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RADC THERMAL GUIDE FOR RELIABILITY ENGINEERS

Hughes Aircraft Company

Gerald N. Morrison, James M. Kallis, Landon A. Strattan, Ivan R. Jones, and August L. Lena

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This guide was developed to provide a reliability engineer, who is not proficient in thermal design and analysis techniques, with the tools for managing and evaluating the thermal design and production of electronic equipment. It defines the requirements and tasks that should be addressed in system equipment specifications and statements of work, and describes how to evaluate performance.

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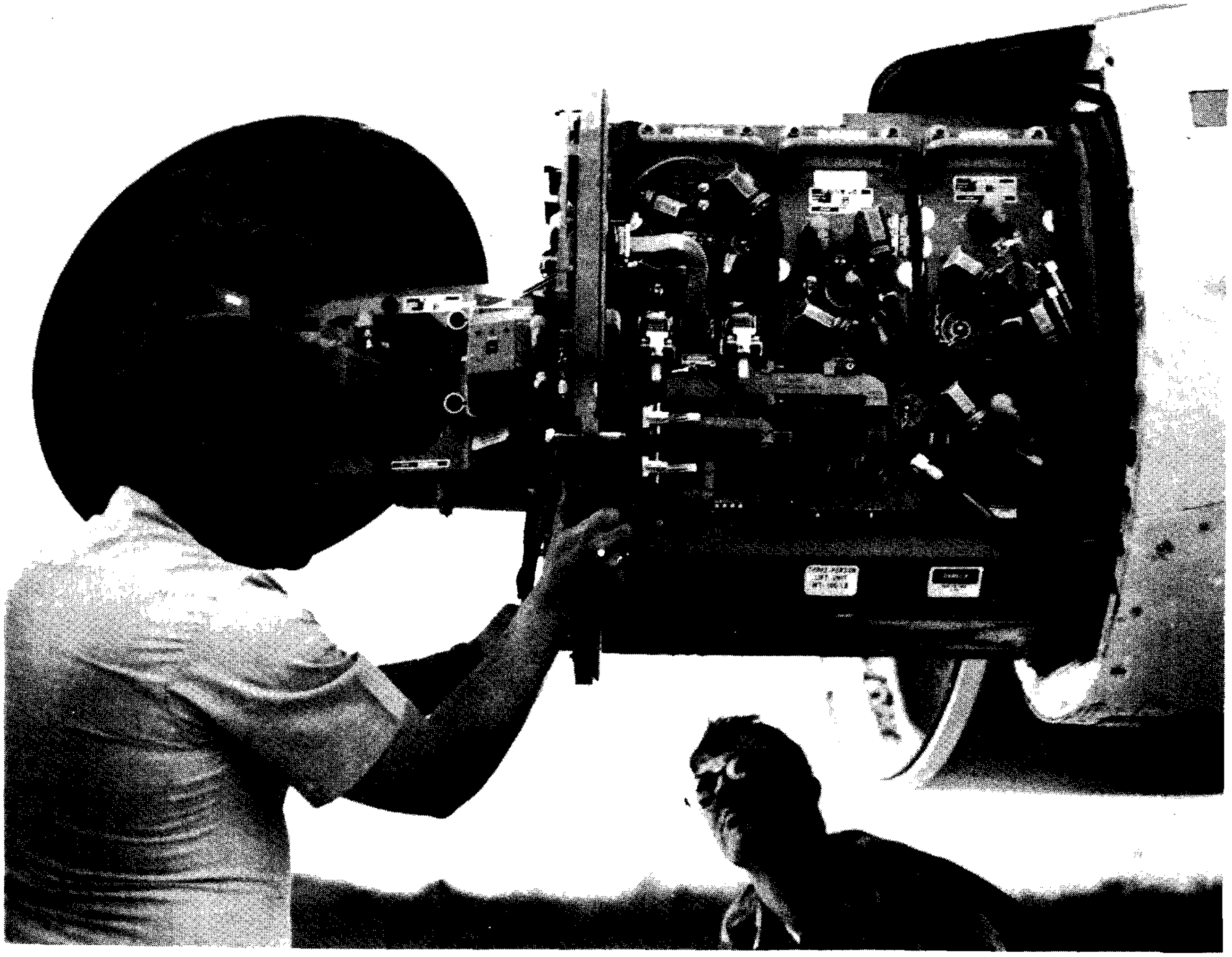

Since temperature influences the reliability of electronic equipment, the reliability engineer must ensure the implementation of a disciplined thermal management program.

MEETING A PRESSING NEED

In light of the vital influence of temperature on the reliability of electronic equipment and the ever more stringent reliability requirements of military systems, a major responsibility of the reliability engineer is ensuring the implementation of a disciplined thermal management program.

Yet many a reliability engineer has little or no knowledge of thermal design and analysis. Moreover, texts and government handbooks published to date have stressed theory and are far too cumbersome to be of use to one whose primary responsibility is reliability.

What has been needed for some time is a short book that gives the reliability engineer the tools to manage and evaluate thermal design.

This guide meets that need.

Part I presents guidelines for assuring the development of a thermally adequate, cost-effective product. It defines the requirements and tasks which must be addressed in equipment specifications and statements of work. And it shows how to tailor the tasks to individual programs.

Part II details the implementation of these tasks. It summarizes the fundamentals of heat transfer; tells how to evaluate not only thermal designs, but the thermal adequacy of production equipment; and explains the thermal aspects of environmental screening. It gives "do's" and "don'ts" and rules of thumb, and shows how to improve existing designs.

Only the essence of each subject is presented. For more detailed information, references are listed in the appendix.

ACKNOWLEDGEMENTS

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Mr. Gerald N. Morrison was the Hughes program manager, and Dr. James M. Kallis was the principal investigator. Mr. Morrison, Dr. Kallis, and Messrs. Landon A. Strattan, Ivan R. Jones, and August L. Lena are the authors of the guide. The guide editor was Mr. George W. Stimson, assisted by Mr. Timothy A. Burke. Technical review was provided by the technical review board and other organizations throughout the country. Their contributions are greatly appreciated.

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PART I—MANAGEMENT

CHAPTER 1
SUCCESS IN THERMAL MANAGEMENT

A small investment in sound thermal management can yield far greater long-term profits. By means of a simple example, this chapter illustrates the potentially high cost of inadequate thermal management. It then focuses on the key ingredients of a successful thermal program.

THE COST OF INADEQUATE THERMAL MANAGEMENT

Primary objectives of modern military electronic programs are minimizing system life-cycle cost and maximizing availability. Yet all too often this cost increases unnecessarily as a result of inadequate thermal management. While examples of this deficiency differ widely, virtually all of them are due to one or more of three basic reasons:

- Program management doesn't recognize the payoffs of sound thermal management.
- The contractor has inadequate thermal expertise.
- The reliability engineers involved in the program have inadequate thermal backgrounds.

To illustrate, consider a hypothetical example. A contract is issued for the design and manufacture of a comparatively simple, straightforward system consisting of three electronic units mounted in a single cabinet. Superficially, there appears to be no need for active cooling. Budgets being tight, the idea of any sort of thermal analysis is deemed out of the question.

The system is designed (Figure 1–2), the individual units are breadboarded and checked out, and prototype hardware is built. No problems.

But when the units are tested as a complete system, several parts repeatedly fail. The contractor's reliability engineer correctly assesses the cause of the failures as high part temperatures and recommends that active cooling be provided.

The contractor happens to have little or no thermal expertise. But that hardly seems necessary. All that is really needed is a couple of blowers in the top of the cabinet.

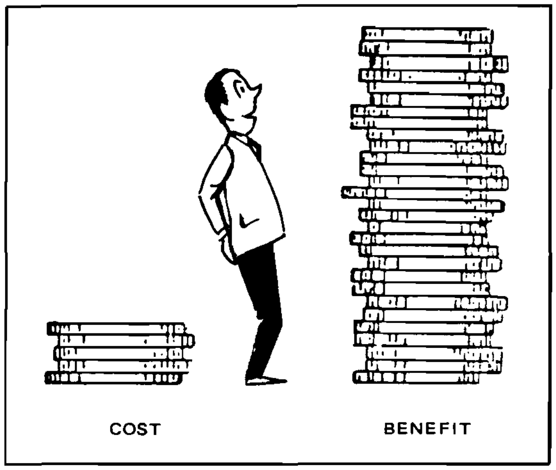


Figure 1-1. Thermal programs are cost-effective.

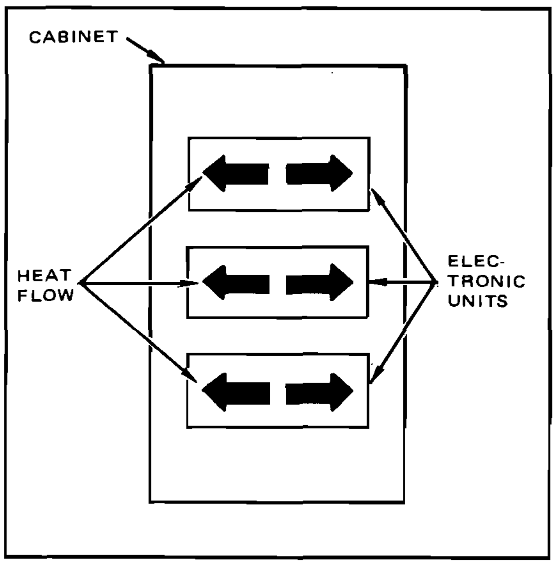


Figure 1-2. In the original design of a comparatively simple electronic system, no provision was made for active cooling; parts overheated and failed.

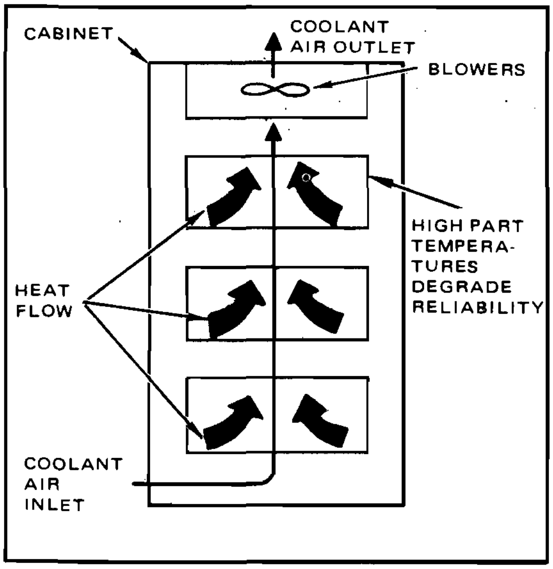


Figure 1-3. In the first redesign, a blower drew coolant air through units serially; but high part temperatures in downstream unit reduced reliability.

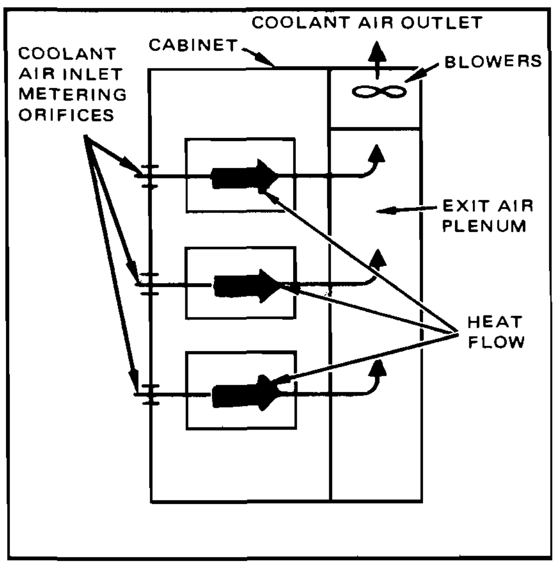


Figure 1-4. In the second redesign, coolant air was drawn through units in parallel, but wrong-sized metering orifices were installed; the resulting part temperatures were still too high.

Even so, the redesign (Figure 1-3) turns out to be unreasonably expensive. To make room for the blowers, the mounting of the units has to be changed and the parts rearranged. To admit and exhaust the coolant air, openings must be made in the cabinet. To duct the air through the units to the blowers, internal passages must be provided. And, of course, power must be supplied for the blowers.

Aside from its excessive cost, the redesign appears to be completely satisfactory. The system passes all tests, is put into production, and several hundred systems are delivered.

But . . . as reports start trickling in from the field, it soon becomes clear that the failure rate is inordinately high. The problem, once again, is assessed as thermal. This time, though, an experienced thermal engineer is called in.

He quickly finds the problem. The blowers were selected and the coolant air passages were designed with no thought for the convection of heat from one unit to the next. As a result, parts in the downstream unit run hotter than they should, degrading reliability.

This error is corrected—at still greater expense than before—by redesigning the system so the coolant air flows through the units in parallel (Figure 1-4).

But the problem doesn't end here, either. By the time the changes are put into production, the thermal engineer has long since departed, and no procedure has been set up to verify workmanship and assembly in the factory. It so happens that the wrong metering orifices are inadvertently installed in the inlets for the coolant air. The parts still overheat. Needless to say, more money and more goodwill are wasted before this error is finally corrected.

In this program, as in all the others that have similarly gone wrong, the cost of a well-planned, well-monitored, well-executed thermal program would have paid for itself many times over through savings that would have been realized all along the line—in development costs, in production costs, in operation and maintenance costs.

KEYS TO SUCCESS

What then are the keys to a successful thermal program? As can be surmised from the preceding example, there are at least four keys:

- Establishment of specific thermal requirements
- Use of thermal specialists
- Adoption of a system-level approach to thermal design
- Performance of thermal tasks in all phases of a program.

To these should be added a fifth key: interaction between disciplines.

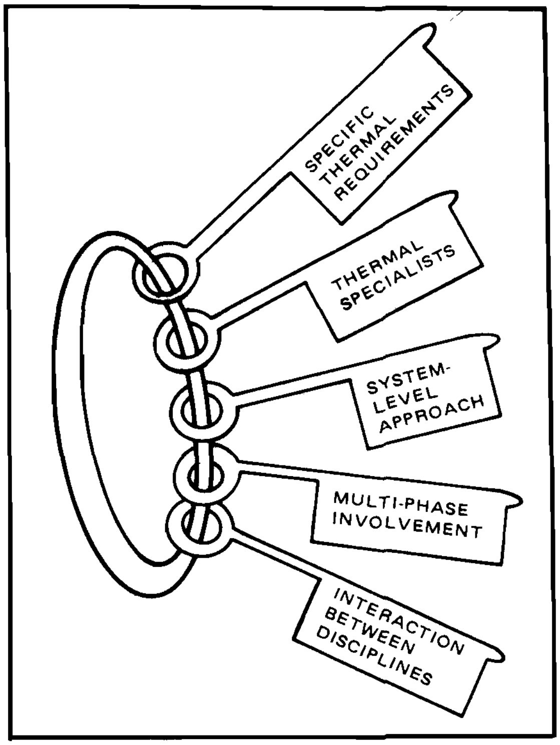


Figure 1-5. There are five keys to a successful thermal program.

Specific Thermal Requirements

Thermal requirements, specifying tasks and requiring formal reporting, are the primary tools available to the Procuring Activity and prime contractor for obtaining thermal management. The inclusion of these requirements in Requests for Proposals (RFPs) will go a long way toward ensuring that the contractor establishes and funds a thermal program and that thermal tasks are performed at appropriate phases of the design and production cycle.

Thermal Specialists

Both the Procuring Activity and the contractor should have thermal specialists involved throughout the program. The reliability manager in the Procuring Activity should see to it that the thermal engineer participates in writing Statements of Work (SOWs), evaluating proposals, and performing design reviews (Figure 1-6). The contractor should see to it that a thermal engineer is involved early in the design process when the thermal design can be economically optimized, as well as at the appropriate points later on. Often, the thermal engineer's involvement is so late that there is insufficient time left for any true optimization. All that can be done then is to "patch up" the more serious deficiencies.

Figure 1-6. Participation by thermal specialists of the Procuring Activity and the contractor is a key to a successful thermal program.

System-Level Responsibility

The temperatures of electronic parts are affected not only by the design of the individual electronic units but by the design of the overall system. Consequently, the reliability engineer must have the

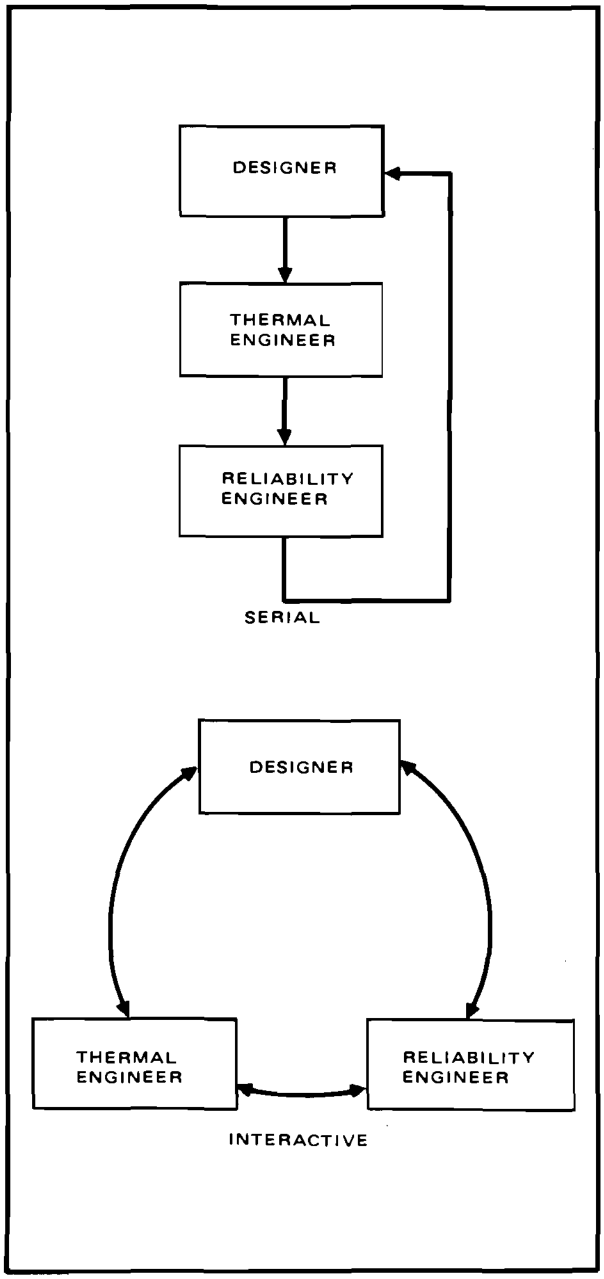


Figure 1-7. To save time and money, communication between the designer, thermal engineer, and reliability engineer should be interactive rather than serial.

responsibility and authority to influence those system-level decisions that impact electronic part temperatures and eventual system reliability. The thermal engineer, too, must have this authority, either directly or through the reliability engineer.

Multi-Phase Involvement

Thermal management must be in effect during all phases of a hardware program. It must start in the conceptual phase when alternative design concepts are identified and explored. It must continue during the demonstration and validation phase and the full-scale engineering development phase. And it must be maintained during the production phase as design and manufacturing changes occur.

Interaction Between Disciplines

Interactive communications between the designer (circuit and/or mechanical), thermal engineer, and reliability engineer are essential throughout the design process. What often happens, however, is that communication between these disciplines is carried out serially. The designer gives the completed design to the thermal engineer. He or she calculates the part temperatures and, in turn, passes these on to the reliability engineer, who determines whether the design satisfies reliability objectives.

If it does, all is fine. But suppose, as sometimes happens, the circuit designer has chosen parts which are too temperature-sensitive for the cooling scheme that has been adopted. Or, suppose he has chosen the parts without due concern for their thermal dissipation, and it exceeds the available cooling capacity. In either case, the entire circuit may have to be changed —at considerable expense in both time and money.

Clearly, the possibility of such waste can largely be eliminated if the designer, thermal engineer, and reliability engineer work interactively (Figure 1-7).

SUMMARY

By preventing thermally induced failures and costly redesign, a sound thermal program can save substantial amounts of time and money and increase availability. The key ingredients of such a program are (1) specific thermal requirements, (2) thermal specialists, (3) a system-level approach, (4) multi-phase involvement, and (5) interaction between disciplines.

CHAPTER 2
SPECIFIC THERMAL TASKS AND REQUIREMENTS

In Chapter 1, the key features of a sound thermal management program were introduced. In this chapter, the specific tasks performed in such a program will be studied, along with the requirements which the reliability engineer of the Procuring Activity (or prime contractor) must establish to ensure that the tasks are properly carried out.

THERMAL TASKS

Since the primary goal of the thermal program is meeting equipment reliability objectives, every thermal task has its roots in the reliability requirements imposed on the equipment. Table 2–1 lists the basic reliability tasks specified by MIL–STD–785 and identifies the thermal tasks that are implicit in each of them.[2-1]

TABLE 2–1. THERMAL TASKS IMPLICIT IN RELIABILITY TASKS OF MIL–STD–785

MIL–STD–785 Task		
Number	**Title**	**Implied Thermal Tasks**
100	**Program surveillance and control**	
101	Reliability program plan	Define thermal tasks.
103	Program reviews	Monitor thermal program.
104	Failure reporting, analysis, and corrective action system (FRACAS)	Thermal and reliability engineers collaborate.
105	Failure review board (FRB)	Review failures suspected of having thermal causes.
200	**Design and evaluation**	
203	Reliability predictions	Provide part temperatures for use in predictions.
208	Reliability critical items	Provide part temperatures resulting from thermal environments.
209	Effects of functional testing, storage, handling, packaging, transportation, and maintenance	Provide part temperatures.
300	**Development and production testing**	
301	Environmental stress screening (ESS)	Develop and implement screening burn-in procedures.
302	Reliability development growth/test (RDGT) program (also known as test-analyze-and-fix (TAAF))	Ensure test realism; participate in performance monitoring, failure detection, failure analysis, and corrective action.
303	Reliability qualification test (RQT) program	Ensure test realism.
304	Production reliability acceptance test (PRAT) program	Ensure that the operating temperatures will be within specified tolerances.

A clearer picture of what a thermal program should include, however, can be gained by breaking out the individual thermal tasks in the order in which they are typically performed. MIL-STD-785 divides the period from the inception of an acquisition program to acceptance of the last system to be delivered into four phases:

- Conceptual
- Demonstration and Validation
- Full-Scale Engineering Development
- Production.

The paragraphs that follow trace the thermal tasks that would be performed during each of these phases in an example of a comprehensive thermal program.

TABLE 2-2. THERMAL TASKS IN CONCEPTUAL PHASE

- Define thermal design requirements.
- Determine equipment reliability or life-cycle cost objectives.
- Identify possible alternative thermal designs.
  1. Evaluate alternative solutions by thermal analyses and developmental tests.
  2. Perform cost-versus-risk analysis for alternatives.
  3. Select candidate solutions.
- Submit Thermal Design Report before Design Review.

Conceptual Phase

Thermal management begins at the Procuring Activity with the derivation of thermal environment and performance criteria (see Table 2-2). This effort culminates in the baseline requirements and other essential thermal design information to be included in the equipment specifications that will be given to the contractors and subcontractors who will be bidding on the program. (Table 2-3 lists the items typically included.) The requirements, it might be noted, should be based on availability and life-cycle cost objectives, although regretably this is often not done.

TABLE 2-3. BASELINE THERMAL REQUIREMENTS

The following items should typically be included in the baseline thermal requirements of each equipment specification:

1. Maximum junction temperatures and derating criteria.
2. Thermal environments in which the equipment is required to operate.
   a. Ambient and/or surrounding temperature extremes
   b. Pressure/altitude extremes (for airborne equipment)
   c. Rates of change of ambient temperature and pressure/altitude (for airborne equipment)
   d. Radiation environment (for radiatively-cooled equipment)
   e. Solar and other infiltrating heat loads
   f. Ambient air velocity (for free-convection-cooled equipment)
   g. Cold plate or structure characteristics, i.e., mounting surface temperature as a function of power dissipation (for equipment using constant-temperature mounting surface supplied by system contractor)
   h. Coolant type, flow rate, supply temperature, and allowable pressure drop (for equipment using coolant supplied by system contractor)
3. Government specifications. Be sure to reference those particular sections that are directly applicable to the specific system being acquired.
4. Mission profile and duration; test mission duration, if different.
5. Design constraints on cooling system.
   a. Type and amount of power available for pumps and blowers (for forced-convection-cooled equipment)
   b. Noise and vibration limits (for forced-convection-cooled equipment)
   c. Maximum allowable air exhaust temperature (for forced-air-cooled equipment)
   d. Available envelope
   e. Weight limits

Having received a contract for this phase of the program, the successful bidder identifies and systematically evaluates the various alternative thermal design solutions or solution concepts, using a realistic set of evaluation criteria. A cost-versus-risk trade-off analysis is an essential part of the evaluation. In some instances, thermal testing may be undertaken to verify the validity of a concept.

The results of this work are documented in a Thermal Design Report which is submitted to the Procuring Activity before the Design Review.

Naturally, the qualifications of the personnel engaged in the conceptual phase of a program are critical. Involving only simple computer models (or hand calculations), the analysis relies primarily on experience. Consequently, thermal analysts with broad backgrounds of practical experience are essential for this phase. Later on in the program, these same people can lead a team of less experienced analysts in performing the various subtasks of standard detailed analyses.

Demonstration and Validation Phase

In this phase (see Table 2-4), several candidate solutions, selected from those considered in the conceptual phase, are refined through more rigorous evaluations. A preferred solution is selected, and other solutions are designated as backups.

Part temperatures are then predicted by performing thermal analyses such as those described in Chapter 8. When appropriate, developmental testing is also performed.

On the basis of the accurate temperature predictions and measurements that have been made, life-cycle costs are predicted.

Design optimization studies are then undertaken to minimize these costs by modifying circuit design, part selection, and part placement so as to reduce part temperatures and thereby increase reliability. (Available automated optimization techniques are described in Chapter 8.) Such changes generally result in trade-offs of two types:

- Electrical circuit performance traded for increased reliability.
- Design and manufacturing costs traded for reduction in operation and maintenance costs.

TABLE 2–4. THERMAL TASKS IN DEMONSTRATION AND VALIDATION PHASE

- Refine candidate thermal design solutions by performing detailed thermal analyses and developmental tests.

1. Perform trade-off analysis of candidate solutions.
2. Select preferred solution and document other candidate solutions for use as backups for the preferred solution.
3. Justify the preferred solution by detailed thermal analysis and/or testing.
4. Determine thermal stresses on basis of predicted equipment temperature for preferred solution.
5. Perform life-cycle cost optimization studies.

- Submit Thermal Design Reports before Design Reviews.

TABLE 2–5. THERMAL TASKS IN FULL–SCALE ENGINEERING DEVELOPMENT PHASE

- Verify thermal design through analysis and tests simulating operating conditions.
  1. Prepare Thermal Test Plan including the following:
     a. what the test verifies
     b. detailed description of tests
     c. instrumentation
     d. test schedule.
  2. Submit Thermal Test Plan before Test Readiness Review.
  3. Perform test.
  4. Evaluate test data.
- Develop screening/burn-in procedures and apply to hardware:
  a. thermal profiles
  b. design of apparatus
  c. instrumentation.
- Submit Thermal Test Reports before Design Reviews.

TABLE 2–6. THERMAL TASKS IN PRODUCTION PHASE

- Verify that operating thermal characteristics of the equipment are within specified tolerances of design values.
  1. Specify tolerances.
  2. Develop Acceptance Test Procedures.
  3. Perform acceptance tests.
- Implement screening/burn-in procedures and adapt to hardware and schedule.

Results of the analyses made during this phase are documented in thermal design reports submitted to the Procuring Activity before the various design reviews.

Full-Scale Engineering Development Phase

In this phase, thermal analyses and tests are performed to verify the thermal design. Thermal analysis and testing are described in Chapters 8 and 9, respectively.

Although the reliability engineer is responsible for specifying the test requirements and generating the test plan, the thermal engineer should also participate in this work. After a thorough evaluation of the test results, the thermal adequacy of the design is assessed.

The system or equipment also is tested under conditions of the specified mission profiles, per MIL-STD-781[2-24] (see Table 2-5). The tests are usually performed on a full-scale engineering model nearly identical to the production model.

The thermal and reliability engineers also collaborate in developing thermal screening and burn-in procedures, as described in Chapter 10. The reliability engineer specifies the limits of the thermal stresses to which the equipment is to be subjected. The thermal engineer ensures that: (1) the thermal profiles are implemented properly, (2) the thermal designs of the screening setups are adequate to produce the required thermal stresses, and (3) the part temperatures will be correctly measured. These efforts should be coordinated with the responsible engineering authority and production engineering.

Production Phase

As Table 2-6 indicates, the objective of the thermal program in this phase is primarily quality assurance. The reliability engineer, in concert with the thermal engineer and production personnel, establish thermally acceptable production tolerances. Then they establish means of verifying that the production hardware will operate within the tolerances.

In the event that changes in hardware design, fabrication processes, or materials are made during the production phase, the changes should be reviewed by the thermal engineer before implementation to make sure they will not degrade reliability.

GETTING THE THERMAL TASKS DONE PROPERLY

There are two avenues through which the reliability engineer of the Procuring Activity can make sure that the thermal tasks on a program are properly carried out: the Request for Proposal (RFP), and the mechanisms set up for monitoring the program.

Preparing the Request for Proposal

Within the various elements of the RFP, the following thermal requirements should be included.

Instructions to Bidders. These instructions should specify that the bidder's proposal include a thermal treatment containing as a minimum the items listed in Table 2–7.

Statement of Work (SOW). The SOW should specify that the contractor establish a properly planned, funded, and staffed thermal program.

Equipment Specification. The specification should include the baseline thermal requirements and essential design data itemized earlier in Table 2–3.

Contract Data Requirements List (CDRL). The CDRL should contain specific thermal items.

These items may be included either separately or as part of a more general reliability data item (see Table 2-8). If they are hidden within another CDRL item, it is important to make sure that they receive proper attention. To avoid generating new Data Item Descriptions (DIDs), it is recommended that the reliability DIDs be modified to include the thermal items. Sample wording is provided in the panel below.

TABLE 2–7. THERMAL PORTION OF THE PROPOSAL

The thermal portion shall include, as a minimum:

1. Identification of all thermally related issues and risks.
2. How the supplier proposes to resolve issues and risks, including as a minimum:
   a. thermal analyses to be performed
   b. trade-off studies to be performed
   c. tests to be performed
   d. schedule in which each task is started and completed
   e. manner in which the tasks are to be monitored.
3. Reporting and type of documentation.
4. Identification of the portion of the total resources allocated to the thermal design.
5. Organization, including:
   a. key personnel and qualifications
   b. relationships between thermal management, reliability management, and other key program personnel.

For this contract, Data Item Description No. DI-R-7082, "Reliability Predictions Report," is modified to add the following item: The junction and hot-spot temperatures listed in the Reliability Predictions Report shall be obtained from a detailed thermal analysis, conducted down to the part level. The Report shall include:

1. description of the equipment analyzed (assembly drawing numbers, dates)
2. sources of estimates of part dissipations
3. thermal resistances (values used, assumptions, coolant flow rates)
4. sources of estimates of sink temperatures
5. analysis method.

TABLE 2-8. THERMAL DATA ITEMS

Thermal Data Item	When Typically Delivered		Reliability Data Item(s) in Which the Thermal Data Item Can Be Cited (See MIL-STD-785B, p. A-31)		Table(s) in Which Contents Are Described
	Program Phase	Milestone	Number	Title	
Thermal Program Plan	CONCEPT	Proposal	DI-R-7079	Reliability Program Plan	2-7
Thermal (Preliminary) Design Report	CONCEPT or VALID	Preliminary Design Review	DI-R-7080	Reliability Status Report	2-2, 2-9
			DI-R-7082*	Reliability Predictions Report	
Thermal (Detailed) Design Report	VALID or FSED	Critical Design Review	DI-R-7080	Reliability Status Report	2-4, 2-9
			DI-R-7082*	Reliability Predictions Report	
Thermal Analysis Report	VALID or FSED	Critical Design Review	DI-R-7082*	Reliability Predictions Report	Panel on p. 9
Thermal Test Plan	FSED	Test Readiness Review	DI-R-7080	Reliability Status Report	2-5
			DI-R-7033	Plan, Reliability Test	
Thermal Test Report	FSED	Design Review	DI-R-7080	Reliability Status Report	2-5
Thermal Aspects of Screening/Burn-in Procedures	FSED	Design Review Production Readiness Review	DI-R-7080	Reliability Status Report	2-5
			DI-R-7040	Report, Burn-in Test	
Thermal Aspects of Acceptance Test Procedures	PROD	Production Readiness Review	DI-R-7035	Procedures, Reliability Test and Demonstration	2-6
Thermal Portions of Progress Reports	Periodically	Regular Intervals; For Example, End of Month	DI-R-7080	Reliability Status Report	2-9

*DI-R-7095, "Reliability Prediction and Documentation of Supporting Data" is often required in lieu of DI-R-7082.

These guidelines apply not only to the Government but also to reliability engineers in prime contractor and subcontractor organizations. If thermal tasks have not been specified, the contractor reliability engineer should ensure that they are included in the overall program.

Monitoring the Program

The primary tool for monitoring the thermal program is the Formal Design Review. Normally there are four of these reviews:

- Preliminary Design Review
- Critical Design Review
- Test Readiness Review
- Production Readiness Review.

Subjects to be covered in each of these reviews are briefly outlined in Table 2-9.

TABLE 2-9. MONITORING THE THERMAL MANAGEMENT PROGRAM

Program Reviews	Additional Monitoring Methods
Preliminary Design Review Results of studies and investigations of alternative design concepts and problem solution concepts shall be presented. The candidate solutions shall be discussed and justifications for the selection of the candidate solutions shall be presented. All conclusions reached during the investigations shall be substantiated by thermal analysis and/or tests and submitted to the Procuring Activity. *Critical Design Review* The results of detailed thermal design analysis and development testing shall be reviewed. Justification for the selection of the preferred solution shall also be presented. A Thermal Analysis Report, supporting the thermal adequacy of the design, shall be submitted to the Procuring Activity. *Test Readiness Review* The Thermal Test Plan for thermal testing to be performed during the full-scale engineering development phase shall be reviewed and critiqued. Appropriate additions and/or modifications shall be made and implemented. *Production Readiness Review* The thermal analysis and test results shall be evaluated to assess whether the design meets the thermal/reliability requirements and objectives of the program.	*Progress Reports* The progress reports submitted to the customer should report the status of the program and include results of the latest analyses, studies, and investigations. Substantiating data, such as preliminary thermal analysis or preliminary thermal test reports, should be submitted with the report. *Internal Design Reviews* Internal design reviews should be held before each formal program review. The material to be presented should be reviewed and critiqued rigorously, so that the thermal issues discussed at the formal reviews are minimized. *Review of Design Changes* Proposed design changes related to thermal design, reliability, and circuit design are reviewed by all affected parties before implementation.

TABLE 2–10. QUESTIONS TO BE ADDRESSED AT REVIEWS

The following questions should be addressed at program reviews:

- Early design phase involvement of thermal engineer?
- Thermal environment tailored to the application?
- Part dissipations minimized and known accurately?
- Cooling technique appropriate for dissipation density, sink temperatures, etc?
- Parts placed and laid out to maximize reliability?
- Parts mounted to minimize operating temperatures?
- Blowers selected and installed properly, and blower noise considered?
- Coolant flow passages designed to enhance cooling of parts and to minimize pressure drop?
- Reliability predictions based on appropriate, accurately evaluated part temperatures?
- Thermal tests realistic, instrumented adequately, interpreted correctly?
- Screening done at most cost-effective level of assembly?
- Thermal parameters of screening procedures appropriate for program?
- Thermal survey performed beforehand?
- Part temperatures measured during screening?
- Method established to ensure that operating temperatures of delivered equipment will be within specified tolerances?

At these reviews government or contractor reliability engineers can help to prevent omissions in the thermal program or errors in the thermal design by asking appropriate questions. Table 2–10 is a checklist of such questions.

In addition to the Formal Design Reviews, other valuable tools for monitoring the thermal program are progress reports, interim design reviews, and the review of design changes. Guidelines for the employment of these monitoring tools are included in Table 2–9.

SUMMARY

Thermal management begins at the Procuring Activity with the baseline thermal requirements in the equipment specification and the tasks and monitoring methods expressed in the Statement of Work. The proposal provides a means of evaluating the thermal approach and qualifications of the candidate contractor or subcontractor. Thermal tasks are performed during the conceptual, demonstration and validation, full-scale engineering development, and production phases. The thermal management program is monitored by program reviews, progress reports, internal design reviews, and contract deliverable data.

CHAPTER 3
TAILORING OF THERMAL MANAGEMENT PROGRAMS

The preceding chapter outlined the tasks that would be performed in an ideal, comprehensive thermal management program. In some instances, certain of the tasks and procedures outlined either are not applicable to the particular equipment that is being developed or are not cost-effective. When that is so, the thermal program must be tailored to the development program. While effective tailoring can result in substantial cost savings, improper tailoring can be costly. This chapter discusses the various methods of tailoring and the pitfalls to be avoided in their use.

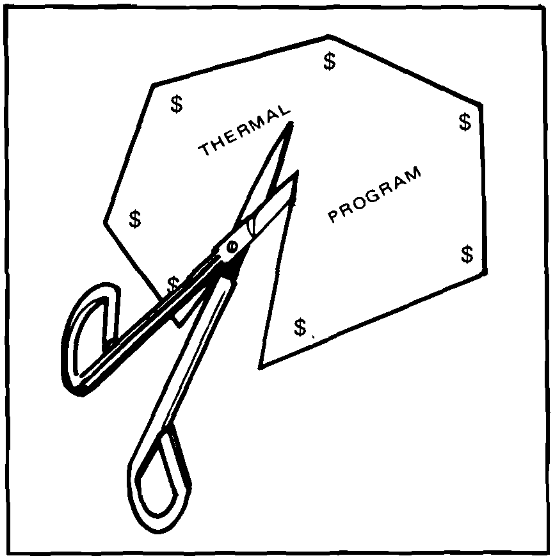


Figure 3-1. Tailoring can trim the cost of a detailed thermal program.

THE TRADE-OFF INVOLVED IN TAILORING

In most cases, tailoring involves a trade-off between cost savings and risk—the savings that may be realized in the cost of the thermal program; the risk of overlooking a deficiency in thermal design. As the cost is reduced, the risk grows increasingly (see Figure 3-2).

The crux of successful tailoring, therefore, is correctly assessing the risk. Evaluating it is invariably imprecise and subjective. Nevertheless, if the correct method of tailoring is chosen and it is judiciously applied by an experienced engineer, the cost of a sound thermal program can be substantially reduced without incurring an appreciable risk.

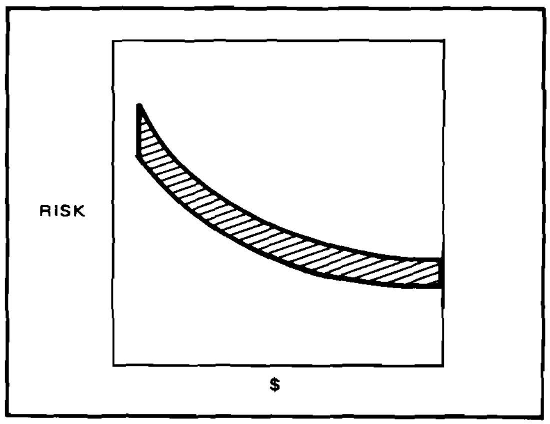


Figure 3-2. Tailoring is an economic trade-off.

TAILORING METHODS

Over the years, four basic methods of tailoring have proved to be highly effective (when properly used) and so are recommended here. They include: (1) overdesign of the cooling system, (2) concentration on thermally sensitive and/or high-dissipation parts, (3) verification that operating temperatures fall within conservative upper limits, and (4) analysis by comparison with similar hardware.

Tailoring Method 1—Overdesign the Cooling System

In some applications, it may be feasible to avoid an extensive thermal program simply by overdesigning the cooling system. For example, cooling of ground-based electronic equipment might be accomplished with one or more large blowers, as shown in Figure 3-3. Applications in which power consump-

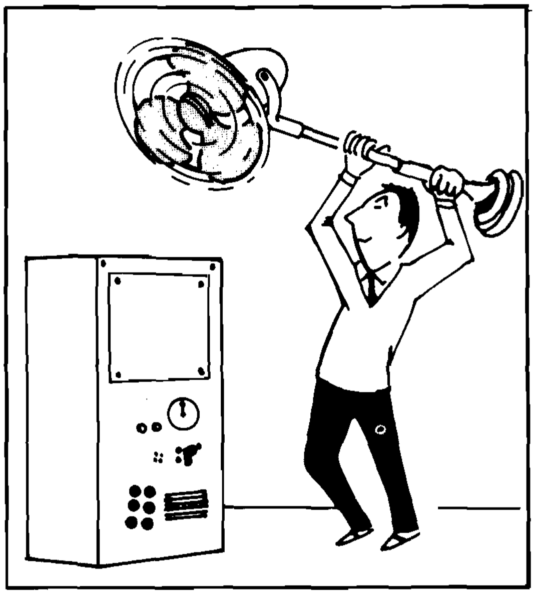


Figure 3-3. Overdesigning the cooling system can save the cost of thermal design analysis and test. However, there might be "hot spots," even with a large cooling system.

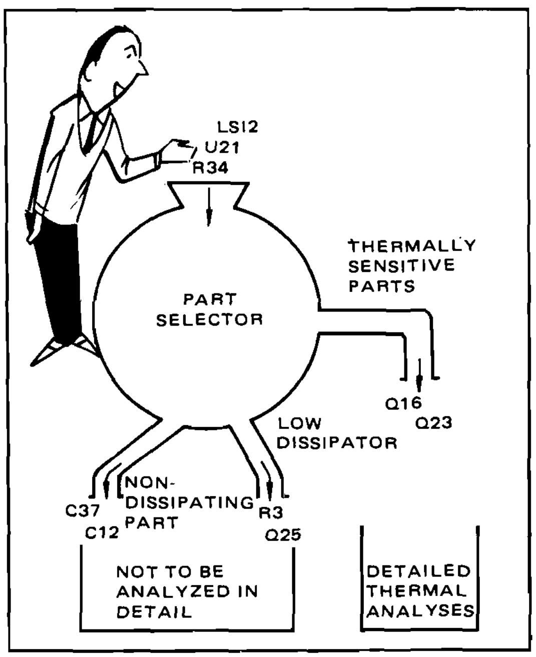


Figure 3-4. Concentrating on thermally sensitive parts can reduce the cost of thermal design and analysis, but some thermally sensitive parts might be overlooked.

tion, weight, and volume are not critical make good candidates for this tailoring method. The cost of the extra cooling capacity may be a small fraction of the total system cost, and possibly a good deal less than the cost of a detailed thermal program.

This method, of course, has its pitfalls. If the blowers are added without due consideration for individual cooling requirements, the cooling system may very well turn out to be inadequate, rather than overdesigned. For example, some parts in units that are cooled by free or forced convection of air may be located in stagnant zones, and even with large blowers, parts having high power dissipations may overheat unless the air is ducted over them. Also, the reliability of the motors and blowers, as well as possible problems due to acoustic and radio noise (electromagnetic interference), must be considered.

Tailoring Method 2—Concentrate on Thermally Sensitive and/or High-Dissipation Parts

In some programs, detailed thermal studies need to be performed only on certain sensitive groups of parts. For example, part temperature predictions could be made only for the semiconductor devices (discrete semiconductors and microelectronic devices) in a given unit. Concentrating on such parts could save the expense of thermal analysis of the other parts, possibly numbering into the thousands. Whole blocks of nonsensitive parts could be assigned an average temperature. Or, if they are an insignificant portion of the lot, they could be overlooked altogether. This approach can be especially justified when these other parts are non-dissipating (e.g., capacitors and connectors).

The risk of this tailoring method is that one or more potential thermal problems may be overlooked. The risk is especially great in equipment containing high-dissipation parts.

Often a viable alternative or a complementary approach is to concentrate on high-dissipation parts such as semiconductors and resistors (as shown in Figure 3-4). These may become excessively hot or cause temperature-sensitive parts to fail, unless special measures are taken to remove the heat.

Tailoring Method 3—Verifying That Operating Temperatures Fall within Conservative Limits

In situations where the equipment will be operating in a particularly benign environment or where the parts are grossly understressed, a detailed thermal analysis may not be necessary. All that is required then is to verify that the operating temperatures of the critical parts will indeed fall within conservative upper limits.

For example, data exist that enable maximum acceptable temperatures to be assigned for certain types of parts in some applications. Figure 3-5 shows various temperature levels for a semiconductor having a maximum operating junction temperature of 175°C. Experience has shown that, in a certain standard space flight environment and for a certain standard mission duration, the mean time to failure will be significantly longer than the mission duration if the junction temperatures are less than 100°C. Therefore, if the junction temperature of a specific part of this type can be shown by an inexpensive thermal analysis to be less than 100°C, then a detailed thermal analysis may be unnecessary.

The risk of this method is that such a universal criterion might be inappropriate to the particular application. In other words, the mission duration and electrical stress could be different than those upon which the criterion is based.

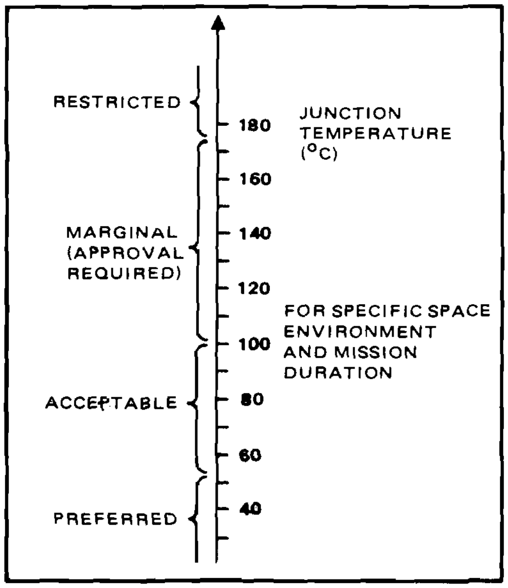


Figure 3-5. Cost of a thermal program can be reduced by verifying that conservative temperature limits will not be exceeded, as in this example.

Tailoring Method 4—Analyze by Comparison with Similar Hardware

Often the hardware being developed is a slight modification of hardware developed in a previous program or employs standard modules (see Figure 3-6). If the earlier hardware has proven to be reliable in the field or has been predicted to be thermally adequate in the previous program, the new thermal program can be tailored to cover only the differences between the original and new hardware. A relatively inexpensive thermal analysis may suffice to show that the new parts will operate cooler than the previous ones or hotter by no more than an acceptable amount.

The risk of such a cursory analysis is that significant differences between the two designs might be overlooked. Key factors to consider are part dissipations and mounting techniques.

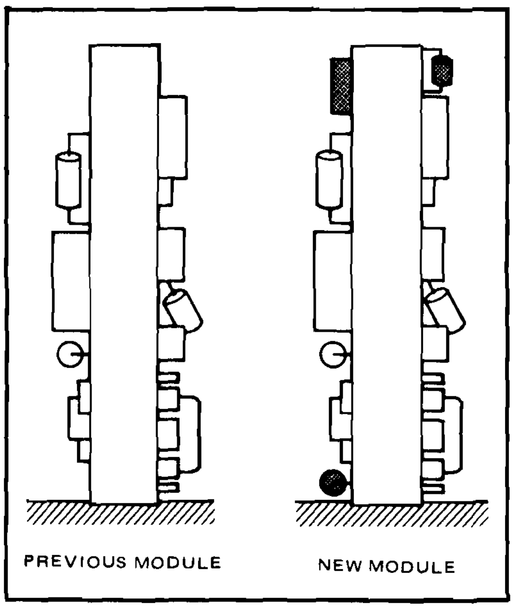


Figure 3-6. Comparison with previous hardware can reduce the scope of the required thermal analysis, but a cursory analysis might overlook significant differences.

Other Tailoring Methods

There are, of course, other forms of tailoring. In fact, virtually every thermal program involves some degree of tailoring. Putting an experienced thermal engineer on the job, for example, will in itself enable certain cost-saving shortcuts to be taken. Then, too, not all tailoring is aimed at scaling down the thermal program. Where a human life or the success of a critical mission depends on the reliable operation of the equipment being developed, the thermal program may be tailored up, rather than down.

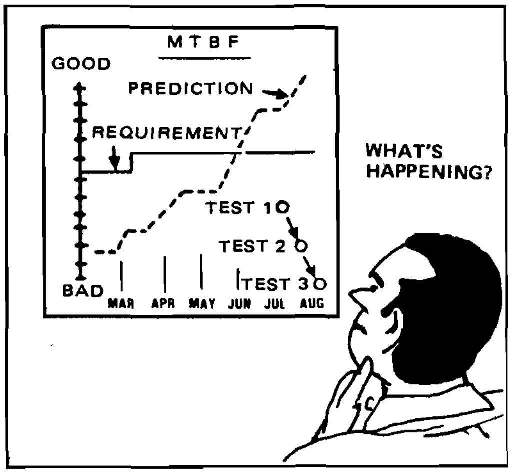


Figure 3-7. Waiving thermal analyses and tests can result in expensive failures in the field.

THE DANGER IN WAIVING THERMAL ANALYSES AND TESTS

All too often, thermal analyses and tests are omitted with no justification other than a belief that money will be saved. This practice is mentioned here only to warn the reliability engineer and program manager against employing it.

The cost of sound thermal analysis is only a small fraction of the total cost of a military electronics program. And thermal analysis often uncovers potential reliability problems at the outset, when they can be corrected inexpensively. Invariably the cost of corrective action after hardware is built far exceeds the cost of whatever original thermal analyses would have been necessary to obviate such action.

The importance of thorough thermal tests is illustrated by the results of a 1971 study by the Air Force Flight Dynamics Laboratory.[3-2] It revealed an almost one-to-one correspondence between waiver of environmental requirements or tests and subsequent severe environmental problems in the field (see Figure 3-7). Regardless of time or cost, environmental testing is an essential part of any reliability program. It is not a wise "money-saving" shortcut. The penalties in life-cycle cost and availability can dwarf any development cost savings.

SUMMARY

Tailoring of thermal management programs can provide a less costly, shortcut approach for implementing thermal/reliability design into a program. Recommended methods for tailoring include overdesigning the cooling system, concentrating on thermally sensitive or high-dissipation parts, verifying that operating temperatures fall within conservative upper limits, and analyzing by comparison with similar hardware. These methods offer substantial benefits with some risk. Waiving thermal analysis and testing is extremely risky and is not recommended.

PART II—EVALUATION

CHAPTER 4
IMPACT OF TEMPERATURE ON RELIABILITY

Inadequate thermal design is presently one of the primary causes of poor reliability in military electronic equipment. Thermal considerations are, therefore, extremely important. This chapter describes the effect of temperature on failure rates of electronic parts and assemblies, explains the causes of thermally induced failures, and outlines the cost benefits to a program of proper thermal design.

TEMPERATURE EFFECT ON FAILURE RATE

High temperature is an enemy of most electronic parts. It causes slow progressive deterioration that eventually results in catastrophic failure. The time to failure of each part is a statistical function of its stress level and the complex interrelationship of thermal history and chemical structure. The failure of individual parts leads to equipment failure.

Parts

A common source for reliability predictions of military electronic parts is MIL-HDBK-217.[4-1] Table 4-1 shows that the predicted failure rate for eight of the 14 major part categories in the handbook depends on temperature.

The predicted temperature effect on part failure rates is illustrated in Figure 4-1. The parts, one each from five of the major part categories, were selected randomly from those employed in an actual fighter aircraft radar set. The failure rates are seen to increase approximately exponentially with increasing temperature.

Assemblies

As a tool for estimating the expected reliability improvement due to lower temperatures, graphs were developed for various electronic-assembly types under different environmental conditions. The types of assemblies were selected to highlight the different levels of reliability improvement attributed to different part-type populations. The sample electronic assemblies and their part-type populations are shown in

TABLE 4-1. MAJOR PART CATEGORIES IN MIL-HDBK-217

* Microelectronics
* Discrete semiconductors
Tubes
Lasers
* Resistors
* Capacitors
* Inductive devices
* Rotary devices
* Relays
Switches
* Connectors
Wire and printed wire boards
Connections
Miscellaneous

* Temperature dependence in failure-rate formula

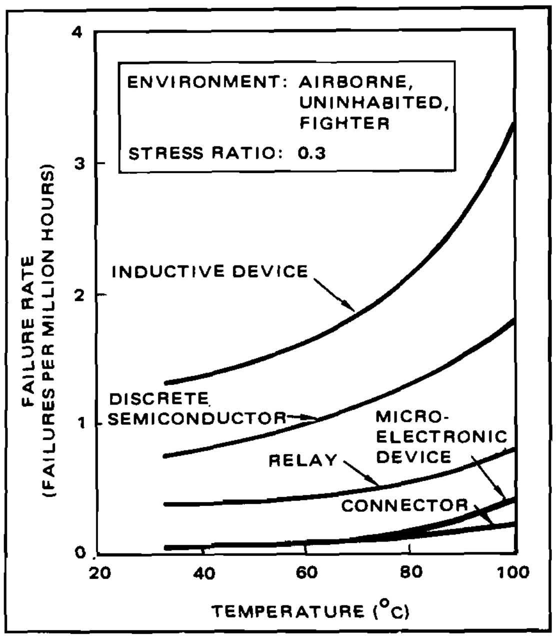


Figure 4-1. Failure rates are accelerated by high temperatures.

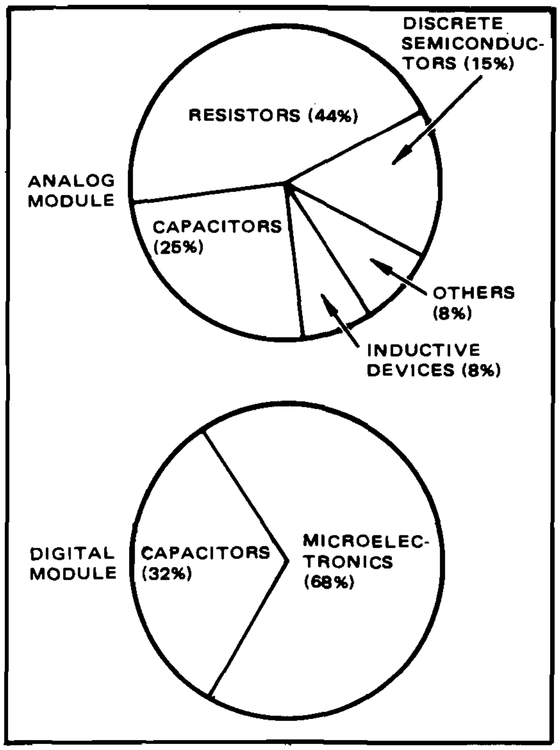


Figure 4–2. Analog and digital equipment have quite different part-type populations.

Figure 4–2. Figure 4–3 shows the effect of different environments on the reliability of a given electronic assembly. As defined in MIL-HDBK-217, the environments are airborne, uninhabited, fighter (A_{UF}); airborne, inhabited, fighter (A_{IF}); ground, fixed (G_F); and ground, benign (G_B).

The basis for the graphs was predicted failure rates from MIL-HDBK-217C, Notice 1. The prediction assumes that each part operates at the same stress ratio and temperature.

No two electronic assemblies are alike; therefore these figures should be used only for a qualitative idea of the effect of temperature on failure rate.

Field Experience

The predicted dependence of failure rate on temperature has been observed in the field. For avionic equipment, Air Force studies concluded that 20 percent of field failures are caused by temperature effects.[4-2] A recent study of avionic equipment concluded that the reliability of equipment cooled by free convection is sensitive to temperature and that the reliability of more complex equipment using flow-through forced-convection cooling is even more sensitive to temperature, as shown in Table 4–2.[4-4]

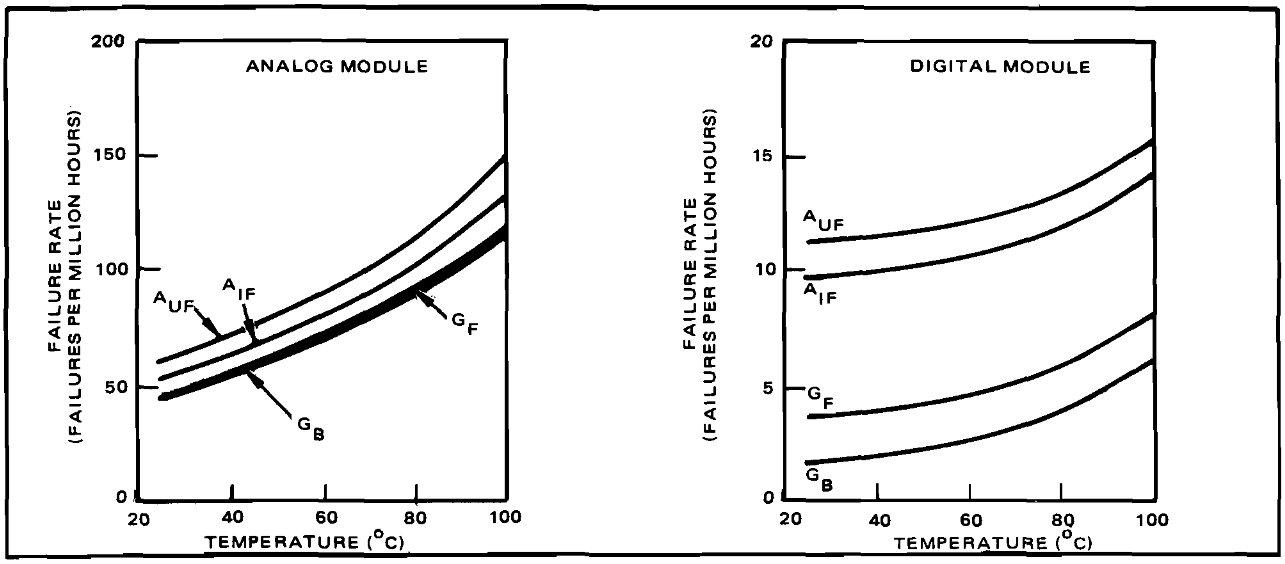


Figure 4–3. The relationship of reliability to temperature depends on the part-type population and the environment.

THERMALLY INDUCED FAILURE MODES

Many failure modes, including those listed in Table 4-3, involve changes in the chemical composition or physical structure of the electronic device. The rate of these chemical reactions or physical changes increases with increasing temperature. Thus, operation at high temperatures increases the failure rate, or decreases the mean time between failures, by accelerating the rate at which these undesired changes occur.

Conversely, does this mean that the colder a part operates, the lower its failure rate will be? Down to temperatures near room ambient, the answer is "yes." But at very low temperatures, the answer is "no." As the temperature decreases below room ambient, the reaction rates slow down, tending to decrease the failure rate. However, adverse effects begin to occur, including: (1) embrittlement of materials,

TABLE 4–2. IMPROVEMENT IN FIELD RELIABILITY OF AVIONIC EQUIPMENT BY TEMPERATURE REDUCTION

Equipment	Percent Decrease in Field Failure Rate per °C Temperature Decrease (%/°C)
C–141 aircraft	
Forced-convection-cooled	4
Free-convection-cooled	1.5
Commercial aircraft	2–3

TABLE 4–3. TEMPERATURE EFFECTS ON AVIONIC EQUIPMENT

Condition (Type)	How Manifested	Principal Effect	Probable Failure Mode
Steady state—hot	Ambient exposure Equipment-induced Mission-induced (certain steady state phases)	Aging—discoloration Insulation deterioration Oxidation Expansion Reduction of viscosity Softening—hardening Evaporation, drying Chemical changes Cracking—crazing	Alteration of properties Shorting Rust Physical damage, increased wear Loss of lubrication, seizing Physical breakdown Dielectric loss
Steady state—cold	Ambient exposure Mission-induced for certain phases and certain equipment	Contraction Viscosity increase Embrittlement Ice formation	Wear, structural failure, binding Loss of lubricity Structural failure, cracked parts Structural failure, alteration of electrical properties Loss of resilience—seal leaks
Thermal cycling	Ground operation Mission operation and environmental control system limits	Temperature gradients Expansion-contraction	Repeated stress variation causes mechanical failure of parts, solder joints, and connections; lifting of microcircuit chips from base material; and delamination
Thermal shock	Mission profile Geography and season	High temperature gradients	Mechanical failure Cracks Rupture

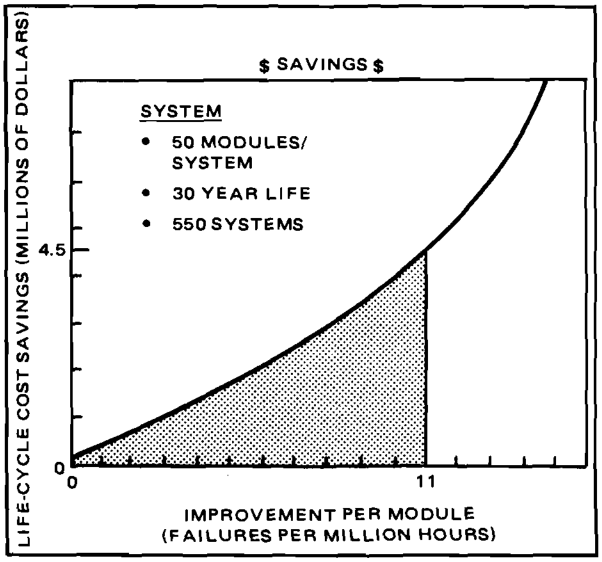


Figure 4-4. Optimized thermal/reliability designs can produce savings in system life-cycle cost.

(2) thermal stresses resulting from differential thermal contraction of dissimilar materials, and (3) shorting and corrosion caused by condensed water trapped within the encapsulation. Thus failures are accelerated at very low temperatures, as well as at very high temperatures.

The rate of these failure processes has an exponential dependence on temperature, known as the Arrhenius relation. The failure rate of parts increases exponentially when operated at very high temperatures. However, the dependence is not this simple, because other failure modes (e.g., those due to vibration) occur simultaneously with temperature-induced failures.

COST BENEFITS OF GOOD THERMAL DESIGN

Improvement of equipment cooling can improve reliability and thereby produce significant savings in system life-cycle cost. In terms of decreased field support cost, the benefits of good thermal design during equipment development far outweigh the additional acquisition cost.

An example of cost-effective thermal design is the arrangement of parts on a circuit board to maximize reliability by minimizing the temperatures of sensitive parts. A Hughes Aircraft Company study of a typical avionic system concluded that, if the system were redesigned in this way, the failure rate of each module would decrease by an average of 11 failures per million hours. As shown in Figure 4-4, the resultant savings in life-cycle cost would be $4.5 million.[4-20] Other studies cited in Appendix F have reached similar conclusions.

SUMMARY

Failure rates of parts increase approximately exponentially with increasing temperature. Inadequate cooling often is considered the primary cause of poor reliability in military electronic equipment and has been observed to cause approximately 20 percent of all field failures of avionic equipment. Good thermal design can substantially improve reliability and thereby produce significant savings in system life-cycle cost.

CHAPTER 5
HEAT TRANSFER PRINCIPLES

To fully appreciate electronic equipment cooling techniques, an understanding of heat transfer principles is necessary. This chapter discusses those principles.

FUNDAMENTAL CONCEPTS

Temperature

Temperature is a measure of how hot or cold an object is. In physical terms, the temperature of an object is a measure of its energy. The hotter the object is, the greater its energy will be.

Thermal Resistance

Energy, in the form of heat, flows naturally from a hotter region to a cooler one. The greater the temperature difference (ΔT), the greater the heat-flow rate (Q) will be. This relation can be written as

$$\Delta T = \theta Q, \qquad (5\text{-}1)$$

where the proportionality factor (θ) is called the *thermal resistance*. If ΔT is expressed in °C and Q in watts (W), then the units of θ are °C/W.

Dissipation

Electronic equipment requires electrical power to operate. Because the parts are not perfectly efficient, much of the power is converted to heat, which causes the temperature of the equipment to rise. The temperature will continue to rise unless the heat can find a path by which to leave the equipment. The purpose of the cooling system is to provide an effective heat path. Therefore, the most important heat-flow rate is usually the dissipation.

Sinks

In the cooling of equipment, heat must be transferred from the part in which the heat is generated to an *ultimate sink*. This ultimate sink is a heat reservoir, such as a body of land, ambient air, the sky, or the ocean (Figure 5–1). It is the final destination of the heat. Such a heat reservoir can be considered to be infinite. That is, it is so large that the heat trans-

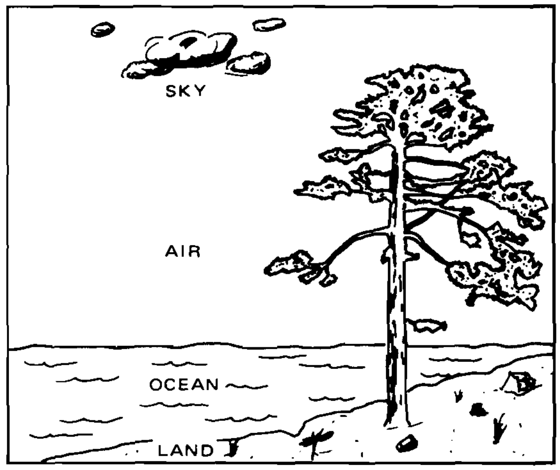


Figure 5-1. Ultimate sinks are the final destination of heat.

TABLE 5–1. FACTORS THAT AFFECT THE OPERATING TEMPERATURE

• Dissipation	• Thermal resistance
• Sink temperature	

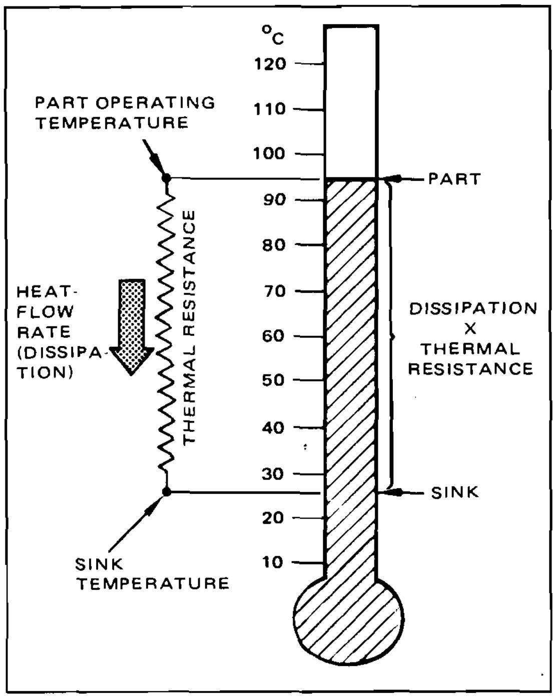


Figure 5–2. The difference between the part and sink temperatures is the product of the part dissipation and the thermal resistance.

TABLE 5–2. HEAT TRANSFER MODES

• Conduction	• Convection
• Radiation	

ferred from the equipment does not produce a significant increase in the reservoir's temperature.

In many applications, the dissipation is transferred to the ultimate sink via a *local sink*. Examples of local sinks are a mounting platform and cooling fluid provided by an environmental control system. In these applications, the local sink temperature, rather than the ultimate sink temperature, is relevant to the electronic unit designer.

To minimize the operating temperature, the thermal designer often mounts parts on metal, commonly called *heat sinks*. These heat sinks improve the effectiveness of the path by which the dissipation is transferred from the part to the ultimate sink.

THE COOLING PROBLEM

With these fundamental concepts, the essence of the problem of cooling electronic equipment can now be described. For a part having a dissipation (Q), a sink temperature (T_S) (which could be the ultimate sink, local sink, or heat sink temperature), and packaged such that the thermal resistance between the part and the sink is θ, the part operating temperature (T_P) is given by Equation (5–1) as

$$T_P = T_S + \theta Q. \qquad (5\text{–}2)$$

Thus the factors that affect the operating temperature can be condensed to those listed in Table 5–1. The lower each of these factors is, the cooler the part will operate.

For a given amount of heat dissipation, it follows from Equation (5–2) that the temperature difference between the part and the sink is proportional to the thermal resistance (see Figure 5–2). Since the temperatures of sinks are usually fixed, minimizing the thermal resistance is the key to minimizing the operating temperature of the part.

MODES OF HEAT TRANSFER

Heat transfer can occur in the three modes listed in Table 5–2. Each mode and its corresponding thermal resistance are described below.

Conduction

Conduction is the transmission of heat by the transfer of kinetic energy from one molecule to another. Conduction can occur in a solid, liquid, or gas and is the only mode of heat transfer occurring in an opaque solid. An example is the transfer of heat to the handle of a metal spoon dipped into a cup of hot coffee.

Conduction is a very important heat transfer mode for electronic equipment. For example, the transfer of heat from the junction to the case of a semiconductor device occurs by conduction. The designer utilizes various portions of the equipment (such as structural members, circuit boards, and leads) as conduction paths. The task is to recognize the available paths and to minimize these thermal resistances.

Thermal Resistance to Conduction. The thermal resistance to conduction (θ_k) is given by

$$\theta_k = L/(kA). \quad (5\text{-}3)$$

The quantities L and A are illustrated in Figure 5-3, and k is the *thermal conductivity* of the material through which the heat flows. To minimize the thermal resistance to conduction of a path, follow the guidelines listed in Table 5-3.

For example, consider an integrated-circuit (IC) flatpack mounted on an avionic circuit board with a thermal-transfer adhesive. At high altitudes, all the IC's dissipation flows through the adhesive bond. If the bond thickness is 7.6×10^{-5} m (3 mils), the flatpack dimensions are 9.5×10^{-3} m $\times$ 0.015 m (3/8 $\times$ 19/32 inch) and the adhesive's thermal conductivity is 0.17 W/(°C-m), then the bond's thermal resistance is

$$\theta_k = \frac{L}{kA}$$

$$= \frac{(7.6 \times 10^{-5}\text{m})}{\left(0.17 \frac{\text{W}}{°\text{C} - \text{m}}\right)(9.5 \times 10^{-3}\text{m})(0.015\text{m})}$$

$$= 3.1 \frac{°\text{C}}{\text{W}}.$$

If the IC dissipation is 1/2 W, then the bottom of the flatpack case will be 1-1/2°C hotter than the top of the circuit board.

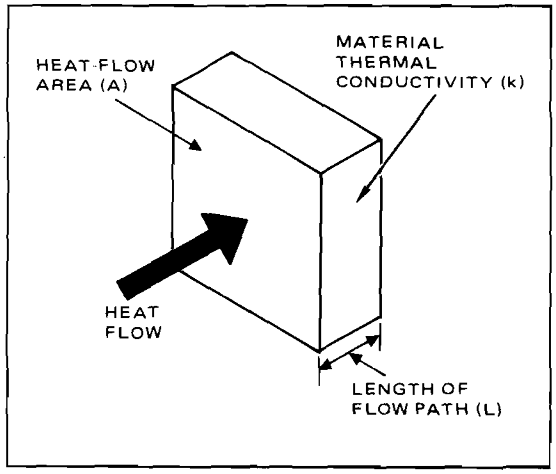


Figure 5-3. The thermal resistance to conduction depends on these parameters.

TABLE 5-3. WAYS TO MINIMIZE THE THERMAL RESISTANCE TO CONDUCTION

• Short path	• Large area
• High thermal conductivity (See Appendix C for typical values)	

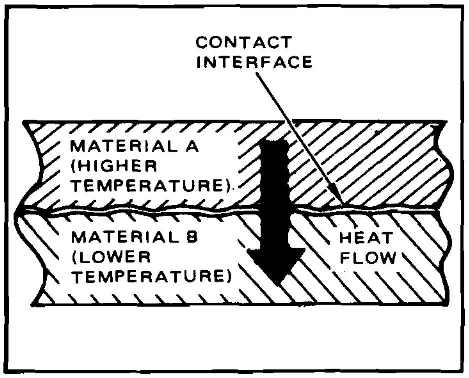


Figure 5-4. An interface between contacting surfaces is a relatively inefficient heat-flow path.

TABLE 5-4. WAYS TO MINIMIZE CONTACT THERMAL RESISTANCE

- Large contact area
- Smooth surfaces
- Soft contacting materials
- High contact pressure (high torque on bolts)
- Uniform contact pressure
- Conductive filler at interface

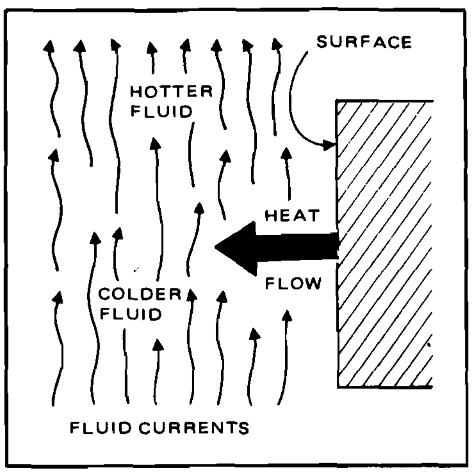


Figure 5-5. In free-convection heat transfer, the difference in density between the hotter fluid at the top and the colder fluid at the bottom causes the fluid to rise.

Contact Thermal Resistance. A special case of heat transfer by conduction occurs when the heat flows across the interface between two contacting surfaces (Figure 5-4). Examples of such interfaces in electronic equipment are bolted interfaces and module guides. Because contact interfaces have relatively high thermal resistances and often are located in regions where the entire dissipation of an assembly flows across them, significant temperature differences can occur across such interfaces. Therefore the designer should minimize the use of such interfaces; when they are used, follow the guidelines in Table 5-4 to minimize the contact thermal resistance.

Junction-to-Case Thermal Resistance. The thermal resistance between the junction and case of a semiconductor device (θ_{JC}) is a key factor in reliability. As an example, for a 54S181 IC flatpack, $\theta_{JC} = 11°C/W$ (referred to the bottom center of the case). If the IC dissipates 1/2 W, then the junction will be 5-1/2°C hotter than the bottom center of the case. Thus the junction will be at least 5-1/2°C hotter than the sink, no matter how low the case-to-sink thermal resistance, since θ_{JC} is a fixed internal resistance.

Convection

Convection is the primary mode of heat transfer between the surface of a solid and a fluid. An example is the cooling one feels when sitting in front of a blower. Heat transfer occurs as a result of the motion and mixing of the fluid which comes in contact with the surface.

In this guide, the resistance to the flow of heat is expressed in terms of the thermal resistance (θ). A widely used term in convection heat transfer is the *heat transfer coefficient* (h), defined by

$$h = Q/(A\Delta T), \tag{5-4}$$

where A is the heat transfer area. The relationship between h and θ is

$$h = 1/(\theta A). \tag{5-5}$$

Low values of θ correspond to high values of h. Magnitudes of h for various cooling techniques are listed in Appendix C.

Convection is commonly used in cooling electronic equipment. The dissipation is first transferred by conduction to a surface in contact with a flowing fluid (local sink), then by convection into the fluid. The fluid then flows to another location, where it transfers the heat to the ultimate sink. Convection processes are classified according to whether the fluid motion occurs naturally (*free* or *natural convection*) or is induced (*forced convection*). Each type of convection heat transfer is described below.

Free Convection. When fluid motion occurs as a result of fluid density differences and temperature gradients, the heat transfer process is called free or natural convection (Figure 5-5). An example is when food is chilled by the cold air (local sink) in a refrigerator. As the fluid comes in contact with the hotter surface, the temperature of the fluid increases. The density of the fluid decreases as its temperature increases, causing the hotter fluid to rise.

Important factors which influence the thermal resistance to free convection include temperature gradients within the fluid and the location and orientation of the surface. Table 5-5 lists guidelines for minimizing the thermal resistance to free convection.

Forced Convection. When the fluid motion is induced by some external force, such as a blower (fan) or pump, the heat transfer process is called forced convection.

Important factors influencing the thermal resistance to forced convection include the type of fluid, its velocity, and the external characteristics of the surface (see Figure 5-6). Table 5-6 lists guidelines for minimizing the thermal resistance. The fluid employed to remove the heat is called the *coolant*. Air is commonly used. Certain liquids having a favorable combination of physical properties are available commercially for use as coolants.

Pressure Drop. When fluid flows over a solid body or inside a duct, the flow is resisted by friction, flow-area restrictions, or sudden changes in direction. As a result, a pressure loss or "drop" occurs, and a blower or pump is required to overcome this pressure drop. The higher the flow speed and the more irregular the surface, the higher the pressure drop. Thus there is a trade-off between minimizing thermal resistance and minimizing the required blower/pump power. Furthermore, blowers and pumps themselves

TABLE 5-5. WAYS TO MINIMIZE THE THERMAL RESISTANCE TO FREE CONVECTION

- Unrestricted fluid current (such as a surface in open air)
- Vertical surface preferable to horizontal
- Small vertical surface dimensions
- Upward-facing surface (if surface must be horizontal)
- Large area

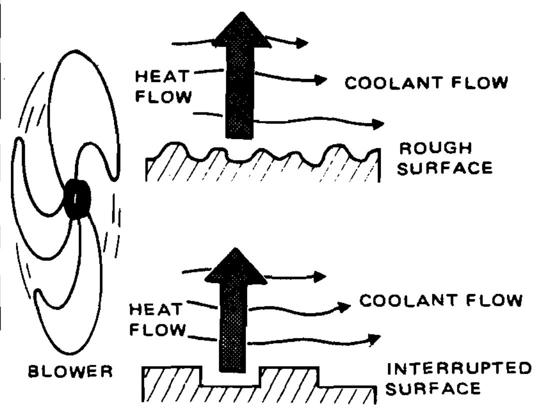


Figure 5-6. Promoting fluid turbulence is an effective way to increase the forced-convection heat transfer coefficient.

TABLE 5-6. WAYS TO MINIMIZE THE THERMAL RESISTANCE TO FORCED CONVECTION

- Liquid preferable to gas
- High flow speed
- Rough or interrupted surface (see Figure 5-6)
- Large area

TABLE 5-7. FREE VERSUS FORCED CONVECTION

Convection Process	Advantages	Disadvantages
Free	Passive	Relatively high thermal resistance
	Simple	Uncontrollable
Forced	Relatively low thermal resistance	Active (requires power to circulate coolant)
	Controllable	Complex

TABLE 5-8. WAYS TO MINIMIZE THE THERMAL RESISTANCE TO RADIATION

- High emissivity
- Good view of the absorber by the emitter (high value of the so-called *view factor*)
- Large areas

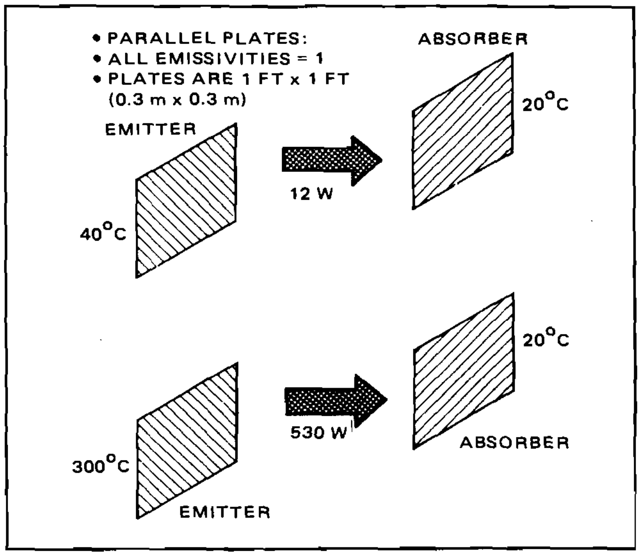


Figure 5-7. The rate of radiation heat transfer is a strong function of the emitter and absorber temperatures.

dissipate heat, which adds to the load on the cooling system. Therefore the geometry of the coolant flow passages and the system pressure drop are important considerations in a forced-convection system. Formulas and data for predicting pressure drop are presented in Appendix C.

Free Versus Forced Convection. The trade-off between free and forced convection is presented in Table 5-7. Rules of thumb for selecting the type of convection process for specific applications are presented in Chapters 7 and 12. The following example demonstrates the relative efficiency of the two types of convection heat transfer. Consider a plate having an area of 1 ft^2 (0.093 m^2) and a temperature of 50°C. The plate is surrounded by air having a temperature of 20°C. The power transferred from the plate to the air by free convection is 10 W. The power transferred by forced convection is more than 30 W; the amount depends on the velocity. For additional information and values used, refer to Appendix C.

Radiation

The only mode of heat transfer that can take place across a vacuum, radiation involves the transfer of photons from a hotter body, the *emitter*, to a cooler body, the *absorber*. An example is the heat one feels when standing next to a fireplace.

Opaque bodies absorb part and reflect the rest of the radiant energy which falls on the surface. The amount absorbed and reflected depends on the surface characteristics of the body, such as color and finish. Perfectly black bodies absorb all the radiant energy, whereas perfectly shiny bodies reflect all energy. The radiation characteristics of a surface are characterized by a dimensionless quantity called the *emissivity*. A perfect absorber and emitter has an emissivity of unity, whereas a perfect reflector has an emissivity of zero. Real bodies have emissivities between zero and one. Emissivities of typical surfaces are listed in Appendix C. Table 5-8 lists guidelines for minimizing the thermal resistance to radiation.

The rate of heat transferred by radiation is low when the difference in temperatures between the emitting and absorbing bodies is small, say 20°C or less, and the temperatures of the bodies are close to normal ambient temperature (25°C). As shown in Figure 5-7, the thermal resistance decreases rapidly as the temperature difference increases, since the heat transfer rate is proportional to the quantity $T_E^4 - T_A^4$, where T_E is the absolute temperature of the emitter and T_A is the absolute temperature of the absorber. The *absolute temperature* is measured relative to absolute zero; in the metric system, it is measured in °K.

ELECTRICAL ANALOGY

Electricity and heat transfer are analogous, as shown in Table 5-9. Thermal resistances are combined in series and in parallel in the same way as electrical resistances.

Usually the thermal resistance from the point of heat generation to the ultimate sink consists of several thermal resistances in series, in parallel, or in combination. Figure 5-8 shows a thermal circuit of a power transistor cooled by free convection to ambient air. The thermal circuit in this example contains thermal resistances in a series/parallel combination.

Thus the minimization of the equivalent thermal resistance of a *thermal network* involves the minimization of the resistance of each series element and maximization of the number of parallel paths. This principle is fundamental for the thermal design of electronic equipment.

HEAT-ADDITION EFFECTS ON COOLANTS

The increase in energy resulting from the absorption of heat can have two effects on a coolant: it can get hotter, or it can change phase. Each effect is discussed below.

The temperature increase of a single-phase coolant as it flows through an electronic system has important reliability implications. The *inlet* coolant temperature is lower than the *outlet* (*exit* or *exhaust*) coolant temperature. As a result, the parts at the inlet end of a module have a lower local-sink temperature than do those at the exhaust end. For this reason, the reliability engineer should urge that temperature-sensitive parts be placed at the inlet end of a module.

Phase-change processes, which occur at constant temperature, include the melting of a solid and the boiling (vaporization) of a liquid. They are used in the cooling of electronic equipment by heat pipes and in applications, such as missiles, where the operating duration of the equipment is relatively short.

TABLE 5-9. ELECTRICAL ANALOGY

Electricity	Heat Transfer
Voltage drop, E	Temperature difference, ΔT
Current, I	Heat-flow rate, Q
Resistance, R	Thermal resistance, θ
E = RI (Ohm's law)	$\Delta T = \theta Q$

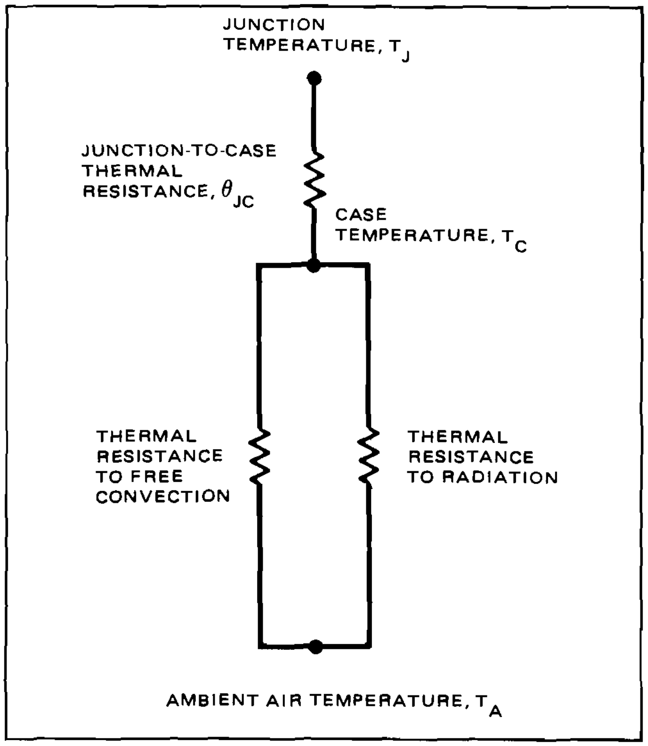


Figure 5-8. The thermal resistance between the junction and the ultimate sink is evaluated in the same way as an electrical network.

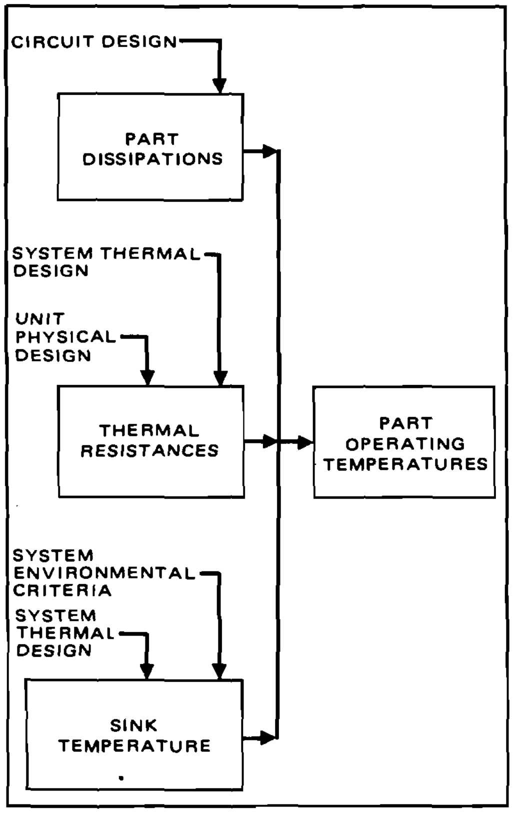


Figure 5-9. Operating temperatures are determined by a variety of aspects of the system design.

SUMMARY

In the cooling of electronic equipment, heat must be transferred from the dissipating part, in which the heat is generated, to an ultimate sink. The thermal resistance between the part and the sink should be minimized to keep the part operating temperature low.

Thermal resistance has different forms, depending on the mode in which heat is transferred. Heat transfer by conduction occurs as a result of the transfer of molecular kinetic energy. Heat transfer by convection occurs by the motion and mixing of a fluid in contact with a surface. Free convection is the natural result of fluid density differences and temperature gradients, whereas forced convection is induced by an external source. Heat transfer by radiation is the flow of photons from a hotter body (emitter) to a cooler body (absorber). The thermal resistances for the various modes of heat transfer can be combined in series/parallel networks to maintain the proper cooling of electronic equipment.

CHAPTER 6
EXPECTED THERMAL ENVIRONMENTS

Expected thermal environments are influenced by the equipment application, whether it be airborne (aircraft, missiles, satellite, shuttle vehicles, and spacecraft) or surface (fixed-ground, mobile-ground, shipboard, submarine, etc.). This chapter describes the process involved in defining thermal environments, typical thermal requirements based on the equipment application, and applicable military/government specifications which cover the thermal environments and thermal design and test.

THE NEED FOR ENVIRONMENTAL DEFINITION

The most sophisticated thermal models and thermal analysis computer programs still depend on an accurate definition of the thermal environment to ensure the validity of the resulting part temperatures used for reliability predictions. Recently, the emphasis in government procurements has been to tailor the environmental definition to the equipment's intended use, thereby avoiding the conservatism associated with blanket requirements which envelop all applications.

For specific programs, considerable effort should be expended in tailoring the thermal environments for specific installations and missions using data from the same or similar installations or generally accepted prediction techniques. Some of these prediction techniques are described in certain military specifications.[6-1, 6-2, 6-3]

To accomplish this task, engineering studies must be undertaken to define service-use environments associated with transportation, storage, and operation of the equipment. For example, to assess the thermal environment for aircraft equipment, one would consider the factors listed in Table 6-1.

Using these data and simplified thermal models, the equipment's maximum and minimum operating and non-operating ambient temperature requirements can be derived, along with the rates of temperature change expected for the equipment usage scenario. An example is shown in Figure 6-1.

TABLE 6-1. FACTORS AFFECTING THE THERMAL ENVIRONMENT OF AVIONIC EQUIPMENT

Aircraft Mission Profiles

- how fast does it fly?
- how long does it fly?
- how high does it fly?

Equipment Location in the Aircraft

- environmental control system (ECS) air-conditioned compartment? (e.g., cockpit or crew area)
- non-conditioned compartment? (e.g., radome)
- ram air-cooled compartment? (e.g., an avionics pod)

Type of Equipment Cooling

- ECS, ram, etc.
- internal cooling using cold plates (see Chapter 7)

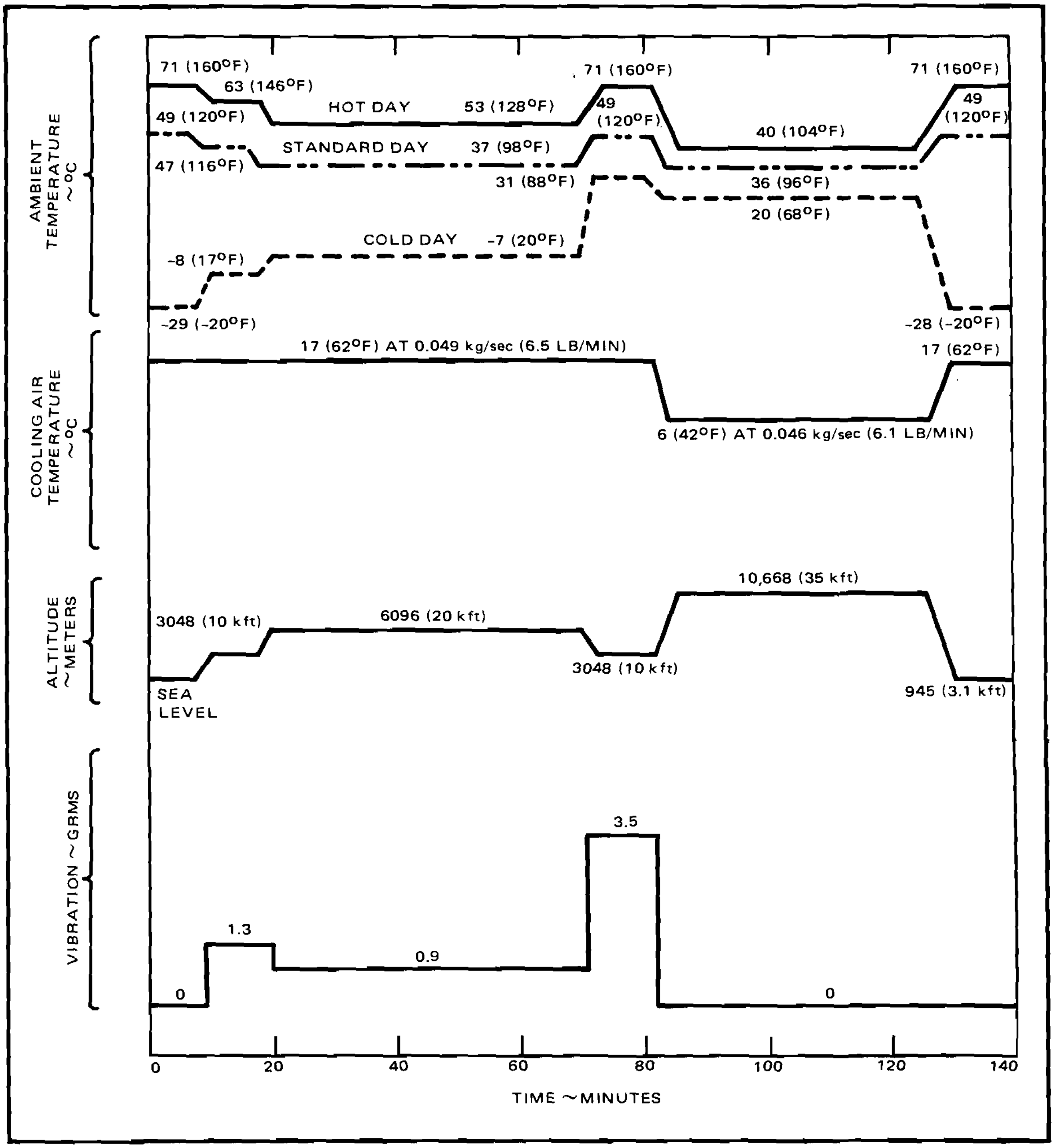


Figure 6-1. Mission profile test requirements, such as these for electronics aboard a typical combat jet aircraft, have a significant effect on the equipment thermal design.

TYPICAL THERMAL REQUIREMENTS BASED ON APPLICATION

Airborne Applications

Table 6–2 shows some typical thermal environments for various airborne applications. The intention here is to give the reliability engineer a feel for the relative magnitudes of temperatures and rates of change of temperature to expect for typical aircraft, missiles, and space vehicles. The temperatures shown are ambient temperatures, except: (1) mounting surface temperatures are used for space applications, since conduction heat transfer paths are employed to remove the parts' dissipation, and (2) skin and structure temperatures are used for missile applications, since parts are usually cooled by conduction to the missile structure. The non-operating temperature range applies when equipment is in storage, in transport, or left inoperative in its installation (e.g., an aircraft parked on a runway). The operating temperature applies to all ground (e.g., built-in test) and airborne mission phases when the equipment is operational. The rate of temperature change is generally based on an analysis of the vehicle mission.

TABLE 6–2. TYPICAL THERMAL ENVIRONMENTS FOR VARIOUS AIRBORNE APPLICATIONS

Application	Location or Mission Phase	Non-Operating Ambient Temperature Range, °C	Operating Ambient Temperature Range, °C	Maximum Rate of Temperature Change, °C/min
Aircraft	Radome	−57 to 95	−54 to 100	20
	Internal equipment bay	−57 to 95	−54 to 71	20
	Cockpit	−54 to 71	0 to 32	NA
Missile*	Captive flight	−54 to 95	−54 to 113	40
	Free flight	NA	−54 to ***	***
Spacecraft**	Launch pad	−30 to 75	NA	NA
	Orbit	0 to 40	0 to 40	

* All missile temperatures are skin temperatures.
** All space vehicle temperatures are mounting surface temperatures.
*** Dependent on individual missile capability—see detailed specification.

Surface Applications

Table 6–3 shows typical thermal environments for surface applications, both land-based and naval-based. The critical variable is whether the equipment is located outside in the elements or inside a shelter (with or without air conditioning). In most surface cases, the rate of change of temperature is negligibly slow.

APPLICABLE MILITARY/GOVERNMENT SPECIFICATIONS

Several military/government specifications define thermal environments for both design and test purposes.

MIL–E–5400, Electronic Equipment, Airborne, General Specification for [6-4]

This specification covers general design requirements for airborne electronic equipment for operation primarily in piloted aircraft, missiles, boosters, and allied vehicles. It includes different temperature and altitude conditions for various classes of equipment as shown in Table 6–4.

TABLE 6–3. TYPICAL THERMAL ENVIRONMENTS FOR VARIOUS SURFACE APPLICATIONS

Application	Non-Operating Ambient Temperature Range, °C	Operating Ambient Temperature Range, °C	Maximum Rate of Temperature Change
Fixed ground			
1) in building without temp. control	−57 to 68	10 to 40	Very slow
2) in building with temp. control	−57 to 68	10 to 25	Very slow
Mobile ground	−57 to 68	−51 to 68*	Usually slow
Shipboard			
1) externally mounted	−51 to 71	−35 to 48	Very slow
2) internally mounted	−51 to 71	0 to 50	Very slow
3) internally mounted with temperature control	−51 to 71	10 to 50	Very slow
Submarine	−62 to 71	0 to 50	Very slow

* Effects of solar radiation included

TABLE 6-4. ENVIRONMENTAL CONDITIONS FOR VARIOUS CLASSES OF EQUIPMENT FROM MIL-E-5400[6-4]

Equipment Class	Equipment Operating				Equipment Operating and Non-Operating	Equipment Non-Operating	
	Temperature Extremes for the Chamber (Without External Cooling Provisions)						
	Continuous, °C	Intermittent (30 min.), °C	Short-time (10 min.), °C	Temperature Shock, °C	Altitude	Temperature Extremes, °C	Temperature Shock, °C
Class 1	−54 +55	+71	—	−54 to +71	Sea level to 15,240 m (50,000 ft)	−57 to +85	−57 to +85
Class 1A	−54 +55	+71	—	−54 to +71	Sea level to 9144 m (30,000 ft*)	−57 to +85	−57 to +85
Class 1B	−40 +55	+71	—	−40 to +71	Sea level to 4572 m (15,000 ft*)	−57 to +85	−57 to +85
Class 2	−54 +71	+95	—	−54 to +95	Sea level to 21,336 m (70,000 ft)	−57 to +95	−57 to +95
Class 3	−54 +95	+125	+150	−54 to +125	Sea level to 30,480 m (100,000 ft)	−57 to +125	−57 to +125
Class 4	−54 +125	+150	+260	−54 to +150	Sea level to 30,480 m (100,000 ft)	−57 to +150	−57 to +150
Class 5**	−54 +95	+125	—	−54 to +125	Sea level to 609,600 m (2,000,000 ft)	−57 to +125	−57 to +125

* Altitude range shown is for operation only. Classes 1A and 1B equipment shall withstand a non-operating altitude of 12,192 m (40,000 ft.).
** For altitude above 30,480 m (100,000 ft.), the equipment's surrounding environment shall not exceed 71°C and means shall be available for rejection of heat into the surroundings by conduction or radiation.

MIL-STD-210, Climatic Extremes for Military Equipment[6-5]

This standard establishes uniform climatic design criteria for military equipment intended for worldwide use. For example, in the case of ground equipment, the design value is that value exceeded not more than 1 percent of the hours for the most extreme month in an average year of the most severe worldwide location. Thus some of the temperatures obtained from this standard may be quite conservative, since the risk of equipment encountering a temperature extreme for the single most severe location in the world is very small, especially if it represents a small area or remote location. This situation led to the adoption of an alternative called AR 70-38.

AR 70–38, Research Development, Test and Evaluation of Material for Extreme Climatic Conditions[6-6]

This regulation, developed for Army equipment, defines climatic design values for items not intended for worldwide use. Consequently, the world was divided into four climatic zones (Figure 6–2), with the temperature and solar radiation values shown in Table 6–5.

MIL–STD–810, Environmental Test Methods[6-1]

This standard established tailorable environment test methods including high and low temperature and temperature/altitude test procedures. It includes generalized environmental test criteria and procedures intended to evaluate the effects of natural and induced environments on equipment utilized in military applications.

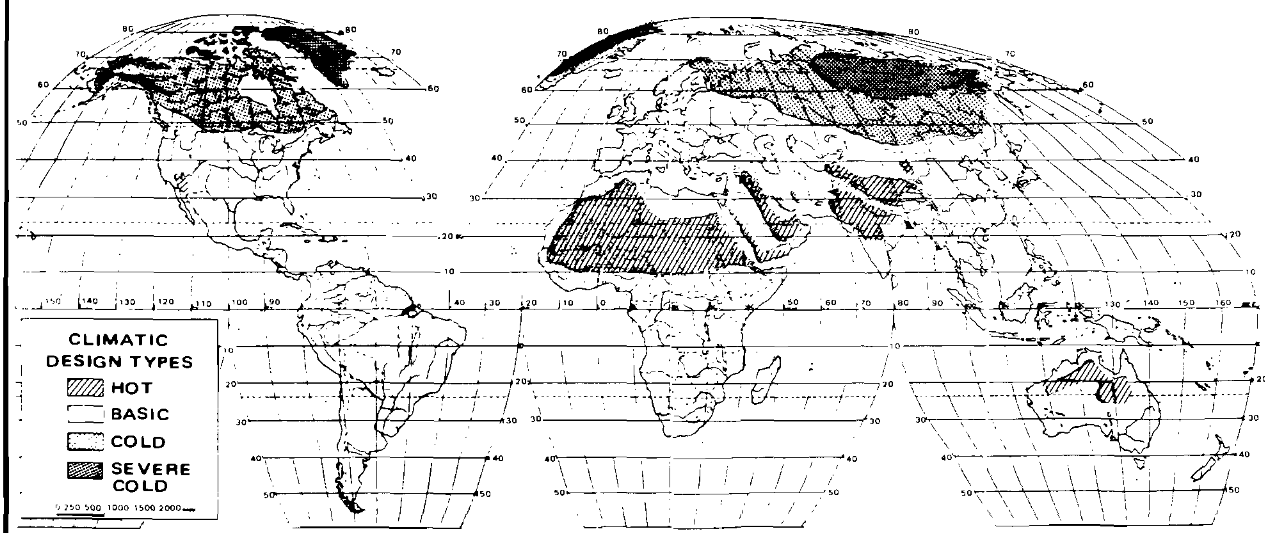


Figure 6–2. Climatic zones from AR 70–38 can be used to establish requirements for equipment not intended for worldwide use.[6-6]

TABLE 6–5. SUMMARY OF TEMPERATURE CRITERIA FROM AR 70–38[6-6]

Parameter		Operational Conditions		Storage and Transit Conditions
Climatic Design Type	**Daily Cycle**	**Ambient Air Temperature, °C (°F)**	**Solar Radiation, $\frac{W}{m^2}$ $\left(\frac{Btu}{hr\text{-}ft^2}\right)$**	**Induced Air Temperature, °C (°F)**
Hot	Hot-dry	32 to 49 (90 to 120)	0 to 1120 (0 to 355)	33 to 71 (91 to 160)
(low-latitude deserts)	Hot-humid	31 to 41 (88 to 105)	0 to 1080 (0 to 343)	33 to 71 (91 to 160)
Basic	Constant high humidity	Nearly constant 24 (75)	Negligible	Nearly constant 27 (80)
(humid tropics and mid-latitude, densely populated, highly industrialized sector)	Variable high humidity	26 to 35 (78 to 95)	0 to 970 (0 to 307)	30 to 63 (86 to 145)
	Basic hot	30 to 43 (86 to 110)	0 to 1120 (0 to 355)	30 to 63 (86 to 145)
	Basic cold	−21 to −32 (−5 to −25)	Negligible	−25 to −33 (−23 to −28)
Cold (northern hemisphere)	Cold	−37 to −46 (−35 to −50)	Negligible	−37 to −46 (−35 to −50)
Severe cold (northern continental interiors and Arctic)	Severe cold	−51 (−60) (Cold soak)	Negligible	−51 (−60)

TABLE 6-6. CATEGORIES OF EQUIPMENT COVERED IN MIL-STD-781[6-2]

Category 1	Fixed Ground Equipment
Category 2	Mobile Ground Vehicle Equipment
Category 3	Shipboard Equipment (Sheltered and Unsheltered)
Category 4	Equipment for Jet Aircraft
Category 5	Equipment for Turbo-Prop Aircraft and Helicopter Aircraft
Category 6	Air-Launched Weapons and Assembled External Stores

MIL-STD-781, Reliability Tests: Exponential Distribution[6-2]

Appendix B of this standard discusses the test conditions for reliability qualification tests, including the analysis necessary to establish conditions appropriate to the particular system or equipment. Again, the emphasis here is on tailoring the test conditions/levels using the equipment's environmental specifications and life/mission profiles. The categories of equipment covered by MIL-STD-781 are listed in Table 6-6.

MIL-STD-1670, Environmental Criteria and Guidelines for Air-Launched Weapons[6-3]

This standard establishes guidelines for the environmental engineering required in support of air-launched weapons, including air-to-air weapons, air-to-surface weapons (including free-fall), and aircraft gun pods. It provides excellent guidelines and calculation techniques for determining the environmental conditions to which air-launched weapons will be subjected during the factory-to-target sequence, including storage and transportation temperature and captive and free-flight temperature computations.

SUMMARY

Sophisticated thermal analysis programs depend on an accurate definition of the expected thermal environment to ensure the validity of temperature and reliability predictions. Engineering studies must be done to define service-use environments associated with transportation, storage, and operation of electronic equipment.

CHAPTER 7
THERMAL DESIGN OF ELECTRONIC EQUIPMENT

Using the material on heat transfer in Chapter 5 and thermal environments in Chapter 6, data are now presented on electronic cooling equipment. This chapter deals with the techniques used in the cooling of electronic equipment, the factors to consider when selecting the type of cooling for a given application, and comparisons of the various cooling techniques.

LEVELS OF THERMAL RESISTANCE

In Chapter 5, the importance of minimizing thermal resistance was emphasized. The cooling techniques discussed in this chapter are ways to eliminate or minimize thermal resistance.

Three levels of thermal resistances are encountered in electronic equipment: internal resistance, external resistance, and system resistance.

Internal Resistance

Internal resistance is the overall thermal resistance between the point or area in which heat is generated and some specified point on the surface of the part, such as the mounting surface. In semiconductor devices, such as transistors and microelectronic circuits, the internal resistance is the junction-to-case thermal resistance, θ_{JC}.

External Resistance

The external resistance is the overall resistance between an arbitrary reference point on the part, such as the mounting surface, and the heat exchanger or the interface between the equipment and the cooling fluid or surroundings. It usually consists of one or more conduction thermal resistances.

System Resistance

The system resistance is the thermal resistance between the equipment's external surface and ambient air, or between the heat exchanger and cooling fluid. Examples of external thermal resistance and system thermal resistance are shown in Figure 7–1.

The internal thermal resistance is usually fixed by the part manufacturer, and not much can be done to reduce it without altering the design of the part.

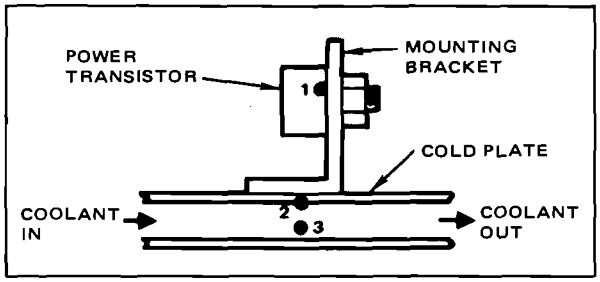


Figure 7–1. The thermal resistance to conduction from point 1 (base of the transistor) to point 2 (interface between the cold plate and the coolant) is an example of an external thermal resistance. The convection thermal resistance between point 2 and point 3 (coolant) is an example of a system thermal resistance.

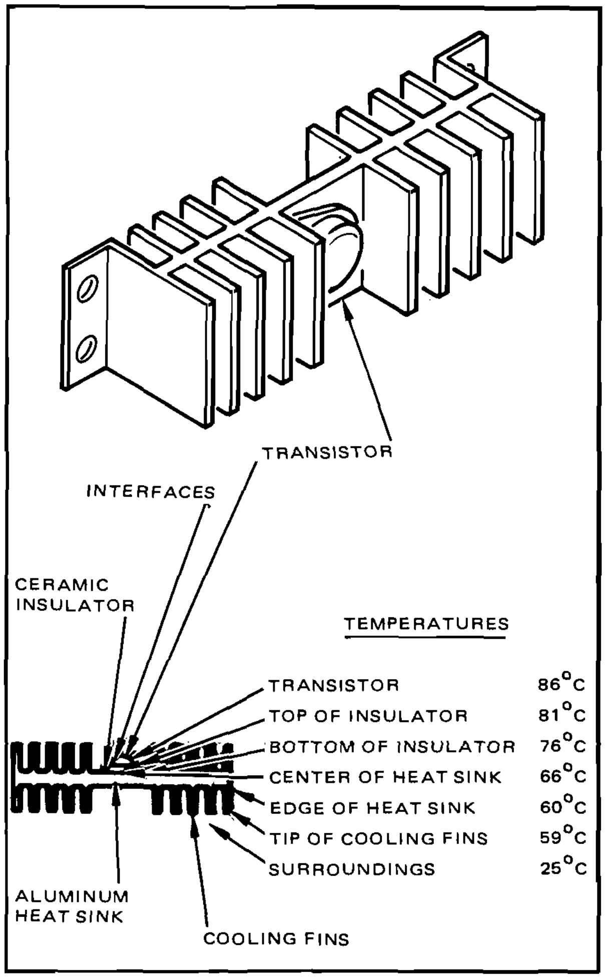


Figure 7-2. Cooling fins reduce the thermal resistance between the part and the sink.

TABLE 7-1. WAYS TO MINIMIZE THE MOUNTING THERMAL RESISTANCE

• Minimize gap between part and circuit board.
• Fill gap with a material having a high thermal conductivity.

On the other hand, the external and system resistances are not fixed and can be minimized by employing good thermal design techniques, as described below.

EXTERNAL THERMAL PATHS

External thermal paths usually are conduction paths. They can be classified according to whether the heat is removed directly from the part or whether the circuit board is employed in the thermal path. Each design option is discussed below.

Direct Cooling of Parts

With this technique, the dissipation is removed by a gas or liquid passing directly over or near the parts. High-dissipation parts are mounted on cooling fins to increase the heat transfer area, thereby decreasing the thermal resistance to convection and radiation. Figure 7-2 presents an example of cooling fins on which a transistor is mounted. The heat is conducted from the transistor to all areas of the cooling fins, from where it is rejected to the sink. Figure 7-2 also illustrates the temperature distribution for a 10-watt transistor in a 25°C environment.

Methods for rejecting the heat to the sink depend on the power density and the environment. With relatively low-power equipment in a ground or shipboard environment, passive cooling by radiation and free convection might suffice. For higher power equipment, forced-air cooling is required (see Figure 7-3). Because the coolant impinges directly on the part or the cooling fin, it is called *impingement cooling* (see Figure 7-4) when the coolant is a gas or *flush cooling* when the coolant is a liquid.

Use of the Circuit Board in the Thermal Path

Another development is the use of the circuit board in the thermal path. The heat is conducted to the bottom of the case and from there to the circuit board. The thermal resistance between the bottom of the case and the top of the board is called the *mounting thermal resistance.* This series element in the thermal network is minimized, as with any conduction path, as described in Table 7-1.

The heat is removed from the circuit board by a gas or liquid flowing through a *heat exchanger* in thermal contact with the board. The coolant does not contact the parts directly. With electronic equipment, a heat exchanger is called a *cold plate* or *coldwall*. The design approaches described below have been developed for removing the heat from the circuit board.

Common Methods for Forced-Air-Cooled Modules

Three common methods of forced-air-cooling modules are impingement, coldwall, and flow-through. The first method cools the parts directly and the other methods use the circuit board in the thermal path.

Impingement. Impingement cooling of electronic modules, illustrated in Figure 7-4, is the simplest but least effective of the three methods. Cooling air is forced through the spaces between the modules, coming in direct contact with the dissipating parts. The thermal resistance between the part and the air is usually high with this parallel-flow method, because the air velocity is relatively low and the heat transfer area (consisting of the outer surface of the part and some portion of the circuit board) is small. Because of the high thermal resistance, the cooling capacity for a nominal cooling air temperature is usually limited to 800 W/m^2. For example, a 9 $\times$ 5 inch circuit card is limited to 25 watts. The thermal resistance to convection can be decreased by mounting the part on a heat transfer fin, as was shown in Figure 7-2, or to a ground plane.Coatings thinner than 2.5×10^{-5}m (1 mil) have little effect on the heat-transfer rate.

A potential problem with impingement cooling is contamination. External-source-supplied cooling air may contain entrained water or other contaminants detrimental to electronic equipment. Consequently, MIL-STD-454 prohibits the use of impingement cooling employing air drawn from the atmosphere, unless the water and contaminants are removed by suitable devices.[7-1] Impingement cooling may be used in closed-cycle coolant flow systems.

Coldwalls. Cooling with coldwalls, shown in Figure 7-5, is generally more effective than impingement cooling. In this method, the walls of the electronic unit serve as the heat exchanger. The heat is conducted to the edge of the card via thermally conductive metal planes which form an integral part of the card. Heat is then conducted from the edge of the

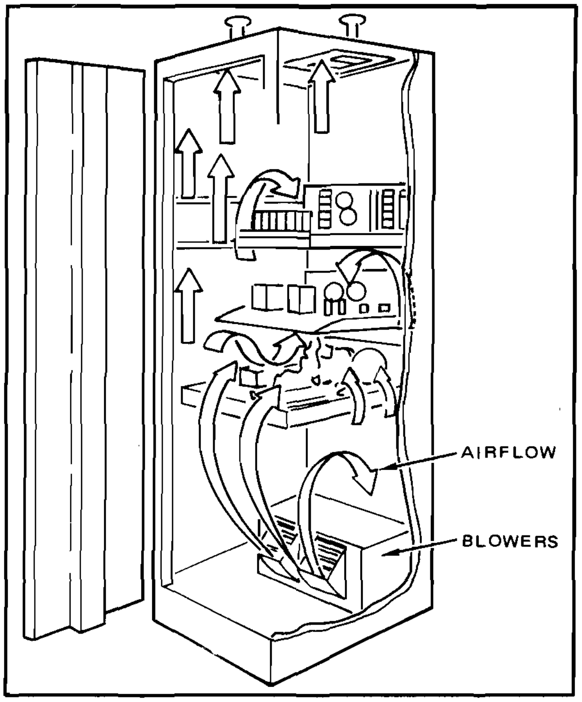


Figure 7-3. Most electronic cabinets are cooled by forcing air through the racks of equipment.

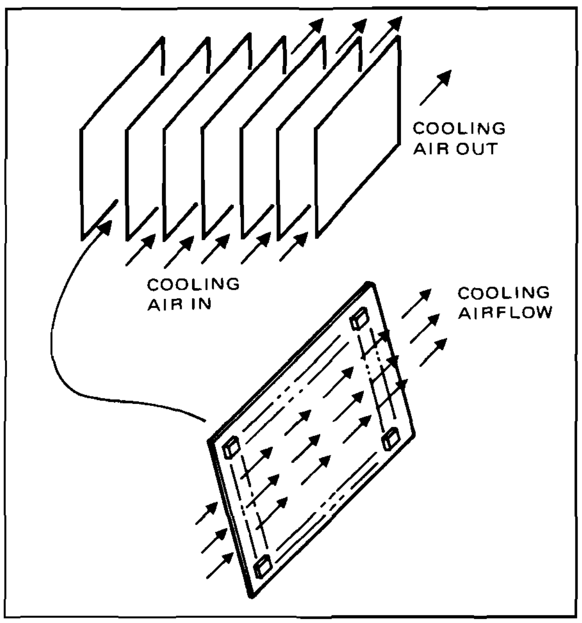


Figure 7-4. Impingement cooling is the simplest method of forced-air cooling.

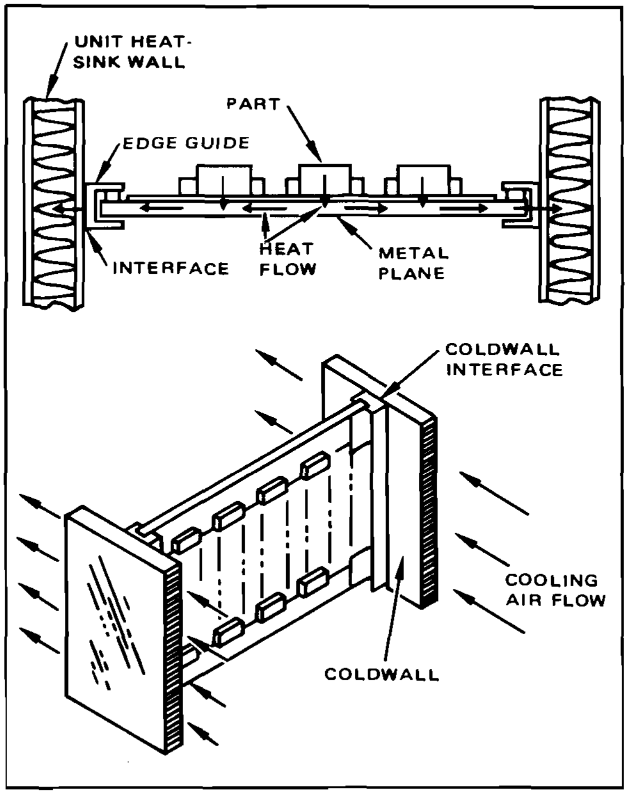


Figure 7-5. Cooling with coldwalls is generally more efficient than impingement cooling.

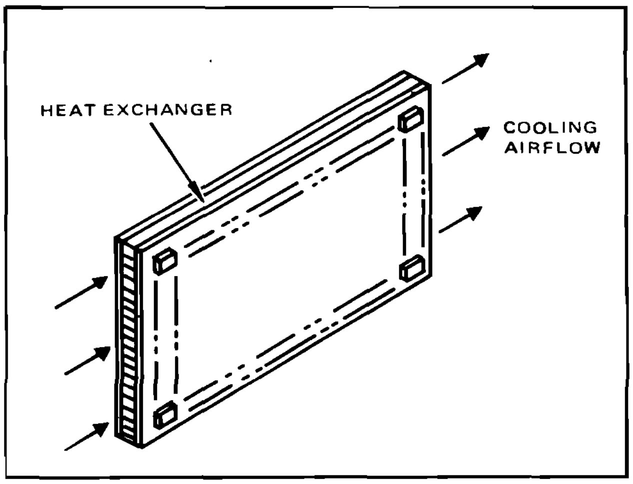


Figure 7-6. Flow-through modules are the most effective means of air cooling printed circuit boards.

card to the heat exchanger across the contact interface between the card edge and the guide rails. The conduction thermal resistances of the metal plane and the contact interface are sometimes excessive, significantly reducing the cooling effectiveness of the coldwall method.

Flow-Through Modules. In flow-through modules, shown in Figure 7-6, the heat exchanger is an integral part of the module. Air enters one end and exits at the opposite end. The walls of the unit serve as air plenums for distribution of airflow to the module, as shown in Figure 7-7. Air is metered through each module to maximize reliability. Since air flows directly between the circuit boards (see Figure 7-6), flow-through modules virtually eliminate the major conduction thermal resistances present in the coldwall cooling method, thus making it the most effective of the three methods. Another advantage is that the proportional airflow allows for reliability optimization by maximizing cooling of temperature-sensitive parts.

Comparison of the Three Methods. Table 7-2 shows the amount of power dissipation which could be effectively cooled from a typical module on which integrated circuits (ICs) are mounted. The coldwall method of cooling can handle approximately two times that of impingement cooling, while the flow-through modules can handle up to 4.5 times. Another comparison of the three methods is shown in Figure 7-8, where the maximum IC junction temperature is plotted as a function of module power dissipation for supply and exit air temperatures of 30°C and 60°C, respectively.

From these comparisons, it is clear that impingement cooling is the least effective, while the flow-through method is the most effective, as shown in Table 7-3. The flow-through method is the most complex to implement, yet the advantages gained in much higher cooling effectiveness may outweigh the added fabrication complexity. Table 7-3 also points out that the air pressure drop is lowest with impingement cooling and highest with the flow-through method. Often it is necessary to make a trade-off between cooling effectiveness and pressure drop.

Heat Pipes

Heat pipes use a combination of evaporation and liquid condensation together with capillary action to conduct heat from the part to the cooling fins, where the heat is rejected by forced convection to air or other fluid. Figure 7-9 shows a schematic of a heat pipe.

Heat pipes are useful because the thermal resistance between the heat-absorption area (evaporator) and the heat-rejection area (condenser) is very low. Large amounts of heat can, therefore, be conducted from the part over large distances with virtually no temperature difference. Heat pipes are also capable of operation in a space environment. Disadvantages of heat pipes are that they are more complicated and more expensive than conventional conduction devices and some designs can be affected by gravitational forces.

SYSTEM THERMAL PATHS

Once the heat has been transferred through the external path, it must be transferred to the sink (which may be the surrounding environment) by one of the following means:

- Radiation and free convection
- Forced air
- Forced liquid
- Phase change

Heat transfer by radiation and free convection is the simplest to design and requires no auxiliary equipment, just the cooling fins themselves. Forced-air cooling requires a pressurized air source or blower and sometimes blower controls, making it more complicated. Forced-liquid cooling requires a pump, coolant reservoir, cooling fluid, etc., and is even more complicated. Phase-change techniques are simple in principle.

A disadvantage of active cooling methods is that pumps, blowers, and motors can fail, resulting in a loss of coolant to the electronic parts. Therefore the reliability engineer should consider the reliability of the cooling equipment itself when evaluating candidate cooling methods.

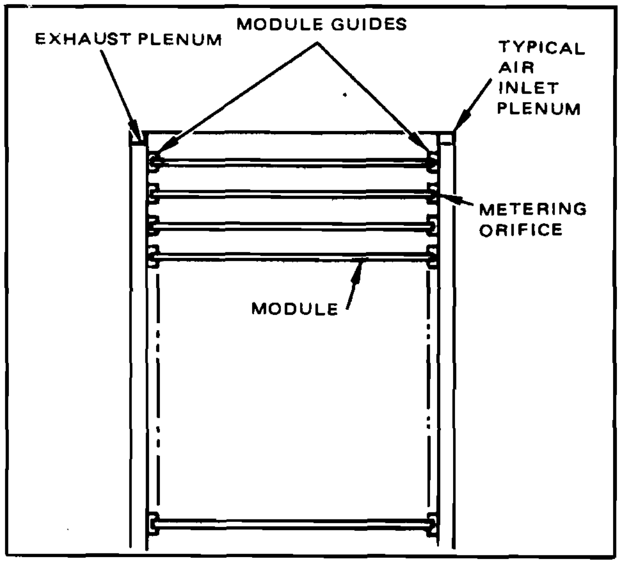


Figure 7-7. Airflow is distributed by plenums to flow-through modules.

TABLE 7-2. RELATIVE CAPACITIES OF THREE METHODS OF COOLING ELECTRONIC MODULES FOR A TYPICAL MODULE

Module Cooling Method	Maximum Cooling Capacity	
	W/m^2	W/in^2
Impingement	800	0.5
Coldwall	1,500	1
Flow-through	3,400	2

Above comparison based on:

Junction temperature:	120°C
Air inlet temperature:	30°C
Air exit temperature:	60°C
Junction-to-case thermal resistance:	50°C/W

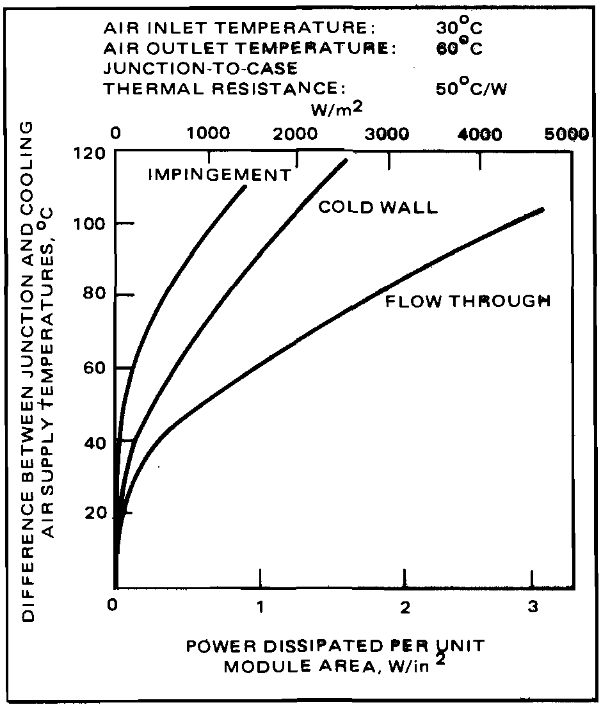


Figure 7-8. IC junction temperatures as a function of dissipated power differ widely for the three methods of module cooling.

The effectiveness of these methods of heat transfer is compared in Figure 7-10, which shows the heat-flow rate that can be transferred per unit surface area when the average fin surface temperature is 100°C and the surroundings are 20°C. For each heat transfer method, the power per unit area that can be transferred varies over a wide range, depending on the details of the cooling design. Figure 7-10 also illustrates that, for most applications, more than one heat transfer method could be used.

Radiation and Free Convection

Radiation and free convection is the simplest of all the heat transfer methods, since it relies on only the cooling fins to remove the heat. The transfer of heat by radiation and by free convection occurs in parallel. The hot fins radiate directly to the cooler surroundings. Air near the hot fins rises and is replaced by cooler air, providing a convective air current. A typical cooling fin used with radiation-and-free-convection cooling was shown in Figure 7-2.

Because of its simplicity, cooling by radiation and free convection is attractive. However, its capability is limited to less than 1300 W/m^2 of heat transfer area for an 80°C temperature rise.

TABLE 7-3. COMPARISON OF METHODS OF COOLING ELECTRONIC MODULES

Parameter	Cooling Method		
	Impingement	Coldwall	Flow-Through
Cooling effectiveness	Low	Medium	High
Implementation	Simple	Medium	Medium to complex
Pressure drop	Low	Medium	Medium to high
Part temperature uniformity	Poor	Good	Best
Cooling air utilization	Least effective	Effective	Most effective
Weight	Heavy	Medium	Medium/light
Cost	Low	Medium	Medium/high

Forced Air

Figure 7-10 indicates that the heat transfer rate is increased by more than an order of magnitude by blowing air over the cooling fins, rather than relying on radiation and natural convection. Most electronic cabinets are cooled by forcing air through the electronic equipment, as illustrated in Figure 7-3. Air motion is usually induced by a blower or a pressurized air supply source such as from an aircraft environmental control system (ECS).

When the cooling air comes in direct contact with the dissipating parts, as in Figure 7-4, this type of forced-air cooling is called impingement cooling. Although impingement cooling is more efficient than radiation and natural convection, its cooling capacity is still limited to approximately 90 W/m^2 per °C temperature difference between the surface and the cooling air. For example, if the average surface temperature of the part is 100°C and the average air temperature is 20°C, the maximum which can be cooled effectively is approximately 7×10^3 W/m^2.

The efficiency of forced-air cooling can be significantly increased by the use of a heat exchanger. In this case, the air does not come in contact with the parts, but flows through a heat exchanger containing cooling fins. The heat is conducted from the dissipating part to the cooling fins where it is rejected to the air by forced convection.

Forced Liquid

Forced-air cooling, although simpler to implement than forced-liquid cooling, has several disadvantages. For example, forced-air cooling provided by a blower may not be suitable for electronic equipment which must be operated at high altitudes where air density is low. The acoustic or electromagnetic noise of the blower or hot air ejected from the equipment may be objectionable.

These disadvantages are eliminated by the use of forced-liquid cooling. A typical liquid cooling system is shown in Figure 7-11. The noisy equipment can be located remotely from the electronic equipment, so that quiet, vibration-free operation can be maintained. Further, the heat transfer coefficient for forced-liquid cooling is an order of magnitude better than for forced-air cooling, as shown in Figure 7-10.

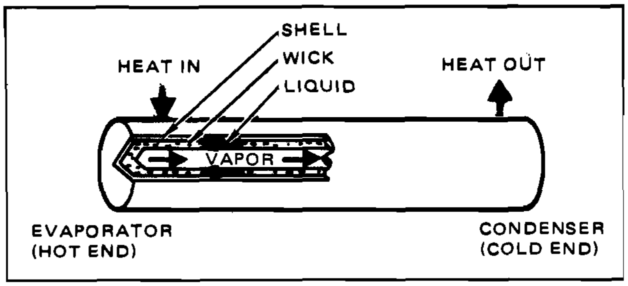


Figure 7-9. Heat pipes use a combination of evaporation and liquid condensation, together with capillary action, to conduct heat from the part to the cooling fins.

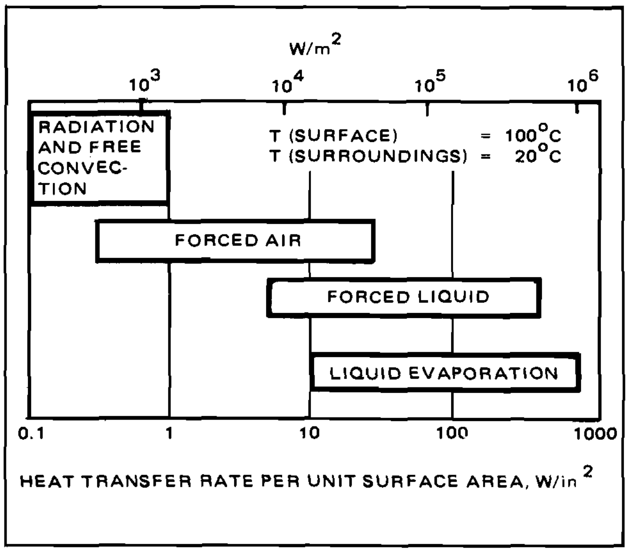


Figure 7-10. Each cooling method has a range of power per unit surface area over which it is effective.

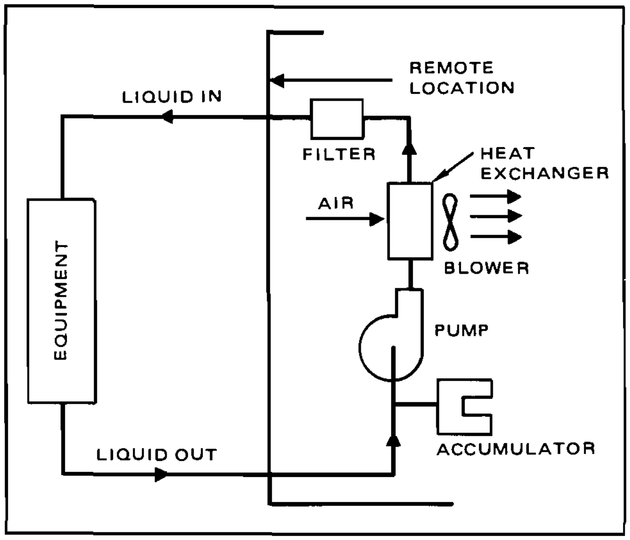


Figure 7-11. Forced-liquid cooling is more efficient than forced-air cooling.

For very-high-power electronic equipment, such as traveling-wave tubes (TWTs), the greater heat transfer capability of forced-liquid cooling is a necessity, because generally the cooling-fin area cannot be made large enough to transfer high powers effectively by forced-air cooling. The use of liquid cooling also permits high-density mounting of lower-power electronic parts, which not only may be desirable from a packaging standpoint but may also be needed to achieve required functional electronic performance.

A main disadvantage of liquid cooling is that liquids are more difficult to handle than is air. The equipment must be more carefully designed to prevent leakage; leakage is not as critical to the safe operation of equipment when air is used. At times contamination of the coolant has been a problem. Flush/fill operations occurring during required periodic coolant changes impact the system's maintainability. Also for laser systems, coolants can become contaminated by exposure to flashlamp radiation. Therefore the choice of coolant is important.

Table 7-4 compares the relative merits of the various cooling methods.

TABLE 7-4. RELATIVE MERITS OF VARIOUS COOLING METHODS

Parameter	Radiation and Natural Convection	Forced Air	Forced Liquid	Phase Change
Typical heat capacity W/m^2 (W/in^2)	500 (0.3)	1.6×10^4 (10)	7.8×10^4 (50)	1.2×10^6 (800)
Implementation	Simplest	Simple	Most complex	Simple to complex
Weight and volume	High	Medium	Low	Low to high
Noise and vibration	None	High	Low	None to low
Power consumption	None	High	Low	None
Fluid leakage problem	None	Usually none	Possible	Possible
Cost	Low	Medium	High	High
Maintainability	Simplest	Simple	Complex	Complex

Phase Change

For some short-duration missions, it is advantageous to transfer the heat to a material and store it in the material's heat of vaporization (liquid evaporation) or heat of fusion (solid melting). Latent heats of various phase change processes are listed in Appendix C. These techniques are described below.

Liquid Evaporation. Evaporation cooling is as effective as, if not more effective than, forced-liquid cooling as seen in Figure 7–10. It can be used for cooling parts with high power densities or for maintaining a constant-temperature bath for electronic parts. The electronic part is cooled by either immersing it in an evaporant bath or circulating the evaporant through a heat exchanger, as shown in Figure 7–12. A large number of evaporants is available, but those most commonly used are liquid nitrogen and fluorocarbons, such as Freon-12.

Evaporation cooling is simple since no coolant pumps are required. A disadvantage of evaporation cooling is that the equipment can operate for only a limited period (transient operation), since the amount of evaporant on board a vehicle is limited.

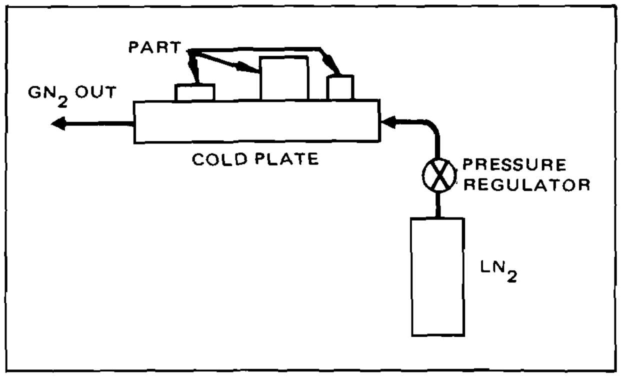


Figure 7–12. Evaporant cooling systems are even more efficient than forced-liquid cooling.

Solid Melting. A material, such as a wax compound, melts as it absorbs heat from the part. Usually the selected material has a melting temperature equal to or near the required temperature of the part. A typical cooler using a melting material is illustrated in Figure 7–13.

The advantages of this cooling method are that it is simple in principle and does not require power. Further, the operating temperature of the part can be maintained within a narrow temperature band if desired, since the melting process can be reversed when heating instead of cooling is required. Disadvantages are that the cooling capacity is limited to the amount of heat-absorbent material used and that the material usually takes up significant weight and space.

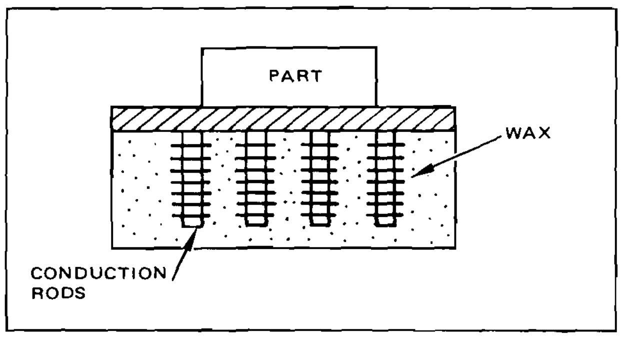


Figure 7–13. A melting process is sometimes used to cool equipment for short-duration missions.

Forced-Convection Systems

Cooling Fins for Heat Exchangers. Heat-exchanger cooling fins reduce the thermal resistance between the heat-exchanger metal surface and the coolant by increasing the heat transfer area. In addition, friction produced by the fins increases the forced-convection

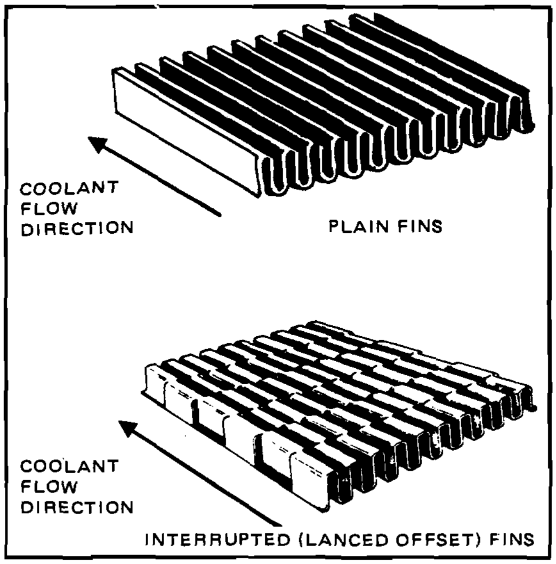


Figure 7-14. Heat-exchanger cooling fins are used to reduce thermal resistance.

heat transfer coefficient. Typical cooling fins are shown in Figure 7-14.

Fins that are broken up into segments along the airflow direction, or are periodically interrupted, tend to have lower thermal resistances to convection than plain fins; the denser the fins and the shorter the segments, the lower the thermal resistance. However, the pressure drop also increases, usually at a more rapid rate than the decrease in thermal resistance. Therefore, the pressure-drop limitations may dictate the type of fin selected.

Blowers for Forced-Air Cooling. Because most electronic equipment is forced-air cooled, blowers are almost as important as the cooling fins or heat exchangers. Blowers used in electronic cooling fall into two basic types, axial and centrifugal, depending on which way the air enters and exits from the blower. With axial blowers, which are usually cylindrical, air flows parallel to the blower axis. With centrifugal blowers, air enters one end (parallel to the axis) and exits in a radial direction. The relative merits of different types of blowers are compared in Table 7-5.

The important blower performance parameters are the flow rate and corresponding *head pressure*. The head pressure is required to overcome the resistance to airflow. Figure 7-15 shows the performance characteristics of the four blowers compared in Table 7-5. The range of head pressures of the blow-

TABLE 7-5. RELATIVE MERITS OF DIFFERENT TYPES OF BLOWERS USED IN ELECTRONIC COOLING

Parameter	Axial			Centrifugal or Squirrel Cage
	Vaneaxial	Propeller	Tubeaxial	
Speed	High	Low to medium	Low	Medium
Airflow rate	High	High	Medium	High
Head pressure	High	Low to medium	Low	Medium
Size	Small	Large	Small to medium	Medium to large
Weight	Low	Low to medium	Low	Heavy
Power type	400 Hz or 27 VDC	60 Hz	60 Hz	400 Hz, 27 VDC or 60 Hz
Power consumption	High	Low	Low	Medium to high
Noise level	High	Low	Low	Medium

ers, 250 to 800 pascals (less than 1 to 3.2 inches of water), is typical for electronic cooling. Vaneaxial blowers with higher head pressures are also available, but they are larger, require more power, and are noisy. The higher the flow rate and corresponding head pressure, the higher the required input power will be.

For two identical blowers in series the total airflow is equal to the airflow of one blower. The head pressure is equal to the sum for the two blowers. For two identical blowers in parallel, the total flow is equal to the sum for two blowers, while the total head pressure is equal to that of one blower.

Most blowers operate at constant speed. Some blowers, designed for airborne application, have variable speed motors. As the density decreases with increasing altitude, the mass of air that a fixed-speed blower can push drops rapidly. The variable-speed blower increases in speed as the air density decreases, compensating in part for the reduced air-mass flow rate. Variable-speed blowers are usually vaneaxial types.

Acoustic requirements often dictate which type of blower may be used. As seen in Table 7-5, the higher the blower performance, the higher the noise level will be. The noise level is usually more critical when the equipment is located near people, such as in the laboratory or the crew compartment of an aircraft. In remote and uninhabited areas, such as the equipment bay of an aircraft, noise is less critical.

It is better to pull (draw) the air through the equipment than to push it. The main advantage of pulling the air is that the power dissipated by the blower motor is absorbed by the air after it has cooled the equipment, making more cooling available for the equipment. Also better airflow distribution is obtained when the air is drawn.

Most electronic equipment requires an air filter to keep the dust out of the equipment, especially when ambient air is used for cooling. The filter increases the resistance to the airflow, and this filter pressure drop must be accounted for in selecting the blower.

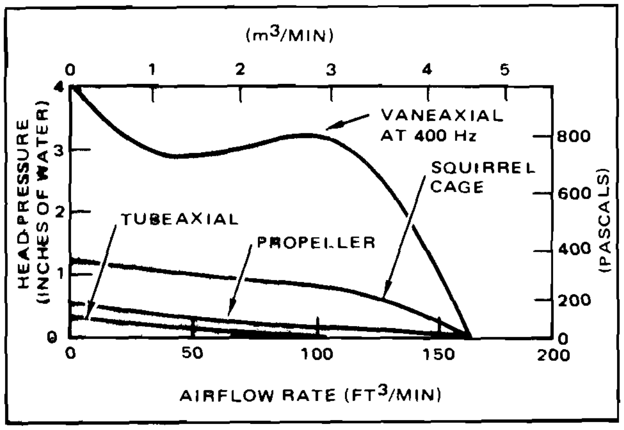


Figure 7-15. Pressure/airflow characteristics are an important consideration in selecting a blower for a specific application.

REFRIGERATION SYSTEMS

When the desired operating temperature of the part is higher than the sink temperature, no refrig-

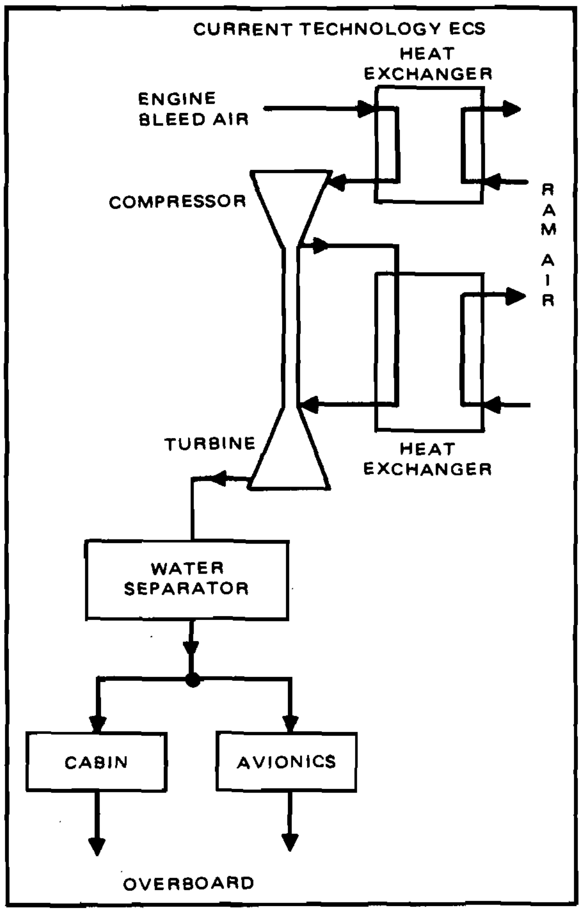


Figure 7-16. Air-cycle refrigeration is used for aircraft ECS.

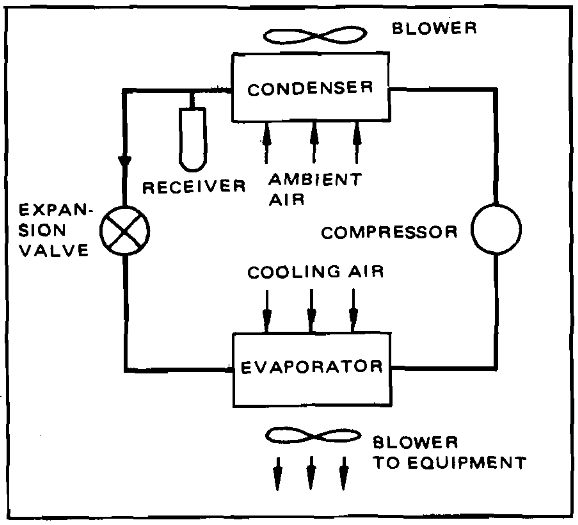


Figure 7-17. Vapor-cycle refrigeration is used mainly for ground and shipboard equipment.

eration is required. In many cooling applications, however, the desired part operating temperature is lower than the temperature of the available sink. In such cases, refrigeration can be used. Refrigeration is simply a method of removing heat from a lower temperature, pumping it to a temperature above the sink temperature, and then rejecting it to the sink. Commonly used types of refrigeration are discussed below.

Air-Cycle Refrigeration

Nearly all aircraft equipment relies on the environmental control system (ECS) for both cooling and heating. The refrigeration portion of a typical aircraft ECS utilizes air-cycle refrigeration, shown in Figure 7-16.

Vapor-Cycle Refrigeration

Vapor-cycle refrigeration uses a refrigerant, such as Freon-12 or Freon-22, as the working fluid. A typical vapor-cycle refrigeration system is illustrated schematically in Figure 7-17. Vapor-cycle refrigeration systems are used mostly with ground and shipboard equipment, but can be used on board aircraft where supplementary cooling is required.

Thermoelectric Refrigeration

Thermoelectric cooling makes use of the phenomenon of reversible flow of heat and electricity to pump heat from a colder region (cold junction) to a hotter region (hot junction). Heat pumping results from the Peltier effect: when voltage is applied across the junction of two dissimilar materials, heat is absorbed or evolved at the junction. The operation of a thermoelectric cooler is shown schematically in Figure 7-18.

Thermoelectric coolers are attractive because they are compact and require no moving parts. They also can be used for cooling infrared sensors, which generally must be maintained at cryogenic temperatures. In this type of application, several thermoelectric coolers are usually staged, because the temperature difference between the sensor and the heat sink (air) exceeds the heat-pumping capability of a single-stage device.

Disadvantages of thermoelectric coolers are (1) their power efficiency is usually low; (2) a single-stage thermoelectric cooler, the type commonly used, can pump heat only up to a 70°C difference between the hot and cold junctions, and the power efficiency drops very drastically when the coolers are staged; and (3) they normally fail when the hot junction temperature exceeds 130°C.

TRENDS IN ELECTRONIC COOLING

Design of electronic equipment has become more complex as the demands on performance continue to increase. Future trends in avionic design would tend to indicate the use of more improved solid-state microelectronics with greater processing capability. A particularly significant trend in the design of avionic equipment is toward increasing the power density, as shown in Figure 7-19. This increased power density has resulted in more stringent packaging design constraints, thereby requiring new cooling design approaches.

Using the flow-through modular design concept as a base, further improvements in the cooling capability will be required. Possible improvements in the flow-through module design will be the reduction of the temperature difference between the junction and the cooling air. This can be achieved by reducing the thermal resistance from the junction to the mounting surface of the module, and by the use of high-performance cooling fins. An expected penalty will be increased cooling-air pressure drop.

Increases in packaging and power density and special system cooling requirements may also produce design innovations involving liquid cooling, heat pipes and other less conventional means of heat transport.

SUMMARY

All cooling techniques are simply methods to minimize or eliminate thermal resistances. Four commonly used cooling methods are radiation and free convection, forced air, forced liquid, and phase change. Trends in electronic cooling are toward increased power densities and resultant packaging and cooling problems. Further improvements in air-cooling techniques will place more high-dissipation parts within the capability of air cooling. Recent aircraft performance increases suggest that liquid cooling replace bleed air, which will require additional improvements in liquid cooling.

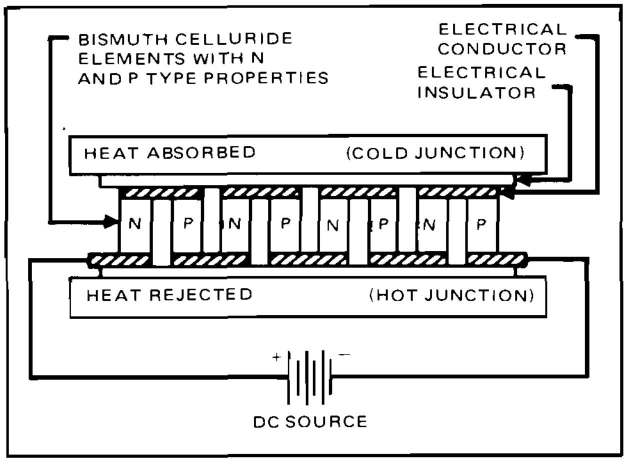


Figure 7-18. Thermoelectric refrigeration is used for airborne and space applications in which volume and weight are critical.

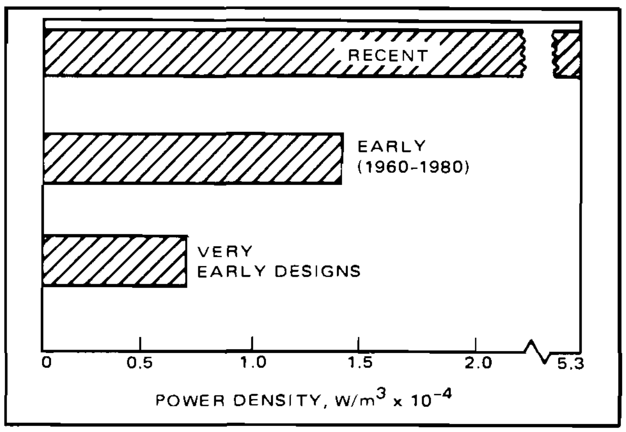


Figure 7-19. A trend in avionic design is the tendency to increase the power density.

CHAPTER 8
THERMAL ANALYSIS

DEVICES WITH HIGHEST FAILURE RATES AND HOTTEST DEVICES			
DEVICE	PREDICTED FAILURES PER 10^6 HRS	DEVICE	PREDICTED TEMPERATURE DEGREES C
U2	0.053	VR1	*65.9
U4	0.052	U1	65.7
U1	0.039	U3	65.6
U3	0.039	U5	61.9
U5	0.035	U2	60.9
U7	0.011	U2	60.6
VR1	*0.009	U4	60.3

*DEVICE WITH MOLY TAB

Figure 8-1. Thermal analysis provides detailed information.

Thermal evaluation is done by analysis, testing, or both. Analysis is presented in this chapter, and testing is described in Chapter 9. This chapter discusses thermal analysis methods and associated costs.

ROLES OF THERMAL ANALYSIS

Thermal analysis has two important roles in a military electronic program: (1) prediction of the temperatures of the parts in their operational environment, and (2) optimization of the thermal design to maximize reliability.

Analysis is an accurate, cost-effective way to obtain information on the thermal characteristics of a specified design. An analysis involves no hardware fabrication, and its cost is relatively low. Therefore a thermal analysis is generally less expensive than a thermal test. Furthermore, design options can be examined more easily by analysis. For example, the variation of materials and placement of parts can be simulated easily by an analysis, whereas the experimental investigation of each option requires a distinct set of hardware.

For these reasons, analytical evaluation generally is employed to screen out candidate designs and to predict whether the final design appears to be adequate, whereas experimental evaluation generally is employed only with the most promising design(s) and to verify the analytical predictions. With modern computer hardware and software (described later in this chapter), it is feasible to predict temperatures down to the part level. The temperatures and failure rates of thousands of parts can be predicted at a relatively low cost (see Figure 8-1).

Comparisons made at Hughes Aircraft Company between measurements and detailed predictions indicate that predicted temperatures are accurate to within 6°C. Acquisition of thermal test data, on the other hand, is limited by considerations of cost and available data channels. Consequently, analyses generally are employed to estimate temperatures for use in reliability predictions, whereas tests generally are employed to measure the temperatures of a selected fraction of the parts. The instrumentation locations for the tests can be selected by examining the analysis results.

Modern analysis techniques also can optimize the thermal design, subject to constraints imposed by interconnection routing and other electrical circuit considerations. Each possible configuration has a predicted failure rate that depends on the set of part temperatures associated with the design. The optimization methods tell the designer which configuration will yield the lowest rate of thermally induced failures. Equipment having an optimized thermal/reliability design will have a much lower life-cycle cost than that having a non-optimized design.

PREDICTION METHODS

To predict the operating temperatures of electronic parts, the thermal analyst solves the partial differential equations that govern heat transfer. Two methods are used to solve these equations: analytical and numerical.

The analytical approach involves a *closed form* or *exact* solution. The solutions for many simple geometries are available in textbooks or can be derived by the mathematically inclined. A disadvantage of this approach is that most electronic equipment is so complicated that the geometry must be simplified to obtain an analytical solution (see Figure 8-2). Another disadvantage is that, for most applications to electronic equipment, the solution is in the form of an infinite series; consequently, a computer program is needed to predict temperatures.

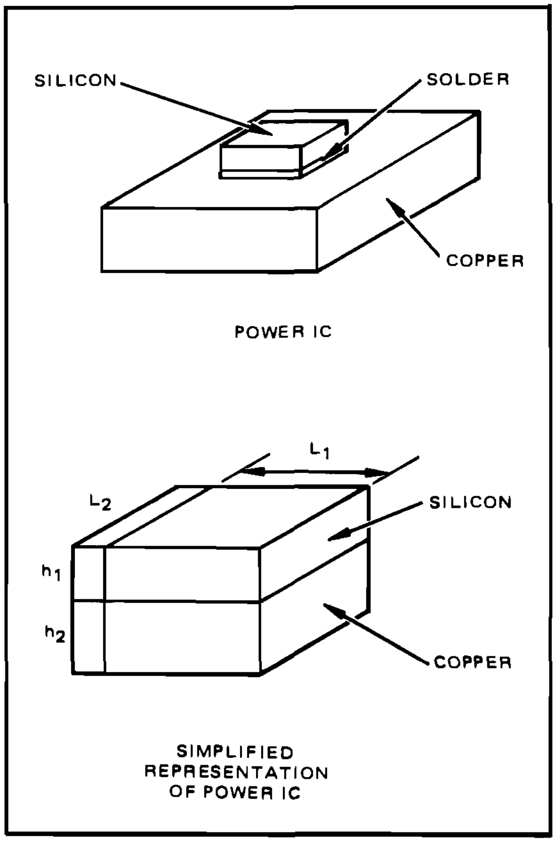
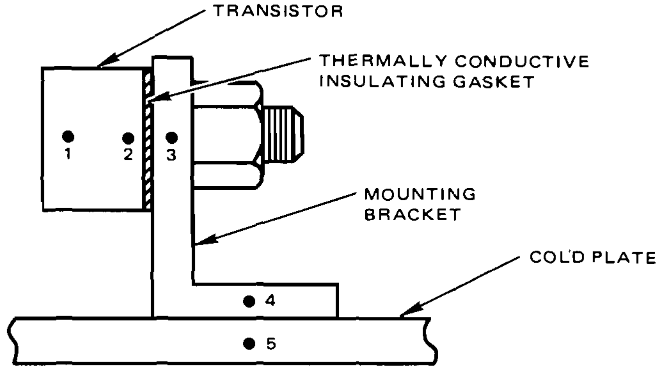
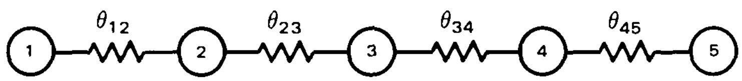


Figure 8-2. An analytical solution can be obtained by a simplified representation.[8-8]

The numerical approach involves the *finite-difference* or *finite-element* solution of the partial differential equations. To use this approach, the analyst develops a *thermal model* of the equipment, consisting of an electrical analog of the series-parallel network of thermal resistances between the parts and the sink. Locations of interest, such as dissipating parts and sinks, are represented in the model by *nodes* (see Figure 8-3). For transient problems, the thermal capacitance of the nodes is included. The number of nodes tends to determine the accuracy and, to a large extent, the cost of the analysis. Thermal models of electronic equipment may have fewer than five nodes, in which case the node temperatures can be evaluated in closed form, or they may have hundreds of nodes, in which case computer programs are employed to calculate the temperatures. Because of its



NOTE: NUMBERS NEXT TO • AND INSIDE CIRCLES INDICATE NODE NUMBERS.
θ DENOTES THERMAL RESISTANCE.



DESCRIPTION OF THERMAL MODEL

NODE	LOCATION	CONNECTED TO NODE	BY RESISTOR NUMBER
1	TRANSISTOR JUNCTION	2	12
2	TRANSISTOR CASE	3	23
3	MOUNTING BRACKET VERTICAL LEG	4	34
4	MOUNTING BRACKET HORIZONTAL LEG	5	45
5	COLD PLATE	4	45

Figure 8-3. A simple thermal model is employed to analyze a transistor, mounting bracket and cold plate assembly.

flexibility and relatively low cost, the numerical approach is well-suited to the thermal analysis of electronic equipment.

LEVELS OF THERMAL ANALYSIS

Thermal analyses are performed during all phases of the program (see Chapter 2 for the recommended thermal tasks). The knowledge of the design and the degree of detail required of the analysis increases as the design progresses (see Table 8-1).

A thermal analysis may be as simple as making a quick on-the-spot evaluation, using "back of the envelope" calculations, or it may involve solving very complex problems requiring the use of highly sophisticated thermal analyzer computer programs. It could be steady-state or a transient calculation, depending on the application. The level of thermal analysis performed depends on the complexity of the problem and the degree of accuracy required. There are three basic levels of thermal analysis: preliminary, intermediate, and detailed.

Preliminary Analysis

This level of analysis is usually performed during the conceptual phase of the program. It is used for performing feasibility studies or identifying and exploring alternative concepts. Since the analysis results need not be highly accurate, only approximate temperature estimates are made, usually with the aid of pocket or desk calculators and little (<$25) or no computer cost. The data found in Appendix E can be used for this type of estimate. These temperature estimates can serve as a basis for making reliability predictions, as long as the user is aware of their limited accuracy. An example of a preliminary thermal model is shown in Figure 8-4.

Intermediate Analysis

This level of analysis is more detailed because better accuracy of the part temperatures is required. At this point there is additional definition of the requirements, and more information on the design. This type of analysis is typically performed during the early stages of the validation phase, when selected candidate solutions are beginning to be refined through extensive analysis.

Detailed Analysis

This level of analysis typically is performed during the later stages of the validation phase and perhaps the early stages of the full-scale engineering

TABLE 8-1. STATUS OF THERMAL DESIGN DURING PRE-PRODUCTION PROGRAM

Parameter	Alternative Design Concepts	Design Concept	Detailed Design Ready for Production
Dissipations	Rough parts counts, dissipation estimates	Final parts counts, preliminary dissipation estimates	Final parts counts, final dissipation
Thermal resistances	Very little knowledge	Preliminary drawings; analysis; perhaps test	Detailed drawings; analysis and tests
Sink temperatures	Rough estimates	More precise calculations	Final calculations
Excessively hot parts	Perhaps a few critical ones identified	Parts identified; solutions conceived	All parts within requirements, or waivers justified for others
Level of thermal analysis	Preliminary	Intermediate	Detailed

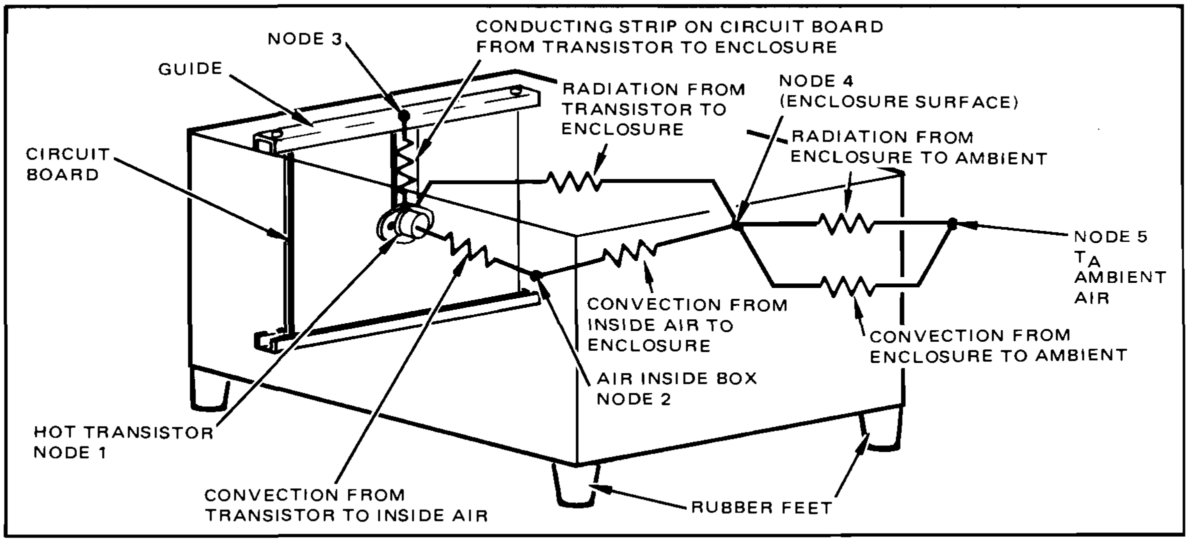


Figure 8-4. This five-node thermal model depicts a transistor/circuit board unit. [8-2]

development phase. At this point the design requirements have been finalized, and the design is close to the final configuration. Accurate temperature predictions are required for inputs to refined reliability predictions, and a high degree of accuracy is required. This level of analysis relies heavily on high-speed computers, because it is cost effective to do the large amounts of required computations.

An example of a detailed thermal model is shown in Figure 8-5. With such a model, the part temperatures can be predicted to within 6°C.

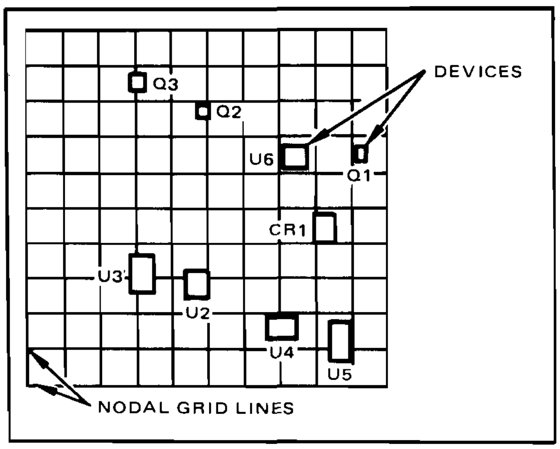


Figure 8-5. This plan view shows a detailed thermal model of a hybrid microcircuit with device locations.

COMPUTER PROGRAMS

Even the most complex problem can be solved by numerical means. The use of the computer has enhanced the ability of the analyst to process the large amounts of calculations inherent in numerical solutions. Advances in computer hardware and software have further allowed the analyst to speed work and consider designs on increasingly higher system levels.

New advances in software and hardware have brought in the era of Computer-Aided Design (CAD) and Computer-Aided Analysis (CAA). The advantages of automated thermal analysis are (1) shorter duration for an analysis, (2) decreased cost, (3) elimination of undetected calculation errors, and (4) greater capability to optimize the design. These advances allow the use of interactive graphics, network model generators, report writers, etc., which continue to expand the capability of the analyst to do a more effective and efficient job. Much of the processing of the large amounts of input and output data involved in a detailed thermal analysis can be automated. Predicted temperatures can be used automatically as inputs to a computerized reliability prediction.

Three types of computer programs are employed in the thermal analysis of electronic equipment: thermal analyzers, specialized programs, and optimization programs.

Thermal Analyzer Computer Programs

A thermal analyzer computer program solves the thermal model developed by the analyst and predicts the node temperatures. Commonly used, readily available thermal analyzers are listed in Table 8-2.

Companies wishing to establish a thermal analysis capability can take one of two approaches. The first approach is to purchase computer programs and make them operational on the company's in-house computer. Secondly, several computer companies have operational thermal analyzers and sell computer time for their use; the service may include instructions in the use of the program.

Specialized Thermal Computer Programs

Many computer programs are available for specific problems, including programs for radiation, heat exchangers (cold plates), aerodynamic heating, and just about every other conceivable thermal problem. Table 8-3 provides a listing of sources for some of these programs. An analyst can employ the help of a programmer to write a custom program for a specific application or, with simple computer languages such as BASIC, the analyst may choose to write specific computer programs.

TABLE 8–2. THERMAL ANALYZER COMPUTER PROGRAMS

Acronym	Name	Source
—	Lockheed Thermal Analyzer	National Aeronautics and Space Administration Houston, TX
SINDA	Systems Improved Numerical Differencing Analyzer	National Aeronautics and Space Administration Houston, TX
MITAS	Martin Marietta Thermal Analyzer System	Control Data Corporation Minneapolis, MN

TABLE 8–3. SPECIALIZED THERMAL ANALYSIS COMPUTER PROGRAMS

Program	Function	Source
Confac2	Radiant Interchange Factors	National Aeronautics and Space Administration Houston, TX
Cold-Plate Heat Transfer Computer Program	Cold-Plate Evaluation	Rockwell International Canoga Park, CA
Aerodynamic Heat Transfer Program	Aerodynamic Heating	Rockwell International Canoga Park, CA
Heat Exchanger Program	Heat Exchanger Performance	Boeing Co. Seattle, WA
TRASYS2	Thermal Radiation	National Aeronautics and Space Administration Houston, TX

Note: For a list of available heat transfer and fluid-flow programs consult:

Computer Software Management and Information Center (COSMIC)
112 Barrow Hall
University of Georgia
Athens, Georgia 30602

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Thermal/Reliability Optimization Computer Programs

Several computer programs have been developed to optimize parts placement on a circuit board for maximum reliability. One was OPTEMP, developed by the Air Force.[8-15] OPTEMP was investigated further under contracts entitled "Computer-Aided Design for Reliability (CAD/R)" and "Integrated Thermal Avionics Design (ITAD)." [8-16, 8-17, 8-18] ITAD is being developed for industry and government use under an Air Force Wright Aeronautical Laboratories contract.[8-19]

These optimization methods have applications other than parts placement. At one end of the scale, they can optimize the allocation of cooling resources, such as the allocation of coolant to the modules of a forced-convection-cooled unit.[8-20, 8-21] At the other end, they can optimize the design of a microcircuit chip to minimize the power dissipation.[8-22]

GUIDELINES FOR HAVING A THERMAL ANALYSIS PERFORMED

Thermal Analysis

Thermal analysis should be performed by specialists having training in heat transfer. Although preliminary temperature estimates can be made with the aid of the graphs in Appendix E, more detailed predictions require computer programs. Thermal specialists have the know-how to use these programs, and have data banks on material properties and thermal resistances.

It is best to have thermal specialists who are full-time employees. However, some organizations do not maintain an in-house thermal group. For such organizations, thermal consultants are available. To use a consulting service cost-effectively, one should give the consultant a specific, well-defined task.

Thermal Analysis Inputs

The information required for a thermal analysis includes all the factors that affect dissipations, thermal resistances, and sink temperatures. The major types of data needed are physical drawings of the electronic equipment, showing part locations and mounting techniques; part specifications, listing such data as junction-to-case thermal resistance (θ_{JC}); and mounting surface temperature, or coolant flow rate and inlet temperature. It is important to provide the analyst with as much of this information as possible, because the labor required to collect these data can represent a large fraction of the total cost of a thermal analysis.

Cost of a Thermal Analysis

The cost (C) of a thermal analysis is given by

$$C = (R_L)(LH) + (R_C)(CH), \qquad (8\text{-}1)$$

where R_L is the hourly labor rate, LH is the number of labor hours, R_C is the hourly rate for computer time, and CH is the number of computer hours. The labor rate for thermal consultants in 1981 is roughly \$50–100 per hour. The labor and computer rates at organizations vary widely and are subject to change.

The number of labor and computer hours required for a thermal analysis depends on the factors listed in Table 8-4. The number of computer

TABLE 8–4. FACTORS AFFECTING THE AMOUNT OF LABOR REQUIRED FOR THERMAL ANALYSIS

- Amount of information that the analyst has to collect
- The experience of the analyst
- Complexity of equipment
    - Number of units
    - Number of circuit boards
    - Number of parts
- Level of analysis

hours depends on the computer, the thermal analyzer used, and the number of nodes in the thermal model.

The computer cost of a thermal analysis is generally much lower than the labor cost. Approximate costs of a thermal analysis of typical electronic equipments are listed in Table 8-5. Future advances in automation can be expected to result in a decrease in the labor cost of a thermal analysis.

SUMMARY

Modern thermal analysis techniques are accurate and relatively inexpensive. Therefore thermal analysis is a cost-effective way to evaluate candidate designs, provide part temperatures for reliability predictions, and identify test instrumentation locations. Furthermore, methods are available to optimize thermal designs for maximum reliability.

TABLE 8-5. APPROXIMATE COSTS OF A THERMAL ANALYSIS

Type of Equipment	Level of Analysis	Number of Nodes in Thermal Model	Labor*	Computer Cost, $
Transformer	Preliminary	Less than 5	1 day	0
	Intermediate	15	1 week	100
	Detailed	50	2 weeks	500
Circuit board	Preliminary	Less than 5	1 day	0
	Intermediate	20	1 week	100
	Detailed	70	2 weeks	1000
Cold-plate-mounted module	Preliminary	Less than 5	2 days	0
	Intermediate	30	1 week	200
	Detailed	100	3 weeks	1000
Electronic cabinet	Preliminary	Less than 5	1 week	0
	Intermediate	100	2 weeks	1000
	Detailed	300	2 months	2000

*Assumes a thermal analyst with a minimum of 5 years experience.

CHAPTER 9
THERMAL TESTING

This chapter discusses the purposes of thermal testing, thermal test plans, and testing procedures (simulation of thermal environments and instrumentation).

PURPOSES OF THERMAL TESTING

A thermal test of electronic equipment consists of the measurement of the part temperatures in a laboratory simulating operating conditions. Testing is an important method for evaluating and determining the acceptability of the thermal design of electronic equipment. The purposes of thermal testing are listed in Table 9-1.

Other tests and processes have similar names. A *thermal survey*, required by MIL-STD-781, locates *hot spots* and measures the thermal stabilization time of selected parts. In a *temperature test*, the equipment is subjected to a variety of thermal environments occurring during its mission profile, and the equipment's ability to withstand these environments is determined. In a *thermal screening* process, the equipment is subjected to a variety of thermal environments (not necessarily identical to the operational environments) for the purpose of detecting flaws.

TABLE 9-1. PURPOSES OF THERMAL TESTING

- Evaluate most promising design(s).
- Provide experimental check of analytical assumptions.
- Uncover hardware problems.
- Verify dissipations.

TESTING IN THE VARIOUS PROGRAM PHASES

Testing is usually required in each of the program phases. It is especially important to test in the early phases where it is most cost effective to correct any problems discovered in the tests.

The type of equipment tested depends on when the test is conducted. Early in the program, the actual hardware is not available; and tests are performed with *thermal mockups* whose physical characteristics are similar to those of the production hardware. Dissipations in thermal mockups may have to be simulated. Later tests use prototypes, which become closer to the production hardware as the program progresses.

PLANNING A THERMAL TEST

Developing a good test plan, one of the most important steps in thermal testing, involves the reliability and thermal engineers. The key elements are setting test acceptance criteria, ensuring test realism

TABLE 9-2. WAYS TO ENSURE TEST REALISM

Dissipations

- Use prototype equipment, and test operational modes; with test of thermal mockup or if some modules are missing, simulate part dissipations.
- Simulate heat loads from adjacent equipment and solar radiation (not important with flow-through or cold-wall modules).

Thermal Resistances

- When available, test equipment having same construction materials and assembly techniques as production hardware.
- Test high-altitude equipment in an evacuated environmental chamber, and insulate the equipment to minimize heat leaks by radiation and free convection to laboratory surroundings.
- Minimize heat leaks by conduction along power leads and thermocouple wires.
- Shield free-convection-cooled equipment from the environmental chamber blowers.
- With forced-convection-cooled equipment, use the same coolant flow rates as in field operation.

Sink Temperatures

- Test free-convection-cooled equipment in air having the same temperature as in the operational environment.
- With forced-convection-cooled equipment, use the same coolant inlet temperatures as in field operation.
- With equipment mounted to a constant-temperature surface, use the same temperature as in the field.

and selecting the quantities to measure and the instrument locations.

Ensuring Test Realism

A realistic thermal test requires laboratory simulation of all the factors which affect the part operating temperatures, namely, dissipations, thermal resistances, and sink temperatures. Guidelines for achieving a meaningful thermal test are listed in Table 9-2.

The reliability and thermal engineers ensure that the tested equipment is representative of the production hardware, that the test setup is an adequate simulation of the field environment, and that the mission is simulated properly. Often an environmental chamber is required for these purposes, as shown in Figure 9-1. The reliability, thermal, and environmental test engineers collaborate in planning a test suitable for the available test facilities.

They also select the level of assembly for the test. Tests can be made with individual parts (such as measurements of the junction-to-case thermal resistance, θ_{JC}, of a semiconductor device), small assemblies (such as a hybrid microcircuit, a printed circuit board, or a flow-through module), or entire units or cabinets. The guidelines in Table 9-2 apply to tests at any level of assembly.

Selecting Instrumentation Quantities and Locations

The quantities to measure in a thermal test are part operating temperatures and quantities which affect them: dissipations, thermal resistances, and sink temperatures (see Table 9-3). The number of parameters which can be measured is dictated largely by the capabilities of the test facility. With modern computer hardware and software (see Figure 9-2), the simultaneous measurement of hundreds of variables is feasible.

Dissipations are measured by standard electrical methods (i.e., measurements of voltage drop and current). The dissipation can be measured easily at the unit level and often down to the module or circuit-board level. Unfortunately, it is difficult to measure the dissipations of the individual circuitry in an assembly. Such measurements would require disruptions to the hardware, such as lifting leads, and generally are not done.

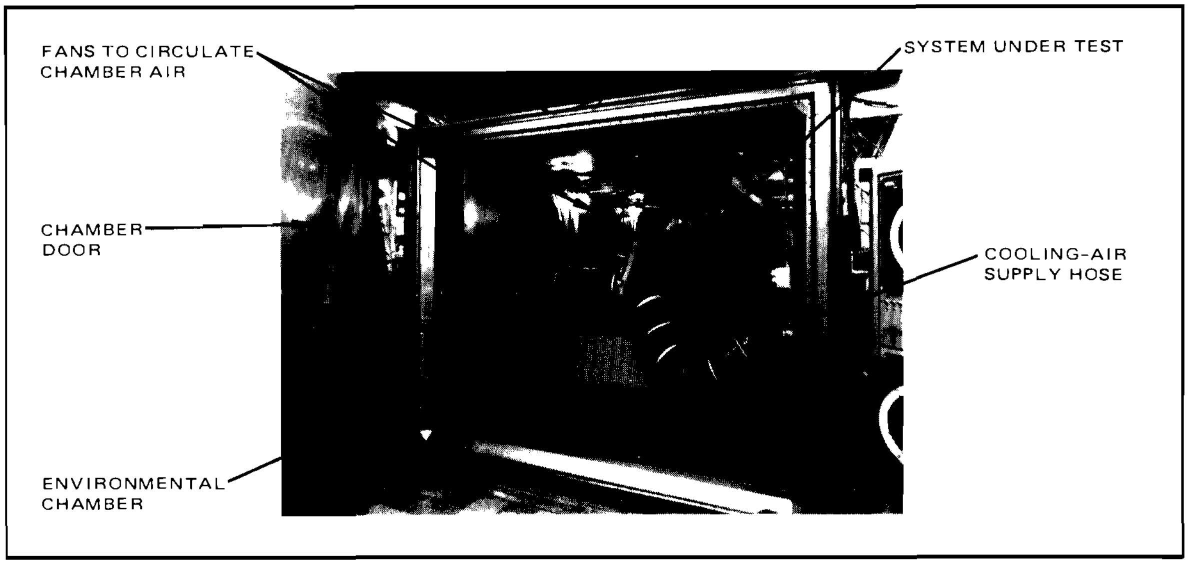


Figure 9-1. An avionic assembly is tested in an evacuated environmental chamber to simulate the flight altitude and ambient temperatures.

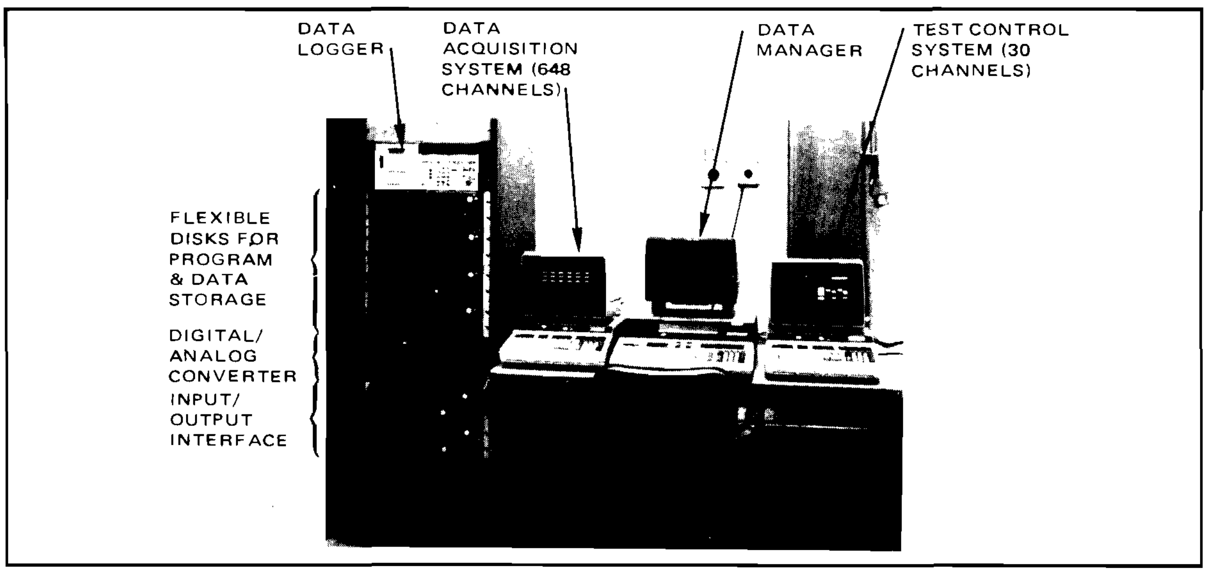


Figure 9-2. Modern data acquisition and control systems enable the measurement of many quantities in a thermal test.

TABLE 9-3. QUANTITIES TO MEASURE AND LOCATIONS TO INSTRUMENT

Part Temperatures (selected using thermal analysis and reliability prediction results)

- Hot parts
- Temperature-sensitive parts
- Representative parts

Dissipations

- Electrical measurement
- With forced-convection-cooled equipment, check with measurement of heat-flow rate into coolant

Thermal Resistances

- Junction-to-case thermal resistance, θ_{JC} (with semiconductor devices)
- Interface thermal resistances
- Coolant flow rate and pressure drop (with forced-convection-cooled equipment)

Sink Temperatures

- Chamber temperature (with free-convection-cooled equipment)
- Coolant inlet and outlet temperatures (with forced-convection-cooled equipment)
- Mounting-surface temperature (with equipment mounted to constant-temperature surface)
- Accessible local-sink temperatures, such as representative circuit-board temperatures

Other

- Simulated altitude in environmental chamber

Consequently, measurements of the dissipation distribution within an assembly are not available to the reliability engineer. Instead, estimated or nominal dissipations must be used in test-data interpretation.

An alternative method of measuring module or unit dissipation is feasible for forced-convection-cooled equipment. Because all the heat goes into the coolant, the measured values of coolant flow rate and inlet and exhaust coolant temperatures provide a check on the electrically measured dissipation. (See section on "Fluid Exit Temperature" in Appendix C.) If the dissipations measured by the two techniques do not agree within the experimental error, then the likely causes of the discrepancy are (1) heat leaks; (2) coolant leaks, a potential problem especially with air-cooled equipment; (3) an error in the electrical measurement (for example, not measuring the voltage drop across the appropriate terminals in the circuit); and (4) an error in the coolant-temperature measurement (when measuring air temperature with a thermocouple, wire no larger in diameter than 36 AWG is recommended to minimize conduction heat leaks).

The thermal resistances listed in Table 9-3 generally are measured indirectly, because it is not feasible to access the necessary instrumentation locations in a packaged assembly. The junction-to-case thermal resistance (θ_{JC}) of a semiconductor device is measured in separate tests of a sample of vendor-supplied parts. Numerous methods for measuring θ_{JC} have been developed.[9-14 through 9-31] Vendor-quoted values of θ_{JC} generally are much higher (more conservative) than values of the supplied parts. If over-temperature problems exist, the values for θ_{JC} can be measured. Thermal resistances of contact interfaces and adhesive bonds also are best measured in a separate test at the part or subassembly level.

The coolant flow rate always is measured in thermal tests of forced-convection-cooled equipment. Methods for measuring the flow rate, pressure, and velocity are well-established, and many instruments are available commercially.[9-1, 9-5, 9-6] Because of the low flow rates and small pressure changes occurring with air-cooled equipment, sensitive flow instrumentation is needed. Pressure drops and the pressure-head capabilities of cooling blowers are on the order of a few hundred pascals (a fraction of an inch or a few inches of water). Therefore inclined water manometers are commonly employed. The flow rate can be measured as a function of the pressure drop for an individual module or unit (see Figure 9-3). This calibration curve can be used subsequently for leak checking, inspecting the pressure-drop characteristics of production hardware, and matching to a blower.

Temperature measurements are the heart of thermal testing. For this reason and because advances in thermal instrumentation have been made in recent years, temperature-measurement methods are described in the following section.

TEMPERATURE MEASUREMENT METHODS

Temperature measurement methods can be categorized according to the temperature sensitive parameters (TSP) employed and according to whether the sensitive element must touch the item whose temperature is to be measured (*contact method*) or the temperature can be measured remotely (*non-contact method*). Some of the methods commonly used in a thermal laboratory are listed in Table 9-4 and described below.

The familiar liquid-in-glass *thermometer* can be used for approximate measurements of the ambient temperature in a laboratory. Spatial and temporal variations of the ambient temperature in a laboratory may be significant.

Temperature-sensitive *paints, lacquers, crayons,* and *pellets* employ materials whose appearance changes irreversibly when the temperature exceeds a specified value. A useful form of this instrument is a *label* containing several indicators, each having a unique temperature rating (transition temperature). Labels small enough for use on modern microelectronic parts are available commercially. They inherently indicate only the maximum temperature reached in a test, and can be useful for approximate measurements of this type.

The *thermocouple* is well-suited to thermal testing of electronic equipment and is widely used. Its advantages include suitability for automated data acquisition (see Figure 9-2) and for temperature measurement of parts in assemblies in environmental chambers. Its disadvantages arise from its contact nature and its electrical sensitivity.

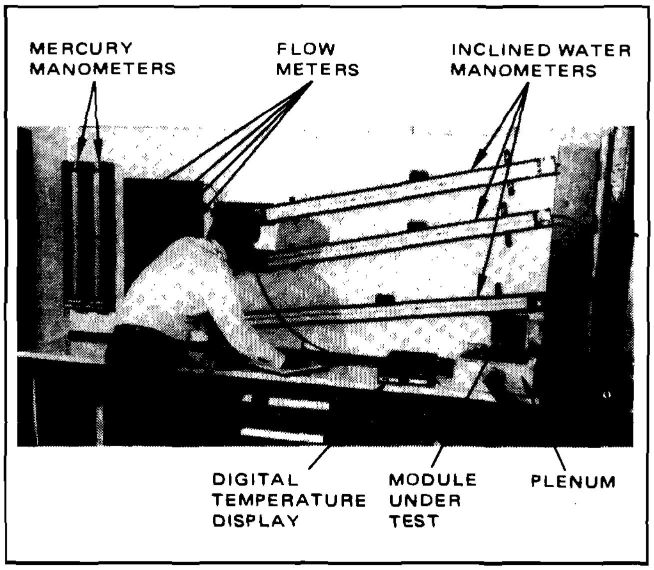


Figure 9-3. The flow-impedance characteristics of forced-convection-cooled equipment can be measured in a separate test on a flow bench.

TABLE 9–4. TEMPERATURE MEASUREMENT METHODS

Method	Temperature-Sensitive Parameter	Application	What to Watch Out for
Contact			
Thermometer	Length of liquid column	Ambient	Spatial variation in laboratory
Labels, etc.	Appearance of material	Approximate measurements	Overshoot during warm-up
Thermocouple	Voltage at junction of unlike conductors	Assemblies in environmental chambers	Improper installation[9-1]
Non-contact			
Infrared	Radiation emitted from surface	Deliverable hardware; detecting hot spots	Emissivity variances; spurious radiation
Laser	Photoresponse of semiconductor junction	Junction temperature of unlidded semiconductor devices	Junction must be accessible to laser beam
Electrical	Solid-state physics phenomena (e.g., diode forward-voltage drop)	Junction temperature of semiconductor devices	Measure location representative of hottest junction

Proper installation of the thermocouple is a key to a meaningful measurement. A poor contact between the thermocouple measurement junction and the measurement surface can lead to an error in the indicated temperature.[9-1] An adhesive bond (e.g., solder or epoxy) is preferred; tape is a less-desirable attachment method. Damage due to a bond might be objectionable with deliverable hardware. Another possible source of error is a spurious voltage signal resulting from the installation of a thermocouple on an ungrounded metallic surface. This error can be prevented by placing a 1-mil thick piece of Mylar tape between the thermocouple bead and the metallic surface to provide effective electrical isolation with negligible thermal effect.

Infrared (IR) thermography is based on the temperature dependence of the radiation emitted from a surface. It is a non-contact technique and has advantages over the contact methods in that: (1) no instrumentation has to be attached to the test item, which is important especially with deliverable hardware; (2) there is no practical limitation on the number of locations at which the temperature can be measured; and (3) the instrumentation locations do not have to be selected in advance, so that a hot spot on a circuit board can be detected even if one was not suspected.

The disadvantages of the IR method arise from its optical nature. Because the test item must be visible, the IR method is unsuitable for temperature measurements in an enclosed unit and/or in an environmental chamber. Furthermore, variances in the emissivity of the test item and spurious radiation from the test apparatus and/or the surroundings can cause an error.

A *laser* technique for measuring junction temperatures of semiconductor devices was developed in the 1970s. The TSP is the photoresponse of a semiconductor junction, which dictates an unlidded part and an unobscured junction. The laser technique appears to have several advantages, including: (1) excellent resolution, (2) very little test-item preparation, and (3) not dependent on the surface emissivity (a key factor with the IR method).

Electrical techniques have been used widely for many years for measuring junction temperatures. The TSP can be any of several parameters involved with the solid-state physics of the device (e.g., the forward voltage drop across a diode on the chip). Electrical methods have the advantages of being non-contact and applicable to a lidded part. A disadvantage is that a suitable measurement location (e.g., a diode on the chip) might not be easily accessible to an electrical measurement. In addition, the measurement diode must have a temperature close to that of the hottest junction on the chip, which will determine the chip's failure rate.

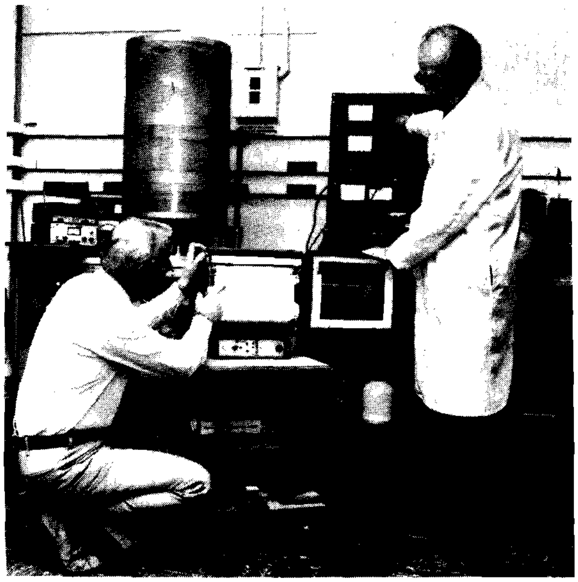


Figure 9-4. Testing is an important thermal evaluation method.

SUMMARY

Thermal testing involves the assembly and testing of hardware to evaluate the thermal design of electronic equipment. Testing may occur in each of the four acquisition phases. The reliability and thermal engineers participate in developing the test plan to ensure test realism and to decide what quantities to measure. An effective thermal evaluation must include simulation of thermal environment factors (dissipations, thermal resistances, and sink temperatures) and proper instrumentation to measure part temperatures and the quantities that affect them.

CHAPTER 10
THERMAL ENVIRONMENTAL STRESS SCREENING (BURN-IN)

This chapter covers the use of thermal screening for flaw precipitation. In particular, it discusses the various equipment levels of thermal screening, the cost benefits of screening at lower levels, and the importance of thermal surveys.

WHAT IS SCREENING?

Screening is a process performed on all items (part, module, unit, or system). It is intended to identify, force, and/or segregate those items defined as defective. An *environmental stress screen* is the application of a specific environmental stress or stresses (for example, thermal and vibration environments) to produce the desired separation or screening effect.

The screening process forces failures to occur in the factory that would otherwise occur in field usage. As a result, field reliability is improved and the cost of repair factory failures is optimized.

Not all environments are effective screening environments. The environment which becomes an effective screen is the environment which precipitates the highest percentage of defects, in the shortest time, without degrading the unit being screened. Screening should not be related to the mission requirements other than to limit the screening stress levels so that design capability is not exceeded.

A screen is not a test. Tests imply accept/reject criteria and minimizing failures; screens do not involve accept/reject criteria, and should maximize the number of defects/failures per unit of time and level of stess.

Screening technology is growing. Many ideas and concepts are changing, and considerable effort has been expended in the definition process. Therefore actual rates of change, temperature limits, and numbers of cycles cannot be universally applied to all types of equipment. Generally they are determined experimentally and tailored to the desired screening results.

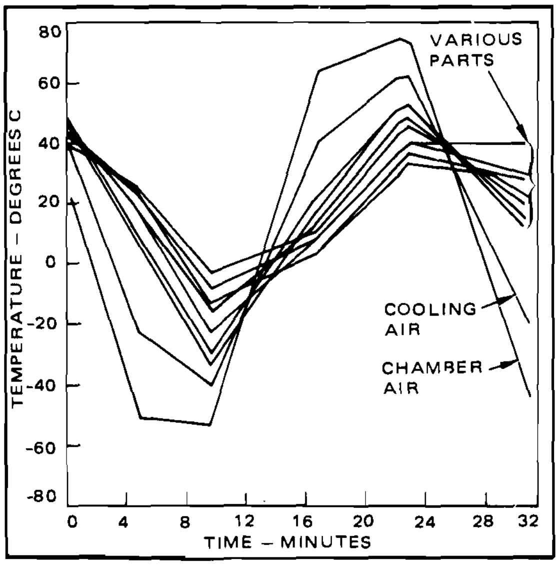


Figure 10-1. Part temperatures lag chamber air temperature.

THE NEED FOR THERMAL SURVEYS

The need to perform thermal surveys before any screening test must be emphasized. As shown in Figure 10-1, the thermal response of hardware can lag the chamber air temperature profile. In addition, if the unit is normally cooled with externally supplied air, the unit is even more insensitive to the chamber air variations. In such units, it is advisable to cycle the cooling-air temperature to achieve temperature response at the part level. In this way, a thermal screen can be designed which imposes meaningful thermal stresses on parts, solder joints, etc., to force flaws to failure. However, the thermal survey should assure a screen which precipitates flaws but does not cause good equipment to fail.

LEVELS OF THERMAL SCREENS

Thermal screens can be conducted on production hardware at the part level, on assemblies (e.g., modules), on units, and finally on the system (groups of units), sometimes called system burn-in. Where practical, screens should be implemented at the lowest possible level, since flaws detected at higher levels (e.g., unit/ system/system integration into vehicle) are more expensive to remove. For example, the costs of finding a bad part for different levels of assembly are documented in Table 10–1. As can be seen, repair costs at the system level are two to three times those at lower levels, while repair costs in the field are an order of magnitude higher than at the system-level.

In most cases, parts screening is done at a vendor for economic and corrective action reasons; also the precipitation of flaws in system-level screens is not particularly cost effective. Therefore this chapter will focus on thermal screening at the module and unit levels of assembly.

Module-Level Thermal Screening

The easiest and most economical thermal screen at the module level is *temperature cycling* with the module unpowered. Studies at Hughes have shown that (except often for optical devices) the rate of change of temperature in unpowered temperature cycling should be high (10–15°C/minute), while still maintaining the desired temperature range (at least 120°C). However, the cycle's extreme temperatures should not exceed the parts specification limits. The study also recommends that the number of thermal cycles be from 20 to 50, depending on the complexity of the modules and any special failure mode that must be screened.[10-3]

TABLE 10–1. HIGH LOGISTIC SUPPORT COSTS OF FINDING A BAD PART [10-1, 10-11]

Level at Which Bad Part Is Found	Cost Divided by Cost of Finding Bad Part at Module Level
Part	0.1
Module	1.0
Unit	1.4
System	3
In Field Use	44

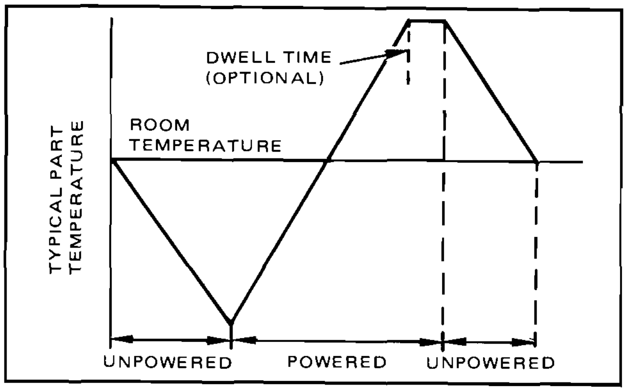


Figure 10-2. The thermal screening profile should reflect part temperature, not chamber temperature.

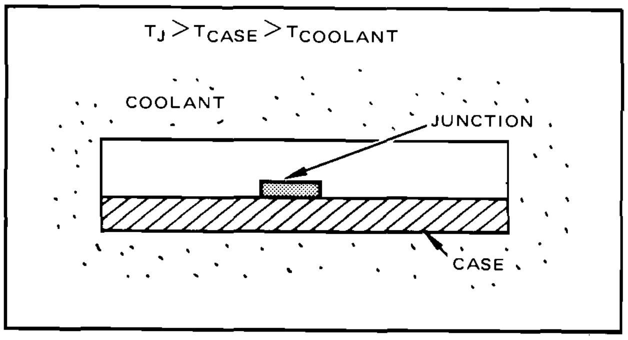


Figure 10-3. It is necessary to identify what the temperature requirement in a burn-in process refers to.

TABLE 10-2. PARTIAL LIST OF FLAWS AND FAILURE MECHANISMS ACCELERATED BY HIGH TEMPERATURE STRESS

Flaws	Failure Mechanisms
Chemical residues	Corrosion/oxidation
Sodium ion	Redistribution
Organic material	Aging
Lubricant	Evaporation
Insulation	Electrical breakdown or cold flow
Mechanical parts	Expansion/jamming or softening
Cracks	Fractures

Guidelines for module-level thermal screening are (1) rates of change greater than 20°C/minute should be avoided because they can cause failures in bonds in optical assemblies and excessive solder cracking, and (2) modules should be tested at low and high temperature extremes to detect performance or timing problems.

Unit-Level Thermal Screening

When unit-level thermal screening is used, the temperature histories of sensitive parts may vary widely from the thermal chamber temperature profile. Therefore, the thermal cycle should be defined by parts temperatures, not by the chamber temperature. Stabilization is usually defined as the time when two-thirds of the parts are at the required temperature. An example of a generalized thermal profile or cycle is shown in Figure 10-2.

The upper and lower temperature limits of the profile and the number of cycles should be defined on a case-to-case basis. In some cases, one could even exceed the operating limits. The rate of change of temperature should be as rapid as possible, with optional dwell times at temperature limits. Typically, one would start with four or five cycles. However, these screens should be adapted to the subsequent failure history; (for example, if the fourth and fifth cycles show no failures, they would be dropped. A key is to have contractual requirements flexible enough to allow such changes.

THERMAL ASPECTS OF PART BURN-IN

In some screening processes (part burn-in), a part is powered while maintained at a constant high temperature for an extended period. For example, the process might consist of operation at 125°C for 168 hours. The part is maintained at a constant temperature by a liquid or gaseous coolant. The coolant temperature and the thermal resistance between the coolant and the part are key factors in the success of the part burn-in process. As has been emphasized in this guide, a dissipating part is always hotter than its coolant. The difference between the part temperature and the coolant temperature equals the product of the part dissipation and the thermal resistance. It is necessary to account for this temperature difference in designing a burn-in process. If operation is too hot, good parts might fail. If operation is too cool, bad parts might not be detected.

In interpreting military documents (e.g., MIL-STD-883), the temperature requirement must be clearly understood.[10-10] For example, does 125°C refer to the temperature of the part junction, its case, or the coolant? They are different, as illustrated in Figure 10-3. For high-dissipation parts (20 W), the case may be 40°C hotter than the coolant; this difference must be accounted for in designing a burn-in process.

FLAWS AND FAILURE MECHANISMS ACCELERATED BY THERMAL SCREENING

Tables 10-2, 10-3, and 10-4 show a partial list of flaws and failure mechanisms accelerated by high temperature stress, thermal cycling, and non-operating cycling.

SUMMARY

Thermal screening is one process by which flaws in production hardware are precipitated. Thermal screens applied at the module and unit levels include high temperature stress, thermal cycling, and non-operating cycling. Before any screening, thermal surveys need to be performed to measure the equipment's response to temperature variations.

TABLE 10-3. PARTIAL LIST OF FLAWS AND FAILURE MECHANISMS ACCELERATED BY TEMPERATURE CYCLING

Flaws	Failure Mechanisms
Moisture	Corrosion from liquid-phase water
Mechanical part cracks	Fracture
Insulation cracks	Electrical breakdown
Unsoldered joints	Open circuit
Open hermetic seals	Contamination

TABLE 10-4. FAILURE MECHANISMS EXPERIENCED IN NON-OPERATING THERMAL CYCLING TEST

Item	Type of Failure
Parts	
IC	Open contact/wire bond fracture/die bond separation
LSI	Cracked quartz/case fracture
Solder	Shorts/fractures
Assemblies	Contamination/shorting Part/board bond separation
Printed wiring boards	Open interfacial connections Barrel cracks
Core memories	Core fracture Memory wire cracks

CHAPTER 11
PRODUCTION HARDWARE THERMAL EVALUATION

This chapter describes thermal evaluation during the production phase of a program. It includes the purpose and elements of production-phase thermal programs, and concludes with a discussion on thermal inspection technology.

TABLE 11–1. ELEMENTS OF THE PRODUCTION-PHASE THERMAL PROGRAM

- Establish tolerances on production processes affecting part temperatures.
- Establish means for verifying that hardware meets those tolerances.
- Evaluate thermal impact of proposed changes.

PRODUCTION PHASE THERMAL EVALUATION

The objective of thermal evaluation in the production phase is to ensure that the operating temperatures of the thermally sensitive parts in the delivered equipment will be within specified tolerances of the design values. Production approval occurs after the system and the principal items necessary for its support have been designed, fabricated, tested, and evaluated in the full-scale engineering development phase. This approval indicates that the design is basically adequate (although design defects can show up in the production phase) and that the contractor can build at least a few thermally adequate systems. Production-phase thermal evaluation differs from that in the earlier phases in its focus on deviations of production systems from the nominal, rather than on the nominal system itself.

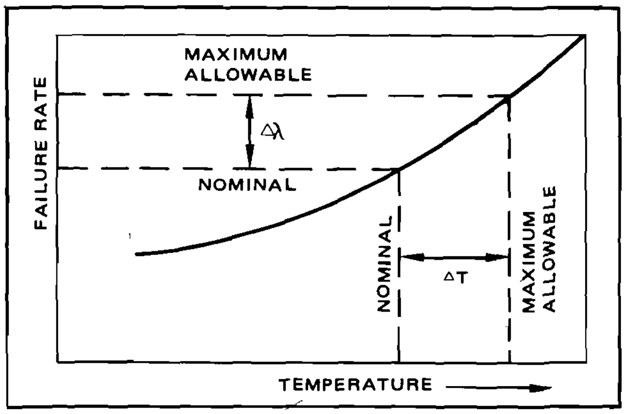


Figure 11–1. The part failure rate dictates the part temperature operating limits.

ELEMENTS OF PRODUCTION PHASE

The elements of the production-phase thermal program are listed in Table 11–1. This program consists of determining the acceptable upper limits on the operating temperatures and ensuring that the operating temperatures of the delivered hardware will not exceed those upper limits. Each step is discussed below.

Establishment of Production Tolerances

Establishing thermally acceptable production tolerances is an iterative process involving reliability engineering, thermal engineering, and manufacturing personnel. The reliability engineer establishes the acceptable failure rate, and allocates it to the individual parts. The reliability prediction method is employed to generate curves, such as the one shown in Figure 11–1, which enable the temperature sensitivity of the parts to be identified. The thermal engineer generates curves, such as those shown in

Figure 11-2, which enable the temperature sensitivity of the manufacturing processes to be identified. The data are employed to specify the allowable tolerances on the temperature-critical processes.

Establishment of Verification Procedures

Key items to watch are those that are sensitive to manufacturing workmanship. A sampling test is needed to assure that the thermal characteristics of the equipment are produced as designed. Some thermal elements that require inspection are listed in Table 11-2.

The thermal engineer is involved in designing inspection procedures and evaluating the first few serial numbers that are produced. Thereafter, routine inspections are turned over to quality control personnel.

Evaluation of Proposed Changes

The thermal/reliability impact of any changes in the design, fabrication techniques, or materials proposed during the production phase is evaluated before implementation. Some of the factors involved in such an evaluation are listed in Table 11-3.

THERMAL INSPECTION TECHNOLOGY

Many manufacturing processes are difficult or impossible to inspect visually. For example, it is impossible to verify visually the presence of adhesive between two opaque surfaces. At best, a visual inspection can reveal only whether adhesive is present around the edges of the interface. Modern thermal inspection techniques, however, can be valuable aids in ensuring a thermally adequate product.

Inspection of the thermal adequacy of a product can be accomplished by a comparison technique. Such a technique is feasible for parts or small assemblies, such as hybrid microcircuits. It is also cost-effective for critical items.

First, establish a standard (i.e., a serial number of the product that is known to be thermally adequate). The thermal testing methods in Chapter 9 can be employed to verify the thermal adequacy of this standard. Second, compare the appropriate temperatures of each serial number that has just come off the production line with those of the standard. Reject all items having temperatures that

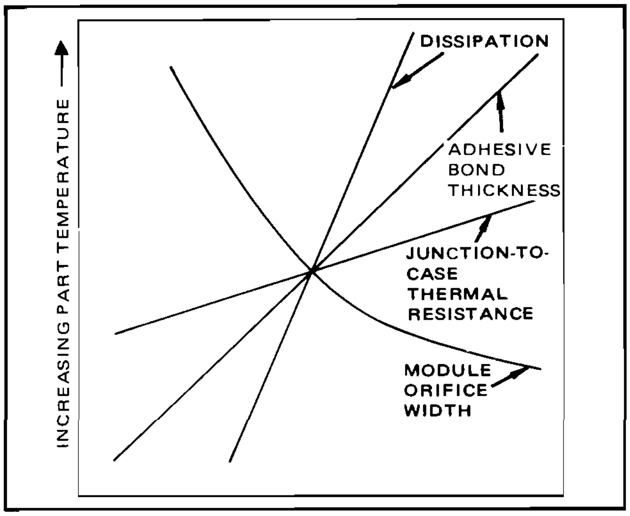


Figure 11-2. Typical curves show the sensitivity of part temperature to various manufacturing processes.

TABLE 11-2. SOME THERMAL ELEMENTS THAT REQUIRE INSPECTION

Thermal Interfaces

- Contact interfaces
- Adhesive bonds

Coolant Flow Systems

- Air seals
- Airflow metering orifice dimensions
- Heat-exchanger pressure drops

TABLE 11-3. THERMAL/RELIABILITY FACTORS INVOLVED IN EVALUATING PROPOSED CHANGES

- Proposed changes in production tolerances
- Thermal conductivity of materials
- Production variances in thermal resistance resulting from fabrication techniques
- Part dissipation changes
- Mounting changes
- Cooling flow path changes

differ by more than a specified amount from those of the standard. Such an inspection-by-comparison technique is well-suited to automation.

The item should be inspected in the earliest possible stage of assembly. For example, the thermal-adhesive bond between a circuit board and a finned heat exchanger should be inspected before mounting parts on the board. This procedure saves the cost of reworking or scrapping assembled modules if the board/heat exchanger bond is found to have an unacceptably high thermal resistance. It also enables direct comparison without the complicating effects of variances in the parts and in the part-to-board thermal bonds. As an example, Figure 11-3 shows a system developed to inspect the thermal bond between the substrate and package of a hybrid microcircuit before the chips are mounted on the substrate.[11-6]

In specifying the maximum acceptable temperatures, any thermal differences between the inspection conditions and the actual operating conditions must be accounted for. For example, it was desired to inspect the thermal bond between integrated-circuit

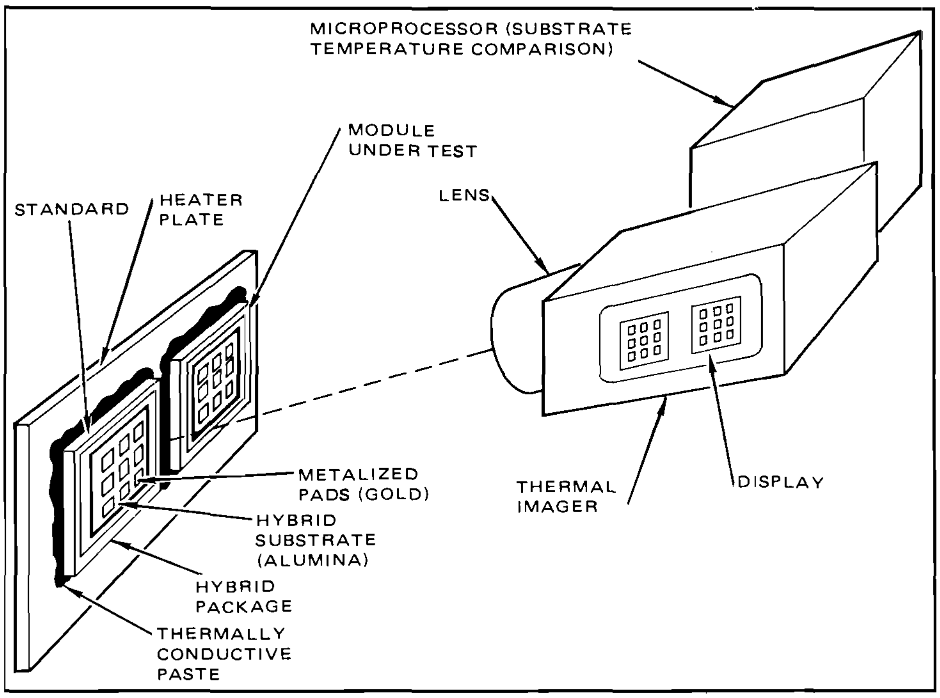


Figure 11-3. Infrared comparison of a module under test with a standard module enables rapid thermal evaluation.

flatpacks and a conduction-cooled circuit board in an avionic unit. For high-altitude operation, the rate of heat transfer to the ambient is negligible, and the dissipation is transferred only by conduction. In an inspection test at sea level, however, heat also can escape by radiation and free convection to the surroundings, as shown in Figure 11-4. Tests have shown that the part temperatures were 6-16°C cooler in the inspection conditions than in the actual operating conditions. Furthermore, the heat losses occurring in the inspection conditions reduced the temperature difference between the well-bonded and poorly bonded flatpacks. Tests showed that a 2°C difference in the inspection test corresponded to an 8°C difference in high-altitude operation. The acceptance/rejection criterion was adjusted accordingly.[11-7]

Infrared thermography is a convenient method for measuring temperatures in inspection tests. Its non-contact nature is an advantage for use with deliverable hardware, and its imaging capability enables defects to be detected at any visible location of the unit under test.

SUMMARY

Thermal evaluation during the hardware production phase is designed to ensure that the operating temperatures of the delivered equipment will be within specified tolerances of the design values. Thermal and reliability engineers participate in establishing production tolerances and inspection methods and in evaluating proposed changes. A useful thermal inspection technique compares the temperatures of production hardware with those of a previously measured and acceptable standard. Infrared thermography is a convenient method for measuring temperatures in inspection tests and is well-suited to automation.

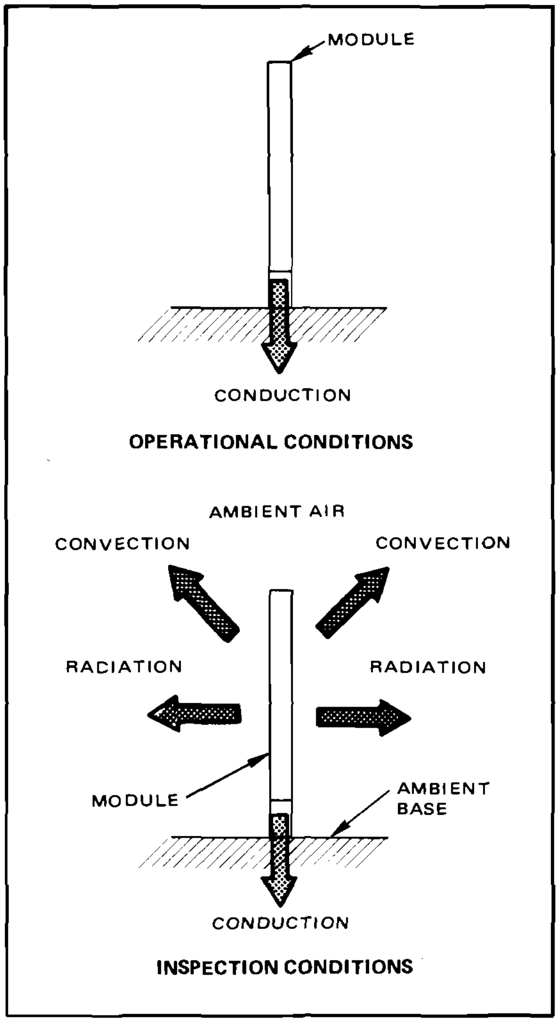


Figure 11-4. Heat transfer paths in inspection conditions might differ significantly from those in operational conditions.

CHAPTER 12
GUIDELINES FOR ACHIEVING RELIABLE THERMAL DESIGNS

TABLE 12–1. COOLING TECHNIQUES FOR EQUIPMENT USED AT SEA LEVEL

Cooling Technique That Will Suffice for Most Applications	Dissipation per Unit Volume	
	W/m^3	W/ft^3
Free convection to ambient air	0–11,000*	0–300*
Forced air	11,000*–35,000	300*–1000
Custom design; thermal considerations should have top priority in physical design.	>35,000	>1000

* 3,500 W/m^3 (100 W/ft^3) instead of 11,000 W/m^3 (300 W/ft^3) if box is poorly ventilated and thermally sensitive parts are mounted horizontally

TABLE 12–2. MAXIMUM DISSIPATION PER UNIT AREA FOR COMMON COOLING TECHNIQUES

Cooling Technique	Maximum Dissipation per Unit Heat Transfer Area	
	W/m^2	W/in^2
Free convection to ambient air and radiation to surroundings	800	0.5
Impingment (forced air)	3,000	2
Air-cooled plate	16,000	10
Free convection to a liquid	500*	0.3*
Liquid-cooled plate	160,000	1000
Evaporation	5×10^7	30000

* Per °C temperature difference between surface and liquid

This chapter presents rules of thumb and "do's and don'ts" for the reliability engineer as guidelines for evaluating thermal designs. The following aspects of thermal design are discussed:

- Limitations on cooling techniques
- Placement/layout of parts
- Mounting parts
- Blower selection/installation
- Coolant flow passage design

LIMITATIONS ON COOLING TECHNIQUES

The relative merits of the various cooling techniques are discussed in Chapter 7. This portion of the guide presents limitations on those techniques.

The cooling techniques are limited primarily by the dissipation density of the electronic equipment (i.e., the ratio of the dissipation to the volume of the box in which the equipment is packaged). Table 12–1 lists rules of thumb for selecting a cooling technique for sea-level-based equipment. Another measure of this quantity is the ratio of the dissipation to the total heat transfer area, including the fin area. Table 12–2 lists maximum dissipation per unit area for common cooling techniques. Table 12–3 lists limitations for forced-air-cooled module microelectronic parts. Table 12–4 lists limitations for other cooling techniques.

PLACEMENT/LAYOUT OF PARTS

Operating temperatures are affected by the location of the equipment and by the arrangement of the parts within the equipment. Thus the equipment's reliability depends on the parts' placement and layout. "Do's and don'ts" of parts placement/layout for maximum reliability follow.

1. Provide as much separation as possible between dissipating parts.
   a. Within a forced-air-cooled unit, try to spread the dissipating parts uniformly along the coldwall.
   b. Do not place thermally sensitive or high-dissipation parts close to each other.
   c. Do not place thermally sensitive parts next to hot parts.
   d. With free-convection-cooled equipment, do not place parts directly above high-dissipating parts. Instead stagger them horizontally, as shown in Figure 12-1.
2. Mount equipment in the coolest available environment.
   a. Do not mount engine accessories containing electronic equipment directly on the engine. Install them instead in a more benign thermal/vibration environment (e.g., on the airframe).
   b. Do not mount an aircraft engine transducer in a hot region, such as the engine exhaust region. Install it instead under the engine and forward of the combustion section. If it must be located on the engine strut, then place it in the forward section away from the engine.
   c. Do not locate an aircraft fire detection control unit in the wing dry bay. The environment there is severe. It has extreme temperatures, high vibration, and excessive moisture.
3. Lay out parts so that the temperature-sensitive parts are in the coolest region. (Reason: to maximize the reliability of the assembly, as described in Chapter 8)

TABLE 12-3. LIMITATIONS ON FORCED-AIR COOLING TECHNIQUES FOR MODULE MICROELECTRONIC PARTS

Cooling Technique	Maximum Cooling Capacity	
	W/m^2	W/in^2
Impingement	800	0.5
Coldwall	1500	1
Flow-through	3400	2

TABLE 12-4. LIMITATIONS ON VARIOUS COOLING TECHNIQUES

Thermoelectric Coolers
Heat-sink temperature ≤100°C
Cooling load ≤300 W
Vapor-Cycle Refrigeration
Power requirement = 250–1000 W per 1000 W of refrigeration
Ambient temperature ≤71°C (≤200°C for specially designed vapor-cycle equipment)
Expendable Evaporant Cooling
Heat sink temperature ≥93°C
Duration of operation ≤3 hrs.

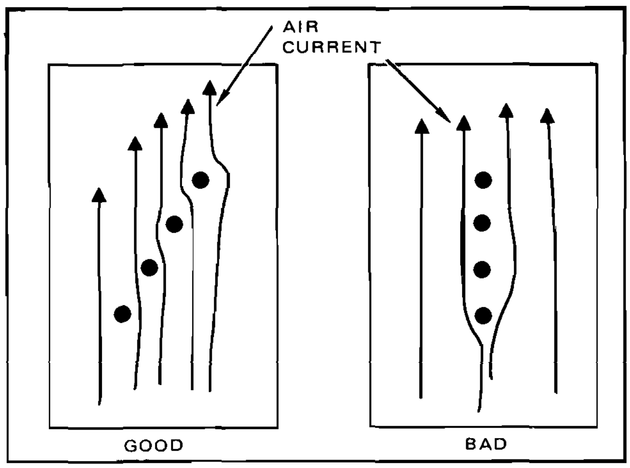


Figure 12-1. With free-convection-cooled equipment, do not place parts directly above high-dissipating parts.

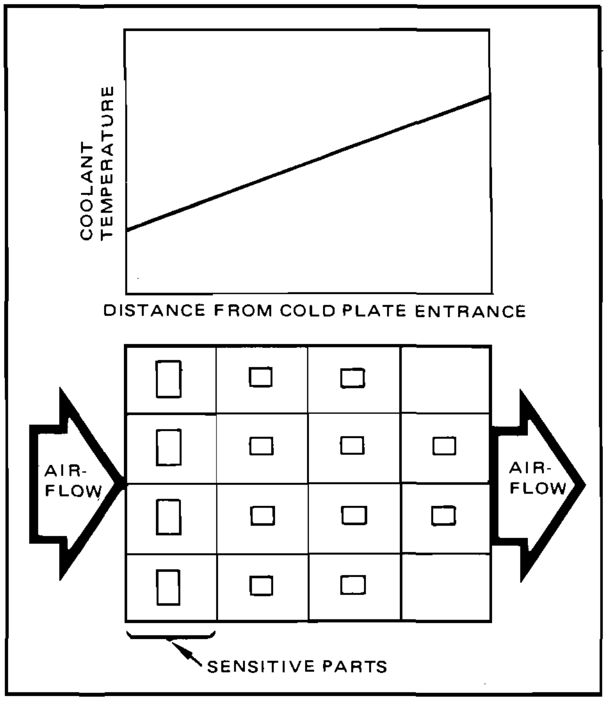


Figure 12–2. With forced-convection-cooled equipment, place the thermally sensitive parts near the coolant inlet side, where the coolant has its lowest temperature.

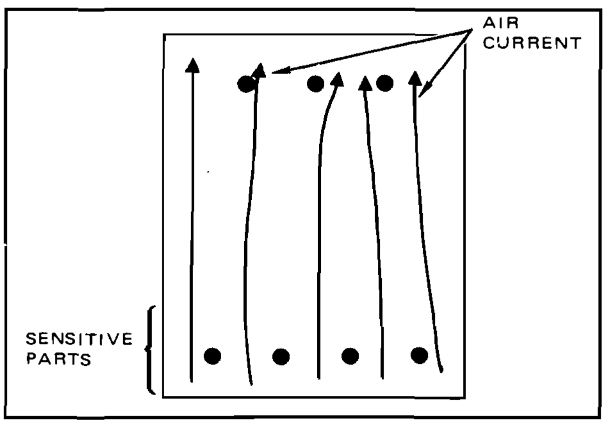


Figure 12–3. With free-convection-cooled equipment, locate thermally sensitive parts at the bottom.

a. With forced-convection-cooled equipment, place the temperature-sensitive parts near the coolant inlet side and the less-sensitive parts on the outlet side, as shown in Figure 12–2.

b. With free-convection-cooled equipment, locate temperature-sensitive parts at the bottom and the others above them, as shown in Figure 12–3.

c. With coldwall-cooled circuit cards, place sensitive parts close to card edge.

MOUNTING PARTS

The thermal design objective in mounting parts is to minimize the thermal resistance between the case and a sink. General guidelines for minimizing the conduction and contact thermal resistances are listed in Chapter 5. Specific guidelines follow.

1. Use short paths. (Reason: to minimize the thermal resistance to conduction, as shown in Equation 5–3)

   a. For cold-plate-cooled equipment, mount the parts directly to the cold plate whenever possible.

   b. Minimize the thickness of adhesive bonds used to attach parts to a module or cold plate.

2. Use large areas. (Reason: to minimize the thermal resistance, as discussed in Chapter 5)

   a. Do not mount parts so that the only conduction path to the heat sink is through the leads.

   b. Mount high-power hybrid microcircuit chips on molybdenum tabs having a larger area than the chip, as shown in Figure 12–4.

   c. Mount high-power parts cooled by free convection and radiation or by impingment cooling on heat transfer fins, as shown in Figure 12–5.

d. Do not use tightly spaced fins for free-convection cooling. Do not use more than four fins per inch, and do not use fins higher than 1 inch.

e. Maximize the areas of all conduction paths and interfaces between the parts and the sink.

3. Use materials having high thermal conductivity. (Reason: to minimize the thermal resistance to conduction, as shown in Equation 5-3)

a. Use metals such as copper and aluminum for heat-conduction paths and mounting brackets.

b. With spacecraft and high-altitude avionic equipment where free convection is non-existent or very small, fill all gaps along the heat-flow path with thermally conductive compounds, as shown in Figure 12-6.

c. With flow-through modules comprised of multi-layer printed wiring boards, use *plated-through-holes* to reduce the thermal resistance to conduction through the board. These copper-plated holes are thermal paths called *thermal vias*, as shown in Figure 12-7.

d. Minimize the use of interfaces between contacting surfaces as thermal paths.

4. When contact interfaces are used, the following practices will minimize the contact thermal resistance.

a. Use as much contact area as possible.

b. Ensure that the contacting surfaces are flat and smooth.

c. Use soft contacting materials.

d. Torque all bolts to achieve a high contact pressure.

e. Use enough fasteners to assure a uniform contact pressure.

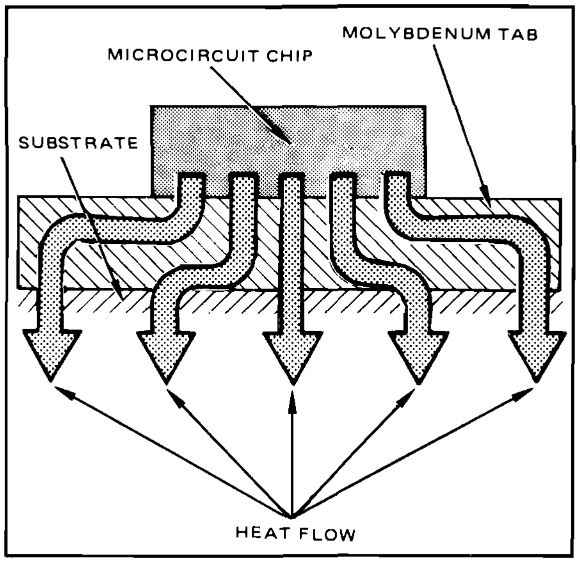


Figure 12-4. Mount high-power hybrid microcircuit chips on oversize molybdenum tabs to increase the area of the conduction path.

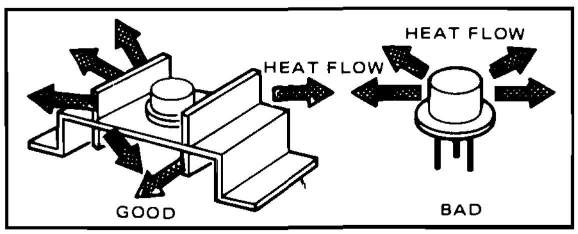


Figure 12-5. Mount high-power parts on finned heat sinks to increase the heat transfer area.

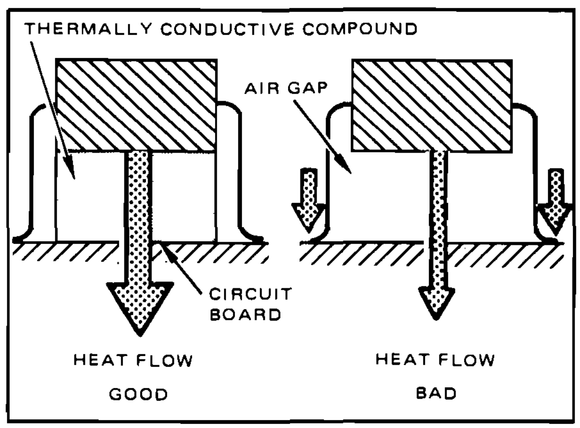


Figure 12-6. Fill gaps under parts in equipment used at high altitudes with thermally conductive compounds.

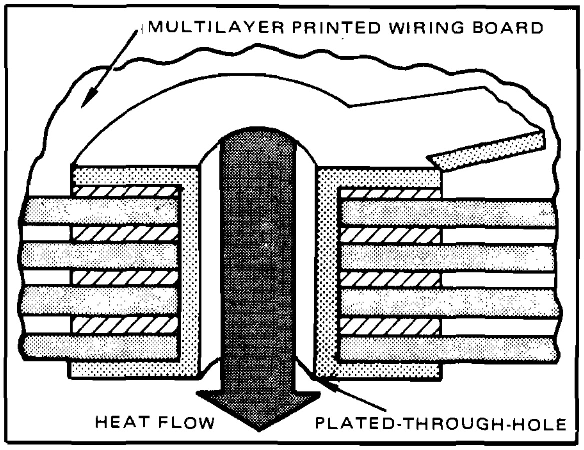


Figure 12-7. Use plated-through-holes in multilayer printed wiring boards as thermal vias to reduce the thermal resistance to conduction through the board.

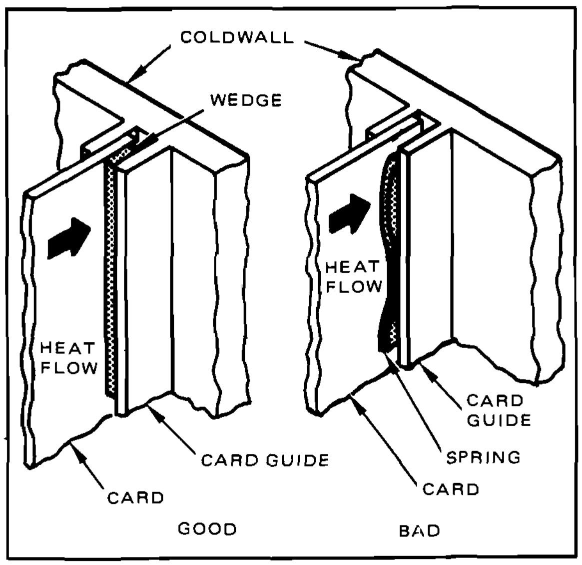


Figure 12-8. Use a positive means to provide contact pressure between a card guide and the card edge with a coldwall-cooled card.

f. With coldwall-cooled cards, do not use spring-loaded card guides to provide contact pressure between the card guide and the card edge. Instead use something positive (e.g., wedge clamps or cam-operated guides, as shown in Figure 12-8).

5. With radiation-cooled equipment, the thermal resistance to radiation can be minimized as follows.

   a. Ensure that the emitting surface has a high emissivity.

   b. Provide the emitting surface with an unobstructed and wide view of the heat sink.

   c. Maximize the emitting area, as shown in Figure 12-5.

6. Circuit cards with a dissipation greater than about 2 W need a copper ground plane. Those cards with 5-10 W need a heat sink.

7. Use materials having similar values of the coefficient of thermal expansion. Mismatches can produce thermal stresses which cause failures.

BLOWER SELECTION/INSTALLATION

Guidelines for selection and installation of blowers with forced-air-cooled equipment are listed below.

1. Use fixed-speed blowers only at low altitudes. For altitudes above 3048 m (10,000 ft), use variable speed blowers.

2. Do not use blowers operating at speeds greater than 10,000 revolutions per minute in an aircraft cockpit area or near a crew area since high-speed blowers are noisy.

3. Cooling blower dissipations should not exceed 10 percent of the thermal load.

4. Install the blower so that it pulls, rather than pushes, the air through the equipment, as shown in Figure 12-9. Pulling the air causes

it naturally to flow uniformly through the volume to be cooled. Pushing the air results in a jet downstream of the blower; it is difficult to design a flow spreader that produces uniform flow. Thus pulling the air provides cooling of all the equipment, whereas pushing the air results in stagnation regions in which parts can get excessively hot. Pulling also has the advantage that the dissipation of the blower is at the exhaust of the equipment.

5. Do not place the inlet of a blower directly downstream of the exhaust of another blower. Hot air might be drawn into the downstream blower.

6. Leave a clearance of at least 1×10^{-2}m (1/2 inch) downstream of the exhaust of a coolant air blower (to prevent degradation of the blower's cooling effectiveness by blockage of the exhaust), as shown in Figure 12-10.

7. Do not put two different blowers in series or in parallel unless the flow rates and head pressures in the system are balanced.

8. Account for short-duration thermal overstress which can cause failures (for example overstress resulting from temporary loss of coolant).

9. Ensure proper cooling of equipment during troubleshooting (for example, when cabinet doors are open or circuit cards are removed from a unit during functional testing).

COOLANT FLOW PASSAGE DESIGN

Guidelines for the design of coolant flow passages in convection-cooled equipment are listed below.

1. Do not obstruct coolant flow over parts (see Figure 12-11).

2. Do not use solid covers on cabinets of electronic equipment cooled by the ambient air. Some parts might be located in stagnation regions and thus be "starved" of coolant air. Instead use perforated covers.

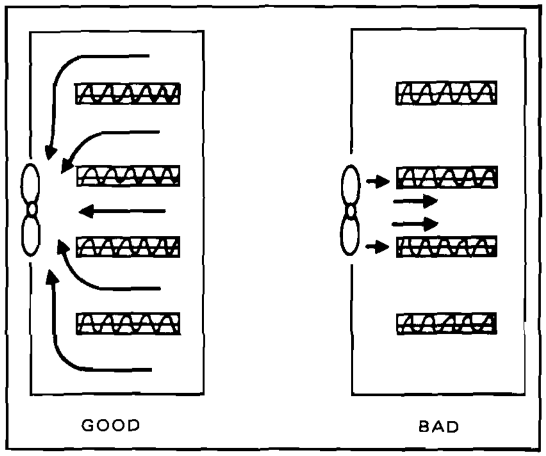


Figure 12-9. Pull, rather than push, cooling air through equipment.

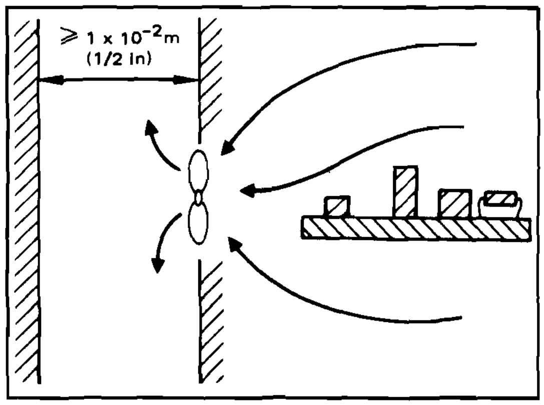


Figure 12-10. Do not block the exhaust of a cooling blower.

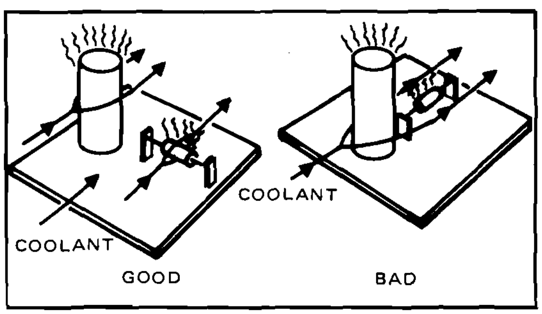


Figure 12-11. Do not obstruct coolant flow paths over parts.

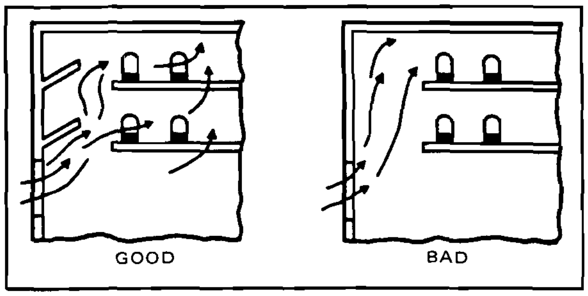


Figure 12-12. Direct flow over hot parts by means of splitters and turning vanes.

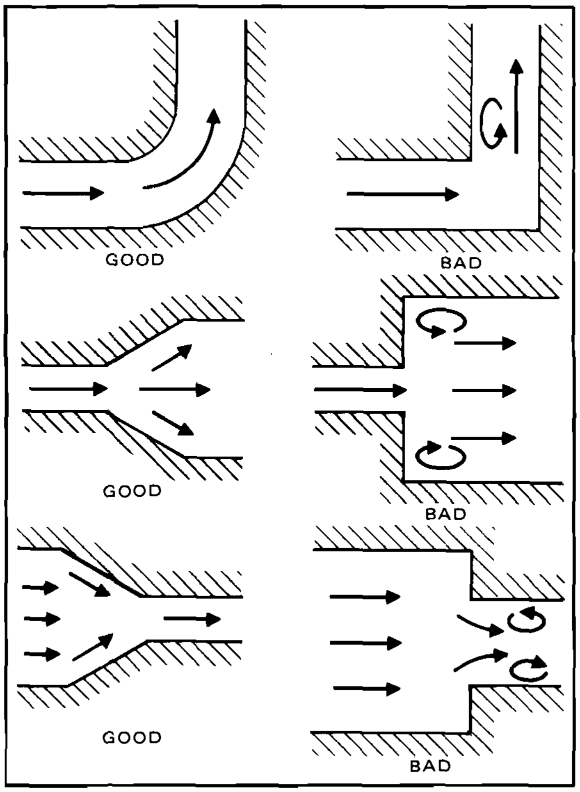


Figure 12-13. Use gradual turns, enlargements, and contractions in coolant flow passages.

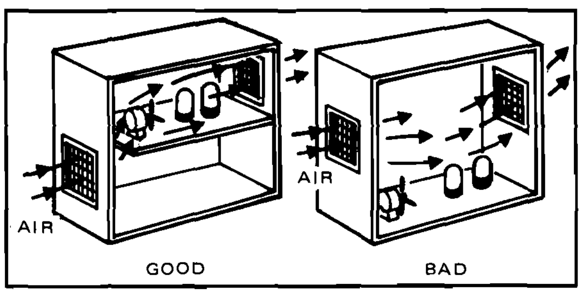


Figure 12-14. Design so that free convection aids forced convection.

3. Direct flow to the parts by means of splitters and turning vanes, as shown in Figure 12-12.
4. Maximize the radii of turns in flow passages (see Figure 12-13).
5. Do not use sudden enlargements or contractions in flow passages (see Figure 12-13).
6. Design so that free convection aids forced convection, as shown in Figure 12-14.
7. For free-convection-cooled equipment, install circuit boards and cooling fins vertically, rather than horizontally.
8. Dust covers should be used for applications utilizing external air. Pressure drop across filters should be accounted for when selecting a blower.

SUMMARY

The choice of a cooling technique for a specific application is dictated primarily by the dissipation density of the equipment. Other limiting factors include the total dissipation and the sink temperature. The placement and mounting of parts have significant effects on the reliability of the equipment. Blower selection and installation and the design of coolant flow passages are key factors in achieving reliable convection-cooled equipment.

CHAPTER 13
CORRECTION OF POOR FIELD RELIABILITY BY IMPROVING THE THERMAL DESIGN

This chapter suggests how to improve reliability deficiencies by improving the equipment thermal design after the equipment already has been designed. Such deficiencies are necessarily expensive and time-consuming to correct. It is more cost effective to prevent failures by ensuring that the original thermal design is adequate; the guidelines for accomplishing this objective are described in Chapters 1-12. This chapter discusses the costs of failures and of correcting them, ways of improving existing thermal designs, and actual examples of successful corrective action.

COSTS OF THERMALLY INDUCED FIELD FAILURES

The Air Force Acquisition Logistics Division has compiled the data listed in Table 13–1 on the costs of thermally induced failures. These data were obtained from the AFALD Lessons Learned Program in 1980.[13-1]

TABLE 13–1. AIR FORCE DATA ON COSTS OF THERMALLY INDUCED FAILURES[13-1]

Equipment	Cause of Failure	Failure Rate	Cost per Failure
Cathode ray tube for aircraft head-up display	Heat, external light, electrical saturation, and vibration	200–400 per year	$800–1000
Aircraft fire detection control unit	Extreme temperatures, high vibration, and moisture	Not listed	6.3 maintenance man-hours

COSTS OF THERMAL MODIFICATIONS

MIL–HDBK–251 quotes the results of a 1968 Navy study on the cost of thermal improvement of existing shipboard equipment.[13-2] The data are listed in Table 13–2. The modified and evaluated equipment was old and used, and the parts had a history of severe thermal overstress. Because major modifications could not be made, the improved thermal design was not optimum. The calculated added incremental cost of providing an adequate thermal design during the initial design and procurement of the equipment was less than the modification cost.

TABLE 13–2. NAVY DATA ON COSTS OF THERMAL MODIFICATIONS OF EXISTING EQUIPMENT[13-2]

Equipment	Time to Pay for Modification Costs, on Basis of Maintenance Cost Savings (months)
Small (100–500 W) equipment	4–6
Large high-power radar	9

WAYS TO IMPROVE EXISTING THERMAL DESIGNS

Improvement of an existing thermal design is accomplished by reduction of one or more of the factors that affect the operating temperature: dissipations, thermal resistances, and sink temperatures. These factors are affected by several aspects of the system design. Design improvements that can reduce these factors are listed in Table 13–3.

TABLE 13–3. WAYS TO IMPROVE EXISTING THERMAL DESIGNS

Factor Affecting Operating Temperature	Design Improvement(s)
Dissipations	Reduce parts dissipations (responsibility of electronic circuit designer).
Thermal resistances	
Conduction	1. Replace semiconductor devices with devices having lower values of θ_{JC}.
	2. Remount parts per guidelines 1b, 2b, 3b, and 4 of Chapter 12 "Mounting Parts."
Convection	1. For free-convection-cooled equipment, install blowers.
	2. For forced-convection-cooled equipment, increase quantity or size of blowers.
	3. For aircraft-ECS-cooled equipment, obtain a higher coolant flow rate (responsibility of aircraft system thermal designer).
	4. Install blower(s) per guidelines 4, 5, and 6 of Chapter 12 "Blower Selection/Installation."
	5. Reallocate available coolant to temperature-sensitive parts by means of flow restrictors, called *orifices.* They act as flow dividers in the same way that resistors act as current dividers.
	6. Modify coolant flow passages per guidelines of Chapter 12 "Flow Passage Design."
	7. Mount temperature-sensitive parts on heat transfer fins, as shown in Figure 12–6.
Radiation	Follow guidelines 5a, 5b, and 5c of Chapter 12 "Mounting Parts."
Sink temperatures	1. Follow guidelines 2a, 2b, and 2c of Chapter 12 "Placement/Layout of Parts."
	2. Decrease the coolant inlet or mounting-surface temperature.
	3. Install a refrigeration system (see Chapter 7 "Refrigeration Systems").

EXAMPLES OF SUCCESS IN ACHIEVING IMPROVEMENT BY THESE MEANS

This section describes case histories of successful improvement of existing thermal designs. The first example involves ground-based equipment originally designed for free-convection cooling, and the second one involves forced-air-cooled avionic equipment.

Electronic Field Test Unit

This equipment was designed for passive cooling, and no thermal analysis or test was performed. The acceptance testing consisted only of electrical functional checks.

Failures occurred in the production-phase acceptance tests, four weeks before the scheduled delivery of the first five units. While undergoing the functional check, the unit shut off after operating for approximately 45 minutes, which was considerably shorter than the required equipment operating period.

Thermocouples were installed on parts deemed to be thermally sensitive, and it was discovered that one of these parts reached the temperature at which a thermal sensing switch would cut off power.

A thermal engineer was called in to help solve the problem. After performing thermal analysis on the design, the thermal engineer recommended that the design be changed by installing a blower inside the unit to circulate the air, as shown in Figure 13-1. The heat was removed from the parts by the internal air through forced convection and then rejected to the skin of the enclosure. It was ultimately rejected by free convection and radiation to the surroundings.

Fighter Aircraft Radar Unit

This equipment utilizes flow-through cooling. The coolant air enters the module cold plates from a plenum, as shown in Figure 13-2. With the orginal coolant airflow passage design, the airflow separated immediately downstream of the 90° turn leading into the plenum. This separation produced a nonuniform plenum pressure distribution. As a result, the modules immediately downstream of the turn received a lower flow rate than was intended. The exhaust temperature was correspondingly higher, and the parts operated excessively hot. At minimum design flow, the radar turned off during flight and ground-cart operation.

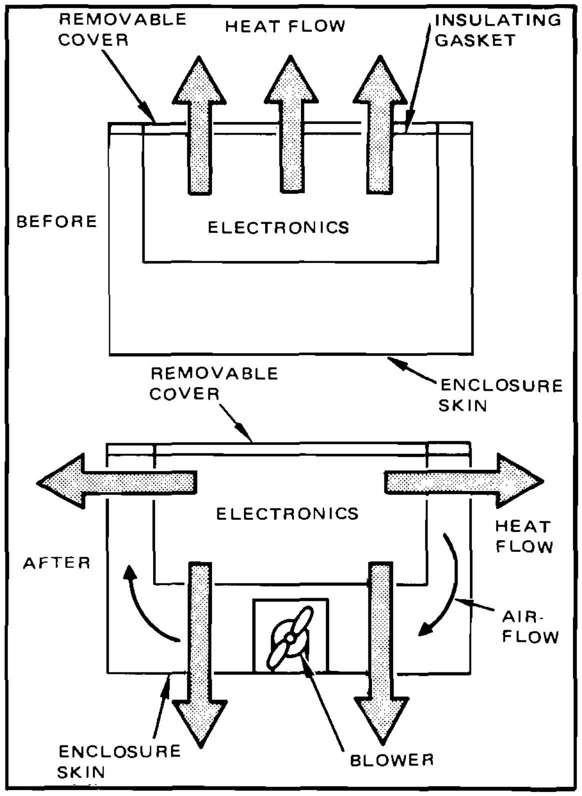


Figure 13-1. The thermal design of this electronic field test unit was improved by the addition of a blower.

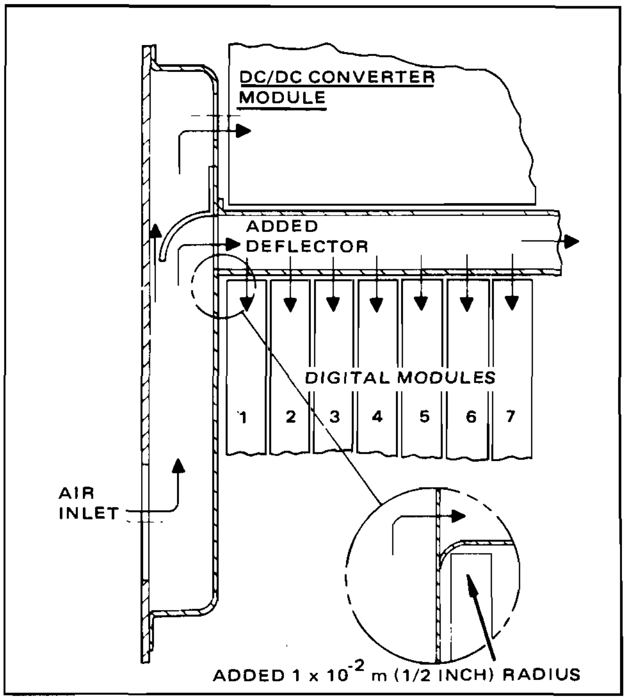


Figure 13-2. Improvement in the plenum design of this fighter aircraft radar unit produced a significant improvement in the field reliability.

The plenum was modified, as shown in Figure 13-2, to avoid flow separation and improve the plenum pressure uniformity. This modification substantially improved the thermal design by reducing the exhaust temperature. Test data showing the improvement are listed in Table 13-4.

SUMMARY

Improving the thermal design of electronic equipment can improve field reliability and prevent the high cost of thermally induced field failures. Promoting adequate thermal design during the initial design stage of electronic equipment costs less than modifying equipment in the field. Thermal designs can be improved by reducing one or more of the factors that affect the operating temperature: dissipations, thermal resistances, and sink temperatures.

TABLE 13-4. EFFECT OF PLENUM DESIGN ON EXHAUST AIR TEMPERATURE

Module*	Exhaust Temperature at Maximum Coolant Airflow (°C)		
	Before Modification	After Modification	Improvement
1	68	53	15
4	52	41	11
7	52	52	0

* See Figure 13-2.

APPENDIX A
DEFINITIONS OF TERMS

The terms listed below are defined according to their use in this guide. Some of the definitions were obtained from the following sources:

- "Reliability/Design, Thermal Applications," MIL-HDBK-251, 19 January 1978.
- *Environmental Stress Screening Guidelines,* Institute of Environmental Sciences, Mount Prospect, IL, 1981.
- "Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety," MIL-STD-721B, 25 August 1966.
- "Dictionary of Technical Terms for Aerospace Use," 1st ed., W.H. Allen (Ed.), NASA SP-7, 1965.

ABSOLUTE TEMPERATURE—The temperature measured relative to absolute zero (see p. 27).

ABSORBER—The body gaining photons in radiation heat transfer (see p. 26).

ACCEPTANCE TEST—A test used to demonstrate compliance of a product to specified criteria as a condition of acceptability for "next" usage (next assembly, customer acceptance, etc.) (see Chapter 2).

AERODYNAMIC HEATING—Heat transfer from atmospheric air to a high-speed vehicle by forced convection (see p. 56).

AIR-CYCLE REFRIGERATION—Refrigeration using air as the working fluid, normally used in aircraft (see p. 48).

ANALYTICAL PREDICTION METHOD—Prediction of part operating temperatures by analytical solution of the partial differential equations governing heat transfer (see p. 51).

ARRHENIUS RELATION—The exponential dependence on temperature of the rates of various processes (see p. 20).

ASSEMBLY—A group of parts which usually performs one or more detailed electronic functions and can be readily removed without special tools from electronic equipment (for example, a packaged plug-in audio amplifier).

AVAILABILITY—A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time.

BLEED AIR—Air from an aircraft engine used for air-cycle refrigeration (see p. 48).

BLOWER—A machine for circulating coolant air (see p. 46).

BURN-IN—A type of environmental stress screening. The main types of burn-in are powered at ambient temperature, powered at high temperature, and powered with temperature cycling (see Chapter 10).

CIRCUIT BOARD—An assembly containing a group of interconnected parts mounted on a single board.

CLOSED FORM SOLUTION—Same as analytical prediction method.

COLD PLATE—Same as heat exchanger.

COLDWALL—A heat exchanger built into the walls of an electronic unit (see p. 39).

CONDUCTION—Heat transfer by the transfer of kinetic energy between molecules (see p. 22).

CONTACT METHOD—Temperature measurement by attaching an instrument to the test item (see p. 63).

CONTACT THERMAL RESISTANCE—The thermal resistance of an interface between contacting materials (see p. 24).

CONVECTION—Heat transfer by fluid motion (see p. 24).

COOLANT—The fluid which removes the heat in forced-convection-cooled equipment (see p. 25).

COOLING FINS—Metal surface on which parts are mounted to increase the heat transfer area (see p. 38); also used in heat exchangers to reduce the thermal resistance to convection (see p. 45).

COOLING TECHNIQUE—Means for removing the dissipation from the electronic equipment (see Chapter 7).

CRYOGENIC TEMPERATURE—In general, a temperature range below the boiling point of nitrogen (−195°C); more particularly, temperatures within a few degrees of absolute zero.

DERATING—Using an item in such a way that applied stresses are below rated values; or the lowering of the rating of an item in one stress field to allow an increase in rating in another stress field.

DETAILED ANALYSIS—The most detailed level of thermal analysis (see p. 54).

DIELECTRIC—A substance that contains few or no free charges and can support electrostatic stresses. Dielectric liquids are used as coolants for electronic equipment.

DISSIPATION—The difference between the electrical input and output powers of an electronic device, manifested as heat (see p. 21).

DISSIPATION DENSITY—Dissipation per unit volume of equipment or per unit heat transfer area.

EMISSIVITY—A measure of the radiation characteristics of a surface (see p. 26).

EMITTER—The body losing photons in radiation heat transfer (see p. 26).

ENVIRONMENTAL CHAMBER—An enclosure for simulating environmental conditions (see p. 60).

ENVIRONMENTAL CONTROL SYSTEM—A system for controlling the temperature in a compartment.

ENVIRONMENTAL STRESS SCREENING—The process or method whereby a group of like items are subjected to the application of physical climatic stresses or forces (or combinations thereof) to identify and eliminate defective, abnormal or marginal parts and manufacturing defects (see Chapter 10).

ENVIRONMENTAL TEST—A test where one or more of the environmental conditions is applied and controlled.

EVAPORATION COOLING—Cooling by storing heat in a liquid's heat of vaporization (see p. 45).

EXACT SOLUTION—Same as analytical prediction method.

EXHAUST TEMPERATURE—Same as outlet temperature.

EXTERNAL RESISTANCE—The thermal resistance between a reference location on a part and the interface with the coolant or surroundings (see p. 37).

FAILURE—The inability of an item to perform within previously specified limits.

FAILURE RATE—The number of failures of an item per unit measure of life (cycles, time, miles, events, etc., as applicable for the item).

FINITE-DIFFERENCE SOLUTION—A numerical method for the solution of partial differential equations (see p. 51).

FINITE-ELEMENT SOLUTION—A numerical method for the solution of partial differential equations (see p. 51).

FLAW—A latent defect in the design, workmanship, or material of an item which eventually will result in the failure of the item (see Chapter 10).

FLOW-THROUGH MODULE—Two circuit boards sandwiched around a heat exchanger (see p. 40).

FLUSH COOLING—Cooling by direct impingement of a liquid on the part or cooling fin (see p. 38).

FORCED AIR—Forced-convection cooling using air as the coolant (see p. 43).

FORCED CONVECTION—Heat transfer by fluid motion induced by an external source (see p. 25).

FORCED LIQUID—Forced-convection cooling using a liquid as the coolant (see p. 43).

FREE CONVECTION—Heat transfer by naturally occurring fluid motion (see p. 25).

FUNCTIONAL TEST—A test which measures a limited number of critical parameters to assure that the test article is operating properly.

HEAD PRESSURE—The pressure rise produced by a blower or pump (see p. 46).

HEAT EXCHANGER—A finned duct through which coolant flows and receives or gives up heat (see p. 38).

HEAT-FLOW RATE—The energy, in the form of heat, transferred per unit time (see p. 21).

HEAT LOAD—Heat transferred to equipment from adjacent equipment or from external sources (for example, solar radiation).

HEAT OF FUSION—The quantity of heat required to melt a unit mass of a solid (see p. 45).

HEAT OF VAPORIZATION—The quantity of heat required to vaporize a unit mass of a liquid (see p. 45).

HEAT PIPE—A self-contained evaporation/condensation device for transferring heat with a very small temperature drop (see p. 41).

HEAT SINK—A metal mounting surface for enhancing heat transfer (see p. 22).

HEAT TRANSFER COEFFICIENT—The heat-flow rate per unit heat transfer area per unit temperature difference, used as a measure of the rate of convective heat transfer between a surface and a fluid (see p. 24).

HEAT TRANSFER FIN—Same as cooling fin.

HEAT TRANSFER PATH—A physical path along which heat flows.

HOT SPOT—A part or other area or region that is abnormally or unacceptably hot. The temperature depends on the item and the application.

IMPINGEMENT COOLING—Cooling by direct impingement of a gas on the part or cooling fin (see p. 38).

INCLINED WATER MANOMETER—A water manometer whose column is inclined relative to the vertical axis to increase its sensitivity. Pressures can be measured to within 2.5 pascals (0.01 inch of water) (see p. 63).

INFRARED THERMOGRAPHY—A temperature-measurement method employing the temperature dependence of the radiation emitted from a surface (see p. 64).

INLET TEMPERATURE—The temperature of a coolant entering a piece of equipment.

INTERNAL RESISTANCE—The thermal resistance between the heat-generation location of a part and some location on the surface of the part (see p. 37).

INTERRUPTED FINS—Fins used in a heat exchanger consisting of periodically interrupted flow passages (see p. 46).

JUNCTION-TO-CASE THERMAL RESISTANCE—The thermal resistance between the junction and case of a semiconductor device (see p. 24).

LATENT HEAT—The quantity of heat required to change the phase of a unit mass of matter (see Appendix C).

LEVEL OF THERMAL ANALYSIS—The degree of detail of a thermal analysis (preliminary, intermediate, or detailed) (see p. 52).

LEVELS OF THERMAL RESISTANCE—The three types of thermal resistance encountered with electronic equipment (internal, external, and system) (see p. 37).

LIFE-CYCLE COST—The sum of all costs contributing to the development, production, operation, support, and phase-out of an equipment or system.

LOCAL SINK—An intermediate destination of heat (see p. 22).

MAINTAINABILITY—A characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources.

MANOMETER—A pressure-measurement instrument employing the pressure sensitivity of the length of a liquid column (see p. 63).

MANUFACTURING DEFECT—A flaw caused by in-process errors or uncontrolled conditions during assembly, test, inspection, or handling.

MEAN-TIME-BETWEEN-FAILURES (MTBF)—For a particular interval, the total functioning life of a population of an item divided by the total number of failures within the population during the measurement interval. The definition holds for time, cycles, miles, events, or other measure of life units.

METERING ORIFICE—Same as orifice.

MISSION—The objective or task, together with the purpose, which clearly indicates the action to be taken.

MODES OF HEAT TRANSFER—The physical mechanisms by which heat is transferred (conduction, convection, and radiation) (see p. 22).

MODULE—The lowest level of an electronic assembly which usually performs one or more electronic functions and is removable as an entity (for example, hybrid microcircuit or a flow-through module).

MOUNTING THERMAL RESISTANCE—The thermal resistance between a part and its mounting surface (see p. 38).

NATURAL CONVECTION—Same as free convection.

NON-CONTACT METHOD—Remote temperature measurement (for example, infrared) (see p. 63).

NUMERICAL PREDICTION METHOD—Prediction of part operating temperatures by numerical solution of the partial differential equations governing heat transfer (see p. 51).

OPERATIONAL—Of, or pertaining to, the state of actual usage.

OPTIMIZATION COMPUTER PROGRAM—A computer program for optimizing a thermal design to maximize reliability (see p. 56).

ORIFICE—Flow restrictor used for controlling coolant flow rates to modules (see p. 41).

OUTLET TEMPERATURE—The temperature of a coolant exiting a piece of equipment.

PART—A small element of electronic equipment, normally not further disassembled into its constituents (for example, a resistor, a transformer, a screw, a capacitor, an integrated circuit or a transistor).

PELTIER EFFECT—The production or absorption of heat at the junction of two unlike materials on the passage of an electrical current (see p. 48).

PHASE CHANGE—Cooling by liquid evaporation or solid melting (see p. 45).

PLAIN FINS—Fins used in a heat exchanger consisting of uninterrupted, straight flow passages (see p. 46).

PLATED-THROUGH-HOLE—Copper-plated hole connecting the layers in a multi-layer printed wiring board (see p. 77).

PLENUM—Compartment used for distributing coolant to forced-convection-cooled equipment (see p. 41).

POWER DENSITY—Same as dissipation density.

PRECIPITATION OF FLAWS—The process of deliberately causing a flawed item to fail earlier than it would in normal usage, so that the flaw can be removed before the item is put into the field (see Chapter 10).

PREDICTED—That which is expected at some future date, postulated on analysis of past experience.

PRELIMINARY ANALYSIS—The least detailed level of thermal analysis (see p. 53).

PRESSURE DROP—The decrease in pressure due to flow resistance which must be overcome by a blower (see p. 25).

RADIATION—Heat transfer by the flow of photons (see p. 26).

RADIATION AND FREE CONVECTION—Cooling by free convection to the ambient air and radiation to the surroundings (see p. 42).

RAM AIR COOLING—Cooling using ambient air forced into an aircraft by the aircraft's motion.

RELIABILITY—The probability that an item will perform its intended function for a specified interval under stated conditions.

SCREENING—A process or combination of processes (for example, visual inspection, temperature and vibration) for the purpose of identifying and eliminating defective, abnormal, or marginal parts and manufacturing defects (see Chapter 10).

SET—A group of assemblies or units which performs an overall series of complete electronic functions (for example, a radar set).

SINK—A destination of heat (see p. 21).

SOLID MELTING—Cooling by storing heat in a solid's heat of fusion (see p. 45).

SPECIALIZED THERMAL COMPUTER PROGRAM—A computer program for providing a specialized thermal analysis (see p. 55).

SUPPLY TEMPERATURE—Same as inlet temperature.

SYSTEM—A group of sets, specially integrated, but which may be in different locations (for example, a guidance system).

SYSTEM RESISTANCE—The thermal resistance between the equipment's external surface (or heat exchanger) and the ambient air (or coolant) (see p. 37).

TEMPERATURE CYCLING—The subjection of equipment to periodic increases and decreases in temperature (see Chapter 10).

TEMPERATURE TEST—The experimental evaluation of the ability of equipment to withstand a variety of thermal environments (see p. 59).

THERMAL ANALYSIS—The analytical evaluation of a thermal design (see Chapter 8).

THERMAL ANALYZER—A computer program for solving a thermal model (see p. 55).

THERMAL CONDUCTIVITY—An intrinsic physical property of a substance, describing its ability to conduct heat as a consequence of molecular motion (see p. 23).

THERMAL CYCLING—Same as temperature cycling.

THERMAL DESIGN—All the aspects of the system design which affect the equipment temperatures.

THERMAL ENVIRONMENT—The environmental factors which affect the equipment temperatures (see Chapter 6).

THERMAL EVALUATION—Evaluation of the adequacy, from a thermal standpoint, of a design or hardware.

THERMAL IMAGING—Imaging with the infrared radiation emitted by a surface (see p. 72).

THERMAL MANAGEMENT—The process during a military electronic equipment program for ensuring that the equipment will be adequate from a thermal standpoint.

THERMAL MOCKUP—Simulated equipment used in thermal tests (see p. 59).

THERMAL MODEL—An analytical tool used for predicting part operating temperatures (see p. 51).

THERMAL NETWORK—A combination of thermal resistances; series, parallel, or both (see p. 27).

THERMAL PATH—Same as heat transfer path.

THERMAL PROFILE—The temporal behavior of the environmental chamber temperature during temperature cycling (see Chapter 10).

THERMAL PROGRAM—The program for implementing thermal management during all the phases of a military electronic program.

THERMAL RESISTANCE—A measure of the resistance to the flow of heat (see p. 21).

THERMAL SCREENING—Screening with high temperatures and/or high rates of change of temperature (see Chapter 10).

THERMAL SHOCK—The subjection of equipment to changes in temperature at a more rapid rate than during thermal cycling.

THERMAL STRESS—Part operating temperature; also structural stress induced by differential thermal expansion or contraction of dissimilar materials.

THERMAL SURVEY—Experimental location of hot spots and measurement of the thermal stabilization time of selected parts (see p. 59).

THERMAL TEST—Measurement of part temperatures in a laboratory simulating operating conditions (see Chapter 9).

THERMAL VIA—A plated-through-hole used as a conduction heat transfer path through a printed wiring board (see p. 77).

THERMALLY SENSITIVE PART—One whose failure rate is sensitive to temperature and whose failure would have a significant impact on the mission.

THERMOCOUPLE—A temperature-measurement instrument employing the voltage difference produced between the junctions of unlike conductors (see p. 63).

THERMOELECTRIC REFRIGERATION—Refrigeration using the Peltier effect (see p. 48).

THERMOMETER—A temperature-measurement instrument employing the temperature sensitivity of the length of a liquid column (see p. 63).

TURBULENCE—The irregular motion of a fluid.

ULTIMATE SINK—The final destination of heat (see p. 21).

UNIT—A mechanical group of parts or assemblies provided within a single enclosure.

VAPOR-CYCLE REFRIGERATION—Refrigeration employing evaporation and condensation of a working fluid (see p. 48).

VIEW FACTOR—A measure of the view of the absorber by the emitter in radiation heat transfer (see p. 26).

APPENDIX B
UNIT CONVERSION FACTORS

The following tables express the definitions of miscellaneous units of measure as exact numerical multiples of coherent International System (SI) Units, and provide multiplying factors for converting numbers and miscellaneous units to corresponding new numbers and SI Units.

The first two digits of each numerical entry represent a power of 10. An asterisk follows each number which expresses an exact definition. For example, the entry "−02 2.54*" expresses the fact that 1 inch = 2.54×10^{-2} meter, exactly, by definition. Most of the definitions are extracted from National Bureau of Standards documents. Numbers not followed by an asterisk are only approximate representations of definitions, or are the results of physical measurements.

Most of the entries were obtained from E. A. Mechtly, "The International System of Units—Physical Constants and Conversion Factors—Revised", NASA SP-7012, 1969.

To Convert From	To	Multiply By
AREA		
$foot^2$	$meter^2$	−02 9.290 304*
$inch^2$	$meter^2$	−04 6.4516*
DENSITY		
$gram/centimeter^3$	$kilogram/meter^3$	+03 1.00*
$lbm/inch^3$	$kilogram/meter^3$	+04 2.767 990 5
$lbm/foot^3$	$kilogram/meter^3$	+01 1.601 846 3
ENERGY (HEAT)		
British thermal unit (Btu) (thermochemical)	joule	+03 1.054 350 264 488
calorie (thermochemical)	joule	+00 4.184*
foot lbf	joule	+00 1.355 817 9
watt hour	joule	+03 3.60*
ENERGY/AREA TIME (POWER/AREA)		
Btu (thermochemical)/$foot^2$ second	$watt/meter^2$	+04 1.134 893 1
Btu (thermochemical)/$foot^2$ minute	$watt/meter^2$	+02 1.891 488 5
Btu (thermochemical)/$foot^2$ hour	$watt/meter^2$	+00 3.152 480 8
Btu (thermochemical)/$inch^2$ second	$watt/meter^2$	+06 1.634 246 2
calorie (thermochemical)/cm^2 minute	$watt/meter^2$	+02 6.973 333 3
erg/$centimeter^2$ second	$watt/meter^2$	−03 1.00*
$watt/centimeter^2$	$watt/meter^2$	+04 1.00*
FORCE		
ounce force (avoirdupois)	newton	−01 2.780 138 5
pound force, lbf (avoirdupois)	newton	+00 4.448 221 615 260 5*

To Convert From	To	Multiply By
HEAT TRANSFER COEFFICIENT		
Btu (thermochemical)/hour foot^2 Fahrenheit	watt/meter^2 Celsius	+00 5.677
LENGTH		
foot	meter	−01 3.048*
inch	meter	−02 2.54*
mil	meter	−05 2.54*
MASS		
pound mass, lbm (avoirdupois)	kilogram	−01 4.535 923 7*
POWER (HEAT-FLOW RATE)		
Btu (thermochemical)/second	watt	+03 1.054 350 264 488
Btu (thermochemical)/minute	watt	+01 1.757 250 4
calorie (thermochemical)/second	watt	+00 4.184*
calorie (thermochemical)/minute	watt	−02 6.973 333 3
foot lbf/hour	watt	−04 3.766 161 0
foot lbf/minute	watt	−02 2.259 696 6
foot lbf/second	watt	+00 1.355 817 9
horsepower (550 foot lbf/second)	watt	+02 7.456 998 7
PRESSURE		
atmosphere	newton/meter^2 (pascal)	+05 1.013 25*
inch of mercury (60°F)	newton/meter^2 (pascal)	+03 3.376 85
inch of water (60°F)	newton/meter^2 (pascal)	+02 2.488 4
lbf/foot^2 (psf)	newton/meter^2 (pascal)	+01 4.788 025 8
lbf/inch^2 (psi)	newton/meter^2 (pascal)	+03 6.894 757 2
SPECIFIC HEAT		
Btu (thermochemical)/pound Fahrenheit	joule/kilogram Celsius	+03 4.1867
Calorie/gram Celsius	joule/kilogram Celsius	+03 4.1867
SPEED		
foot/hour	meter/second	−05 8.466 666 6
foot/minute	meter/second	−03 5.08*
foot/second	meter/second	−01 3.048*
inch/second	meter/second	−02 2.54*
kilometer/hour	meter/second	−01 2.777 777 8

To Convert From	To	Multiply By
TEMPERATURE		
Celsius	kelvin	$t_K = t_C + 273.15$
Fahrenheit	kelvin	$t_K = (5/9)(t_F + 459.67)$
Fahrenheit	Celsius	$t_C = (5/9)(t_F - 32)$
Rankine	kelvin	$t_K = (5/9)t_R$
THERMAL CONDUCTIVITY		
Btu (thermochemical)/hour foot Fahrenheit	watt/meter Celsius	+00 1.7303
THERMAL RESISTANCE		
hour Fahrenheit/Btu (thermochemical)	Celsius/watt	+00 1.896
VISCOSITY		
lbm/foot second	newton second/meter^2	+00 1.488 163 9
lbf second/foot^2	newton second/meter^2	+01 4.788 025 8
VOLUME		
foot^3	meter^3	−02 2.831 684 659 2*
gallon (U.S. liquid)	meter^3	−03 3.785 411 784*
inch^3	meter^3	−05 1.638 706 4*
liter	meter^3	−03 1.00*

APPENDIX C
USEFUL FORMULAS AND DATA

Formulas and data which are commonly used in heat transfer analysis are presented in this appendix. Included are formulas and data used to calculate fluid exit temperatures; heat transfer by conduction, convection and radiation; heat absorbed or removed during a phase change process; and fluid pressure drop. Miscellaneous formulas include those used to calculate fluid density, fluid velocity and hydraulic diameter of a fluid passage. Thermal properties of commonly used fluids and materials are also included. The units of the parameters used herein are listed in Table C-8 for the International and English systems.

Some of the data were obtained from the following sources:

- *Handbook of Heat Transfer*, W.M. Rohsenow and J.P. Hartnett (Eds.), McGraw-Hill Book Co., New York, 1973.
- W.H. McAdams, *Heat Transmission,* 3rd ed., Appendix, McGraw-Hill Book Co, New York, 1954.
- M. Jakob and G.A. Hawkins, *Elements of Heat Transfer*, 3rd ed., John Wiley and Sons, New York, 1957.
- E.R.G. Eckert and R.M. Drake, Jr., *Heat and Mass Transfer,* 2nd ed., pp. 493-522, McGraw-Hill Book Co., New York, 1959.
- B.H. Jennings and S.R. Lewis, *Air Conditioning and Refrigeration,* p. 33, International Textbook Company, 1965.
- *Handbook of Fundamentals*, pp. 289 and 324, American Society of Heating, Refrigeration, Air-Conditioning Engineers, Inc. (ASHRAE), 1967.
- "1981 Materials Selector," *Materials Engineering*, December 1980.

FLUID EXIT TEMPERATURE

$$T_O = T_I + \frac{Q}{mc_p} \qquad \text{(C-1)}$$

where

T_O = Fluid exit temperature

T_I = Fluid inlet or supply temperature

Q = Power dissipation or heat load

(Note: Q is positive if heat absorbed by the fluid and negative if heat is given up by the fluid)

m = Fluid mass flow rate

c_p = Fluid specific heat.

Specific heat varies with temperature. However, the variation over the temperature range typical for electronic cooling applications is small, particularly for gases. Using c_p values at 27°C (80°F) should give a reasonable estimate. Specific heat of typical fluids used in electronic cooling at 27°C (80°F) are given in Table C-1.

TABLE C-1. SPECIFIC HEAT OF TYPICAL FLUIDS

Fluid	Specific Heat (c_p)	
	J/kg-°C	Btu/lbm-°F
Gases		
Air	1,005	0.240
Nitrogen	1,042	0.249
Helium	5,200	1.242
Hydrogen	14,335	3.419
Liquids		
FC-75	1,047	0.25
Coolanol-25	1,884	0.45
Ethylene glycol-water mixture (60% glycol)	3,098	0.74
Water	4,187	1.0

HEAT TRANSFERRED BY CONDUCTION

$$Q_k = \Delta T/\theta_k \qquad \text{(C-2)}$$

where

Q_k = Heat-flow rate

θ_k = L/(kA) = Conductive thermal resistance (see p. 23)

ΔT = Temperature difference.

Values of thermal conductivity (k) at 27°C (81°F) for typical materials used in electronic cooling are given in Table C-2. Thermal conductivity varies with temperature. Use of these values for temperatures below 17°C (63°F) or above 37°C (99°F) should be restricted to approximate calculations.

HEAT TRANSFERRED BY CONVECTION

$$Q_h = (T_S - T_F)/\theta_h \qquad \text{(C-3)}$$

where

Q_h = Heat-flow rate

θ_h = 1/(hA) = convective thermal resistance

h = Heat transfer coefficient

T_S = Surface temperature

T_F = Temperature of surrounding fluid (such as ambient air).

The heat transfer coefficients for different cooling techniques are given in Table C-3.

TABLE C-2. THERMAL CONDUCTIVITY OF TYPICAL MATERIALS AT 27°C

Material	Thermal Conductivity	
	W/m-°C	Btu/ hr-ft-°F
Non-Metals		
Plastic Foam	0.017-0.14	0.01-0.08
Air	0.0261	0.0151
Fiberglass	0.048	0.028
Plastic (Polystyrene)	0.15	0.09
Epoxy	0.17-1.5	0.1-0.87
Water	0.604	0.349
Glass	1.7-3.4	1.0-2.0
Metals		
Kovar	17	10
Stainless Steel	17	10
Steel	48	28
Nickel	61	35
Tin	66	38
Molybdenum	146	85
Aluminum	211	122
Gold	294	170
Copper	381	220
Silver	415	240

TABLE C-3. CONVECTION HEAT TRANSFER COEFFICIENT

Cooling Technique	Heat Transfer Coefficient h	
	W/m^2-°C	Btu/hr-ft^2-°F
Free Convection	2.8 to 5.7	0.5 to 1
High Altitudes [21,336 m (70 kft)]	Closer to 2.8	Closer to 0.5
Sea Level	Closer to 5.7	Closer to 1
Air Impingement	17 to 28	3 to 5
Forced Convection		
Air over plain fins	34 to 170	6 to 30
Air over interrupted fins	3 to 5 times higher than plain fins	3 to 5 times higher than plain fins
Liquid Cooling		
Dielectric liquid	570 to 2,270	100 to 400
Water	2,800 to 57,000	500 to 10,000

HEAT TRANSFER BY RADIATION

$$Q_R = \sigma \epsilon_R F_{ES} A (T_E^4 - T_S^4) \qquad \text{(C-4)}$$

where

Q_R = Heat-flow rate

σ = Stefan-Boltzmann constant (see Table C-8)

ϵ_R = Relative emissivity between the surface and the surroundings (approximately equal to the product of both emissivities)

F_{ES} = View factor between the part and the surroundings

A = Radiating area

T_E = Absolute temperature of the radiating surface

T_S = Absolute temperature of the surroundings.

Note: Q_R can also be expressed in terms of the radiation thermal resistance as

$$Q_R = (T_E - T_S)/\theta_R \qquad \text{(C-5)}$$

where

θ_R = Radiation thermal resistance

$= 1/[\sigma \epsilon_R F_{ES} A (T_E^2 + T_S^2)(T_E + T_S)]$. (C-6)

The view factor, whose value is between 0 and 1, is a measure of how well the emitter sees the absorber. Typical values are given in Table C-4.

TABLE C-4. VIEW FACTORS FOR VARIOUS CONFIGURATIONS

Configuration	View Factor
Infinite parallel planes	1.0
Body completely enclosed by another body; internal body cannot see any part of itself	1.0
Two squares in perpendicular planes with a common side	0.20
Two equal, parallel squares separated by distance equal to side	0.19
Two equal, parallel circular disks separated by distance equal to diameter	0.18

The emissivity also varies between 0 and 1. A perfectly black body has an emissivity of 1, while a perfectly shiny body has an emissivity of 0. Real bodies have emissivities between 0 and 1. Emissivities of typical metals and non-metallic materials are given in Table C-5.

TABLE C-5. EMISSIVITY OF TYPICAL SURFACES AT 4°C (40°F)

Surface	Emissivity (ϵ)
Silver	0.02
Aluminum (buffed)	0.03
Aluminum foil (dull)	0.03
Gold (plated)	0.03
Gold (vacuum deposited)	0.03
Aluminum foil (shiny)	0.04
Aluminum (polished)	0.05
Stainless steel (polished)	0.05
Chrome	0.08
Tantalum	0.08
Beryllium (polished)	0.09
Beryllium (milled)	0.11
Rene 41	0.11
Nickel	0.18
Titanium	0.20
Aluminum (sandblasted)	0.40
White silicone paint (gloss)	0.75
Black silicone paint (flat)	0.81
Black vinyl phenolic (dull)	0.84
Lamp black	0.95
Magnesia	0.95
Grey silicone paint	0.96

HEAT GIVEN UP OR ABSORBED DURING A PHASE CHANGE OF A SUBSTANCE

$$H = M\,\pounds \qquad \text{(C-7)}$$

where

H = Heat given up or absorbed (a positive Q indicates absorption while a negative value indicates heat is given up)

M = Mass of the substance

£ = Latent heat or heat of transformation.

Typical values for the latent heat (£) are given in Table C-6.

TABLE C-6. TYPICAL VALUES FOR LATENT HEAT AT SEA LEVEL

Process	Latent Heat	
	Cal/g	Btu/lbm
Boil Freon-12	32	58
Boil Nitrogen	44	80
Melt Ice	80	144
Boil Ammonia	327	589
Boil Water	539	970

PRESSURE DROP OF A FLUID

- Friction loss, such as flow through a pipe:

$$\Delta P = f\frac{L}{D_H}\frac{\rho V^2}{2} \qquad \text{(C-8)}$$

- Shock or momentum loss, such as sudden turn or sudden expansion to an infinitely large area:

$$\Delta P = K\frac{\rho V^2}{2} \qquad \text{(C-9)}$$

where

ΔP = Pressure drop

f = Friction factor

L = Length of flow section

D_H = Hydraulic diameter of flow section (equal to the tube diameter in a round section; see Equation C-12)

ρ = Density of the fluid

V = Velocity of fluid

K = Loss coefficient.

The friction factor (f) depends on many factors, such as the flow regime and the shape and surface roughness of the flow section. For flows within electronic equipment, f varies between 10^{-3} and 1.

The loss coefficients (K) for sudden expansion or contraction to a relatively large area are 1 and 0.5, respectively. Values of k for sudden turns are given in Figure C-1.

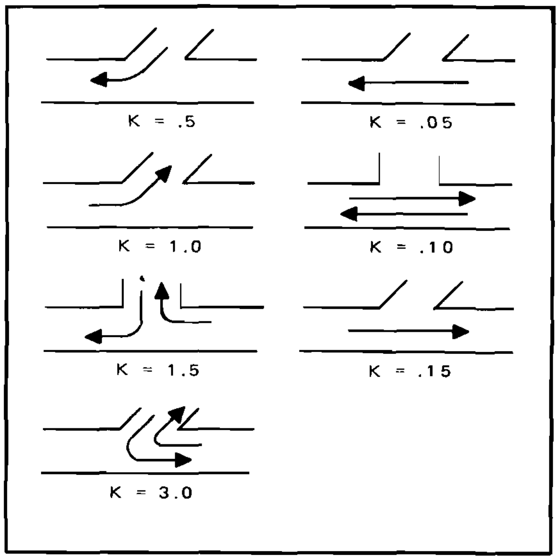


Figure C-1. Turning loss coefficients for fluids.

MISCELLANEOUS FORMULAS

- Density of a gas

$$\rho = \frac{P}{RT} \qquad \text{(C–10)}$$

- Velocity of a fluid

$$V = \frac{F}{A} \qquad \text{(C–11)}$$

- Hydraulic diameter of fluid passage

$$D_H = \frac{4A}{P_w} \qquad \text{(C–12)}$$

where

ρ = Density
R = Gas constant
P = Pressure
T = Absolute temperature
V = Velocity
F = Volumetric flow rate
A = Cross-sectional or flow area
D_H = Hydraulic diameter
P_w = Wetted perimeter (or inner circumference of the passage).

Typical values for the gas constant (R) are given in Table C–7.

TABLE C–7. GAS CONSTANT OF TYPICAL GASES

Gas	Gas Constant (R)	
	N-m/ kg-°K	lbf-ft³/ lbm-in²-°R
Carbon Dioxide	189	0.24
Oxygen	260	0.34
Air	287	0.37
Nitrogen	297	0.38
Water Vapor	458	0.59
Helium	2.08×10^3	2.68
Hydrogen	2.23×10^3	2.9

TABLE C–8. UNITS USED IN APPENDIX C

Parameter	Symbol	International System	English System
Temperature	T	°C, °K	°F, °R
Heat-Flow Rate	Q	W	Btu/sec
Mass-Flow Rate	m	kg/sec	lbm/sec
Specific Heat	c_p	J/kg-°C	Btu/lbm-°F
Thermal Resistance	θ	°C/W	°F-hr/Btu
Thermal Conductivity	k	W/m-°C	Btu/hr-ft-°F
Area	A	m^2	ft^2
Length	L	m	ft
Heat Transfer Coefficient	h	W/m^2-°C	Btu/hr-ft^2-°F
Stefan-Boltzmann Constant	σ	0.516×10^{-7}W/m^2-°K^4	0.174×10^{-8} Btu/hr-ft^2-°R^4
Emissivity	ϵ	Dimensionless	Dimensionless
View Factor	F_{ES}	Dimensionless	Dimensionless
Pressure Drop	ΔP	N/m^2 (pascals)	Inches of Water
Friction Factor	f	Dimensionless	Dimensionless
Hydraulic Diameter	D_h	m	ft
Density	ρ	kg/m^3	lbm/ft^3
Velocity	V	m/sec	ft/sec
Loss Coefficient	K	Dimensionless	Dimensionless
Heat	H	Cal or J	Btu
Mass	M	kg	lbm
Latent Heat or Heat of Transformation	£	Cal/g or J/kg	Btu/lbm
Gas Constant	R	N-m/kg-°K	lbf-ft^3/ lbm-in^2-°R
Wetted Perimeter	P_w	m	ft
Volumetric Flow Rate	F	m^3/sec	ft^3/sec

APPENDIX D
ADJUSTMENT FACTORS FOR MIL–HDBK–217C FAILURE RATES

NEED FOR ADJUSTMENT FACTORS

Many of the failure rates included in MIL–HDBK–217 for parts such as transistors and diodes are based on ambient temperatures, regardless of the cooling technique used.* This basis is reasonable if the cooling method is free convection to ambient air and radiation to the surroundings. The temperature differences between the case (or surface) and the ambient air for different dissipation densities for free convection and radiation are given in Table D–1. An average of the thermal resistances to free convection for horizontally and vertically oriented parts was used in calculating these temperature differences. The heat transfer coefficient is 5.7 W/(m^2-°C) [1 Btu/(hr-ft^2-°F)]. The emissivities and the view factor were taken to be unity. The dissipation density is obtained by dividing the dissipation by the total surface area of the parts and cooling fins exposed to the ambient air. Note that the maximum density given in the table is 1549 W/m^2 (1 W/in^2), which is the maximum practical dissipation density for this type of cooling.

TABLE D–1. CASE TEMPERATURE CHARACTERISTICS OF PARTS COOLED BY FREE CONVECTION TO AMBIENT AIR AND RADIATION TO THE SURROUNDINGS

Dissipation Density		Case-to-Ambient Temperature Difference, °C
W/m^2	W/in^2	
15.5	0.01	1.4
77.5	0.05	6.8
155	0.10	12
232	0.15	18
310	0.20	24
387	0.25	30
465	0.30	36
542	0.35	41
620	0.40	46
775	0.50	56
930	0.60	66
1084	0.70	74
1239	0.80	82
1394	0.90	89
1549	1.00	95

Cooling by free convection and radiation gives the highest case temperature, hence the highest junction temperature. The case and junction temperatures are lower for other types of cooling, which are more efficient. Generalized methods of estimating case temperature and thereby obtaining adjustment factors to the temperatures in MIL–HDBK–217 are given below for the following types of cooling:

- Free convection to a liquid
- Impingement cooling with air
- Flush cooling
- Cold-plate-mounted parts using forced-air/liquid cooling

DEFINITION AND USE OF ADJUSTMENT FACTORS

The adjustment factor (ΔT_A) is the decrease in the junction temperature resulting from the use of a cooling technique which is more efficient than radiation and free convection to ambient air (see Figure D–1). Consider the example on page 2.2.12–5 of MIL–HDBK–217C, Notice 1: a silicon NPN general-purpose JAN-grade transistor operating at a stress ratio (S) of 0.4 and an ambient temperature (T) of 30°C. From Table 2.2.1–7 of the handbook, the base failure rate for T = 30°C and S = 0.4 is 0.0079 failure/10^6 hours. This failure rate is based on the temperature that the transistor junction would have if the transistor were operating in a 30°C air environment. Now assume instead that the transistor is immersed in a 30°C liquid bath and that the adjustment factor is 20°C. Then the appropriate temperature to use in the table is 30°C − 20°C = 10°C. This means that the case temperature is the

*"Reliability Prediction of Electronic Equipment," MIL–HDBK–217C, Notice 1, 1 May 1980.

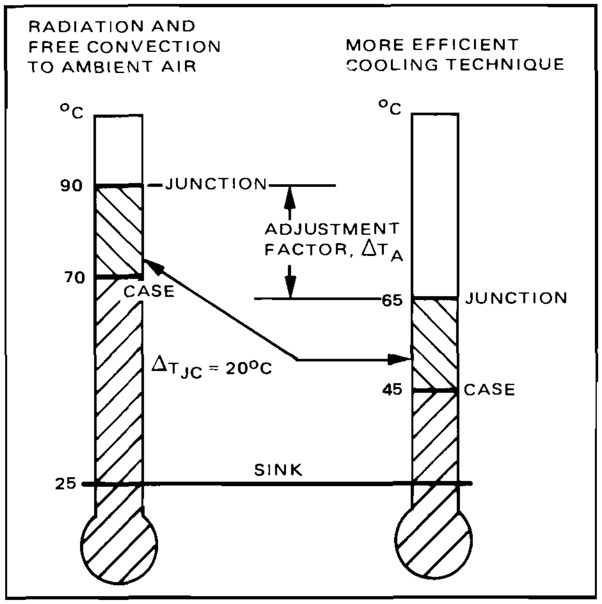


Figure D-1. Using a more efficient cooling technique results in a reduced junction temperature because the case-to-sink thermal resistance is smaller.

same in a 30°C liquid bath as in a 10°C air environment. From Table 2.2.1-7 of the handbook, the base failure rate for T = 10°C and S = 0.4 is 0.0064 failures/10^6 hours.

This last step implies that: (1) the failure rate depends only on the junction temperature and (2) the junction-to-case thermal resistance (θ_{JC}) is independent of the type of cooling (see Figure D-1). Both of these assumptions are over-simplifications. Nevertheless, these adjustment factors produce more realistic reliability predictions for discrete semiconductors than can be obtained using the present version of the handbook.

ADJUSTMENT FACTORS FOR OTHER COOLING METHODS

Free Convection To Liquid

Cooling by free convection to a liquid takes place when the part is immersed in a stagnant body of liquid, usually a dielectric liquid such as Coolanol-25. This type of cooling is approximately 20 times as efficient as cooling by free convection to ambient air and radiation to the surroundings. The case-to-liquid temperature difference can be obtained by the following equation:

$$\Delta T_{CL} = 0.00432\, q, \qquad \text{(D-1)}$$

where ΔT_{CL} is the case-to-liquid temperature difference in °C and q is the dissipation density in W/m^2.

The adjustment factor (ΔT_A) is obtained by subtracting ΔT_{CL} from the corresponding case-to-ambient temperature difference for free convection and radiation to the surroundings (given in Table D-1). For example, if a given part has a dissipation density of 1549 W/m^2 (1 W/in^2), ΔT_{CL} is 6.7°C. The corresponding case-to-ambient temperature difference from Table D-1 is 95°C. Therefore, the adjustment factor is ΔT_A = 95°C − 6.7°C ≅ 88°C (i.e., the case will be 88°C cooler in a liquid bath than in an air environment).

Impingement Cooling

Impingement cooling may use either ambient air (usually circulated or forced over the parts by a blower) or temperature-regulated air, as supplied by an aircraft environmental control system (ECS). Figure D-2 shows the reduction in case temperature as

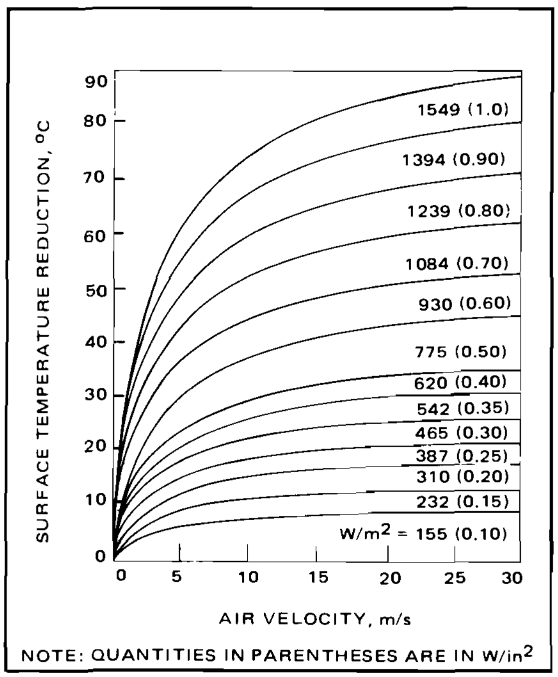


Figure D-2. Case temperature reduction for air impingement cooling.

a function of cooling air velocity for the range of dissipation densities given in Table D-1. If ambient air is used for cooling, ΔT_A equals the surface (or case) temperature reduction in Figure D-2. For example, for a part having a dissipation density of 1549 W/m^2 (1 W/in^2) and cooled by impingement with ambient air at a velocity of 5 m/s, $\Delta T_A = 63°C$ (see Figure D-2).

If temperature-regulated air is used for cooling, the temperature difference between ambient air and the cooling air supply is added to the surface temperature reduction to obtain the adjustment factor. If, in the above example, the ambient air temperature is 30°C and the cooling air supply temperature is 20°C, the temperature difference between the ambient and the cooling air supply is 10°C. Adding this to 63°C (obtained from Figure D-2) gives ΔT_A = 73°C. In other words, the case will be 73°C cooler when impingement-cooled by 20°C air than when free-convection-and-radiation-cooled in 30°C air.

Flush Cooling

Flush cooling is approximately 20 times more efficient than impingement cooling. The case-to-liquid temperature difference is obtained by the following equations:

$$\Delta T_{CL} = \begin{cases} 0.00432\ q, & V \leq 0.27, \\ 0.0009\ q\ (3.05/V)^{0.65}, & V > 0.27, \end{cases} \qquad \text{(D-2)}$$

where ΔT_{CL} is the case-to-liquid temperature difference in °C, q is the dissipation density in W/m^2, and V is the liquid velocity in m/s.

The adjustment factor (ΔT_A) is obtained by subtracting ΔT_{CL} from the corresponding case-to-ambient temperature difference given in Table D-1 and adding the difference between the ambient and the liquid supply temperatures. For example, a part having a dissipation density of 1549 W/m^2 (1 W/in^2) is impingement-cooled with a liquid at a velocity of 5 m/s and a supply temperature of 20°C. The ambient air temperature is 30°C. The case-to-liquid temperature difference, using Equation D-2, is 1°C. The difference between the ambient air and liquid supply temperatures is 10°C. Using Table D-1, one obtains ΔT_A = 95°C − 1°C + (30°C − 20°C) = 104°C.

Cold-Plate-Mounted Parts

Parts mounted on cold plates are either air-cooled or liquid-cooled. The difference between the case and fluid supply temperatures is obtained by the following equation:

$$\Delta T_{CL} = K_1 + K_2\, q\, (4.6/V)^{0.65} + Q\theta_{CB} \qquad \text{(D-3)}$$

where ΔT_{CL} is the case-to-liquid temperature difference in °C; K_1 is the mean fluid temperature increase as heat is absorbed (for air, K_1 = 27°C; for liquid, K_1 = 6.5°C); K_2 is a proportionality constant which depends on the type of fluid and the type of cooling fins (see Table D-2); q is the dissipation per unit area of the cold plate mounting surface (equal to the total dissipation on the coldplate divided by the coldplate mounting surface area); V is the fluid velocity in m/s; Q is the power dissipated by the part in watts; and θ_{CB} is the case-to-mounting surface thermal resistance in °C/W.

The adjustment factor (ΔT_A) can be obtained by subtracting ΔT_{CL} from the case-to-ambient temperature difference given in Table D-1 and adding the difference between the ambient air and fluid supply temperatures. For example, a part is mounted on an air-cooled cold plate; the dissipation density is 1549 W/m^2 (1 W/in^2); the air supply temperature is 20°C, and the ambient temperature is 30°C. The fluid velocity is 3.05 m/s. An intermediate range fin for which $K_2 = 1.5 \times 10^{-3}$ is used. The part dissipates 0.25 watt, and the case-to-mounting-surface thermal resistance is 15°C/W.

The difference between the case and air supply temperatures, as obtained by Table D-2 and Equation D-3, is 34°C. Using Table D-1, one obtains ΔT_A = 95°C − 34°C + (30°C − 20°C) = 71°C.

TABLE D-2. VALUES FOR CONSTANT, K_2*

Air	Liquid
$7.1 \times 10^{-4} - 3.6 \times 10^{-3}$	$3.9 \times 10^{-5} - 1.8 \times 10^{-4}$

*Low end of range of values of K_2 is for fins having low thermal resistance and high pressure drop (for example, 20 fins/inch interrupted every 1/8 inch). High end is for fins having high thermal resistance and low pressure drop (for example, plain fins with 5 fins/inch).

APPENDIX E
APPROXIMATE PART TEMPERATURES FOR COMMONLY ENCOUNTERED THERMAL DESIGNS

A simple first-step analysis is to consider the bulk effects of the environmental and/or coolant upon the design. From this, overall temperature levels can be established. For example, the coolant exhaust temperature can be simply determined by knowing the flow rate and equipment dissipation (see Appendix C). This simple calculation gives a very important basis for estimating part temperatures, and sizing cooling systems.

A level above this analysis is an approximate temperature estimate. Approximate temperature estimates can serve as a basis for making reliability estimations. Such temperature estimates can be made by using Figures E-1 through E-12, which are comprised of curves and simple calculation procedures for commonly used cooling techniques, as shown in Table E-1. The data given in these figures provide means for estimating the temperature of the case (outer surface of the parts) or the temperature of the mounting surface. When it is necessary to estimate the junction temperature, as in the case of microelectronic circuits, θ_{JC} and the case-to-mounting-surface thermal resistance, θ_{CB}, must be known. Examples of θ_{JC} data are shown in Table E-2 to illustrate the order of magnitude of their values. Such data are usually obtained from manufacturer publications. The value of θ_{CB}, which depends on the mounting technique, can be calculated or measured.

These data are based on experience accumulated by Hughes thermal engineers. The results of many past thermal analysis tasks, which involved these twelve cooling methods, were surveyed. The data presented represent the most typical results.

It should be emphasized that these temperature estimates are only approximate values. They should be used only for preliminary evaluation purposes and not to design the equipment.

TABLE E-1. COOLING METHODS FOR VARIOUS TYPES OF PARTS

	Type of Parts							
Application	Micro-electronics	Power Transistors	Capacitors	Resistors	Transformers	Oscillators	Gyros	Traveling Wave Tubes (TWT)
Airborne-fighter	B, C, D, E	E, F, G, H	A, B, C, D, E, F, G	A, B, C, D, E, F, G, H	B, C, D, E, H	A	A, B	G, I
Airborne-cargo	B, C, D, E	C, F, G, H	A, B, C, D, E, F, G	A, B, C, D, E, F, G, H	B, C, D, E, H	A	A, B	G, I, J
Missile	A, G	A, G, H	A, G	A, G, H	A, G, H	A, G	A, G	G, I
Space	G, L	G, L	G, K, L	G, K, L	G, K, L	K	G, K, L	G, K, L
Ground	A, B, D, E, F, G	A, B, D, E, F, G, H	A, B, D, E, F, G	A, B, D, E, F, G, H	A, C, J, H	A	A, B	G, I, J
Shipboard	A, B, D, E, F, G	A, B, D, E, F, G, H	A, B, D, E, F, G	A, B, D, E, F, G, H	A, B, D, E, F, G, H	A	A, B	G, I, J

Type of cooling

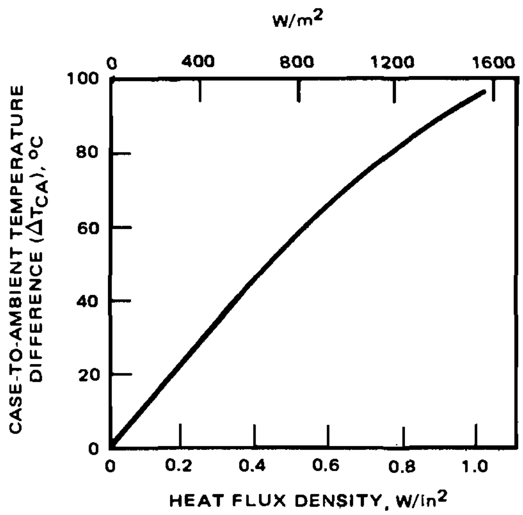
- A: Free convection to ambient air and radiation
- B: Air impingement, non-card-mounted
- C: Air impingement, card-mounted
- D: Card-mounted, air-cooled cold walls
- E: Card-mounted, flow-through modules
- F: Cold-plate-mounted, air-cooled
- G: Cold-plate-mounted, liquid-cooled
- H: Free convection, liquid heat sink
- I: Flush-cooled
- J: Liquid evaporation
- K: Radiation to space
- L: Space radiator with liquid transport loop

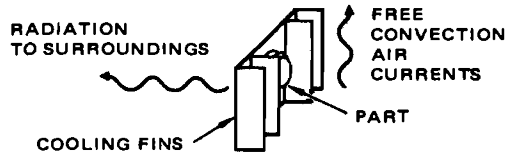
TABLE E–2. THERMAL CHARACTERISTICS OF TYPICAL MICROCIRCUITS AND DISCRETE SEMICONDUCTORS

Part Type	Commercial Part Number	Military Part Number	Rated Power (Watts)	Junction-to-Case Thermal Resistance (Vendor-Quoted Values), θ_{JC} (°C/W)*
Digital IC	54LS00	MIL-M-38510/30001	0.0143	51
Digital IC	54LS139	MIL-M-38510/30702	0.0600	51
Digital IC	54LS163	MIL-M-38510/30902	0.1800	51
Digital IC	5440	MIL-M-38510/00301A	0.400	150
Digital IC	5440	MIL-M-38510/00301C	0.400	80
Digital IC	5402	MIL-M-38510/00401A	0.120	90
Digital IC	5402	MIL-M-38510/00401C	0.120	80
Digital IC	54181	MIL-M-38510/01101E	0.795	20
Digital IC	54181	MIL-M-38510/01101J	0.795	40
Digital IC	—	MIL-M-38510/08201E	0.605	70
Digital IC (CMOS)	4000A	MIL-M-38510/5201A	0.200	150
Digital IC (CMOS)	4001A	MIL-M-38510/5202C	0.200	80
Transistor	2N342	MIL-S-19500/16	1.0	125.0
Transistor	2N539	MIL-S-19500/38	11.0	2.3
Transistor	2N326	MIL-S-19500/40	7.0	8.5
Transistor	2N665	MIL-S-19500/58	35.0	2.15
Transistor	2N1011	MIL-S-19500/67	50.0	1.5
Transistor	2N1120	MIL-S-19500/68	90.0	0.80
Transistor	2N1890	MIL-S-19500/225	3.0	58.1
Transistor	2N2222	MIL-S-19500/255	1.80	97.1
Transistor	2N962	MIL-S-19500/258	0.300	250.0
Transistor	2N2481	MIL-S-19500/268	1.20	146.0
Transistor	2N1131	MIL-S-19500/177	2.0	75.0
Diode	1N5546	MIL-S-19500/437	0.400	375
Transistor	2N2857	MIL-S-19500/343	0.200	585
Diode	1N3305	MIL-S-19500/358	50.0	2.0
Diode	1N5148	—	2.0	75
Diode	1N5281	—	0.500	250
Diode	1N5314	—	0.600	208
Diode	1N6073	—	11.5	13.0

*Vendor-quoted values of θ_{JC} generally are much higher (more conservative) than actual values of the delivered parts.

FREE CONVECTION TO AMBIENT AIR AND RADIATION





NOTES:

1. VIEW FACTOR = 1.0 AND EMISSIVITY = 1.0
2. MOUNTING THERMAL RESISTANCE = 0
3. THE PART JUNCTION TEMPERATURE IS OBTAINED AS FOLLOWS:

   $T_J = T_A + \Delta T_{CA} + \theta_{JC} Q$

   WHERE

   T_J IS THE JUNCTION TEMPERATURE

   T_A IS THE AMBIENT TEMPERATURE

   ΔT_{CA} IS THE CASE-TO-AMBIENT TEMPERATURE DIFFERENCE

   θ_{JC} IS THE JUNCTION-TO-CASE THERMAL RESISTANCE IN °C/W

   Q IS THE POWER DISSIPATION IN WATTS
4. ALL TEMPERATURES ARE IN °C

Figure E-1. Estimated part temperatures for free-convection-and-radiation-cooled equipment, using sea-level ambient air as heat sink (Cooling Type A).

Example

Estimate the junction temperature of a microcircuit (54LS00) with a power dissipation of 0.0120 W and having an external area (including fins) of 5×10^{-5} m^2, cooled by free convection and radiation in 60°C air.

1. Compute heat flux density:

$$\frac{0.0120 \text{ W}}{5 \times 10^{-5} \text{ m}^2} = 240 \text{ W/m}^2$$

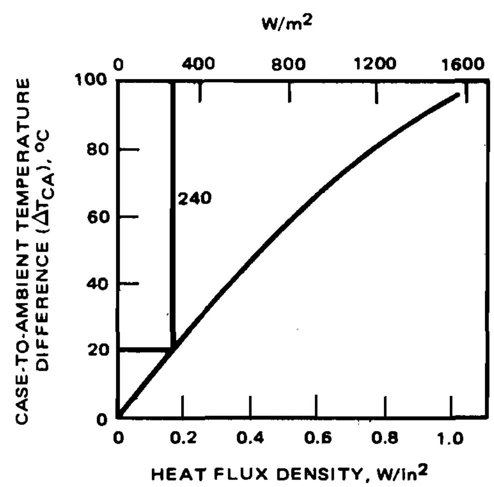
2. From Table E-2, θ_{JC} = 51°C/W for 54LS00.

3. From Figure E-1, ΔT_{CA} = 20°C.

4. From Note 3 in Figure E-1,

$$\begin{aligned} T_J &= T_A + \Delta T_{CA} + \theta_{JC} Q \\ &= 60°C + 20°C + (51°C/W)(0.0120 \text{ W}) \\ &= 80°C + 0.612°C \end{aligned}$$

$$T_J = 81°C.$$



AIR IMPINGEMENT, NON–CARD–MOUNTED

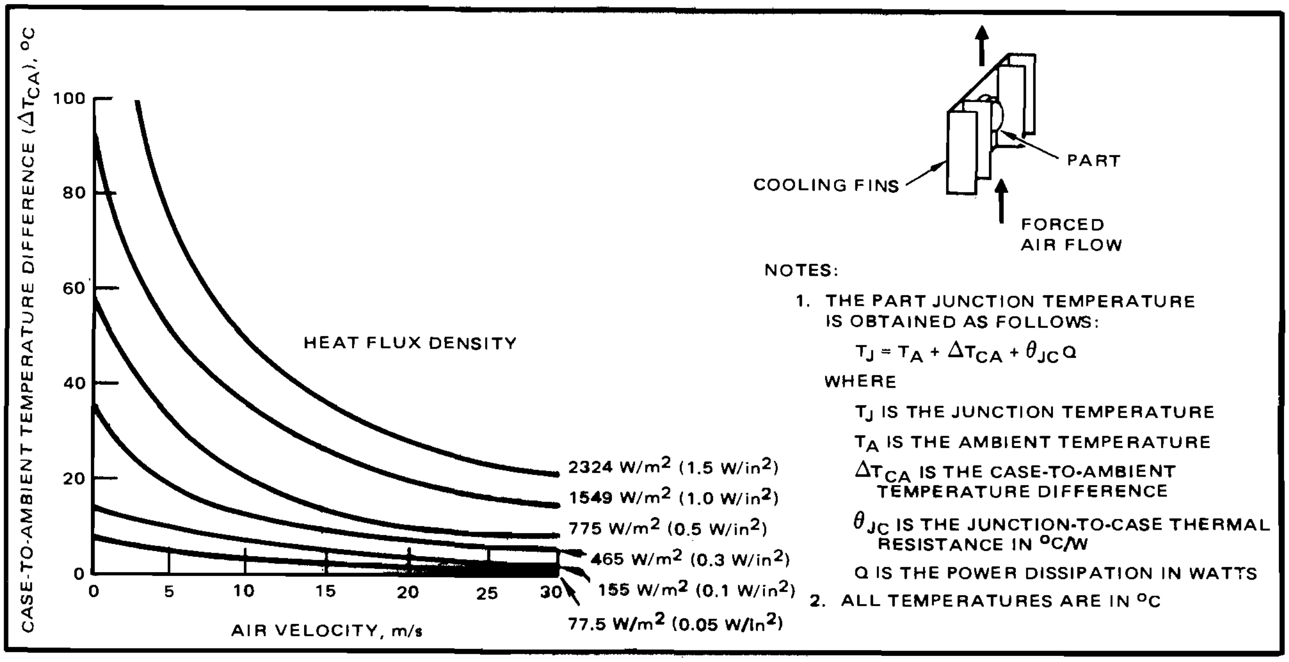


Figure E-2. Estimated temperatures of non-card-mounted parts using forced-air impingement cooling at sea level (Cooling Type B).

Example

Estimate the junction temperature of a transistor with a power dissipation of 10 W, cooled by impingement of 60°C air at 15 m/s, if $\theta_{JC} = 0.2°C/W$ and the total area exposed to the air (including cooling fins) is $0.00625\ m^2$.

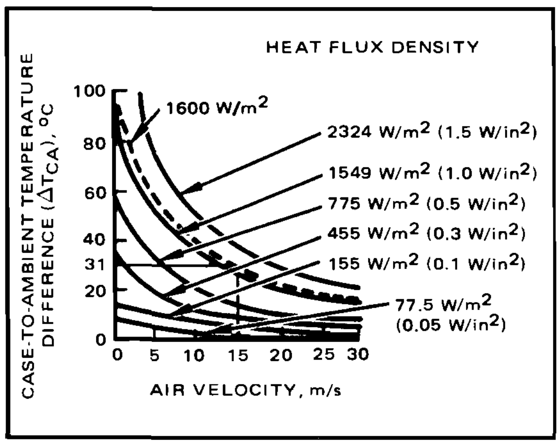
1. Compute heat flux density:

$$\frac{10\ W}{0.00625\ m^2} = 1600\ W/m^2$$

2. From Figure E-2, $\Delta T_{CA} = 31°C$.

3. From Note 1 in Figure E-2,

$$\begin{aligned} T_J &= T_A + \Delta T_{CA} + \theta_{JC}\, Q \\ &= 60°C + 31°C + (0.2°C/W)\,(10\ W) \\ &= 91°C + 2°C \\ T_J &= 93°C. \end{aligned}$$



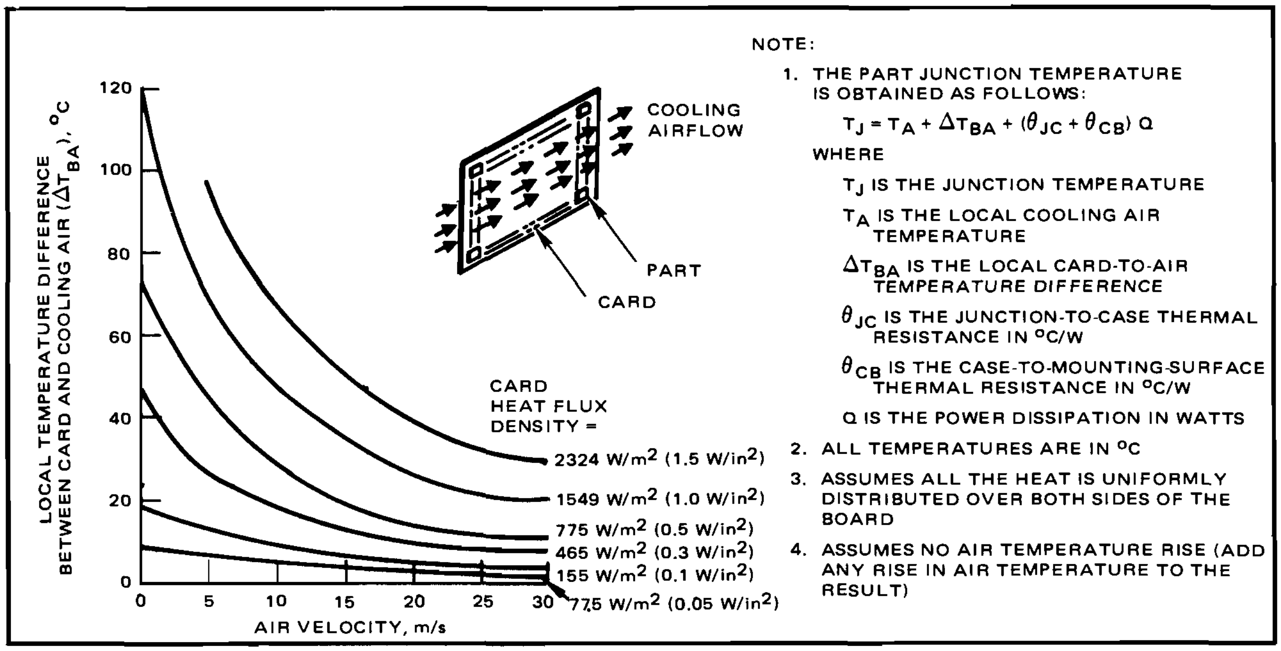


Figure E-3. Estimated temperatures of card-mounted parts using forced-air impingement cooling at sea level (Cooling Type C).

Example

Estimate the junction temperature of a part dissipating 0.25 W and mounted on a circuit board cooled by impingement with ambient air at 40°C and a velocity of 15 m/s. The circuit board, whose dimensions are 0.102 × 0.152 m, has a total power dissipation of 20 W. The part, whose mounting base is 0.00635 × 0.00953 m, is attached to the board with a 7.61×10^{-5} m (3 mils) thick bonding compound whose thermal conductivity (k) is 0.25 W/m-°C. The junction-to-case thermal resistance (θ_{JC}) of the part is 50°C/W.

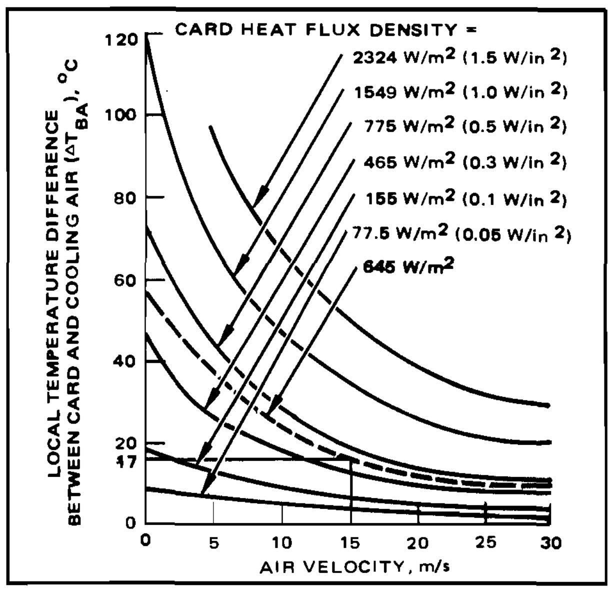
1. Compute the card heat flux density (see Note 3 in Figure E-3):

$$\frac{20\ \text{W}}{2\ (0.102\ \text{m})\ (0.152\ \text{m})} = 645\ \text{W/m}^2.$$

2. From Figure E-3: $\Delta T_{BA} = 17°C$.

3. Calculate θ_{CB}: From Equation 5-3,

$$\theta_{CB} = \frac{7.61 \times 10^{-5}\ \text{m}}{(0.25\ \text{W/m-°C})\ (0.00635\ \text{m} \times 0.00953\ \text{m})} = 5.03°\text{C/W}.$$



4. From Note 1 in Figure E-3,

$$T_J = T_A + \Delta T_{BA} + (\theta_{JC} + \theta_{CB})\ Q$$
$$= 40 + 17 + (50 + 5.03)\ 0.25$$
$$T_J = 71°C.$$

CARD-MOUNTED, AIR-COOLED COLDWALLS

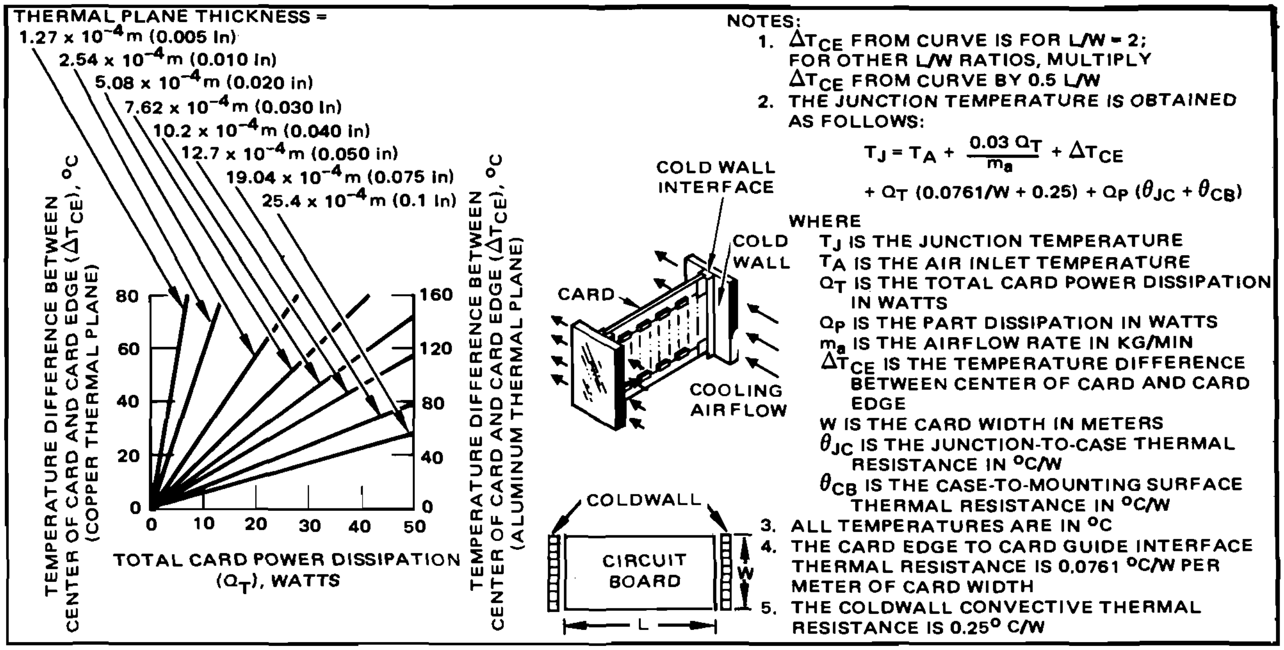


Figure E-4. Estimated temperatures of card-mounted parts using forced-air cooled coldwalls (Cooling Type D).

Example

Estimate the junction temperature of a 0.25-W microcircuit mounted at the center of a coldwall-cooled circuit board, 0.152 × 0.102 m, with a total power dissipation of 20 W. The part, which has a mounting base of 0.00635 × 0.00953 m, is attached to the board with a 7.6×10^{-5} m (3 mils) thick bonding compound whose thermal conductivity (k) is 0.25 W/m-°C. The forced airflow rate is 1.8 kg/min with an inlet temperature of 45°C. The board contains a 5.08×10^{-4} m (0.020 inch) thick copper thermal plane. The θ_{JC} of the part is 50°C/W.

1. From Figure E-4, $\Delta T_{CE} = 57°C$ for L/W = 2.

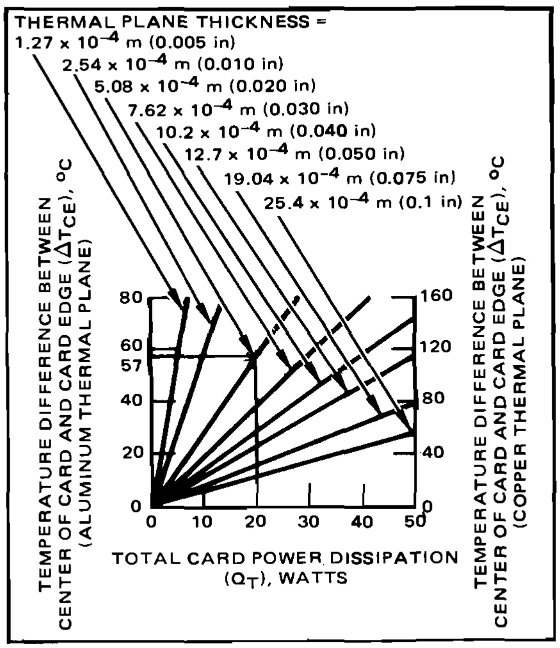
$$\text{Actual L/W} = \frac{0.152 \text{ m}}{0.102 \text{ m}} = 1.49, \text{ so}$$

$$\text{Corrected } \Delta T_{CE} = (0.5)(1.49)(57°C) = 42.5°C$$

2. Calculate θ_{CB}. From Equation 5-3,

$$\theta_{CB} = \frac{7.6 \times 10^{-5} \text{ m}}{(0.25 \text{ W/m-°C})(0.00635 \text{ m})(0.00953 \text{ m})} = 5.03°C/W$$

3. From Note 2 in Figure E-4,



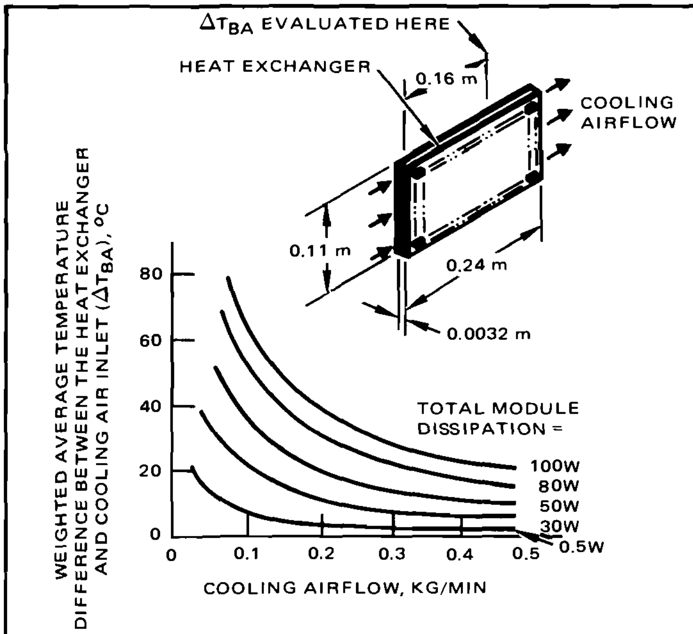
$$T_J = T_A + \frac{0.03\, Q_T}{m_a} + \Delta T_{CE} + Q_T\,(0.0761/W + 0.25) + Q_P\,(\theta_{JC} + \theta_{CB})$$

$$= 45 + \frac{0.03\,(20)}{1.8} + 42.5 + 20\left(\frac{0.0761}{0.102} + 0.25\right) + 0.25\,(50 + 5.03)$$

$$= 45 + 0.33 + 42.5 + 19.9 + 13.8$$

$$T_J = 122°C.$$

CARD-MOUNTED, FLOW-THROUGH MODULES



NOTES:

1. MODULE DISSIPATION UNIFORMLY DISTRIBUTED AND APPLIED ON BOTH SIDES
2. THE PART JUNCTION TEMPERATURE IS OBTAINED AS FOLLOWS:

   $T_J = T_A + \Delta T_{BA} + (\theta_{JC} + \theta_{CB})\, Q_P$

   WHERE

   T_J IS THE JUNCTION TEMPERATURE

   T_A IS THE COOLING AIR INLET TEMPERATURE

   ΔT_{BA} IS THE WEIGHTED AVERAGE HEAT-EXCHANGER-TO-COOLING-AIR-INLET TEMPERATURE DIFFERENCE (SEE NOTE 4)

   θ_{JC} IS THE JUNCTION-TO-CASE THERMAL RESISTANCE IN °C/W

   θ_{CB} IS THE THERMAL RESISTANCE BETWEEN THE CASE AND THE HEAT EXCHANGER IN °C/W

   Q_P IS THE PART DISSIPATION IN WATTS
3. ALL TEMPERATURES ARE IN °C
4. WEIGHTED AVERAGE TEMPERATURE DIFFERENCE IS THE VALUE AT A LOCATION TWO THIRDS OF THE DISTANCE FROM THE INLET TO THE OUTLET, AS SHOWN IN SKETCH. EXPERIENCE HAS SHOWN THAT THE TEMPERATURE AT THIS LOCATION APPROXIMATES THE AVERAGE BOARD TEMPERATURE.

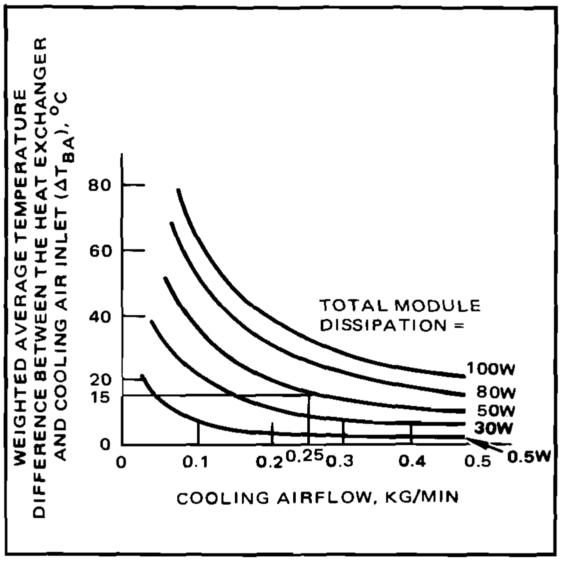
Figure E-5. Estimated temperatures of card-mounted parts using forced-air-cooled flow-through modules (Cooling Type E).

Example

Estimate the junction temperature of a 0.25-W microcircuit mounted on a flow-through forced-air-cooled module, which has a total dissipation of 50 W. The cooling flow rate is 0.25 kg/min, and the inlet temperature is 30°C. The junction-to-case thermal resistance (θ_{JC}) is 55°C/W, and the total thermal resistance between the case and the heat exchanger (θ_{CB}) is 17°C/W.

1. From Figure E-5, ΔT_{BA} = 15°C.
2. From Note 2 in Figure E-5,

$$T_J = T_A + \Delta T_{BA} + (\theta_{JC} + \theta_{CB})\, Q_P$$
$$= 30 + 15 + (55 + 17)\ 0.25$$
$$T_J = 63°C.$$



COLD–PLATE–MOUNTED, AIR–COOLED

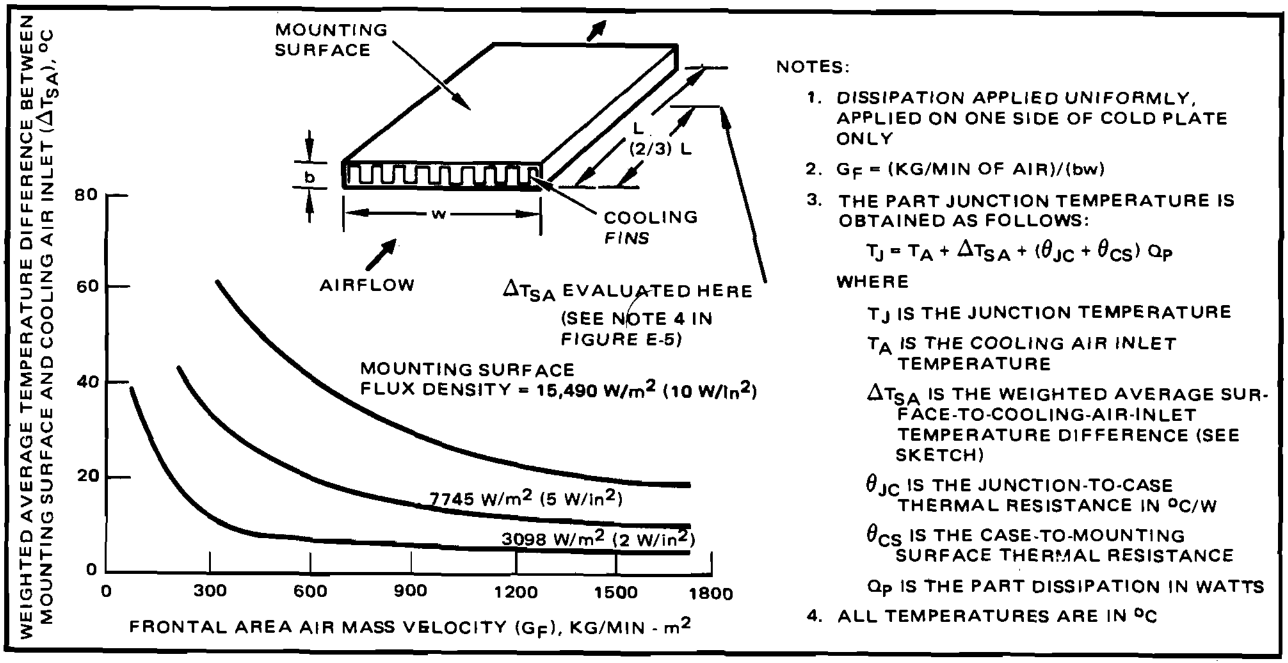


Figure E–6. Estimated temperatures of cold-plate-mounted parts using forced-air cooling (Cooling Type F).

Example

Estimate the junction temperature of a 5–W part mounted on an air-cooled cold plate whose dimensions are as follows: height (b) = 0.0127 m, width (W) = 0.153 m, and length (L) = 0.228 m. The total dissipation is 156 W. Cooling air is supplied to the cold plate at an inlet temperature of 40°C and a flow rate of 1.75 kg/min. The part, whose mounting base is 0.0254 × 0.0508 m, is attached to the cold plate with a 1.27×10^{-4} m (5 mils) thick bonding compound whose thermal conductivity (k) is 0.26 W/m-°C. The part junction-to-case thermal resistance (θ_{JC}) is 2°C/W.

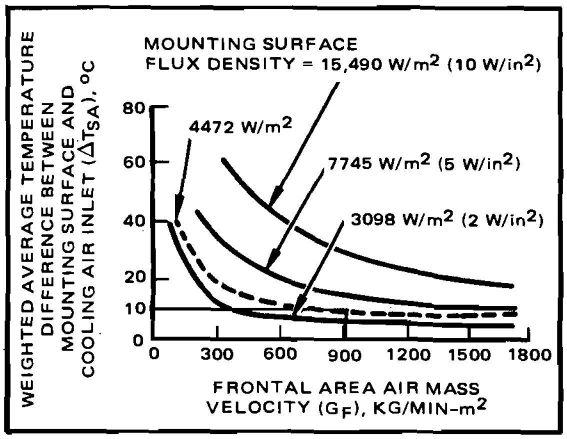
1. Calculate mounting surface flux density:

$$\frac{\text{Total dissipation}}{\text{WL}} = \frac{156\ \text{W}}{(0.153\ \text{m})\ (0.228\ \text{m})} = 4472\ \text{W/m}^2.$$

2. Calculate G_F:

$$G_F = \frac{\text{kg/min of air}}{\text{bW}} = \frac{1.75\ \text{kg/min}}{(0.0127\ \text{m})\ (0.153\ \text{m})} = 901\ \text{kg/min-m}^2.$$

3. From Figure E–6, ΔT_{SA} = 10°C.



4. Calculate θ_{CS}: From Equation 5–3,

$$\theta_{CS} = \frac{1.27 \times 10^{-4}\ \text{m}}{(0.26\ \text{W/m-°C})\ (0.0254\ \text{m} \times 0.0508\ \text{m})} = 0.38\text{°C/W}.$$

5. From Note 3 in Figure E–6,

$$\begin{aligned} T_J &= T_A + \Delta T_{SA} + (\theta_{JC} + \theta_{CS})\, Q_P \\ &= 40 + 10 + (2 + 0.38)\ 5 \\ T_J &= 62\text{°C}. \end{aligned}$$

COLD-PLATE-MOUNTED, LIQUID-COOLED

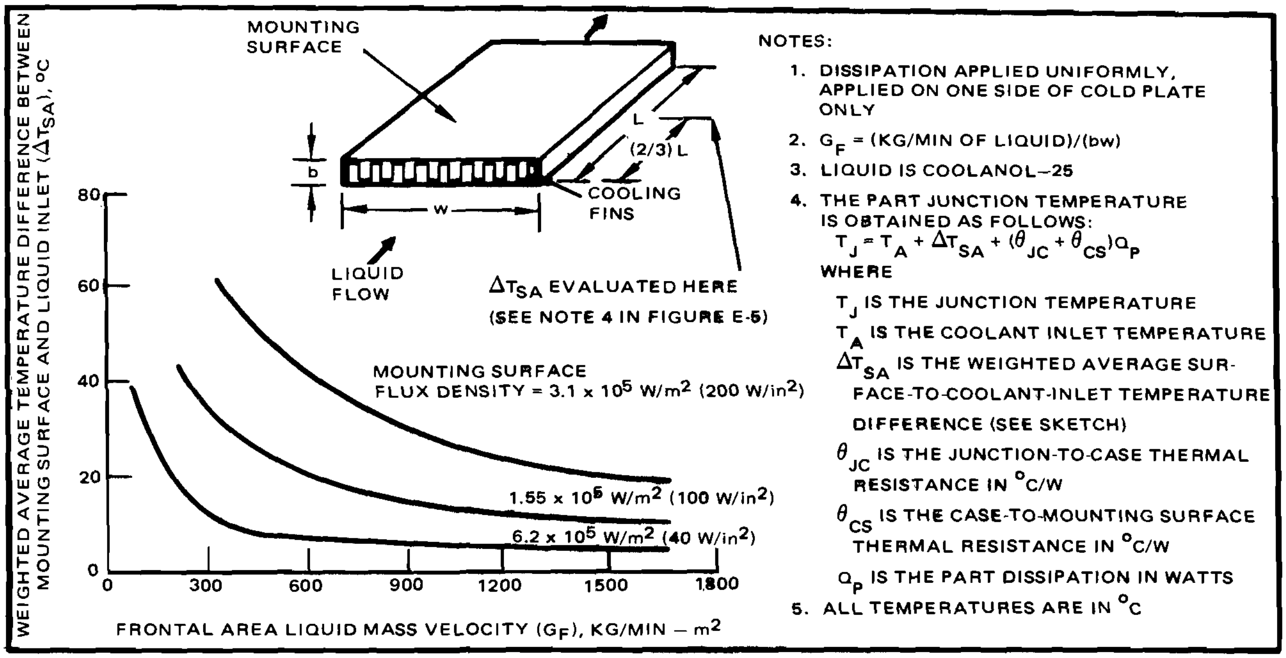


Figure E-7. Estimated temperatures of cold-plate-mounted parts using forced-liquid cooling (Cooling Type G).

Example

Estimate the junction temperature of a 10-W part, mounted on a forced-liquid-cooled cold plate whose dimensions are as follows: height (b) = 0.00635 m, width (W) = 0.101 m and length (L) = 0.127 m. The total dissipation is 3207 W. Liquid is supplied to the cold plate at an inlet temperature of 40°C and a flow rate of 0.577 kg/min. The part, whose mounting base is 0.0254 × 0.0508 m, is attached to the cold plate with a 1.27×10^{-4} m (5 mils) thick bonding compound whose thermal conductivity (k) is 0.26 W/m-°C. The junction-to-case thermal resistance is 2°C/W.

1. Calculate the mounting surface density:

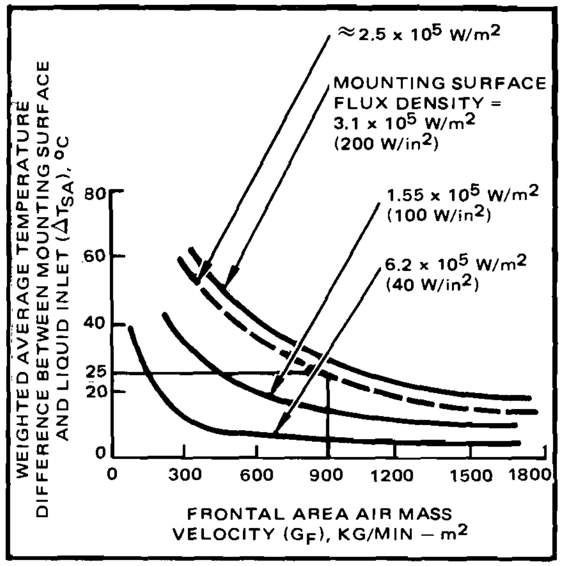
$$\frac{\text{Total dissipation}}{WL} = \frac{3207\ \text{W}}{(0.101\ \text{m})(0.127\ \text{m})} = 2.5 \times 10^5\ \text{W/m}^2.$$

2. Calculate G_F:

$$G_F = \frac{\text{kg/min}}{bW} = \frac{0.577\ \text{kg/min}}{(0.00635\ \text{m})\ (0.101\ \text{m})} = 900\ \text{kg/min-m}^2.$$

3. From Figure E-7, $\Delta T_{SA} = 25°C$.

4. Calculate θ_{CS}: From Equation 5-3,



$$\theta_{CS} = \frac{1.27 \times 10^{-4}\ \text{m}}{(0.26\ \text{W/m-°C})\ (0.0254\ \text{m})\ (0.0508\ \text{m})} = 0.38°\text{C/W}.$$

5. From Note 4 in Figure E-7,

$$\begin{aligned} T_J &= T_A + \Delta T_{SA} + (\theta_{JC} + \theta_{CS})\ Q_P \\ &= 40 + 25 + (2 + 0.38)\ 10 \\ T_J &= 89°C. \end{aligned}$$

FREE CONVECTION, LIQUID HEAT SINK

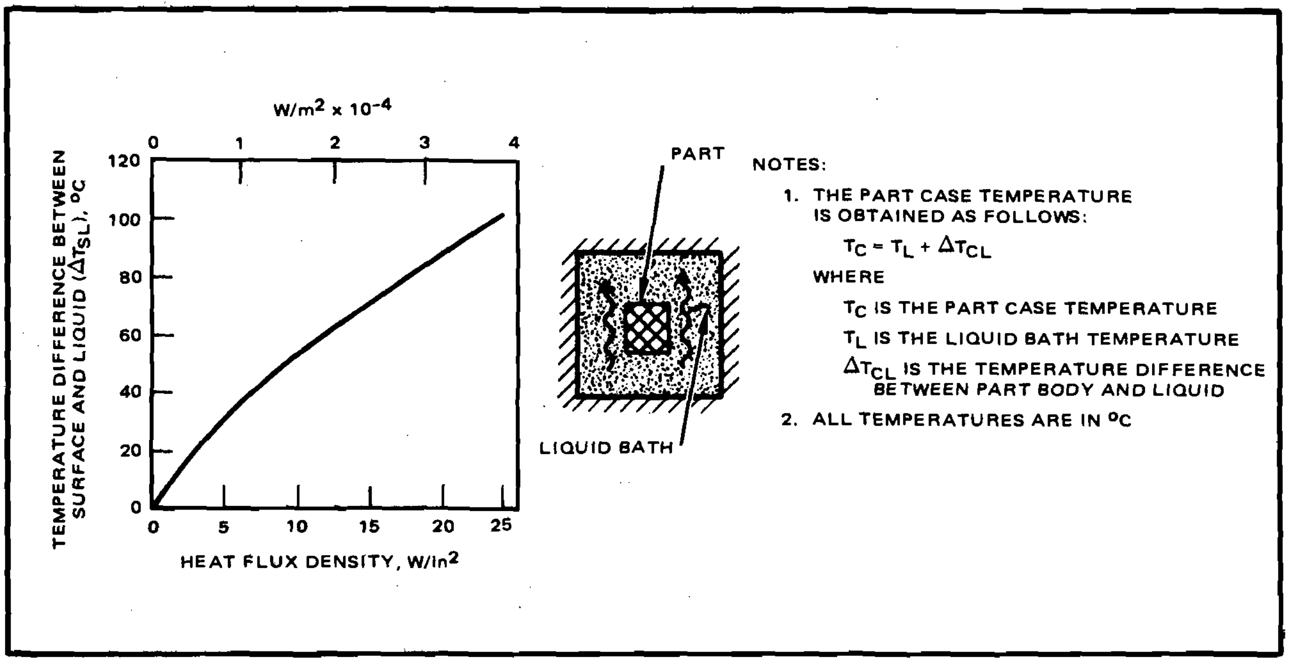


Figure E-8. Estimated temperatures of free-convection-cooled parts using liquid as heat sink (Cooling Type H).

Example

Estimate the case temperature of a 0.65-W part having a total surface area exposed to coolant equal to 3.2×10^{-5} m^2, and cooled by free convection using a liquid heat sink at 45°C.

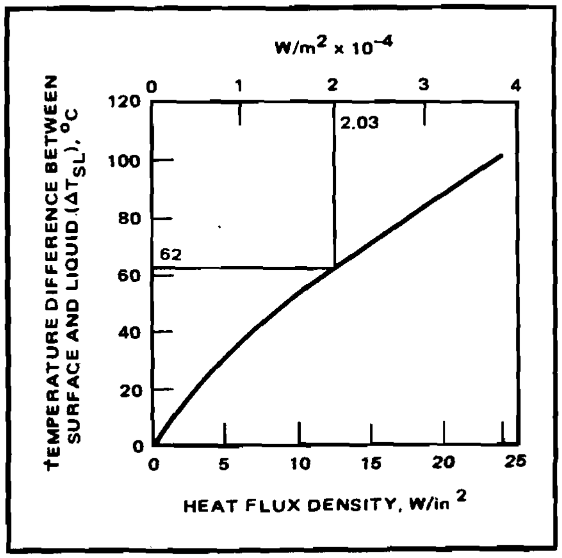
1. Compute the heat flux density:

$$\frac{0.65 \text{ W}}{3.2 \times 10^{-5} \text{ m}^2} = 2.03 \times 10^{+4} \text{ W/m}^2.$$

2. From Figure E-8, $\Delta T_{CL} = 62$°C.

3. Using Note 1 in Figure E-8,

$$T_C = T_L + \Delta T_{CL}$$
$$= 45°C + 62°C$$
$$T_C = 107°C.$$



FLUSH–COOLED

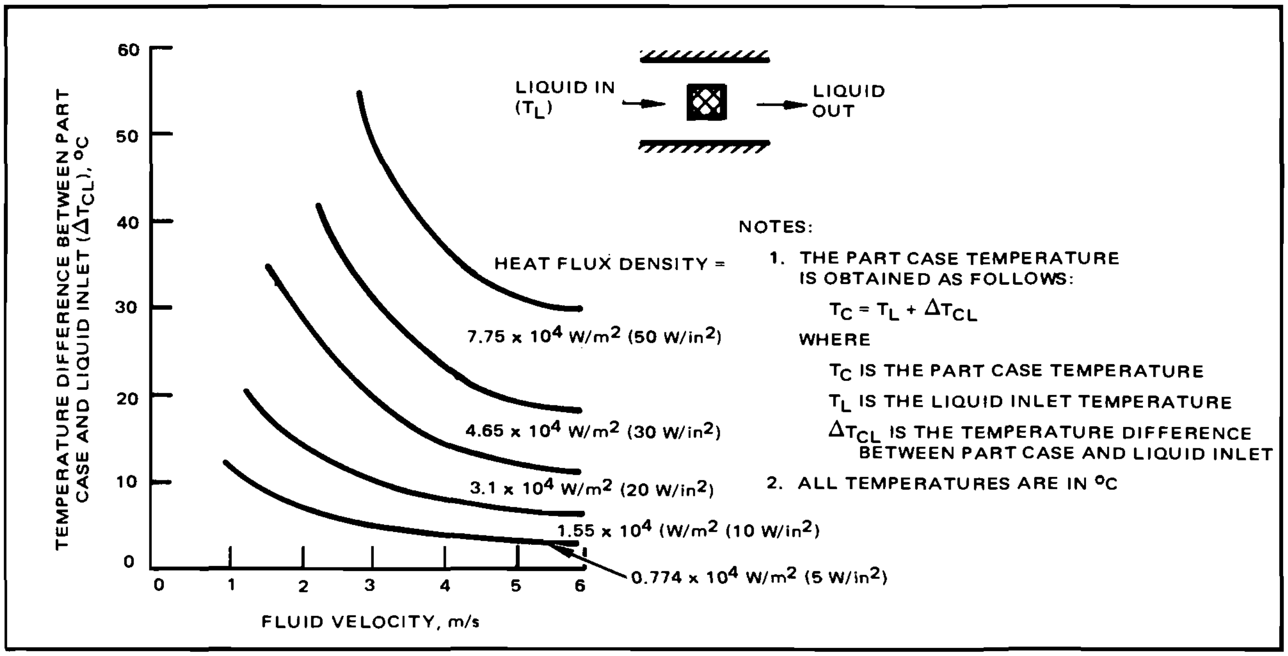


Figure E–9. Estimated temperatures of flush-cooled equipment (Cooling Type I).

Example

Estimate the case temperature of a 300-W unit with case dimensions of 0.051 × 0.03 × 0.058 m, flush-cooled by liquid at a velocity of 2 m/s and an inlet temperature of 50°C.

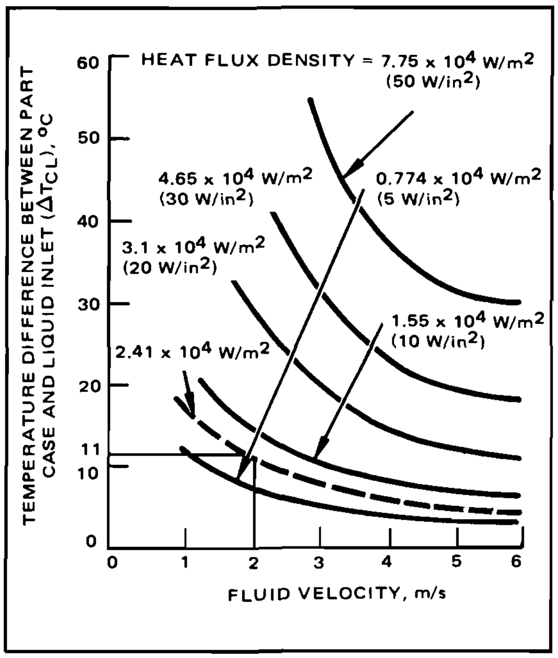
1. Compute the heat flux density:

$$\frac{300 \text{ W}}{2(0.051 \times 0.03 + 0.051 \times 0.058 + 0.03 \times 0.058)\text{m}^2} = 2.41 \times 10^4 \text{ W/m}^2.$$

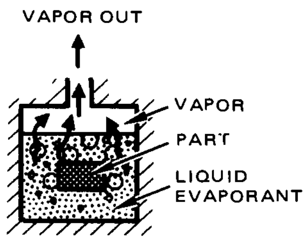
2. From Figure E–9, ΔT_{CL} = 11°C.

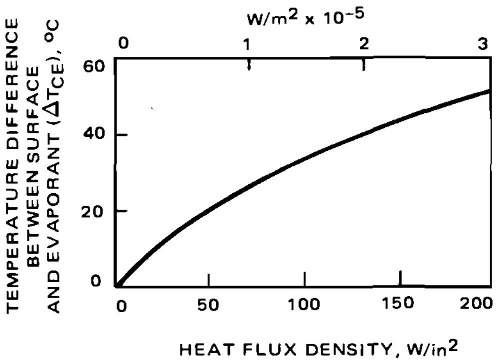
3. Using Note 1 in Figure E–9,

$$T_C = T_L + \Delta T_{CL}$$
$$= 50°C + 11°C$$
$$T_C = 61°C.$$



LIQUID EVAPORATION





NOTES:

1. THE PART CASE TEMPERATURE IS OBTAINED AS FOLLOWS:

   $T_C = T_E + \Delta T_{CE}$

   WHERE

   T_C IS THE PART CASE TEMPERATURE

   T_E IS THE EVAPORANT TEMPERATURE

   ΔT_{CE} IS THE TEMPERATURE DIFFERENCE BETWEEN THE PART SURFACE AND THE EVAPORANT

2. ALL TEMPERATURES ARE IN °C

Figure E-10. Estimated temperatures of parts cooled by liquid evaporation (Cooling Type J).

Example

Estimate the case temperature of a 200-W part whose case dimensions are 0.04 × 0.01 × 0.005 m, cooled by evaporation of a 60°C liquid.

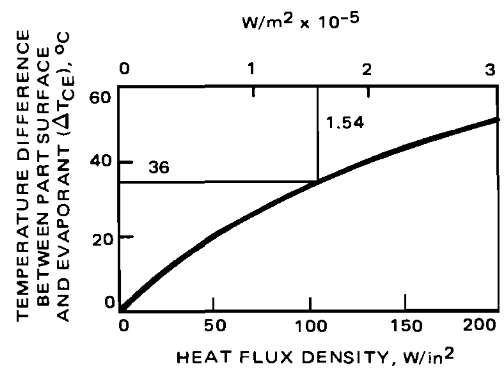
1. Compute the heat flux density:

$$\frac{200\ \text{W}}{2\,(0.04 \times 0.01 + 0.04 \times 0.005 + 0.01 \times 0.005)\text{m}^2} = 1.54 \times 10^5\ \text{W/m}^2.$$

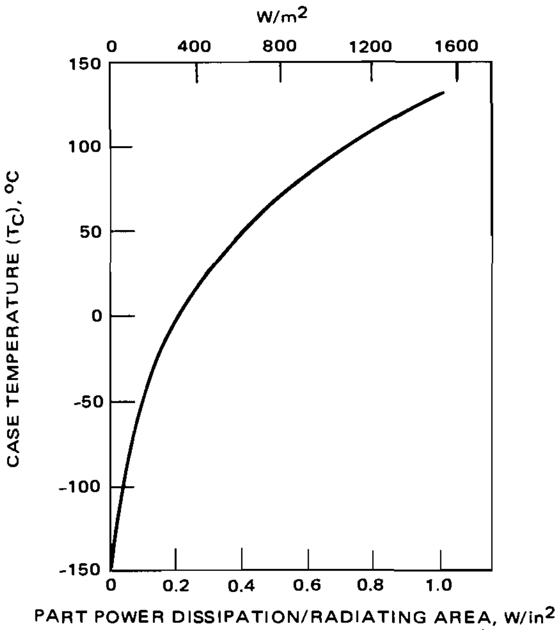
2. From Figure E-10, $\Delta T_{CE} = 36°\text{C}$.

3. Using Note 1 in Figure E-10,

$$T_C = T_E + \Delta T_{CE}$$
$$= 60°\text{C} + 36°\text{C}$$
$$T_C = 96°\text{C}.$$



RADIATION TO SPACE



NOTES:

1. VIEW FACTOR = 1.0
2. EMISSIVITY = 1.0
3. FOR SEMICONDUCTOR DEVICE, THE JUNCTION TEMPERATURE IS OBTAINED AS FOLLOWS:

   $T_J = T_C + \theta_{JC} Q$

   WHERE

   T_J IS THE JUNCTION TEMPERATURE

   T_C IS THE CASE TEMPERATURE

   θ_{JC} IS THE JUNCTION-TO-CASE THERMAL RESISTANCE IN °C/W

   Q IS THE PART POWER DISSIPATION IN WATTS
4. ALL TEMPERATURES ARE IN °C

Figure E-11. Estimated temperatures of parts cooled by direct radiation to deep space (Cooling Type K).

Example

Estimate the junction temperature for a 0.065-W semiconductor with a view factor of 1.0, a junction-to-case thermal resistance (θ_{JC}) of 85°C/W, radiating surface dimensions of 0.01 × 0.01 m, and cooled by direct radiation (assume one face radiates).

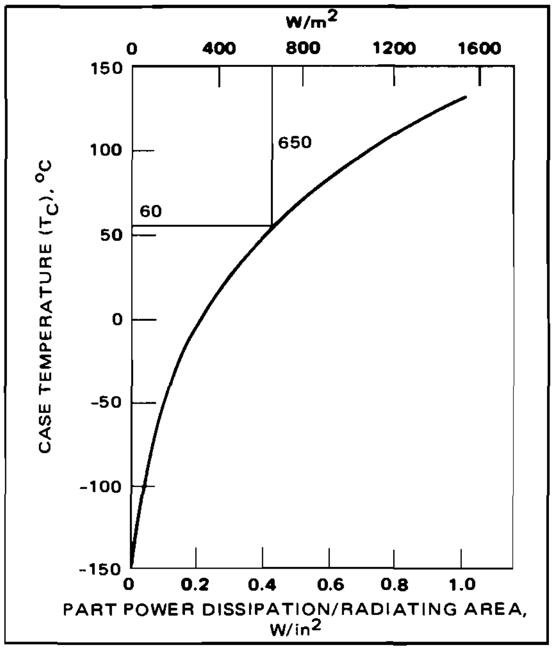
1. Compute the dissipation/radiating area:

$$\frac{0.065\ \text{W}}{0.01\ \text{m} \times 0.01\text{m}} = 650\ \text{W/m}^2.$$

2. From Figure E-11, T_C = 60°C.

3. Using Note 3 in Figure E-11,

$$\begin{aligned} T_J &= T_C + \theta_{JC}\, Q \\ &= 60°\text{C} + (85°\text{C/W})\ (0.065\ \text{W}) \\ &= 60°\text{C} + 5.525°\text{C} \\ T_J &= 66°\text{C}. \end{aligned}$$



SPACE RADIATOR WITH LIQUID TRANSPORT LOOP

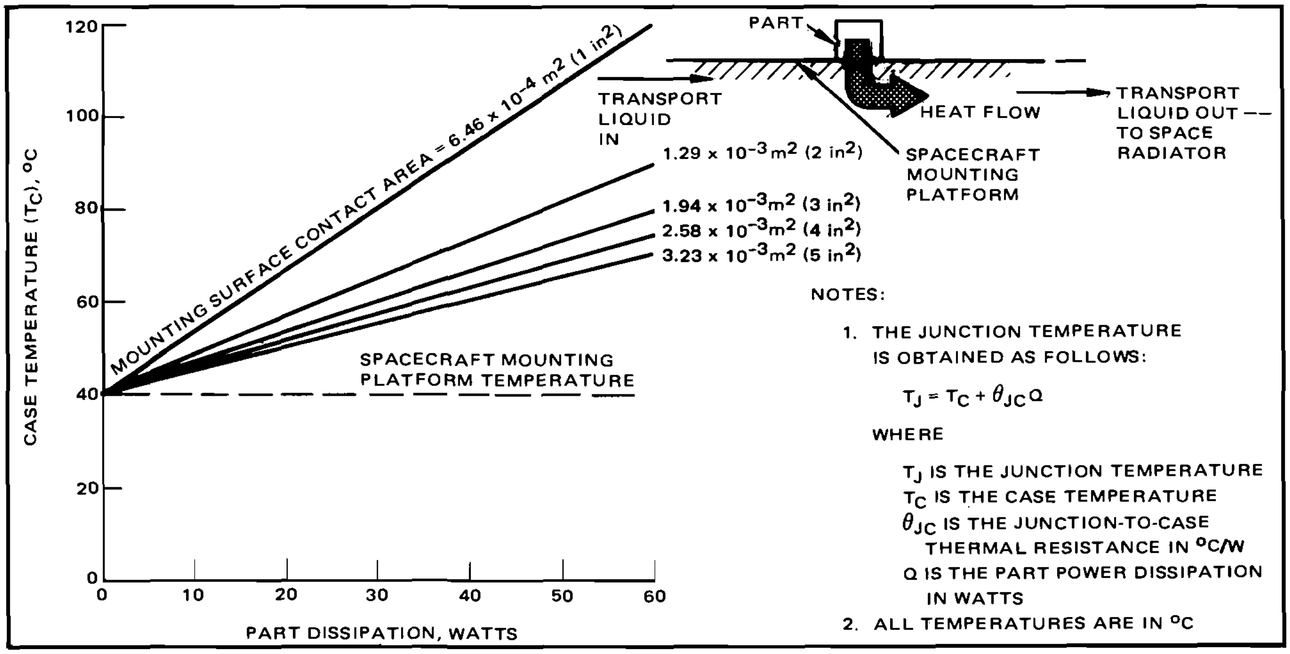


Figure E-12. Estimated temperatures of parts cooled by liquid-transport loop using deep space as the ultimate sink (Cooling Type L).

Example

Estimate the junction temperature of a 25-W part mounted on a surface 0.07 × 0.008 m with a junction-to-case thermal resistance (θ_{JC}) of 1°C/W and cooled by a liquid transport loop.

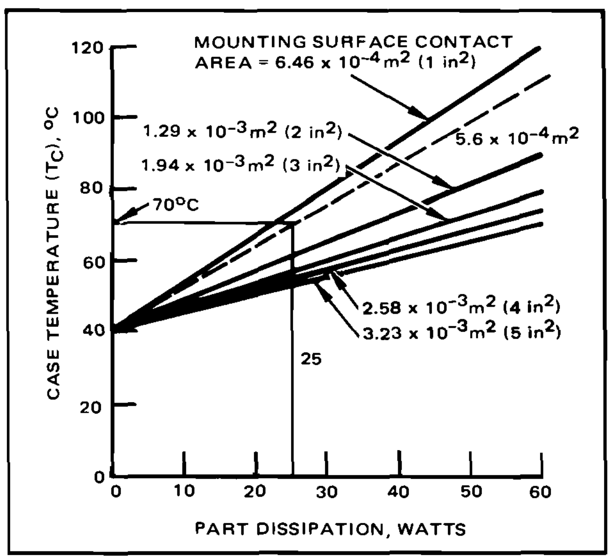
1. Compute the mounting surface area:

   $0.07 \text{ m} \times 0.008 \text{ m} = 5.6 \times 10^{-4} \text{ m}^2$

2. From Figure E-12, T_C = 70°C.

3. Using Note 1 in Figure E-12,

$$\begin{aligned} T_J &= T_C + \theta_{JC} Q \\ &= 70°C + (1°C/W)(25 \text{ W}) \\ &= 70°C + 25°C \\ T_J &= 95°C. \end{aligned}$$



APPENDIX F
FOR MORE INFORMATION

CHAPTER 1: SUCCESS IN THERMAL MANAGEMENT

1-1 "Reliability/Design, Thermal Applications," MIL-HDBK-251, 19 January 1978.

1-2 "Military Program for Systems and Equipment Development and Production," MIL-STD-785B, 15 September, 1980.

CHAPTER 2: SPECIFIC THERMAL TASKS AND REQUIREMENTS

Thermal Tasks. Reliability program management is described in References 2-1 through 2-4.

Thermal Requirements. Thermal specifications and requirements for military electronic equipment are stated in References 2-5 through 2-12. References 2-6, 2-7, and 2-9 through 2-11 state that the thermal design shall be in accordance with Reference 2-5. Thermal Data Item Descriptions are listed as References 2-13 through 2-20. Environmental test methods are described in Reference 2-21. Test specifications for airborne and USAF spaceborne equipment are described in References 2-22 and 2-23. Reliability tests are described in Reference 2-24. USAF technical reviews are described in Reference 2-25.

2-1 "Military Program for Systems and Equipment Development and Production," MIL-STD-785B, 15 September 1980.

2-2 "Reliability Program Requirements for Space and Missile Systems," MIL-STD-1543 (USAF), Notice 2, 22 July 1977.

2-3 A. Coppola and A.N. Sukert, "Reliability and Maintainability Management Manual," RADC-TR-79-200, AD-A073299, July 1979.

2-4 R.S. Cazanjian, "Design Practices and Review Procedures for Reliability," in *Reliability Engineering for Electronic Systems*, R.H. Myers, K.L. Wong, and H.M. Gordy (Eds.), Chapter 6, pp. 152-173, John Wiley and Sons, New York, 1964.

2-5 "Standard General Requirements for Electronic Equipment," Requirement 52 (Thermal Design), MIL-STD-454G, 15 March 1980.

2-6 "Electronic Equipment, Ground; General Requirements For," MIL-E-4158E (USAF), Amendment 1, 24 August 1976.

2-7 "Electronic Equipment, Airborne, General Specification For," Paragraph 3.2.5, MIL-E-5400T (for DOD airborne equipment and procurements after 5 September 1980 of DOD missiles, boosters, and allied equipment), 16 November 1979.

2-8 "Electronic Equipment, Aerospace, Extended Space Environment, General Specification For," Paragraph 3.6.5, DOD-E-8983C, 29 December 1977.

2-9 "Electronic, Electrical, and Electro-Mechanical Equipment, Guided Missile and Associated Weapon Systems, General Specification For," Paragraph 3.3.14, MIL-E-11991D (MI), 27 February 1976.

2-10 "Electronic, Interior Communication, and Navigation Equipment, Naval Ship and Shore, General Specification For," Paragraphs 3.8, 4.8.7, and 6.2.2, MIL-E-16400G (Navy), 1 December 1976.

2-11 "Test Equipment for Use with Electronic and Electrical Equipment, General Specification For," MIL-T-21200L, 2 July 1973.

2-12 "Air Force Avionics Installation Standard," Draft, Proposed MIL-STD-XXX, 15 June 1981.

2-13 "Environmental Criteria Report," DI-E-1119 (Army), 15 December 1969.

2-14 "Report, Environment, Reliability," DI-R-2116 (Navy), 29 August 1973.

2-15 "Integrated Circuit Thermal Analysis Report," DI-R-5458 (NSA), 19 April 1977.

2-16 "Report, Thermal Survey," DI-R-7036 (DOD), 21 October 1977.

2-17 "Electronic Parts/Circuits Tolerance Analysis Report," DI-R-7084 (DOD), 14 October 1980.

2-18 "Report, Environment," UDI-R-21138 (Navy-AS), 9 August 1973.

2-19 "Report, Reliability Stress Analysis," UDI-R-21423 (Navy-AS), 30 July 1975.

2-20 "Data, Cooling Design," UDI-T-21341A (AT-015A) (Navy-AS), 22 October 1974.

2-21 "Environmental Test Methods," MIL-STD-810C, 10 March 1975.

2-22 "Testing, Environment, Airborne Electronic and Associated Equipment," MIL-T-5422F (AS), 30 November 1971.

2-23 "Test Requirements for Space Vehicles," MIL-STD-1540A (USAF), 15 May 1974.

2-24 "Reliability Tests: Exponential Distribution," MIL-STD-781C, 21 October 1977.

2-25 "Technical Reviews and Audits for Systems, Equipments and Computer Programs," MIL-STD-1521A (USAF), 1 June 1976.

CHAPTER 3: TAILORING OF THERMAL MANAGEMENT PROGRAMS

3-1 "Military Program for Systems and Equipment Development and Production," MIL-STD-785B, 15 September 1980.

3-2 A. Coppola and A.N. Sukert, "Reliability and Maintainability Management Manual," RADC-TR-79-200, AD-A073299, July 1979.

CHAPTER 4: IMPACT OF TEMPERATURE ON RELIABILITY

Effect of Temperature on Failure Rate. See the latest version of MIL-HDBK-217 (Reference 4-1), on which the reliability prediction calculations in this guide are based. Air Force studies of failures of avionic equipment are reported in References 4-2 through 4-5. References 4-6 through 4-8 examine the dependence of failure rate on temperature for a variety of types of electronic equipment. The effect of temperature on the reliability of semiconductor devices is discussed in References 4-9 through 4-14.

Thermally Induced Failure Modes. See References 4-6, 4-9, and 4-12 through 4-16. For a different viewpoint developed by Hughes, see References 4-17 and 4-18.

Cost Benefits of Thermal Design. See References 4-19, 4-20, and page 24 of 4-21.

4-1 "Reliability Prediction of Electronic Equipment," MIL-HDBK-217C, Notice 1, 1 May 1980.

4-2 G. Hirschberger and A. Dantowitz, "Evaluation of Environmental Profiles for Reliability Demonstration," RADC-TR-75-242, AD-B007946, September 1975.

4-3 A. Dantowitz, et al., "Analysis of Aeronautical Equipment Environmental Failures," AFFDL-TR-71-32, May 1971.

4-4 J.J. Duhig, Jr., and T.E. Weaver, "Effects of Temperature on Avionics Reliability," *Proc. 1977 Annual Reliability and Maintainability Symp.*, pp. 409-413, 1977.

4-5 G.A. Kern and T.M. Drnas, "Operational Influences on Reliability," RADC TR-76-366, AD-A035016, December 1976.

4-6 H.S. Blanks, "The Temperature Dependence of Component Failure Rate," *Monitor—Proc. IREE Australia*, pp. 122-133, September/October 1978.

4-7 A.R. Eames, "Prediction Methods for Equipment Reliability Evaluation," *The Radio and Electronic Engineer* (British), Vol. 48, pp. 333-340, July/August 1978.

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Purposes of Thermal Testing. Discussed in detail in Reference 9-1 and briefly in References 9-2 and 9-3.

Simulation of Thermal Environment. Discussed in Reference 9-1.

Instrumentation. Reference 9-4 discusses the nonuniformity of the case temperature of a flatpack. Reference 9-1 describes methods for measuring temperature, pressure, and flow rate in detail. Reference 9-5 presents a concise, introductory description, with many photographs of instruments. Reference 9-6 reviews some recently developed measurement methods and instruments.

Reference 9-7 shows numerous photographs of contact temperature instruments and presents some useful thermal data. Reference 9-8 is a user-oriented discussion of thermocouples and several other common temperature transducers. Reference 9-9 discusses a potential error source for thermocouples. Reference 9-10 is an excellent textbook on infrared techniques, and References 9-11 and 9-12 describe applications to electronic equipment. Reference 9-13 reviews new optical temperature-measurement techniques.

Reference 9-14 describes the standard methods, infrared (IR) and electrical, for measuring semiconductor-device junction temperatures. Reference 9-15 compares the IR, contact, and electrical methods. References 9-16 through 9-18 describe IR measurement techniques and applications. References 9-19 through 9-21 discuss chip transparency and emissivity considerations in IR measurements. References 9-22 and 9-23 describe the promising new laser-scanning technique and compare it with the IR technique; see also References 9-24 and 9-25. References 9-26 and 9-27 compare the electrical and IR methods. References 9-28 and 9-29 discuss pitfalls in evaluating junction temperatures from electrical measurements. References 9-30 and 9-31 describe other techniques.

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Thermal Inspection Technology. The comparison technique for thermal inspection is described in

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CHAPTER 13: CORRECTION OF POOR FIELD RELIABILITY BY IMPROVING THE THERMAL DESIGN

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