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SPACECRAFT HEAT REJECTION METHODS: ACTIVE AND PASSIVE HEAT TRANSFER FOR ELECTRONIC SYSTEMS - PHASE I

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A Phase 1 program has been completed which investigated the application of innovative methods for enhanced heat transport and storage in avionics, spacecraft and electronics systems. Microencapsulated phase change materials (PCMs) in a two-component water slurry were used with an active liquid-coupled, closed-loop system to provide significant enhancement of both the thermal capacitance and the heat transfer coefficients. The Phase I effort also sponsored the design and testing of a novel, miniature heat exchanger/thermal coupler and demonstrated the conceptual feasibility of removing excess heat from a simulated microelectronics device with internal 500 micron passages. No destruction of the microscopic PCM capsules was observed in the pumping process. In addition, both microencapsulated and pure PCM were used to passively reduce the temperature extremes of electronic components during transient surges as well as demonstrate the effectiveness of a PCM-filled flexible blanket for passive shielding from intense bursts of thermal irradiation or convective loads. Data illustrating the behavior of

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various materials are presented along with recommendations for further research during a Phase II effort.

The further development of these novel and innovative techniques for enhanced heat transport and storage could have significant impact upon the design and operation of thermal management systems for avionics, spacecraft and electronic systems where either or both weight and volume are critical. Removal of heat from electronic components improves both their performance and reliability. Further advancements in both materials and engineering systems can be expected. Significant interest has been indicated from several potential electronics and computer manufacturers.

PREFACE

The work described in this report was conducted as a Phase I Small Business Innovation Research (SBIR) program to explore the feasibility of using microencapsulated phase change materials (PCM) in spacecraft thermal control and electronic equipment cooling systems. The encapsulated PCM particles can be carried in a liquid slurry or mixed in coatings for electronic components or insulation blankets. Use of encapsulated PCM can improve both the efficiency and effectiveness of thermal control methods on both aircraft and spacecraft.

Principal investigator for the program was Dr David P. Colvin. Other significant contributions were made by the following personnel.

James C. Mulligan, Ph.D., Consultant
Karen Core, Mechanical Engineer
Charles Lord, Electrical Engineer
Yvonne Bryant, Ph.D., Research Chemist
Michael Gildner, Physicist
Virginia Colvin, Research Assistant
John Duncan, Electronics Technician
Raymond Whitney, Master Machinist

This report was submitted to the Air Force on 16 July 1986.

Results of this Phase I effort showed sufficient promise to warrant Phase II continued development. Technology will be pursued to demonstrate the availability of encapsulated PCM for use in advanced electronic cooling systems and to provide the engineering data necessary for these applications.

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INTRODUCTION

The thermal management of energy systems is important because of a significant increase in intense and cyclic thermal loads and the growing need to minimize systems weight and volume. In the case of spacecraft without sufficient energy transport or storage, the heating and cooling systems must be sized to satisfy maximum peak loads and thus must have considerable idle capacity for much of the time. If the combined weight or volume of a smaller system with sufficient thermal energy storage is significantly less without undue complexity, then a significant advantage can be achieved. The use of expendable fluids to transport heat away from a spacecraft may also not be a viable option because of potential damage and interference they may impose on optical or photographic sensors.

Future military spacecraft can be expected to utilize a variety of power systems for different mission applications. Many electronic instruments, particularly computer and avionic electronic components, are notably sensitive to temperature variations and thus could utilize enhanced thermal storage and transport as an advanced means of temperature control. The cooling of modern electronic components is one of the prime areas for the application of advanced thermal control techniques. Improvements in the reliability and packaging density of electronic logic and microwave devices can be traced to advances in thermal design. Consequently, the choice of thermal control technology and the particular decisions made in the course of evolving the thermal packaging design often have far-reaching effects on both the reliability and cost of the electronic system or assembly. In order to produce a successful military electronic system and competitive commercial electronic product, rational thermal design must begin at the earliest stage of product and system development. Insufficient attention to thermal control can lead to equipment failure and excessive replacement and maintenance costs. For spacecraft applications where long missions are involved, thermal energy storage becomes particularly important for maintaining the electronic and computer components. The development of phase change material (PCM) coatings or compounds for thermal control of sensitive electronics could also contribute to greater system reliability as well as a more optimal and simpler design.

In addition to the benefits of controlling temperature at their source with thermal storage, it may be feasible to utilize smaller thermal radiators for excessive heat rejection as well as smaller volumes of refrigerant, thus saving considerably on size and weight of these materials or components. The development of a systems-isolating, enhanced heat transfer thermal connector for use between two independent thermal control fluid loops could also be of great significance for thermal management of large spacecraft and electronic systems by permitting both fluids isolation and simple connection of modular components to a thermal bus using central heat rejection. Finally, the further development of a PCM flexible thermal blanket for shielding from transient radiation could also be of significant benefit to USAF missions.

In 1984, Triangle Research and Development Corporation proposed in an SBIR Phase I to NASA to investigate the concept of providing enhanced heat transport and storage with microencapsulated PCM slurries for application to thermal control in spacecraft. A Phase I SBIR was subsequently awarded which led to the present Phase II effort currently in progress. In the Phase I program for NASA, the basic concept was validated through analytical modeling using a simple heat exchange loop, and experiments were conducted to determine the potential reductions in pumping power possible and desirable for space applications where electrical power is limited. Some of the same problems encountered earlier by GE were also encountered in this initial work, although a milestone was achieved by finding suppliers of microencapsulated materials who were willing and enthusiastic about developing their PCM manufacturing processes. Experimentally, enhanced heat transfer and reduced pumping power were demonstrated in accordance with predictions, but capsule break-up under pumping also occurred. In the Phase II effort for NASA, more detailed research is being done to perfect the microencapsulation process, to eliminate the possibility of particle break-up, to develop improved slurry pumps, to characterize better the viscosity of such two-component fluids, and to determine experimentally the heat transfer and pumping power requirements of liquid-coupled heat exchange that uses such fluids. The emphasis for the NASA program is with environmental control systems at temperatures of 25 to 40 C and the process is believed to be useful to both volume and/or weight critical applications such as would be encountered in the space station. Work for NASA dos not directly include electronic or microelectronic applications.

During the course of the NASA work, it was recognized that a potentially important application is for the enhanced cooling of electronic and microelectronic components; i.e., if a two-component fluid can be designed by seeding it with extremely small PCM particles, then such a fluid slurry could be circulated directly through or around electronic circuitry components. Also, since many of these applications have adequate power supplies, the viscosity and pumping power do not play as important a role as enhanced heat transfer, thus the solids content could possibly be increased to truly maximize the heat transfer and temperature control without considering the penalty of increased pumping power. In addition, if microelectronic circuitry is to be thermally protected by circulating a two-component fluid through a closed-loop, it would be highly desirable to have some type of coupler or connector between individual circuit loops and a thermal bus coolant loop. A high heat flux, quick-disconnect coupler capable of efficiently connecting a secondary liquid loop to a primary heat dissipation loop is not currenty available, and the performance of such a coupler carrying a two-component fluid could only be imagined.

Other electronic heat transfer applications of microencapsulated PCM's were also considered for passive thermal control, wherein particles could be seeded within various types of potting compounds and used to coat electronic components to perhaps limit unwanted thermal transients. Another important potential application was for radiation shielding, wherein a layered configuration of ultra-thin reflective materials was cooled by microencapsulated PCMs between the layers. A flexible blanket or shield could be produced with enhanced thermal capacitance and be less sensitive or responsive to impulse and cyclic irradiation such as could be experienced by transient solar heating or laser pulses.

In the fall of 1985, a Phase I SBIR project was initiated with the USAF to study and demonstrate these latter concepts of utilizing microencapsulated PCMs for both active enhanced heat transport and passive, enhanced heat storage. This final report describes a summary of the important aspects of the Phase I work completed under the USAF sponsorship.

RELATED WORK

In the early 1970's, preliminary work on microencapsulation of phase change materials was begun at General Electric under the sponsorship of the U.S. Department of Energy. This was the first such attempt and was directed toward the development of a two-component heat transfer fluid for use in solar systems for residential applications. The work ran into early difficulties because of the premature break-up of the PCM particles in the fluid and the inexperience of the suppliers of the microencapsulated PCM's to develop new and improved processes. Most importantly, however, the work at GE was not continued by DOE because of the perceived high cost of the PCM materials and the belief that such a material could never be cost-effective in residential energy applications when compared with water. The entire concept, therefore, was left in disarray. Kaska and Chen in 1984 carried out an analytical study of the potential benefits of the idea and showed some remarkable improvements in heat transfer and temperature control that are possible in residential solar systems. Again, little interest was stimulated in the energy research community. The principals in the present project were also conducting phase-change energy storage research for DOE in the mid-1970's and had the opportunity to observe the GE work and discuss it with the participants at that time. Some successes were achieved although the overriding issue was the obvious inability of such storage concepts to compete with conventional means on a cost basis. Neither suppliers of the microencapsulated PCM nor DOE were enthusiastic about the work and it's high-tech image. The entire effort was dropped, only to surface again momentarily with the publication of Kaska and Chen. Meanwhile in 1984 Triangle Research and Development Corporation had proposed to NASA that the concept be further investigated for application to thermal control in spacecraft and a Phase I SBIR was awarded which led to the present Phase II effort currently in progress.

Programs relating to thermal energy storage have been conducted in the Mechanical and Aerospace Engineering Department of N.C. State University for the past twelve years. Dr. J. C. Mulligan has been involved either directly or indirectly in all of this work. Studies of natural convection within storage systems were carried out in the early 1970's under sponsorship of the National Science Foundation. The utility of phase-change energy storage in pure paraffins, also sponsored by NSF, was evaluated in the mid 1970's. Attendant to this work, investigations of the proper design of PCM thermal capacitors were carried out for NASA. Additionally, the performance of common waxes as PCM materials was evaluated under DOE support in the late 70's, using various types of macroencapsulation. Much of this work is referenced in the reference section of this report (1,3,14,15). More recently, a packed bed of macroencapsulated spheres of calcium chloride hexahydrate was designed for residential energy storage and incorporated into a heat pump system (12). In all of this, special emphasis has been placed on identifying candidate PCM's, evaluating cyclic performance, developing techniques of encapsulation, developing techniques of augmenting heat transfer, and evaluating system performance through mathematical modeling and experimentation.

Techniques and applications for microencapsulation have been widely investigated and discussed in the literature (4-7). Microencapsulation has been used for pressure-sensitive copier paper, medicines, perfumes and fragrances, various oils, rust-inhibitors, adhesives, colors, liquid crystals, fertilizers, military purposes such as smoke screen agents, powders, and propellants, and microballoons for gases. A number of devices have also been developed for production of these microcapsules; they include: in situ polymerization, orifice in-liquid process, aqueous solution phase separation or coacervation, complex emulsion, meltable dispersion and cooling, powder bed process, air-suspension or Wurster process, spray-drying, vacuum-evaporation deposition or NRC process, and electostatic bonding (4). The coacervation process has reportedly been used to microencapsulate PCM materials (5,17).

The National Cash Register Company has conducted extensive research into this area and has a number of products derived from this research. There are four types of encapsulation utilizing the system of phase separation from an aqueous solution: complex coacervation or phase separation resulting from two oppositely charged colloids neutralizing one another; simple coacervation where a nonelectrolyte, such as alcohol, causes formation of a separate polymer-rich phase; salt coacervation where a polymer separates as a result of a salting-out process; and precipitating and insolubilizing a polymer by changing the pH of the aqueous solution system.

George Britton, an engineer with the USAF PRAM office at Wright-Patterson AFB, has also indicated that PCM materials have been developed that can be used at temperatures to 200 C. Sizes can be as small as one micron in diameter with only 0.1 micron wall thickness. Sufficient quantities of the material have been produced and have been used within a fluid to provide its enhanced thermal storage and heat transport performance. William Haskin, our project officer at WPAFB, visited TRDC in May 1986 to observe our Phase I progress. He was shown PCM slurries under pumped conditions, primary and secondary fluid test loops, a miniature compact heat exchanger/thermal connector, a 500 micron microelectronic simulation device, PCM-encased electronic components, and a PCM-filled flexible thermal shield or blanket. The core material used for the Phase I USAF program was n-eicosane, a wax that melts at 39.6 C and available in 99.9% purity. Samples were obtained from two outside vendors who subcontracted for the job as well as by our own chemist, Dr. Yvonne Bryant, who has worked in microencapsulation for several years.

Dr. David Colvin, the Principal Investigator, has been involved in thermal science research and development for a variety of agencies and industries for over 24 years. At Boeing in New Orleans for 5 years, he was responsible for the development of thermal instrumentation including both total and radiation calorimeters and heat transfer analysis on the NASA Saturn/Apollo S-1C. His doctoral research was conducted at the NASA Mississippi Test Facility on thermal scale modeling of spacecraft radiators using forced convection, conduction, and radiative heat transfer (8,9). He later moved to NASA-Houston where he was involved in the science management of three Apollo ALSEP experiments for lunar heat flow on Apollo 15, 16, and 17 as well as the infrared scanning radiometer and surface electrical property experiments on Apollo 17. While at the MSC, he also assisted other scientists in the determination of the thermal conductivity of lunar soil (10). Dr. Colvin has also been involved in numerous programs that included precision thermal measurements and control as well as university projects in energy conservation and solar energy. His relationship with N.C. State University as an Adjunct Assistant Professor goes back a number of years and he has sponsored the graduate research of a number of students.

Triangle Research and Development Corporation is currently investigating for NASA-MSFC in Huntsville the potential application of particular microencapsulated PCMs for enhanced heat transfer and storage with emphasis toward development of a liquid packed-bed energy storage module as well as an initial study of a two-component liquid slurry for enhanced thermal management for environmental control in the space station. Laboratory tests using a 2,500 micron macroencapsulated PCM (methyl palmitate) in a packed bed has been conducted and both the heat transfer coefficients and effective specific heats using a liquid slurry with 30 micron particles have been investigated.

The NASA Phase I results indicated both a significant enhancement of heat transport and storage using PCMs. Since NASA is primarily concerned with pump work, most of the reported data was in that regard. It was shown that the data closely matched the analytical computer modeling for water. The data showed a significant improvement in the heat transfer coefficient by the use of the PCM slurry with 30 micron particles. Likewise the data appeared to indicate approximately a 3X improvement in the effective specific heat, but premature breakup of the microencapsulated PCM particles prevented further confirmation. In the Phase I NASA effort, it was noted that there was a 90% reduction in pumping power using the PCM slurry. Based upon these results and the promise of further development, NASA awarded TRDC a Phase II SBIR in 1985. Under their sponsorship, we have continued our PCM materials development, our analytical computer modeling, developed improved slurry pumps, constructed new primary/secondary fluid loops together with improved instrumentation and a data acquisition system, and plan to run extensive slurry tests with stackable macroencapsulated PCM thermal storage modules to determine PCM fatigue life, specific heat enhancement, and system model scaling factors. The equipment in these NASA systems were used for testing of the slurries for the USAF Phase I effort. Some components that were unique to the USAF effort were purchased under its budget, but most of the equipment was purchased for NASA. Practically all of the USAF Phase I funds were alloted to R&D labor and purchase of slurry materials.

Because of the many and varied applications of thermal energy storage in spacecraft and space station design, no generally applicable and optimal technique has evolved to date. Many techniques have been studied ranging from the commonplace to the exotic. Some have specific high temperature applications and others are directed to the lower temperatures. Some utilize expendable materials whereas others may use non-expendable substances. The use of sealed PCMs in spacecraft temperature control was first introduced in 1965 with a rather exhaustive study of their application to electronic temperature control (11). Since that time, the use of phase change energy storage materials (PCMs) has been studied extensively for space as well as terrestrial applications (3,12-15). In all of this work, the design of PCM thermal capacitors of various configurations was undertaken. The advantages of the solid-to-liquid phase change technique are high energy storage density, relatively low weight, and stability and reversibility under frequent cycling. Such materials as pure paraffins, waxes, inorganic salts, and even some metallic compounds have been used. A listing of potential candidate materials has also been compiled (15-18).

The difficulties encountered in PCM thermal storage have mostly revolved around excessive cost for terrestrial applications and the encapsulation in general. Most PCMs are not good heat conductors; they experience significant volume changes with change-of-phase, and some have surface tension characteristics which make them difficult to contain. The major task for their usage in a particular application, therefore, is to design a method of encapsulating the PCM in order to facilitate rapid heat transfer and minimize or eliminate PCM leakage. For terrestrial applications, these difficulties forced costs to significantly exceed those for water tank and rock bin storage - options which do not have the isothermal, minimum weight, and small size requirements of a space station. For spacecraft, PCM thermal storage offers profound advantages when these difficulties can be overcome. Most of the work which has been carried out on PCM thermal storage has utilized macroencapsulation. Hexcell honeycomb filled with paraffin (14), rectangular-finned straight tube heat exchangers filled with wax (15), corrugated-plate finned tube heat exchanger filled with wax (15), and spherical shells filled with calcium chloride hexahydrate in a packed bed (3) all offer possible applications in spacecraft temperature control.

A promising technique of using microencapsulation was studied briefly by General Electric (2) for terrestrial applications and offers the potential of very high energy storage rates, high energy density, very high surface area-to-volume ratios for the PCM, and the exciting possibility of mixing microencapsulated PCMs of different melting temperatures and thus creating a storage medium applicable to both high as well as low temperature situations. To our knowledge, the technique has not been studied in relation to its potential in spacecraft thermal energy storage.

Kaska and Chen at Argonne National Laboratory have indicated that a slurry containing a PCM will have much higher heat transfer coefficients than conventional single-phase working fluids, but they did not produce any experimental data to substantiate that claim. Because of the high latent heat, the phase-change slurry also requires lower pumping rates and smaller volumes than single-phase fluids for the same energy content (18). Earlier discussions with Dr. Arnold Mayer at WPAFB at the ASME winter annual meeting in 1984 indicated their interest in the application of microencapsulated PCM slurry to enhanced cooling and thermal conditioning of avionic electronics and microelectronics (19). It is felt that the development of both heat sink compounds and active slurries could significantly improve component operation, stability, and lifetimes (21). Likewise, the development of a thermal connector for coupling of isolated systems could be of significant value for centralization of thermal management equipment aboard large spacecraft.

Computer modeling of PCM slurries has been initiated by Sengupta at the University of Miami (22). Such research has also been disclosed by Bahrami at JPL (23). The need and applications of thermal analysis and control with electronic equipment has been published by Kraus and Bar-Cohen (24). Advanced methods of electronic cooling such as with the IBM TCM module has also been discussed by Chu and Simons (25). A fine review paper of advanced methods of liquid cooling of electronic modules was published by Oktay at IBM in the March 1986 issue of Mechanical Engineer (26). Tuckerman at Stanford Electronics Laboratories has also studied the heat-transfer microstructures for integrated circuits including the use of substrate microcapillaries for enhanced electronics heat transfer (27). Finally, advanced techniques of microelectronic heat transport were discussed by Bergles, Kroman and others at the AIAA/ASME 4th Thermophysics and Heat Transfer Conference in Boston in early June, 1986 (28,29). The enhanced heat transport provided by microencapsulated phase change materials in a two-component slurry for NASA will be discussed by Colvin at the ASME/JSME conference in Hawaii in March 1987 (30).

PHASE I TECHNICAL OBJECTIVES

The general objective of the USAF Phase I project was to investigate various ways in which small diameter microencapsulated phase change materials or PCMs might be used to aid in temperature control and thermal protection of electronic and microelectronic components. Various specific concepts were to be demonstrated and preliminary tests and evaluations carried out. These specific objectives were as follows:

1. Utilize an experimental liquid-coupled fluid loop to demonstrate the use of a small particle, two-component fluid slurry as a circulating heat transfer media;

2. Develop a small particle, two-component fluid that can be pumped without destruction and which can be utilized in the experimental loop to demonstrate enhanced heat transfer and temperature control;

3. Develop a high heat flux, compact, quick-disconnect coupler that could be used to demonstrate the coupling of the experimental loop to a primary cooling loop and evaluate the performance of the coupler;

4. Demonstrate and evaluate the use of microencapsulated PCM in laminated thermal shielding;

5. Demonstrate and evaluate the use of microencapsulated PCM in a putty or paste for passive temperature control of electronic components.

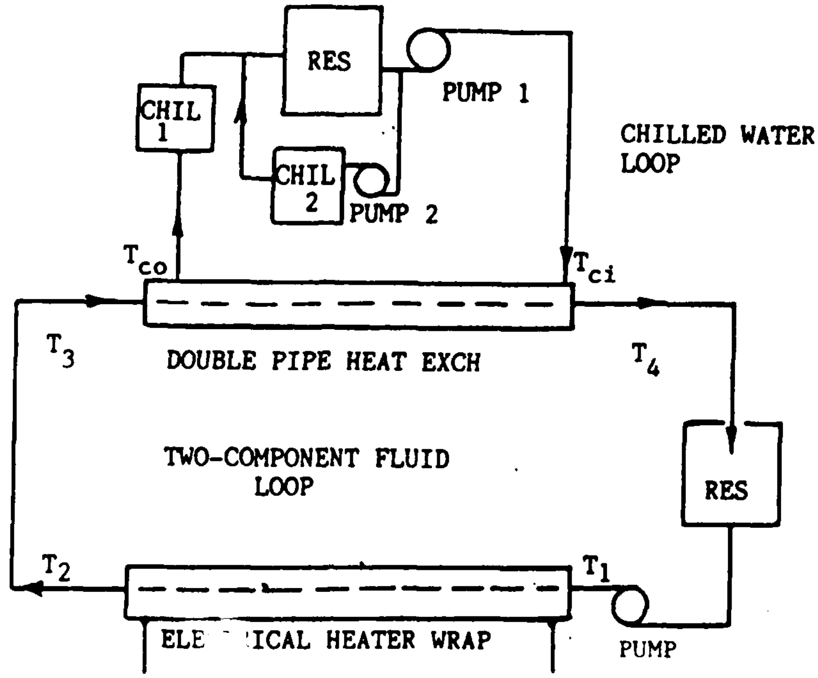
PHASE I TEST RESULTS

1. Experimental Cooling Loop Test Results

For practical applications, the two-component fluid would be used in a circulating, liquid-coupled, heat exchange loop, wherein heat released by electronic sources would be transported within a primary heat rejection loop via a heat exchanger to another secondary heat rejection loop or thermal bus. The primary fluid loop which was adapted for this project consisted of an electrical heat source, a variable-speed pump, a fluid reservoir, connecting tubing, and a heat rejection heat exchanger coupled to a secondary cooling loop. The system was designed so that the rejection heat exchanger could be removed and replaced with the compact, high heat flux, quick-disconnect connector which was designed and constructed as part of the project. The heater element could also be replaced by the simulated microelectronic element. A schematic of the system is shown in Figure 1.

The experimental fluid test loop was designed for three purposes. First, performance tests would be run on a two-component slurry in the loop in order to evaluate the enhancement of the heat transfer and collect meaningful data characterizing the heat transfer fluid. Hence, it was anticipated that the loop would be used principally for research. Toward this end, components were selected to optimize the information obtained. For example, the internal diameter of the loop is uniform throughout and smooth to reduce pressure losses and limit flow obstructions. The heating element was designed to deliver a constant and relatively uniform heat flux to the fluid in order to facilitate an accurate determination of an inside heat transfer coefficient. A double-pipe heat exchanger was used as a heat rejection coupler because the theoretical performance of this type of component is known at the outset. Thus, with such a system, experiments can be run at a variety of heating rates to determine the performance of the fluid slurry when compared to water.

A second objective in designing the system was to demonstrate the use of the quick-disconnect coupler by replacing the double-pipe rejection heat exchanger with this prototype device.



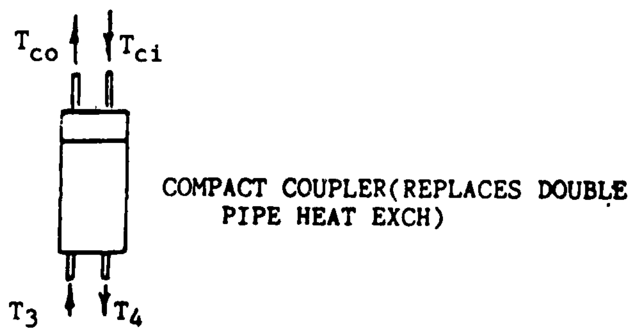


Fig. 1. Schematic of Test Loop Showing Standard Double-Pipe Heat Exchanger and Compact Coupler

In this configuration, information can be obtained on the performance of the coupler although full and complete information from the fluid tests were not obtained because of the limited thermal capacity of the coupler. Such information was not necessary, however, since it could be obtained with the loop in the initial configuration. The heating element in this loop is a 1/8 inch diameter heater wire wrapped around a straight 1/4 inch diameter thin wall copper tube. A length of 36 inches and a wrapping pitch of approximately 1/2 inch provides up to 1500 watts of electrical input to the loop, distributed uniformly over the surface of the heater. This device was custom manufactured specifically for this work.

A third purpose of the experimental test loop was to demonstrate the system's ability to remove excess heat from a simulated microelectronics device with multiple micron-sized passages. For the purposes of the Phase I effort, it was decided that the conceptual feasibility could be satisfactorily demonstrated by replacing the electrical heater with such an element. The prototype Phase I microelectronics simulation device consisted of an insulated aluminum block, 1.5 inches square by 0.5 inch thick, with four 10-watt precision resistors mounted around its perifery. Electrical power was applied and the generated heat was conducted into an internal web containing over 625 drilled holes, approximately 500 microns in diameter. Fluid flowing through the web was sufficient for the removal of the 40 watts of heat generated by the resistors. It is anticipated that considerable more energy can be removed by the PCM slurry and further testing is planned during the Phase II effort.

A chilled water loop, developed for a NASA Phase II program and shown in Figure 1, was utilized to provide proper heat rejection and control for these experiments. Two chillers are used, together with a 50 gallon, insulated reservoir. With this system, it was possible to supply an unlimited amount of chilled water at a preselected temperature from 6 C to 25 C, and maintain primary loop fluid flow without significant thermal deviation. This capability is very important to permit the balancing of the hot and cold sides of the two-component fluid loop. Ideally, the loop should operate near it's melting point (39 C in the case of n-eicosane, and 29 C in the case of methyl palmitate,) with only a few degrees deviation on the hot and cold sides of the loop. The system's chiller loop provides this capability. A computer-based data acquisition system was also developed for use with the project. The system uses an Apple II+ microcomputer with a 10 MB hard disk and is capable of multiple thermocouple and voltage inputs, floppy disk storage, processsing, and print out. We believe this system will play an important role in future work.

2. Microencapsulated PCM Slurry

Much of the effort for the USAF Phase I project was devoted to the development of microencapsulated PCM's of small diameter for potential use in microelectronics. In our previous Phase I NASA project, larger particles were used with, in some respects, disastrous results. They were successful thermally and from a heat-transfer point-of-view, but structurally they were not strong enough to withstand pumping and would not satisfactorily contain the PCM. Hence, our first priority in the Air Force project was to find out why the previous material broke up, to develop the qualification specifications, to find suppliers who could provide us the material to meet our specifications, to find a pump which would not destroy the particles, and to test the materials for integrity under pumping conditions. This was all done successfully. Two suppliers were identified who are capable of supplying materials with the quality and in the quantity that we requested. Small diameter PCM particles (5-15 microns) were subsequently purchased from the two companies and tested. It was found that these materials could be pumped continually for up to three days around the loop while being alternately heated and cooled, without any evidence of rupture. This was believed to be a milestone in the development of useful two-component PCM fluid slurries.

One of the most important characteristics of such a PCM-slurry loop is its ability to be tuned. That is, by properly adjusting the cooling load (coolant flow rate and inlet temperature), the heating load (electrical power), and the fluid flow rate, the fluid can be made to operate within a small temperature range just bounding the PCM melting temperature. Under these circumstances, the apparent heat capacity of the fluid, C_p , will become very large since most of the heat is absorbed and released in phase change, and the overall ΔT of the loop will be at its minimum. Such behavior has never been demonstrated before, although theoretically it was clearly possible. This can be clearly demonstrated as seen by the relatively large values of specific heat illustrated in Figure 2. Clearly, seeding a carrier fluid with microencapsulated PCM dramatically increases the specific heat if the loop is operated properly; i.e., with a small ΔT. The various data points in Figure 2 correspond to the different slurries provided by the suppliers.

During the course of the experimentation some unanticipated behavior was also observed. First, a phase-reaction kinetics problem was observed in that at the higher flow rates, the particle phase change (melting) did not completely occur in the heater tube but required an additional insulated length of tube to fully complete the phase-change within the microparticles. This behavior was very pronounced in all of our runs at higher flow rates and introduced difficulty for fully measuring the heat transfer. It did not appear to occur in the cooling process (freezing) on the heat rejection side of the fluid loop. Apparently the kinetics during heating are somewhat different from those during cooling. Secondly, the pressure drop and increased viscosity difficulties which we had experienced previously in the NASA Phase I work were not as severe in this USAF work. The enhancement of the heat transfer coefficient is illustrated in Figure 3. In these experiments, coefficients of approximately 2.75 times those of laminar water were observed, and compare to 2.75 to 3.5 in the NASA Phase I work. The

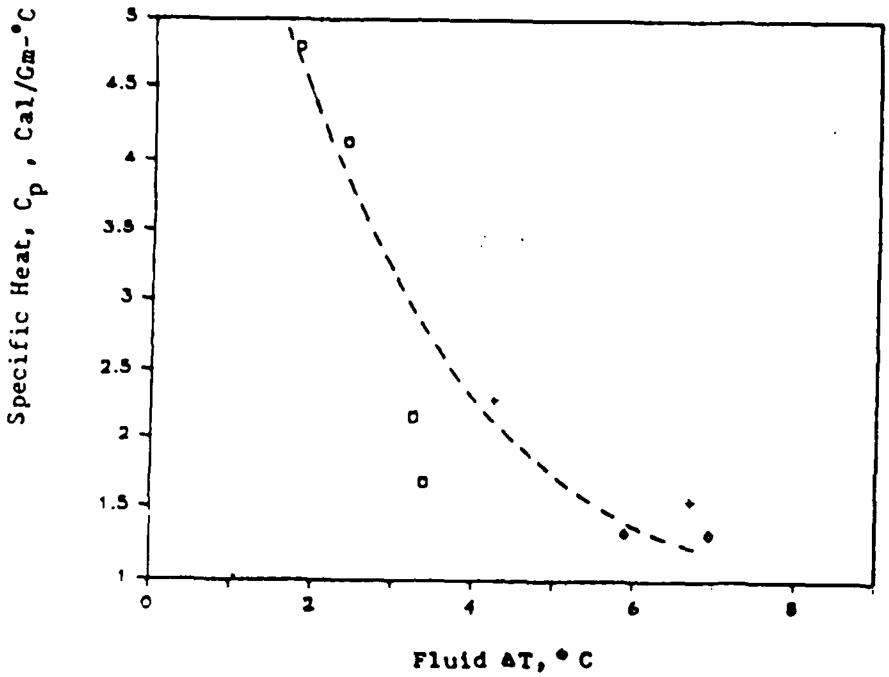


Figure 2. Slurry Specific Heat Versus Slurry Temperature Change, Illustrating Loop Tuning and High C_p that Results

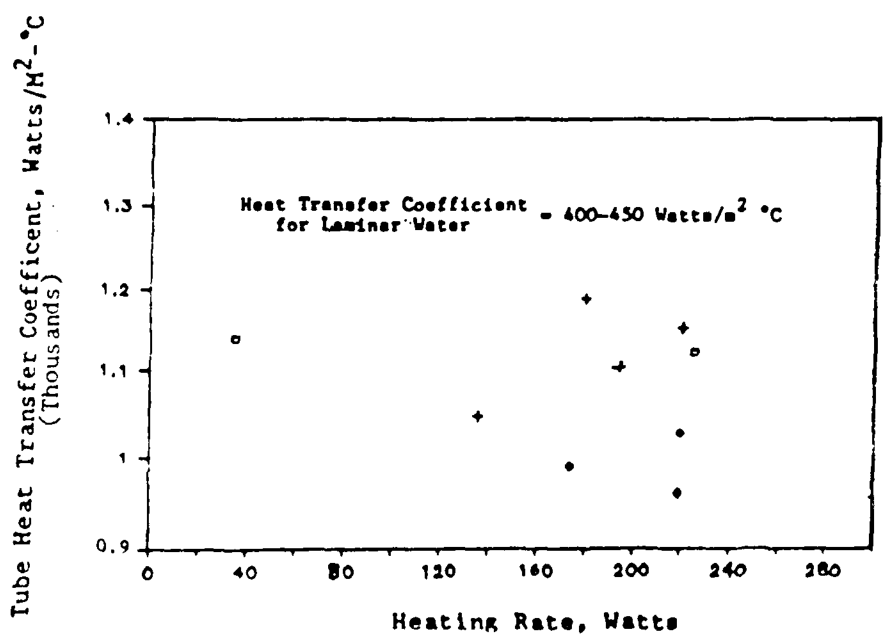


Figure 3. Heat Transfer Coefficient Inside Heater Tube, for Various Runs of Different PCM Slurries

smaller factor, although in itself significant, would appear to be an effect of the extremely small particles (5-10 microns) used in this Phase I effort, and the low concentrations (approximately 10-20%) used to reduce the pumping power.

Overall, the experimental loop runs were very successful. Flow control, loop balance, and long-term stability of operation were achieved for the first time. It is strongly believed that such fluids will work well. However, it was also shown that the heat transfer and fluid flow mechanisms in such fluids are very complex and still difficult to predict accurately. The short time of the Phase I simply did not allow a complete clarification of all of the factors which influenced the heat exchange. Particle size, concentration, and reaction kinetics are factors that are now believed to be extremely important and, in the future it will be necessary to account for them in design correlations.

3. Quick-Disconnect Thermal Coupler

A quick disconnect thermal coupler is a compact heat exchanger which allows various liquid cooling loops to be coupled and uncoupled quickly without loss of cooling fluids. Such a device could be extremely important in future space and electronic applications because it allows systems to be constructed and assembled in a modular fashion. For avionics, it would allow electronic and microelectronic components, which are individually cooled, to be assembled and disassembled conveniently. It also permits various subsystems, whatever they might be, to be quickly coupled and uncoupled from secondary thermal bus loops. Such a device has been talked about for some time, but to our knowledge, no one, to date, has developed such a unit. The difficulty in developing this type of device is that it must be relatively compact and manageable, and at the same time it must transfer a significant amount of heat. Hence, it becomes a compact, high heat flux device even though it must have a contact resistance between the independent coupling components and at least two wall thicknesses through which to conduct heat. This is likely to be a necessary item in the implementation of two-component, PCM slurry fluids because of the need to prevent the loss of such exotic fluids when assembling and disconnecting cooling loops.

In the Phase I project an attempt was made to design such a coupler. A sketch of the device is shown in Figure 4. The plug portion of the device is an 0.875 inch diameter cylinder which is approximately three inches long. The receptacle is designed to receive this element with as tight a fit as possible and still allow easy manual disconnect. Oftentimes in such devices, the contact resistance and conductive resistance are the controlling factors which reduce performance. In this development we made every attempt to maximize thermal performance, realizing that it may not be successful because of the nature of the problem. The device was constructed and tests run to determine the thermal "effectiveness" and the overall heat transfer coefficient. These results are shown in Figure 5 for pure water. The solid lines on the effectiveness curve represent the theoretical effectiveness versus NTU, the "number of transfer units" for a counterflow double pipe heat exchanger. The solid points represent data taken on a standard double pipe, counterflow heat exchanger, and the open points represent the data taken using the compact coupler. Both sets of data indicate the heat exchangers are performing exactly as they should, that conditions during the tests were steady, and that basic heat balance requirements were satisfied.

The overall heat transfer coefficient for the compact unit is shown in the smaller figure as compared to this same parameter for the larger double pipe standard unit. It can be seen that even though there are two walls through which heat is transferred, in addition to a contact resistance at the mating interface, the overall heat transfer coefficient for the coupler is 10 to 20% higher. Another difficulty often encountered in such devices is the inability to maintain high convective

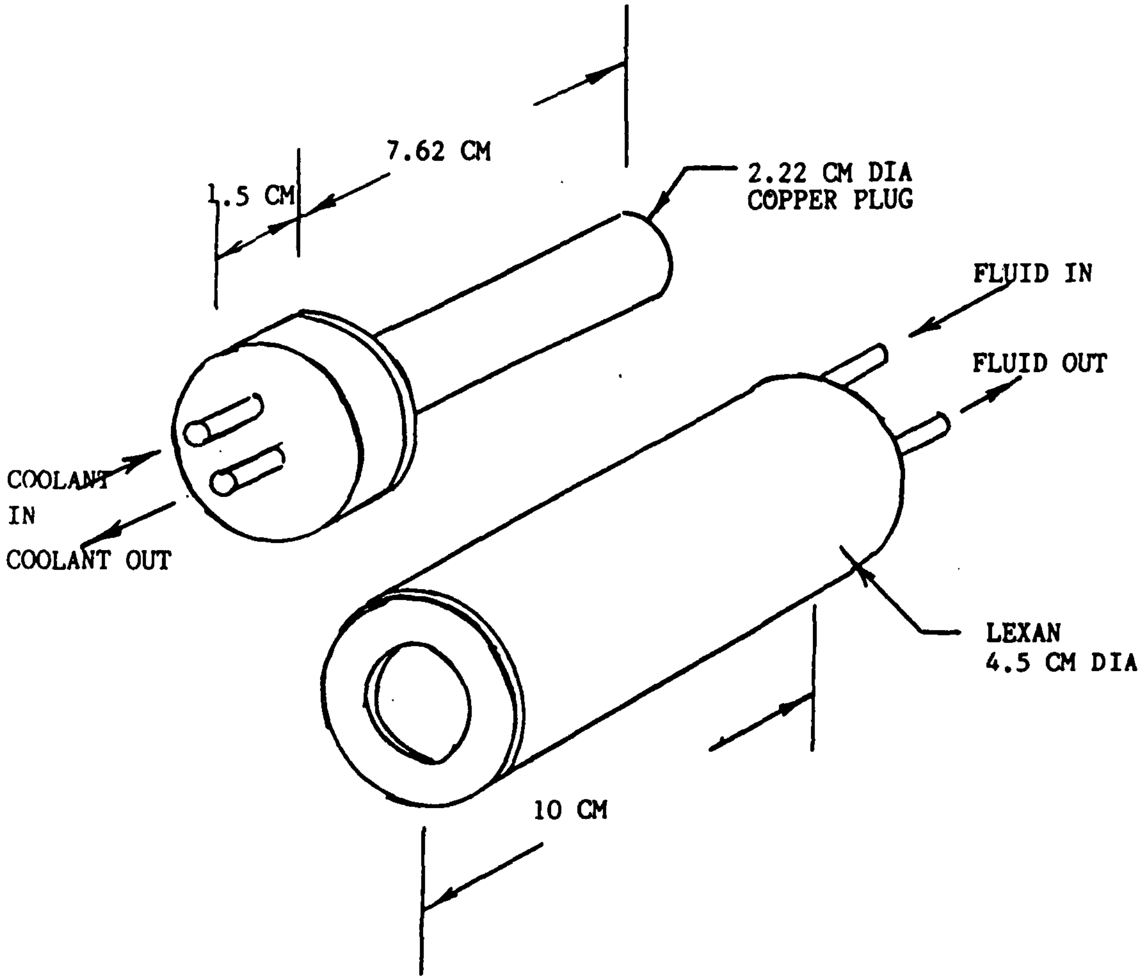
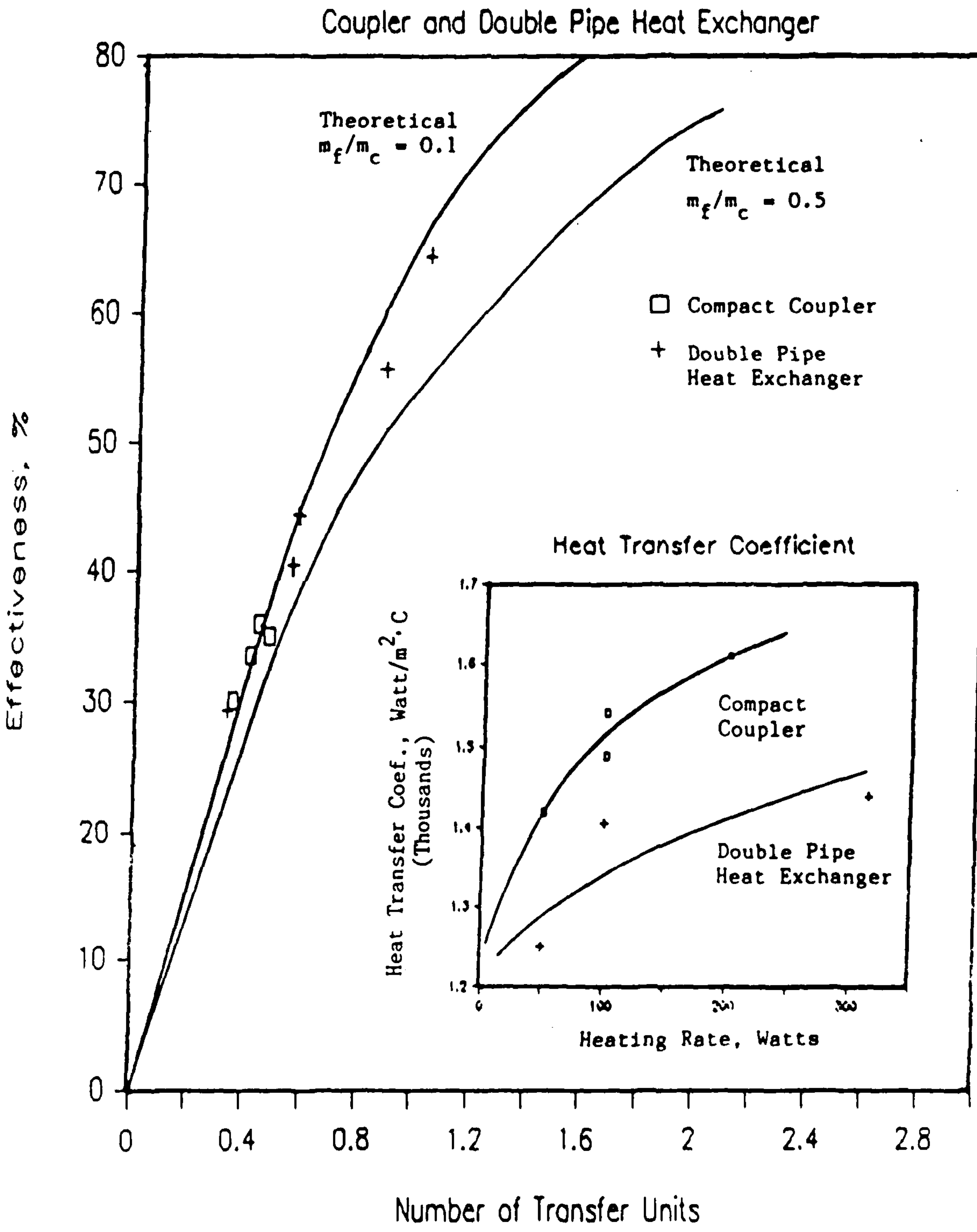


Fig. 4. Quick Disconnect Thermal Coupler Illustrating General Size and Construction

FIG. 5 - HEAT TRANSFER COEF. AND EFFECTIVENESS



coefficients within the small passages of the unit. In this particular device, the inside heat transfer coefficients were significantly increased due to a proprietary design. We believe this to be a very significant development which can be improved in the future and which will be important to the eventual utilization of two-component PCM fluids, and perhaps other fluids as well.

4. PCM Enhanced Reflective Shield

Temperature control of electronic components is important in some situations in which external irradiation of short duration is present, in situations in which short duration and high intensity convective heating is present, and in applications in which it may be desirable to wrap electronic packages in blankets of temperature control material. In the present project, aluminized mylar sheets were layered together with intervening PCM to create a thin composite sheet which possesses both desirous reflective properties as well as enhanced thermal mass. Several samples were made up for testing, each containing five layers of mylar. Each layer of mylar was approximately 0.001 inch thick. A sketch of the material structure and experimental apparatus is shown in Figure 6. The various PCM compounds used between the mylar sheets are as follows:

Sample #1: Pure n-eicosane

Sample #2: Thermal compound without PCM

Sample #3: Acrylic latex caulking without PCM

Sample #4: Caulking with 20% by weight of microencapsulated methyl palmitate

Sample #5: Thermal compound with 20% by weight of microencapsulated eicosane (encapsulated in polyamide shell)

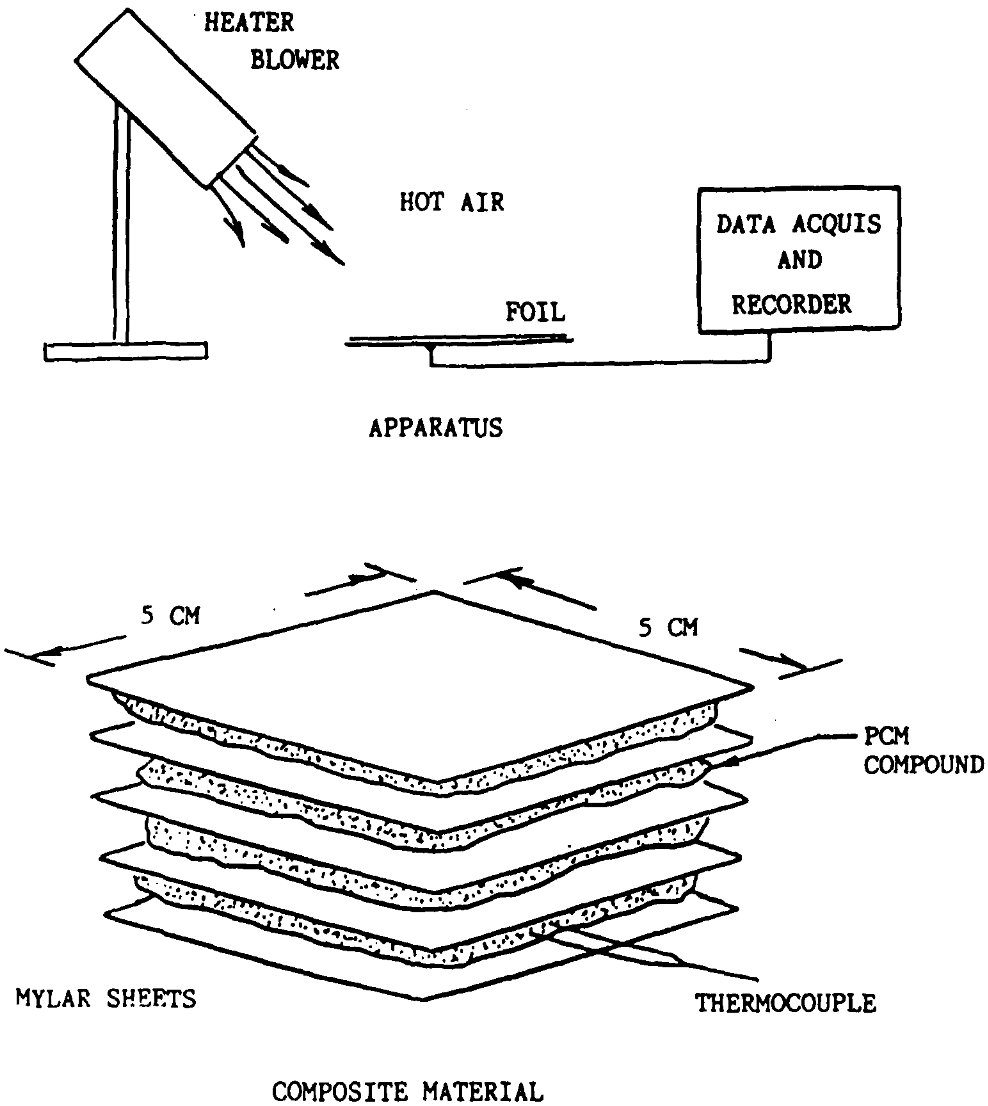


Fig. 6. Sketch of PCM Thermally Enhanced Reflective Blanket Material Illustrating Construction and Test Apparatus

Each of these composite materials was subjected to impulse heating from a heater as shown in the apparatus. The temperature response of the thermocouple located at the bottom layer was then recorded to determine the additional thermal mass added by the PCM. These results are shown in Figures 7 & 8. The first set of curves shows the temperature response of the composite with pure caulking as compared to the temperature response of the composite with the methyl palmitate, PCM-enhanced caulking. The delay in the response and the thermal mass effect of the PCM is clearly evident. Such results were repeated many times and are thus believed to be genuine. The third curve in the figure is the temperature response of the composite which utilizes pure unencapusulated eicosane between the sheets of the mylar. The temperature plateau for this case is very pronounced and discrete. It also occurs at a higher temperature which is a reflection of the 39 C melting temperature of eicosane as compared to the 29 C melting temperature of methyl palmitate. The eicosane results were also tested for repeatability. Figure 8 illustrates the enhanced storage that is obtained by seeding a base compound with microencapsulated PCM. However, the characteristic plateau is not typically obtained in such applications, especially at a level of 20% solids. It is believed that such materials would be successful if the PCM loading could be increased to a level of 80%.

After carrying out such tests on all of the samples, we believe that it certainly is possible to significantly increase the thermal mass of such thin materials. However, it is clearly evident that the pure phase change material contained between the sheets offers the most dramatic and quantitatively meaningful enhancement. Future work should be directed to developing techniques of containing such materials directly rather than first encapsulating them and then compounding with a non-PCM base material. The advantage of the latter alternative is that the PCM is not as free to run and redistribute when

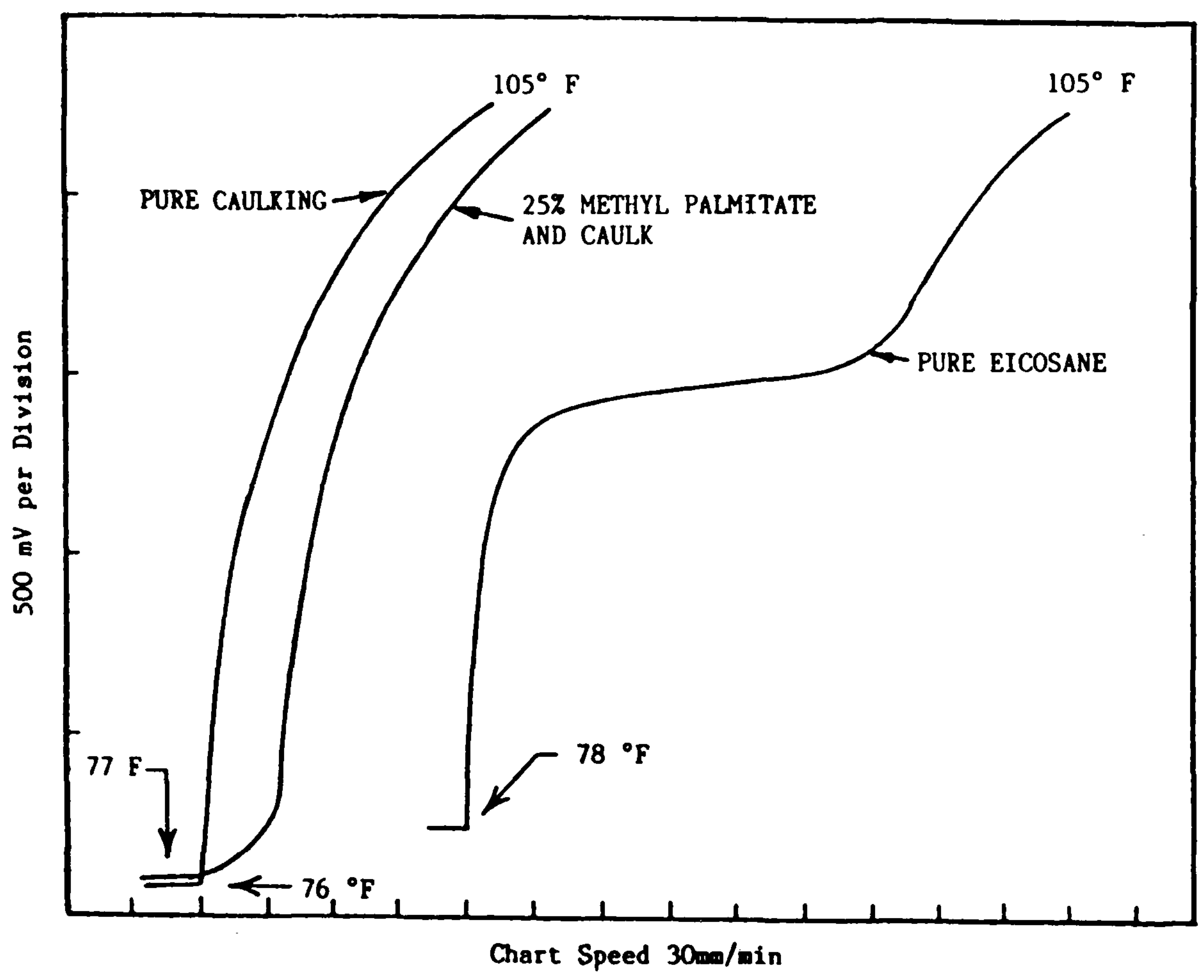


Fig. 7 - Temperature Response of Mylar Sandwich or Laminated Composite Containing Caulk, PCM-Enhanced Caulk, and Pure Eicosane

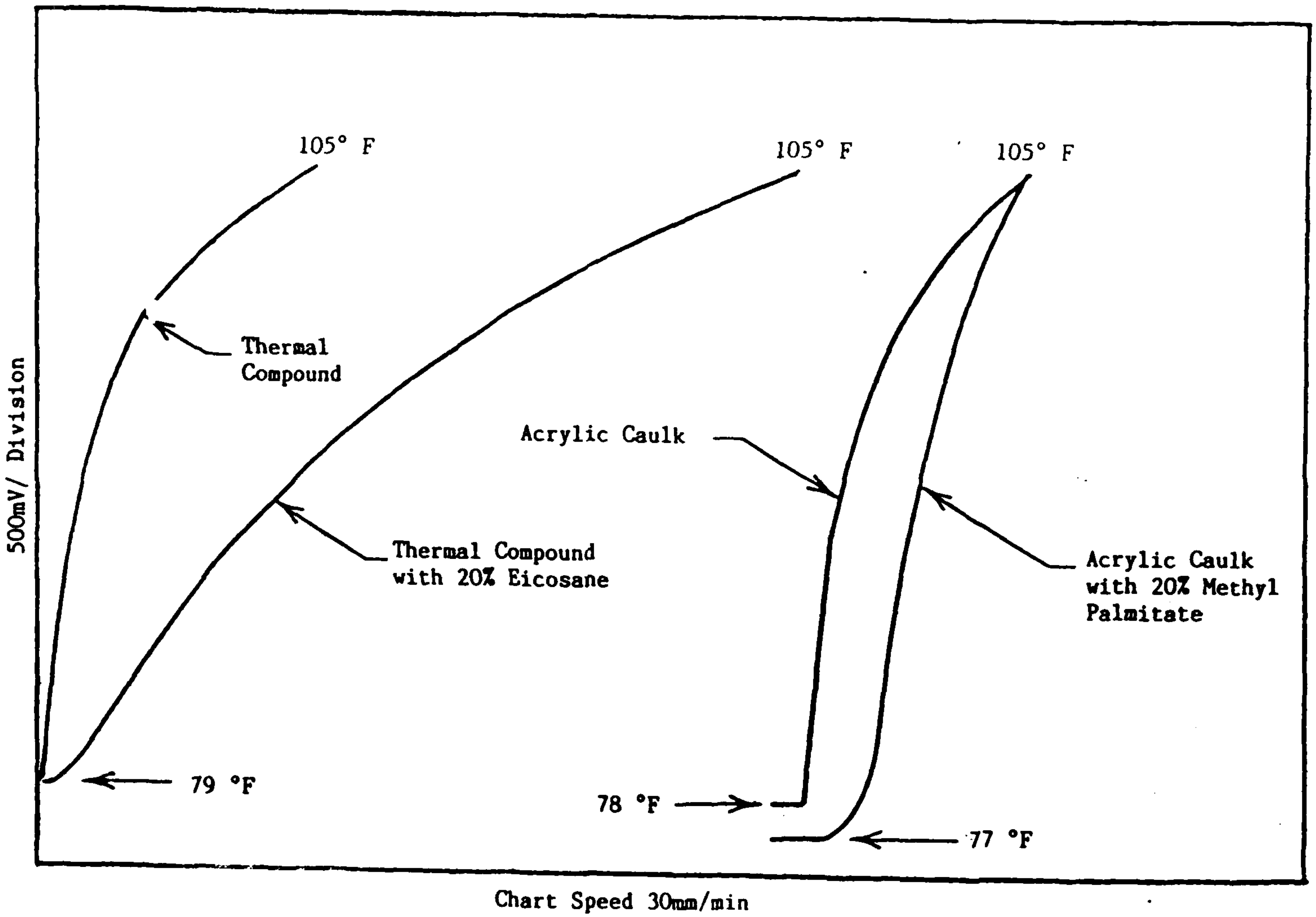


Fig. 8 - Temperature Response of Mylar Sandwich or Laminated Composite Containing Normal or Enhanced Thermal Compound and Acrylic Caulk

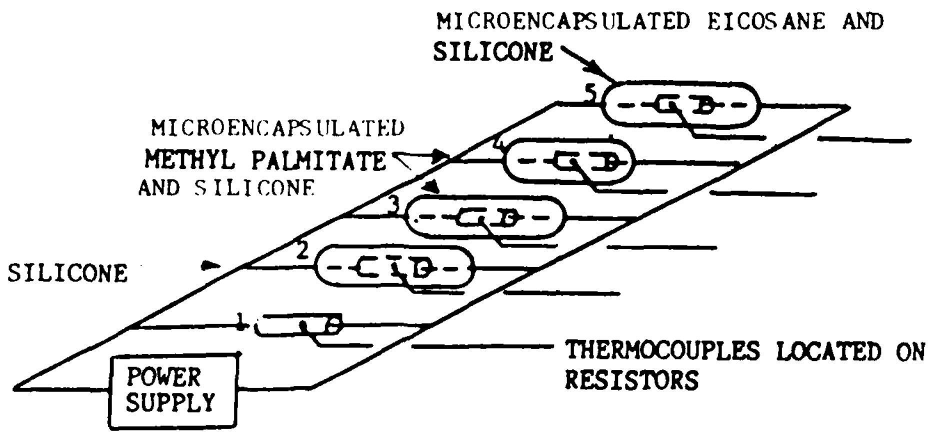
liquid. If this is found to be the important factor then future work should be directed to developing techniques of increasing the weight percentage of the PCM in the compound. Twenty percent is clearly not sufficient. It would appear that 80% would produce good results, but it was found to be difficult to mix the small particles above a 20% solids loading.

5. PCM Enhanced Potting Compounds

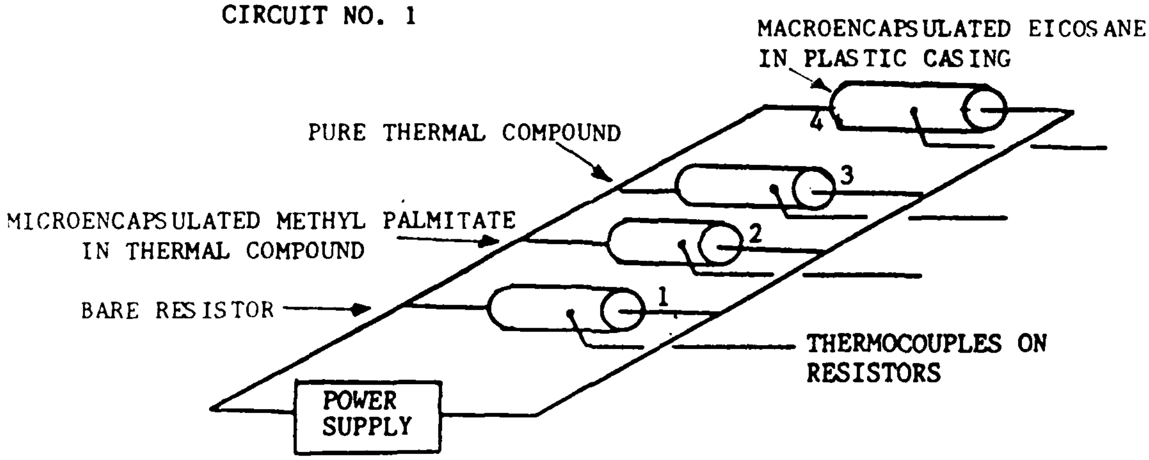
Temperature control during start-up and cyclic operation is important for the life time and reliability of electronic components in space and avionics applications. The extent to which control might be enhanced by coating components with potting compounds, which are seeded with phase change materials, was studied by constructing test circuits of resistors with such coatings. Figure 9 illustrates the circuit schematics and some of the data pertinent to these circuits.

In the first circuit tested, microthermocouples were attached to three identical 1/4-watt resistors (#s 3, 4 and 5) and then coated with a silicone-based compound seeded with microencapsulated PCM's (approximately 25% by weight), another resistor (#2) was coated with only the silicone base for comparison, and still another resistor (#1) was exposed openly in air for comparison. A constant voltage power supply was used to supply the same current to each resistor. A second circuit was tested in which identical plastic casings were used to encapsulate a coating around 1-1/4 watt resistors. One resistor was encased in pure eicosane (#4), one in pure thermal compound (#3), one in a 25% mixture of microencapsulated methyl palmitate (#2), and one resistor simply left exposed to air within an identical plastic casing. Again, the resistors were identical (within 2%) and energized with a constant voltage power supply.

Tests were run at different voltages to assess the degree to which the coatings and capsules controlled the temperature of the resistors. Fine thermocouples were attached to the



CIRCUIT NO. 1



CIRCUIT NO. 2

Fig. 9. Schematic of the Two Circuits Used to Measure the Temperature Response of Coated Resistors

resistors to indicate the temperature response after voltage application, and the temperature decay after voltage removal. Some of these data for the encased resistors, which are representative, are shown in Figures 10 through 14. It can be seen in Figures 10 and 11 that the most dramatic result occurs for the 100% pure eicosane capsule (resistor #4 in circuit 2). Upon heating, the PCM prevents the resistor from exceeding 51 C until all the PCM has melted. Upon cooling, the PCM prevents the resistor from falling below 35 C until all the PCM has frozen. Figure 12, however, suggests that these limits also depend upon the power level. In addition, relatively long high-side and low-side limits are achieved with a relatively small amount of PCM. Moreover, even when all the PCM has melted, the steady-state temperature of the resistor is well below that of the uncoated, bare resistor. The increase of heat transfer surface area alone aids the cooling process and actually creates a cooler circuit. In all of our experiments this same phenomenon was observed. One simply has to increase surface area by encapsulation to significantly increase cooling at steady state.

The use of microencapsulated PCM's in a mixture with a compound, either a caulking material or thermal compound, did not prove to be as advantageous as anticipated at the low concentrations used. Some additional capacitance was achieved although it was not deemed to be necessarily useful. The reason for this is believed to be the relatively low weight percent of PCM in the mixture (approximately 20% maximum). This behavior could be improved if a technique were developed to increase this to greater than 80%. Significant difficulty was experienced in reaching even 20% by simply mixing the PCM particles into the compounds. Also, in the case of the silicone caulking, it was difficult to control exactly the formation of the composite material around the resistors. Thus, some variability in the percent solids as well as the composite thickness occurred in the experiments involving circuit number 1. Hence, the temperature response recordings for the various resistors showed

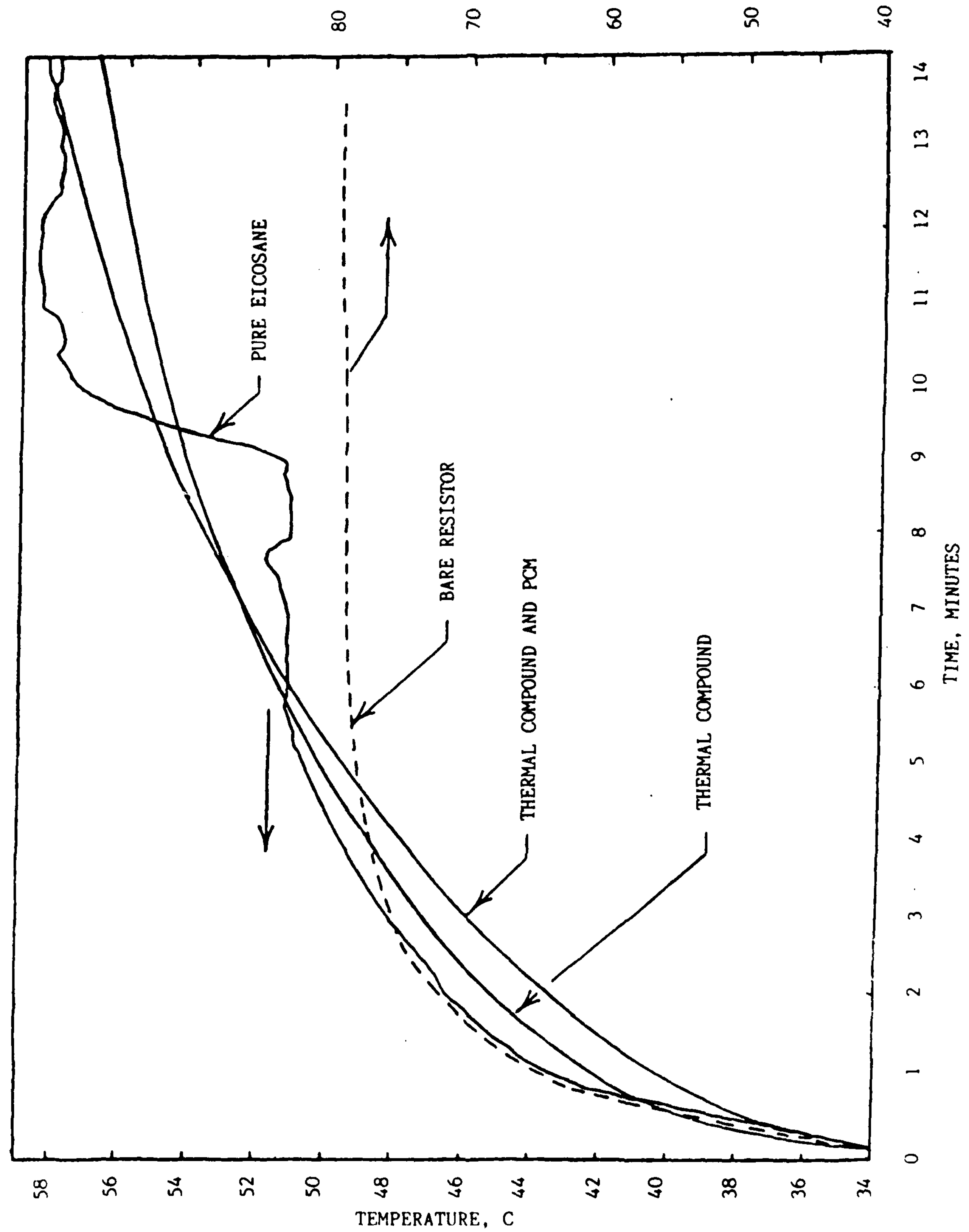


Fig. 10 – Temperature Response of the Resistors of Circuit Number 2, Macroencased Resistors, After Sudden Application of Voltage.

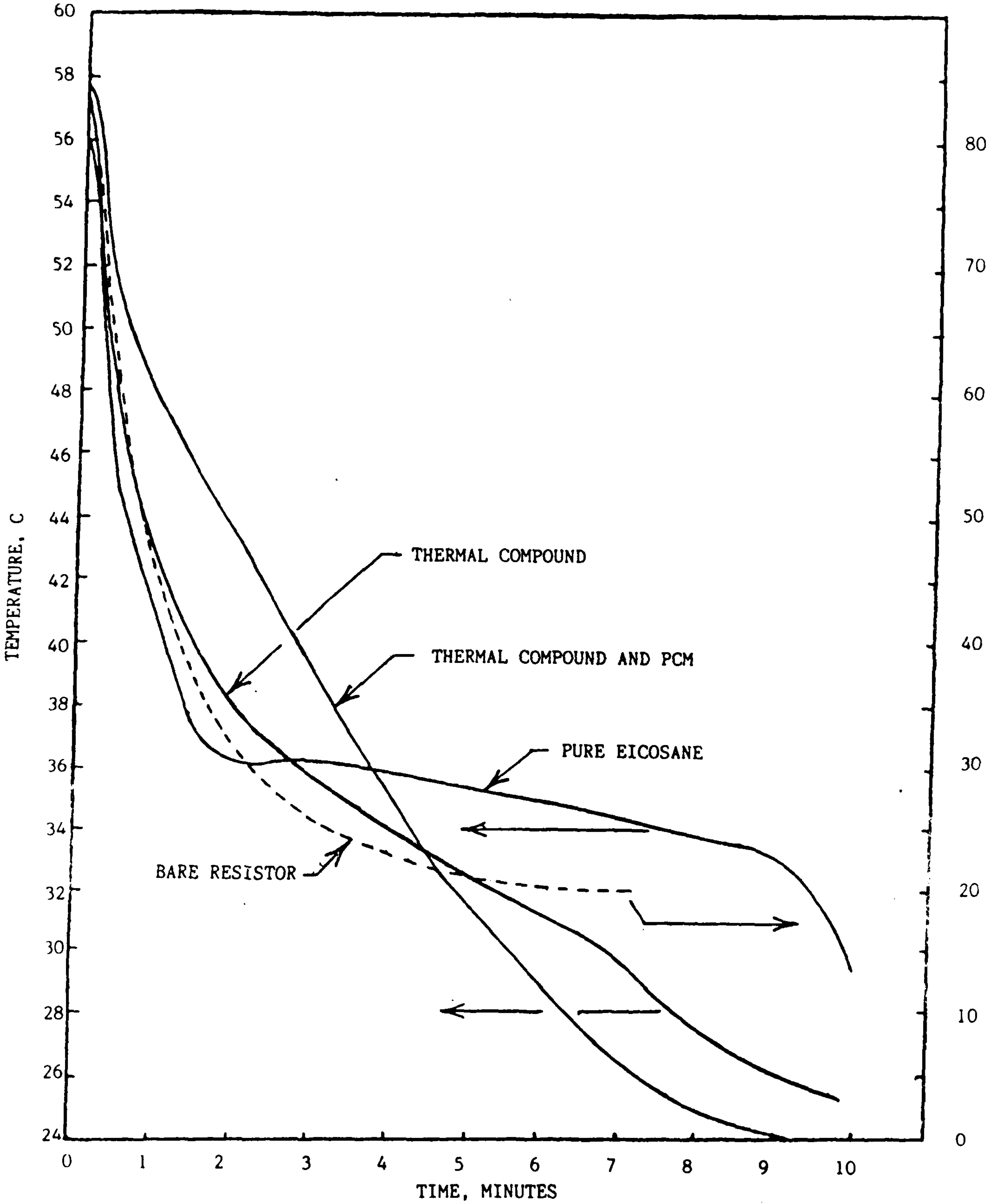


Fig. 11 - Temperature Decay of Resistors of Circuit Number 2 After Sudden Removal of Voltage

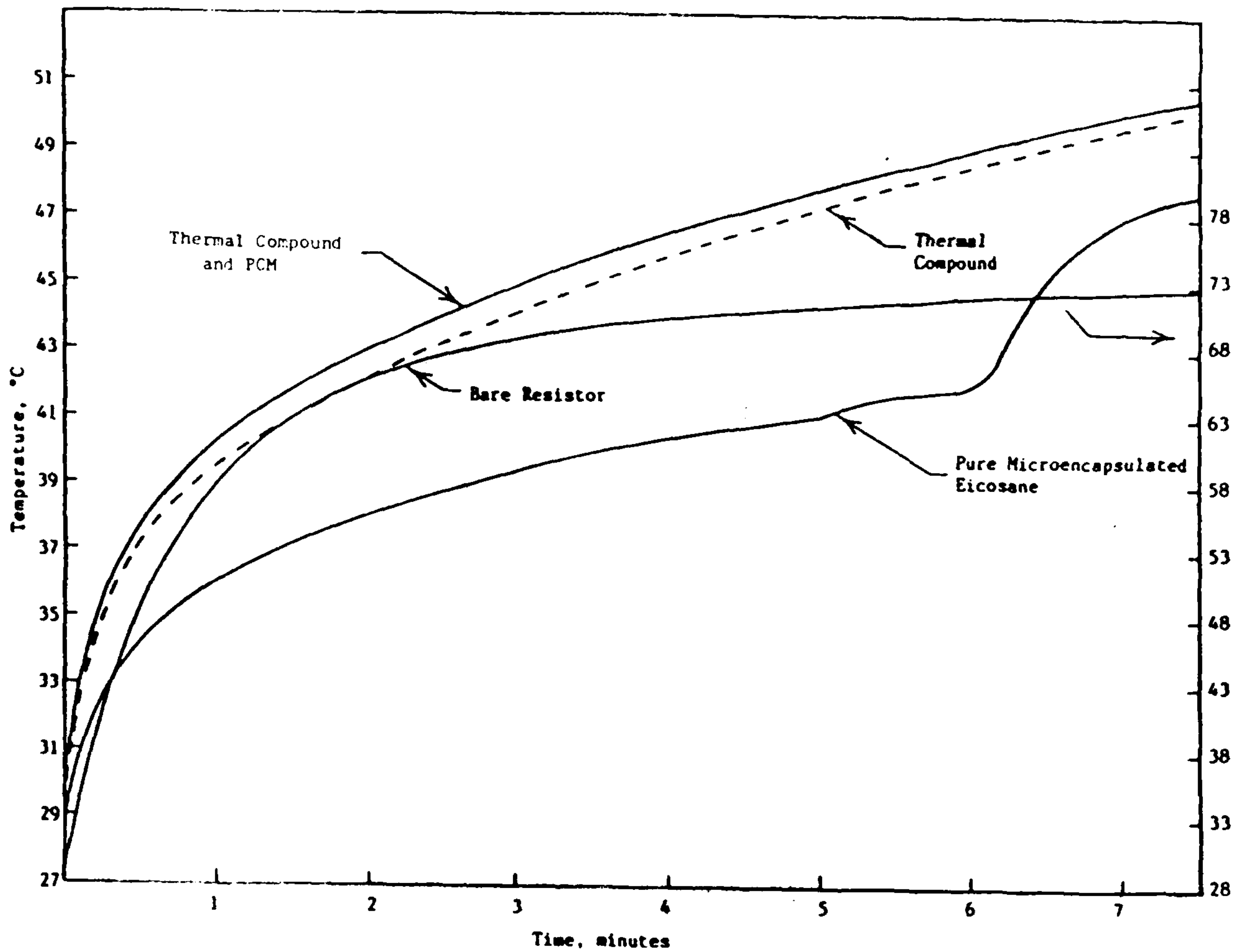


Fig. 12 - Temperature Response of the Resistors of Circuit #2, Macroencased Resistors, After Sudden Application of Voltage.

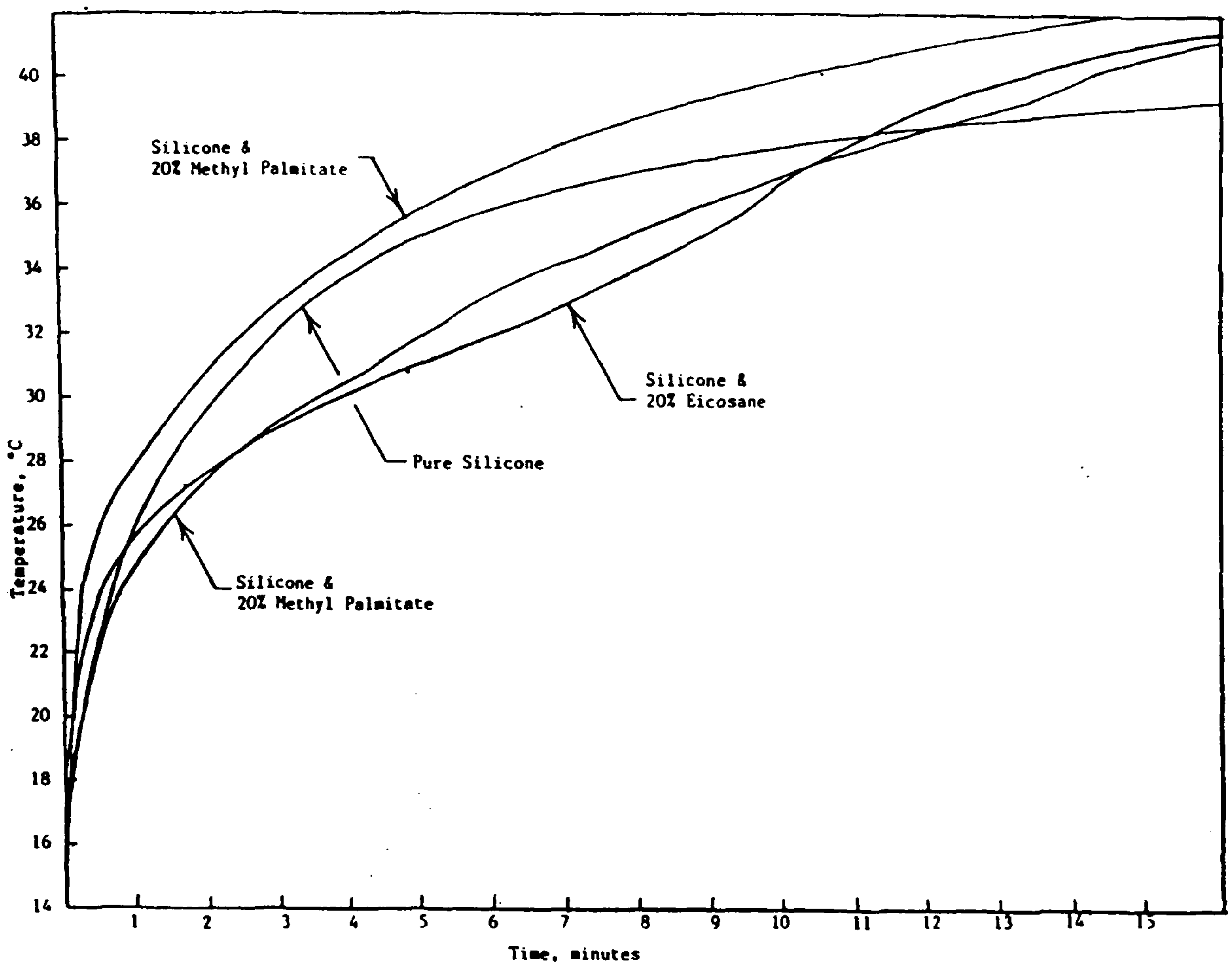


Fig. 13 - Temperature Response of the Resistors of Circuit Number 1, Macroencased Resistors After Sudden Application of Voltage.

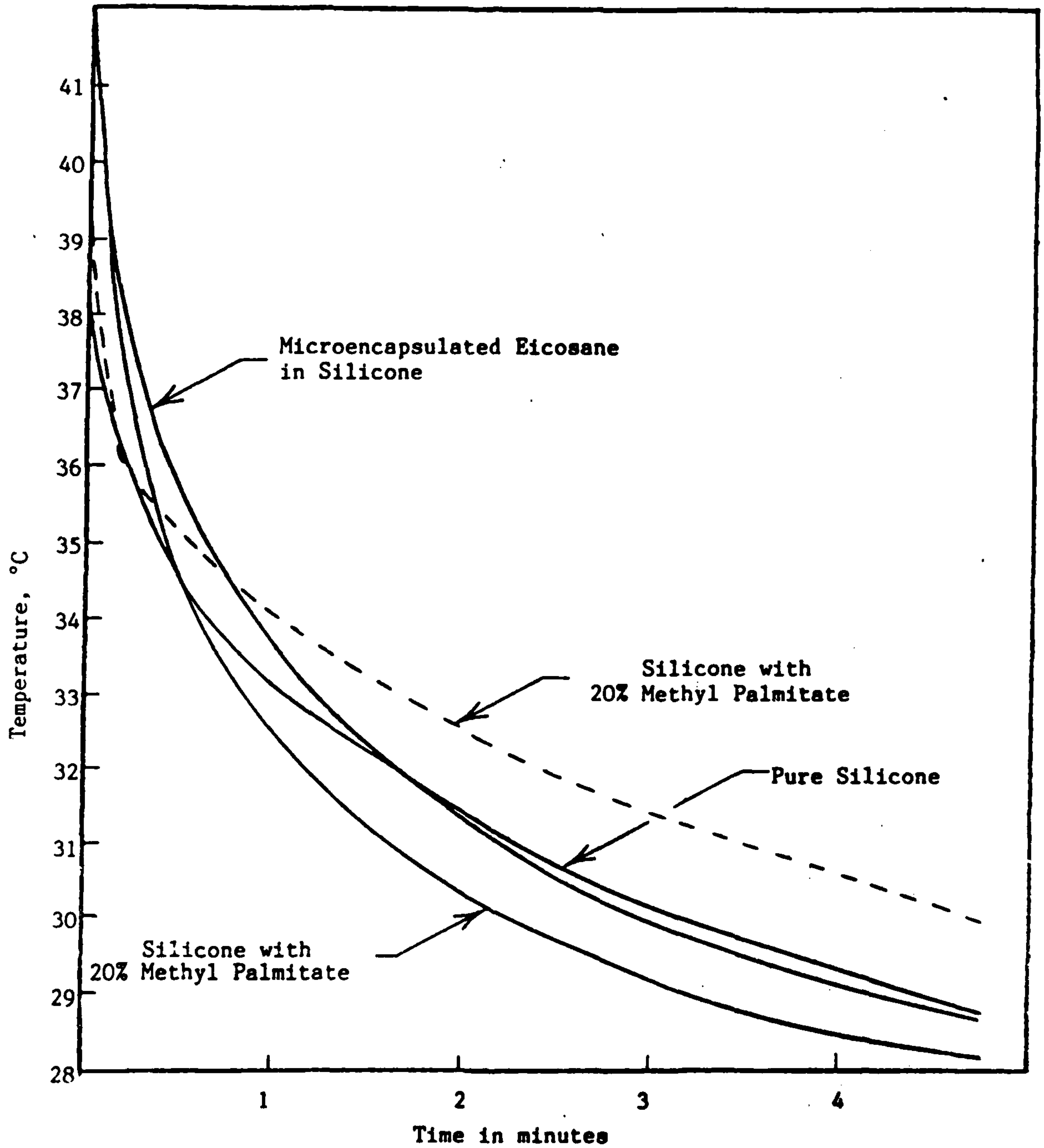


Fig. 14 - Temperature Decay of Resistors of Circuit Number 1 After Sudden Removal of Voltage.

some slight deviations in magnitude, which were expected. These can be seen in Figures 13 and 14 by observing the two methyl palmitate and silicone curves. In all of these experiments, a phase change plateau which could be interpreted as significant was observed only in the one case of silicone and eicosane shown in Figure 13.

CONCLUSIONS AND RECOMMENDATIONS

Based upon the data taken during the course of this Phase I project as summarized by the results presented in this report, the various operational experiences and skills gained in conducting the experiments as well as interactions with the various suppliers of the microencapsulated PCM materials, it can be stated that the Phase I effort was highly successful and provided strong and well-defined recommendations for further work. The results and conclusions are summarized as follows.

The conceptual feasibility of using a two-component fluid slurry for enhanced heat transport and storage was demonstrated satisfactorily. Materials specifications were developed, based upon earlier SBIR efforts for NASA, and sufficient quantities of the PCM slurries were obtained for evaluation and testing. The materials selected were examined with both optical and electron microscopy as well as differential scanning calorimetry in order to quantify their size, shape, heat content, and both melting and freezing points. The nature of the encapsulation process is proprietory, but microcapsulated phase change materials were produced with both polymer and gelatin shells. Samples of the slurries were also circulated for several hours within a pumped, closed-loop system containing water as the base fluid without obvious damage or particle breakup. The slurries were then circulated for periods up to three days within an instrumented, closed-loop system that permitted alternate cyclic heating and cooling of the fluid. Caloric content and thermal behavior of the slurries were observed for different flowrates and heating levels. Heating was provided by a 1500-watt, flow-through electrical heater and cooling by electrical chillers and a reservoir tank system connected to the primary loop via a counterflow heat exchanger. This latter device was also substituted with a miniature, quick-disconnect thermal coupler for tests with a device to connect the adjacent and independent fluid loops.

As described earlier in this report, successful results were obtained with the slurries and the quick-disconnect thermal coupler. The slurries demonstrated an enhanced heat capacity that approached a specific heat of 5.0 for a fluid temperature differential of 2 C. In addition, the heat transfer coefficient was seen to be enhanced by 2.8 times that for water. Likewise, the miniature, quick-disconnect coupler exhibited a higher effectiveness than a typical double-wall heat exchanger. Laboratory tests also showed that the fluid loop could be used to transfer heat from a simulated microelectronic device with mulitiple 500 micron holes through its structure for enhanced cooling.

Passive thermal storage techniques were also successfully evaluated for enhanced thermal management of electronic devices and a thermal radiation shield. PCM was compounded into a putty or paste and applied to precision resistors on which thermocouples had been mounted. The temperature of the coated devices was significantly reduced in comparison to identical uncoated devices when transient power was applied to the resistors. Likewise, the use of PCM between alternate layers of aluminized mylar or aluminum foil was seen to introduce a significant thermal lag into the temperature rise of a flexible thermal shield.

It is important that work be continued on the development of the two-component, PCM fluid. The physical principles governing the heat transfer and fluid mechanics of such fluids are not known well enough to understand the behavior and performance of a system which utilizes this type of fluid. This was clearly shown in the Phase I results. Such topics as phase-change kinetics, convective heat transfer, laminar versus turbulent flow wth PCM particles, the effects of various sizes in various concentrations, and evaluation of the various transport properties must all be addressed in more detail. A two-component PCM fluid is a complex medium and there is very little information in the literature to provide a basis for estimating performance. A data base is being developed and better understanding of the physics of heat, mass, and momentum transfer in these fluids is needed to effect optimal application.

The Phase I project was also successful in illuminating many of those aspects of enhanced thermal transport and storage using microencapsulated PCMs, particularly in regard to those relating to the particle size and concentration. Some aspects of the Phase I project which pertain to the passive temperature control using blanket-type laminated composite sheets and potting compounds were more successful than others. At least two avenues of approach should be further investigated for passive control during a Phase II effort. First, alternative macroencapsulation techniques should be studied wherein pure PCM can be used as a coating. Secondly, an effort should be made to develop a technique for addition of microencapsulated PCM particles to a compound in order to produce a higher solids loading of up to 80%. These developments potentially could provide significant temperature control in electronic devices, particularly when exposed to transient thermal environments. Low-load microencapsulated PCM's in a compound for potting purposes were not found to provide a significant amount of protection; however, pure PCM encased between foils and encased around resistors was found to add a very significant level of thermal mass.

The dramatic success of the high flux, compact coupler almost demands further development. It is believed that with additional work, this device can be significantly improved and provide an even greater contribution. Such a device is important as an adjunct to the development of two-component fluids. It is recommended that further work include the reduction of internal thermal resistance by addition of turbulators in the flow streams. Also, additional testing with two-component PCM slurries should be carried out. In future work, it is also recommended that two-component fluids using fluorocarbons as carrier fluids also be investigated. Past work has utilized comparisons with water, the prime heat transfer fluid, which probably is not the most desirable for use with electronic devices. Since fluorocarbons are important fluids in current use with electronics, it is clear that further work should involve these materials.

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