NAVSHIPS 900,189

HEAT TRANSFER
IN
MINIATURIZED ELECTRONIC EQUIPMENT

BUREAU OF SHIPS
NAVY DEPARTMENT
WASHINGTON 25, D. C.

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. - - - Price $1.25

Navy Department
Bureau of Ships
1 February 1955

Heat Transfer In Miniaturized Electronic Equipment, NAVSHIPS 900,189, was originally published as Cornell Aeronautical Laboratory, Incorporated, report Number HF-710-D-10, dated 3 March 1952, under Bureau of Ships Contract NObsr-49228. It is the first of a series on the subject of heat transfer. The second report, Number HF-845-D-2, dated 1 June 1953, was prepared under Contract NObsr-63043 with Cornell Aeronautical Laboratory, Incorporated, and is available in the publications supply system under NAVSHIPS 900,187.

Thermal design considerations are rapidly attaining a position of primary importance along with electronic and mechanical considerations as factors leading to increased reliability of electronic equipment. Miniaturization, with its small space factor, leads to an increased concentration of thermal energy. This report is a survey of current thermal design methods and heat transfer techniques. Included also, is a brief summary of some cooling techniques under investigation.

This publication, in part or in entirety, may be used to facilitate the preparation of other government publications.

Requests for additional copies of this publication should be directed to the nearest District Publications and Printing Office. Commercial firms must submit requests to the local Navy Inspector.

W W Leggett Jr
Rear Admiral, USN
Chief, Bureau of Ships

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

This report encompasses a survey of current and under development methods of heat transfer in electronic equipment. The work has been accomplished as the initial phase of a research program directed toward the preparation of a heat transfer design manual to assist electronic engineers in the design of miniaturized equipment with satisfactory thermal performance. The scope of the originally planned survey was broadened due to recent advances in electronic cooling to include not only a bibliographical study, but also a thorough survey and inspection of techniques and methods now in use at prominent facilities throughout the nation.

It has been necessary for electronic organizations to conduct individual investigations related to their thermal problems, an expensive means of self-education. In some cases the work has been duplicated because of security or "trade secret" restrictions. As a result of this situation and the void of electronic thermal knowledge, the U.S. Navy Bureau of Ships has sponsored the preparation of this report to disseminate the known thermal information.

The rapid growth of the application of electronic equipments has exceeded the improvement of reliability of equipment performance. The maintenance problems resulting from reduced reliability are becoming serious. A number of efforts recently directed towards reliability improvement include ruggedized tube developments, plug in subassembly techniques, the application of improved high temperature parts, design derating of tubes and parts, isolation of sensitive components from environmental effects through hermetic sealing or plastic embedment, improved mechanical design to better withstand vibration and shock, and reduction of operating temperatures. One of the primary causes of poor reliability in current electronic equipment is inadequate heat removal. The improvements realized through a decrease in operating temperature will not be immediately apparent but will significantly increase the equipment life - especially that of the vacuum tubes.

The importance of the thermal considerations cannot be overemphasized. It has been stated that the degree of success of future aircraft and missile developments is closely related to the satisfactory miniaturization of the electronic equipment involved. This in turn is directly related to the effectiveness of the methods of heat removal.

Miniaturization, with its small space factor, leads to an increased concentration of thermal energy, since the total dissipated electrical power is usually as great, if not greater, than that of an equivalent equipment of conventional construction. The utilization of auxiliary cooling devices is frequently prohibited because of space factor requirements. In addition, miniaturized equipments are frequently required to operate in environments of high ambient temperature. Effective heat transfer is therefore of prime importance in obtaining satisfactory life, reliability and electronic performance in miniaturized equipment.

Miniature electronic equipments of conventional construction with greater packaging densities than those currently in use can be produced, but these devices usually will have a short life because of the resultant excessive temperatures. Even so, such equipments do not operate at the power densities soon to be encountered. Power amplifier type subminiature tubes capable of delivering appreciable power output recently have been made available and there are under development even more powerful tubes. The utilization of these tubes with heat dissipations many times greater than those of the current types will create an acute thermal problem.

A number of organizations are at present concerned with the thermal considerations encountered in miniaturization. In some instances, serious equipment failures have occurred and redesigns are in work. Heat transfer specialists have recently been added to the technical staffs of organizations that have recognized the problem.

Some of the direct effects of excessive temperatures in electronic equipments are: shortened tube life through loss of emission and the release of gas, electrolysis of the glass envelopes at the base, decomposition and dielectric failure of capacitors, resistors and insulating materials, instability and shifts of values, and oxidation. Hot spot temperatures as high as 400°C. can be obtained in miniaturized electronic equipments of haphazard thermal design. Such equipments can operate for only short periods of time prior to failure, since temperatures of the order of 85°C. are the upper limit for common electronic parts, other than tubes. The thermal design of electronic equipment has been, for the most part overlooked by many electronic engineers especially those engaged in miniaturization. The average electronic engineer is not well informed in thermal matters because such knowledge has not to date been necessary to his work. This program is intended to assist such engineers and to bridge the gap between applicable heat transfer theory and practice. Techniques and methods presently utilized in the fields of refrigeration, aircraft cooling, heating and ventilating, etc., are not commonly known by electronic engineers and in many cases their application to electronics are considered an advancement of the art.

This survey is not restricted exclusively to miniaturized equipment. Because of special heat removal methods utilized, conventional equipments were also included.

A minimum of definite design data is presented in this report. Detailed design parameters, photographs, curves, etc., are to be presented later in the Design Manual.

Heating at low temperature is not discussed in this report. The injection of heat into electronic equipment is not considered to be directly related to heat removal. Specific thermal data is not generally listed in so much as definite conclusions have not been made due to differences in measurement techniques, configurations, and other variables. Also, the cooling may be adequate in one instance, but not in another, depending upon the delineation of the performance requirements. The discussion section of this report is related only to steady state heat transfer at equilibrium. Thermal inertia and transient thermal data have not been considered.

A bibliography and cross index of reference numbers related to this bibliography is presented for those who wish further information relative to the design details of particular systems and equipments. This information can be obtained from the sources listed. The bibliography associated with this report contains only those references pertinent to the contents. A complete bibliography for this program has been listed in current interim reports. Since this report is restricted, it has been necessary for security reasons to omit some source information and to publish a Supplemental Classified Survey Bibliography, C.A.L. Report HF-710D-10A. The discussion of this report has been coded to provide a means of cross reference to the Bibliography. Plain numbers refer to data obtained from contributors listed in Appendix I, while numbers preceded by the letter 'B' refer to literature presented in the Bibliography Appendix II. Classified publications are followed by the letter 'R' or 'C'.

Ohio State University Research Foundation is engaged in an "Investigation of Methods for the Cooling of Electronic Equipment in General", sponsored by the U.S. Air Force. The O.S.U. program is primarily concerned with the cooling of airborne electronic equipment of all sizes, whereas this program is specializing in the cooling (and heating) of miniaturized electronic equipment for all military applications. The accomplishments of O.S.U. in this new field of electronics have been excellent and these contributions constitute a noteworthy advancement of the art.

It was necessary to conduct this Survey in order to establish a firm foundation for the second phase of this program. A comprehensive bibliographical search to obtain electronic heat transfer data was conducted by the technical library of this Laboratory. Pertinent text books, papers, reports and publications were studied. It was apparent that additional specific thermal information could be obtained from organizations throughout the Nation active in this field. A form-type questionnaire was prepared and forwarded to one hundred and seven prominent electronic organizations. The replies were screened and those organizations which could contribute useful thermal data were visited by representatives of this Laboratory. Most of the selected organizations were, in all respects, very cooperative.

This Laboratory cannot assume responsibility for performance claims obtained from Survey sources. It is anticipated that the second phase of this program will include the evaluation and the determination of the effectiveness of various heat transfer methods.

II. SUMMARY

The power densities and ambient temperatures encountered in current miniaturized electronic equipment exceed those of conventional equipment, and special methods of heat removal are in use. The heat transfer techniques presently applied are in an early stage of development and the thermal findings of several organizations differ from those of others. Some confusion and disagreement has naturally followed. This is a healthy condition and the recognition of the importance of adequate heat removal by the electronics industry will aid in the ultimate alleviation of this problem.

Because of a void of heat transfer design criteria, electronic engineers have been severely handicapped in developing miniaturized electronic equipment with the desired thermal performance. Specific parameters and methods of accurately determining the thermal designs are rarely known. Most of the successfully miniaturized equipments are the result of a series of "cut and try" experiments and compromises devoted exclusively to the particular configuration involved. Only a few electronic organizations have a well defined approach to their thermal problems. It is realized that long life reliable miniaturized electronic equipments are new to the electronics art and it is not abnormal, therefore, to find that the heat transfer concepts associated with this new field are undergoing evolution. Only recently has the need for designed heat removal been recognized by electronic organizations. Heat transfer specialists recently added to engineering staffs were frequently at a disadvantage, since they were consulted only after thermal difficulties were encountered, rather than during the basic design phase.

The primary heat transfer problem in electronics is the removal of internally developed heat through a reduction of the thermal impedance between heat sources and the ultimate sink. A low impedance thermal path will reduce the temperature rise of heat producing electronic parts. Electronic heat removal can be divided into three phases: the removal of heat from the source, the intermediate phase of transferring the heat along the thermal buss to the ultimate sink and the dissipation of the heat at the ultimate sink.

It is necessary that the electronic designers and the manufacturers of electronic parts cooperate in solving the problems of the first phase. New concepts are in order, since electronic parts are designed and rated only for natural cooling in air at sea level pressures. Operation of electronic parts in low pressure environments will require extensive thermal derating and conversely, increased ratings can be applied in liquid environments. Also, parts with increased power dissipations will be ultimately required. Little is known of these matters, especially in terms of life and reliability.

This heat transfer program is mainly concerned with the intermediate phase design problems involved in transferring heat from the source to the ultimate sink. Two basic approaches to this phase are in current use:

The "brute force" approach, wherein high temperature electronic parts are utilized without special cooling means, has frequently found application in miniaturized electronic equipment. High temperature electronic parts, currently available in limited quantities have been satisfactorily utilized for this purpose. These parts are particularly suited to equipments operating at ambient temperatures of the order of 100°C.

The designed approach embodies the most practical and effective methods of heat removal. This technique requires careful design of the entire heat transfer system and the establishment of controlled thermal gradients. Some organizations have achieved excellent results after extensive investigation and analysis.

The dissipation of heat at the ultimate sink requires the transfer of heat into the earth's atmosphere. Some excellent progress in this phase has been accomplished by the Ohio State University Research Foundation.

The phases of heat removal are inter-related. The method of ultimate heat dissipation depends somewhat on the type of intermediate heat transfer provided and, for a complete heat removal system, all three cooling phases must be considered.

Vacuum tubes, resistors, and reactors are the principal sources of heat in electronic equipment. The vacuum tubes are usually the primary heat sources and most subject to failure. Their overall efficiency is low and a large percentage of the total input power is converted into heat. Vacuum tubes are fundamentally variable resistors and it appears that little can be accomplished in improving their efficiency. In some instances, magnetic amplifiers or similar types of variable reactors have been utilized, since such devices exhibit higher efficiencies. The n-p-n transistor also shows promise and apparently will be ultimately used in many applications in place of vacuum tubes.

Hermetic sealing of miniaturized electronic assemblies and subassemblies to eliminate the deleterious effects of corrosion and moisture has found wide acceptance in England. Electronic organizations in the United States are slowly acknowledging the advantages of this treatment. In miniaturized electronic equipments with parts operating in the neighborhood of 200°C. oxidation becomes serious. Many parts are provided with protective films and coating to alleviate this condition. These films are easily damaged, however, and their failure frequently leads to decreased reliability. In some instances, the failure of electronic parts was believed to be caused by corrosion or excessive temperature or combination thereof. The intimate relation between these failure types has not been completely recognized by industry.

Many electronic engineers tend to apply the marginal design practices common to the domestic television and radio receiver industry in the design of miniaturized electronic equipment for military usage. The operation of electronic parts near their maximum power ratings has increased the need for improved heat transfer and reliability. In addition, high transconductance pentodes with large heater powers are frequently used in circuits wherein low transconductance pentodes with approximately one-half the heater power could be utilized, if available.

Temperature measuring techniques differ widely. In some instances oversize thermocouple leads were removing heat from the equipment. Careless measuring techniques contribute to many of the divergent thermal findings. It is apparent that some standardization of procedure in temperature determination is in order.

Natural methods of heat removal have been suitable for miniaturized electronic assemblies in free air with power densities smaller than .5 watts per sq.in. of cooling surface. High conductivity thermal paths of metal are necessary when the power dissipation exceeds .25 watts per sq.in. Plastic embedment, especially of vacuum tubes, has been found to be applicable to miniaturized equipments of low power densities. The poor conductivity and other thermal properties of the plastics are not compatible with high power densities, especially when subjected to continuous duty service. Convection cooling of heat sources in miniaturized electronic equipment has been provided by some organizations. However, the general trend is toward higher power densities which require the utilization of other cooling methods. Radiation cooling has not been employed as a primary means of heat removal.

Forced air cooling is frequently used in miniaturized and conventional electronic equipment. Special air-to-air heat exchangers with forced circulation have been developed for airborne electronic assemblies. Turbulent air cooling has been applied in devices of higher power densities.

Liquid cooling has found acceptance for heat removal in several miniaturized equipments. Direct or indirect liquid cooling can be provided dependent upon the compatibility of the coolant with the electronic parts and circuit performance. Efficient heat transfer in high power density devices has been achieved with silicone fluids, petroleum base oils, and water.

Vaporization cooling of miniaturized electronic equipment can be accomplished by direct, indirect, expendable or non-expendable cooling systems. The absorption of the latent heat of vaporization of the coolant provides an efficient means of heat removal, especially in equipment of high power densities.

The removal of heat from vacuum tubes has been achieved by many methods. However, improved means of cooling subminiature vacuum tubes, without the use of liquid or vaporization cooling, are required for equipments of medium power densities. The relationship of life to vacuum tube temperature has been found to be of the utmost importance.

The Hilsch-Vortex tube may, at some time in the future, be used as a cooling device on high speed aircraft. At present, experimental tubes exhibit refrigeration efficiencies of only 20 percent.

Steam ejector cooling of miniaturized electronic equipment is feasible. Similar systems have been installed on railroad cars to provide air conditioning and refrigeration.

In general, miniaturized electronic equipment can be successfully cooled utilizing the currently known techniques. However, due to the trend toward increased packaging densities in miniaturized electronic equipment, much remains to be accomplished to determine: the effects of adequate heat removal on reliability; improved heat removal methods, especially for vacuum tubes; design parameters to alleviate the tedious "cut and try" techniques; standard thermal measuring procedures, and the limitations of each method of heat removal. In addition, electronic engineers must recognize the necessity for integrally designing heat removal systems into equipment and industry must provide improved electronic parts for operation in various environments. It is apparent, based upon present knowledge, that future equipments of high packaging densities will require liquid or vaporization cooling systems.

III. PRESENT ELECTRONIC HEAT TRANSFER TECHNIQUES

A. NATURAL METHODS

Most conventional electronic equipments utilize natural heat transfer for cooling. Natural methods can be defined as those wherein heat transfer occurs without additional energy being supplied to accelerate the process. Conventional electronic parts including vacuum tubes, resistors, capacitors, reactors, etc., have been designed for natural cooling in a free air environment at pressures of the order of an atmosphere. The cooling (and heating) of conventional equipments utilizing these parts has heretofore been of minor importance except in precision laboratory instruments. The cooling achieved has been reasonably satisfactory since the power densities seldom exceeded 1/10 watt per square inch of cooling surface.

Natural heat transfer methods have been found to be effective for miniaturized constructions wherein the packaging and power densities are not large. The majority of current miniaturized electronic equipments are within this category. However, the present practices of electronic cooling by natural heat transfer methods are in need of improvement. With more efficient thermal designs, natural methods can be utilized for equipments of increased power densities.

Conduction, convection and radiation cooling are of course always present in combination. Electronic equipments are usually designed so that one type will predominate. Conduction and convection cooling are most common. The thermal designs for natural cooling were, until recently, modifications which were incorporated into the equipment if hot spots were encountered. In miniaturized electronic assemblies some preliminary consideration has been given the thermal problem. Heat transfer by metallic conduction (excluding liquid conduction cooling, discussed later in the report) to a thermal sink is widely used.

1. Heat Transfer by Metallic Conduction

To efficiently remove heat by metallic conduction it has been found necessary to design electronic packages with low impedance thermal paths from the vacuum tubes to the case and to provide heavy case walls with a uniform path of low thermal impedance on the surface. Equipments with one-quarter inch thick aluminum cases, drilled solid metal blocks containing the vacuum tubes and good thermal bonds to the external surface have obtained power dissipations of the order of 0.5 watts per square inch of cooling surface in free air. With this type of construction, the hot spots were 10° to 15°C. cooler than those of corresponding light metal case construction. The cooler parts were also increased in temperature so that a more uniform temperature distribution existed throughout the entire equipment.[18]

It has been recommended that when neither lower ambients nor thermal ground points are available nearby, it may be useful to design miniaturized equipment entirely of unit assemblies from which the heat can be conducted along solid rods to a collection center where it may be removed by other means.[B-343]

A unique power supply package design has been developed, dissipating two hundred watts with a temperature differential of only 15°C. between the hot spots and the surface of the case.[7] This was accomplished by constructing the end plates and partitions of the power supply of one quarter inch thick aluminum plate and connecting all heat sources to the plate with a low impedance thermal bond. Since the internal ambient temperatures of the power supply ranged between 100°C. and 115°C., high temperature materials were utilized for the reactors.

A series of subminiature amplifiers for operation in ambient temperatures of from -40°C. to +110°C. with power densities as great as .3 watts per square inch are under development. The first models were plastic encapsulated with a resultant low thermal conductivity. It was found that tube envelope temperatures exceeded the rated values. Several methods of conducting the heat to the outside of the plastic were investigated. Since none of the redesigned configurations resulted in any particular degree of success, the plastic encapsulation method of construction was rejected. Solid brass shields in direct contact with the tubes were then utilized. The improvement in the cooling was excellent and electroformed metal tube covers were later developed for the amplifiers. A further reduction in temperature was achieved and the technique was extended to include an aluminum investment casting in two halves enclosing the complete subassembly. Each subminiature tube is wrapped with aluminum foil. The current design includes a three stage amplifier mounted on a quarter inch aluminum plate.[20]

A vacuum tube manufacturer has performed extensive work in the field of isolating heat sources in electronic equipment and disposing of the heat by conduction.[30 & 31] More complete coverage of this work is presented in Section F, titled, "Methods of Cooling Vacuum Tubes".

An airborne receiver with an exceptionally low thermal impedance also provides a good example of conduction cooling. Buffed 24ST aluminum .18 inch thick "T" sections 1.5 inches wide at the base, 3.5 inches high and 13 inches long form the chassis. Subminiature tubes are firmly mounted with .25 inch thick split aluminum "pillow blocks" at each end of internally blackened tube shields.[11]

Approximately twelve to sixteen tubes are widely mounted on the chassis to provide accessibility. The aluminum is buffed and polished while the inside of the cover is coated with black wrinkle enamel.

Another unit of miniaturized equipment which is designed for conduction cooling is contained in a 9 x 10.5 x 10.5 inch aluminum package.[18] The components are suspended from a top cover painted black on the inside and dull grey on the outside. It is anticipated that natural means will be adequate to dissipate 95 watts in this package with 0.17 watts/square inch of cooling surface. A similar package is designed to mount the tubes in solid aluminum blocks fastened directly to the inside surface of the .25 inch thick aluminum case. Component parts are mounted on other inside surfaces of the case away from the heat of the tubes. Extensive tube cooling tests and temperature measurements show that thick walled packages provide 17°C. lower temperatures at the hot spots than a thin-walled aluminum case of .06 inch wall thickness.

The reduction of the vacuum tube temperature in IF Amplifiers originally developed by the Bureau of Standards has been accomplished through the use of metal sleeves.[14] The early models utilized cylindrical ceramic tube shields with surface attached parts. Since the ceramic shields were known to be poor thermal conductors, it was believed that the temperature of the tubes could be reduced by inserting metal sleeves, welded to the metal case, between the ceramic shields and the tubes.

The following temperatures were achieved:

Bureau of Standards prototype - - hot spot tube temp. 180°C.
Model with .010 inch brass sleeve - - hot spot tube temp. 150°C.
Model with .006 inch brass sleeve - - hot spot tube temp. 165°C.

Due to production tolerances of the vacuum tubes .006 inch sleeving was found to be the optimum physical size.

The external dimensions of the metal case of the IF Amplifier subassemblies are .75 x 2.06 x 6.06 inches. Included therein are a duodiode and nine type 5840 subminiature tubes.

The packaging density and power densities follow:

Total area	Approx. 36 sq.in.
Total input power	Approx. 22 watts
or approx.	.6 watts per sq.in. of cooling surface
Packaging density	.9 cu.in. per tube

This is the most compact packaging encountered during the survey.

Low melting temperature bismuth alloys obtained from Cerro De Pasco Copper Corp., 40 Wall Street, New York, N.Y., were employed to encapsulate subminiature tubes in metal tube blocks. The alloys became liquified at the equilibrium temperature of the tubes and furnished a low thermal impedance between the tubes and the block. The alloy surfaces exposed to the atmosphere were cool and remained solid to provide a seal. "O" Rings were also provided for sealing with lower temperature alloys. This novel cooling scheme was abondoned, however, since the tubes operated only 6 to 8°C. cooler than with silicone jell.[5]

Three types of subminiature subassemblies for continuous duty at 100°C. ambient have been developed.[8] A high conductivity thermal path is provided by special beryllium copper tube shields fastened to a .031 inch thick copper subchassis spring loaded to contact .031 inch thick copper outer cases. Copper sink "blocks" with combination thermal, electrical, and mounting connectors are attached to one end of the outer cases to permit conduction to an ultimate sink. The greatest rise above ambient is approximately 75°C. at the base of a subminiature tube dissipating 5.5 watts. The average rise above ambient for most of the tubes is of the order of 40°C. Capacitors, resistors and reactors utilized in these equipments are designed for operation at 200°C. It is claimed that several of the subassemblies will function at ambient temperatures as high as 150°C. A power supply subassembly with similar high temperature characteristics is under development.

In general, the largest temperature gradient of importance in miniature electronic equipments exists between the vacuum tubes and their shields. In some instances, a large thermal gradient was observed between the subchassis and the thermal sink.

a. Plastic Embedment

Conduction cooling is also utilized with embedded electronic subassemblies. The cooling provided by the plastic and by the wiring is considerably less than that provided by metallic conduction.[8, 10, 20] It was stated by one of the contributors that plastic "had the same thermal conductivity as fire brick". A number of plastic embedded electronic subassemblies have utilized metallic conduction cooling. The tubes and other heat producing parts were mounted on .062 inch thick aluminum angles which formed a side and the bottom of the subassembly to provide connections to the thermal sink.[23] Plastics with metal particles as a binder to increase the thermal conductivity have also been used. Copper thermal conductors embedded within the subassembly and connected to the thermal sink have found limited application. Measurements of the power dissipation and derating of embedded resistors are in progress at several organizations.[3, 11] A cluster of four type T-2 subminiature diodes were embedded in

NEL casting resin to form a cylinder .625" dia. x 1.75" long. Difficulty has been experienced with cracked and overheated plastic at an input of 3 watts.[11] A servo amplifier 2.5 x 1 x 3 in. with an input of 13 watts, has been embedded somewhat successfully utilizing aluminum particles in the resin.[11]

2. Heat Transfer by Convection

Convection cooling has also been utilized as the primary cooling means in electronic equipment. Considerable heat removal usually takes place by natural convection, especially in equipment operated at or near atmospheric pressure. In addition, vacuum tubes and resistors in conventional electronic equipment rely on natural convection currents of air for much of their cooling. Vertical ducts have been provided to obtain a "chimney effect" flow of heated air. Convection cooled equipments usually have poor performance at altitude unless considerable tube and part derating has been applied. Vacuum tubes and parts with dissipations exceeding .5 watts per sq.in. have required forced air cooling. Typical subminiature tubes operated in free air will achieve hot spot temperatures approaching 200°C.

Convection cooling of the ultimate sinks is common. Large surfaces are usually provided (See Section III-G of this Report). Convection cooling of ultimate sinks is not considered practical at altitudes of 30,000 feet or higher.

3. Heat Transfer by Radiation

Radiation cooling has not been used as the primary cooling means in electronic equipment because the temperature differentials and surfaces are usually too small for the radiation of large quantities of energy. Blackening and/or polishing of cases, tube shields and parts is a common practice to improve the emmissivity and/or reflectivity.[7, 8, 30] In marginal instances these techniques have improved the cooling sufficiently to provide satisfactory heat removal. Black wrinkle enamel has been found to be somewhat superior to other finishes.

Reflective insulation has been utilized to obtain a designed thermal gradient in a high temperature subminiature subassembly currently under development.[5] Temperature sensitive circuits and parts are mounted in the lower section of the subassembly separated from the heat sources by insulation and polished chromium plated reflectors. Thermal gradients of the order of 60°C. have been achieved.

An oscillator and power supply for a precision recording system is mounted on a chassis 8 x 5 x 13.5" and has an input power of 250 watts.[10] Chrome plated reflector plates are provided adjacent to the hotter vacuum tubes to protect temperature sensitive circuits.

A unique miniaturized equipment designed to utilize all types of natural cooling has been developed.[9] T-812 phenolic was fabricated into terminal strips and mounting boards for the tubes and components. Subminiature tubes were mounted towards the metal case in front of tiny windows provided in the phenolic for air circulation. Metal strips 1.5 inches wide were bonded (thermally) to the chassis and to the outside of the phenolic and included integrally formed tube shields. This configuration resulted in an excellent radiating surface. The tubes were mounted in the vertical plane to permit free flow of convection currents and louvers in the outside case were located opposite the tubes. Small holes were provided in the tube shields to permit direct radiation from the tubes.

B. HIGH TEMPERATURE ELECTRONIC PARTS

The "brute force" approach to the thermal problem, wherein high temperature electronic parts are utilized without special cooling means, has found acceptance especially in subminiaturized equipments. This approach is not a complete solution to the thermal problem, but when used in conjunction with metallic conduction cooling, it is a practical means of achieving satisfactory performance in high temperature environments. Conversely, when applied alone at lower ambient temperatures to alleviate the effect of "hot spots", it can be inherently inefficient and expensive.

Several organizations have determined, after extensive thermal studies of small packages, that the optimum results were achieved with 150°C. parts and forced air cooling of the hot spots.[9, 16, 19] At high temperatures special protection of parts is necessary to prevent the corrosion and oxidation which can occur rapidly in free air. Evacuating, filling with inert gas, and hermetic sealing of the package have been found to be a practical means of alleviating this problem. The special high temperature electronic parts are relatively new to the field and it is believed that a short discussion related to their thermal characteristics and the limitations of conventional electronic parts is in order. In general the special parts can withstand peak operating temperatures of approximately 150 to 200 C. and exhibit characteristics superior to those of conventional electronic parts.

1. Fixed Capacitors

a. The best paper dielectric capacitors have an upper temperature limit of 125°C. The possibility of extending their temperature range to 200°C. seems remote. Organic dielectrics (paper and petroleum oil) cannot remain stable at elevated temperatures.

b. Conventional mica dielectric capacitors are limited to peak temperatures of the order of 120°C. by their plastic cases. Mica is an excellent high temperature dielectric and uncased mica capacitors can be utilized for high temperature applications.

c. Barium titanate and similar high dielectric constant ceramic dielectric capacitors have poor temperature coefficients of capacitance (except low K capacitors) and upper temperature limits of the order of 85 to 100°C. At higher temperatures large departures from nominal values occur and the leakage resistance rapidly decreases. The ceramic body type K-1200 shows promise for application at elevated temperatures, however, the temperature coefficient of capacitance is large.

d. Glass dielectric capacitors, manufactured by Corning Glass Works, exhibit excellent characteristics for service at 200°C. The glass has a dielectric constant of the order of 8.45 which is approximately 55 percent greater than that of mica. This permits some reduction in space factor. The dissipation factor at 200°C. at 1.Mc is .014 percent. The temperature coefficient is approximately +.025 percent per degree C. Capacitances ranging from a few uufd to .015 mfd. in a multiplicity of voltage ratings are available.

e. Vitreous enamel dielectric capacitors produced by Vitramon, Inc. are rated for application at 200°C. The electrical characteristics are similar to mica capacitors. Values ranging from .5 to 1000 uufd. nominally rated at 500 V.D.C. can be obtained.

f. Tantalum electrolytic capacitors manufactured by Mallory, Inc. are rated for continuous service at 200°C. These capacitors exhibit lower leakage currents, better low temperature performance, reduced power factor and smaller space factors than conventional electrolytics. The Mallory capacitors are totally hermetically sealed to prevent leakage of the electrolyte.

A similar capacitor, manufactured by General Electric Company, is rated at 150°C. maximum temperature.

g. duPont "V-Film" holds promise as a dielectric for a 200°C. capacitor to replace paper dielectric capacitors. Also under development for 200 C. service is a capacitor with a .0005 inch thick Teflon dielectric. The application of metalized coatings to high temperature plastic films is under investigation.[13]

2. Resistors

a. Conventional wire wound vitreous resistors are satisfactory for high temperature service. Miniature wire wound resistors manufactured by Painton & Co., Ltd., Northampton, England, are very small and can be operated at temperatures as high as 400°C. "Dalohm" power resistors manufactured by Dale Products, Inc. of Columbus, Nebraska, are also of interest. The resistor elements are housed in die-cast black anodized aluminum cases with radiator fins. The cases are provided with mounting lugs for direct attachment to sink plates. Available are 25 and 50 watt resistors with resistances to 55,000 ohms.

b. Conventional composition carbon resistors have upper temperature limits of the order of 100°C. and are, therefore, not considered usable for high temperature service.

c. Palladium film resistors, produced by Continental Carbon Co., are rated for utilization at 200°C. These resistors exhibit low noise, a temperature coefficient of +.035 percent per °C., and excellent load characteristics. The normal tolerances are ±1 or ±5 percent.

d. The miniature carbon composition resistor, manufactured by the Globar Division of the Carborundum Corporation, is one of the smallest commercially available resistors. The external dimensions are .25 in. x .06 in. dia. It is rated for application at 150°C. maximum.

e. Several brands of printed resistors are rated for high temperature service. In general, printed resistors have a higher temperature coefficient of resistance than composition carbon resistors, wide production tolerances and inferior life characteristics. The art of printing resistors is relatively new and will ultimately be improved.

A tape type resistor recently developed is rated for service at 185°C.[21]

f. A number of types of cracked carbon and borocarbon resistors, which are rated for high temperature duty, have been developed recently. The characteristics of these resistors usually fall between those of composition carbon and the palladium film types.

Of interest is a carbon film resistor capable of operation at 200°C. for 1000 hours with only 2 percent change in resistance.[2] A 10 to 12 percent change in resistance has been observed during temperature cycling from -60 to +200°C. The stability after cycling is within 1 or 2 percent. A protective covering was necessary to overcome oxidation at temperatures exceeding 60°C. Production techniques for fabricating carbofilm resistors to 1 percent tolerances are known. It is planned to develop miniature and subminiature types in the near future.

Promising progress has been achieved in the development of a similar resistor with an improved temperature coefficient of resistance and reduced oxidation tendencies.[2]

g. A miniature carbon potentiometer with an upper temperature limit of 150°C. is manufactured by the Chicago Telephone and Supply Corporation.

3. Conductors

a. An assortment of printed, fired, etched and stamped metal conductors are available for high temperature service. Silver and copper are commonly utilized as the conducting metals. The temperature is limited by the bonding adhesives and the base material to which the metal conductors are attached.

b. Since the peak operating temperatures in miniaturized electronic equipments approach the softening temperature of conventional solder, high temperature solders containing a small percentage of silver are generally used.

c. Ceroc and Ceroc T (Teflon) magnet wires have excellent characteristics for high temperature service and have found wide acceptance throughout industry.

Silicone enamel magnet wires are not often used for 200°C. service because the softening of the enamel at high temperatures frequently leads into turn to turn short circuits in reactor windings.

Glass covered magnet wire has found limited application in high temperature reactors.

Teflon covered and silicone impregnated Fiberglas covered stranded wire is commonly utilized for 200°C. service.

4. Reactors

Class H (150°C.) reactors have recently been made commercially available in limited quantities. A comprehensive service life record of the performance of these reactors has not been compiled to date.

In reactors, miniaturization and high temperature operation are not compatible. Since magnetic core materials saturate readily at high temperatures, it is usually necessary to increase core size for high temperature operation. Also, high temperature insulations are thicker than those used at lower temperatures. For these reasons, miniaturized high temperature reactors can easily approach the size of their conventional counterparts.

Power supplies utilizing Class H reactors frequently exhibit inferior regulation characteristics. The conductor current densities are increased in the interest of miniaturization and the I^2R losses are greater due to the wider range of operating temperature.

Until recently, means of internally cooling electronic reactors were not known. The winding and insulation densities would not permit the penetration of coolants to the internal hot spots. The insertion of metallic thermal conductors into the hot spots was considered and rejected by many manufacturers because of the resultant increased size and general impracticability. However, one organization has successfully miniaturized and cooled reactor by this method.[25]

A technique of photo etching reactor conductors on thin flexible plastic sheets, assembling, and spot welding the sheets to form "pie wound" windings has been developed by Technography Printed Circuits Company of Tarrytown, New York. With this method the cross sectional area of the internal conductors can be printed larger than that of those near the surface to provide a means of alleviating hot spots. Also, cooling conductors can be integrally printed to permit conduction cooling of the internal hot spots. It is claimed that reactor windings can be fabricated more economically with this technique than with conventional winding methods.

5. Subminiature Vacuum Tubes

Ruggedized premium subminiature tubes are commercially available from several tube manufacturers. Most of these are the end products of research and development programs sponsored by the Armed Services. Electrical equivalents of many standard GT and miniature tube types are being produced.

The premium tubes are rated at 80% minimum average life for 5000 hours at 30°C. ambient temperature. Reasonable life expectancies can be achieved if the hot spot envelope temperatures are limited to 175°C. At the absolute maximum temperature (250°C.), the tube life is considerably reduced. Further thermal data related to these tubes is presented under item 7 of this section and in Section III-F of this report, "Methods of Cooling Vacuum Tubes".

Additional tube types are under development and production facilities are being rapidly expanded.

6. Other Materials and Miscellaneous Parts

Silicone and Teflon impregnated Fiberglas laminates are acceptable for 200°C. service. Separation of printed conductors from bases of silicone laminates has occurred at elevated temperatures due to the softening of the resin. Asbestos filled bakelite, when protected from the atmosphere, is usable to 200°C. The electrical characteristics at elevated temperatures are poor. The filler helps ruggedize the plastic but does not provide a hermetic seal.[13]

Johns-Manville asbestos insulating sheet, "Quinterra", has been frequently employed in winding high temperature reactors. The power factor at 60 cycles ranges from 25 to 30 percent.

Teflon has excellent thermal and electrical characteristics, but it is at present somewhat difficult to utilize. Miniature tube sockets and hermetic seals of Teflon are available from The U.S. Gasket Company. Care must be exercized in exposing Teflon to extreme temperatures, since highly toxic fluorine gas is released.

A satisfactory embedding plastic for high temperature subassemblies has not, to date, been developed. High quality potting materials currently available have absolute upper temperature limits of 175°C. for short periods.[8] Stypole resin has been successfully utilized for connectors operating at high temperatures.[8] At present, it can be used as an embedding material for only small parts, not complete subassemblies.

Kovar and Fusite hermetically sealed plugs are excellent for 200°C. applications.

Almost all fired electrical ceramics are satisfactory for high temperature utilization. Steatites have been frequently fabricated into baseplates for high temperature printed conductors. Stupalith exhibits promising characteristics. The electrical parameters are excellent and the coefficient of thermal expansion is almost nil. In general, all ceramics are fragile and, therefore, require special mechanical consideration.

Winchester melamine connectors have been converted to hermetically sealed connectors by encapsulating the male pins with Stypole. Satisfactory operation for several hundred hours at 200°C. has been achieved.[14] A disk type semi-conductor rectifier for operation from -60 to 200°C. is under development.[2]

P.R. Mallory and Company is planning to produce a hermetically sealed magnesium copper sulfide rectifier rated from -70 to 200°C.

7. Thermal Derating of Electronic Parts

It is recognized throughout industry that thermal derating of electronic parts is necessary for high temperature service. A number of manufacturers have established derating "bench marks" for particular parts. However, little is known in these matters of the characteristics of the majority of electronic parts, especially in terms of long life and reliability.

Many electronic engineers, engaged in the design of military equipment, unconsciously apply the marginal ratings that are common practice in the design of domestic television and radio receivers. Equipment so designed frequently has short life and poor reliability. In addition, engineers, anxious to obtain the maximum gain or output per stage, design circuits wherein the vacuum tubes are operated near or at their maximum ratings. This concept is not compatible with long life, reliability, or good thermal practice.

Examples of the marginal ratings currently in use in the United States compared to the conservative British ratings is exemplified by the resistor ratings published by Painton, Ltd.

Type	Length	Max.Dia.	British Rating	Nominal U.S. Equivalent
72	.5"	.156"	1/8 Watt	Greater than 1/4 Watt
73	.81"	.219"	1/4 Watt	Greater than 1/2 Watt
74	1.06"	.219"	1/2 Watt	Approximately 1 Watt
75	1.38"	.344"	1 Watt	Greater than 1 Watt
76	2.06"	.344"	2 Watts	2 Watts and over

Ratings for liquid and forced air cooling of resistors are also published by Painton.

Thermal derating of vacuum tubes is discussed in Section III-F of this report.

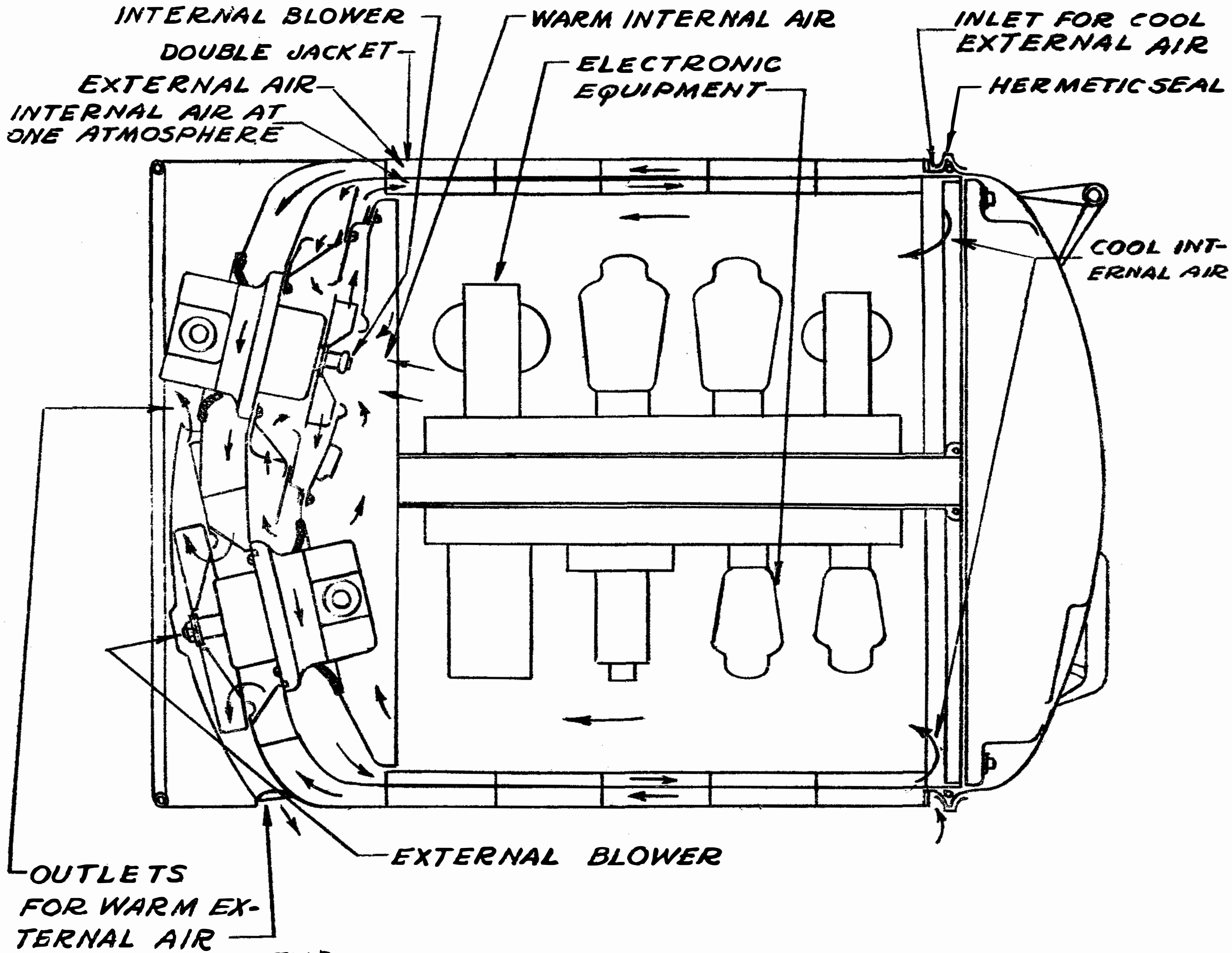
C. FORCED AIR COOLING

1. In recent years, several manufacturers have expended considerable effort toward increasing the efficiency of "forced air" cooling of electronic equipment. Current advances include the development of cooling ducts, turbulent air cooling, and air-to-air heat exchangers. Forced air is usually directed to the heat sources by means of ducts and baffles. In several instances, forced air cooling was utilized to supplement convection cooling when "hot spots" were encountered.

2. Air to Air Heat Exchangers

One of the primary difficulties encountered with forced air cooling is related to the variation of the density of air with altitude. At high altitudes the rarefied atmosphere loses much of its cooling capacity, and electrical insulation fails through corona formation. One solution is the utilization of an "air to air" heat exchanger case in which the electronic equipment is hermetically sealed at a pressure of one atmosphere. An internal fan usually transfers the heat from the source to the heat exchanger jacket, which also serves as the case, while an external fan draws the ambient air across the outside of the case to cool the heat exchanger (See Fig. 1). At least six organizations have developed "air to air" heat exchangers of this type.

The exchangers are of many configurations and capacities. The most successful units were cylindrical tanks with convex dished heads. It was necessary to design the electronic equipment in special



TYPICAL AIRBORNE AIR TO AIR HEAT EXCHANGER
FIGURE 1

shapes to fit inside the cases. It was found that high strength material was required for the heat exchanger cases in order to withstand the pressure differentials. A method has been developed for fastening circular parts together with a pressure tight seal when either thick or soft aluminum sheet stock is used for construction of the case.[8]

Some of the characteristics of a typical "air to air" heat exchanger case designed to remove 1060 watts from electronic equipment are listed.[8] The case was of a cylindrical shape with outside dimensions of 20 inches in diameter and 30 inches in length. The double jacketed heat exchanger included finned aluminum radiator cores which also formed part of the case. The outside air was forced through the external core in one direction while the internal air was drawn through the internal core in the opposite direction.

At sea level, atmospheric pressure, 55°C. ambient air temperature, and a dissipated power of 1060 watts, the temperature at the entrance of the inside heat exchanger was 77°C. while the highest temperature of air discharged from the tubes was 111.5°C.

At an altitude of 50,000 feet and an ambient temperature of 31°C., the highest temperature at the entrance of the inside heat exchanger was 73°C. When the inside air was evacuated to an equivalent pressure altitude of 10,000 feet, the inside heat exchanger entrance temperature was 79.6°C.

Another case, similar to the above, with an outside diameter of 18 in. and an overall length of 26 in. was developed to dissipate 650 watts intermittently and 200 watts continuously. With both external and internal fans in operation, the equipment operated so cool that it was decided to use an internal thermostat to control the outside fan motor.[8]

An "air to air" heat exchanger case has been constructed in the form of a cylinder 19" in diameter and 21" high.[29] The external air entered a plenum chamber at the bottom of the cylinder and was passed through twenty-four .5 inch diameter tubes which serve as heat exchangers to the inside of the case. External air is supplied to the plenum chamber by the airframe manufacturer. At 30°C. ambient temperature, sea level pressure and with a heat input of 780 watts, a 250 C. rise above ambient at the hot spot and a 13°C. rise at the cold spot were observed. These tests were performed with air circulating through the heat exchanger case at 133 CFM and with a static pressure at the entrance of the case of 0.066 in. H_2O. The temperature of the exhaust air from the case was 15°C. above its entrance temperature.

Hermetically sealed air to air heat exchangers in oblong shaped packages have also been developed.[9] Two current pressurized units dissipate 175 watts and 145 watts respectively.

A special high altitude heat exchanger dissipating approximately .75 KW has been developed by an aircraft manufacturer.[11] Flattened tubes, for pressurized internal air and atmospheric external air, are arranged around the periphery of the 30 in. diameter by 36 in. long cylindrical body. The dished heads at the ends of the exchanger are extremely complex magnesium castings, incorporating pressure seals, electrical connectors, etc.

An air to air heat exchanger to dissipate 1000 watts in a pressurized case 20 in. in diameter and 29 in. high is under development.[7] Thermal evaluation has been initiated utilizing an external fan with a 3-13/16 inch diameter Torrington wheel operated at 9000 RPM at sea level and 12,000 RPM at 60,000 feet.

Several electronic organizations have produced airborne electronic equipment without incorporating any integral cooling equipment. The airframe manufacturers have promised to provide the required cooling air at the necessary temperature to cool the electronic equipment.

One equipment is to be cooled by cabin exhaust air which will enter the case at 30°C. or lower at a density not less than that equivalent to 30,000 feet.[4]

Another equipment under development dissipates 400 watts in a case designed for forced air cooling.[7] The airframe manufacturer is required to supply the desired airflow for cooling the equipment. To insure proper cooling, the first seven models of this equipment incorporated thermocouples attached to the hot spots so that the operating temperatures could be externally monitored until the cooling air was properly adjusted.

In an airborne electronic equipment which has been recently miniaturized, the synchronizer was reduced to a package 2 x 9 x 14 in.[16] Eight plug-in subassemblies, with a total of approximately 70 subminiature tubes, a blower, a 300 watt heater, and blower controls are included in this unit. Approximately 300 watts of input power are required for its electronic operation. Printed conductors on laminated phenolic plates, with conventional resistors, and capacitors, are utilized. Due to the temperature sensitivity of several critical "RC" circuits, it has been necessary to accelerate the normal "warm-up" with a heater and recirculate internal air with a blower. After the required temperature is achieved, the heater is disconnected and the blower, by means of an electrically operated shutter, circulates external air through the assembly. It is necessary to maintain the exhaust air temperature at 55°C. plus or minus 5°C.

3. Blowers

A radiator manufacturer initiated the development of a prime cooler in the form of a blower which would deliver a constant mass of air rather than a constant volume. Since conventional blowers become ineffective at 30,000 feet altitude, such a blower might extend the service ceiling of aircraft from 30,000 to 50,000 feet. The design problems of such a blower have been explored.[24] This project was discontinued but may be re-initiated in the future.

A miniaturized spot blower for cooling hot spots is under development by Fairchild Camera and Instrument Corporation. The total volume occupied by the blower is not to exceed 2.5 cubic inches, of which 2 cubic inches is for the motor-blower and 0.5 cubic inches for the motor capacitor. The motor is to develop 1.75 watts output at 24,000 rpm when operating from 115 volts, 400 cps, single phase, and the impeller is to deliver 10 CFM of free air at 25°C. This blower is to be a completely integrated unit which will operate in 200°C. ambient temperatures. Delivery of the first prototype is planned for the immediate future.

4. Turbulent Air Cooling

Increased air cooling efficiencies can be obtained by the utilization of turbulent air techniques. This cooling method is considered by some organizations to be a new advancement. The application of these techniques to electronics is new; however, turbulent air cooling has been used by the aircraft and automotive industries for many years.

The principal function of the turbulent air technique is to reduce the stagnant boundary layer or air film which constitutes the resistance to heat, mass, and momentum transfer through the application of high velocity cooling air. It has been found that the stagnant layer can be greatly reduced by turbulence. The thickness of the stagnant layer is a function of the Reynolds number,* the diameter of the duct, and a dimensionless coefficient usually referred to as the Prandtl or Schmidt number. In general, not much can be accomplished practically to modify the Prandtl number.

----

* A non-dimensional term involving the essential parameters of the flow; namely -velocity, density, viscosity, and physical dimension in the direction of flow which provides an index of the nature of the flow, whether uniform or non-uniform and the degree thereof.

The parameters which can be freely varied are the Reynolds number and the diameter. By increasing the Reynolds number and decreasing the diameter, conditions can be modified so that the stagnant layer thickness is considerably reduced. As a result, under favorable conditions, heat transfer, momentum transfer, and mass transfer can be increased by a factor of 10 to 100 within practical design limitations. Theoretically, the heat, momentum, and mass transfer can be increased to values approaching molecular speeds but the design problems would mount very rapidly as the velocity of the fluid is increased above the speed of sound.[B-363]

The high Reynolds number combined with small diameters usually requires the high velocity movement of gases or liquids which, in turn, necessitates that a considerable amount of power be expended into the pump or compressor.[B-363]

Some of the advantages of the turbulent fluid techniques are:

a. It is possible to achieve mass transfer at either reduced volume or at lower temperatures than under stagnant conditions.

b. With equal temperature and volumetric considerations a gain in the speed of mass transfer can be obtained.

c. The turbulent fluid techniques combined with high temperature and high concentration gradients across the stagnant layer can permit an increase in speed of operation by a factor as great as one hundred. This may lead to the development of new fields in drying, depositing of chemicals, painting, paint removing, etc.

The disadvantages of turbulent fluid techniques are:

a. The turbulent fluid technique inherently introduces an irreversible process leading to a limitation in the efficiency of the system.

b. If temperature limitations are not involved in the process, the turbulent techniques will in general offer no advantage since the same mass, heat or momentum transfer can usually be obtained by increasing temperatures and concentrations in the stagnant processes. Under such conditions the extra expenditure of equipment for turbulent motion may not be economical.

5. Applications of Turbulent Air Techniques

The turbulent fluid technique can best be applied where there is either a limitation as to the maximum temperature that can be employed; a limitation as to the maximum time during which an operation can take place; or if there is a limitation on the maximum surface area which is available for heat transfer. Because of the inefficiencies of ordinary methods of stagnant transfer and the large conduction and rapid radiation losses incurred in stagnant processes, the turbulent techniques so far used compare favorably with the commercial stagnant drying techniques utilized in a number of industries.

It should be realized that whereas the efficiency of the turbulent technique is limited by the power which must be wasted for the destruction of the stagnant layer, the conventional techniques are not limited by such an item.[B-363]

Generalized Turbulent Flow Data:

Laminar flow requires six times as much air volume as turbulent air for equivalent cooling. The heat transfer coefficient is ten to one hundred times greater for turbulent flow than for laminar flow. This amounts to an eight to one gain in efficiency when the compressor losses are included.

For a given pressure difference or flow of air, the dimensions for a duct to produce turbulent flow may be calculated to provide optimum heat transfer characteristics.

A laboratory test model was designed to remove 300 watts from a magnetron with turbulent air cooling.[25] A solid brass block was drilled with seven holes for the insertion of elements to simulate the magnetron heat dissipation. A heat exchanger core of copper tubing about .125 inches square was soldered around the brass block and connected to a fitting the size of a ten centimeter wave guide. Turbulent forced air reduced the block temperature to 170°C.

A second lab test configuration demonstrated the simulation of an air to air heat exchanger for a ground based equipment which was to operate unattended for a month in a salt water spray and a sand atmosphere.[25] The exchanger core was constructed of rectangular ducts about 1 x .25 in. soldered together along the one inch surface to form a duct about 8 inches wide. The warmed and cooled air was circulated through alternate ducts in opposite directions. These ducts were in contact with each other for a distance of about four feet until the ducts were reduced by a throat to approximately 1 x 3 inches. The test blower motors consumed approximately 220 watts.

It is claimed that the thermal efficiency of this heat exchanger was almost 100%; that is, the air leaving the heat exchanger was within less than one degree of the operating temperature of the equipment.[25] The heat transfer coefficient is claimed to be ten times greater than that obtained with laminar flow. The energy expended by the motors powering the blowers was not mentioned.

A turbulent air heat exchanger plate designed to dissipate 100 watts operated at 35°C. above ambient with a differential air pressure of 10 pounds gage.[25] An aluminum model of improved performance which will operate at 27°C. above ambient for 100 watts of cooling has been demonstrated.

D. LIQUID COOLANT SYSTEMS

The state of the art of liquid cooling has been found to be well advanced in special types of electronic equipment. With currently available piping, pumps, and heat exchangers, etc. it has been possible to construct usable auxiliary equipment. Piping has provided a convenient means of transporting heat from electronic equipment to the ultimate sink. It has a small volume, relatively light weight, and is capable of conducting large quantities of heat.

Liquid cooling can be separated into two categories, direct and indirect systems. Direct systems are those wherein the coolant is in direct contact with the electronic parts. Indirect systems are those wherein the coolant is not in contact with the electronic parts.

For direct systems, careful selection of a coolant compatible with the immersed electronic parts has been necessary to reduce the deleterious effects of decomposition, corrosion, and electrolysis. The coolant requirements for indirect systems were not as critical because it is only necessary that the coolant be compatible at the operating temperatures with the heat exchangers and piping.

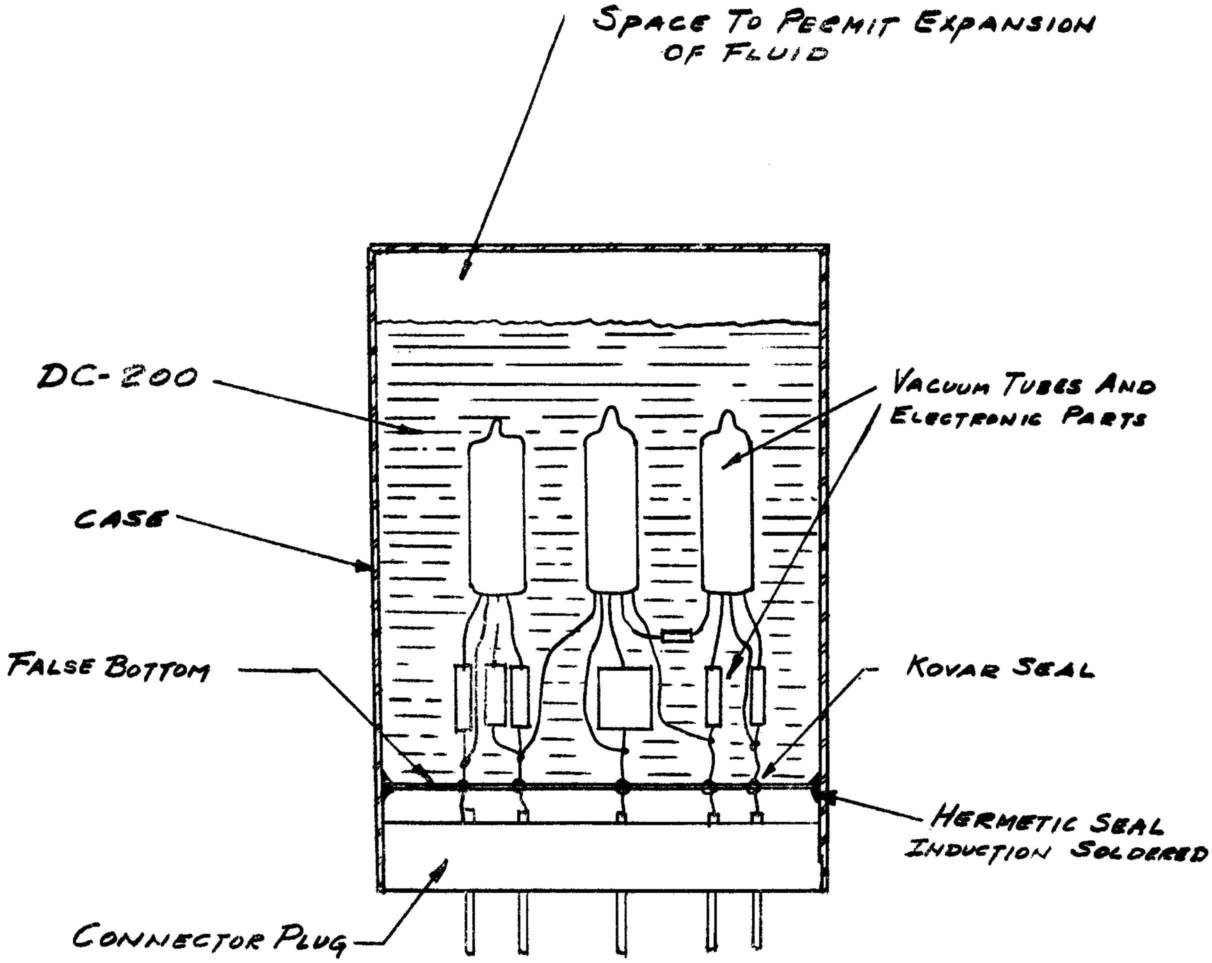
1. Direct Liquid Cooling Systems

a. Simple Systems

With power densities of 0.5 watts per square inch of cooling surface or less, it has generally been found satisfactory to immerse the electronic parts directly in a coolant, for instance, silicone oil, and seal the package. Thus, the primary heat transfer from the components to the coolant was accomplished directly. The heat transferred to the liquid was transported to the surface of the case by natural convection and reached the ultimate sink by conduction through the case (See Fig. 2).

b. Direct Systems in More Complex Form

For power densities exceeding 0.5 watts per square inch of cooling surface, additional equipment has been required. A circulating pump was usually necessary to remove the heat carrying liquid from the electronic equipment compartment



TYPICAL LIQUID COOLED AND HERMETICALLY SEALED SUBASSEMBLY

FIG 2

to a heat exchanger, for heat rejection to the ultimate sink. A return line from the exchanger to the electronic compartment formed a completely closed continuous circuit.

2. Indirect Liquid Cooling Systems

In indirect systems, the coolant usually circulated through a wall panel or jacket heat exchanger enclosing the electronic parts to be cooled. Natural radiation, conduction, convection or forced air were relied upon as the primary means of moving the heat from the electronic parts to the internal heat exchanger where it was transferred to the coolant. The heated liquid was pumped to an external heat exchanger for heat transfer to the ultimate sink, and subsequently returned to the internal heat exchanger by a pump in the return line.

3. Desirable Coolant Liquid Characteristics

It has been found necessary, when selecting a liquid coolant for and indirect system, to consider the change in the thermal and physical characteristics of the liquid over the entire operating temperature range as well as its compatibility with the metals and materials of the heat exchangers, piping, and pumps, with which it comes in contact.

For direct liquid cooling systems additional properties including the compatibility with electronic equipment and parts, the dielectric constant, the power factor, the viscosity, the vaporization temperature, the flash point, toxicity, and the coolant life must be evaluated.

a. Silicone Fluids

Silicone oils have been used successfully as liquid coolants for both direct and indirect cooling applications. These fluids have been found to exhibit satisfactory thermal and electrical characteristics. High temperature operation is excellent and is limited only by the cracking temperature of the fluid.

Properties of two representative silicones that are in general use are presented:

Characteristics	DC-200	DC-550
Dissipation Factor at 1. M.C.	.0003	.0003
Dielectric Constant at 1. M.C.	2.78	2.20
Pour point	-65.0° C.	-50.0° C.
Specific Heat Cal/gram	.34	
Flash point (min.)	163.0°C.	316.0°C.
Boiling Point (1 Atm.)	200.0°C.	
Thermal Conductivity	.000236 to .000338 gram calories/sec/cm^2/C°	
Thermal Expansion Parts/°C		1.598×10^{-3}

Temperature differentials of from 5 to 10 degrees C. have been obtained in silicone fluids utilized in direct cooling systems. If the liquid is agitated, the temperature differential may be maintained within 2 or 3 degrees C. Containers of silicone oil are usually hermetically sealed in applications not requiring an external heat exchanger or agitator.

In equipment mounted so that it will always remain in the same position. it has not been necessary to include a hermetic seal on the silicone filled container, provided the boiling point of the silicone fluid is not exceeded. The coefficient of expansion of the silicone fluid in sealed units must be considered. Expansion of silicone fluid has been compensated for by metal bellows and silicone rubber diaphragms.[20]

b. Freon

Freons have not been utilized as liquid coolants because of the high operating pressures at coolant temperatures of the order of 100°C.

c. Petroleum Oils

Power frequency reactors and switch gear for public utility and industrial service have, for many years, used direct liquid cooling. Petroleum base oils normally furnish satisfactory cooling for such equipment. Power transformers of large capacity generally are provided with oil circulating pumps and heat exchangers to transfer the heat to the ultimate sink. The heat is removed from the exchangers by forced ventilation or water cooling.

Petroleum base oils ("Nujol" mineral oil) have found application in direct liquid cooling of electronic equipment with hot spot temperatures of the order of 175°C. The oil oxidizes readily and it must be changed frequently. Mineral oil losses at high frequencies are lower than those of silicone oil; however, mineral oil cracks and oxidizes at lower temperatures than silicone oil.

The following are the pertinent characteristics of acceptable unused transformer oil (type 10C):

Specific gravity at 15.5°C.	.898
Flash point	132°C.
Fire point	149°C.
Saybolt viscosity at 40°C.	57 sec.
Dielectric strength Volts/mil for .1 in specimen	300
Pour point	-45.6°C.
Dielectric constant at 1. M.C.	2.22

The hermetic sealing techniques in use include preheating of the electronic assembly and the coolant fluid to the maximum anticipated temperature and solder sealing the completely filled container at this temperature. When the liquid cools, a vacuum-like space of volatile products remains in the container to permit thermal expansion of the fluid. At room temperature and at one atmosphere, the sides of the cases are frequently concave due to the pressure differential. Packages with provisions for an expansion of coolant liquid may be filled without preheating.

4. Examples of Liquid Coolants in Use

a. Closed Systems

During the development of a miniaturization program, it was concluded that natural means of cooling were not adequate for the power densities encountered.[18] An existing electronic equipment was miniaturized into a design that required forced liquid cooling. The engineering model of the unit consisted of two subassemblies wherein the electronic parts were completely immersed in the coolant and three subassemblies wherein the coolant circulated through the case walls.

The electronic connections, as well as fluid coolant connections, were provided with plug-in couplings at each of the subassemblies. The complete assembly initially used Freon 113 as the coolant and operated at a temperature of 130°C. and a pressure of 50 psig. Because of the high operating pressures, the Freon 113 was later replaced with DC-200 silicone fluid. This equipment dissipated 250 watts and required an external pump and heat exchanger for heat removal to the ultimate sink.

The original engineering model of the miniaturized unit is being redesigned for production.[18] It is planned to have the modulator and oscillator hermetically sealed and immersed in DC-200 silicone fluid and to depend upon natural convection in the silicone for cooling. Thus, the need for an external heat exchanger and coolant pump is eliminated.

An amplifier in current production dissipates 40 watts in a package 2.37 x 2.62 x 4.0 inches filled with DC-200, 50 centistokes silicone fluid. This device was designed to dissipate approximately 0.5 watts per square inch of surface area with an internal temperature rise of about 50°C. above ambient.[27]

An R.F. transmitter, which operates in the "S" band, was designed to operate in Nujol.[20] This transmitter was packaged in a 9 inch cube and dissipates about 300 watts. A silicone rubber diaphragm was used to compensate for the expansion of the mineral oil. The outside of the oil filled case operated at 150 C. and some of the hot spots on the case reached 175°C. A blower in the equipment cooled the outside of the case. The cavity size was reduced during this development for immersed use in the mineral oil. The Nujol mineral oil must be changed after every 400 hours of operation to remove the carbon particles formed by oxidation. This equipment has been in service for a year and to date no failures have been reported due to the mineral oil. Silicone oil, because of its dielectric losses at high frequencies, was not considered satisfactory for this application.

An 8 kw cooling unit weighing 125 pounds has been developed.[28] DC-500 is used as the coolant liquid in conjunction with a liquid-to-air heat exchanger for cooling. In prototype test, its performance at altitude was not satisfactory.

b. Expendable Coolant Systems

Telemetering equipment packaged in a case about 18 inches in diameter and 36 inches long is being miniaturized.[18] The problem is to package 200 to 350 tubes, that dissipate in the neighborhood of 1000 watts, in a metal disc 18" in diameter and 3.5" thick. It is planned to provide a copper cooling tube in a flat spiral, sandwiched between two aluminum blocks containing the tubes. The copper tube will contain 80 cubic inches of water, circulating at a gallon per minute, with an inlet temperature of 40°C. or less and a 7°C. difference between inlet and outlet temperatures. A continuous flow of water is to be supplied from an external source during test operations.

5. Miscellaneous Data

Silicone fluid has contributed to the wearing action of certain combinations of metals. Teflon seals were recommended by a pump manufacturer but failed during testing. A standard type pump was substituted and satisfactory results were obtained.[28]

Teflon feels slippery to the touch but is not self-lubricated. Teflon bearings must be provided with lubrication. If operated dry, heat due to friction will soften Teflon and cause a pump bearing or seal to leak. Teflon seals can withstand corrosive liquids for short periods when most other materials used for pump gaskets or seals disintegrate almost immediately.

Thermik spined tubing has found application in liquid to air heat exchangers. It provides a favorable ratio of cooling surface area to volume.

Thermal ratings of liquid cooled resistors are discussed in Section III-B-7, "Thermal Derating of Electronic Parts".

E. VAPORIZATION COOLING

1. General

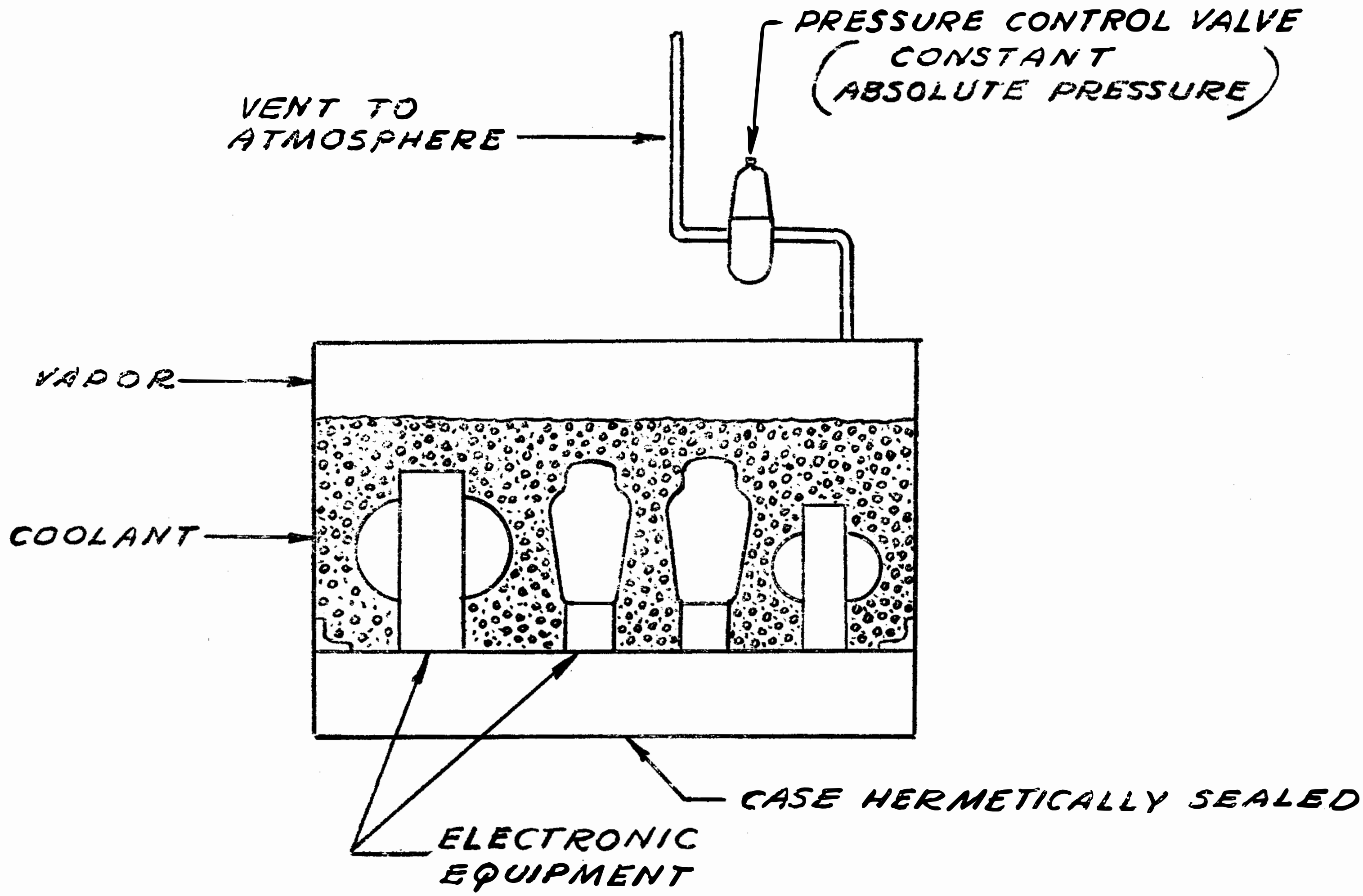
In vaporization cooling systems, heat is removed from the electronic equipment by the vaporization of the coolant from the fluid state into the vapor state and the absorption of the latent heat of vaporization of the coolant. It has been found that even though vaporization cooling is not in general use, it appears to be the most efficient method of cooling electronic equipment of high power densities as well as the only practical cooling method for many high-altitude and non-atmospheric applications where other types of cooling are not feasible.

Direct evaporative cooling can be more effective in removing the heat generated by electronic parts than direct air or liquid cooling. The heat can be removed at the rate at which it is generated since the cooling fluid can be supplied as it is required.

Vaporization cooling can be classified into two categories: direct and indirect systems. A direct system can be defined as one in which the refrigerant comes in direct contact with the electronic parts. An indirect system is one in which one refrigerant does not come in contact with the electronic parts.

2. In a direct vaporization cooling system it is necessary that the electronic equipment be installed in a hermetically sealed package. The operating temperature of the package is determined by the vapor pressure of the coolant. The vapor pressure may be controlled by a constant pressure valve installed in each subassembly or in subassemblies with individual pumps. This valve can regulate the flow rate of the pump to maintain a constant pressure and refrigerant operating temperature (See Fig. 3).

In applications utilizing the direct system, the coolant liquid must be carefully selected so that it will be compatible with the electronic parts, have a low power factor and a constant dielectric strength to reduce the possibilities of current leakage, voltage breakdown, corona and associated power losses. Freon-11 and Freon-113 are



TYPICAL DIRECT EXPENDABLE VAPORIZATION COOLED ELECTRONIC EQUIPMENT

FIGURE 3

typical coolants utilized in direct evaporative cooling systems. The Freons are of low toxicity, practically odorless and because of their comparatively high boiling points are adaptable to simple equipment servicing procedure. Some of the characteristics of the Freons are listed below:

	Freon-11	Freon-113
Dielectric strength (vapor)	3.0	2.6
Boiling point (1 atm.)	23.7°C.	47.5°C.
Freezing point	-111.1°C.	-35.0°C.
Latent heat of vaporization	84.0 BT /lb.	70.62 BTU/lb.

At present, Freon-113 is the most commonly utilized evaporative coolant for the immersion of electronic components. It is convenient to handle at room temperatures when servicing the equipment and at any given temperature its vapor pressure is less than Freon-11. However, Freon-11 is more suitable for operation at extremely low temperatures.

3. Indirect Systems

A wider selection of liquid coolants is possible in an indirect vaporization system because the coolant does not come in direct contact with the electronic parts. This permits the selection of the coolant to be based on the desired thermal characteristics.

In an indirect vaporization cooling system the electronic equipment may be cooled by any of several means. The primary coolant may be forced air or forced liquid. The refrigerant (secondary coolant) can be circulated directly through a cold wall or jacket provided in the equipment. The primary coolant removes heat from the electronic equipment and sebsequently transfers it to the vaporization system secondary coolant by means of an air-to-liquid or liquid-to-liquid heat exchanger (See Fig. 4).

The following coolants have been suggested as suitable for vaporization cooling in an indirect system: (also listed are their latent heats) acetone-242BTU/lb., methyl alcohol-495 BTU/lb., carbon tetrachloride 97 BTU/lb., ethyl alcohol 389 BTU and water 1039 B U/lb.[B-407]

The change of conditions during the evaporative process of an aqueous ammonia solution and of a methanol-water mixture have been calculated.[B-406]

4. Expendable or Open-Cycle System

In the simplest vaporization cooling system the refrigerant is in a closed container from which the vapor is expended through a valve to the atmosphere. This type of system has a short operating period, the length of which is determined by the rate of heat production in the equipment, the latent heat of vaporization of the coolant, and the quantity of coolant available.

In an expendable evaporative cooling system the operating temperature of the electronic equipment is determined by the pressure of the vapor inside of the closed electronic package. This pressure is usually held constant by a valve which is insensitive both to external temperature and pressure. A special valve, which meets the requirements above, has been developed for this specific application.[B-409]

A primary advantage of expendable evaporative cooling is that an ultimate sink is inherently provided.

5. Continuous or Non-Expendable Systems

In the continuous or non-expendable system, a condensing heat exchanger is required to remove the heat and return the refrigerant from its vapor-state to its liquid state so that it may be recirculated through the closed system. If electronic equipment is required to operate longer than an hour at a time, a continuous or closed system is usually necessary (See Fig. 4).

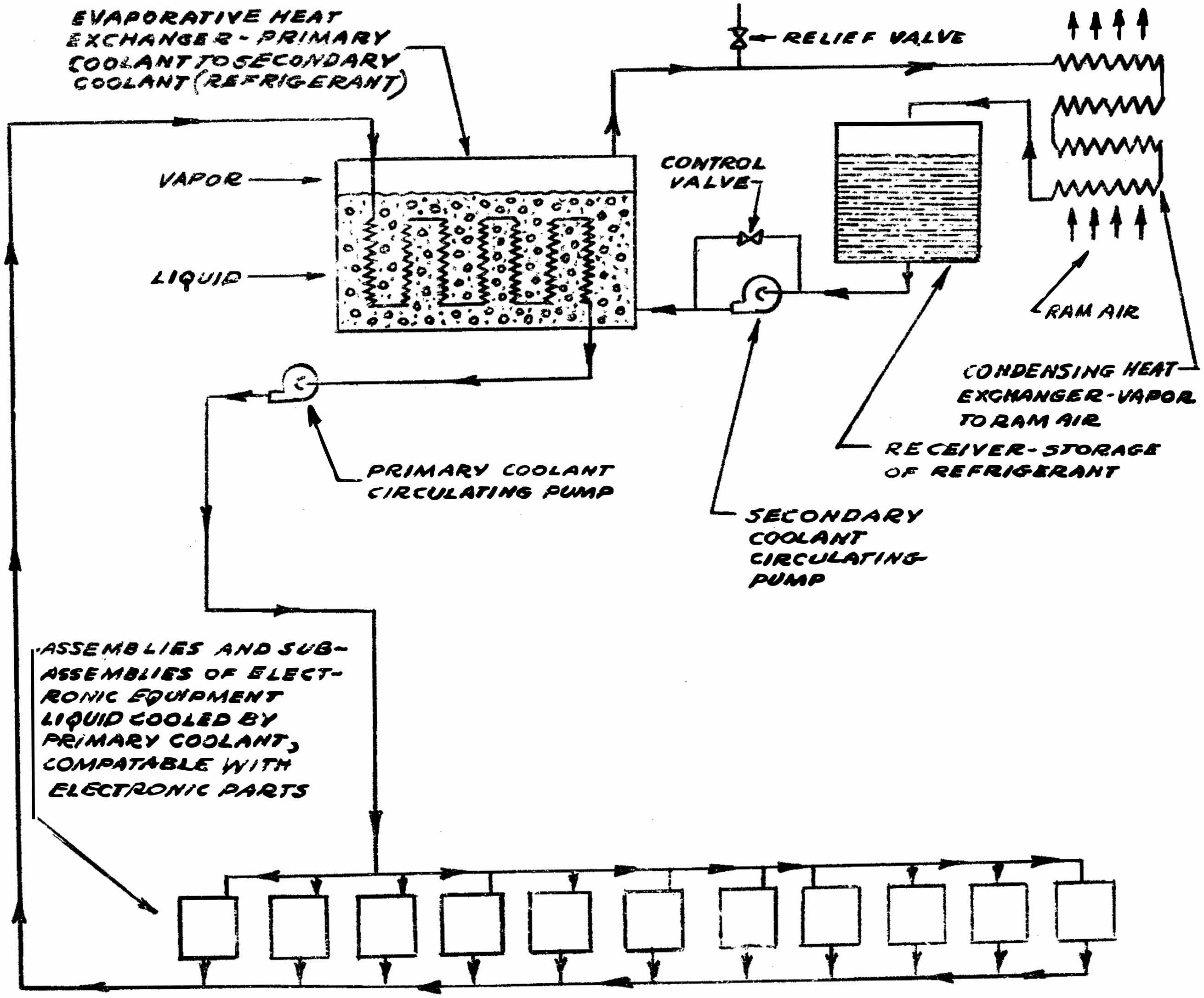
Several organizations have developed closed systems, but there are none that are known to be in continuou operation.

The use of Freon as the evaporative coolant leads to a pump lubrication problem. In a domestic refrigeration system the refrigerant is normally used as a vehicle for the compressor lubricating oil. Since Freon-113 is a solvent for oil and has a drying effect on pump bearings, it has been necessary to operate vane and reciprocating type pumps for direct evaporative cooling systems without lubrication. In such systems the pump must also be capable of pumping vapor as well as liquid. The continuous indirect systems do not experience as many pump difficulties. Also, the selection of a different coolant may alleviate many of the pump problems.

A small axial flow turbine type pump packaged as a single unit is under development and should prove useful for application in continuous systems.[24]

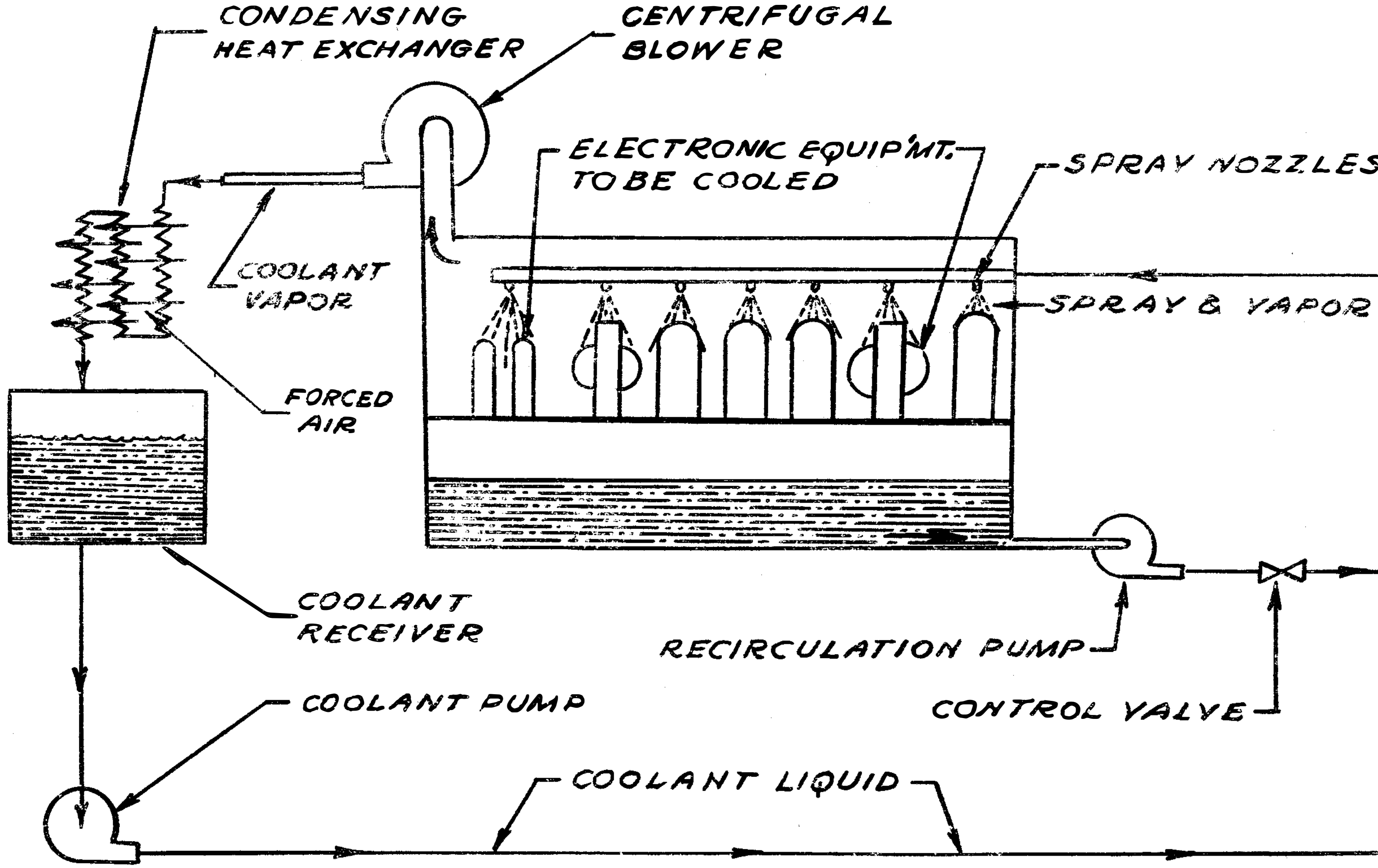
6. Spray Cooling

Spray cooling is a direct vaporization system in which the refrigerant is sprayed over the electronic parts. This reduces the quantity of refrigerant and decreases the overall weight of the equipment (See Fig. 5).



TYPICAL CONTINUOUS INDIRECT VAPORIZATION COOLING SYSTEM

FIGURE 4



TYPICAL SPRAY COOLED CONTINUOUS VAPORIZATION
COOLING SYSTEM
FIGURE 5

Evaporation spray-cooling tests with Freon-113 have been conducted on an RCA 5763 tube for a wide range of flow rates at saturation temperatures of 150, 200, and 250°F. The minimum Freon flow rates required to reproduce free convection surface temperatures on the tube were not only extremely low (of the order of one-half pound per hour), but almost independent of temperature.[B-402]

Similar investigations have been made utilizing Freon-11. The test results were very similar to those obtained with Freon-113 except that the flow rates required to reproduce the same tube temperatures were much lower using Freon-11. This is understandable since Freon-11 has a higher latent heat of vaporization.[B-402]

Spray cooling tests conducted using Freon-11 on the KS-9117 transformer permitted the reactor to be operated at 100% overload before it reached its normal surface operating temperature.[B-402]

Comparative thermal tests were performed on a 30 watt, 5 ohm resistor. The temperature rise at 107 watts input under spray cooling with Freon-11 was the same as that for 30 watts dissipation with free air convection. The increase in resistor capacity was 260%.[B-403]

7. Examples of Vaporization Cooling in Use

An existing electronic equipment which has been miniaturized incorporates both direct and indirect vaporization cooling in various sections of the unit.[18] Since the modulator, oscillator and power supply dissipated the greatest power they were completely immersed in the refrigerant. In the indirectly cooled portion of the first model, the refrigerant was passed through jackets to which the tubes and electronic parts were mounted. The first model used Freon-113 as the coolant operating at a temperature of 130°C., a pressure of 48 pounds gage, and required the use of an external pump and heat exchanger. In order to reduce the pressure, it was found preferable to utilize Dow Corning DC-200 silicone fluid and convert from vaporization to liquid cooling. DC-200 has an equivalent dielectric constant and a vapor pressure of only 3 millimeters of mercury at 100°C.

The above equipment is unique in that the components are grouped into a chassis consisting of seven subassemblies. Each subassembly is replaceable, as a unit, by the removal of four screws. It was designed so that each subassembly could be removed from the chassis, simultaneously disconnecting the electrical connections and the liquid coolant connections. Since the liquid coolant connections were gasketed, the simple operation of placing the subassembly in position and the tightening of the four mounting screws restored both the electrical and the liquid coolant connections. This permitted the removal of a defective subassembly in about a minute and its replacement within another minute or two. Since Freon-113 evaporates rapidly, the subassemblies can be individually serviced almost immediately.

Complete electronic equipments which will use evaporative cooling are under development.[6, 23] Investigations of mixtures of ammonia, water, and alcohol in combination with other methods of heat removal are in progress.

8. Condor Coolers

The Condor Cooler is a unusual heat transfer device manufactured by Condor Radio Manufacturing Company of Prescott, Arizona. It consists of a length of copper tubing partly filled with a volatile liquid and sealed. The lower end is soldered, bolted or clamped to the part to be cooled, and the upper end to the skin of the equipment or some other heat sink. The liquid in the lower end boils, absorbing heat of vaporization. The vapor carries this latent heat to a cooler part of the tube and releases it by condensation. The cycle is completed by the liquid moving down inside the tube (See Fig. 6).

It is claimed that the conductivity of this device is equivalent to a copper bar of equal diameter and 1.5 inches long. The large thermal conductivity permits utilization of plastic embedment in miniaturized equipments of high power density.

A typical cooler is .25 inches in diameter, 4 to 6 inches long; and is rated to transfer 10 watts with a temperature gradient of 25°C.

The primary disadvantages of this device are that it must be mounted vertically or nearly so and is sensitive to acceleration parallel to its larger dimension.

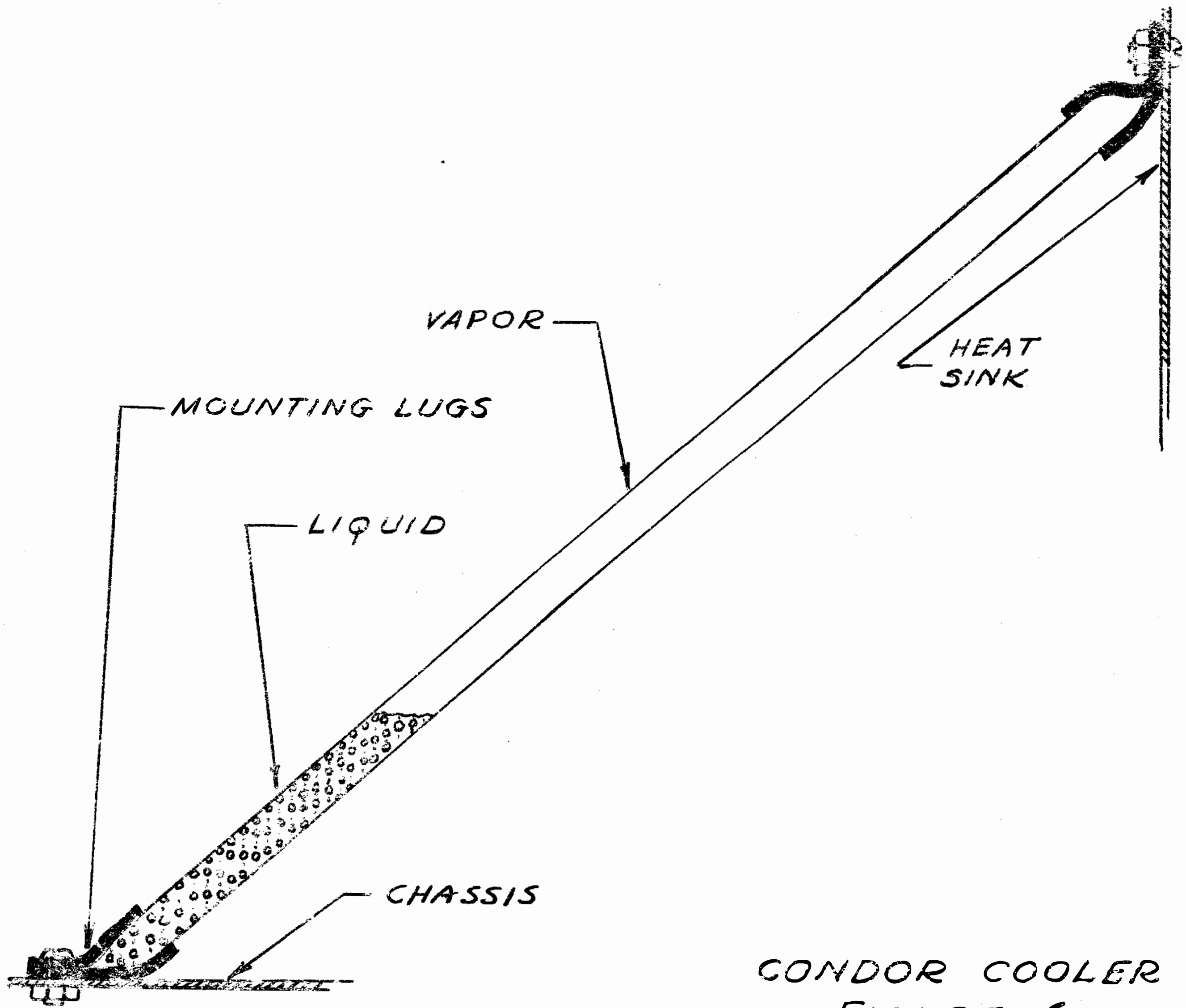
9. Vaporization Cooling Notes

With vaporization cooling a constant operating temperature, controllable by simple pressure regulation, is maintained over a wide range of altitude and ambient temperature.

The dielectric strength of the vapor can be many times that of air at one atmosphere. If the equipment is sealed under constant pressure, the dielectric strength remains constant regardless of the altitude of operation.

Since an ultimate sink is not required, open vaporization cooling systems are operable at almost any altitude.

The prospective altitude operational limit for closed liquid and vaporization cooling systems has been extended to any conceivable altitude dependent only upon the heat transfer capacity of the



CONDOR COOLER
FIGURE 6

external heat exchanger at that respective altitude and the ability of the pressure sealed case to withstand the differential pressure.B-409

F. METHODS OF COOLING VACUUM TUBES

1. General Information

In recent years considerable study and experimentation has been directed toward the determination of means of cooling vacuum tubes to increase tube life and obtain improved electronic equipment reliability. It has been found that a combination of cooling techniques is necessary to achieve satisfactory vacuum tube cooling. An efficient means of removing heat from vacuum tube envelopes remains to be determined. Many of the new tubes in the 5500, RTMA, and JETEC series have been assigned temperature ratings by their manufacturers so that life and reliability expectancies can be estimated. The vacuum tubes have been recognized to be the most short-lived and temperature sensitive parts utilized in electronic equipment. The life of vacuum tubes, at elevated temperatures, has been investigated and found to be an inverse non-linear function of the bulb temperature above approximately 150°C. It is possible for an improperly cooled subminiature tube to achieve temperatures in excess of 250°C. Overheating of vacuum tubes has resulted in decreased cathode emission, the release of gas from the electrodes, grid emission and electrolysis of the leads at the glass envelope. Any one of the above can lead to failure and poor reliability.

A study has been made of the "Tube Life vs. Temperature and Mechanical Failure" to assist in the development of more reliable long life tubes.[31] Curves of the rate of failure, for various reasons, at 30°C. and 175°C. ambient temperatures have been published. At 30°C. ambient, the rate of failure decreased up to 1000 hours of life and then remained relatively constant, while at 175°C. ambient the rate of failure decreased up to 1000 hours and then the failures, due to deteriorations of performance characteristics, increased at an extremely high rate.

A large thermal gradient usually exists on the envelope of a subminiature tube in free air. Some of the power dissipated by the anode is transferred to the glass envelope by radiation from the anode. The remainder of the power dissipated by the anode and the power dissipated by the other tube elements is conducted along the metal leads into the base of the envelope. This results in a hot spot at the base of the tube at the seals, which are unfortunately less able to withstand high temperatures than the other parts of the envelope.

2. Conduction Cooling of Vacuum Tubes

The majority of current miniaturized electronic equipments utilize conduction cooling of subminiature tubes. Many configurations have been developed to provide the required heat removal. All are related to increasing the thermal conductivity between the tube envelopes and the thermal sink.

There are two basic methods by which the conduction cooling of subminiature tubes has been increased. The use of heavy electrical conductors to the tube terminals, with the connections located as close to the tube as practical, has resulted in improved thermal conduction through the tube leads and a reduction of the possibilities of electrolysis.[B-385] Tight fitting shields, with additional hardware forming a low impedance thermal path between the shield and the chassis have provided satisfactory cooling. A shield design with good thermal conduction in several directions has been recommended for subminiature tubes in which the flexible leads constitute a non-rigid socket, and the tube shield provides the rigid support.[B-385]

It has been found that the tube clamps, sockets and shields serve to drain away, through conduction, a portion of the heat which in well designed mountings can easily exceed that carried away by convection plus radiation. Many organizations consider a firm metallic connection to the envelope by a thermally grounded spring clamp or foil wrap-around shield to be the best means of ensuring control of subminiature tube temperatures. Fuse-type clips have been used for this purpose. Shields have also been fabricated from metal foil, wire mesh, and spring materials. Metals of high thermal conductivity are considered preferable. It has been recommended that the clamp or wrap should contact the glass over as large an area as possible, and extend entirely to the base of the tube.[31] While a fuse clip having a relatively small area of clamping will reduce tube temperatures 20°C., a thermally grounded wrap will achieve a reduction of 50°C. or more for the same tube. Choice of spring materials has been mainly limited by their strength at the temperatures under consideration.[31]

Tube shields have been effective for cooling only when in thermal contact with a heat carrier extending to cooler metal in the equipment. When this was not possible, a mounting plate designed to serve as a radiator was used.[31]

Subminiature tube shields are considered, by most users, to be in need of thermal improvement. Frequently, a large thermal gradient has been observed between the tube envelope and the shield. The irregular and sometimes eccentric envelope surfaces of subminiature tubes do not permit a large contact area between the envelope and the shield. Several unique shields have been designed to increase this area of contact and decrease the thermal gradient.

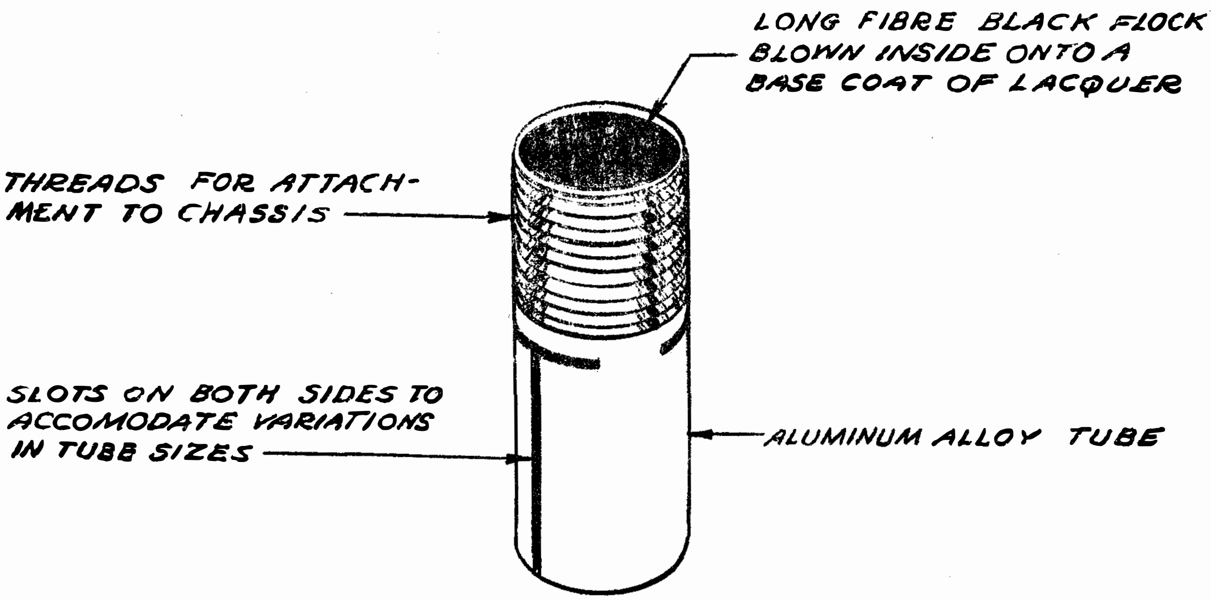
A special shield, threaded at the lower end for chassis mounting has been developed. This shield was fabricated of aluminum tubing and slotted at the upper end. The inside surface was coated with lacquer and black rayon flock was blown in to provide a tight fit for the tubes. It is claimed that improved conduction cooling was obtained.[7] (See Fig. 7.)

Another special shield, recently produced, is fabricated of beryllium copper and slotted perpendicular to the major axis of the subminiature tube. This slotting allows the sections of the shield to accommodate variations of the envelope and increases the area of contact between the shield and the envelope. A modified version of this shield with clips at one end to grip the press base type subminiature tube was also developed. Thermal gradients of from 10° to 30°C. lower than those obtained with conventional shields were achieved.[8] (See Fig. 8.)

When extremely effective conduction cooling is applied to a tube so that the envelope temperature is reduced below its nominal value for operation at room temperature, it is not advisable to increase the internal electrical dissipations appreciably above the room temperature published values.[B-385]

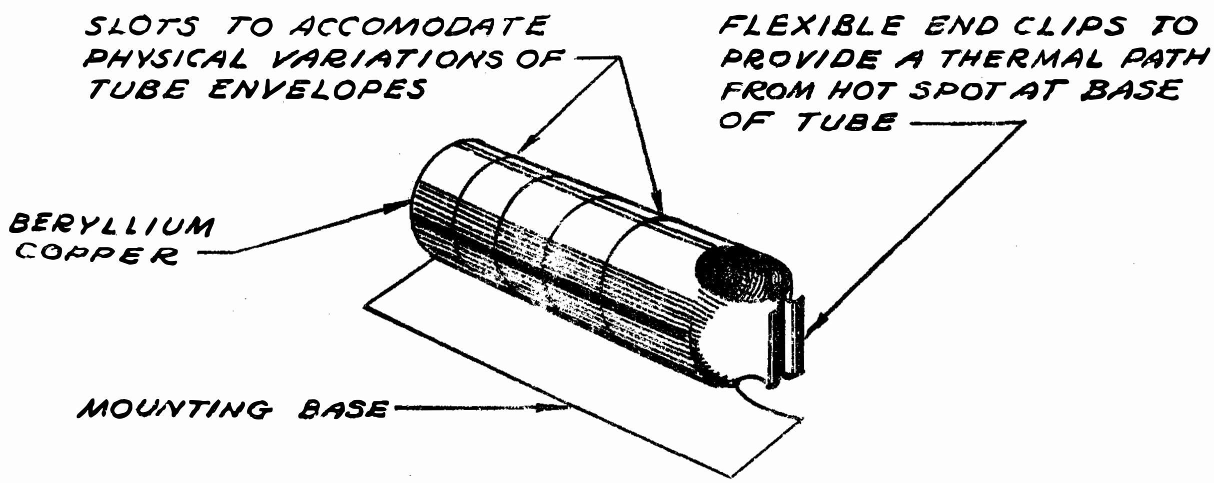
A typical subminiature tube, rated at 2.5 watts but normally operated at 2.1 watts dissipation, was used as a standard for thermal evaluations by one organization.[31] When operated standing in free air with an ambient and a mean radiant temperature of 25°C., the envelope attained an average temperature of 111°C. When a 1.9 in. long by 1.12 in. dia. cylindrical aluminum case surrounding the tube was replaced by a perforated aluminum case with openings equivalent to 34 percent of its area, the envelope temperature was lowered from 169°C. to 127°C. The case temperature, likewise, declined 16°C. It was further determined that with a perforated aluminum case of the same outline and openings equivalent to 78 percent of its area, the tube temperature was reduced another 16°C. When the size of a cylindrical enclosure around a subminiature vacuum tube was decreased, the tube temperature was increased. The absorption of radiation on the inside of such enclosures has often been substantially improved by roughening and blackening the interior, the improvement in overall transfer being represented by reductions of as much as 15°C. in the envelope temperature of the heat source.[B-343]

Many of the thermal difficulties of miniaturization have become acute due to the double enclosure of electronic parts. This has been common in conventional construction wherein tubes and other heat sources were placed in containers inside of the chassis. For example, the typical 2.1 watt subminiature tube with a shield can, placed inside a chassis, leads to a high ambient temperature



SHIELD FOR ROUND BASE SUBMINIATURE TUBES

FIGURE 7
(ENLARGED)



SHIELD FOR FLAT PRESS BASE SUBMINIATURE TUBES

FIGURE 8
(ENLARGED)

and an envelope temperature of 265°C. Removing the can lowered the tube temperature to 230°C.; removing the chassis reduced the temperature to 151°C.; and removing both the can and chassis decreased the tube temperature to 111°C. The design trend of subminiature equipment is toward the elimination of double walls between parts and the heat sink.[B-343]

The standardized miniature tube shield (which is not close fitting) has not provided a good thermal contact to the envelope of the tube or to the chassis so that this device effectively constituted a barrier which raised the envelope temperature.[B-385]

The embedding of tubes and entire circuits in plastic materials has been found to have some very desirable features which commend its use with filament type and other low wattage tubes, despite the limitation of heat conductivity which excludes many subminiatures from this treatment.[33]

The practicality of embedding other than filamentary types was ascertained only by experimental casting and comparison of operating temperatures with recommended tube temperature values. Frequently a desirable design was achieved by potting all circuit elements except tubes, thus obtaining the advantages of the potted assembly with a minimum of experimental work on temperature problems.[33]

Small circuit assemblies have been thermally isolated by glass wool packing. The temperature of a subminiature tube, so treated, rises rapidly and the tube is ultimately destroyed. Heat generated by subassemblies of low power density has been removed through a small copper rod of several inches in length and later dissipated in a radiator attached to the rod. Theoretically, a .125 inch diameter copper rod can carry 2.1 watts for 1.5 inches with a 28°C. temperature gradient.

Soldered and welded junctions generally constitute a much greater discontinuity in thermal circuits than might be expected from casual electrical analogy.[B-343]

3. Convection Cooling of Vacuum Tubes

Convection cooling of vacuum tubes has been used extensively in conventional electronic equipments. However, it has not found many applications in miniaturized equipments, especially those utilizing subminiature tubes. The general trend of industry is toward increased power densities and other means of vacuum tube cooling.

It is apparent that the most important consideration in the convection cooling of subminiature tubes is related to the mounting of the envelope. Mounting position has been shown to produce an appreciable effect on the efficiency of convective cooling. It has been necessary to mount tubes in the vertical position in order to utilize fully the chimney effect for convection cooling. Thermal measurements of a subminiature tube operating free of any conducting support, and standing in air of room temperature indicated that the tube radiated about 40% of its thermal dissipation from the bulb and leads, while the remainder was carried away by free convection of air. Under these conditions the temperature of surrounding objects was found to assume considerable importance.

It has been shown that tube life is materially shortened if the envelope temperature is operated above its rated value for extended periods of time. The envelope temperature ratings provided by manufacturers are for standard pressures. Since the density of the atmosphere and its cooling capabilities decrease with altitude, it has been necessary to decrease the thermal power dissipation of tubes that are exposed to other than standard pressure conditions.

A study of the altitude derating of electron tubes has been completed and families of curves for the derating of specific tubes at different altitudes have been prepared.[3] Several classified and unclassified reports have been published that contain derating data pertinent to a few of the tubes in general use.

4. Radiation Cooling of Vacuum Tubes

Attempts to improve the radiation from tube envelopes by blackening or sandblasting the glass have resulted in higher rather than lower temperatures, because these surfaces absorb heat normally radiated through the glass, thus increasing the envelope wall temperature.[31]

Glass begins to be a poor transmitter of infrared radiation at a wave length of 2.5 microns. It can be shown that for a radiation source at 500°C., only 6% of the infrared energy will be below 2.5 microns and, therefore, 6% of the infrared energy will be transmitted directly through the glass, 94% of the energy will be absorbed by the glass and then re-radiated. It has been found by numerous experiments that black paint on the inside of close fitting subminiature tube shields does not appreciably assist heat removal.[8]

5. Liquid Cooling of Vacuum Tubes

High powered transmitting tubes have been water cooled for many years. Little is known, however, of the parameters for liquid cooling of subminiature tubes. In one instance, the tube life was increased considerably by liquid cooling.[27]

Interaction among tubes in a cluster was evaluated with a seven tube thermal test model which was liquid and air cooled. For the tube spacing employed, it was shown that the rate of heat dissipation from each tube was principally dependent on the air temperature in its immediate vicinity and was not noticeably affected by surrounding components and their temperatures. The change in chamber heights between 4 and 2.75 inches caused increases in the required temperature differences between tube surfaces and chamber walls of the order of 20%.[24]

The temperature differential of the chamber filled with silicone fluid was one-fifth of that of the air filled chamber. With equal tube temperatures, the chamber wall temperature for air approached 0°F., while that for the silicone fluid approached 400°F.[24]

Silicone grease or jelly has been used to assist heat removal when subminiature tubes were mounted in drilled metal blocks.

Dissipations of from 1300 to 6500 watts per sq.in. (200 to 1000 watts per sq.cm.) have been obtained with water cooled anodes of high power tubes. The lower value is most commonly used.[12] The flow rate and water temperature for each water cooled tube type have been determined experimentally by its manufacturer.

6. Forced Air Cooling of Vacuum Tubes

Forced air cooled vacuum tubes are commonly utilized in high power military electronic equipments. Much cooling information has been published by the tube manufacturers. To date, the vacuum tube industry has been unable to reduce the design of cooling fins and other thermal parts of these tubes into basic parameters. "Cut and try" experimental methods have been found to be the most economical and practical design techniques.[12]

Additional information on forced air cooling of vacuum tubes is presented in Section III-C of this report.

7. Miscellaneous Vacuum Tube Cooling Data:[12]

a. When the glass envelope external surface temperature of a vacuum tube is 175°C., the envelope internal surface temperature can be as great as 400°C.

b. The absolute maximum temperature of copper leads and other vacuum tube connectors is 600 to 700°C.

c. Little is known of the maximum temperatures and basic phenomena associated with oxide coated cathodes. Wide performance differences exist between controlled laboratory samples. The maximum safe emission current for oxide coated cathodes is 40 amps per sq.cm. or 260 amps per sq.in.

d. Cathodes and gold plated grids can be operated to a maximum temperature of 825°C.

e. Alloy types X, Y_1, Y_2, and wolfram can be utilized to 1300°C.

G. ULTIMATE SINKS FOR THE DISSIPATION OF HEAT

The preceding sections are concerned mainly with the removal of heat from the electronic heat sources. This section is related to methods of dissipating the heat after it has been removed from the electronic equipment. The mode by which the heat is transferred to the sink is optional, based upon the design configuration and environment. Directly or indirectly, the earth or its atmosphere absorbs the heat and becomes the ultimate sink. It is therefore necessary, in any heat removal system, that an ultimate sink "connection" of low thermal impedance be employed.

In simple cooling systems utilizing natural or "brute force" methods, the heat is usually dissipated directly from the surface of the case to the atmosphere. With such systems, heat removal and rejection to the surrounding environment is readily accomplished as long as the equipments are of low power densities and have adequate exposed surface areas.

With equipments of higher power densities of the order of .25 watts per square inch or more, heat rejection becomes difficult. It is in this field that further investigation is in order.

The choice of the ultimate sink depends upon the type of equipment that is being cooled, the type of environment in which it is operated, and the type of sinks of unlimited capacities that may be available.

When forced air cooling is utilized, the heated air is usually dissipated directly to the atmosphere, while a new supply of air is obtained from the atmosphere to cool the equipment.

If the equipment is convenient to a liquid sink, an air to liquid heat exchanger may be utilized to remove the heat from the air so that the air may be recirculated in the system.

With liquid cooling systems, the heat may be rejected from the liquid to the atmosphere by means of a liquid to a forced air heat exchanger. If a liquid sink is available a liquid-to-liquid heat exchanger can be used to reject the heat to the sink.

It is also possible to employ the latent heat of vaporization of a liquid as an ultimate sink. In expendable vaporization cooling systems the vapor is directly vented as the ultimate sink to the atmosphere.

Vaporization cooling can be provided to cool the electronic equipment directly or as the ultimate sink for a forced air or liquid cooling system.

In free space beyond the earth's atmosphere, a radiation cycle may be employed to dissipate the heat directly to space. This radiation cooling system could employ a liquid cooling system to cool the electronic components; the liquid could then be circulated through a radiation jacket located on the outside surface of the vehicle. Since the efficiency of the radiation cycle is not high, an alternate system of greater efficiency could be obtained through the use of an expendable evaporative cooling system. It would be necessary to provide an adequate supply of coolant for the length of service desired.

Ohio State University Research Foundation has prepared a technical report for the Air Force entitled, "Methods for the Ultimate Dissipation of Heat Originating with Airborne Electronic Equipments".[24 & B378] This report discusses seven methods of ultimate heat dissipation that are applicable to various types of airborne vehicles. The characteristic features of each system and the dynamic range over which the performance of each system is practicable are outlined.

The seven basic methods are:

1. Air cooling by the use of blowers
2. Ram air cooling
3. Expanded ram air cooling
4. Air cooling by flush skin heat exchangers
5. Heat dissipation to expandable evaporative coolants
6. Heat dissipation to fuel
7. Heat dissipation by radiation to space

The first three systems involve air cooling while the last four involve liquid cooling. It is apparent that the cooling of high power density electronic equipment can best be accomplished at high altitudes by the use of a liquid cooling system.

IV. THERMAL DESIGN METHODS IN USE

A. GENERAL DISCUSSION

It was found during this survey that the "cut-and-try" method was the thermal design technique most commonly used by electronic engineers. This method can be very expensive if a complex thermal problem is encountered. Examples were noted wherein electronic equipment had been redesigned and rebuilt as many as five times before the thermal problem was solved by "cut-and-try" methods. Several manufacturers of electonic equipment have recently added heat transfer specialists to their staffs to assist in solving thermal problems. In general, the heat transfer engineers were responsible for the design of special heat exchangers and cases for new equipment. A period of adjustment is necessary for electronic and heat transfer engineers to become entirely cognizant of each others problems. However, when their efforts were coordinated during the initial design of an equipment, many potential electrical and thermal problems were minimized. At present, it is possible to solve few electronic thermal design problems by mathematics. Most thermal designs are almost impossible to compute because of lack of data and the many unknown variables. Empirical methods have been proven to be best with the present limited knowledge. Electrical analogues can be used if some information is available relative to the temperatures and the thermal characteristics of the materials involved.

B. ANALYTICAL SOLUTIONS

Many of the thermal computations necessary for the design of electonic equipment are too complicated for a complete analytical solution. If an analytical solution is to be attempted, the usual procedure is to idealize the geometry and consider the possible mathematical solutions.

The accuracy of the analytical method depends upon the number of assumptions that have to be made to idealize the geometry and simplify the physical conditions. The solution may be obtained by mathematical description, graphical methods, or by the analogue method. In general, the relationships and methods of solution are too complicated to solve by direct analytical means. Practical tests have shown that this type of problem lends itself well to solution by electrical analogues.

C. ELECTRICAL ANALOGY

The electrical analogy method of investigation of heat flow is based on the identity of the equiations governing heat flow and the flow of electricity in a resistance-capacity circuit.

The analogy between thermal and electrical phenomena is known to be:

Thermal Terms	Equivalent Electrical Terms
Temperature difference	Voltage
Rate of heat flow	Current
Thermal conductivity	Electrical conductivity
Thermal capacity	Electrical capacity

In order to use this method, knowledge of temperature and thermal properties of the substances through which the heat is to flow is required. This requirement may prove difficult, because of the inadequacy of the thermal data and the expense and skill required for determining heat capacity coefficients.

The study of a thermal problem by means of the analogy method includes the following steps:

1. Establishing the analogous condition (calculation).
2. Constructing a resistance-capacitance circuit to simulate the thermal problem.
3. Subjecting this circuit to the appropriate analogous initial conditions (applying a given voltage at one end of the circuit, which is equivalent to exposure to a given temperature; or applying a current corresponding to a certain heat flow into a body, etc.).
4. Measuring the electrical units; voltage and currents at points in the circuit analogous to those points at which temperatures and heat flow are to be measured in the body being subjected to heat flow.
5. Converting the results of the electrical investigation into heat units (calculation).

This method is simple and accurate since it substitutes electrical measurements, which are readily made, for thermal measurements, which are difficult, cumbersome, inaccurate, and in many cases impossible to obtain. It involves, of course, knowledge of temperatures and the thermal properties of the substances through which the heat is to flow.

V. TECHNIQUES INVESTIGATED NOT CURRENTLY IN USE

A. AIR COOLING REFRIGERATION CYCLE

Air cycle refrigeration systems are especially applicable to the cooling of electronic equipment in aircraft because of their light weight. Air from existing jet engine compressors or ram air may be expanded in an intercooler to provide equipment cooling. Some of the possible air-cycle refrigeration systems for the cooling of electronic equipment are:[B-28]

1. Air turbo-compressor unit for jet propelled aircraft
2. Air turbine unit for jet propelled aircraft
3. Air turbo-compressor unit for reciprocating engine driven aircraft
4. Vapor jet compression unit

It is claimed that these systems hold promise for cabin and equipment cooling in aircraft.[8]

B. HILSCH-VORTEX-TUBE

The Hilsch tube may, at some time in the future, be used as a cooling device on high speed aircraft.[8] The Hilsch or Vortex Tube consists of a precision-configured "tee" type chamber into which air is forced tangentially. One tube is connected to each end of the tee. The longest of the two has a throttling valve on the opposite end from the tee and is known as the hot tube while the shorter tube, which is known as the cold tube, is reduced to a diaphragm with a small aperture near the tee end (See Fig. 9). Compressed air passing tangentially into the tee forms a vortex in the tee. The lighter air with less thermal energy flows to the center of the vortex and passes through the aperture in the center of the cold tube to be discharged out the open end of the tube. The denser air with more thermal energy flows down the hot tube in a spiral and out through the throttling valve which is used to control the operating temperatures.[B-159, 160]

The efficiency of the tube is not affected by any particular shape of the container and tubes, provided the whole is of rotational symmetry. One model in which the tube was of .25 inch copper tubing had a warm tube 12 in. long and a cold tube 6 in. long. Optimum results were obtained with the diaphragm as near the nozzle as possible. Since the shape of the aperture of the diaphragm does not appear to be significant, a circular opening is used.[B-162]

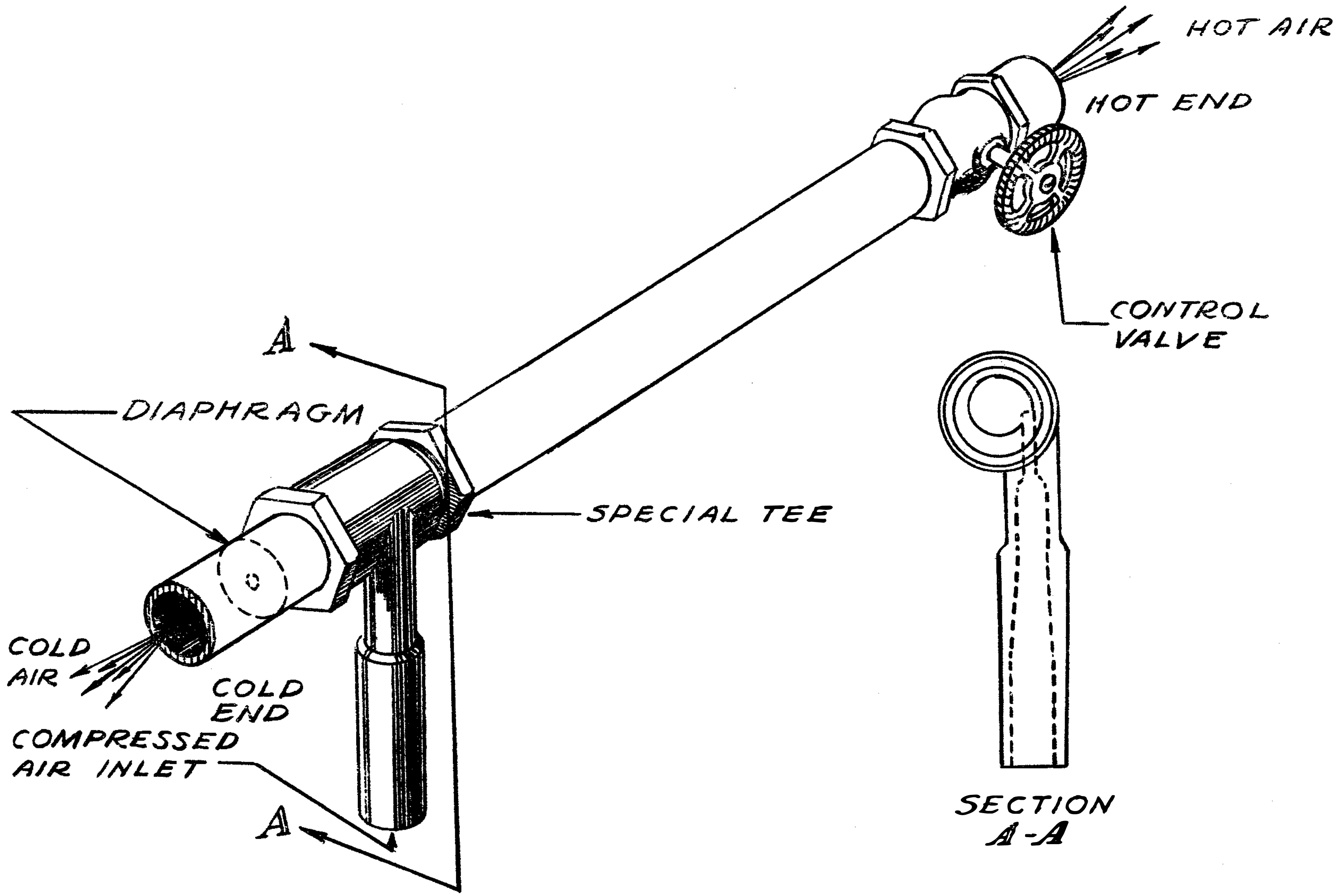
Varying ratios of hot and cold air can be obtained by adjusting the throttling valve at the warm air end. The tube is capable of simultaneous temperatures of plus 106°F. and minus 56°F. At "hot" adjustment, it can produce up to 350°F. While the Hilsch tube provides 15 to 20 times greater cooling than the ordinary laboratory method (expansion of gas through a nozzle under the Joule-Thomson principle), it has a refrigerating efficiency of only 20%, compared to 70% for household refrigerators and close to 90% in larger cooling installations.[B-161]

A theoretical method of evaluating the temperature T_c of the stream of cold air flowing in one direction, and the temperature T_h of the hot air flowing in the opposite direction has been determined.[B-157]

The general design of the Hilsch tube is fairly simple but there are many variables which control the temperatures of the tubes.[B-162]

1. External pressure and temperature of the atmosphere or chamber into which the air is discharged.
2. Tube dimensions: diameters of hot and cold tubes, diameter of nozzle, diameter of orifice in diaphragm.
3. Pressure of air before expansion by the nozzle (nozzle pressure) and rate of flow of air from nozzle.
4. The mass of cold air through the cold air tube varies with throttle pressure and setting.

Because the Hilsch tube has no moving parts, it is particularly adapted to high stagnation temperatures, especially when ceramic materials are used. It is probable that the Hilsch tube will maintain its efficiency at high pressure ratios. This may make it applicable for the cooling of certain vehicles at very high Mach numbers. The Hilsch tube will



TYPICAL HILSCH TUBE
FIGURE 9

probably find application in installations where very small flow rates are required. B-158

Only about one-third of the air entering the Hilsch tube reaches the low temperature level to be available for cooling purposes. According to Hilsch's tests, the tube length can be chosen at about 250 times the diameter of the nozzle. Thus, for additional cooling, a tube three inches in diameter would have a length of 14 to 18 feet Although there are no test results available of Hilsch tubes with dimensions more than 50 times those Hilsch used, it is generally believed that no basic differences in performance will arise due to scale effect. B-158

C. HYDROGEN INERTING

A survey of available gases indicated that hydrogen would provide an excellent thermal environment for more effective cooling of hermetically sealed and inerted electronic equipment. Because of its low density and favorable heat transfer characteristics, hydrogen is considered to be the gas most suitable for this purpose.

The thermal conductivity of hydrogen is almost seven times that of air and the heat transfer coefficient for ventilating surfaces in hydrogen is about 15 times that of air. In an atmosphere of hydrogen, corona has little, if any, effect on insulation because in the absence of oxygen fires cannot occur. Mixtures of air and hydrogen containing more than 70% hydrogen are non-explosive.

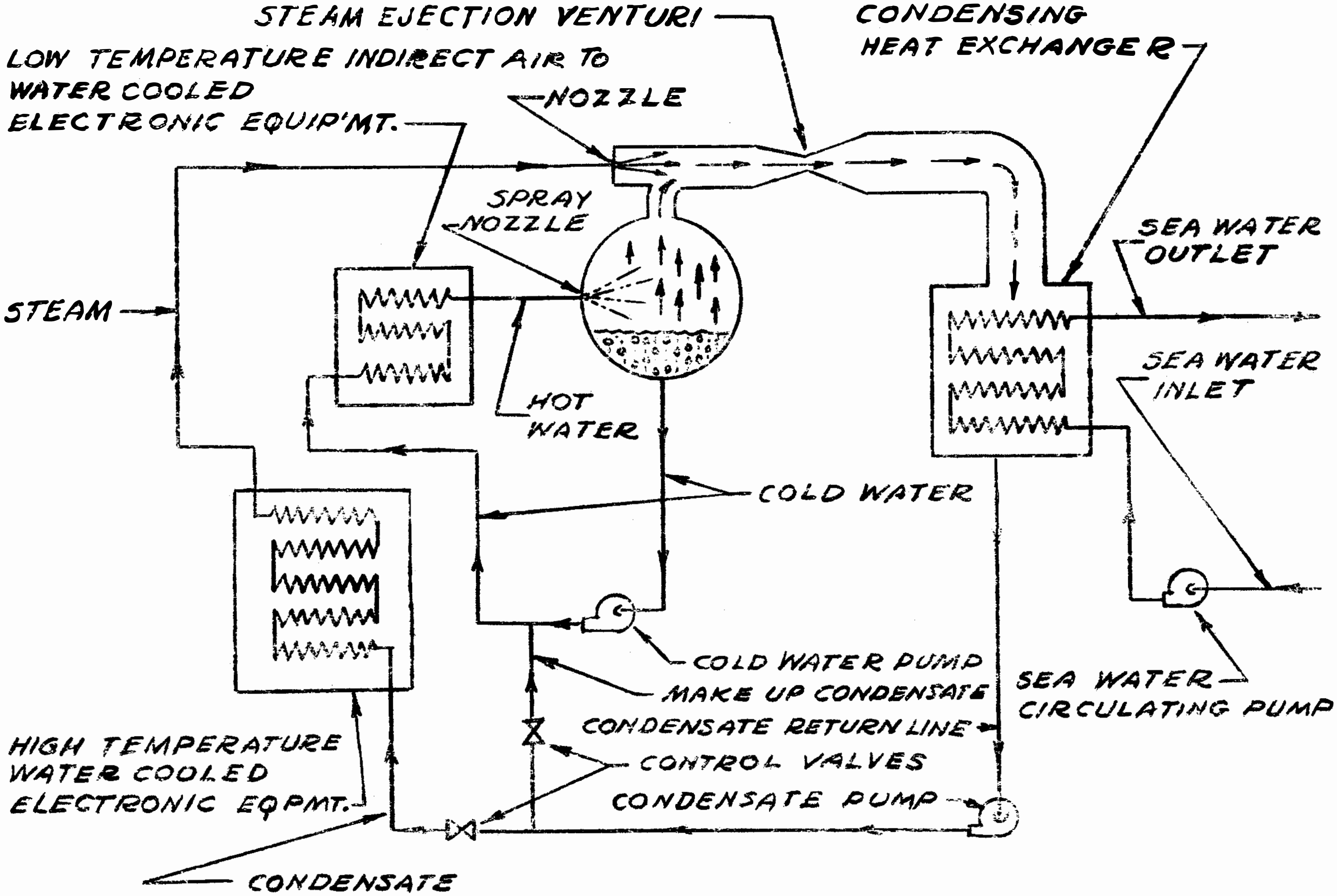
Hydrogen cooling has been extensively utilized by the public utilities and industry for cooling large rotating electrical devices.

D. STEAM EJECTOR COOLING

Steam ejector cooling systems have been installed in railroad cars to provide air conditioning and refrigeration. A similar system is feasible as a means of cooling electronic equipment since the steam for its operation could be obtained as a by-product of vaporization cooling of electronic equipment.

The system could consist of a number of closed thermodynamic circuits: the cold water circuit, the refrigeration circuit, the air-condensate removal circuit and the condenser heat removal circuit. These are so inter-related that it is necessary only to supply steam for compression, a small amount of water for condensation, and power for air and water circulation, to obtain refrigeration. B-326

The functional description of a typical system (Fig. 10) follows:



SHIPBOARD STEAM EJECTOR COOLING SYSTEM

FIGURE 10

Cold water, circulating through the cooling coils of an air-to-liquid heat exchanger receives heat from the air and flows thence to a chamber or evaporator into which it is sprayed. The evaporator is evacuated sufficiently to permit the boiling of the water at a temperature of 40 to 50°F. The evaporation of a portion of the water cools the remaining water which is then re-circulated by a pump to further cool the heat exchanger. The vacuum, which permits this evaporation, is maintained by a steam ejector.

At the ejector, steam from an independent source is admitted through a nozzle to the end of the venturi shaped tube forming the ejector. In expanding from its fixed positive pressure to the high vacuum, it attains a high velocity which permits it to entrain vapor from the evaporator. This vapor enters the ejector near the nozzle. It is first accelerated and mixed with the high velocity steam, then due to the shape of the venturi the mixture is compressed, changing its velocity energy to pressure. The compressed mixture is delivered to a special type of air condenser to be condensed. The function of the ejector, similar to that of the mechanical compressor, is to remove refrigerant from the evaporator and compress it so that it can be condensed by releasing heat to the outside air.[B-326]

E. SUBLIMATION

Methods of cooling electronic equipment by sublimation of solid refrigerants have been examined, and found feasible.

The development of compact light weight methods for feeding the solid refrigerant into the sublimation chamber would further increase the value of these systems and make packaging simple and effective. One method proposed the storage of dry ice (CO_2) in a tank of methyl alcohol. The heat absorbed during sublimation cools the alcohol which is circulated by a pump through a heat exchanger and then back to the storage tank where it is sprayed over the dry ice. The air to be cooled is passed through the heat exchanger.[B-28]

F. THERMOELECTRIC METHODS

The possibility of converting thermal energy to electrical energy by thermoelectric means and dissipating the energy in an external resistance has been evaluated. This method cannot be accomplished with thermocouples of the available alloys generally used for temperature measurements, since the thermoelectric efficiency is less than one percent. The size of the thermopile and conductors using available alloys in a practical instance would be such that the heat source would be directly cooled by metallic conduction.

A review of the theoretical efficiency calculations indicated that higher efficiencies can be attained with thermoelectric materials to which the Wiedemann-Franz-Lorenz relation is applicable, when their thermoelectric power is greater than 200 microvolts/^{o}C. Some zinc-antimony alloys with added metals approach the above conditions and have produced an experimental efficiency in excess of 5%.

The criteria of high efficiency have been applied to semi-conductors, deriving the optimum conditions. Lead sulfide with excess lead was found to be the only suitable material at present, which in combination with the zinc-antimony alloy produces an efficiency of seven percent.

Higher thermoelectric efficiencies can be produced only by developing new materials which can attain the theoretically required high values of thermoelectric power, low heat conductivity, and low specific resistance.[B-103]

G. LOW MELTING TEMPERATURE METALS

The utilization of low temperature melting metals for conduction cooling was discussed in Section III-A_1 of this report. Further investigations have not been promising.

Mostly negative results have been obtained using the new metals similar to gallium and indium as heat transfer agents because of their oxidation tendencies.

H. CHEMICAL METHODS

1. Endothermic reactions properly controlled provide another means for removing heat. Of these, solutions of inorganic salts in water appear to be of interest. These reactions feature the removal of large quantities of heat and ease of reversibility. In the solution of potassium nitrate (KNO_3) in water approximately 8.5 kilogram calories per mole dissolved are absorbed.

   The practicability of utilizing endothermic reations for the cooling of electronic equipment seems remote.

2. Venable, E., "Cooling Electrical Apparatus", U.S. Patent 2,354,159. This invention proposes to embed the electrical elements of the apparatus being cooled, in a solid inorganic substance which provides for a good thermal dissipation and a high degree of electrical insulation.

   Ordinarily, materials which have high thermal conductivity likewise exhibit good electrical conductivity. However, a few crystalline minerals or salts are exceptions to this general rule. Among these minerals are: calcium fluoride (CaF_2), sodium chloride (NaCl), potassium chloride (KCl), sodium fluoride (NaF), and potassium fluoride (KF). These minerals have thermal conductivities of 0.026, 0.0166, 0.0166, 0.025 and 0.016, respectively, in calories per second per square centimeter, per centimeter thickness per degree centigrade. The mineral filling is in a good heat transfer relation to the electrical members after solidification. The recrystallized mineral possesses high thermal conductivity to dissipate the heat with a low thermal gradient between heated members and the casing.

3. Troy, M.O., "Liquid-Cooled Electronic Apparatus", U.S. Patent 2,214,865, September 17, 1940. This invention suggests that a transformer or device be immersed in a liquid chlorinated organic compound surrounding and insulating said device and a heat brake comprising a relatively large body of immiscible lighter liquid having a higher specific heat superimposed on said chlorinated compound, said material being volatilized at temperatures too low to injure said device. Liquid halogenated compounds are chlorinated diphenyl benzene, chlorinated benzotrifluoride, chlorinated napthalene, chlorinated phenyl benzoate; sealing liquids are H_2O, or monohydric alcohol.

4. Semenza, Marco, "A System for the Cooling of Electrical and Similar Machinery at Low Temperature", British Patent Specification No. 319,707 (September 26, 1928). This patent recommends the use of liquified gases similar to air or nitrogen for cooling electrical machinery at low temperatures. The main claim is related to the temperature area of operation: "by using for each gas that pressure which will give the lowest possible evaporation temperature without reaching the freezing point, this temperature being below the normal refrigerating temperature for the gas". "There is also a certain pressure at which equilibrium will be obtained between the energy saved and the energy required to liquify the necessary gas. Below this value of the pressure the economic advantage of the system increases until the pressure is reached at which the evaporating point of the liquified gas would coincide with its freezing point". It is also claimed the temperatures are sufficiently low to produce considerable reduction in ohmic resistance of the conductors.

VI. APPENDIX A - LIST OF CONTRIBUTORS

The assistance and cooperation of the following organizations is largely responsible for making this report possible and is hereby gratefully acknowledged.

1. Arma Corporation, Brooklyn, New York
2. Battelle Memorial Institute, Columbus, Ohio
3. Bell Aircraft Corporation, Niagara Falls, New York
4. Bell Telephone Laboratories, Murray Hill and Whippany, New Jersey
5. Bendix Aviation Corp., Pacific Division, North Hollywood, California
6. Boeing Airplane Company, Seattle, Washington
7. Capehart-Farnsworth Corporation, Fort Wayne, Indiana
8. Cornell Aeronautical Laboratory, Inc., Buffalo, N.Y.
9. Collins Radio Company, Cedar Rapids, Iowa
10. Consolidated Engineering Corporation, Pasadena, California
11. Consolidated Vultee Aircraft Corporation, San Diego, California
12. Eitel-McCullough, Inc., San Bruno, California
13. Emerson and Cuming Company, Boston 15, Massachusetts
14. Erie Resistor Corporation, Erie, Pennsylvania
15. General Electric Company, Knolls Research Laboratory, Schenectady, New York
16. General Electric Company, Electronics Park, Syracuse, New York
17. Globar Division of Carborundum Company, Niagara Falls, New York
18. Hazeltine Electronics Corporation, Little Neck, New York
19. John Hopkins University, Applied Physics Laboratory, Silver Springs, Maryland
20. Melpar, Inc., Alexandria, Virginia
21. National Bureau of Standards, Washington, D.C.
22. Naval Research Laboratory, Washington, D.C.
23. North American Aviation, Inc., Downey, California
24. Ohio State Research Foundation, Columbus, Ohio
25. Raytheon Manufacturing Company, Newton, Massachusetts
26. R.C.A. Tube Division, Harrison, New Jersey
27. Servomechanisms, Inc., Mineola, New York
28. Sorenson and Company, Stamford, Connecticut
29. Sperry Gyroscope Co., Inc., Great Neck, Long Island, New York
30. Sylvania Electric Products, Inc., Physics Laboratory, Flushing, Long Island, New York
31. Sylvania Electric Products, Inc., Engineering and Development Laboratory, Kew Gardens, Long Island, New York
32. Stanford Research Institute, Stanford, California
33. Wright-Patterson Air Force Base, Dayton, Ohio
34. **R. C. A. Victor Division, Camden, New Jersey**

APPENDIX B - BIBLIOGRAPHY

TABLE OF CONTENTS

VII. APPENDIX B - BIBLIOGRAPHY
(See Supplement No. HF-710D-10A for Classified Reports)

AIR COOLING

B-1 Ostlund, E.M. Air cooling applied to external-anode tubes Electronics Vol. 13 Pg. 36 (June 1940)

B-2 Harrison, A.M. Ventilation of rotating electrical equipment on shipboard transactions A.I.E.E. Vol. 67 - Part II Pg. 1263 (1948)

B-3 Design and application notes on the TV image dissector blowers used for cooling external anode, tube header or electrode seal, or glass envelope of radiation - cooled anode type tubes Communications Pg. 24 (February 1948)

B-4 Elenbaas, W Dissipation of heat by free convection Philips Research Reports Vol. 3 - No. 5,6 Pg. 338 (October 1948)

B-5 Zimmerman, R.M. and Robinson W. Study of a system for cooling of electronic equipment by utilization of cabin exhaust air Report No. 30C AMC, W.P.A.F.B., Dayton Ohio Contract W33-038 ac-14987 Ohio State University Research Foundation (November 28, 1949)

B-6 Touloukian, Y.S. Heat transfer by free convection from heated vertical surfaces to liquids Trans. A.S.M.E. Vol. 70 Pg. 13 (January 1, 1948)

B-7 Robinson, W., Lynch, R.H, and Beitler, S.R. Progress of project work report #19 Ohio State University Research Foundation (May 15, 1948)

B-8 Lynch, R.H. and Robinson, W. Weight, power and space requirements for typical cooling systems, employing heat rejection to an aircraft fuel system I (Internally air cooled equipment) Ohio State University Research Foundation Report No. 24a (October 1948)

B-9 Tusting, W. Ventilation problems preventing overheating and frequency drift Wireless World Vol. 52 No. 3 72-5 (March 1946)

B-10 Wilkie, Harry Cooling of electronic apparatus at high altitudes CADO Technical Data Digest Vol. 15 No. 12 30-32 (December 1950)

B-11 New constructional techniques for the operation of radar equipments under all climatic conditions Telecommunications Res. Estab. Report T.2061

AIR COOLING (contd.)

B-12-C (See Classified Supplement)

B-13-C (See Classified Supplement)

B-14 Gelbard, R.B., Robinson, W. and Beitler, R. The calculation of rates of heat dissipation from electronic components by free and forced convection. (Review of available information and suggestions for needed experimentation) Ohio State University Research Foundation Report No. 22A (August 1948)

B-15 Lynch, R.H., Robinson, W. and Beitler, S.R. Experimental study of free convection heat transfer in a closed vertical annular cylindrical air space with heated internal surface and cooled external surface Ohio State University Research Foundation Report No. 22B (August 1948)

B-16 Zimmerman, R.M. and Robinson, W. Development of charts for the analysis of compressible flow, with heat addition and friction, in a circular tube of constant cross sectional area and constant wall temperature Ohio State University Research Foundation Report No. 25A (December 6, 1948)

B-17 Robinson, W. and Zimmerman, R.H. An analysis of some design criteria of tubular heat exchangers for simple ram air cooling systems Ohio State University Research Foundation Report No. 26A (February 7, 1949)

B-19 **Robinson,** W. Cooling methods for electronic equipment in general Progress of Project Work (December 1950 to January 1951) Ohio State University Research Foundation Report No. 38 (February 5, 1951)

B-20 McElroy, J.C. I.D.R. for radio receiving set AN/ARN-19(XA-1) Collins Radio Company Report IDR-204-1,2,3,4,5 (September 1, 1949 to May 1, 1950)

B-21 Robinson, W., Han, L.S., and Essig, R.H. Design charts for forced air cooled airborne electronic equipment Contract W33-038 ac-14987 Ohio State University Report No. 42 (October, 1951)

AIR COOLING REFRIGERATION CYCLE

B-26-C (See Classified Supplement)

B-27-C (See Classified Supplement)

AIR COOLING REFRIGERATION CYCLE (contd.)

B-28 Crowell, W.E., Iskyan, H.S. A preliminary study of air conditioning for cabins of high speed unpressurized aircraft Cornell Aeronautical Laboratory, Inc. Report No. HE-330-S-1 (January 16, 1945)

B-29-C (See Classified Supplement)

B-30-C (See Classified Supplement)

B-31-C (See Classified Supplement)

B-32 Barron, W.A. Cooling equipment, design study - limits of operation and off design performance of air cycle cooling systems Republic Aviation Corporation Report No. F-5028-110 (October 7, 1949)

B-33 Barron, W. and Hermann, C. Cooling equipment, design study performance - charts for air expansion aircraft cooling systems (Part 3) Republic Aviation Corporation Report No. F-5028-103

B-34 Lewis, Martin H. Cooling equipment, design study - altitude airspeed operation limits of air expansion aircraft cooling systems (Part 2) Republic Aviation Corporation Report No. F-5028-102

B-35 Barron, W.A. Cooling equipment, design study - the vapor compression cycle applied to aircraft cabin cooling (part 4) Republic Aviation Corporation Report No. F-5028-111 (October 7, 1949)

AIR COOLED VACUUM TUBES

B-41 DeBray, H. and Rinia, H. An improved method for the air-cooling of transmitting valves Philips Technical Review Vol. 9 - No. 6 Pg. 171 (1947)

B-42 Bauermeister, H.A. Metal-ceramic air-cooled microwave triodes AF translation F-TS-4945-RE (ATI-X28181) (September 1944)

B-43 Nekut, A.G. Blower selection for forced-air cooled tubes Electronics Vol.23 No. 8 88-93 (August 1950)

B-44-C (See Classified Supplement)

ASSEMBLY TECHNIQUES

B-51 Electronic assembly technique wiring by welding method
Interim Report Radio Frequency Laboratories, Inc.
Boonton, New Jersey Contract NObsr 49242
(September 8, 1950)

B-52 Development and application of automatic assembly techniques
for miniaturized electronic equipment Interim Report No. 1
Stanford Research Institute Contract AF33(038)-18976
(November 15, 1951)

BLOWERS - SUBMINIATURE

B-56-C (See Classified Supplement)

CASTING RESINS

B-57 Rolle, Edward NEL casting resins NEL Resin No. 177
Interim Report No. 2 Navy Electronics Laboratory
Report No. 165 (February 23, 1950)

B-58 Franklin, Philip J., French, David M., Nyberg, Wilbur C.
Development of the National Bureau of Standards casting resin
Circular 493 National Bureau of Standards (May 22, 1950)

B-59 Venable, E. Cooling Electrical Apparatus U.S. Patent
No. 2,354,159 (July 18, 1944)

B-60 Lippitt, L. The use of electron tubes in potted assemblies
Research and Development Board Committee on Electronics
Panel on Electron Tubes (January 18, 1951)

CAPACITORS

B-61 Progress Reports on high temperature miniaturized capacitors
Contract No. AF-33(038)-9328 Sprague Electric Co.
(Second Progress Report - July 1, 1950) (Third Progress
Report - October 1, 1950)

B-62 Development leading toward improved or new designs of glass
dielectric capacitors Interim Reports Corning Glass
Works Contract No. W36-039 sc-38136

B-63 A study of high dielectric constant films for high temperature
operation (Final Report) Balco Research Labs. Contract
No. W36-039 sc-32361

CIRCUIT DESIGN FOR THERMAL COMPENSATION

B-66 Connor, John A. and Troxel, David L. Electronics, circuit-design techniques, precise thermal stabilization of tuned L-C circuits NRL Problem No. 39R10-63D Bureau Request Number S1502

CONDUCTION COOLING

B-71-C (See Classified Supplement)

B-72-C (See Classified Supplement)

B-73-C (See Classified Supplement)

B-74 Hannahs, W.H., Caffiaux, J.A., and Wheeler, W.R. Heat transfer in miniaturized unit assemblies Sylvania Technologist Vol. III - No. 3 13-17 (July 1950)

B-75-C (See Classified Supplement)

B-76 Mersman, Berggren and Boelter The conduction of heat in composite infinite solids University of California Publications in Engineering Vol. 5 - No. 1 Pg. 1-22 7 figures in text University of California Press (1942)

FINS FOR HEAT TRANSFER

B-86 Norris, R.H. and Spofford, W.A. High performance fins for heat transfer Transactions A.S.M.E. Vol. 64 489-96 (July 1942)

B-87 Gardner, Karl A. Efficiency of extended surface Transactions A.S.M.E. Vol. 67 - No. 8 621 (November 1945)

B-88 Young, A.J. Radiators for transmitting valves The Marconi Review Vol. 12 - No. 94 85-91 (July/Sept. 1949)

FORCED AIR BLOWERS - SELECTION OF

B-91 Robinson, W., Zimmerman, R.H., and Stevenson, J.A. Design and control of blower for uniform cooling of electronic equipment from sea level to 70,000 ft. altitude Ohio State University Research Foundation Report No. 33A (April 7, 1950)

B-92 Steinberg, E.B. Improved cooling of electrical devices Electrical Manufacturing Vol. 45 - No. 1 70-75 (January 1950)

FORCED AIR BLOWERS - SELECTION OF (contd.)

B-93 Wheeler, J.S.C., Rowe, G.W. Small fans for radar equipment TRE Report No. T2119 Duplicate ATI No. 55248

GENERAL INFORMATION

B-96 Drake, D.T. Electronic equipment cooling in a high temperature environment Northern American Aviation, Inc. West Coast IRE Conference on Electronic Components (April 27, 1951)

B-97 Pfaff, R.W. Equipment cooling in high altitude high speed airplanes Boeing Airplane Company Document No. D-10814 (January 8, 1951)

B-98 Fuller, F.L. and Barron, W.A. Summary of aircraft cabin cooling equipment design study (Part I - revisional) Republic Aviation Corporation Report No. F-5028-110A (October 18, 1949)

B-99 Steinberg, E.B. Improved cooling of electrical devices Electrical Manufacturing Vol. 45 - No. 1 70-75 (January 1950)

B-100 McAdams, W.H. Some recent developments in heat transfer Purdue University Engineering Bulletin Research Series No. 104

B-101 Shaw, E.N. The overheating of miniature resistors during soldering Telecommunications Res. Estab. Technical Note No. 12

B-102 Jakob, Max A survey of the science of heat transmission Purdue University Engineering Bulletin Research Series No. 68 (August 1939)

B-103 Telkes, Maria The efficiency of thermoelectric generators I Applied Physics Vol. 18 1116-1127 (December 1947)

HEAT DISSIPATION FROM CABINETS

B-106 Littlejohn, H.C. Heat dissipation from cabinets for electrical instruments The General Radio Experimenter Vol. XX No. 8 4-5 (January 1946)

HEAT DISSIPATION FROM CABINETS (contd.)

B-107-R Miller, M.L. and Ragni, V.F. Heat dissipation capabilities of aluminum containers for electronic components Navy Dept. Contract NOrd-9099 Capehart-Farnsworth Corp. Report No. FAR-1-L (January 4, 1950)

B-108-R Miller, M.L. and Ragni, V.F. Heat dissipation capabilities of aluminum containers for electronic components Navy Dept. Contract NOrd-9099 Capehart-Farnsworth Corp. Report No. JHU/APL-CM 600 (April 20, 1950)

B-109 Bibbero, R.J. Estimating temperature rise in electronic equipment cases Proceedings of the I.R.E. Vol. 39 No. 5 504-508 (May 1951)

B-110 Robinson, W. and Beitler, S.R. Operating temperature measurements on components, enclosures, and mounting surfaces of radar set AN/APG-7 Ohio State University Research Foundation Report No. 20A (July 1948)

HEAT EXCHANGERS

B-116-R Ludwig, L.G. The development of a hermetically sealed heat exchanger case for military aircraft transceiver Cornell Aeronautical Laboratory, Inc. Report No. HM-608-S-6 (August 1949)

B-117 Robinson, W. and Zimmerman, R.H. An analysis of some design criteria of tubular heat exchangers for simple ram air cooling systems Ohio State University Research Foundation Report No. 26A (February 7, 1949)

B-118-R Vick, Eugene 225-400MC multichannel transmitter-receiver AN/ARC-27 Collins Radio Company Report No. IDR-261 (April 1, 1950)

B-119 O'Donnell, W.J. Cooling equipment design study - heat exchangers for aircraft cabin cooling systems (Part 9) Republic Aviation Corporation Report No. F-5028-109 (October 7, 1949)

B-120 Fuller, F.L. and Barron, W.A. Summary of aircraft cabin cooling equipment design study (Part 1 - Revisional) Republic Aviation Corporation Report No. F-5028-110A (October 18, 1949)

HEAT AND MASS FLOW

B-126 Bradley, C.B. and Ernst, C.E. Economic thickness of thermal insulation for intermittent operation Trans. A.S.M.E. Vol. 67 - No. 2 93 (February 1945)

B-127 Paschkis, Victor Periodic heat flow in building walls determined by electrical analogy method Heating, Piping and Air Conditioning Vol. 14 - No. 2 133-138 (February 1942)

B-128 New heat transfer research tool Mechanical Engineering Vol. 64 - No. 2 95-96 (February 1942)

B-129 Paschkis, Victor and Baker, H.D. A method of determining unsteady state heat transfer by means of an electrical alogy Trans. A.S.M.E. Vol. 64 105-112 (1942)

B-130 Paschkis, Victor Establishment of cooling curves of welds by means of electrical analogy American Welding Society Journal Vol. 22 - Part 2 462-s-483-s (1943)

B-131 Paschkis, Victor and Heisler, Michael, P. The accuracy of measurements in lamped R-C cable circuits as used in the study of transient heat flow Trans. A.I.E.E. Vol. 63 165 (April 1944)

HERMETIC SEALING

B-136 Leiss, W.J., Moltrup, G.R., Slaton, J.H., and Waynick, A.H. Hermetically sealed electric components Electronics Vol. 21 80-81 (November 1948)

B-137 Hanson, Robert M. Hermetically sealed transformers Electronics Vol. 18 136 (February 1945)

B-138-R Design and development of miniature hermetically sealed power transformers Contract No. W36-039 sc-38221 Armour Research Foundation of Illinois Institute of Technology Report No. 9

B-139 Anderson, Arthur L. Hermetic sealing Radio Vol. 30 No. 3 25-27+ (March 1946)

B-140 Herbert, Geoffrey Hermetic sealing Radio Vol. 29 No. 11 44-47 (November 1945)

B-141-C (See Classified Supplement)

HIGH TEMPERATURE VACUUM TUBE OPERATION

B-146 Mouromtseff, I.E. and Kozanowski, H.N. Grid temperature as a limiting factor in vacuum tube operation Proceedings I.R.E. Vol. 24 - No. 3 47 (March 1936)

B-147-R Kessler, Gerhart Fluctuations in hot cathode amplifiers due to temperature and their effects, particularly on DC amplifiers AF Translation F-TS-5825-RE (ATI 51912)

B-148 Danforth, W.E. and Haddad, T.A. Radiation transfer considerations in the heating of a cathode sleeve Franklin Institute Vol. 250 - No. 2 135 (August 1950)

B-149 Booth, R.E., Feinberg, M., and Wheeler, W.R. Correlation of Bulb Temperature with ambient temperature for subminiature tubes Sylvania Electric Products, Inc. Report No. BL/60/48-1 (July 1, 1948)

B-150 Research and development of double diodes, low-mu triodes, high-mu triodes and RF pentodes for operation within hermetically sealed expendable assemblies Sylvania Electric Products, Inc. Report No. AD-TD-6 (July-August 1947)

B-151 Research and development of double diodes, low-mu triodes, high-mu triodes, and RF pentodes for operation within hermetically sealed expendable assemblies Sylvania Electric Products, Inc. Report No. AD-TD-1 (January 14, 1947)

B-152 Mechanical consideration affecting vacuum tube reliability Tele-Tech (February 1952)

HILSCH - VORTEX - TUBE

B-156 MacGee, Roy Fluid action in the vortex tube Refrigeration Engineering Vol. 58 974 (1950)

B-157 Burkhardt, Gerd The Hilsch centrifugal jet Zeitschr. Naturforschung Vol. 3 46 (1948)

B-158 Knoernschild, Eugene M. and Morgensen, Otto P., Jr. Application of Hilsch tube to aircraft and missiles MCREXE-664-510A GS-USAF Wright Patterson 128 (June 10, 1948)

B-159 Finamore, O.B. A method for the experimental investigation of the Hilsch tube Cornell Aeronautical Laboratory, Inc. Report No. HF-566-A-1 (August 30, 1948)

B-160 Chapman, Seville The Ranque-Hilsch tube and applications to air temperature measurements Cornell Aeronautical Laboratory, Inc. Report No. HF-686-P-1 (April 17, 1950)

HILSCH - VORTEX - TUBE (contd.)

B-161 Maxwell's demon comes to life Popular Science (May 1947) and Astounding Science Fiction (January 1950)

B-162 Martino, Peter V. The Hilsch tube The Manhattan Engineer (March 1949)

HYDROGEN COOLING

B-166 Ross, M.D. Hydrogen cooling for turbine generators Electrical Engineering Vol. 50 211-214 (March 1931)

B-167 Davis, R. Hydrogen cooling Electrical Review Vol. 138 27-29 (January 4, 1946)

B-168 Davidson, D.F. The advantages of hydrogen-cooled generators Electrical Times Vol. 115 - No. 2995 418-424 (March 31, 1949)

B-169 Horsley, W.D. Hydrogen-cooled alternators Engineer No. 4846 587-589 (December 10, 1948) and No. 4847 614-618 (December 17, 1948)

LIQUID COOLING

B-176 Mouromtseff, I.E. Water and forced air cooling of vacuum tubes - Nomenclature problems in electronic tubes Proc. I.R.E. Vol. 30 190 (1942)

B-177 Parsons, P.W. and Gaffney, B.J. Comparing fluids as heat transfer agents A.I.C.E. Transactions Vol. XL - No. 6 655-673 (December 25, 1944)

B-178 Chen, C.Y. and others Heat transfer in annuli Trans. A.S.M.E. Vol. 68 - No. 2 99 (February 1946)

B-179 Lynch, R.H. and Robinson, W. Weight, power and space requirements for typical cooling systems, employing heat rejection to an aircraft fuel system II (non-evaporative and evaporative liquid cooling systems) Ohio State University Research Foundation Report No. 28A (June 1949)

B-180 Beitler, S.R. and Lynch, R.H. Discussion of methods of removing heat from electronic equipment Ohio State University Research Foundation Report No. 6 (April 1947)

B-181 Troy, M.O. Liquid cooled electronic apparatus U.S. Patent 2,214,865 (September 17, 1940)

LIQUID COOLING (Contd.)

B-182 Wilkie, Harry Cooling of electronic apparatus at high altitudes CADO Technical Data Digest Vol. 15 - No. 12 30-32 (December 1950)

B-183-R Best, M. Initial interim engineering report on cooling assembly, circulating liquid, pressure type ATI 31187 Sorensen and Co., Inc. (October 7, 1947)

B-184-R Best, M. Interim engineering report #2 on cooling assembly, circulating liquid, pressure type ATI 33113 Sorensen and Co., Inc. (December 1947)

B-185-R Best, M. Interim engineering report on cooling assembly, circulating liquid, pressure type ATI 33111 Sorensen and Co., Inc. Report No. 4 (April 1948)

B-186-R Best, M. Interim engineering report #5 on cooling assembly, circulating liquid, pressure type Sorensen and Co., Inc. Report No. 5 ATI 38401 (July 13, 1948)

B-187-R Best, M. Cooling assembly, circulating liquid, pressure type ATI 56833 Sorensen and Co., Inc. Report No. 8 (February 1949)

B-188-R Best, M. Interim engineering report on cooling assembly circulating liquid, pressure type ATI 58824 Sorensen and Co., Inc. Report No. 9 (May 1949)

LIQUID COOLED VACUUM TUBES

B-189 Jenny, F. The development of a water-cooled transmitting triode of 50 KW anode dissipation The Brown Boveri Review Vol. XXXIII - No. 8 211 (August 1946)

B-190 Snijders, M.J. A transmitting valve cooler with increased turbulence of the cooling water Philips Technical Review Vol. 10 - No. 8 239 (February 1949)

B-191 Water cooling versus air-cooling for high power valves Engineering No. 4338 258 (March 18, 1949)

LIQUIFIE GASES

B-196 Semenza, Marco A system for the cooling of electrical and similar machinery at low temperature British Patent Specification No. 29,227/29

MANUFACTURERS ACTIVITIES

B-201-R Beitler, S.R. and Lynch, R.H. Survey of anticipated cooling problems on future airborne electronic equipment installations Ohio State University Research Foundation Report No. 9-R-1 (June 1947)

B-202 Electronic equipment construction Contract N7ONR-32103 Stanford-Research Institute Terminal Report (June 1, 1950)

MATERIALS

B-206 Guyer, Edwin M. Electrical glass Proc. I.R.E. Vol. 32 743 (December 1944)

B-207 Marbaker, Edward E. Materials for wire-wound resistors - some recent developments Materials & Methods Vol. 25 83 (May 1947)

B-208 Cohen, M.U. A study of high dielectric constant films for high temperature operation General Research Laboratories Report No. 4 (November 1946)

B-209 Cohen, M.U. High temperature, high dielectric constant films for high temperature operation General Research Laboratories Report No. 6 (January 1947)

B-210-R The distribution of temperature in thin films Capehart-Farnsworth Corp.

B-211 Zirconia Refractory good to 4600°F. Steel Vol. 128 - No. 5 68 (January 29, 1951)

B-212 Properties of selected commercial glasses Corning Glass Works, Corning, N.Y.

MEASUREMENT TECHNIQUES

B-216 Beitler, S.R. and Lynch, R.H. Status of test apparatus and literature survey on convective heat transfer Ohio State University Research Foundation Report No. 18 (April 22, 1948)

B-217 Beitler, S.R. and Lynch, R.H. Status of test apparatus and literature survey on surface temperature measurement Ohio State University Research Foundation Report No. 17 (March 15, 1948)

B-218 Watson, J.D. and Dixon, H.E. A six-point high-speed thermocouple temperature-recording equipment J. Sci. Instruments in Industry Vol. 26 - No. 1 17-18 (January 1949)

MEASUREMENT TECHNIQUES - (contd.)

B-219 Clearwaters, W.L., Kulik, N. and Kemlek, E.N. The development of a cooling meter to determine an indication of the effectiveness of the cooling of air cooled aircraft engines Purdue University Engineering Experiment Station Army Air Corps Cooperative Research Project M-115-3 (December 30, 1942)

B-220 Beitler, S.R. and Lynch, R.H. Status on design and construction of heat transfer apparatus and study of thermodynamic cycles Ohio State University Research Foundation Report No. 11 (August 1947)

B-221 Hirsch, L.H. Investigation of hot-spot temperatures in fractional horsepower motors Trans. A.I.E.E. Vol. 64 - No. 3 128-136 (March 1945)

B-222 Mohun, W.A. Precision of heat transfer measurements with thermocouples - Insulation error Canadian Journal of Research Vol. 26 Section E 563-583 (1948)

B-223 Earle, Marshall D. Development of thermocouples for use on thermoelectric generators Franklin Institute Laboratories Progress Report No. P-1992-12 (March 11, 1950 to June 10, 1950)

B-224 Kays, W.M. and London, A.L. Heat transfer and flow friction characteristics of some compact heat exchanger surfaces Part 1 - test system and procedure Part 2 - design data for thirteen surfaces Heat Transfer Division of American Society of Mechanical Engineers Part 1 - Trans. A.S.M.E., Vol. 72 - No. 8 1075-1085 (November 1950) Part II - Trans. A.S.M.E., Vol. 72 - No. 8 1087-1097 (November 1950)

B-225 Dunkle, R.V. and Gier, J.T. The two radiometer method for the simultaneous determination of emissivity and surface temperature Thermal Radiation Project Contract No. N7-ONR-295 Task 1 Report Code NR-015-202 University of California at Berkeley Dept. of Engineering

METHODS OF SOLVING THERMAL PROBLEMS

B-231 Jakob, Max Some investigations in the field of heat transfer Proc. of the Physical Society (Buffalo Publication) Vol. 59 726-755 (September 1947)

B-232 Eyres, N.R. and Hartree, D.R. The calculation of variable heat flow in solids Trans. Royal Society Vol. 240 1-57 (1946)

METHODS OF SOLVING THERMAL PROBLEMS (contd.)

B-233 Higgins, T.J. Formulas for calculating temperature distribution in transformer cores and other electrical apparatus of rectangular cross section Trans. A.I.E.E. Vol. 64 190 (April 1945)

B-234 Cowen, Don Heat transfer lectures NEPA 804-IER-10 Fairchild Engine and Airplane Corporation NEPA Division Oak Ridge, Tennessee

B-235 Coyle, M.B. An airflow analogy for the solution of transient heat conduction problems British J. Applied Physics Vol. 2 - No. 1 12-17 (January 1951)

B-236 Jakob, Max Heat transfer in evaporation and condensation Part 1 Mechanical Engineering Vol. 58 643 (October 1936) Part 2 Mechanical Engineering Vol. 58 729 (November 1936)

B-237 Brunot, A.W. and Buckland, Florence F. Thermal contact resistance of laminated and machined joints Trans. A.S.M.E. Vol. 71 253 (April 1949)

B-238 Goldenberg, H. A problem in radial heat flow British J. Applied Physics Vol. 2 - No. 8 233-237 (August 1951)

PRINTED CIRCUITS

B-246 Jacobs, Yale Resume' of printed circuits AF Memo MCREE-49-20 (ATI 54420) (April 8, 1949)

B-247 New advances in printed circuits U.S. Bureau of Standards Publication No. 192 (November 22, 1948)

B-248 Printed circuit techniques U.S. Bureau of Standards Circular No. 468 (November 15, 1947)

RAM AIR COOLING

B-251 Zimmerman, R.H., Robinson, W. and Stevenson, J.A. Performance and control of simple ram air cooling systems for "off-design" operation from sea level to 70,000 ft. altitude at flight speeds between mach 0.7 to 2.0 Report No. 27A Ohio State University Research Foundation (April 1949)

B-252 Beitler, S.R., Zimmerman, R.H. and Robinson, W. Study of methods of ultimate heat dissipation III Ohio State University Research Foundation Report No. 22 (August 15, 1948)

RAM AIR COOLING (contd.)

B-253 Zimmerman, R.H. Study of compressors for compressed ram-air systems Ohio State University Research Foundation Report No. 30C (November 1949)

B-254-C (See Classified Supplement)

RADIATION

B-256 Blackshaw, J.L. and Houghton, F.C. Radiation of energy through glass Trans. American Society of Heating and Ventilating Engineers Volume 40 93 (1934)

B-257 Barnes, B.T., Forsythe, W.E. and Adams, E.Q. The total emissivity of various materials at 100-500°C. J. Optical Society of America Vol. 37 - No. 10 80-87 (1947)

B-258 Winter, L.L. and MacPherson, H.G. Effect of surface finish and wall thickness on the operating temperature of graphite-radio-tube anodes Proc. I.R.E. Vol. 33 834 (December 1945)

B-259 Wohlenberg, W.J. Heat transfer by radiation Purdue University Engineering Bulletin Research Series No. 75 (August 1940)

B-260 Canada, A.H. Simplified calculation of black body radiation General Electric Co. General Electric Review Vol. 51 - No. 12 50-54 (December 1948)

RECTIFIERS

B-261 Selenium rectifier uses new cooling method Electrical World Vol. 133 - No. 5 138 (January 30, 1950)

B-262 Benzer, S. Temperature dependence of high voltage Germanium rectifier D.C. characteristics Purdue University OSRD, NDRC, Div. 14 NDRC Report 579 (October 31, 1945)

B-263 Walters, C.W. Rectifiers, dry-disc type, variable frequency, miniature for operating at high and low ambient conditions of temperature P.R. Mallory & Co., Inc. Interim Engineering Report ENG-3519-H (ENG 3519-009) (April 1947)

B-264 Walters, C.W. (a) Rectifiers, dry-disc type, variable frequency, miniature for operating at high and low ambient conditions of temperature P.R. Mallory & Co., Inc. ENG 3519-L (ENG 3519-013) (August 15, 1947)
(b) ENG 3519-I (ENG 3519-010) (May 12, 1947)
(c) ENG 3519-A (ENG 3519-002) (September 12, 1946)

RECTIFIERS (contd.)

B-265 Hofmann, W. Effects of temperature on metallic rectifiers AF Translation F-TS-4108-RE (ATI 18927) (January 13, 1948)

B-266 Walters, Charles W. Rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory & Co., Inc. ENG-3519-K (ENG 3519-012) (July 1947)

B-267 Lawson, A.W., Maurer, R.J., Miller, P.H., and others DC burn-out temperature in silicon rectifiers University of Pennsylvania Report No. 113 (January 1943)

B-268 Walters, Charles W. Interim engineering report on rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory and Co., Inc. ENG-3519-G (March 1947)

B-269 Walters, Charles W. Interim engineering report on rectifiers dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory and Co., Inc. ENG-3519-O (November 1947)

B-270 Walters, Charles W. Supplement to final engineering report on rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory & Co., Inc. ENG-3519-Q (May 1948)

B-271 Gamble, Milton E. Interim engineering report on rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory and Co., Inc. ENG-3519-A (ENG-3519-002) (July-September 1946)

B-272 Walters, Charles W. Interim engineering report on rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory and Co., Inc. ENG-3519-1 (ENG 3519-010) (May 1947)

B-273 Walters, Charles W. Interim engineering report on rectifiers, dry-disc type, variable frequency, miniature, for operating at high and low ambient conditions of temperature P.R. Mallory and Co., Inc. ENG-3519-L (ENG 3519-013) (August 1947)

RESISTORS

B-276 Cohen, M.U. and Balamuth, L. A study of miniature composition resistors for high temperature operation Balco Research Lab.

RESISTORS (contd.)

B-277 Development of high temperature resistors Battelle Memorial Institute

B-278 Witchell, F.D. Twelfth interim engineering report on high temperature, fixed, wire wound resistors Shallcross Mfg. Co. Report No. P60-12 (July to August 1947)

B-279 A high temperature adhesive tape resistor National Bureau of Standards Technical News Bulletin Vol. 35 - No. 7 100-102 (July 1951)

B-280-C (See Classified Supplement)

RUGGED ELECTRON TUBES

B-281 Rugged electron tubes J. Franklin Inst. Vol. 249 85-86 (January 1950)

B-282 Acheson, Marcus A. and McElwee, Eleanor, M. Concerning the reliability of electron tubes The Sylvania Technologist Vol. IV - No. 2 (April 1951)

B-283 Gibbs, Leo L. Ruggedized subminiature tubes U.S.A.F. Report No. 6205 (July 1950)

B-284 Development of rugged electron tubes (Final Report) Chatham Electronics Corp. Contract No. W36-039 sc-33677

SILICONE FLUID COOLANTS

B-286 Beiter, S.R. and Lynch, R.H. Analysis of film coefficients using DC-550 silicone fluid with agitation Ohio State University Research Foundation Report No. 14 (December 1947)

B-287 Beitler, S.R. and Lynch, R.H. Burning properties of DC-703 silicone fluid and volatility data on DC-550 and DC-703 fluids Ohio State University Research Foundation Report No. 15 (January 1948)

B-288 Beitler, S.R. and Lynch, R.H. Film coefficients up to 600°F. using DC-550 silicone fluid with agitation Ohio State University Research Foundation Report No. 16 (February 20, 1948)

B-289 Lynch, R.H. and Robinson, W. Design charts for tubular heat exchangers with heat rejection from DC-200 silicone fluid to engine fuel Ohio State University Research Foundation Report No. 28B (June 1949)

SILICONE FLUID COOLANTS (contd.)

B-290 Beitler, S.R. and Lynch, R.H. Status on construction of test apparatus and temperature distribution test in DC-550 silicone fluid with natural convection and agitation Ohio State University Research Foundation Report No. 12 (October 15, 1947)

SUBMINIATURE UNITIZED ASSEMBLIES

B-296-C (See Classified Supplement)

B-297-C (See Classified Supplement)

B-298 Richards, J.A.K. Miniaturization techniques for medium frequency multiband receiving equipment Lear, Inc. AF Technical Report No. 6494 (April 1951)

B-299 Miller, M.L. The design of electronic equipment using subminiature components Proc. I.R.E. Vol. 38 - No. 2 130-135 (February 1950)

B-300 Ainsworth, M.J. State of the art of electronic subminiaturization Contract NObsr 43430 Pacific Division, Bendix Aviation Co. (March 15, 1951)

B-301-C (See Classified Supplement)

B-302 Marbaker, Edward E. Materials for wire-wound resistors - some recent developments Materials & Methods Vol. 25 83-88 (May 1947)

B-304-C (See Classified Supplement)

B-305 Subminiatures call for new skills Aviation Week Vol. 50 - No. 15 18 (April 11, 1949)

B-306 Henry, R.L. and Shapiro, G. Subminiaturization of intermediate frequency amplifier National Bureau of Standards Technical News Bulletin Vol. 33 - No. 4 (April 1949)

B-307-C (See Classified Supplement)

B-308 Henry, Robert L., Scal, R.K.F., and Shapiro, G. New techniques for electronic miniaturization Proc. I.R.E. Vol. 38 - No. 10 1139-1145 (October 1950)

B-309 Scal, Robert K.F. Thermal requirements of components for compact multitube subminiature electronic assemblies National Bureau of Standards Electronics Division Report No. OD-6-202R (April 1948)

SUBMINIATURE UNITIZED ASSEMBLIES (contd.)

B-310 Reid, J.G. Electronic miniaturization (NAer 00685) O.P.B. (National Bureau of Standards) 100949 (Final Report) (no date)

B-311 Austin, A. Electronic miniaturization Quarterly progress report for April, May, and June 1948 National Bureau of Standards Electronics Division ATI 40956

B-315 Sierra Engineering Company Potting of electronic circuits Developmental Report No. 25 Contract No. NObsr-42441 Index No. NE 020603 U11954 R4191 (August 10, 1950)

B-316-C (See Classified Supplement)

B-317 Brunetti, Cledo, Morrin, T.H. and Dawson, J.W. Unitized electronic design and construction techniques Stanford Research Institute Electrical Manufacturing Vol. 47 - No. 2 78-83+ (February 1950)

B-318-C (See Classified Supplement)

B-319-R Powell, Edwin L. Miniaturization trends Naval Research Lab. Radio Techniques Section Radio Division 11 (no no.) (no date)

B-320-C (See Classified Supplement)

B-321 Electronic miniaturization and maintenance Miniaturization in England Interim Report Task Order #3 Stanford Research Institute (no no.) (November 28, 1949)

B-322 Printed circuits (NAer 00686) O.P.B. (National Bureau of Standards, Eng. Electronics Section) 100950 (no date)

STEAM EJECTOR COOLING

B-326 Ashley, C.M. Steam ejector system for car conditioning Electrical Engineering Vol. 53 406-410 (March 1934)

SUBLIMATION

B-329 Heath, W.H. Cooling equipment, design study - aircraft cooling by sublimation of solid refrigerants, Part 5 Republic Aviation Corporation Report No. F-5028-105 (no date)

SUBMINIATURE VACUUM TUBES

B-336 Subminiature versions of RMA types 6L6, 6AG7, and one-half of 6AS7G Raytheon Manufacturing Company Contract No. AF33(038)-5734 Report No. 1041-1 (September 6, 1949)

SUBMINIATURE VACUUM TUBES (contd.)

B-337 Sylvania Subminiature tubes Sylvania Electronic Products, Inc. Premium Performance Type (catalog)

B-338 Freedman, G. and Holland, D.O. Electron tube research and development, subminiature versions of RMA types 6L6, 6AG7, and one-half of 6AS7G Raytheon Manufacturing Co. Report No. 1041-2 (November 1949)

B-339 Freedman, G. and Holland, D.O. Electron tube research and development, subminiature versions of RMA types 6L6, 6AG7, and one-half of 6AS7G Raytheon Manufacturing Co. Report No. 1041-3 (January 1950)

B-340 Fahnestock, James D. Military requirements for subminiature tubes Electronics Vol. 24 - No. 4 108-109 (April 1951)

B-341 Bibbero, Robert J. Rating of vacuum tubes at very high altitudes Bell Aircraft Corp.

B-343 Hannahs, W.H., Caffiaux, J.A. and Wheeler, W.R. Heat transfer in miniaturized unit assemblies Sylvania Technologist Vol. III - No. 3 (July 1950)

B-344 Gibbs, Leo L. Ruggedized, subminiature electron tubes AF Technical Report No. 6205 Components and Systems Laboratory Electronic Subdivision Wright Patterson AF Base (July 1950)

B-345 Subminiature tube characteristics and data published by Raytheon, National Union, General Electric, Radio Corporation of America, Sonotone and Kip Electronics

THERMAL MEASUREMENTS OF JOINTS

B-346 Brunot, A.W. and Buckland, Florence F. Thermal contact resistance of laminated and machined joints Trans. of the ASME Vol. 71 - No. 3 253-257 (April 1949)

B-347 Weills, N.D. and Ryder, E.A. Thermal resistance measurements of joints formed between stationary metal surfaces Trans. ASME Vol. 71 - No. 3 259-267 (April 1949)

TRANSFORMERS

B-351 Interim Engineering Report on Research, analysis, and investigation carried on to develop an audio transformer of small size and weight capable of operating over wide temperature range United Transformer Co. Report No. 3 (July 1 - December 1, 1947)

TRANSFORMERS (contd.)

B-352 Power transformers - high operating temperature type Progress Report for period ending March 26, 1947 Bell Telephone Lab. (no no.) (April 1947)

B-353 Research, analysis and investigation carried on to develop an audio transformer of small size and weight capable of operating over wide temperature range I.E.R. No. 2 United Transformer Corporation ATI 33405 (July 1, 1947)

B-354 Research, analysis and investigation carried on to develop an audio transformer of small size and weight capable of operating over wide temperature range I.E.R. Final Engineering Report United Transformer Corporation ATI 57868 (April 27, 1949)

TURBULENT FLOW

B-361 Snijders, M.J. A transmitting valve cooler with increased turbulence of the cooling water Phillips Technical Review Vol. 10 - No. 8 239 (February 1949)

B-362 Zimmerman, R.H. and Robinson, W. Development of charts for the analysis of compressible flow, with heat addition and friction, in a circular tube of constant cross-sectional area and constant wall temperature Ohio State University Research Foundation Report No. 25A (December 6, 1948)

B-363 Katz, L. Basic considerations in the application of turbulent air techniques Raytheon Manufacturing Company Memo No. 110 (March 20, 1950)

B-364-R Katz, L. Conference on AN/FPN-10 Raytheon Manufacturing Company Memo Report No. 72 (May 31, 1949)

B-365-R Kaye, J. Study report on cooling of AN/FPN-10 Raytheon Manufacturing Company Memo Report No. 3 (January 27, 1949)

B-367 Moore, John F. Turbulent air cooling for AN/APT-16 Raytheon Manufacturing Company Memo Report No. 18 (June 26, 1950)

B-368 Moore, John F. Revision of air flow chart No. 4 Raytheon Manufacturing Company Memo Report No. 23 (March 6, 1951)

B-369-C (See Classified Supplement)

B-370-C (See Classified Supplement)

TURBULENT FLOW (contd.)

B-371-C (See Classified Supplement)

B-372 Moore, John F. High efficiency in electronic equipment cooling Raytheon Manufacturing Company Memo Report No. 26 May 8, 1951

B-373-R Moore, John F. Analysis of turbulent air cooling Raytheon Manufacturing Co. Memo Report No. 7 (July 26, 1949)

ULTIMATE SINKS

B-376 Robinson, W. and Beitler, S.R. Progress of project work - study of methods of ultimate heat dissipation I Ohio State University Research Foundation Report No. 20 (July 1948)

B-377 Robinson, W., Zimmerman, R.H. and Beitler, S.R. Study of methods of ultimate heat dissipation II Ohio State University Research Foundation Report No. 21 (July 1948)

B-378 Robinson, W. and Zimmerman, R.H. Methods for the ultimate dissipation of heat originating with airborne electronic equipment AF Technical Report No. 6493 Ohio State University Research Foundation (March 1951)

VACUUM TUBE COOLING

B-381 Progress of project work Ohio State University Research Foundation Report No. 35 (August 3, 1950)

B-382 Progress of project work Ohio State University Research Foundation Report No. 33 (April 3, 1950)

B-383-R Kaye, J. Interim report on heat dissipation in an AN/FPN-10 Raytheon Manufacturing Company Memo Report No. 1 (November 3, 1948)

B-384 Weeks, P.T. Reliability in miniature and subminiature tubes Proc. I.R.E. Vol. 39 - No. 5 499-503 (May 1951)

B-385 Report of symposium on the application of tubes in guided missiles for maximum reliability Issued through the Panel on Electron Tubes, Committee on Electronics Research & Development Board Department of Defense Published under Contract DA 36-039-sc-5597 with New York University, College of Engineering

B-386 Buckland, B.O. Electron-tube heat-transfer data Electrical Engineering Vol. 70 962-966 (November 1951)

VAPORIZATION COOLING

B-401 DeKoning, T. Vaporization cooling of electric machines Electrical Engineering Vol. 68 - No. 5 385-392 (May 1949)

B-402 Progress of project work Ohio State University Research Foundation Report No. 34, Project No. 269

B-403 Progress of project work Ohio State University Research Foundation Report No. 35, Project No. 269

B-404 Information on evaporative cooling of electronic components and status of survey on cooling problems Ohio State University Research Foundation Report No. 9 (July 1, 1947)

B-405 Weight, power and space requirements for typical cooling systems, employing heat rejection to an aircraft fuel system 2 (non-evaporative and evaporative liquid cooling systems) Ohio State University Research Foundation Report No. 28A (June 17, 1949)

B-406 Robinson, W. and Han, L.S. Cooling systems for electronic equipment utilizing expendable evaporative coolants Ohio State University Research Foundation Report No. 30B (November 1949)

B-407 Wilkie, Harry Cooling of electronic apparatus at high altitudes CADO Technical Data Digest Vol. 15 - No. 12 30-32 (December 1950)

B-408 Miniaturized radio submerged in Freon refrigerant A.T.I. Technical Data Digest Vol. 13 - No. 19 (October 1, 1948)

B-409 Greene, Albert D. and Wightman, John C. Engineering study of direct evaporative cooling for electronic equipment A.M.C. MCREE 48-32 (June 10, 1948)

B-410 Beitler, S.R. and Lynch, R.H. Discussion of methods of removing heat from electronic equipment, including endothermic processes, plating processes and notes on heat transfer to boiling liquids Ohio State University Research Foundation Report No. 7 (May 12, 1947)