error using a thermal performance test as the criteria for judgement. The fill tube should be as short as possible so as not to contribute significantly to the heat pipe volume. The fill fluid has a tendancy to condense and collect in the fill tube and causes a reduction in performance of the heat pipe.

(5) Care should be taken not to bend or dent the shell or cover since they are constructed from soft 101 type copper.

(6) The surfaces of the heat pipe and heat exchanger should be very flat and a test should be made to determine the total area of metal to metal contact. Small areas not in direct contact become hot spots and significantly reduce the overall heat transfer, i.e., the contact thermal resistance must be made as small as possible.

4. Phase IV – Final Design and Fabrication of Hughes Improved Heat Exchanger Module

The design of the Hughes Improved Heat Exchanger Module was finalized and detailed. The HIHE was designed to permit the electronic components of the MERDC IPS to assemble in the exact same positions and orientation thereby making the HIHE interchangeable with the IPS assembly. The heat pipe surfaces were milled flat to 0.003 in. TIR and 16 RMS surface quality. This enhances the overall heat transfer from the IPS power terminal strip to the heat pipe and heat exchanger by reducing the contact resistance shown in Figures 3 and 4. The heat exchanger requirements were analyzed and a computer program was written to optimize the dimension parameters (given the envelope constraints). The convoluted fin parameters which were optimized are shown in Figure 8. The pressure drop through the heat exchanger was programmed as a critical parameter to minimize. This was requested by MERDC. The fin material is aluminum (6061-T6) and was dip brazed to the "U" shaped channel to provide maximum heat transfer to the fins.

Materials used for the heat pipe were based on a material and technical analysis. The analysis indicated that a hexane fill fluid would produce a satisfactory figure of merit for the heat pipe efficiency. The stainless steel artery wick (Dynalloy 11) proved to have excellent capillary and porosity properties. The combination of materials proved to have excellent heat pipe condenser and evaporator properties for optimization of the overall heat transfer parameters.

The leak rate test indicated that a ten (10) year life based on leak rates may be exceeded since the test indicated a leak rate of 10^{-9} STD cm^3/sec (helium atmosphere) and the 10 year life requirement is 10^{-7}. The leak test was conducted with a Veeco helium leak detector.

5. Phase V – Performance Test

The test procedure is discussed in detail in Section 4 and the results are shown in Section 3.

The relative performance of the Hughes Improved Heat Exchanger was based on the design goals. The objective was to produce a system which could operate at a 85°C base plate temperature for a thermal power load of 400 watts (200 watts per side). The critical parameter; however, was to minimize the pressure drop (ΔP) across the convoluted fin heat exchanger was compared with the HIHE to determine the relative performance level. The relative performance was taken as the ratio of base plate temperatures for the same thermal power load. The base plate temperature (or interface temperature) was defined as the temperature measured below the electrical insulation strip (or the base plate temperature) on the MERDC system and the top of the HIHE heat pipe which is the equivalent to the MERDC IPS base plate. The air flow and pressure deop were controlled and the temperatures recorded. It appears that a significantly higher (3X) amount of air flow will flow through the HIHE than through the IPS heat exchanger for the same pressure drop.

SECTION 3
CONCLUSIONS

SECTION 3. CONCLUSIONS

The results of the HIHE performance test and conclusions of the overall development program are summarized below.

A. RESULTS

(1) The Hughes Improved Heat Exchanger fulfills the requirements and goals of the contract. The thermal power load capacity of the heat pipes is 400 watts and the base plate temperature is 85°C.

(2) The pressure drop through the heat exchanger fins was minimized for the air flow requirements.

(3) The performance tests on both the Hughes heat exchanger module and the MERDC IPS indicate an improvement of a factor of two (2) over the original IPS. The factor of two is based on the temperature of the base plate of each system where the IPS temperature is approximately twice as high as the HIHE base for the same thermal heat load.

B. RECOMMENDATIONS

The following recommendations are made based on the experience of fabrication and performance testing.

(1) The heat pipe should have very good contact with the terminal power strip and the heat exchanger. No raised or significant voide areas should be allowed since this reduces the overall heat transfer capacity and creates a hot spot.

(2) A heat transfer compound should be used between the heat pipe and the heat exchanger and between the top of the heat pipe and power terminal to improve the thermal performance. The compound serves to fill gaps and small voids. The deliverable HIHE was applied with thermal compound on the bottom of the heat pipe. Thermal compound should be placed on top of the heat pipe before use.

(3) The air flow used for cooling must be directed into the heat exchanger with as little leakage as possible in order to maximize the effect of the air mass flow. The MERDC IPS heat exchanger is even less forgiving for wasted air flow.

(4) Provide approximately 35 CFM air flow through the HIHE module.

SECTION 4
TEST PROCEDURE FOR HUGHES IMPROVED HEAT EXCHANGER (HIHE) MODULE

SECTION 4. TEST PROCEDURE FOR HUGHES IMPROVED HEAT EXCHANGER (HIHE) MODULE

A. TEST PROCEDURE, HIHE

OBJECTIVE: To determine the thermal performance of the Hughes Improved Heat Exchanger system and to compare the performance with the MERDC IPS heat transfer system under the same test conditions.

TEST SET UP: The HIHE was assembled with an IPS simulated thermal load which consisted of thermal resistors mounted on a copper plate. The placement of the simulated load approximates the orientation of the IPS power terminal strip. The HIHE module was attached to a large plenum chamber and the suction end of the blower was attached to the opposite end of the plenum. The plenum served to maintain a relatively constant pressure down stream of the HIHE module which permitted the air flow P of the module to be measured more readily and accurately. A mercury "U" tube was used to measure the pressure drop between the open front end of the HIHE and the plenum down stream of the HIHE. An air flow rate meter (gentile tube) was placed downstream of the plenum, and the blower (suction) was placed downstream of the flow rate meter. See Figure 9.

Several thermocouples were placed on the simulated heat load and the heat pipe to record the temperatures. Thermocouple locations are shon in Figure 10. The thermal load resistors were connected to a variac for variable thermal power control. The power input was connected to a wattmeter and since the HIHE module heat load was insulated, it was assumed that nearly all the electrical power input was converted to thermal heat load power. The diagram for the HIHE set up is shown in Figure 11.

B. TEST PROCEDURE, MERDC IPS HEAT EXCHANGER

The set up of the MERDC IPS heat exchanger was basically the same as the HIHE module except that the triangular fin heat exchanger was enclosed on the open side and air was directed into the forward enclosed end. This was done in order to ensure control over the amount of incoming air mass flow. Without this adaption, there was no predictable way of measuring the thermal performance versus the air flow. See Figure 12.

SECTION 5
DATA AND RESULTS OF HIHE PERFORMANCE TEST

SECTION 5. DATA AND RESULTS OF HIHE PERFORMANCE TEST

A. BASE PLATE TEMPERATURE VS AIR FLOW PRESSURE DROP

The results of the thermal performance test are shown graphically below. The results indicate that the HIHE module reduces the temperature of the base plate by approximately a factor of two (2) over the MERDC IPS heat exchanger with a steady state thermal load. The relative performance of the HIHE increased with a higher air flow and pressure drop. The MERDC heat exchanger appeared to have an asymptotic limit of temperature with increasing air flow stabilizing at approximately 80°C base plate temperature air flows corresponding to a pressure drop over 1.0 inches of water. The HIHE appeared to have an asymptotic limit at approximately 30°C base plate temperatures for air flows corresponding to a pressure drop over 2.0 inches of water. See Figures 13 and 14.

$$\text{The performance ratio, PR} = \frac{T_{\text{IPS}}\ \text{base plate } ({}^{\circ}\text{C})}{T_{\text{HIHE}}\ \text{base plate } ({}^{\circ}\text{C})}$$

B. BASE PLATE TEMPERATURE VS THERMAL POWER LOAD

The results indicate that the base plate temperature varied linearly with input thermal power for both the HIHE and the MERDC IPS systems. The HIHE module base plate temperature, however, was consistently lower than the IPS base plate temperature by approximately a factor of two (2) for a wide range of thermal power at a constant air flow. The air flow pressure drop was held constant in both cases (although the specific flow rates are different for each heat exchanger). The thermal load plate temperature ratios for both the MERDC IPS and the HIHE were also compared. The IPS load plate temperatures at 0.85 inche of water pressure drop was approximately 35°C higher than the HIHE base plate temperature at 100 watts and 67°C higher at 200 watts (see Figure 15). The IPS base plate was 20°C higher at 100 watts and 42°C higher at 200 watts (ΔP = 0.6 inches of water). The IPS base plate was 25° higher at 100 watts and 40°C higher. The effectiveness of the HIHE therefore appears to be the highest for 0.85 inches of water pressure drop; however, the performance was only slightly higher than that at 0.6 in. of water. The thermal performance is proportional to the air flow rate but only a small increase in performance is gained for high flow rates. The design goals are therefore best achieved by running the HIHE at 0.6 inches of water pressure drop. This sacrifices a small amount of base plate temperature which could be further reduced by 0.85 inches of water air flow pressure drop. See Figures 14, 15, 16, 17.

The effect of the heat pipe is to lower the temperature at the hot end and to distribute the heat load over a larger area (area of the heat pipe) in such a manner as to level the temperature distribution over the surface of the base plate.

SECTION 6
ILLUSTRATIONS

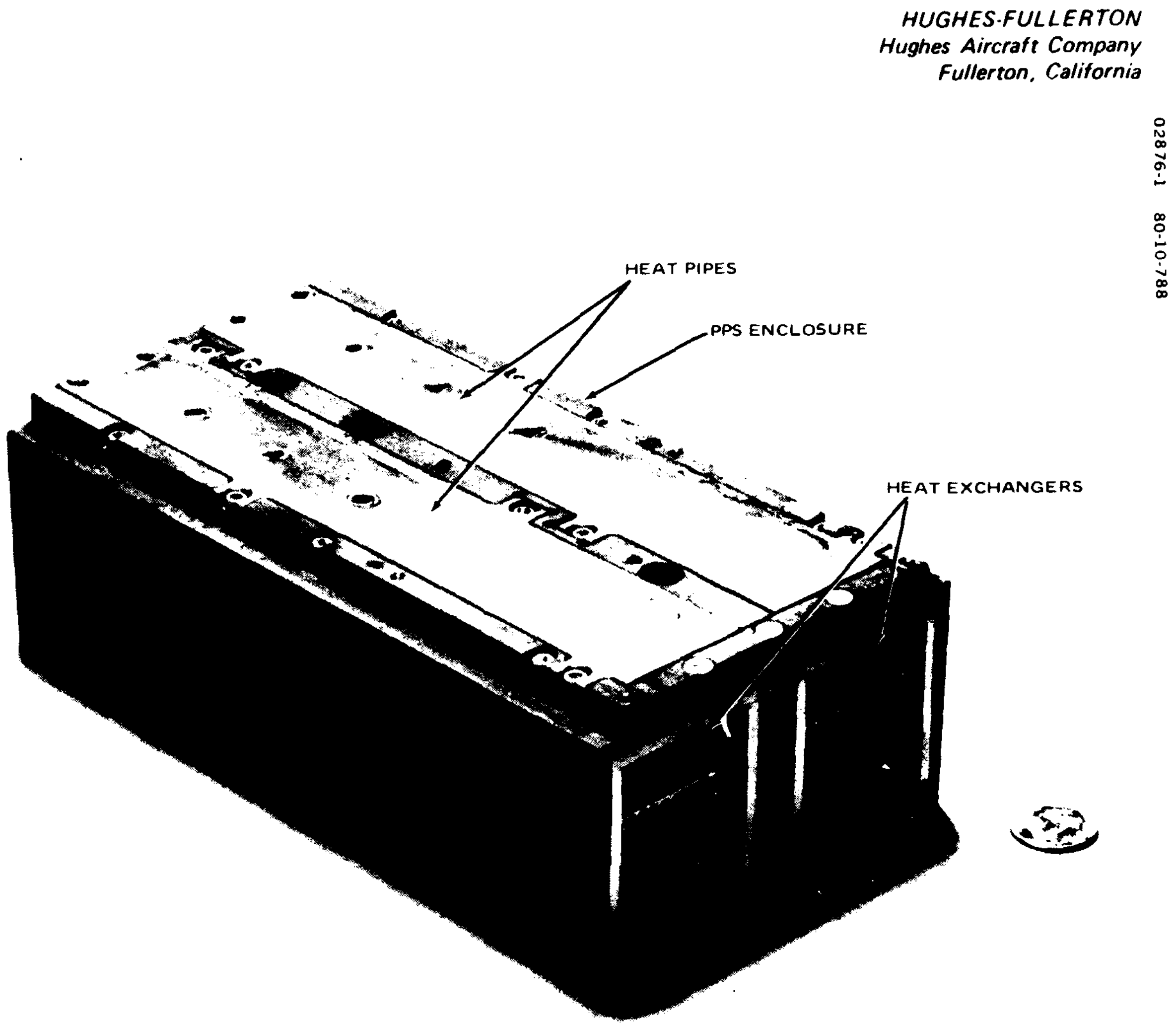

Figure 1. Hughes Improved Heat Exchanger Module with Heat Pipe

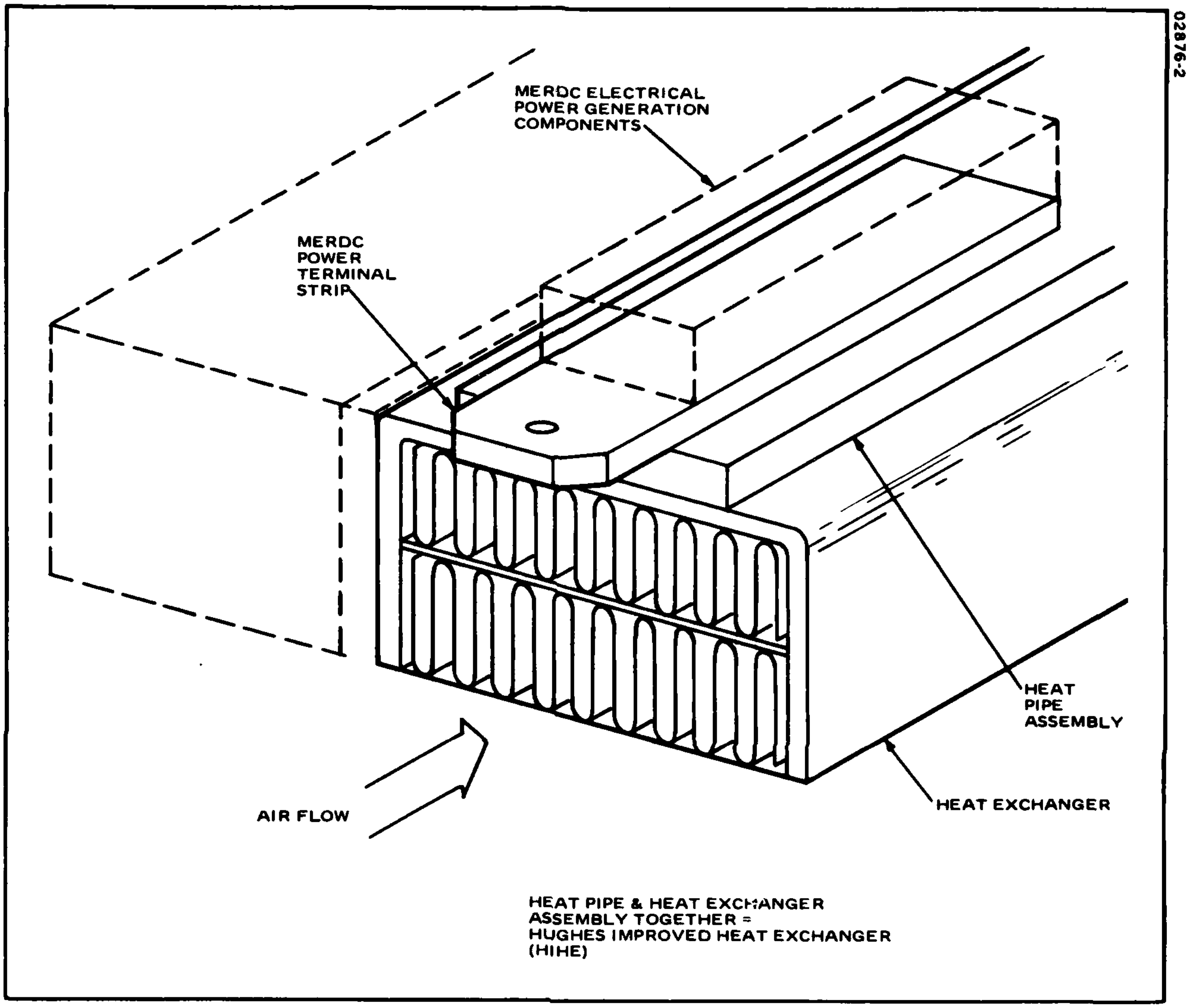

Figure 2. Basic Hughes Improved Heat Pipe and Heat Exchanger (HIHE)

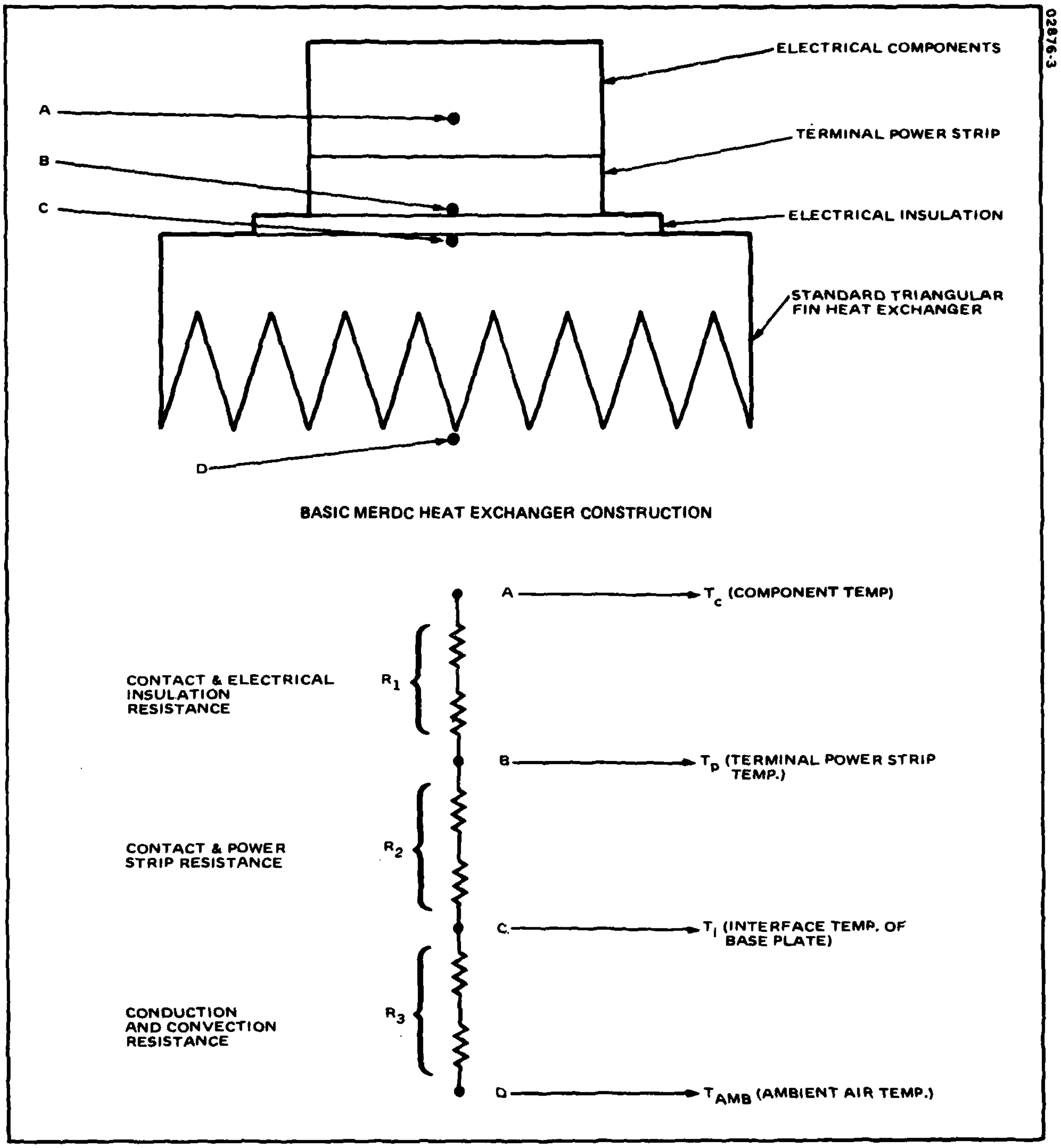

Figure 3. Heat Path and Thermal Resistance for MEROC IPS and Heat Exchanger

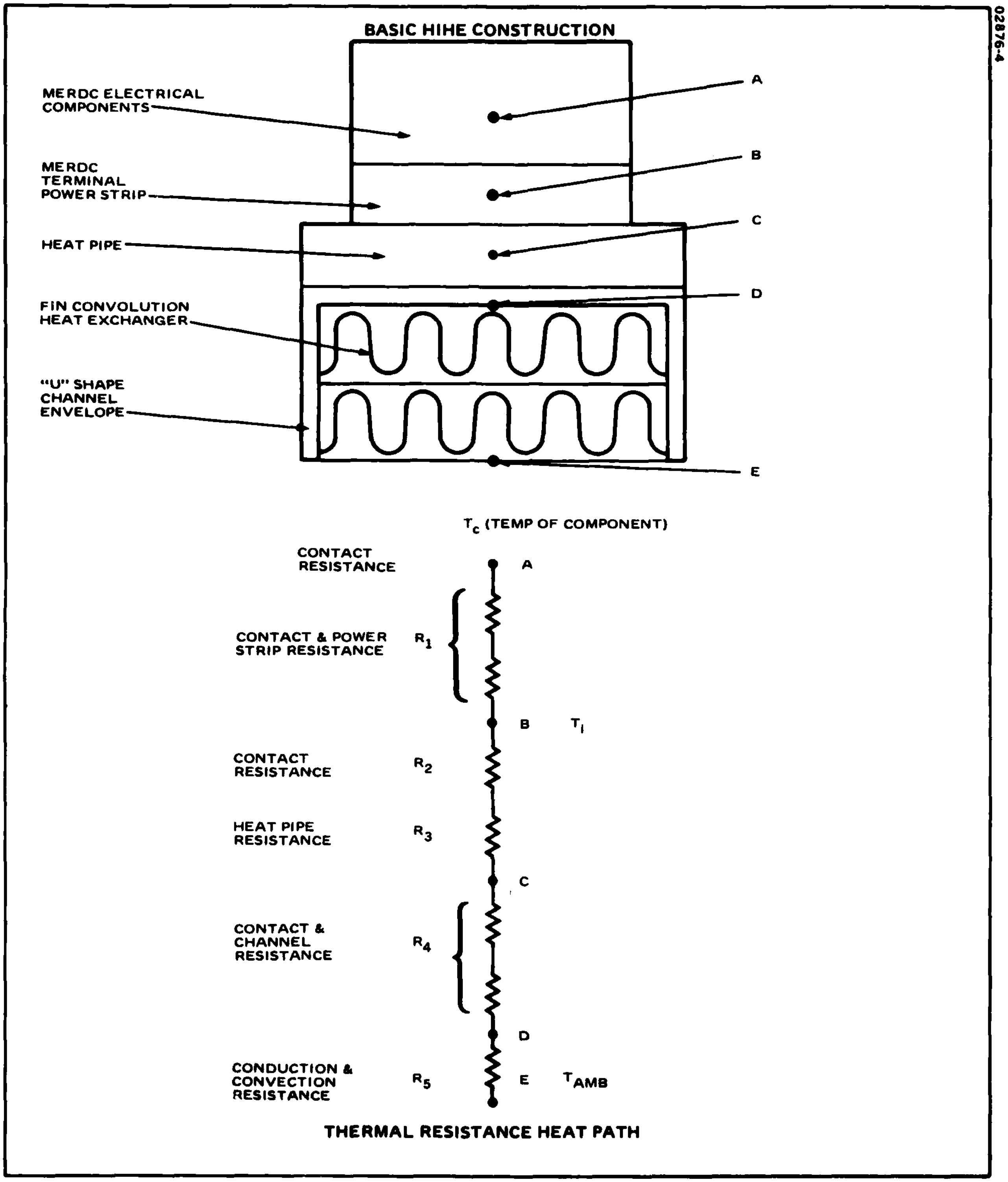

Figure 4. Heat Path and Thermal Resistance for IPS and Hughes Improved Heat Exchanger

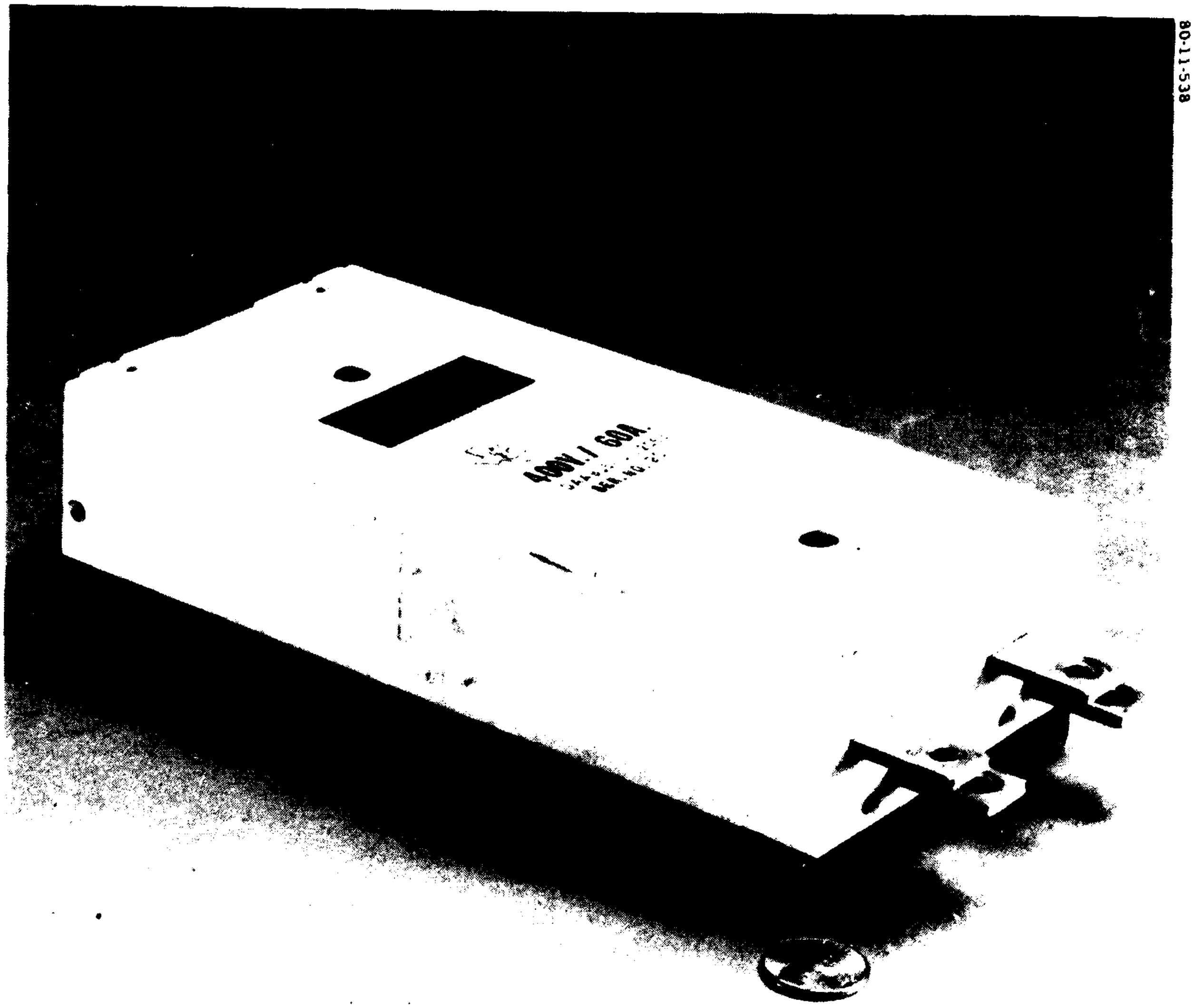

Figure 5. MERDC IPS Module (Closed)

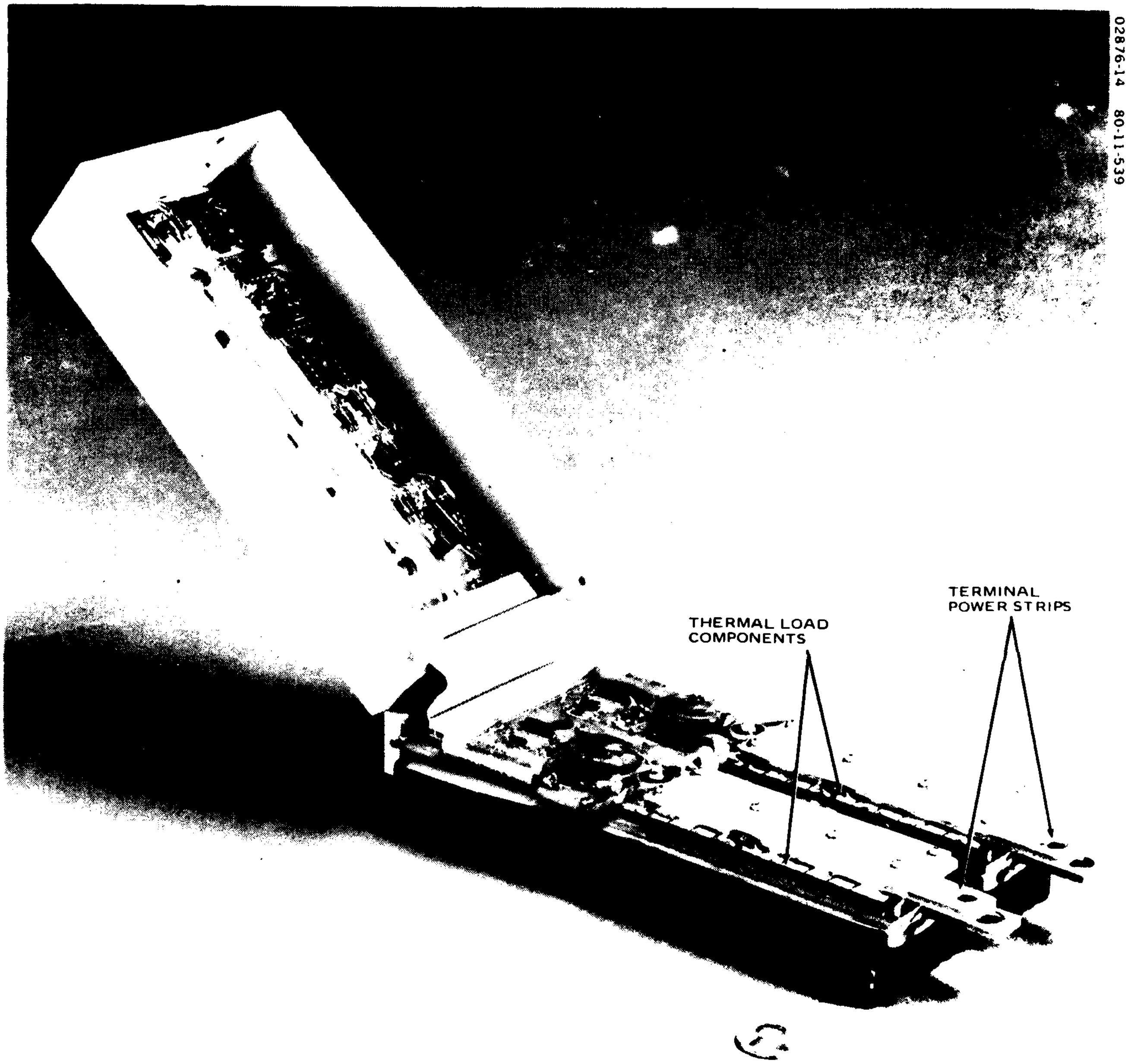

Figure 6. MERDC IPS Module (Open)

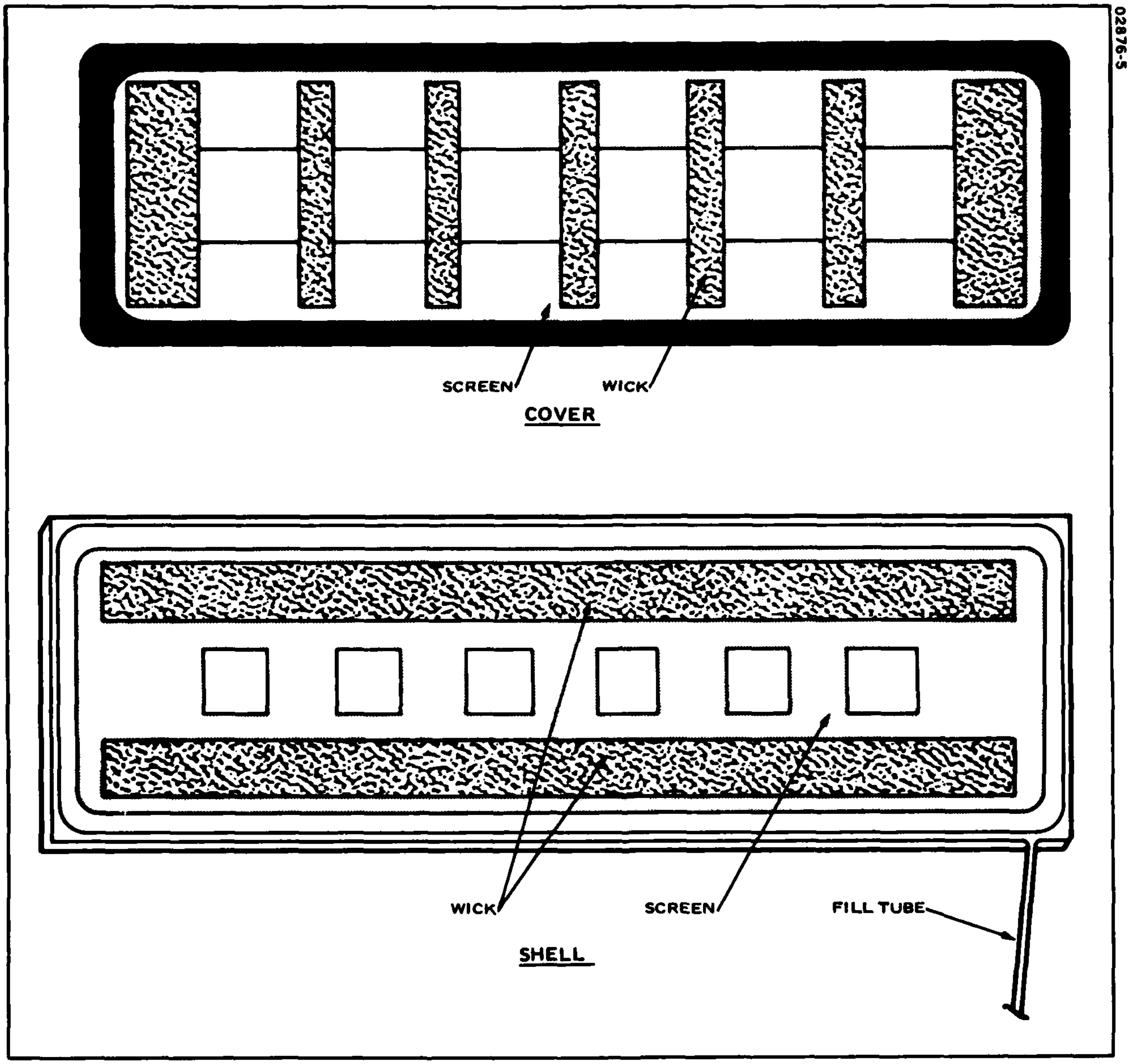

Figure 7. Prototype Heat Pipe Module Shell and Cover Open

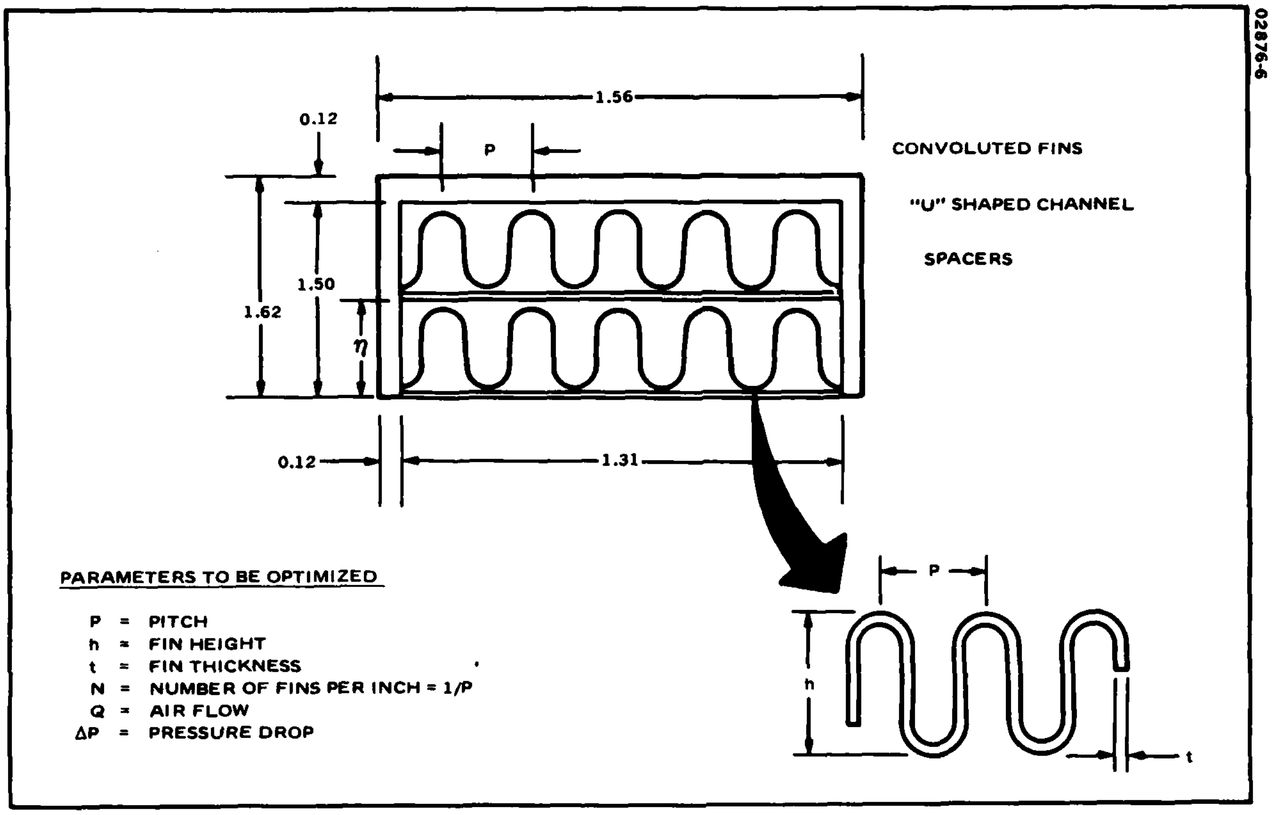

Figure 8. Heat Exchanger Parameters for Optimization Analysis

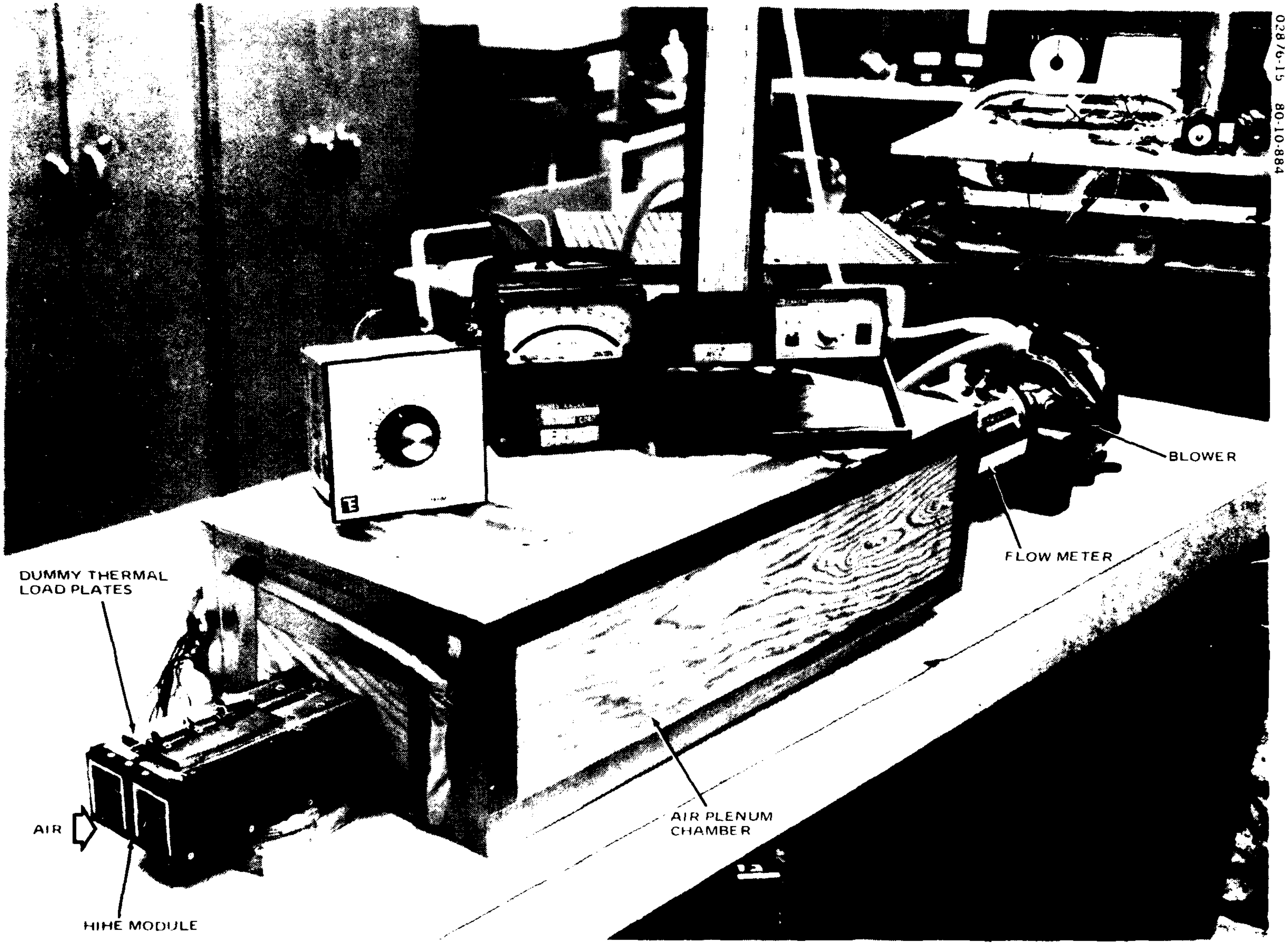

Figure 9. HIHE Module, Test Set-Up

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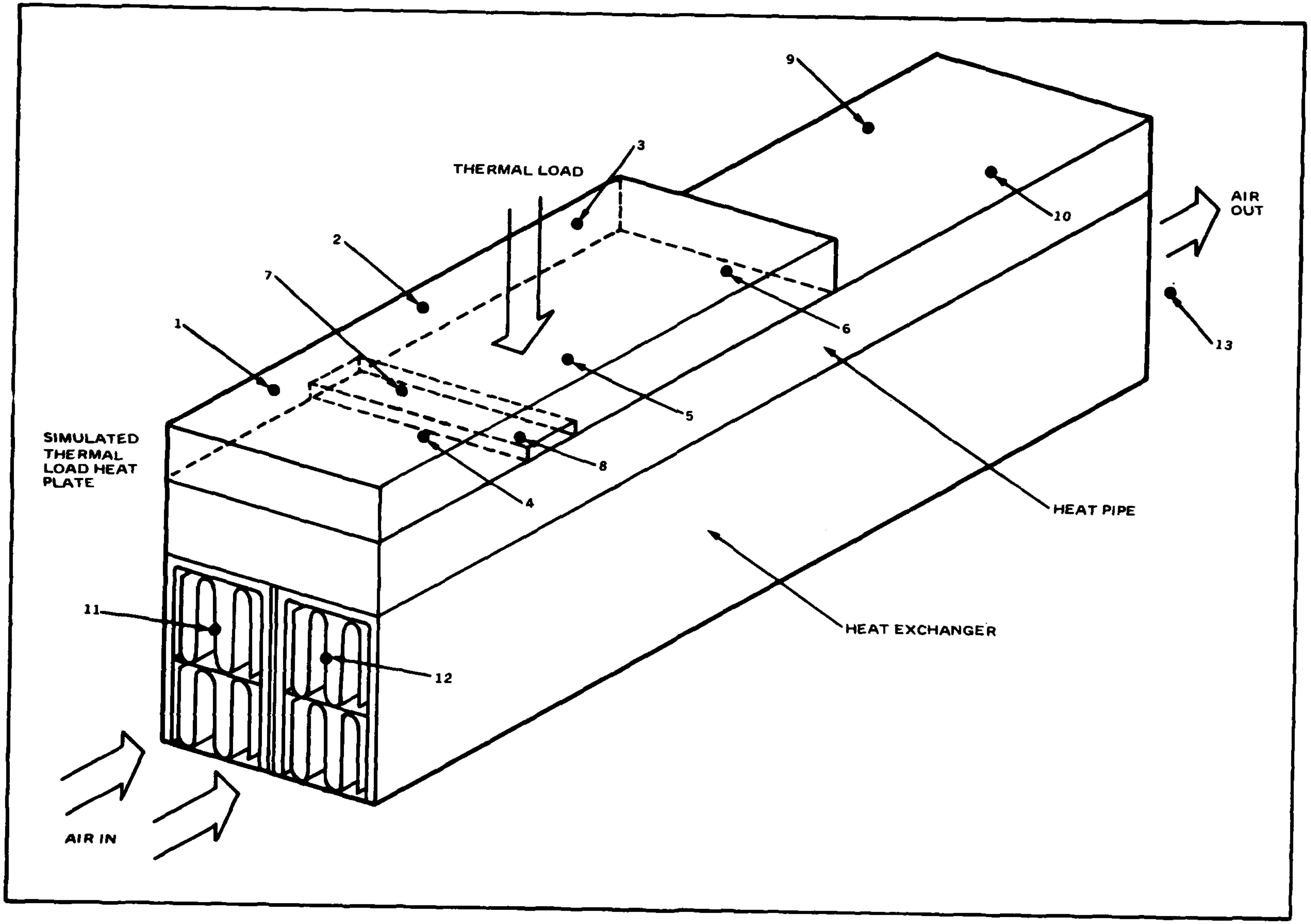

Figure 10. Thermocouple Locations, HIHE Performance Test.

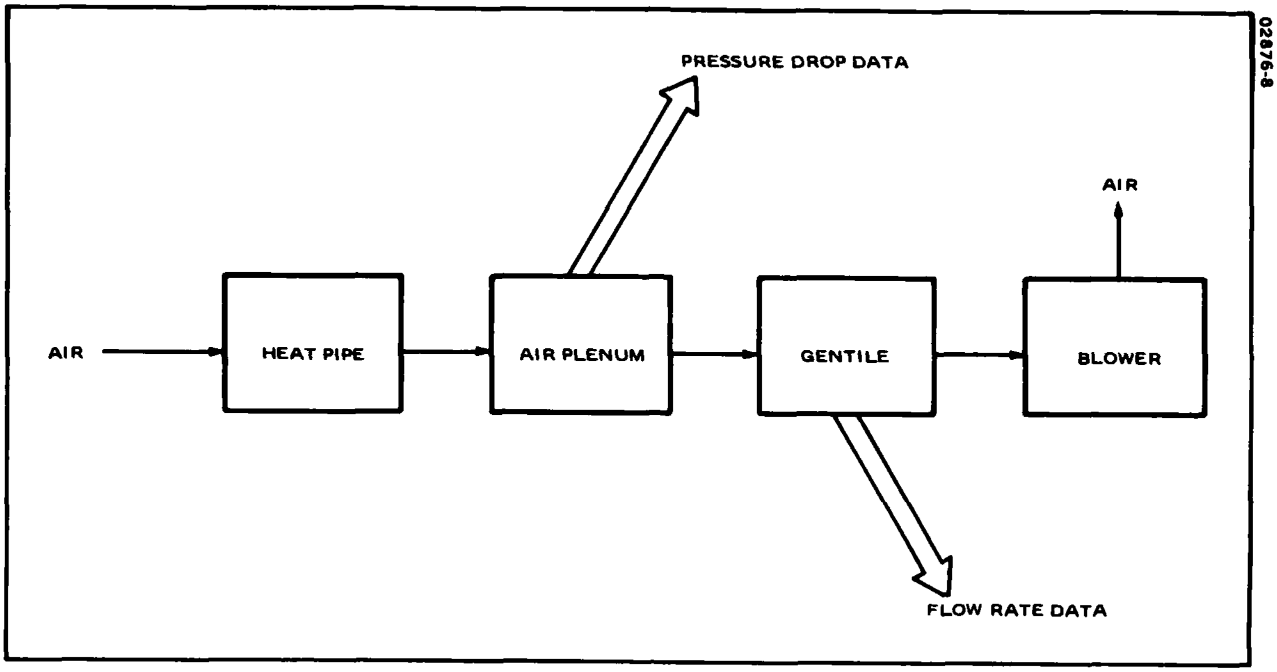

Figure 11. Diagram of HIHE Performance Test Set-Up

80 10-883

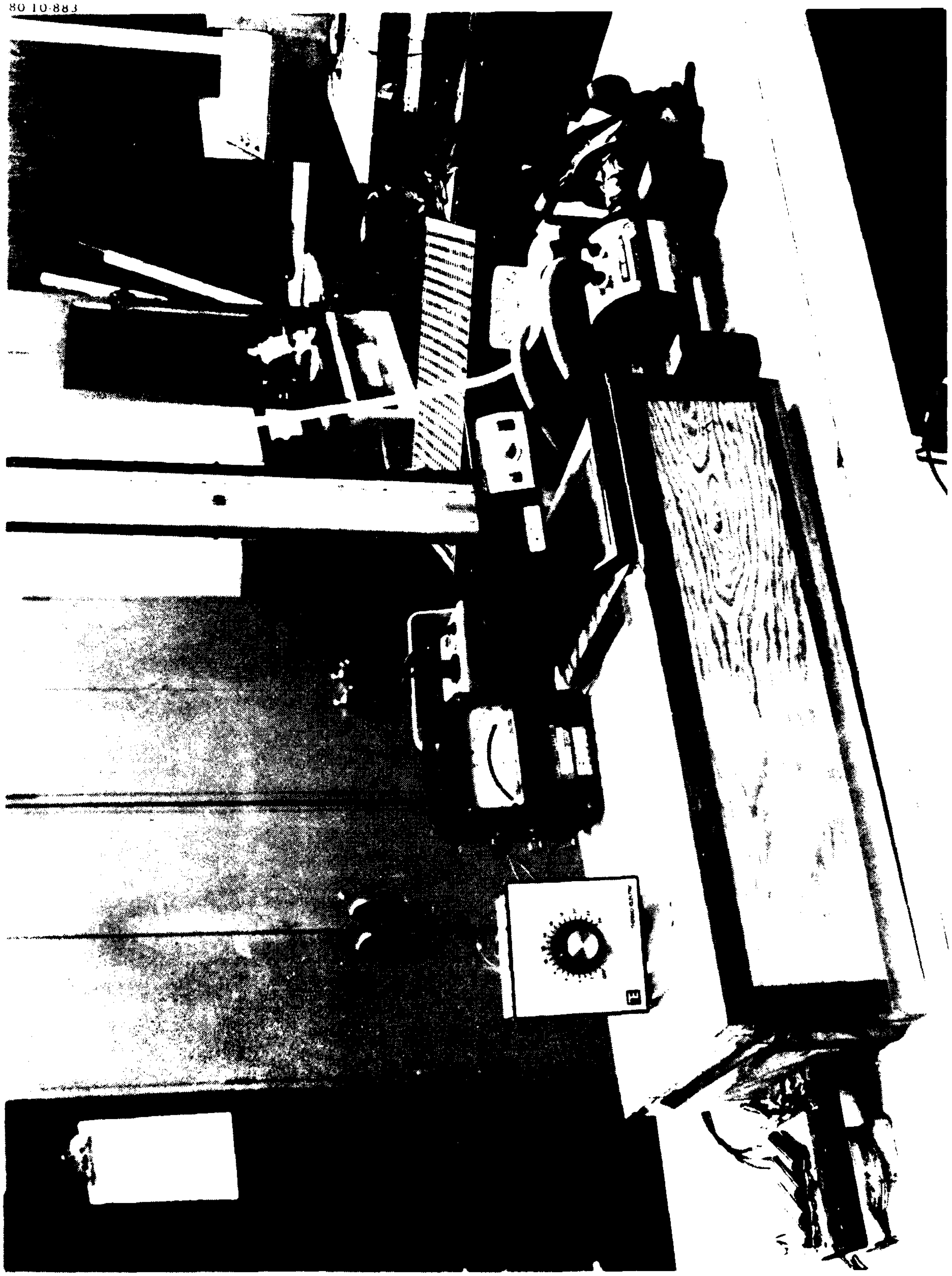

Figure 12. MERDC IPS Heat Exchanger Test Set-Up

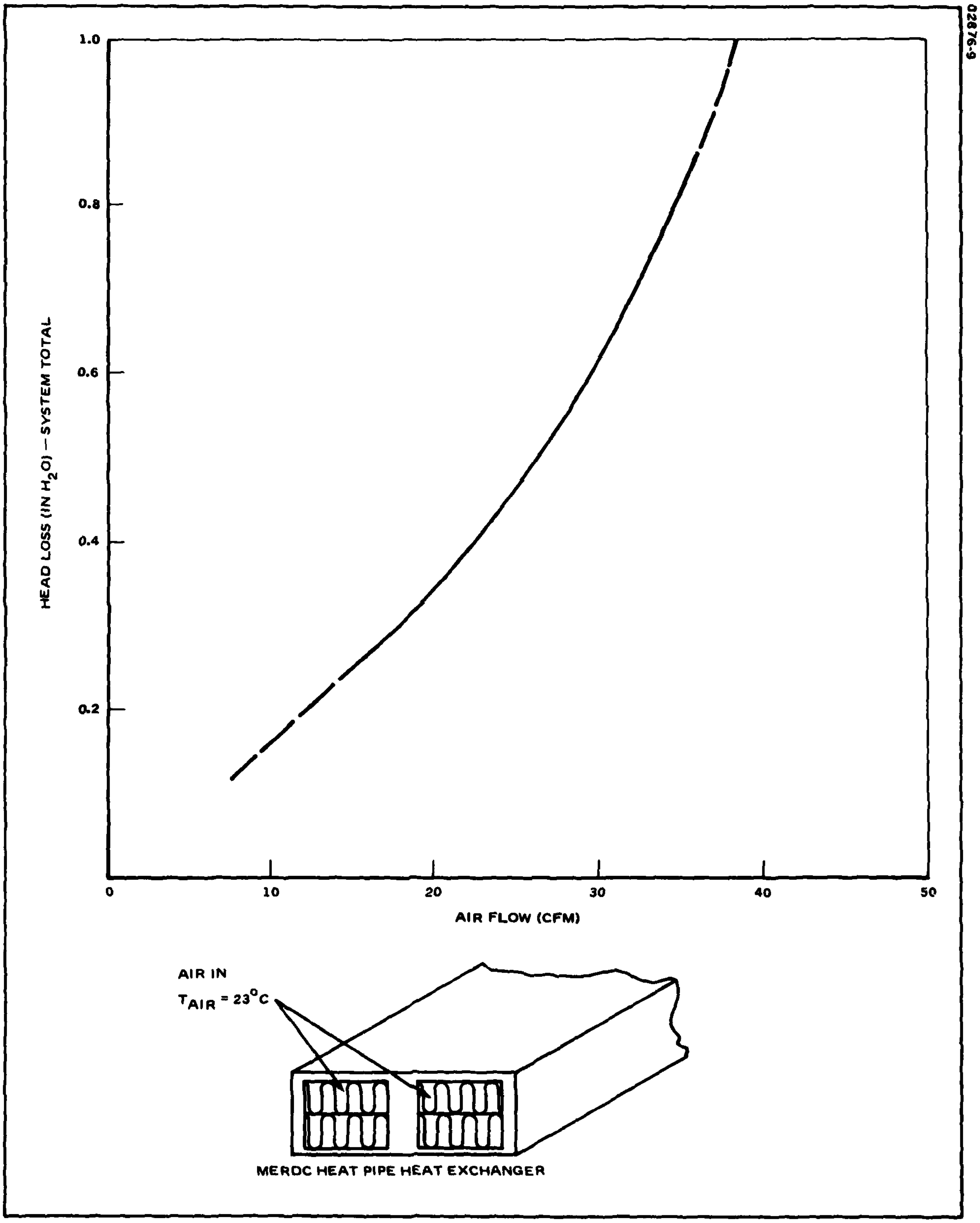

Figure 13. Pressure Drop versus Flow Rate, HIHE

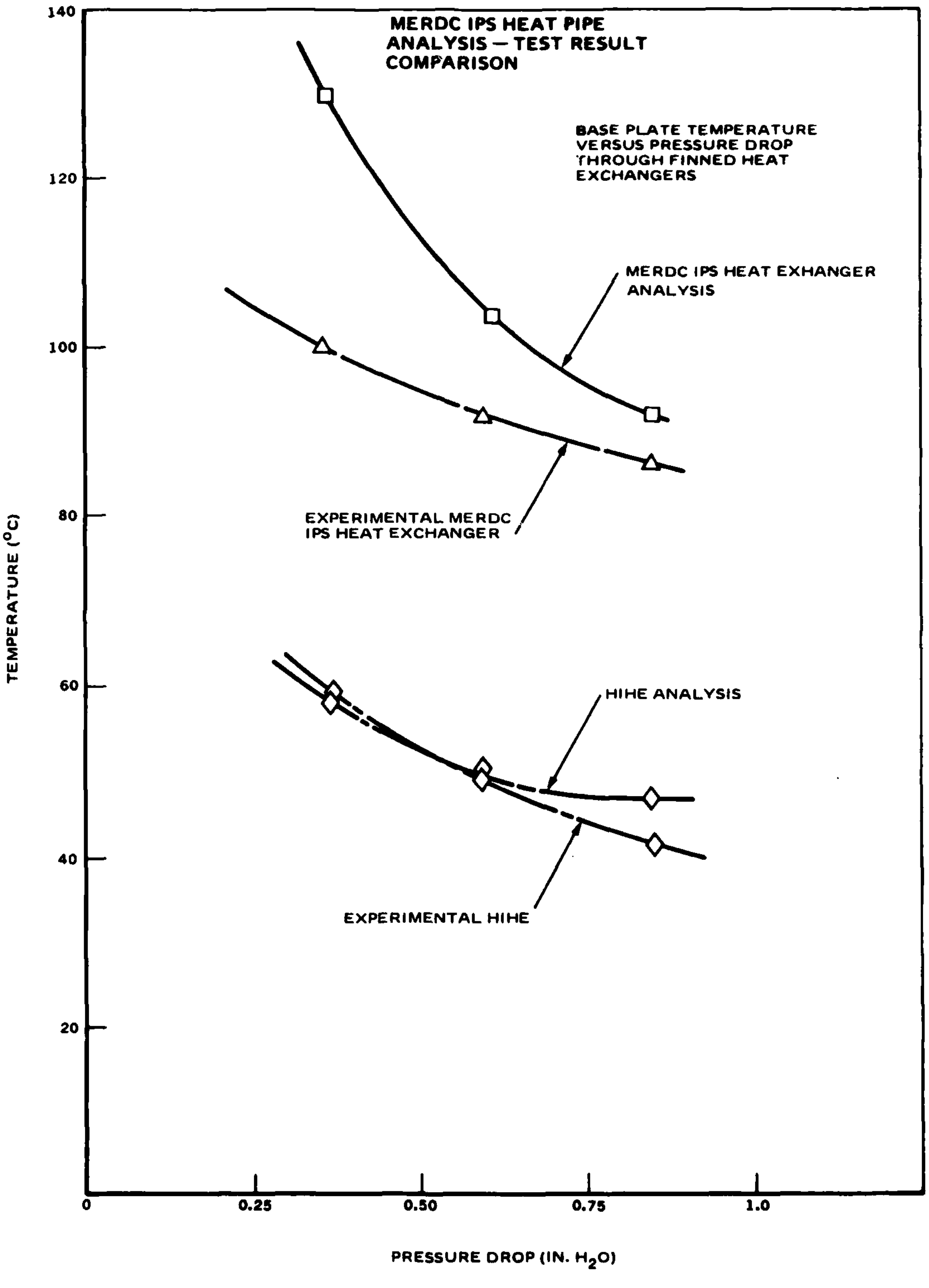

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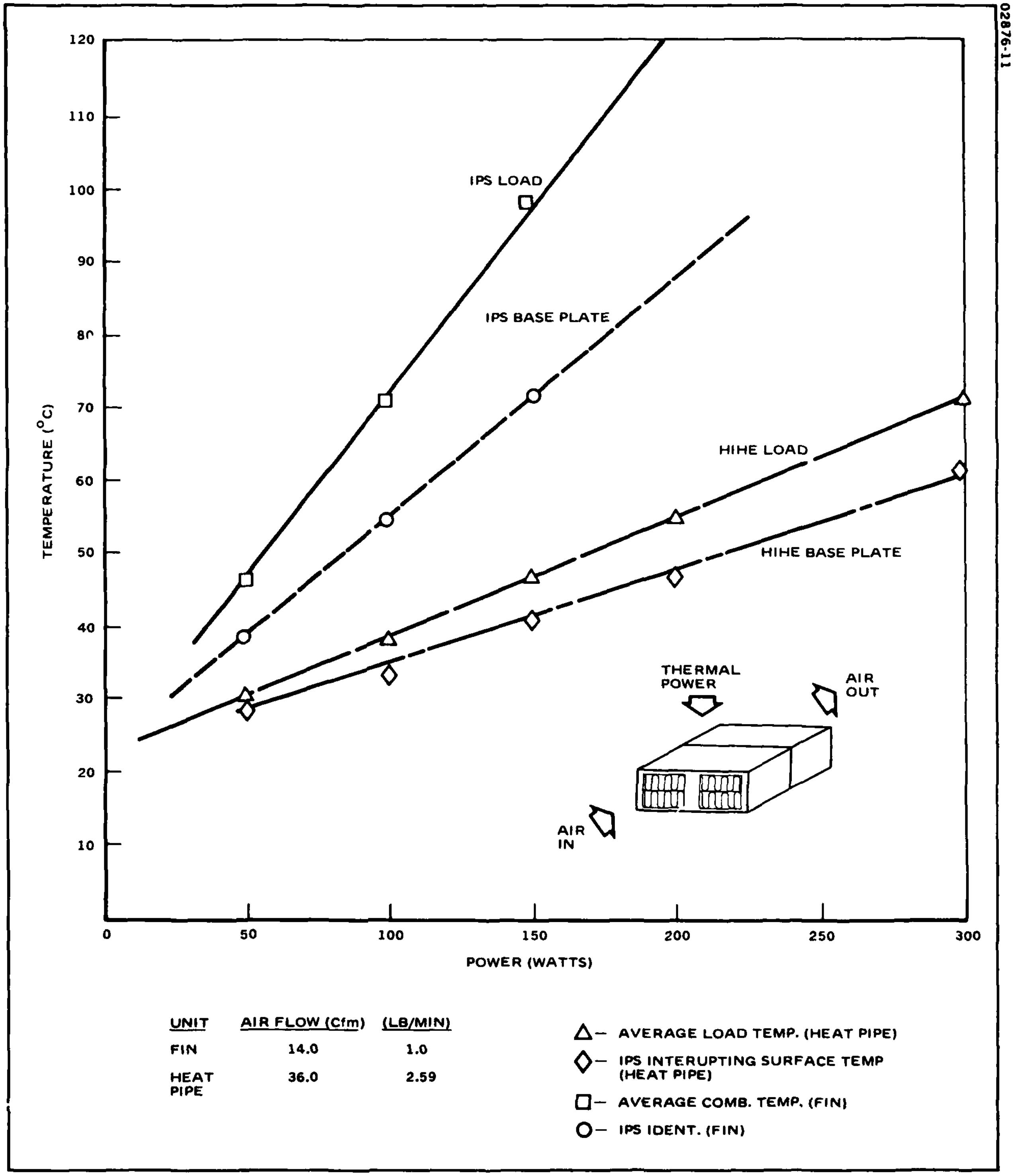
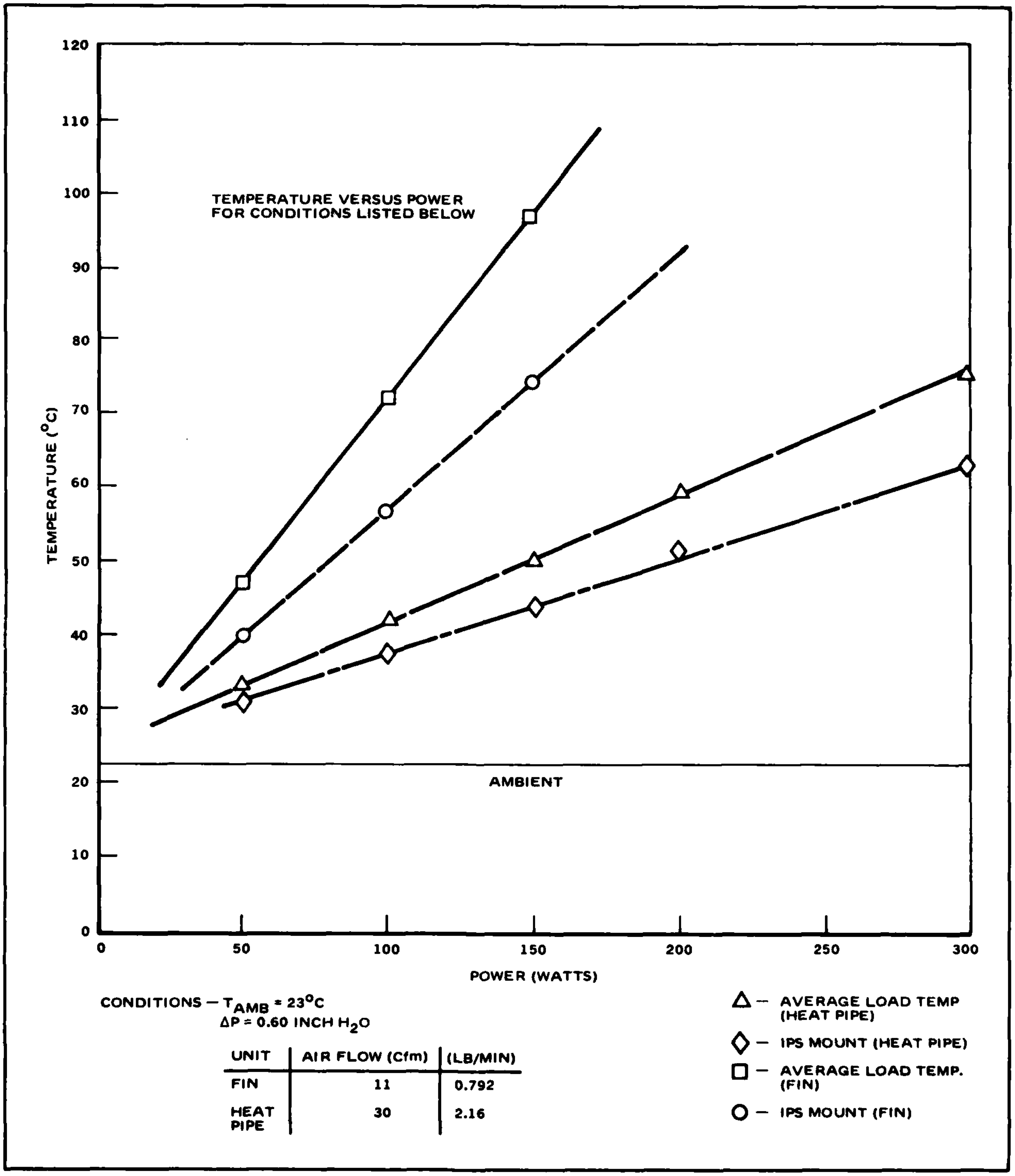
Figure 14. Temperature of Base Plate versus Pressure Drop



UNIT	AIR FLOW (Cfm)	(LB/MIN)
FIN	14.0	1.0
HEAT PIPE	36.0	2.59

△— AVERAGE LOAD TEMP. (HEAT PIPE)
◇— IPS INTERUPTING SURFACE TEMP (HEAT PIPE)
□— AVERAGE COMB. TEMP. (FIN)
○— IPS IDENT. (FIN)

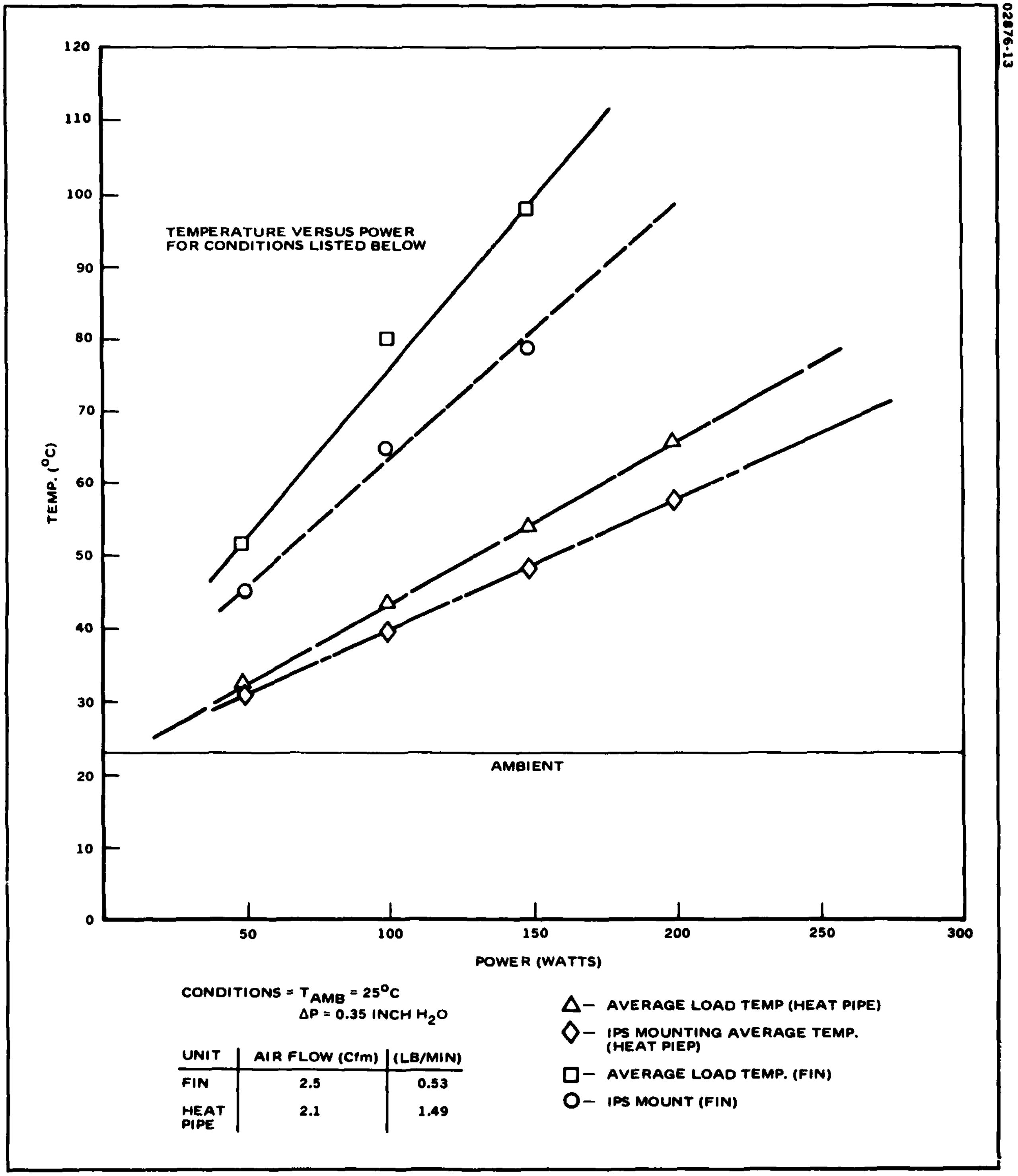
Figure 15. Power versus Base Plate Temperature (HIHE) $\Delta P \approx 0.85"$ H_2O



CONDITIONS – $T_{AMB} = 23°C$
$\Delta P = 0.60$ INCH H_2O

UNIT	AIR FLOW (Cfm)	(LB/MIN)
FIN	11	0.792
HEAT PIPE	30	2.16

Figure 16. Power versus Base Plate Temperature (HIHE) $\Delta P = 0.60"$ H_2O



CONDITIONS = T_{AMB} = 25°C
ΔP = 0.35 INCH H_2O

UNIT	AIR FLOW (Cfm)	(LB/MIN)
FIN	2.5	0.53
HEAT PIPE	2.1	1.49

Figure 17. Power versus Base Plate Temperature (HIHE) ΔP = 0.35" H_2O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