ELECTRONIC COMPONENT COOLING ALTERNATIVES: COMPRESSED AIR AND LIQUID NITROGEN

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, Superfund-related activities, and pollution prevention. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Passage of the Pollution Prevention Act of 1990 marked a significant change in U.S. policies concerning the generation of hazardous and nonhazardous wastes. This bill implements the national objective of pollution prevention by establishing a source reduction program at the EPA and by assisting States in providing information and technical assistance regarding source reduction. In support of the emphasis on pollution prevention, the "Waste Reduction Innovative Technology Evaluation (WRITE) Program" has been designed to identify, evaluate, and/or demonstrate new ideas and technologies that lead to waste reduction. The WRITE Program emphasizes source reduction and on-site recycling. These methods reduce or eliminate transportation, handling, treatment, and disposal of hazardous materials in the environment. The technology evaluation project discussed in this report emphasizes the study and development of methods to reduce waste and prevent pollution.

E. Timothy Oppelt, Director
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ABSTRACT

The goal of this study was to evaluate tools used to troubleshoot circuit boards with known or suspected thermally intermittent components. Failure modes for thermally intermittent components are typically mechanical defects, such as cracks in solder paths or joints, or broken bonds, such as interconnections inside integrated circuit packages or capacitors. Spray cans of refrigerants (R-12 [CFC-12] and R-22 [HCFC-22]), which are commonly used in electronics manufacturing and repair businesses for this purpose, served as the benchmark for the evaluation.

A promising alternative technology that was evaluated in this study is a compressed-air tool that provides a continuous stream of cold air that can be directed toward specific components. Another alternative technology that was considered is a Dewar flask that dispenses cold nitrogen gas as the cooling agent. Critical parameters were measured for each cooling method to provide a basis for comparison of compressed air and liquid nitrogen with spray cans of refrigerant. These parameters are accuracy, electrostatic discharge risk, cooling capability, technician safety, pollution prevention potential, and economic viability.

This study was performed in accordance with the *Quality Assurance Project Plan for Cold Compressed Air for Electronic Component Cooling Study*, dated August 1991. Although the plan was written specifically for the evaluation of compressed air, the test plan was written to include an evaluation of liquid nitrogen because test site staff were interested in evaluating this technology. The liquid nitrogen evaluation showed that it could be a viable alternative. Therefore, with the concurrence of the Project Officer, this final report includes the results of both compressed air and liquid nitrogen.

Newark Air Force Base, in Ohio, was the site for evaluating compressed-air technology. Electronic circuit boards from a variety of Air Force Systems are tested and repaired on a daily basis. A percentage of these circuit boards demonstrate thermally intermittent failure modes and were used for comparison testing.

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SECTION 1

PROJECT DESCRIPTION

INTRODUCTION

The objective of the U.S. Environmental Protection Agency (EPA) Waste Reduction Innovative Technology Evaluation (WRITE) Program is to evaluate, in a typical workplace environment, examples of prototype technologies that have potential for reducing wastes at the source or for preventing pollution. In general, for each technology to be evaluated, three issues should be addressed.

First, it must be determined whether the technology is effective. Because pollution prevention or waste reduction technologies usually involve recycling or reusing materials or using substitute materials or techniques, it is important to verify that the quality of the materials and the quality of the work product are satisfactory for the intended purpose.

Second, it must be demonstrated that using the technology has a measurable positive effect on reducing waste or preventing pollution.

Third, the economics of the new technology must be quantified and compared with the economics of the existing technology. It should be clear, however, that improved economics is not an absolute criterion for the use of the prototype technology. There may be justifications other than saving money that would encourage adoption of new operating approaches. Nonetheless, information about the economic implications of any such potential change is useful for understanding the overall impact of implementation.

PROJECT OBJECTIVES

The goal of this study was to evaluate cold compressed-air tools and liquid nitrogen as methods for cooling electronic components while searching for the causes of thermally intermittent electronic circuit failure. Aerosol cans of refrigerant (i.e., R-12 and R-22), which have been used commonly in electronics manufacturing and repair businesses for this purpose, served as the benchmark for the evaluation. The questions to be answered by this study were:

1. Would the technicians' ability to find causes of failure be degraded by use of the alternatives?
2. How did the cooling characteristics of the alternatives compare to aerosols with those of aerosols used by technicians?
3. Would the risk of electrostatic damage to electronic components be increased by use of the alternatives?
4. Would the noise generated during compressed-air tool operation be an occupational safety hazard?
5. How much refrigerant release would be avoided by using the alternatives?
6. What were the economics of implementing either alternative?

The first two issues are related but required different approaches. The cooling characteristics of the alternatives were known to differ from each other and from refrigerant aerosols but were not well understood. Also not understood was the effect the characteristics would have on the troubleshooting process. For example, while it was known that the compressed-air tool could not cool thermocouples as low as R-12, it was not known whether the temperature difference would affect the technicians' ability to find causes of thermally intermittent circuit failures. The cooling characteristics could be compared using fabricated test boards, but a variety of active circuit boards with various real thermally intermittent failure modes were the best method to address the first issue. Approaches used to address all six issues are discussed later in this section.

DESCRIPTION OF THE TECHNOLOGY

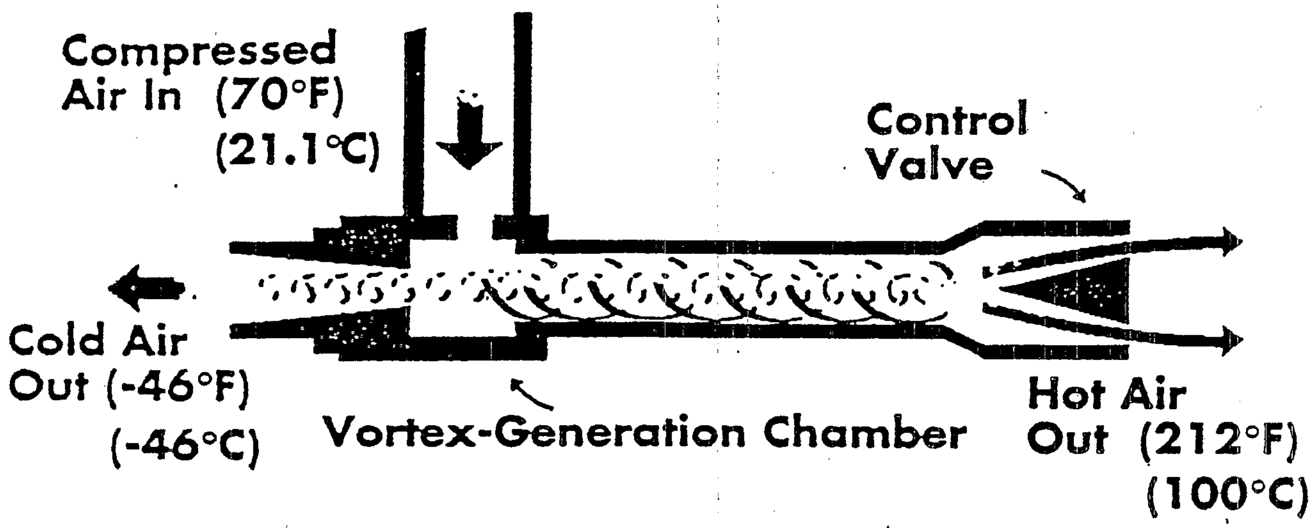
Trouble-shooting circuit boards with known or suspected thermally intermittent components is a common operation in the electronics manufacturing and repair industries. If, for example, an electronic device works when first turned on but fails as it warms up in operation, a technician may spray refrigerant towards board areas or on specific components to reduce temperatures until the device begins to work again. Failure modes for thermally intermittent components are typically mechanical defects, such as cracks in solder paths or joints, or broken bonds, such as interconnections inside integrated circuit packages or capacitors. Thermally intermittent failures can occur when temperature changes and material expansion or contraction aggravate the mechanical failure to create an electrical discontinuity condition. The component that, when cooled, causes the failure mode to appear or disappear is replaced.

Finding the causes of thermally intermittent circuit failures is often a difficult task. It is not uncommon to test, replace a component, and retest a circuit several times before eliminating the failure mode. In some cases, the cause of failure cannot be determined and the circuit board is condemned. Even with trouble-shooting tools such as freeze compound, it is a trial-and-error operation.

As trouble-shooting tools, aerosol cans of refrigerant (R-12 and R-22) are very common. They can be used easily to cool an entire circuit board or a single solder connection, are portable, and are relatively inexpensive. However, as recognized in the Montreal Protocol of 1987, chlorine released by decomposing chlorofluorocarbons (CFCs), such as R-12, decreases stratospheric ozone. The protocol calls for the elimination of CFC manufacture in the future. As a result, many businesses are seeking technologies that will replace current uses of CFCs. Hydrochlorofluorocarbons (HCFCs) such as R-22 also will be phased out, although they have lower stratospheric ozone depleting potential.

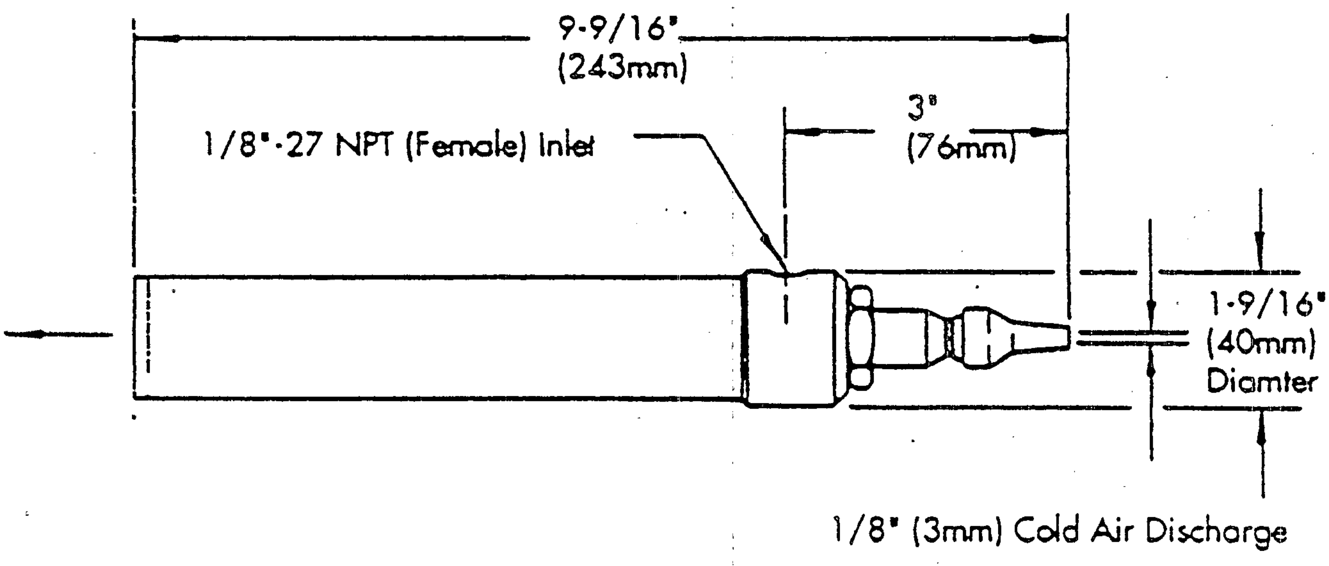
The first alternative technology evaluated was a compressed-air tool that provides a continuous stream of cold air that can be directed towards components. A schematic of how the tool operates is shown in Figure 1; a drawing of a typical compressed-air tool is shown in Figure 2. Compressed air enters a tangentially drilled stationary generator, which forces the air to spin down the long tube's inner walls toward the hot-air control valve. A percentage of the air, now at atmospheric pressure, exits through the needle valve at the hot-air exhaust. The remaining air is forced back through the center of the sonic-velocity airstream where, still spinning, it moves at a slower speed, causing a simple heat exchange to take place. The inner, slower moving air gives up heat to the outer, faster-moving air column. When the slower inner air column exits through the center of the stationary generator and out the cold exhaust, it has reached an extremely low temperature. To obtain temperatures in the range of −35°C to −40°C, the tool requires clean, dry, room temperature air flowing at 15 scfm at 100-psi pressure.

The second alternative technology evaluated uses liquid nitrogen. A half-liter Dewar flask (illustrated in Figure 3) can be used with a release valve that allows a stream of nitrogen gas and liquid droplets to be directed through a small-diameter stainless-steel nozzle. As the valve and nozzle are cooled by the nitrogen flow, the portion of the stream that is droplets increases and the output stream drops in temperature. A variety of valves, nozzles, and heat exchangers are available to tailor the delivery and cooling characteristics of the stream of nitrogen. The Dewar flask can be refilled from a bulk container of liquid nitrogen.



Source: Vortec Catalog

Figure 1. Compressed-air tool operating principle.



Source: Vortec catalog

Figure 2. Typical compressed-air tool dimensions.

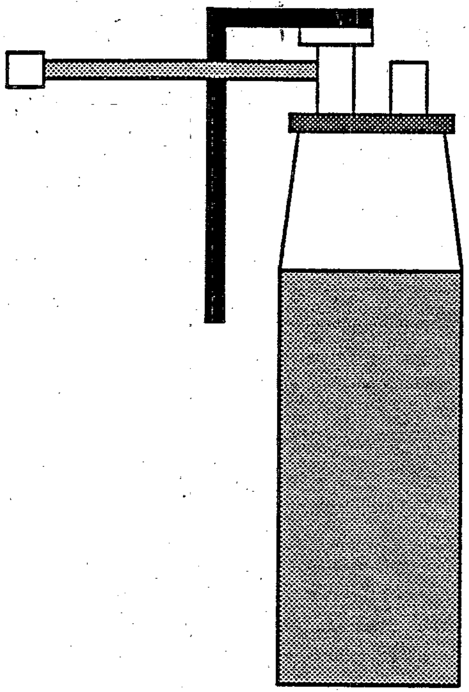


Figure 3. Typical ½-L liquid nitrogen dispenser.

DESCRIPTION OF THE SITE

Newark Air Force Base (NAFB), in Ohio, was the site at which compressed-air and liquid-nitrogen alternative technologies were evaluated. During the study, it was announced that Newark AFB would be closed; the exact fate of the work performed there was unclear. Electronic circuit boards from a variety of Air Force systems are tested and repaired at NAFB daily. Examples are inertial guidance systems used in KC-135, C-5, and C-141 aircraft and a fuel saver advisory system used in the KC-135. A percentage of the circuit boards tested demonstrate thermally intermittent failure modes; during the test period, these boards became test articles for comparison testing. R-12 was used for this study as the benchmark.

Each repair shop at NAFB is responsible for specific systems, such as the KC-135 fuel-control system. Because compressed air typically is not available at the test stations where cooling materials are needed, it was necessary to select one shop for the study. After evaluating several shops, the Carousel Shop was selected as the test site for the following reasons:

- Test stations included fixtures capable of reducing circuit board temperature (using carbon dioxide) while the board is tested. This feature provided confirmation that thermally intermittent failure mode existed but did not provide a trouble-shooting capability because the entire board was cooled at one time.

- The systems repaired in the Carousel shop contained circuit boards in a variety of sizes, component densities, and component varieties.

- Installation costs to deliver compressed air could be minimized because the three test stations utilized for the study are in close proximity.

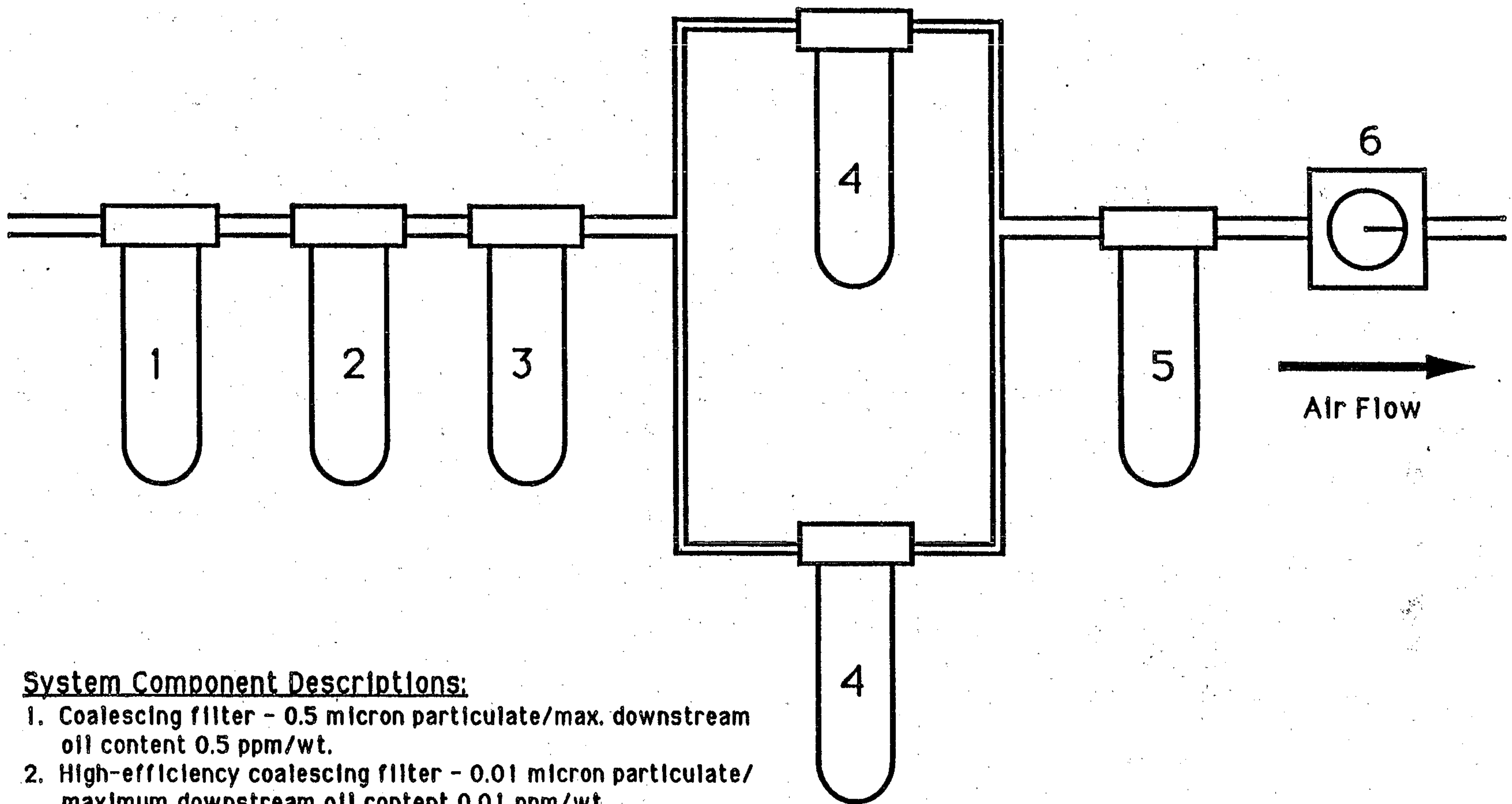
The compressed-air system utilized for the study consisted of a large industrial compressor with a refrigeration system to chill the compressed air as it passed into a storage tank. The air passed through approximately 50 ft of half-inch line with nonrestrictive couplings to three outlets. A filtration and drying system, as described in Figure 4, was installed approximately 20 ft from the test stations.

SUMMARY OF APPROACH

Accuracy

An objective of the study was to compare the effect of using alternative cooling materials on technician ability to find causes of thermally intermittent circuit failures using refrigerant aerosol as the benchmark. This parameter of the cooling materials was termed "accuracy" because it is a measure of the accuracy with which technicians could find causes of circuit failures. Two key elements of accuracy that were unknown were how differences in cooling material dispensing characteristics would affect technician ability to isolate circuit failure causes and if the temperatures to which active circuit components could be cooled would be low enough to cause circuit failures to appear or disappear, depending on the failure mode. Standard measures or measurement methods of this parameter did not exist, so they were devised so that, in addition to fulfilling the study objective, they fit within constraints imposed by the site selected and the study schedule.

As described in the project objectives, active circuit boards with thermally intermittent failure modes rather than a fabricated test circuit board were needed to compare the accuracy of the cooling methods. Building a test circuit board to simulate a circuit board with a thermally intermittent failure mode was not considered feasible, primarily because the temperature to which active circuit components must be cooled to eliminate the failure mode was unknown and was expected to vary among circuit boards. A comparison of the three cooling methods through testing of active circuit boards with real thermally intermittent failure modes was expected to provide the most useful data to readers.



System Component Descriptions:

1. Coalescing filter - 0.5 micron particulate/max. downstream oil content 0.5 ppm/wt.
2. High-efficiency coalescing filter - 0.01 micron particulate/maximum downstream oil content 0.01 ppm/wt.
3. Adsorption filter - oil vapor removal/max. downstream oil content 0.003 ppm/wt.
4. Drier - silica gel
5. Afterfilter - 0.5 micron particulate filter
6. Regulator

Figure 4. Test site compressed-air filter system.

The decision to use real circuit boards required a test site that encountered such circuit boards in reasonable quantity and variety and which could support testing with all three cooling materials. The Carousel Shop at Newark AFB met these criteria, although it imposed constraints on the project. The constraints were as follow:.

1. Although circuit boards with thermally intermittent failure modes were identified routinely in the shop, the number that would be identified during the test period was unknown due to fluctuations in workload. Past experience in the shop indicated that it was unlikely that the number would exceed that sufficient to meet the study needs.

2. There were only three technicians in the Carousel Shop with one working each of three shifts.

3. It would not be feasible to track the test/repair/retest process of every test article through to conclusion during the study test period. Delivery cycles for replacement components are routinely long enough that for many test articles, the repair and retest steps would occur after the end of the test period.

The first two constraints imposed by the site selection affected the experiment design. The limited number of test articles meant that each had to be tested with all three cooling methods. Each of the three tests had to be performed by a different technician to avoid prior knowledge of the suspected cause of the circuit failure. Because the technician factor could not be held constant by having one technician test each article with all three cooling methods, the assignment of cooling method to technicians for each test article was randomized. Variability of test results caused by technicians was also minimized because all three had at least eight years experience and all three had opportunities to become familiar with the alternative cooling methods prior to the test period. With this experiment design, it was expected that comparisons could be made between cooling methods even though variability, although minimized as much as possible, in technicians was a factor.

The selection of a measure of accuracy was affected by the first and third constraints. The measure of accuracy could not be based on the results of the circuit board repair process because it was likely that many test articles would not have been repaired and retested by the end of the test periods. If an abundance of test articles were expected, it would have been feasible to plan to drop out any which had not been retested at the end of the test period. Because this was not the case, the measure of accuracy had to be based solely on the results of the initial test step.

The measure of accuracy which was devised to use the results of the initial test step was a subjective evaluation by the technician of the probability that the cause of the circuit failure had been identified. During testing, the technician searches a circuit board by cooling progressively smaller areas to find the likely cause of the circuit failure. At some point, the technician stops searching and decides what repair action to take. This point usually occurs when the technician is satisfied that the circuit failure cause has been pinpointed has been isolated to the extent possible given the circuit board characteristics and the cooling method. This confidence was selected as the best measure of cooling material accuracy given the constraints described above.

The measure of accuracy, technician confidence, was termed the Component Identification Confidence (CIC) and technicians were asked to rate their level of confidence at the end of each circuit board test. They were asked to select from four different levels of confidence as follows:

100% - Specific component identified as defect

66% - Small group of components isolated; able to make experience-based selection using component type as criteria. Repair by replacing most likely component

33% - Small group of components isolated; unable to make experience-based selection using component type as criteria. Repair alternatives are to replace all components at once or one-at-a-time.

0% - Unable to isolate a single component or group of components.

Technicians were asked also to categorize subjectively test articles as having high or low component variety and component density. It was thought that these circuit board attributes might be factors that would affect the accuracy of the cooling materials. For example, it was reasonable to expect that it would be more difficult to isolate a single component in a densely populated area of the circuit board, but it was unknown whether the cooling material characteristics would make one cooling material a more effective tool in such a situation. Because component density and component variety were subjective measures, pictures of each test article were taken and are provided in this report so that readers can compare them with their own products.

<u>Electrostatic Discharge Risk</u>

The amount of electrostatic charge buildup generated by the cooling material as it is dispensed is a concern because components can be damaged by electrostatic discharge. Two experiments were designed to compare the electrostatic charge generated by the following cooling method/nozzle combinations:

- R-12 aerosol with a plastic tube nozzle
- R-12 aerosol with a steel tube nozzle

- Compressed-air tool with a single-section plastic nozzle
- Liquid nitrogen Dewar flask with a straight stainless-steel nozzle approximately 4-in long.

The measurements for these experiments were taken following general laboratory practices used for evaluation of equipment, supplies, and worker apparel related to electronic equipment manufacture and repair.

The first experiment measured the electrostatic charge generated on the nozzle during release of cooling material. During a 10- to 12-second material release, the nozzle was held parallel to and approximately one inch from the platen of a Monroe Electronics, Inc., Model 175 Charged Platen Monitor*, which measured charge buildup. Two measurements were taken for each cooling method/nozzle combination.

The second experiment measured electrostatic charge buildup when cooling material was dispensed towards circuit boards placed on the platen of a Monroe Electronics, Inc. Model 175 Charged Platen Monitor. The dispenser was held so that the nozzle was approximately 0.5 inch from the edge of the circuit board, both horizontally and vertically, and at approximately 45 degrees relative to the horizontal surface of the circuit board (see Figure 5). Six circuit boards were evaluated, with two measurements taken for each cooling method/nozzle combination. The six circuit boards were selected to provide component and density variety.

Cooling Rate and Absolute Temperature Drop

The characteristics measured for each method were cooling rate and absolute temperature drop. An experiment was designed to estimate the rate of change of component temperature by using thermocouples buried inside components at which cooling materials were dispensed. Two test boards were fabricated, one having integrated circuits and the other having wound-film capacitors. Each test board contained three components with thermocouples (TC-1, TC-2, TC-3) and one exposed (TC-REF) thermocouple (see Figure 6).

During tests, all four thermocouples on a test board were connected to a Yokogawa LR4110 four-channel data logger, which simultaneously recorded temperatures of all four thermocouples as cooling material was directed at the target component. For each test board, cooling material was applied from two directions and two distances. Two measurements were taken for each combination of test board, cooling method, direction, and distance. Before each measurement for R-12 and compressed air was taken, the cooling material was dispensed directly at

* Mention of trade names and products does not constitute endorsement for use.

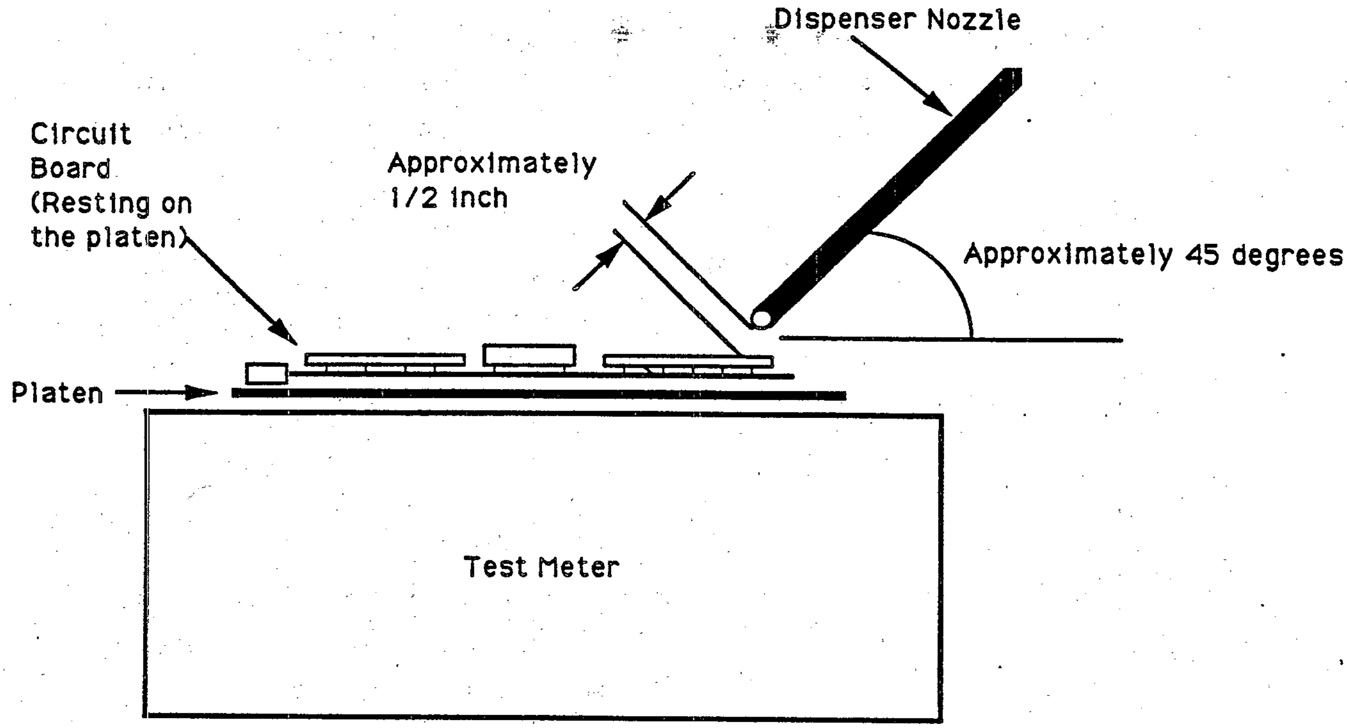


Figure 5. Electrostatic charge measurement method.

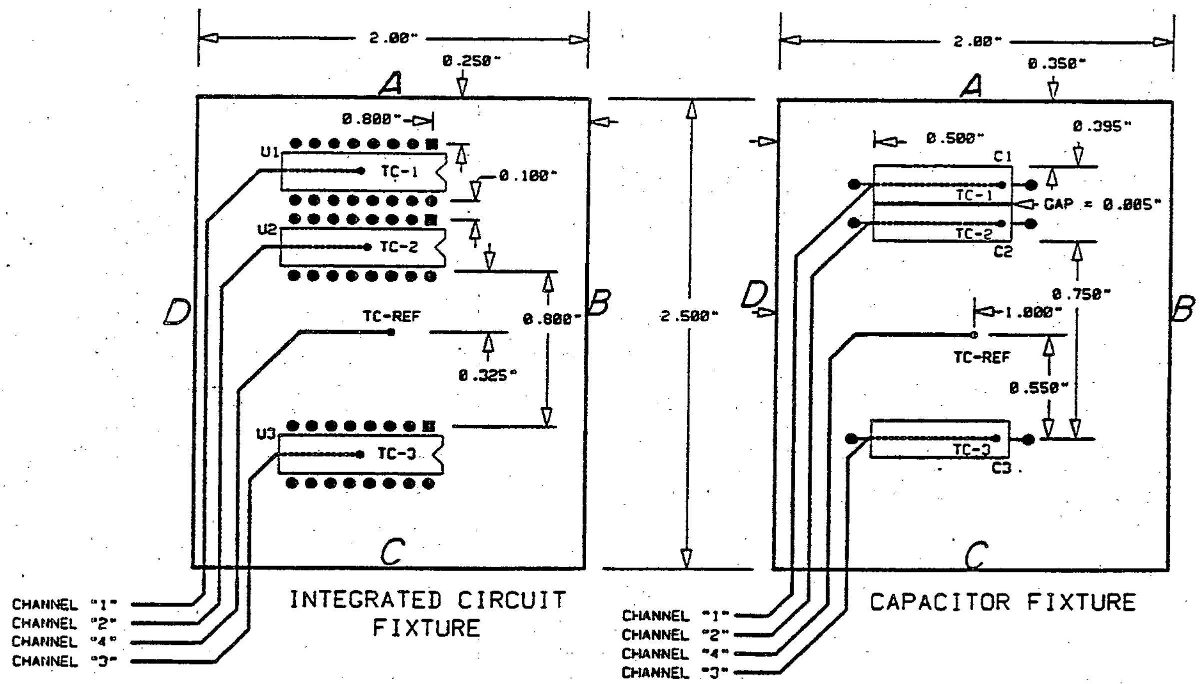


Figure 6. Test board design for absolute temperature drop and cooling rate experiment.

the exposed thermocouple to determine the absolute lowest temperature that could be achieved given the test distance, direction, and cooling method. This was not necessary for liquid nitrogen because it was known that the thermocouple would reach the lowest measurement limit of −175°C.

Understanding the characteristics of and differences between cooling methods will enable technicians to use alternate cooling materials effectively. If, for example, the distance between the applicator nozzle and the component does not significantly affect the cooling rate of aerosol cans of R-12 but is a significant factor in the cooling rate provided by compressed air, a technician should be aware of the difference.

Technician Safety

Exposure to sound created by operation of the compressed-air tool was the only safety concern that required measurement. To assess the potential safety hazard, sound-level measurements were taken by personnel from the Newark AFB Bioenvironmental Engineering group during operation of the air tool. Other safety concerns associated with the alternative cooling methods include handling pressurized air and liquid nitrogen, both of which are readily addressed by providing safety training and using appropriate equipment. Other than potential air tool noise problem, neither alternative was considered to pose safety risks greater than using refrigerant in aerosol cans.

Pollution Prevention Potential

The purpose of replacing aerosol cans of refrigerant is to reduce the amount of pollutants released into the atmosphere. As indicated in the discussion of accuracy (see page 6), the weight of R-12 released during evaluation of each circuit board with thermally intermittent failure modes was determined. These data provide a measure of the average pollution per circuit board that could be avoided if either of the alternative cooling methods were adopted.

Compressed air and nitrogen are released to the atmosphere by the alternatives, but neither are considered pollutants. Pollution generated during the production of either liquid nitrogen or electricity to power air compressors was beyond the scope of the study.

Estimation of Economics

The approach used to estimate operating costs was to measure the volume of each cooling material used during test article accuracy evaluations and calculate a per-board material cost. Although material costs are only one aspect of operating costs, it was the only aspect that could be measured during the tests. Material costs for each cooling method were estimated using the following methodologies:

- R-12 cost was estimated by dividing the total weight of R-12 used by the weight of one can and then by the number of articles tested to obtain the average cans required per test article. An average cost for a can of R-12 was used to estimate an R-12 cost per test article. The weight of the empty can was subtracted during calculations.

- Compressed-air cost was estimated by multiplying the air tool operation time (release time) by the tool's consumption rate (15 scfm at 100 PSI) to obtain the volume of air used. Dividing the volume of air by the number of test articles and multiplying by an average cost to generate compressed air yielded an average cost of compressed air per test article.

- Liquid nitrogen cost was estimated by dividing the total weight of liquid nitrogen used by the number of test articles and converting to liters to obtain the average volume used per test article. Multiplying the volume by an average price of liquid nitrogen per liter gave the average cost of liquid nitrogen per test article.

The approach to estimating investment cost focused on the cost of dispensers, which is the only significant investment for the liquid nitrogen alternative. For compressed air, investment cost is expected to range widely because the condition and capacity of existing compressed-air supplies at test stations will vary widely. Some sites may not have any existing air supply. Potential users will need to determine what, if any, investment is required to obtain compressed air in the quantities and quality required.

SECTION 2

ACCURACY EVALUATION

RESULTS

Test article characteristics and Component Identification Confidence (CIC) scores are summarized in Table 1. Seventeen circuit boards with thermally intermittent failure modes were identified during the 5-month test period. It was determined later by the Newark AFB test engineer that 4 circuit boards (Test Articles 5, 8, 11, and 12) should not be included in the evaluation because they were not thermally intermittent (e.g., loose connector) or because the defective components were known from previous experience with a specific model circuit board. The latter type of circuit board would have given the technicians prior knowledge of the cause of failure and

TABLE 1. ACCURACY EVALUATION SUMMARY FOR COOLING METHODS

Test Article	Circuit Board Characteristics				Component Identification		
	Component Density	Component Variety	Width	Length	R-12	Liquid Nitrogen	Compressed Air
1	High	High	4.50	6.25	100%	0%	33%
2	High	High	5.50	6.00	33%	0%	67%
3	High	High	6.50	11.50	0%	0%	67%
4	High	High	9.00	8.00	33%	100%	67%
6	Low	High	4.63	5.63	100%	100%	100%
7	High	High	6.25	10.50	100%	33%	100%
9	High	Low	4.50	6.25	67%	33%	67%
10	High	High	7.25	10.75	33%	100%	33%
13	High	Low	5.75	6.50	33%	100%	67%
14	High	High	6.25	10.50	0%	100%	67%
15	High	High	6.50	10.50	33%	67%	100%
16	High	High	6.25	10.50	33%	33%	100%
17	High	High	6.50	10.50	33%	0%	0%

would not have been a valid test of the cooling methods. Evaluation results specific to each test article are described below; component identification confidence ratings for each evaluation are provided in parentheses (see the discussion of accuracy on page 6). If repairs were made and retest data are available, these data are provided. However, in several cases replacement components were still on order at the end of the test period and it was not possible to make final determination of accuracy.

Test Article 1: 1.2 KHz Inverter

The module exhibited sine source output with fluctuating amplitude. The output was displayed on an oscilloscope during evaluation.

The compressed-air evaluation identified capacitor C51 of the amplitude feedback control as the suspected component (33%). The R-12 evaluation identified an output power transistor, Q5, on the opposite side of the circuit board as being the defective component (100%). The liquid nitrogen evaluation was unable to identify any components (0%). The failure mode was not corrected by replacement of transistor Q5; therefore, the module was submitted for additional testing.

A photograph of Test Article 1 with suspected defective components indicated is included as Figure 7.

Test Article 2: 1.2 KHz Inverter

The module exhibited a failure mode similar to that of Test Article 1.

The R-12 evaluation identified a group of 2 resistors and 2 diodes suspected of containing the defective component(s) (33%). The compressed-air evaluation selected one component, A4, as the defective component (67%). A4 is an operational amplifier used to control the phase and frequency of the output and is located adjacent to the group of components identified during the first evaluation. During the liquid nitrogen evaluation, the technician was unable to cause the circuit to fail when the entire module was cooled. Therefore, the liquid nitrogen evaluation of test article #2 could not be performed. Component A4 was selected as the most likely cause of the failure mode, but replacement was delayed until a new component could be requisitioned.

A photograph of Test Article 2 with suspected defective components indicated is included as Figure 8.

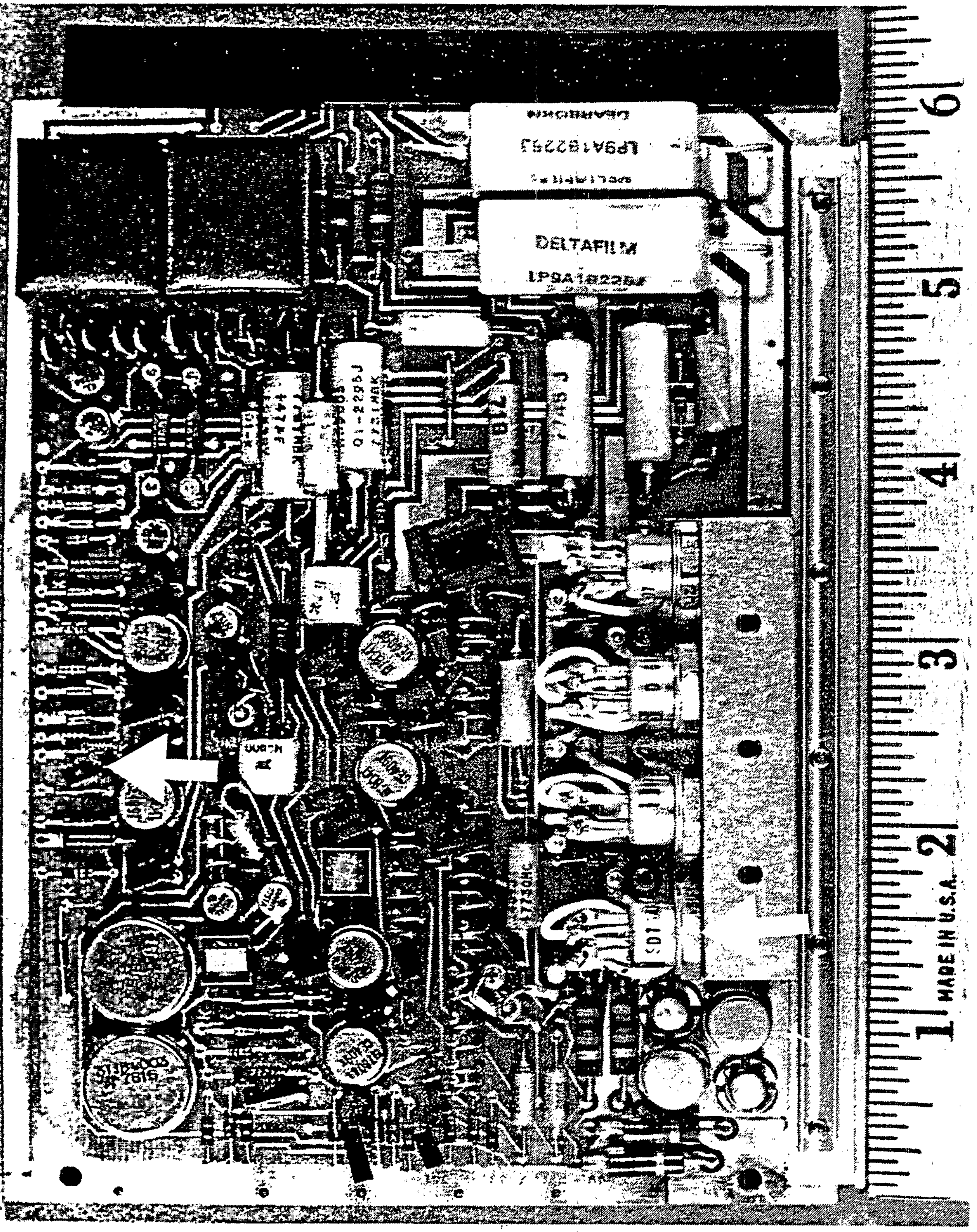


Figure 7. Test article #1.

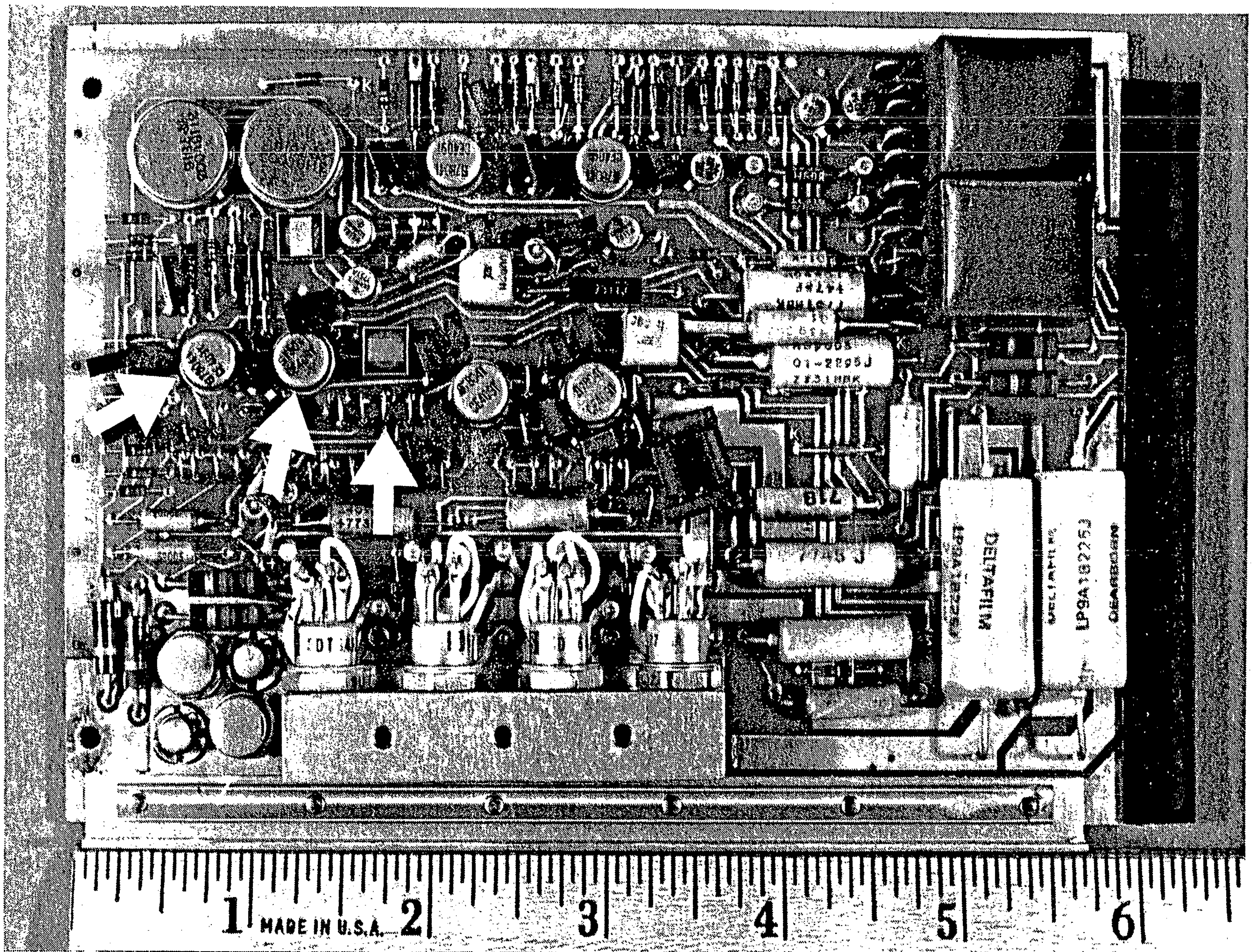


Figure 8. Test article #2.

Test Article 3: FMC Tank Processing Unit

This module is used to gauge the amount of fuel in a tank. The failure mode involved an erroneous quantity being given when the module was cold.

The compressed-air evaluation identified a capacitor, C116, as defective (67%). During the liquid nitrogen evaluation, the circuit failed when a large area of the module was cooled; by probing in this area, the technician identified an operational amplifier, U105, as defective (0)%. Because cooling alone did not enable the technician to identify a component, the component identification confidence of 0% was applied. When the R-12 evaluation was performed, a defective component could not be identified (0%). Because C116 is a decoupling capacitor for U105, it is likely that the defective component is in this area. The module was placed on engineering hold for additional evaluation because the R-12 evaluation was unable to identify a failure.

A photograph of Test Article 3 with suspected defective components indicated is included as Figure 9.

Test Article 4: IFMP Primary Microprocessor

The module was causing loss of primary functions of the Integrated Fuel Management Panel (IFMP) when cold. The module was tested by running the IFMP while the components were being cooled.

The R-12 evaluation identified a group of components suspected of containing the defective component (33%). The liquid nitrogen evaluation identified a random access memory (RAM) device, U18, as the defective component (100%). During the compressed-air evaluation, the technician was able to make an experience-based selection of diode CR19 (67%). The subsequent repair process of Article 4 replaced diode CR19 and eliminated the failure mode. Possible reasons for selection of U18 during the liquid nitrogen evaluation are: CR19 was cooled enough to cause the circuit failure when cooling material was directed at U18 or the low temperature of U18 resulting from liquid nitrogen spray may have temporarily changed the access time, which would cause loss of primary function.

A photograph of Test Article 4 with suspected defective components indicated is included as Figure 10.

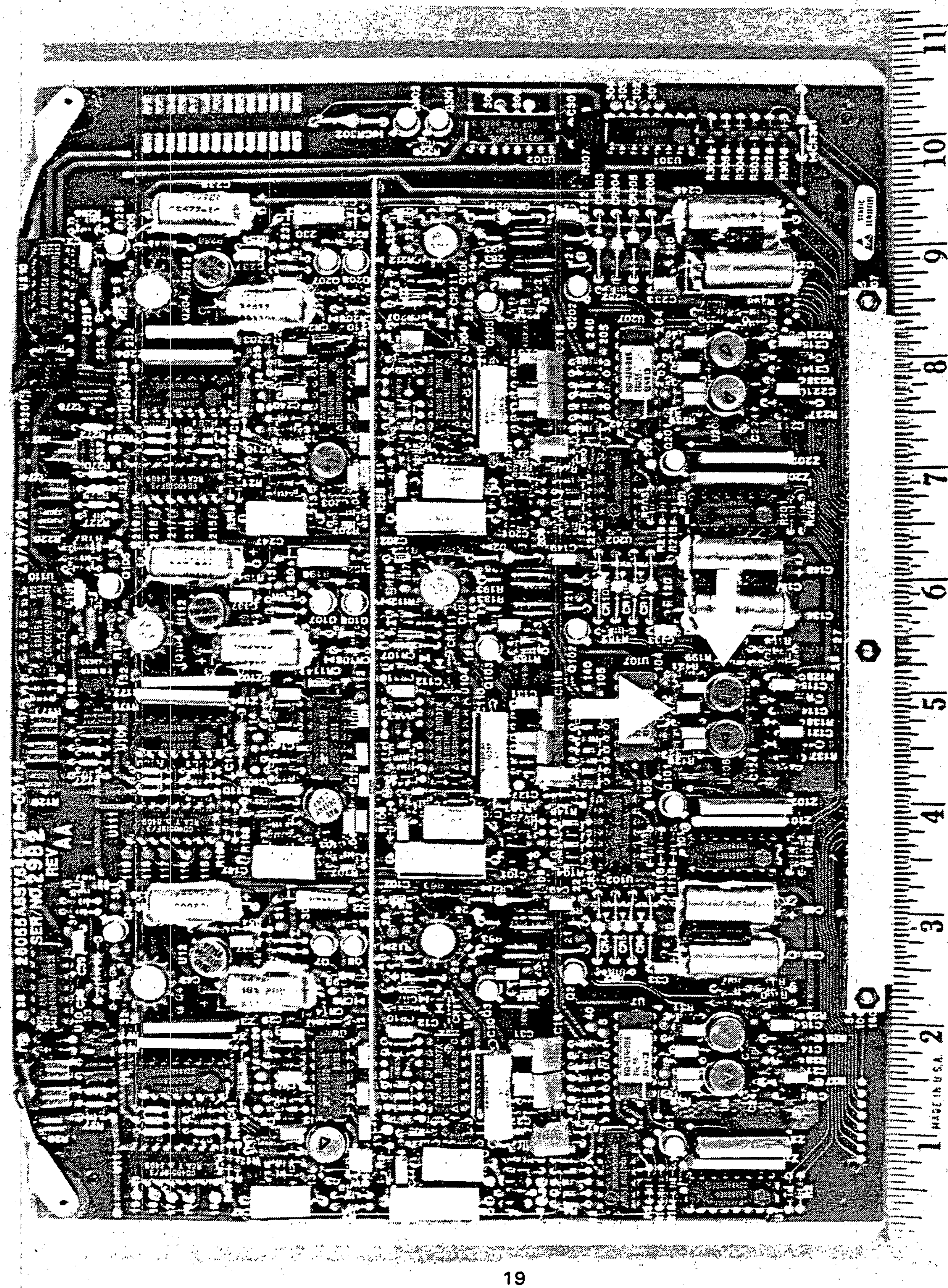


Figure 9. Test article #3.

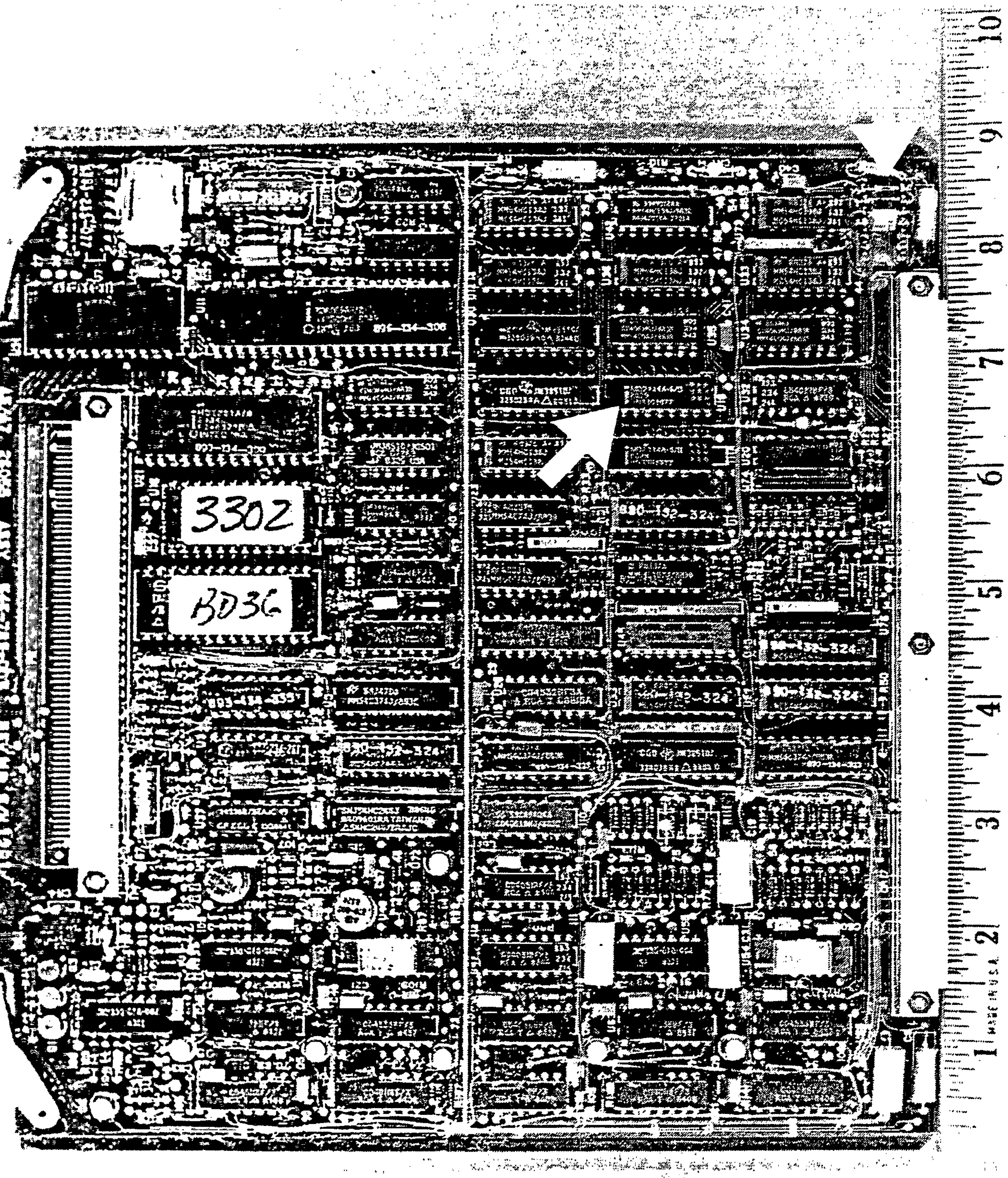


Figure 10. Test article #4.

Test Article 6: Pitch Gimbal Buffer

The module was causing the pitch gimbal to drive to the physical stop when the system was turned on. The "cage" output was saturated.

The liquid nitrogen evaluation identified transformer T2 as the defective component (100%). The other two cooling methods identified transformer T1 as the defective component (100%). Replacement of T1 corrected the thermally intermittent failure mode.

A photograph of Test Article 6 with suspected defective components indicated is included as Figure 11.

Test Article 7: FMC Primary Microprocessor

The module was causing the FSK communication link between the fuel management computer and the IFMP to drop off.

The compressed-air evaluation identified U45 as the defective component (100%). The liquid nitrogen evaluation selected a data buffer, U37, from a group of components (33%). The R-12 evaluation identified a resistor array, U40, as the defective component (100%). Because the output of U40 is directly linked to the FSK signal, U40 was selected for replacement. After replacement, the failure mode remained, and the module was returned for additional testing. All three components are in an area approximately 2 inches by 2 inches, with U40 and U45 separated by about 0.5 inch.

A photograph of Test Article 7 with suspected defective components indicated is included as Figure 12.

Test Article 9: Carousel Instruction Processing Unit

The module is two-sided and uses flat-pack integrated circuits with surface-mount solder joints. It was removed from a Carousel INU because of a history of computer-related failures.

All three cooling methods identified components on the B side of the circuit board as defective. It was determined that the cause of failure was corrosion between component leads and circuit traces throughout the board. The circuit board was condemned.

A photograph of Test Article 9 is shown in Figure 13. The failure mode was related to the circuit board itself rather than to any specific components.

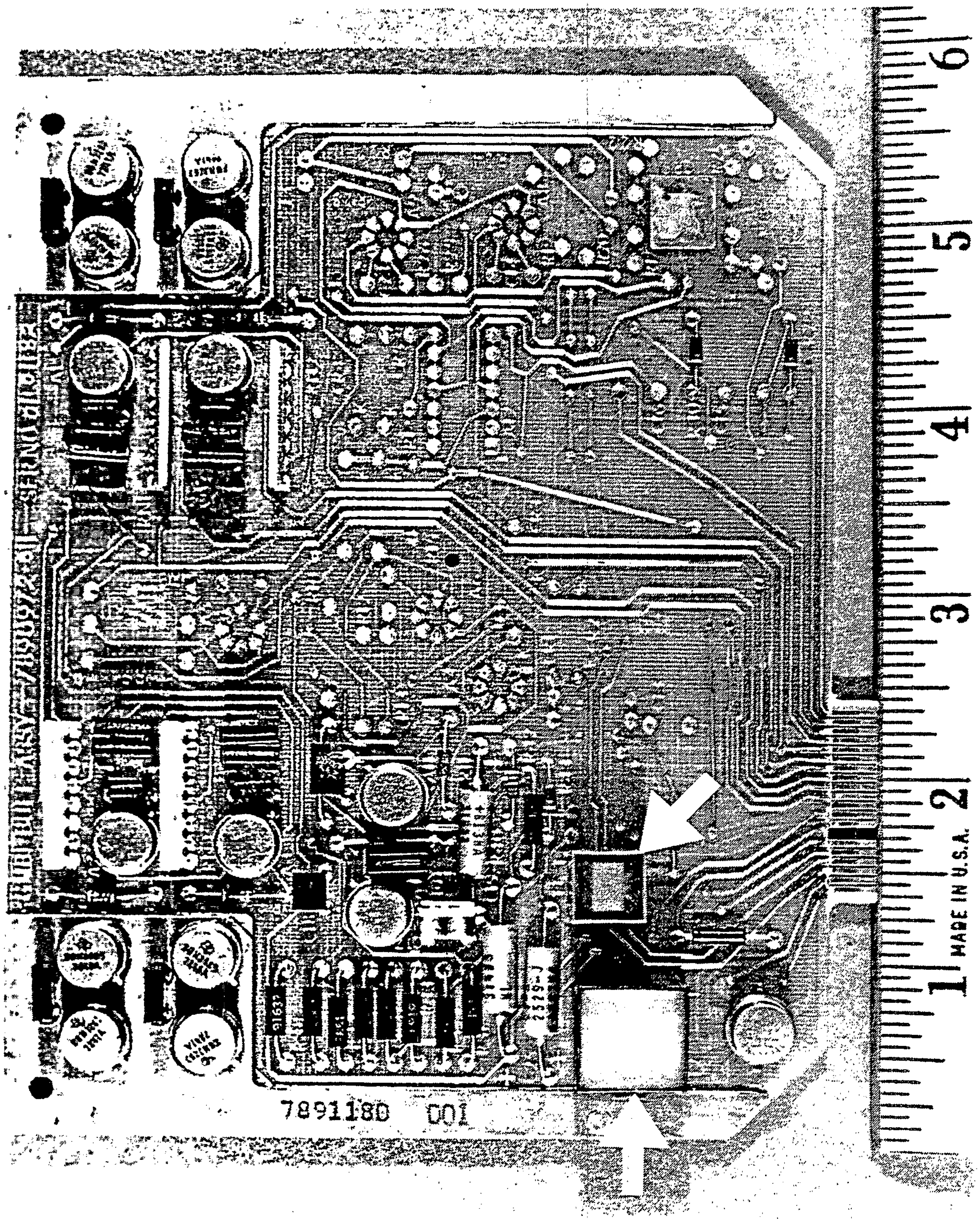


Figure 11. Test article #6.

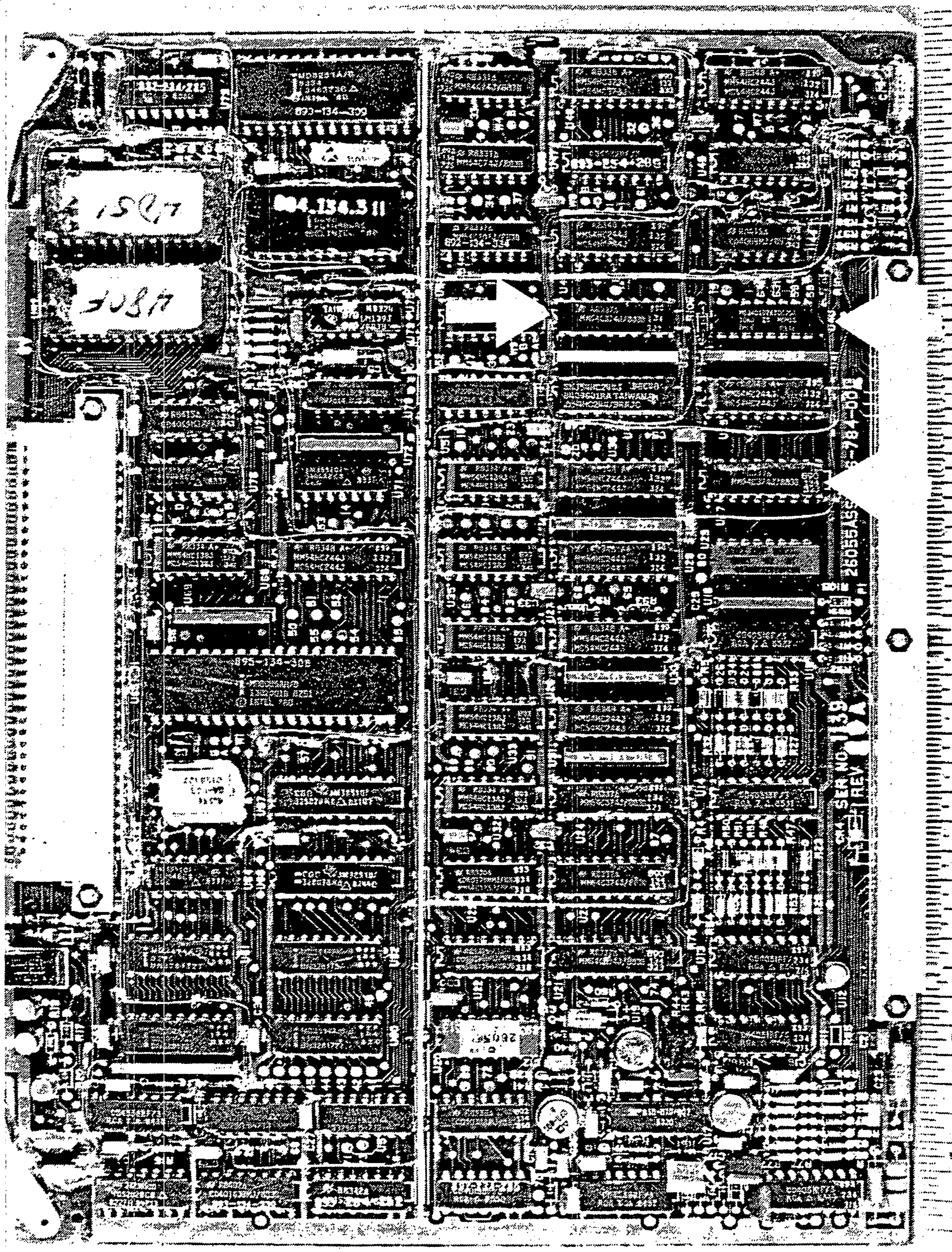


Figure 12. Test Article #7.

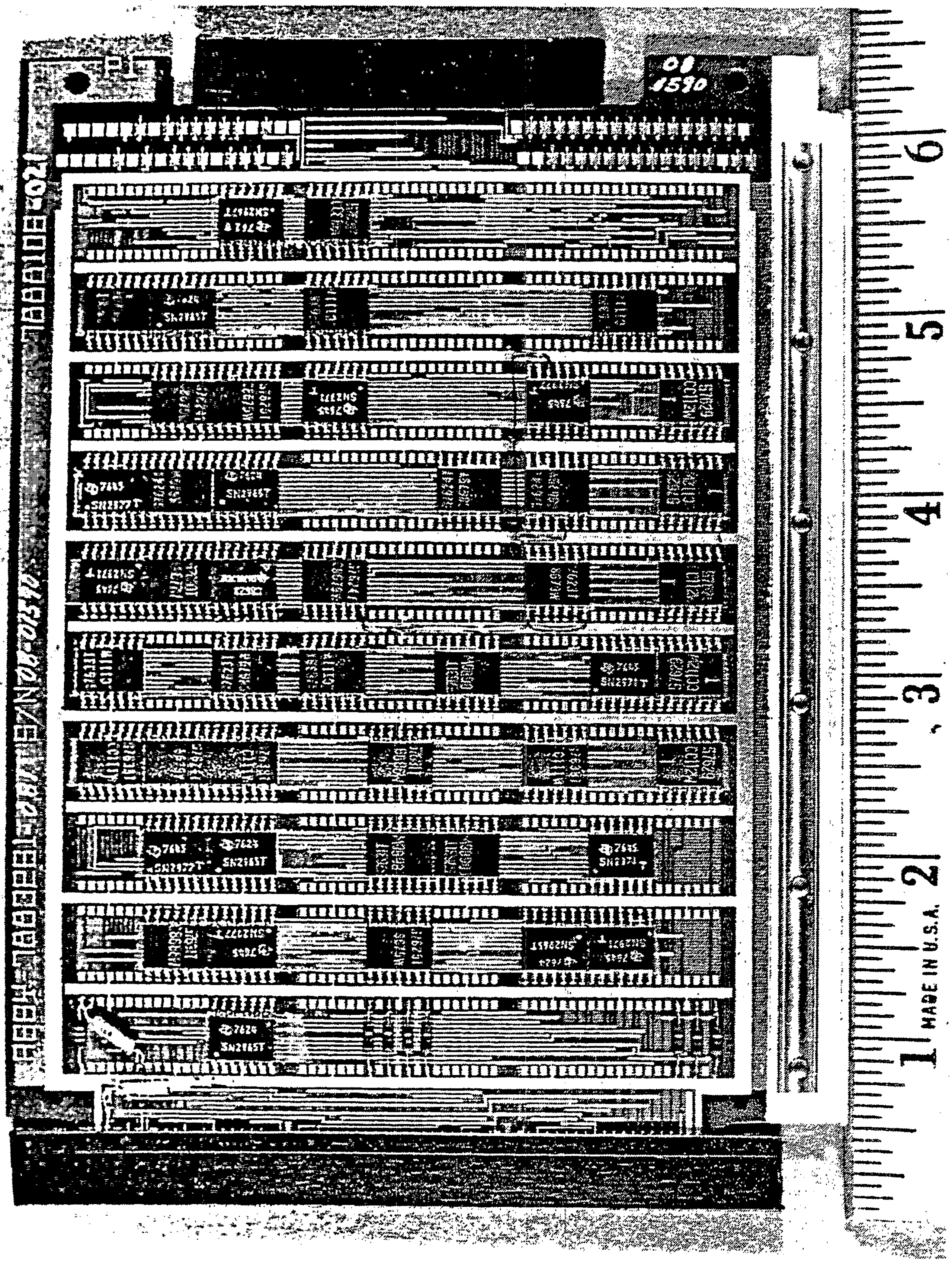


Figure 13. Test Article #9.

Test Article 10: FMC Tank Processing Unit

The module was causing a particular tank to indicate dashes, which means that the value being calculated is "unreasonable".

The compressed-air evaluation identified a group of two operational amplifiers, U5 and U6, as containing the defective component (33%). The R-12 evaluation selected U6 as the suspected defective component (33%). The liquid nitrogen evaluation selected R42, which is a gain resistor for U6, as the defective component (100%). All components are located in an area approximately 1-inch by 1.5 inch. Because replacement of R42 did not eliminate the failure mode, U5 and U6 were replaced. Because the failure mode still remained, the module was delivered to the engineering group for further evaluation.

A photograph of Test Article 10 with suspected defective components indicated is included as Figure 14.

Test Article 13: FSAC Central Processing Unit

The module is the microprocessor for the Fuel Savings Advisory Computer (FSAC). It failed on the automated module tester during cold soak.

The liquid nitrogen evaluation selected a 4-bit latch, U12, as the defective component (100%). The R-12 evaluation selected an large-scale integrated circuit (LSI) 4-bit latch, U6, from a group of components (33%). The compressed-air evaluation selected another 4-bit latch, U18, from a group of components (67%). U12 and U18 are adjacent to each other, but U6 is located at the other side of the circuit board. Any of the three components could cause the failure mode.

A photograph of Test Article 13 with suspected defective components indicated is included as Figure 15.

Test Article 14: FMC Tank Processing Unit

The module caused a particular tank to read 0 when cold.

The compressed-air evaluation selected an operational amplifier, U208, from a group of components (67%). The R-12 evaluation was unable to identify a defective component (0%). The liquid nitrogen evaluation identified another operational amplifier, U204, as the defective component (100%). The two identified components are approximately 0.5 inches apart and either could cause the failure mode.

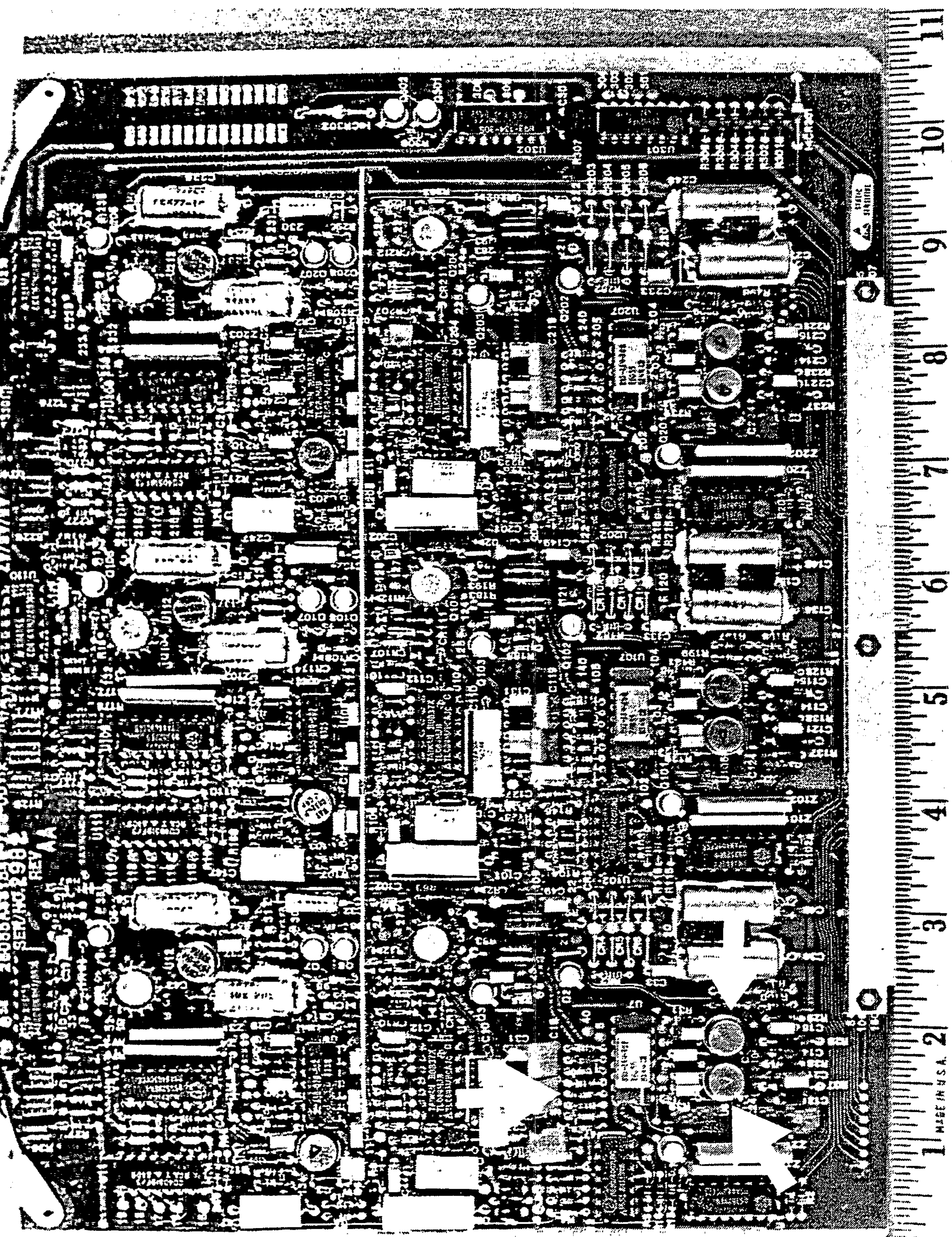


Figure 14. Test Article #10.

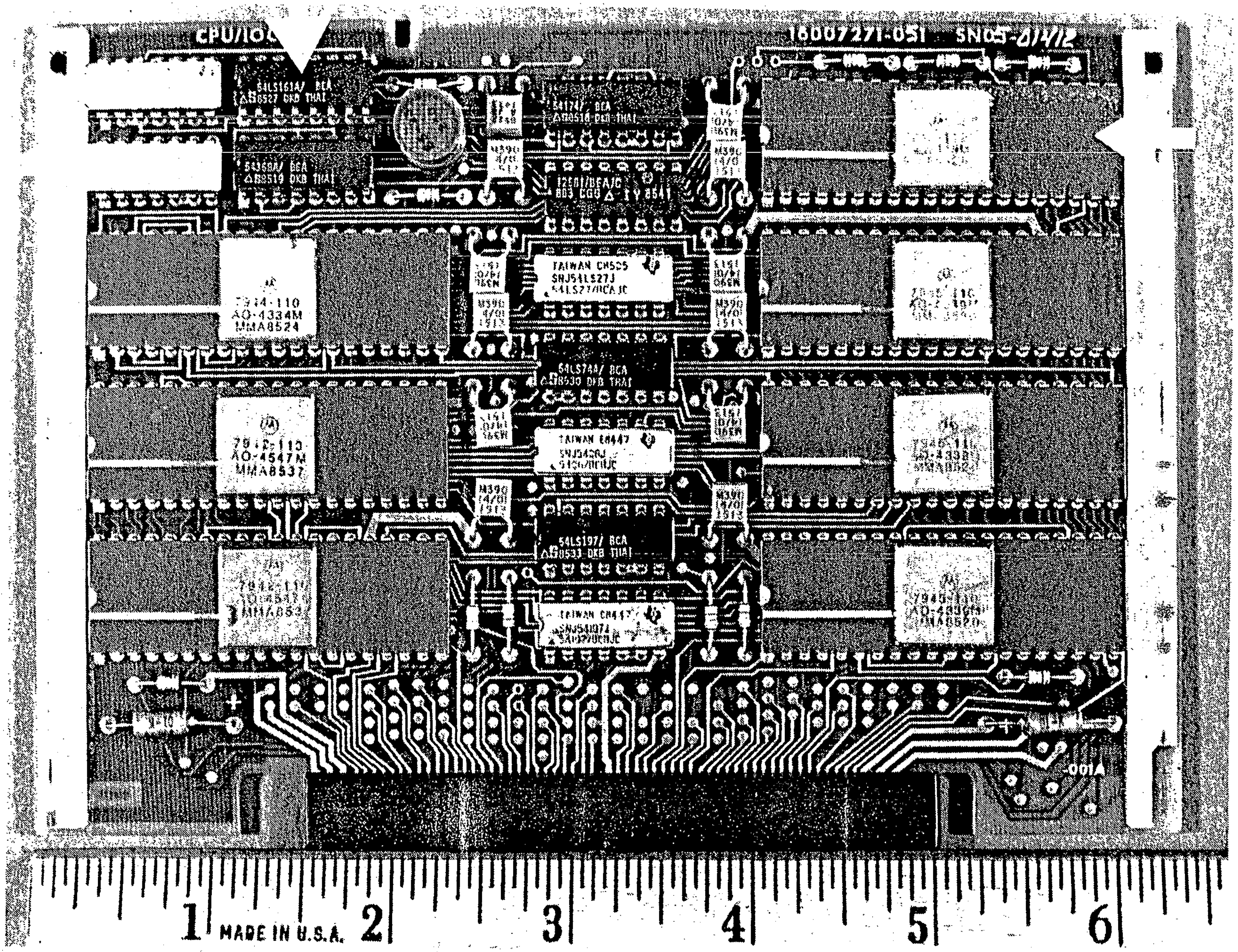


Figure 15. Test Article #13.

A photograph of Test Article 14 with suspected defective components indicated is included as Figure 16.

Test Article 15: FMC Tank Processing Unit

The module caused a tank to read too high when cold.

The R-12 evaluation selected a 4-bit multiplexer, U109, from a group of components (33%). The liquid nitrogen evaluation selected an operational amplifier, U103, from a group of components using technician experience (67%). The compressed-air evaluation identified two integrated circuits, U104 and U108, as defective (100%). All four components are located in an area approximately 3 inches by 1.5 inches in size.

A photograph of Test Article 15 with suspected defective components indicated is included as Figure 17.

Test Article 16: FMC Tank Processing Unit

The module caused a particular tank to drift and then to read dashes.

The R-12 evaluation identified four feedback capacitors, C113, C114, C115, and C121, as suspected of containing the defective component(s) (33%). The compressed-air evaluation identified an FET switch, U107, as defective (100%). The liquid nitrogen evaluation identified a group of two operational amplifiers, U105 and U106, as defective (33%). All seven components are located in an area approximately 2 inches by 1 inch in size.

A photograph of Test Article 16 with suspected defective components indicated is included as Figure 18.

Test Article 17: FMC Tank Processing Unit

The module caused a tank reading value to be too high.

The liquid nitrogen and compressed-air evaluations were both unable to identify a defective component (0%). The R-12 evaluation was able to selected an FET switch, U7, from a group of components (33%).

A photograph of Test Article 17 with suspected defective components indicated is included as Figure 19.

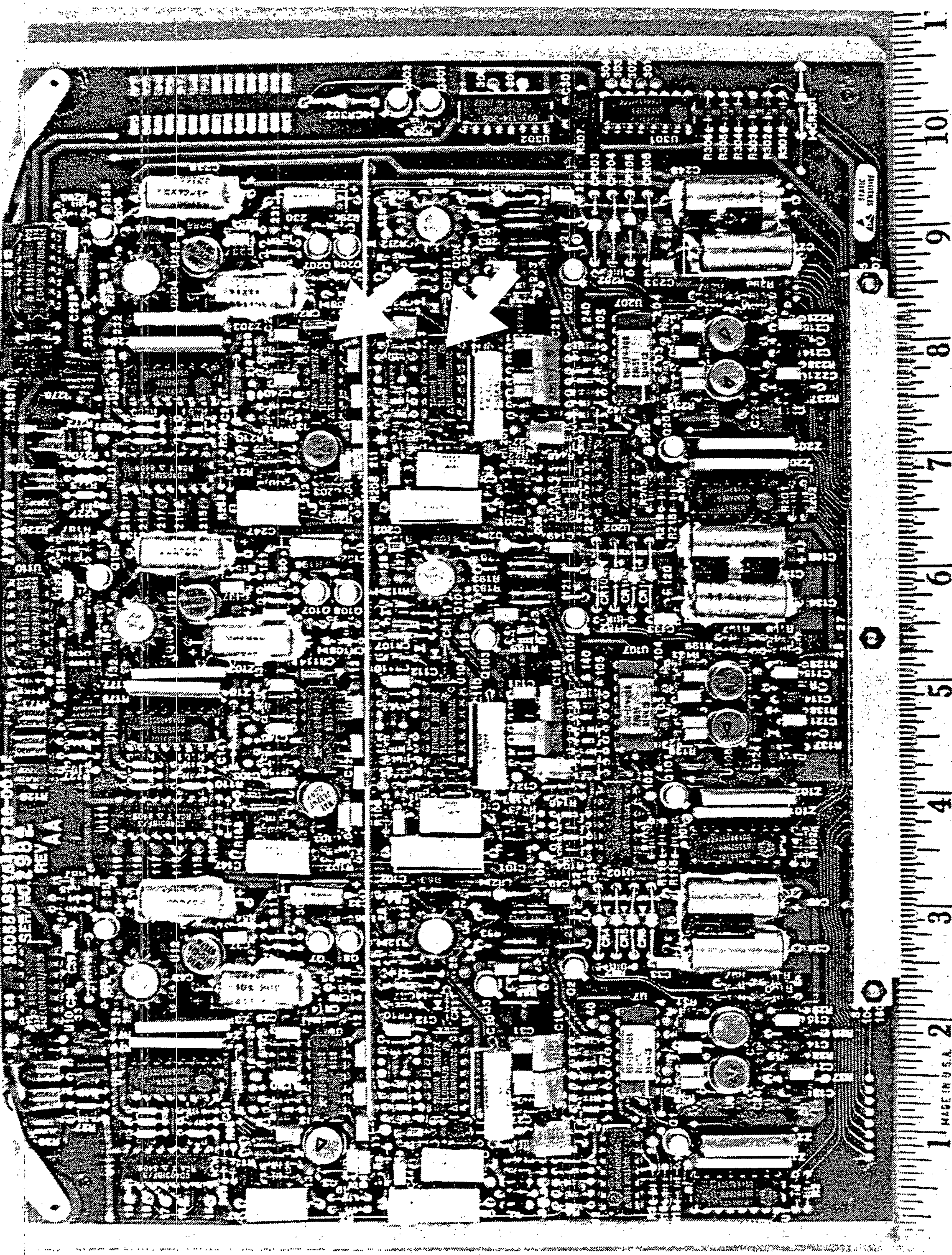


Figure 16. Test Article #14.

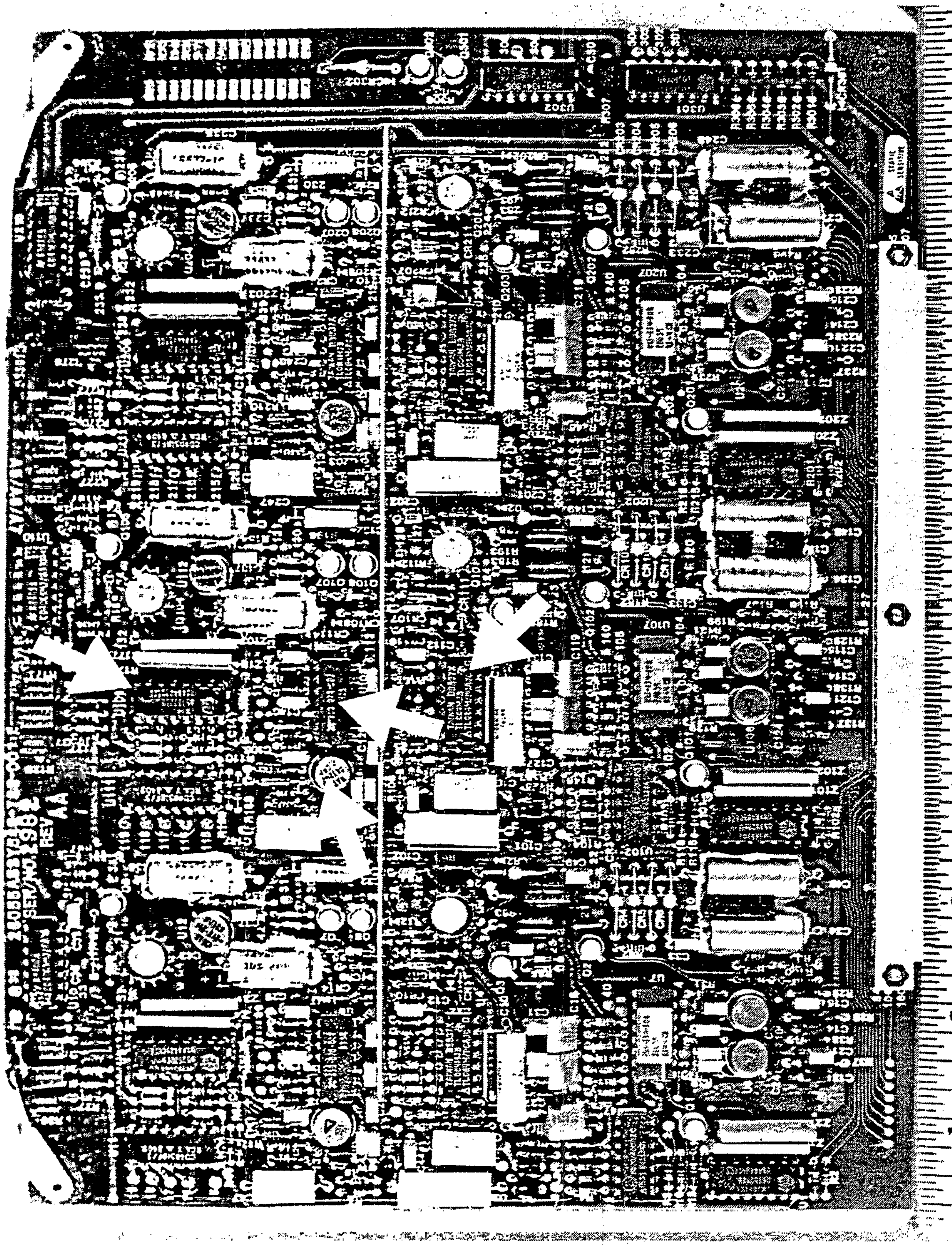


Figure 17. Test Article #15.

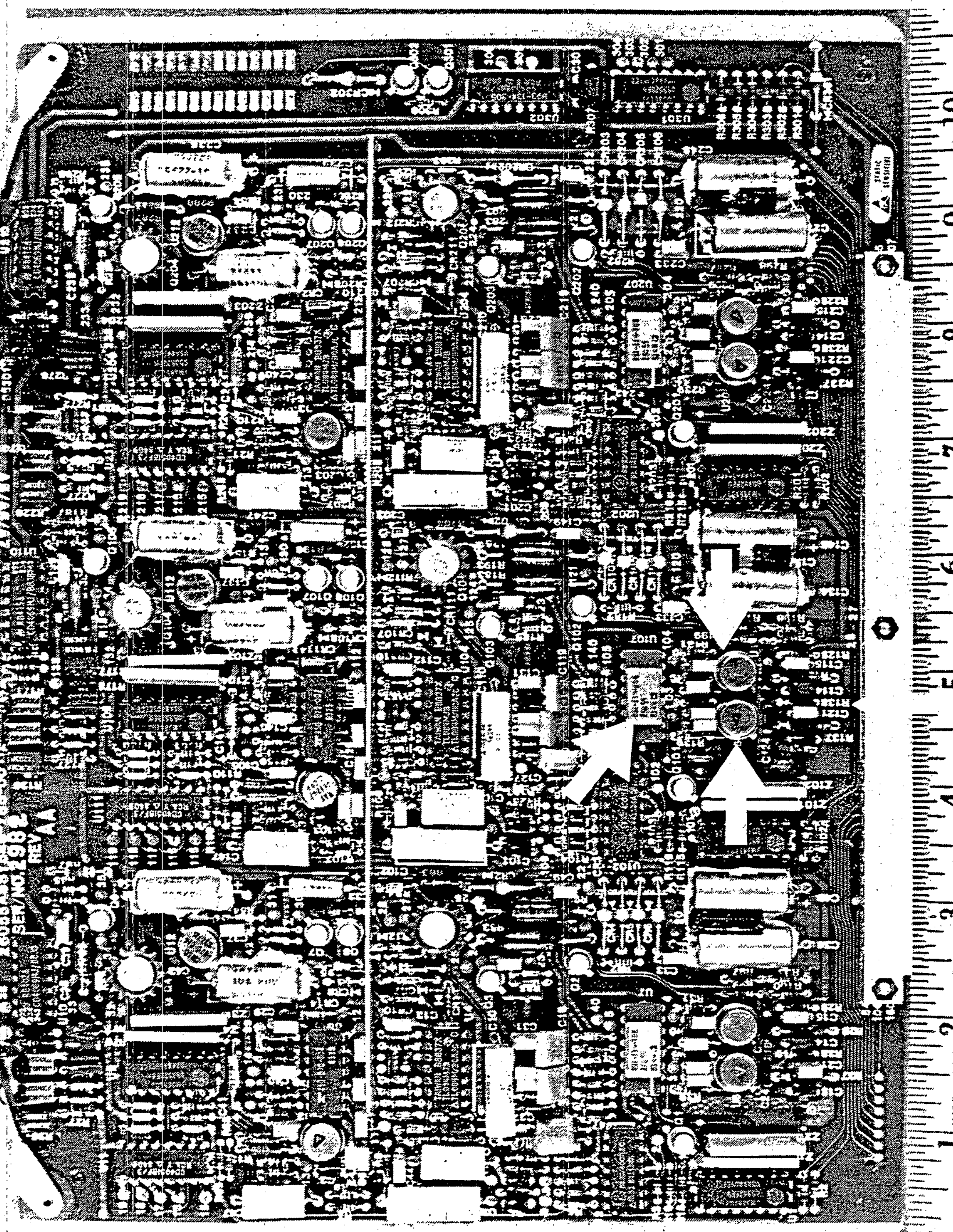


Figure 18. Test Article #16.

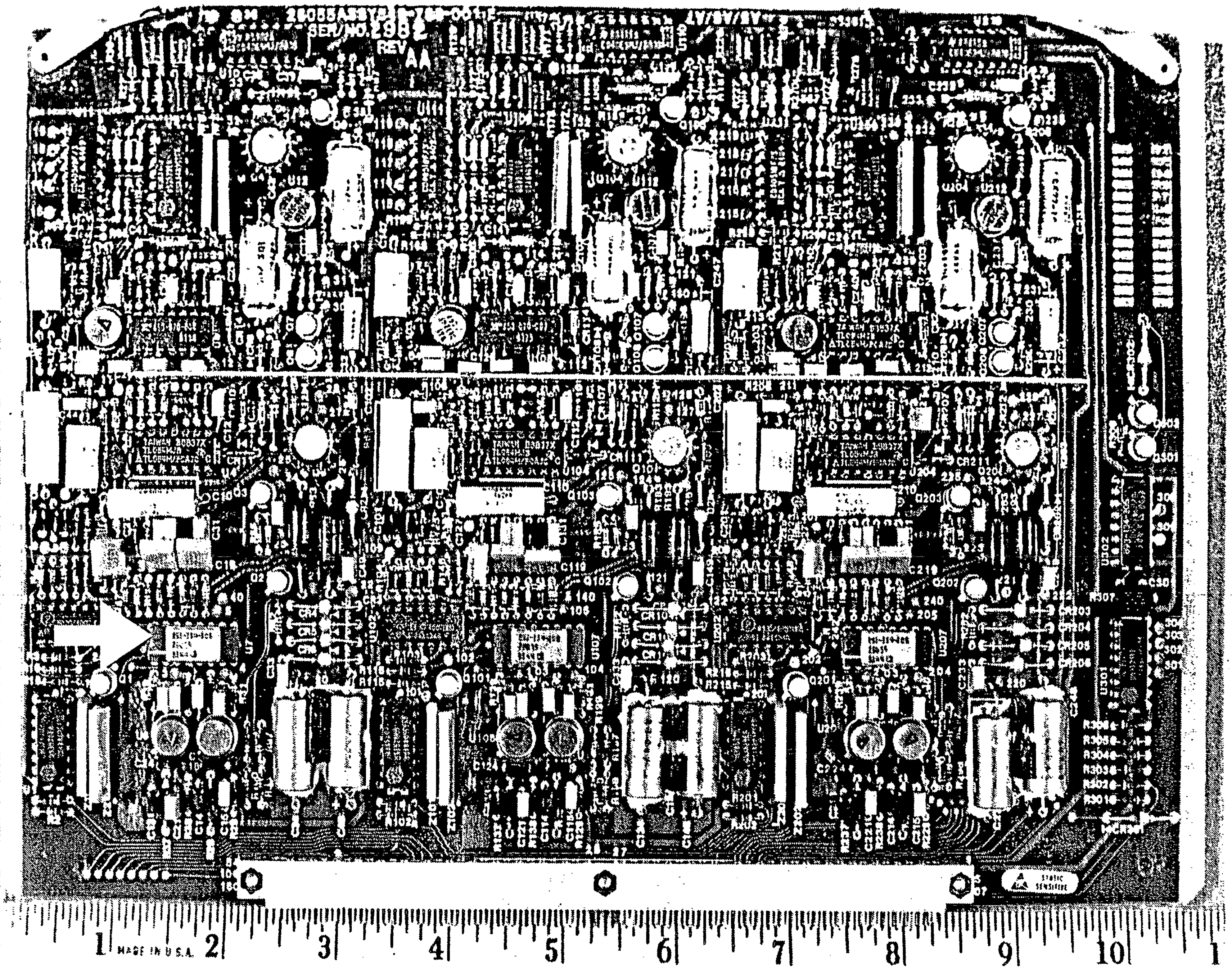


Figure 19. Test Article #17.

INTERPRETATION

To be an effective trouble-shooting tool, a cooling material must be capable of cooling components to the temperature where a failure occurs (or disappears). However, it must not damage components with low temperatures, and it must be able to isolate the defective component(s). Although the number and variety of test articles were less than hoped for, the results of the accuracy evaluation still provide important information to potential users of the alternatives and make possible the following interpretations:

- The data obtained during the Absolute Temperature Drop/Cooling Rate experiment (see Section 4) indicate that compressed air fails to cool components to the levels obtained with R-12. In 12 of 13 circuit boards tested during the Accuracy Evaluation, the CIC obtained with compressed air exceeded 0%. Therefore, the cooling capability of compressed air was sufficient, in all but one case, to reproduce circuit failures.

- A potential problem related to liquid nitrogen temperatures may have been identified during testing of Article 4. The 100%-confident identification of a RAM chip as defective when a diode proved to be the defective component may be a case where the low temperature temporarily made the device appear to be the cause of the thermally intermittent circuit failure. Potential users of liquid nitrogen may want to consider temperature control strategies to avoid low temperatures that could temporarily change component functions or even damage components. Several potential strategies are discussed in Appendix A.

- As shown by the CIC data in Table 1, in 8 of the 13 test articles, liquid nitrogen enabled the technicians to identify the components having thermally intermittent failure mode with an equal or greater confidence level than that for R-12. Given that the temperatures attainable with liquid nitrogen are much lower than those with R-12, variability of application technique is the most likely explanation for the four test articles with a liquid nitrogen CIC level of 0%. The results seem to point to a need for technician understanding of the characteristics of alternative cooling methods. These characteristics are discussed in Section 4.

SECTION 3

ELECTROSTATIC DISCHARGE RISK EVALUATION

Section 3 contains the results and interpretations of the results of measuring electrostatic charge buildup. A description of the procedures used is provided in Section 1, page 9 (Electrostatic Discharge Risk).

RESULTS

Circuit Board Tests

Table 2 summarizes the electrostatic charge measurements obtained as cooling materials were dispensed towards the six circuit boards selected. Using averages of each pair of measurements:

- For all six test articles, the compressed-air alternative generated lower charge buildup than did R-12 dispensed through a plastic nozzle.
- For four of the six test articles, the liquid nitrogen alternative generated lower buildup than did R-12.

TABLE 2. ELECTROSTATIC CHARGE MEASUREMENTS: CIRCUIT BOARD TESTS

Electrostatic Charge Buildup	Aerosol R-12 w/Plastic Nozzle (volts)	Aerosol R-12 w/Steel Nozzle (volts)	Compressed Air Tool (volts)	Liquid Nitrogen Dewar (volts)
Test Board #1	−251	623	−58	152
Test Board #2	158	443	−1	28
Test Board #3	−411	−666	−6	133
Test Board #4	−1366	−900	−80	92
Test Board #5	−143	−139	−80	300
Test Board #6	−138	−40	−45	174

- For three of the six test articles, R-12 generated lower buildup dispensed through steel nozzles than R-12 dispensed through plastic nozzles.

Nozzle Tests

Table 3 summarizes the electrostatic charge measurements obtained as cooling materials were dispensed to the atmosphere. Both the compressed air and liquid nitrogen alternatives generated lower electrostatic charge buildup than did R-12 through either plastic or steel nozzles. R-12 dispensed through steel nozzles generated lower electrostatic charge than when dispensed through plastic nozzles.

INTERPRETATION

The electrostatic charge buildup data do not support a conclusion that electrostatic discharge risk is increased by using either of the alternative component cooling technologies. However, the quality of compressed air should be considered (see the filtering and water separation system described in Section 1, Description of the Site, page 5) because it is the contaminants in flowing air (e.g., oil, water, and particulates) that cause electrostatic charge to buildup. If aerosol cans of R-12 have been utilized successfully, either compressed air or liquid nitrogen should be acceptable alternatives.

TABLE 3. ELECTROSTATIC CHARGE MEASUREMENTS: NOZZLE TESTS

	Aerosol R-12 w/Plastic Nozzle (volts)	Aerosol R-12 w/Steel Nozzle (volts)	Compressed Air Tool (volts)	Liquid Nitrogen Dewar (volts)
Electrostatic Charge Buildup	376	10	2	3

SECTION 4

COOLING RATE AND ABSOLUTE TEMPERATURE DROP EVALUATION

The procedure used to obtain temperature vs time data is described in Section 1, Cooling Rate and Absolute Temperature Drop (page 10). In Section 4, the data are presented and interpreted. Figure 20 illustrates the application parameters that were varied during the tests.

RESULTS

In all tests, the cooling material dispensers were positioned and aimed manually. Using visual feedback from the data logger chart to determine when a stable minimum temperature was reached, the technician adjusted the angle of elevation slightly to ensure that minimum temperatures were obtained for each application direction and distance. Different angles of elevation result in underspray or overspray of cooling material, thus changing the cooling rate and the difference in temperature between the target component and other components on the test fixtures. As a result, the absolute temperature drop data presented are used for direct comparison of cooling materials; but cooling rate and temperature difference data, while they indicate performance that may be obtained in actual use, are not used for direct comparisons.

Absolute Temperature Drop

Tables 4, 5, and 6 summarize the minimum temperatures achieved using different cooling materials, components, and application directions and distances. Minimum temperatures for both the target component and the exposed thermocouple are provided to show the effect of component mass. Using Type K thermocouples with the data logger, temperatures below −175°C could not be measured. After cooling the exposed thermocouple with liquid nitrogen during the initial tests, it was obvious that the minimum measurable temperature would be reached each time. Therefore, the step was eliminated for subsequent tests.

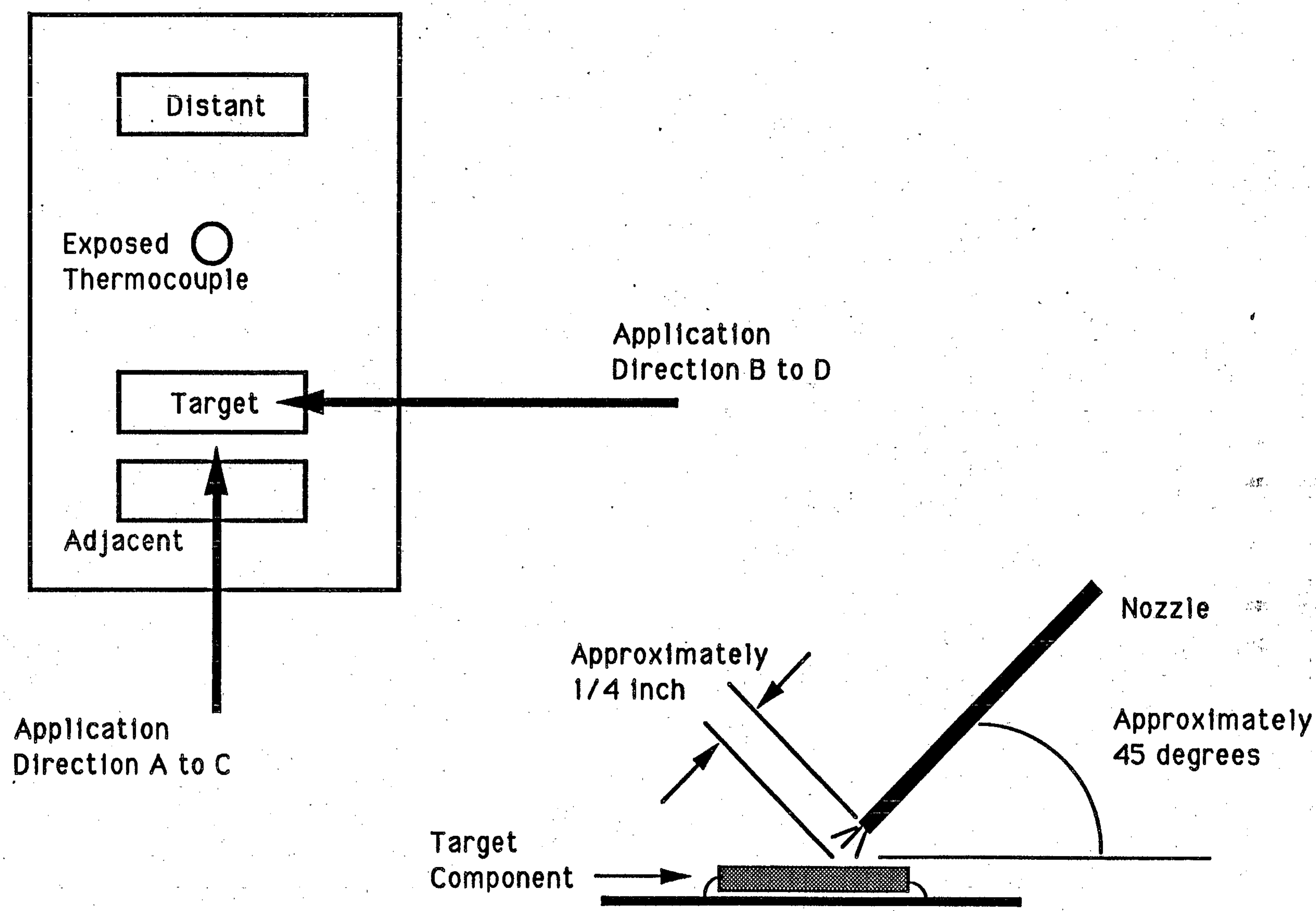


Figure 20. Cooling material application parameters.

TABLE 4. MINIMUM TEMPERATURE ACHIEVED (AT ¼" DISTANCE), DIRECTION A TO C

			Aerosol R-12 Test H-3-1		Compressed Air Test A-3-1		Liquid Nitrogen Test N-3-1	
			Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)
Component Type	Integrated Circuit Tests	Target Component	−45.0	18.0	−27.5	29.0	−175.0	31.0
		Exposed Thermocouple	−54.5	—	−35.5	—	−175.0	—
	Wound-Film Capacitor Tests	Target Component	−53.5	77.5	−11.5	121.0	−134.0	51.0
		Exposed Thermocouple	−59.5	—	−35.0	—	−175.0	—

Note: Minimum thermocouple temperature assumed to be −175°C, based on wound-film capacitor tests.

TABLE 5. MINIMUM TEMPERATURE ACHIEVED: 1" DISTANCE, DIRECTION A TO C

			Aerosol R-12 Test H-6-1		Compressed Air Test A-6-1		Liquid Nitrogen Test N-6-1	
			Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)
Component Type	Integrated Circuit Tests	Target Component	−53.0	50.0	−6.0	33.0	−134.0	73.0
		Exposed Thermocouple	−55.0	—	−12.0	—	*	—
	Wound-Film Capacitor Tests	Target Component	−57.5	115.0	6.0	64.0	−101.0	95.0
		Exposed Thermocouple	−55.5	—	−22.0	—	*	—

* Minimum thermocouple temperature assumed to be −175°C, based on wound-film capacitor tests (Table 4).

TABLE 6. MINIMUM TEMPERATURE ACHIEVED: ¼" DISTANCE, DIRECTION D TO B

			Aerosol R-12 Test H-9-1		Compressed Air Test A-9-1		Liquid Nitrogen Test N-9-1	
			Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)	Temperature (°C)	Elapsed Time (seconds)
Component Type	Integrated Circuit Tests	Target Component	−51.0	76.0	−18.5	68.0	−175.0	31.5
		Exposed Thermocouple	−58.0	—	−36.0	—	*	—
	Wound-Film Capacitor Tests	Target Component	−52.5	77.0	−12.0	7.0	−150.0	90.0
		Exposed Thermocouple	−57.5	—	−35.0	—	*	—

* Minimum thermocouple temperature assumed to be −175°C, based on wound-film capacitor tests (Table 4).

Cooling Rate

Figures 21, 22, and 23 compare the cooling rates of the three methods for three combinations of direction and distance from the target integrated circuits. Figures 24, 25, and 26 present similar information for wound-film capacitors. Table 7 summarizes calculated cooling rates over approximately the first 50% of the temperature range.

Figures 27 through 44 compare the cooling rates of one exposed thermocouple and three thermocouples embedded in components on test boards (see Figure 1). A legend provided with each figure describes the test number and other parameters. The final data point for each thermocouple represents the stable temperature level reached as cooling material was directed at the target component. Thermocouples in nontarget components typically reached a stable minimum temperature before the target component thermocouple reached a stable minimum temperature.

Table 8 summarizes temperature differences between the target and the adjacent components for each cooling rate test. The temperature difference between these components is an indicator of the ability of a cooling method to isolate a component with a thermally intermittent failure mode. The temperature differences were determined from the data logger charts at the point when the target component reached −10°C. These differences were adjusted to allow for the difference in starting temperatures; for example, the difference was reduced if the adjacent component started at a higher temperature.

INTERPRETATION

The purpose of the cooling rate and absolute temperature drop tests was to obtain cooling characteristic information for each material. This information will help potential users who are experienced with aerosol cans of R-12 use the alternative methods effectively.

General Component Cooling Characteristics

The three cooling materials differed in how they cooled components as described below:

- As R-12 was sprayed towards components, it built up a "slush" on and around the component. When the spray of R-12 was stopped, the slush continued to evaporate and lower the component temperature even further. The fastest initial cooling rates were obtained with R-12, although the cooling rate decreased as component temperature dropped.

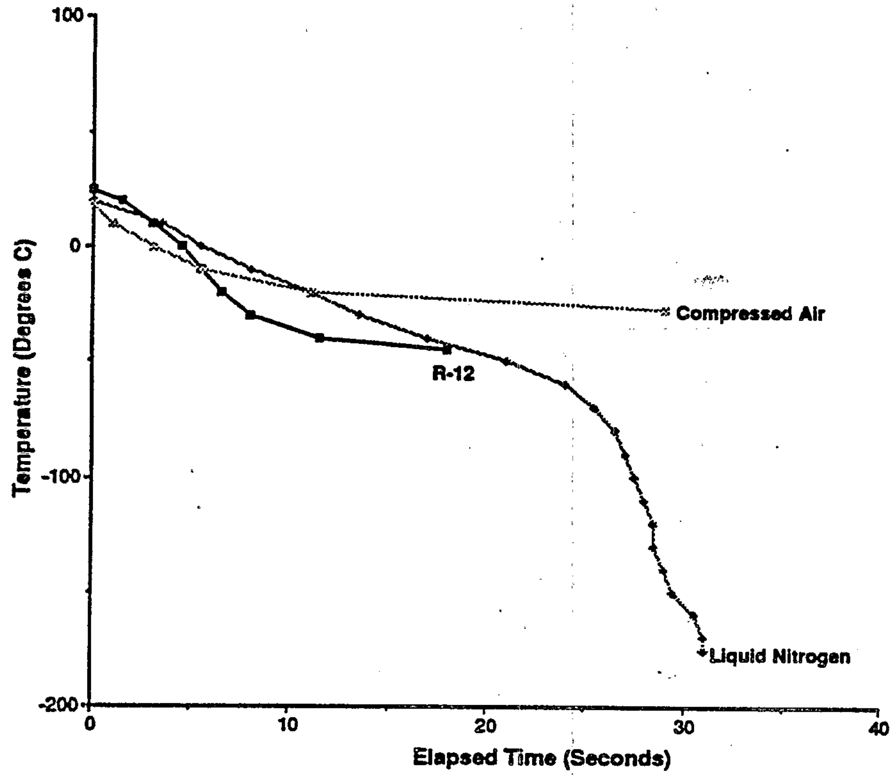


Figure 21. Cooling rate comparison for integrated circuits: distance ¼", direction A to C.

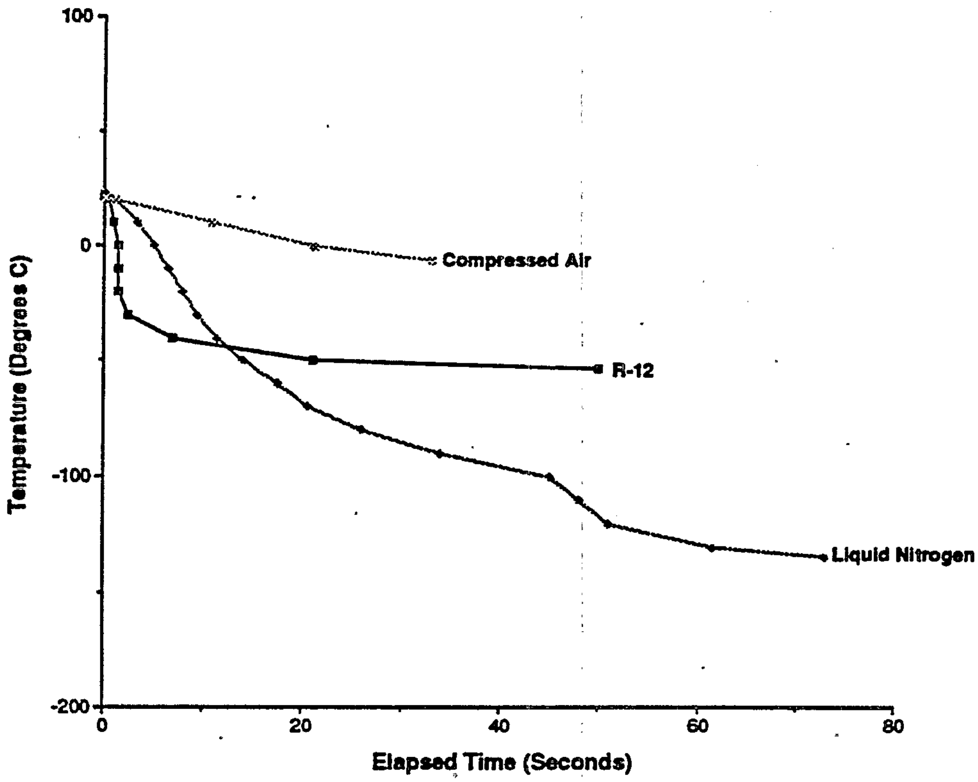


Figure 22. Cooling rate comparison for integrated circuits: distance 1", direction A to C.

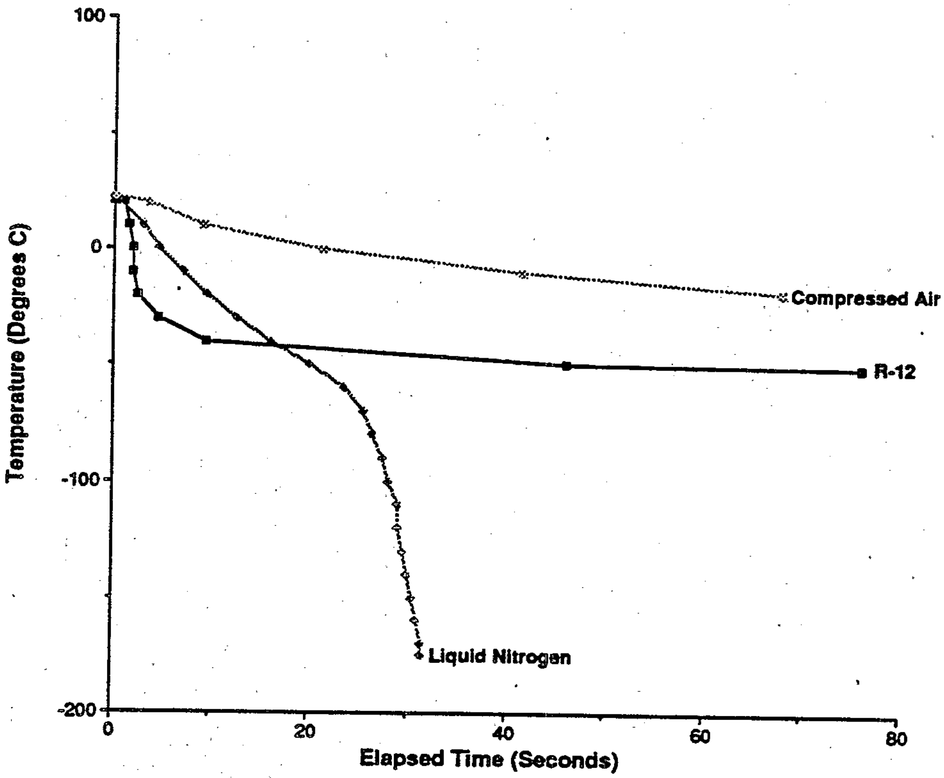


Figure 23. Cooling rate comparison for integrated circuits: distance ¼", Direction D to B.

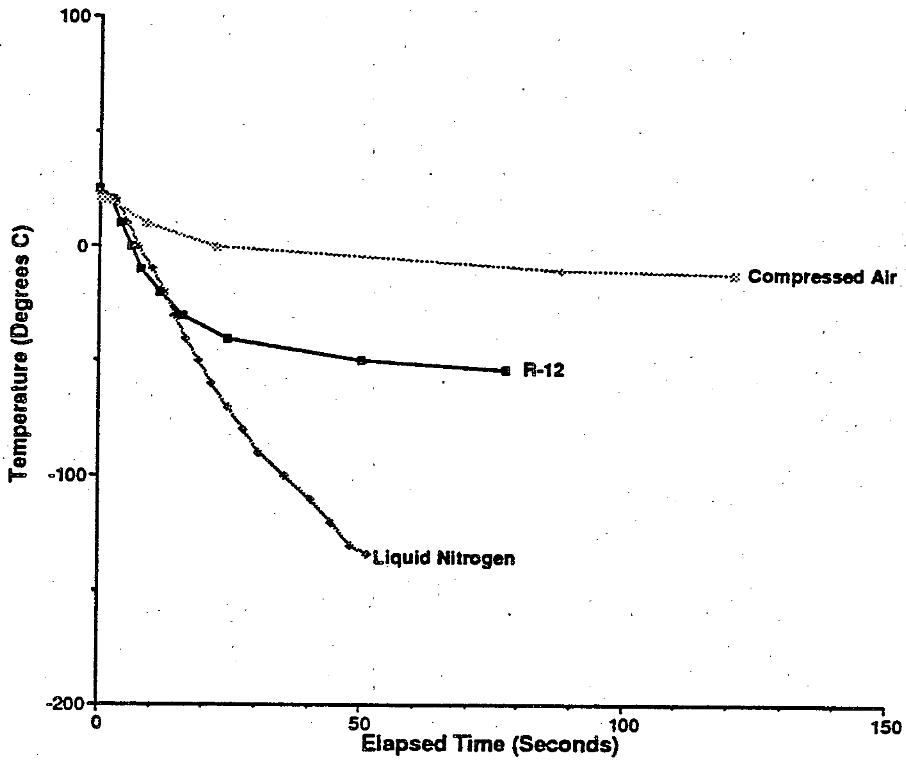


Figure 24. Cooling rate comparison for capacitors: distance ¼", direction A to C.

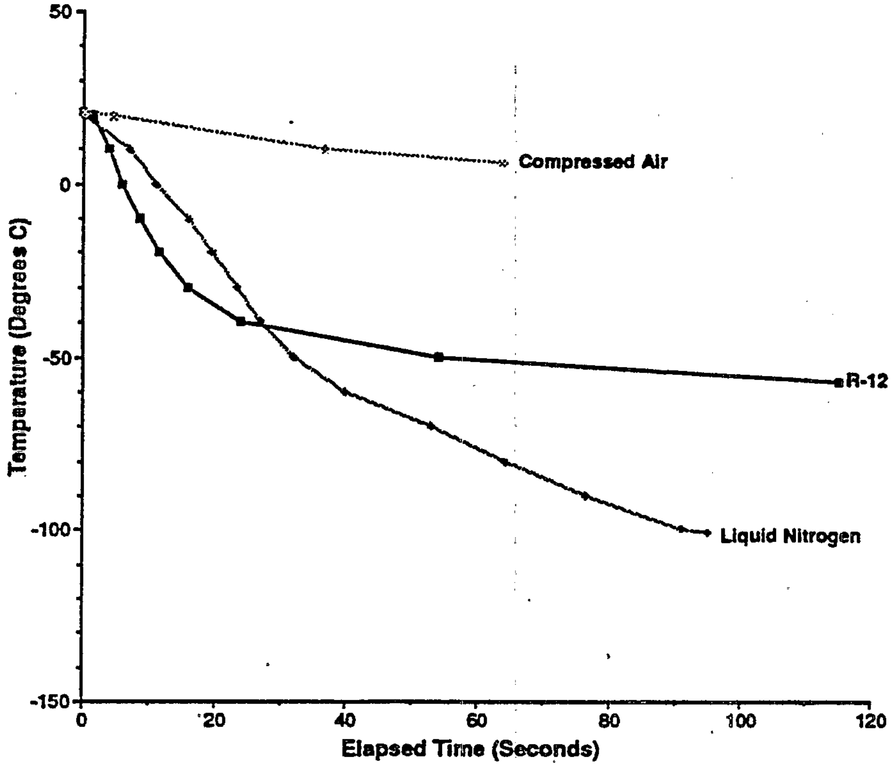


Figure 25. Cooling rate comparison for capacitors: distance 1", direction A to C.

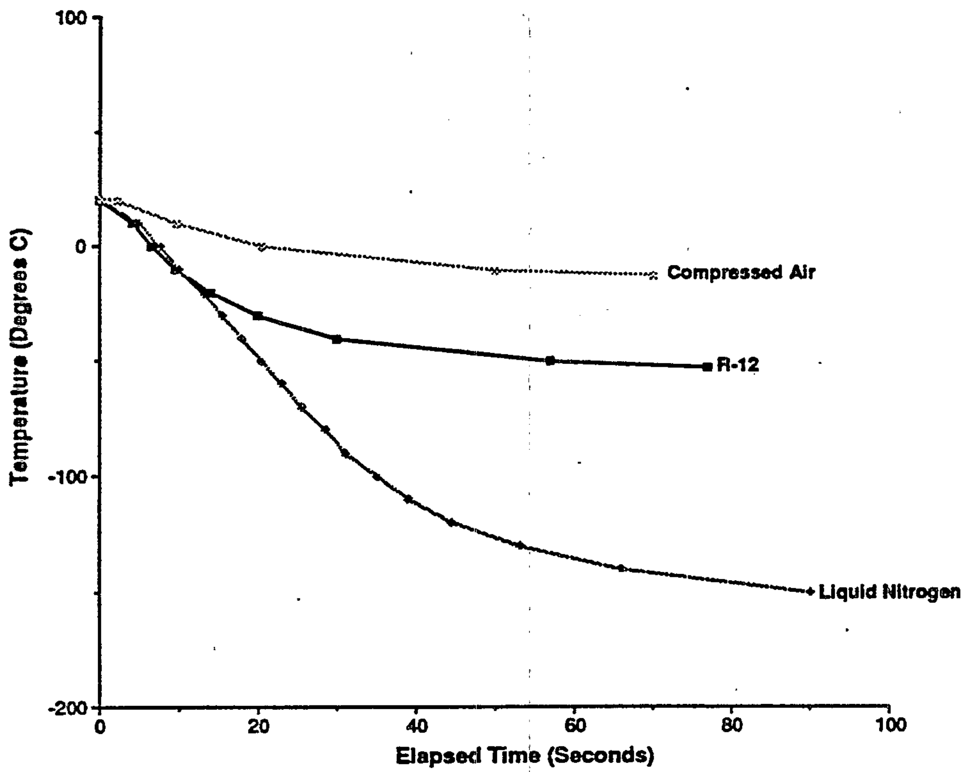


Figure 26. Cooling rate comparison for capacitors: distance ¼", direction D to B.

TABLE 7. COMPONENT COOLING RATE COMPARISON

Cooling Material	Component Type	Test	Distance/ Direction	Starting Temperature (°C)	Ending Temperature (°C)	Delta Temperature (°C)	Elapsed Time (seconds)	Cooling Rate (°C/sec.)
R-12	Integrated circuit	H-3-1	1/4" A to C	24.5	-20.0	44.5	6.5	6.8
		H-6-1	1" A to C	21.5	-20.0	41.5	1.5	27.7
		H-9-1	1/4" D to B	21.0	-20.0	41.0	2.5	16.4
	Wound-film capacitor	H-3-1	1/4" A to C	24.5	-20.0	44.5	11.5	3.9
		H-6-1	1" A to C	21.0	-20.0	41.0	11.5	3.6
		H-9-1	1/4" D to B	20.0	-20.0	40.0	14.0	2.9
Liquid nitrogen	Integrated circuit	N-3-1	1/4" A to C	20.0	-70.0	90.0	25.5	3.5
		N-6-1	1" A to C	23.0	-70.0	93.0	20.5	4.5
		N-9-1	1/4" D to B	21.0	-70.0	91.0	25.5	3.6
	Wound-film capacitor	N-3-1	1/4" A to C	23.0	-70.0	93.0	24.5	3.8
		N-6-1	1" A to C	20.0	-70.0	90.0	53.0	1.7
		N-9-1	1/4" D to B	20.0	-70.0	90.0	25.5	3.5
Compressed air	Integrated circuit	A-3-1	1/4" A to C	19.0	0.0	19.0	3.0	6.3
		A-6-1	1" A to C	20.5	0.0	20.5	21.0	1.0
		A-9-1	1/4" D to B	23.0	0.0	23.0	21.0	1.1
	Wound-film capacitor	A-3-1	1/4" A to C	20.5	0.0	20.5	22.0	0.9
		A-6-1	1" A to C	21.0	10.0	11.0	36.5	0.3
		A-9-1	1/4" D to B	21.0	0.0	21.0	20.5	1.0

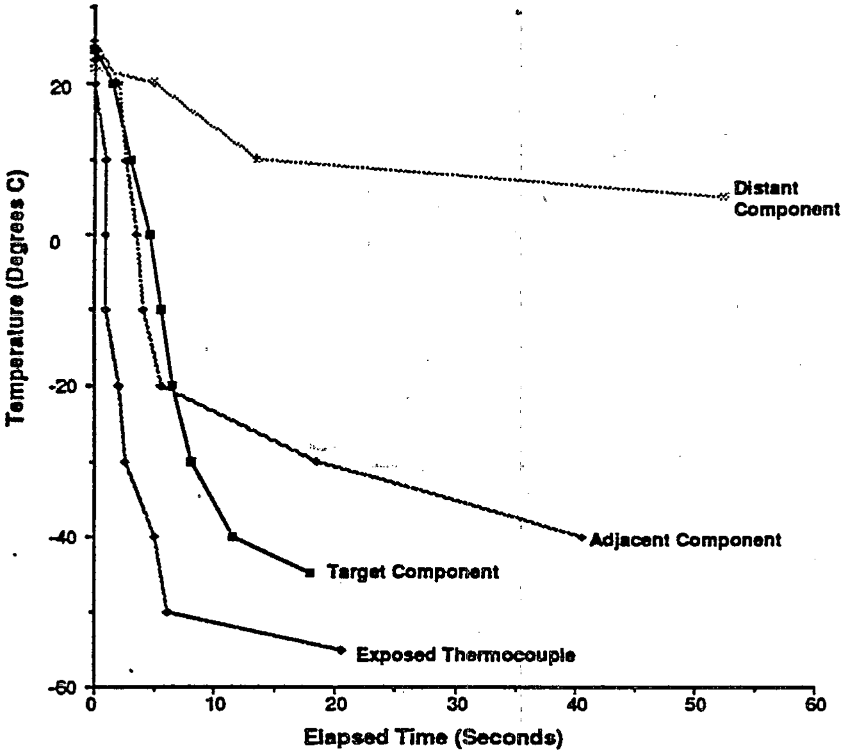


Figure 27. IC (H-3-1) time/temperature plot.

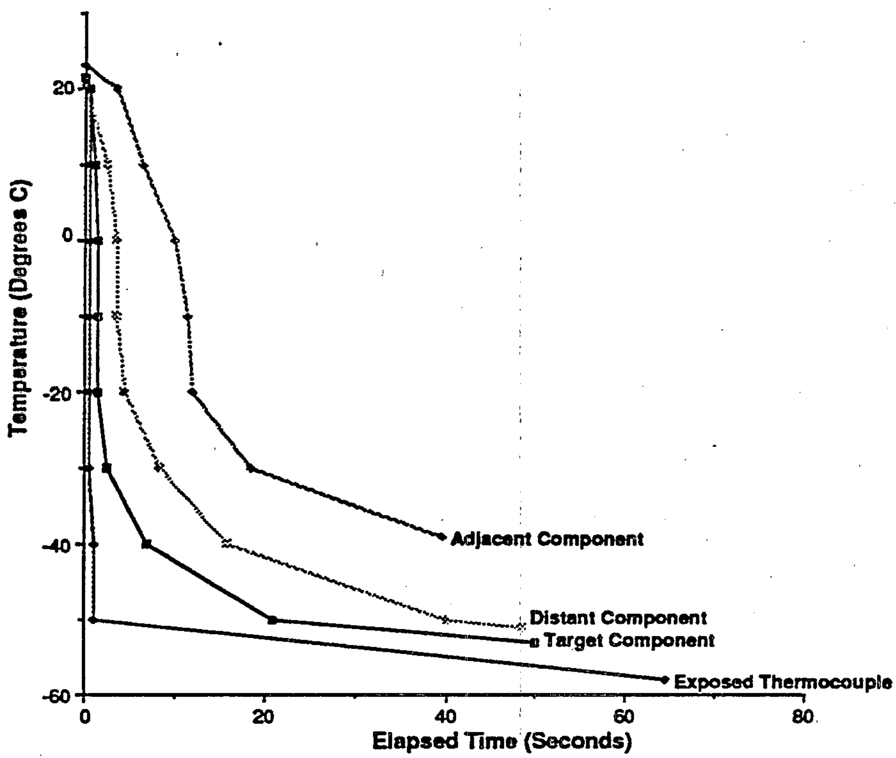


Figure 28. IC (H-6-1) time/temperature plot.

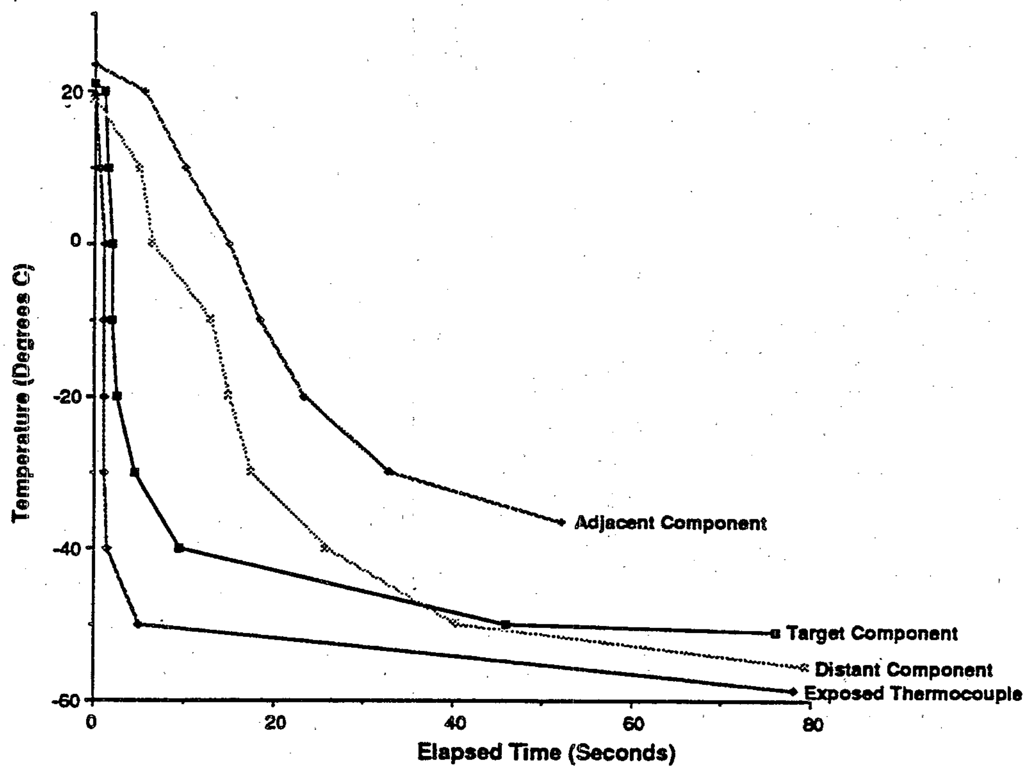


Figure 29. IC (H-9-1) time/temperature plot.

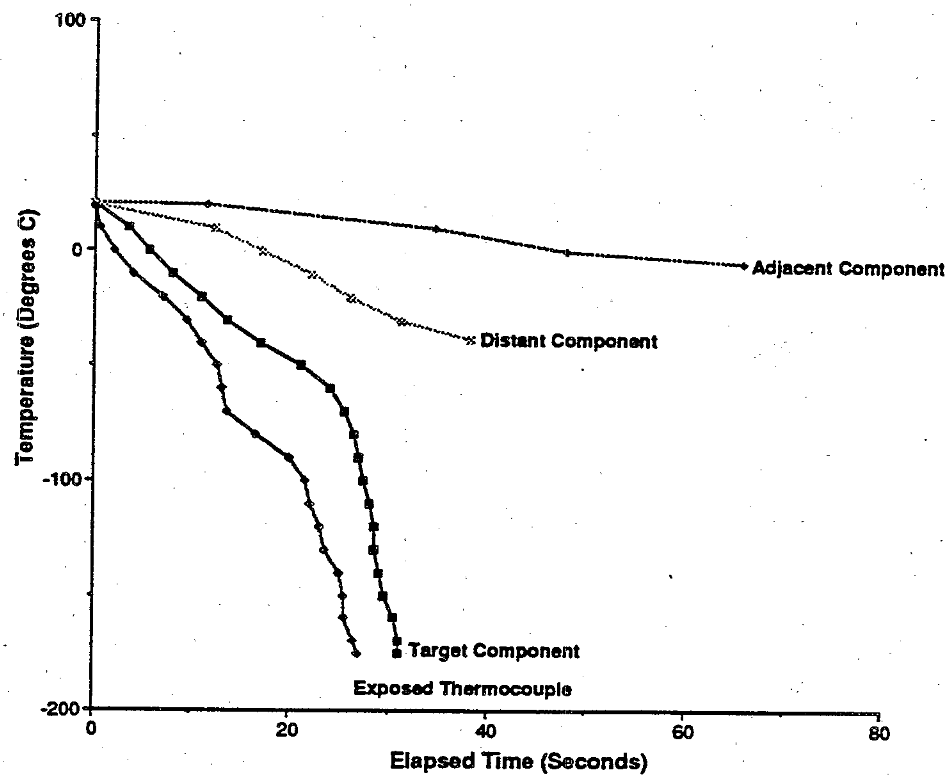


Figure 30. IC (N-3-1) time/temperature plot.

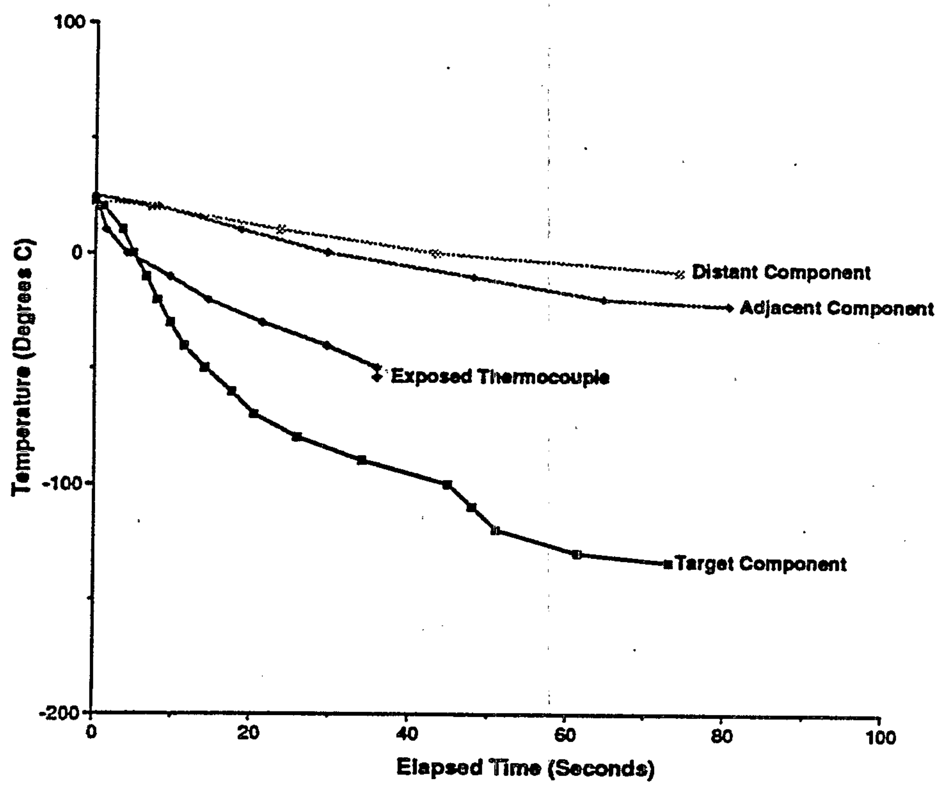


Figure 31. IC (N-6-1) time/temperature plot.

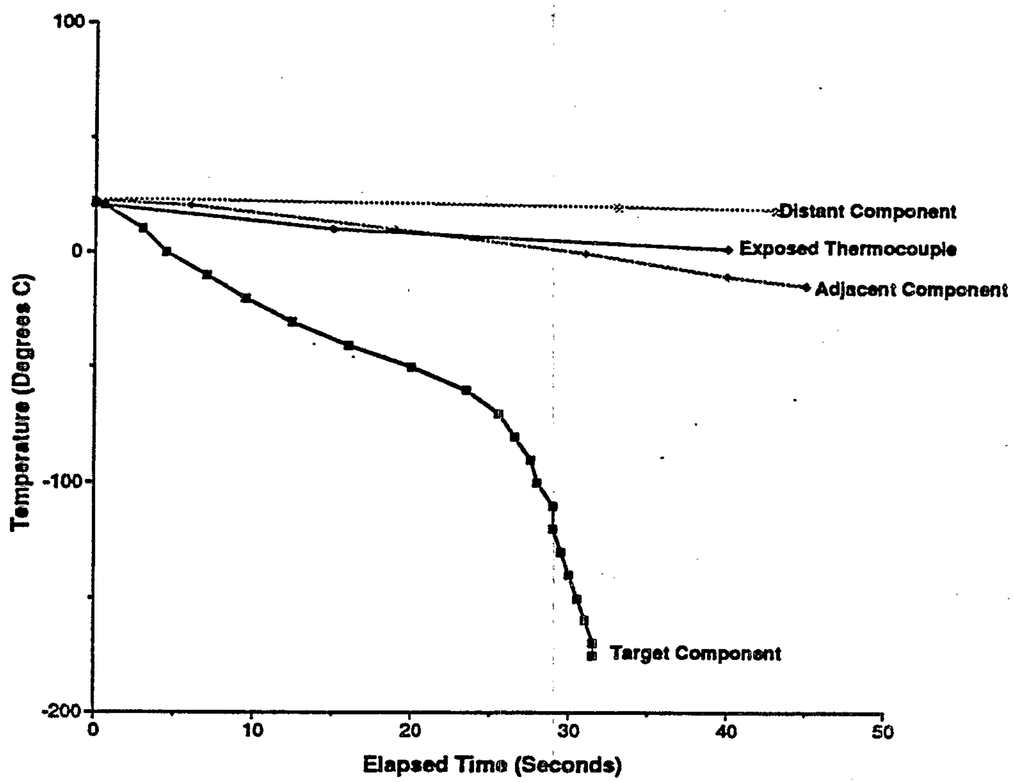


Figure 32. IC (N-9-1) time/temperature plot.

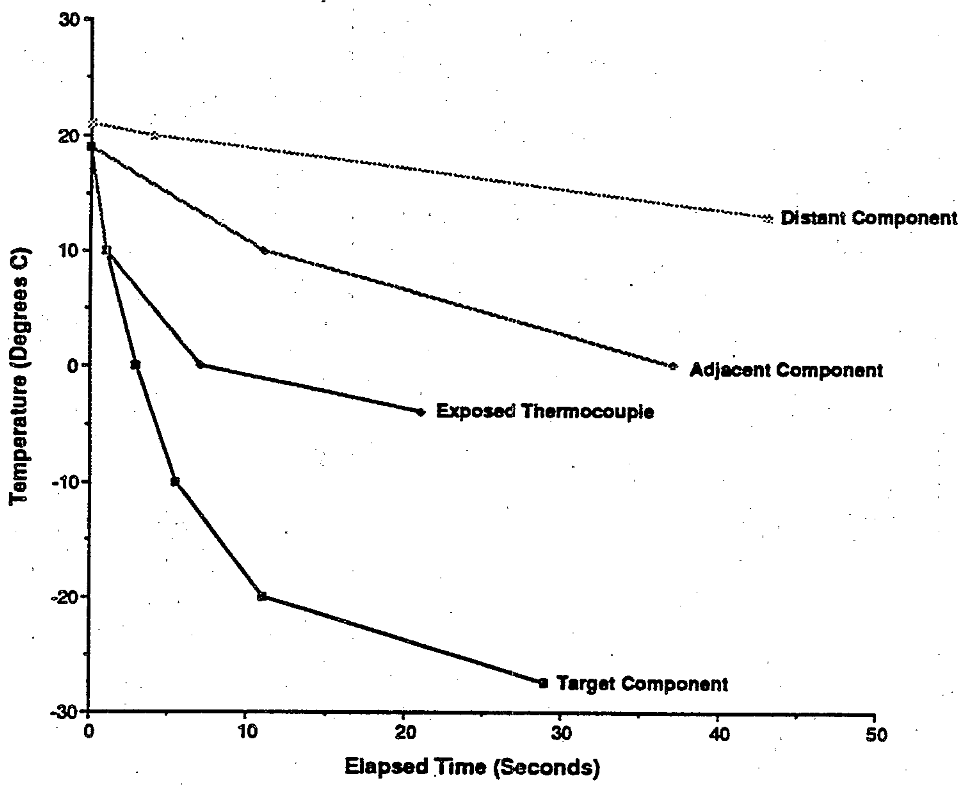


Figure 33. IC (A-3-1) time/temperature plot.

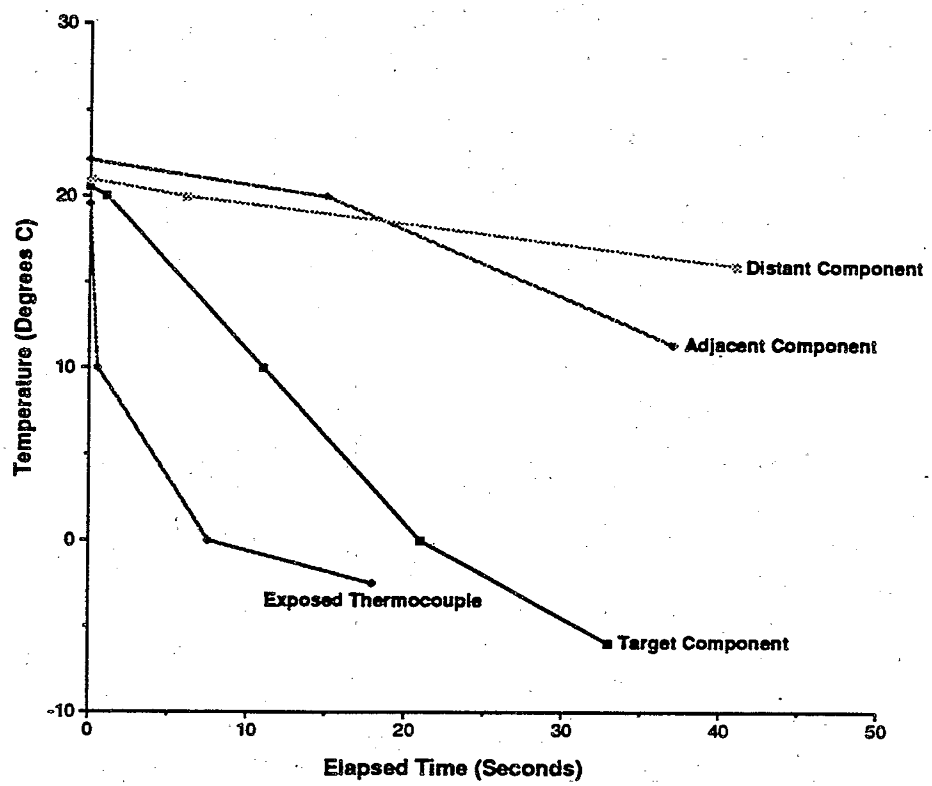


Figure 34. IC (A-6-1) time/temperature plot.

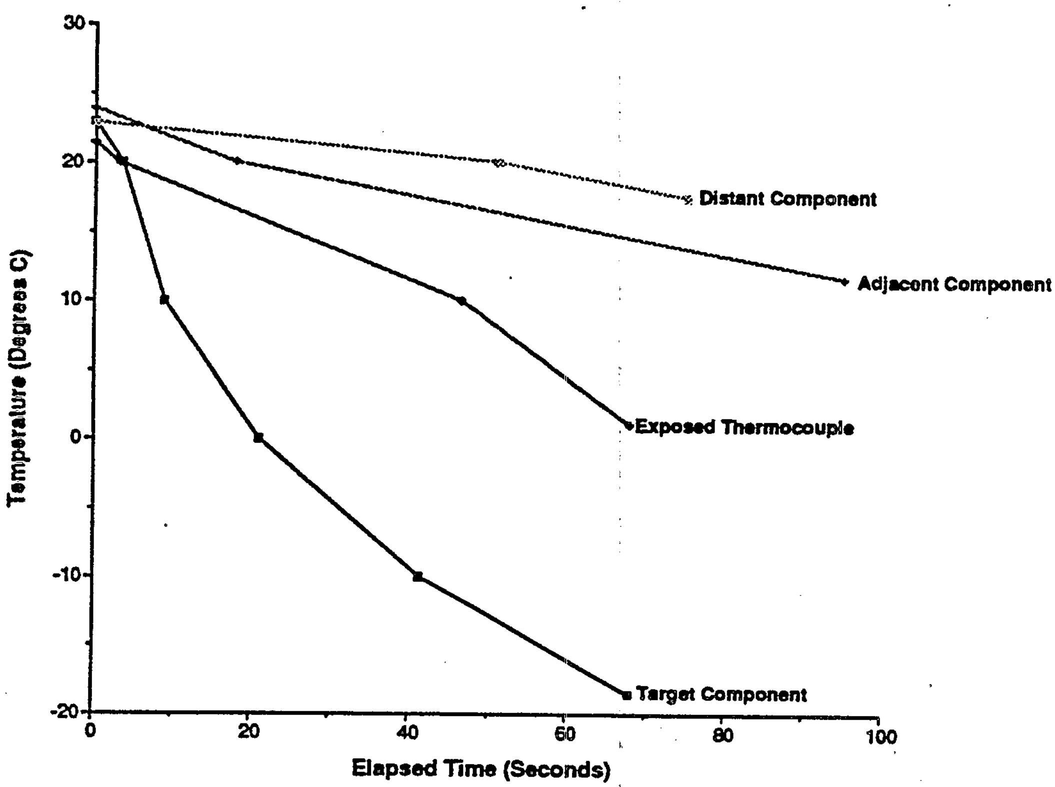


Figure 35. IC (A-9-1) time/temperature plot.

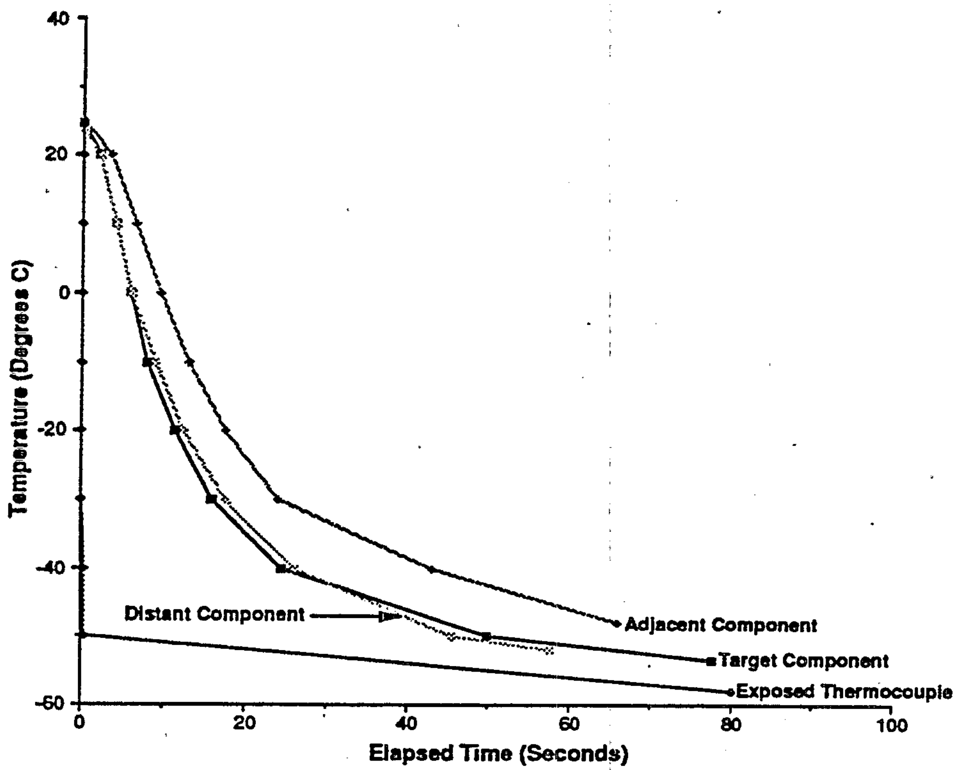


Figure 36. Capacitors (H-3-1) time/temperature plot.

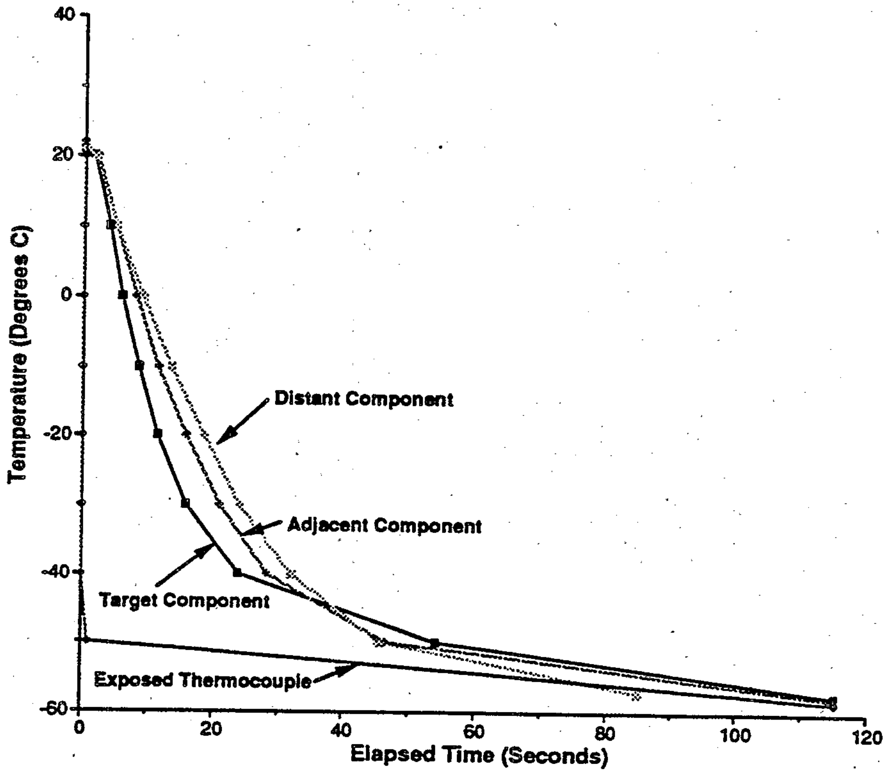


Figure 37. Capacitors (H-6-1) time/temperature plot.

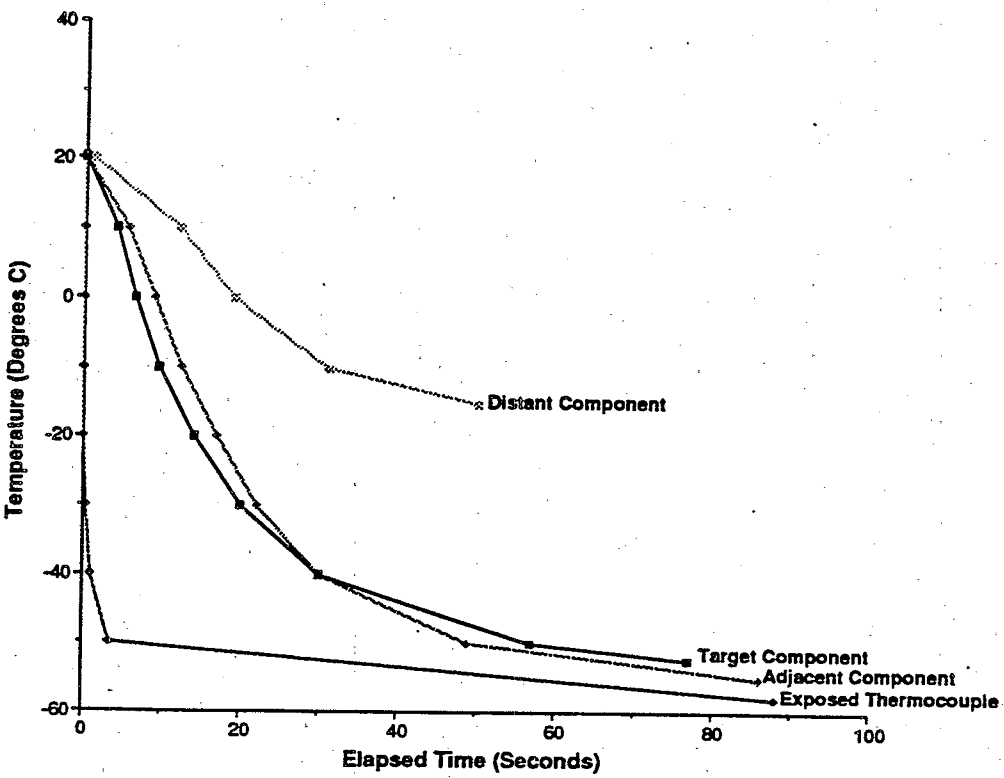


Figure 38. Capacitors (H-9-1) time/temperature plot.

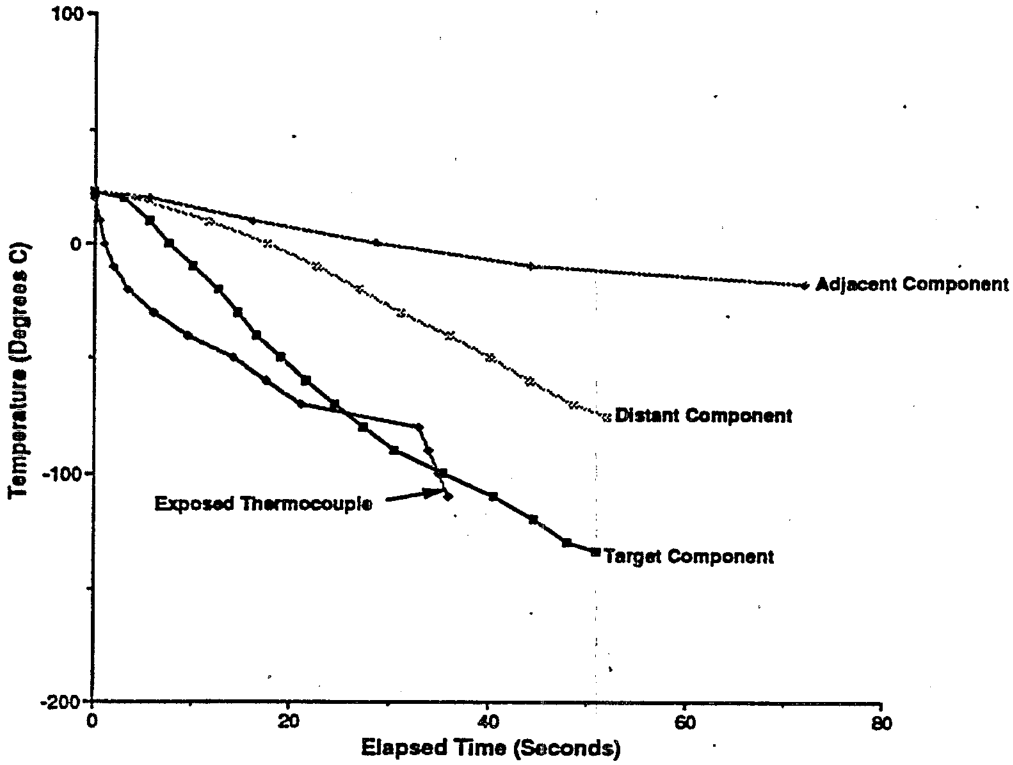


Figure 39. Capacitors (N-3-1) time/temperature plot.

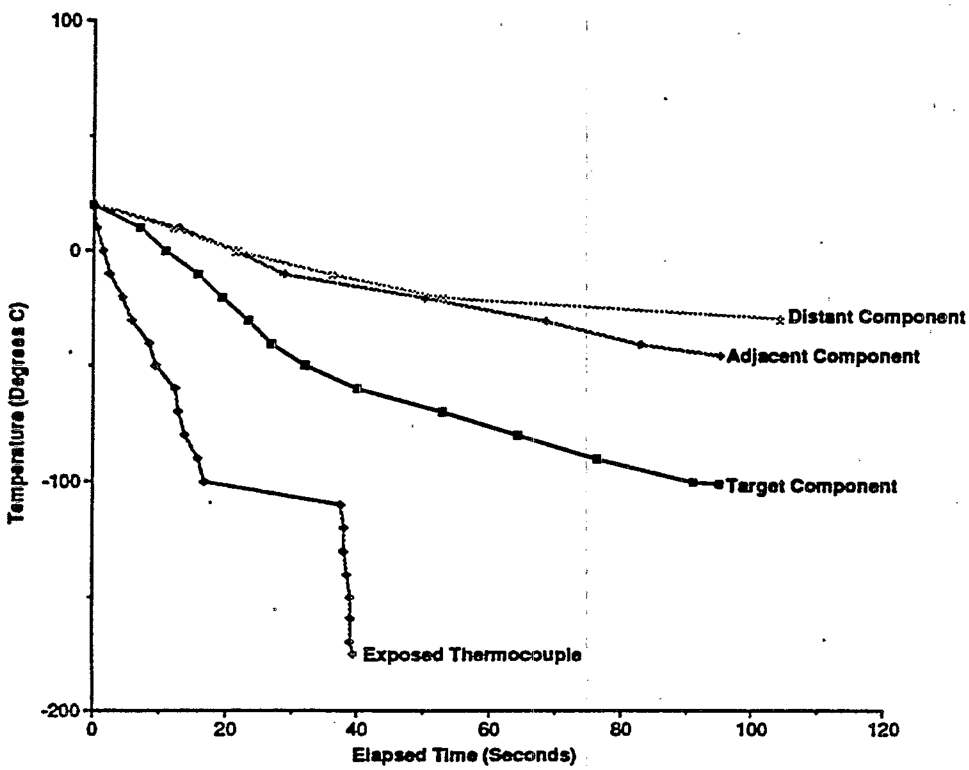


Figure 40. Capacitors (N-6-1) time/temperature plot.

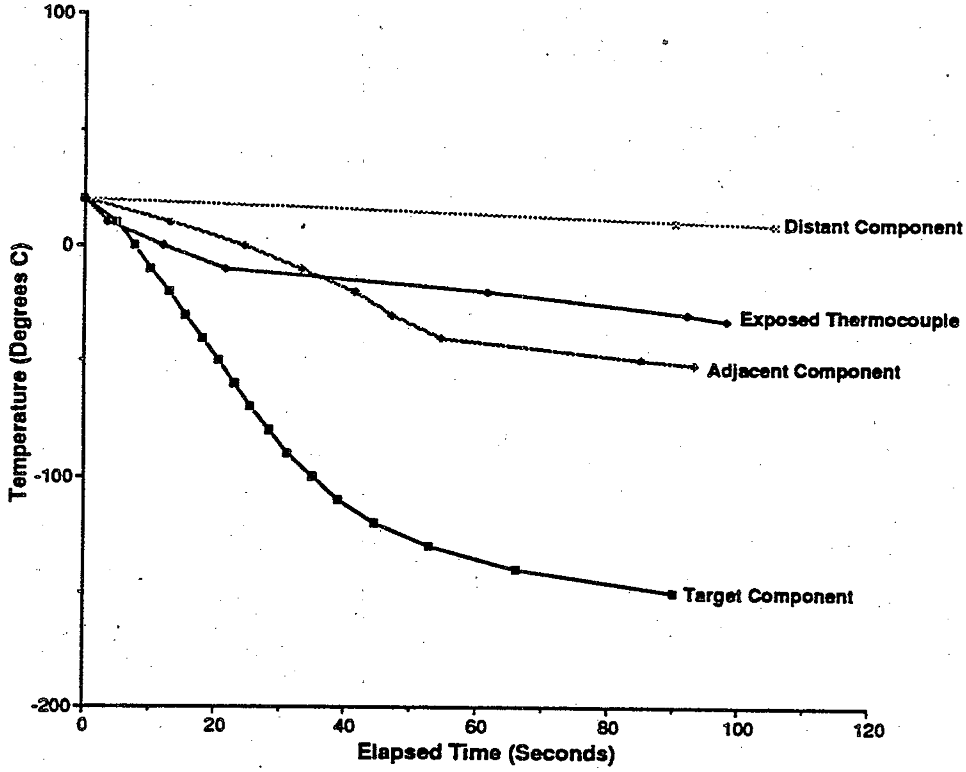


Figure 41. Capacitors (N-9-1) time/temperature plot.

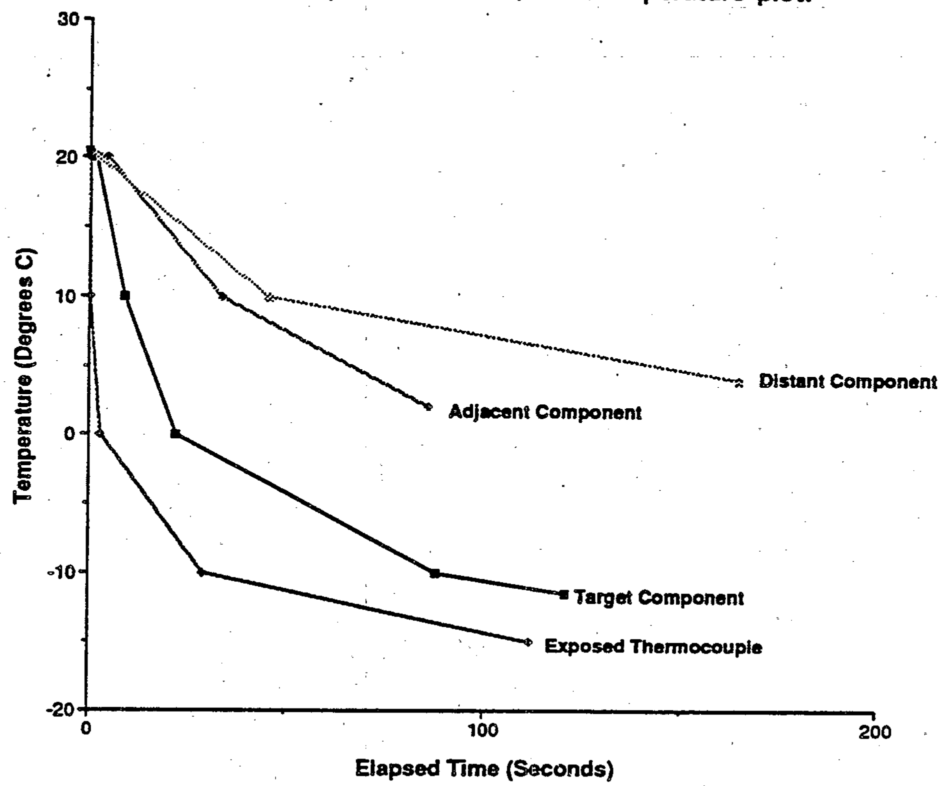


Figure 42. Capacitors (A-3-1) time/temperature plot.

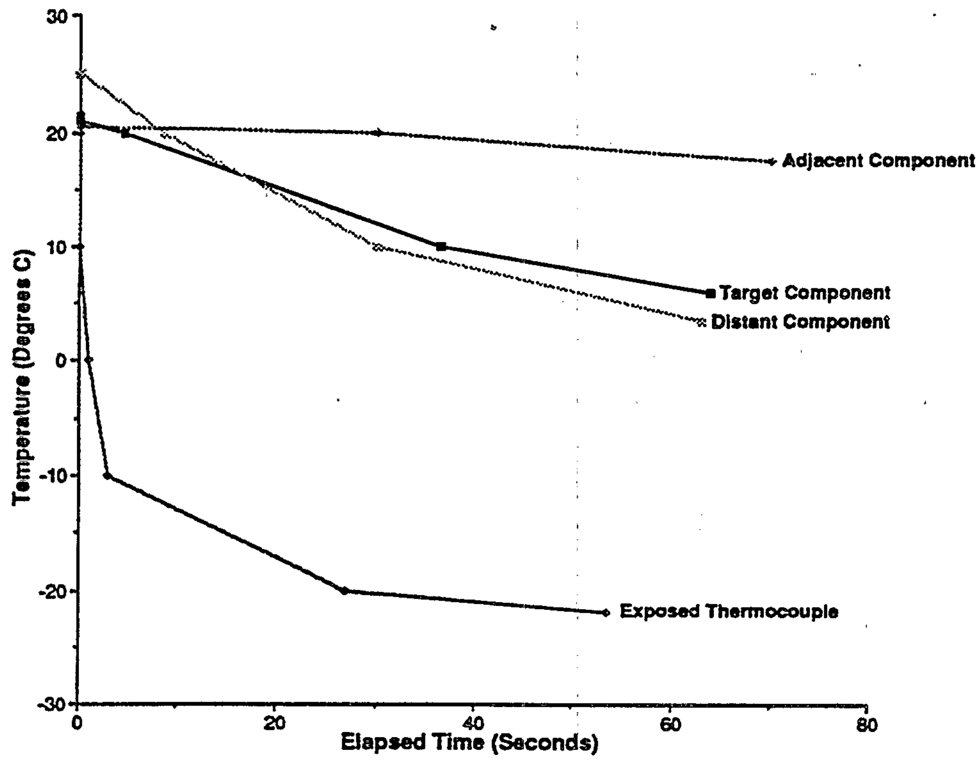


Figure 43. Capacitors (A-6-1) time/temperature plot.

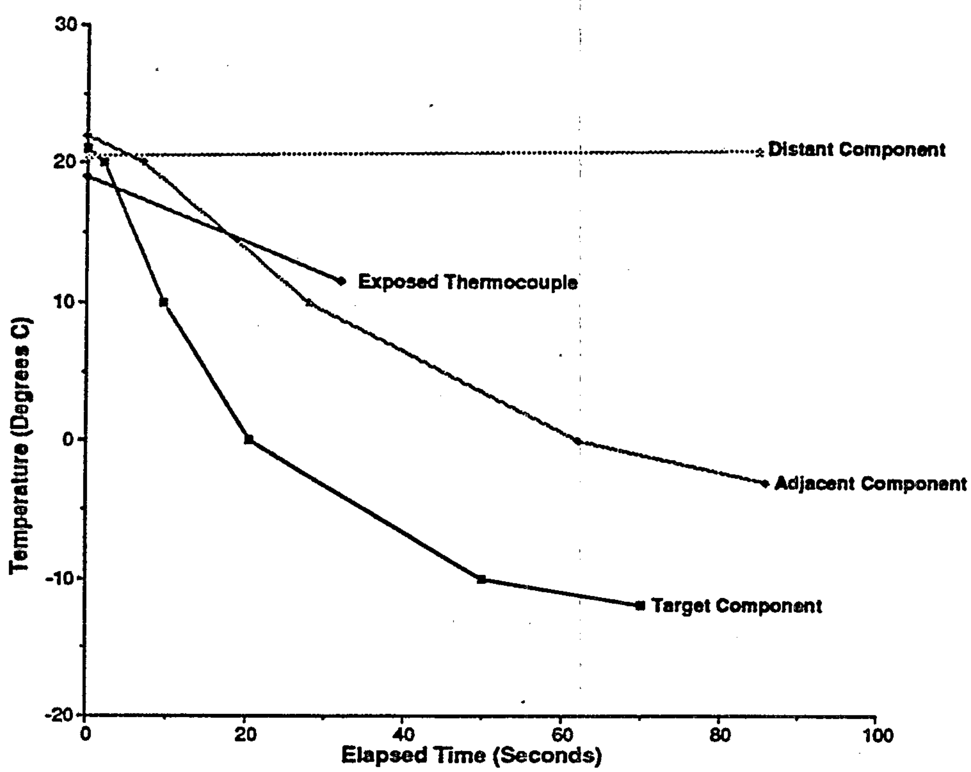


Figure 44. Capacitors (A-9-1) time/temperature plot.

TABLE 8. TARGET/ADJACENT COMPONENT TEMPERATURE DIFFERENCE

Component Cooling Material	Component Type	Test	Application Direction	Application Distance	Component Temperature Difference (°C)[a]
R-12	Integrated Circuits	H-3-1	A to C	¼"	−11.0
		H-6-1	A to C	1"	31.5
		H-9-1	D to B	¼"	31.0
	Wound-Film Capacitors	H-3-1	A to C	¼"	13.5
		H-6-1	A to C	1"	8.5
		H-9-1	D to B	¼"	8.5
Compressed Air	Integrated Circuits	A-3-1	A to C	¼"	25.5
		A-6-1	A to C	1"	(b)
		A-9-1	D to B	¼"	24.0
	Wound-Film Capacitors	A-3-1	A to C	¼"	12.0
		A-6-1	A to C	1"	(b)
		A-9-1	D to B	¼"	11.5
Liquid Nitrogen	Integrated Circuits	N-3-1	A to C	¼"	30.0
		N-6-1	A to C	1"	30.0
		N-9-1	D to B	¼"	28.0
	Wound-Film Capacitors	N-3-1	A to C	¼"	25.0
		N-6-1	A to C	1"	15.0
		N-9-1	D to B	¼"	22.0

(a) Negative difference indicates that the adjacent component was colder than the target component when the target component reached −10°C; positive difference indicates warmer adjacent component.

(b) Target Component did not reach −10°C during test.

- Liquid nitrogen provided the coldest temperatures of the three cooling materials. In contrast to R-12, an accelerating cooling rate was obtained when liquid nitrogen was used (see Figure 28). The cooling material consists of nitrogen gas and droplets of liquid nitrogen; as the dispensing valve and nozzle cools, the proportion of droplets increases. The increase in droplets could be heard as increased "sputtering" of cooling material during material release. Frost buildup on the components during cooling was minimal.

- Compressed air provided the least cold temperatures and the slowest cooling rate. As with R-12, the cooling rate decreased as component temperature dropped. Compressed-air cooling resulted in a slight frost buildup on the components.

Sensitivity to Application Parameters

The three cooling methods varied in their sensitivity to parameters such as component type, application distance, and application direction. Evaluation of minimum target component temperature data in Tables 4, 5, and 6 indicate that:

- For all three combinations of application distance and direction, both liquid nitrogen and compressed air provided lower temperatures with integrated circuits. R-12 was less sensitive to the type of component cooled; minimum temperatures for capacitors and integrated circuits were not significantly different under each application distance/direction combination.

- The component cooling capabilities of both compressed air and liquid nitrogen are sensitive to distance from the target component. A comparison of temperature data in Table 5 to data in Tables 4 and 6 reveals that, as the distance from the component to the nozzle increased from 0.25 inch to 1 inch, the minimum component temperature decreased for both alternative methods. This relationship does not exist for R-12, indicating that it is not as sensitive to distance.

- Comparing component minimum temperature data in Table 4 (A to C direction) to Table 6 (D to B direction) indicates that R-12 is not sensitive to application direction. Lower component temperatures for integrated circuits were obtained with compressed. air, but liquid nitrogen yielded lower component temperatures for wound-film capacitors. The most likely explanation of this difference is the variability resulting from manual positioning of the dispensers.

SECTION 5

TECHNICIAN SAFETY EVALUATION

RESULTS

Personnel from the Newark AFB Bioenvironmental Engineering Office took sound-level measurements during operation of the compressed-air tool. A sound level of 81 dBA was recorded at the operator work position. Because the sound levels did not exceed 84 dBA, additional measurement was not required by the Air Force and, in accordance with Air Force Regulation 161-35, hearing conservation precautions were deemed unnecessary.

INTERPRETATION

Sound level during operation of the compressed-air tools is not expected to represent a hazard to operators.

SECTION 6

POLLUTION PREVENTION POTENTIAL EVALUATION

RESULTS

Table 9 summarizes the amounts of R-12 dispensed to evaluate each of 13 test articles. The data collection process is described on pages 9 and 10.

TABLE 9. R-12 REFRIGERANT USAGE

Test Article #	Dichlorodifluoromethane — R-12	
	R-12 Released (grams)	Equivalent 15-ounce cans
1	249.31	0.76
2	153.72	0.47
3	360.91	1.10
4	386.83	1.18
6	167.58	0.51
7	34.86	0.11
9	65.53	0.20
10	239.27	0.73
13	399.48	1.22
14	331.19	1.01
15	163.76	0.50
16	204.94	0.63
17	267.07	0.82
Total	3024.45	9.23
Average	232.65	0.71

INTERPRETATION

A total of 3024.45 grams (6.67 pounds) of R-12 were released to test the 13 articles. The average release per article was 232.65 grams (0.51 pounds). The variability of R-12 released per circuit board is related to the difficulty of finding the suspected cause of circuit failure.

With the adoption of either alternative technology, release of R-12 would be eliminated along with the wastestream of empty aerosol cans. The pollution prevention potential of widespread adoption of one or both of these technologies cannot be estimated with any confidence because neither usage nor production information for the United States was available when this report was written. The quantities consumed vary by user, ranging from a few cans per month in repair shops to over a thousand cans per year in production operations.

SECTION 7

ESTIMATION OF ECONOMICS

RESULTS

It was not possible in this evaluation of alternative component-cooling materials to measure all potential impacts on operating costs, particularly those for direct labor and materials. If an alternative cooling material is less able to isolate the specific component causing a thermally intermittent circuit, components may be replaced unnecessarily. Each component replacement adds cost in the form of direct labor for replacement and retesting, component costs, and risk of circuit board damage. If a cooling method is unable to identify a component, a circuit board may be condemned unnecessarily. The comparison of the ability of cooling materials to isolate thermally intermittent components was addressed in the accuracy evaluation (Section 2) and the absolute temperature drop/cooling rate evaluation (Section 4). Cooling material costs, estimated based on actual use during the accuracy evaluation, are the basis for the economic evaluation performed in this section.

Cooling Material Costs

Cooling material costs for each cooling method are summarized in Table 10. Labor costs were not considered. Cooling material costs are based on the usage data collected during the accuracy evaluation of thirteen test articles. Usage data were converted to cost data as follows:

- R-12 cost was based on a cost of $7.50 per 16-ounce aerosol can. Purchase price of R-12 or R-22 freeze compound ranges from $6 to $15; $7.50 was selected as a conservative estimate.
- Compressed-air cost was calculated using an air tool consumption rate of 15 cfm at 100 psi and an estimated compressed-air generation cost of $0.26 per thousand cubic feet. The generation cost will vary based on power costs and other factors and should be verified by potential users.
- Purchase cost of liquid nitrogen varies widely; $0.25 per liter was used as a typical cost. Potential users should obtain price quotations from local suppliers.

TABLE 10. COOLING MATERIAL USAGE AND COST

Test Article	Dichlorodifluoromethane - R-12			Liquid Nitrogen			Compressed Air		
	R-12 Released (grams)	Conversion to 15-ounce cans @ 328 g/can	Cost of Aerosol R-12 @ $7.50/can	Liquid Nitrogen Released (grams)	Conversion to liters @ 814 g/L	Cost of Liquid Nitrogen @ $0.25/L	Compressed Air Release Time (minutes)	Air Consumed at 15 scf/min	Cost of Compressed Air at $0.26/Kscf
1	249.31	0.76	$5.71	89.57	0.11	$0.03	5.08	76.13	$0.02
2	153.72	0.47	$3.52	307.82	0.38	$0.10	1.27	19.01	$0.00
3	360.91	1.10	$8.26	180.20	0.22	$0.06	20.57	308.51	$0.08
4	386.83	1.18	$8.86	274.10	0.34	$0.08	6.05	90.75	$0.02
6	167.58	0.51	$3.84	5.00	0.01	$0.00	22.12	331.85	$0.09
7	34.86	0.11	$0.80	567.23	0.70	$0.18	32.62	489.30	$0.13
9	65.53	0.20	$1.50	124.90	0.15	$0.04	4.15	62.25	$0.02
10	239.27	0.73	$5.48	105.70	0.13	$0.03	26.95	404.27	$0.11
13	399.48	1.22	$9.15	31.90	0.04	$0.01	30.45	456.78	$0.12
14	331.19	1.01	$7.58	36.99	0.05	$0.01	4.40	66.00	$0.02
15	163.76	0.50	$3.75	168.60	0.21	$0.05	11.01	165.20	$0.04
16	204.94	0.63	$4.69	90.49	0.11	$0.03	22.29	334.34	$0.09
17	267.07	0.82	$6.11	212.50	0.26	$0.07	52.82	792.24	$0.21
Total	3024.45	9.23	$69.24	2195.00	2.72	$0.68	239.77	3596.60	$0.94
Average	232.65	0.71	$5.33	168.85	0.21	$0.05	18.44	276.66	$0.07

Investment Costs

There is no investment cost for R-12. Costs for the alternative cooling material dispensing equipment are as follows:

Implementation of compressed air requires, at a minimum, investment in the air tools at approximately $200 per unit. The investment required to generate and deliver 15 scfm at 100 psi to the tools at a work position will vary with each potential user. Assuming no compressed air is available in a shop, the minimum equipment required to supply one air tool is a 5-horsepower compressor, oil-filter and desiccant filters, and nonrestrictive air lines, connectors, and valves. Purchase and installation costs also will vary for each potential user.

Implementation of liquid nitrogen would require approximately $500 for each half-liter Dewar flask. Heat exchangers or other accessories would be additional costs. Cylinders for bulk liquid nitrogen generally are provided by the suppliers at no charge. If use rate is low, suppliers may require a leasing arrangement for the bulk containers.

INTERPRETATION

Based on cost data in Table 10, a material cost savings of $5.28 per circuit board can be projected if testing is done with liquid nitrogen instead of R-12. This would result in payback of a $500 investment after 95 circuit boards have been tested.

For a shop with an existing adequate air supply, the average operating cost savings of $5.26 per board would pay back a $200 air-tool investment after testing 38 circuit boards. The payback period would be extended if additional investment were required to compress and deliver air to the work positions.

Table 11 summarizes investment and payback fgures for each alternative technology.

TABLE 11. INVESTMENT COST AND PAYBACK

Cooling Method	Investment	Payback (circuit boards tested)
Compressed Air	$200	38
Liquid Nitrogen	$500	95

SECTION 8

QUALITY ASSURANCE

LIQUID NITROGEN EVALUATION

This study was performed in accordance with the *Quality Assurance Project Plan for Cold Compressed Air for Electronic Component Cooling Study*, dated August 1991. Although the QAPP was written specifically for evaluation of compressed air, the test plan was written, with concurrence from the Technical Project Manager, to include an evaluation of liquid nitrogen. Data collection procedures were the same for both alternative cooling methods. The results of the liquid nitrogen study indicated that it is a viable alternative, offering both advantages and disadvantages when compared to compressed air and to refrigerant. The Technical Project Manager approved a request from the Battelle Study Leader to include the liquid nitrogen evaluation results in the final report.

Adding the liquid nitrogen evaluation necessitated changes and additions to the Quantitative QA Objectives (QAPP Table 2-1). Table 12 shows the original objectives and changes, as well as objectives related to one additional measurement: Liquid Nitrogen Released. Performance against revised Quantitative QA Objectives is summarized in Table 13 and discussed in this section.

ACCURACY EVALUATION

R-12 Substitution

A change to the QAPP was authorized by the Battelle Study Leader. This change was the substitution of R-12 freeze compound (CFC, dichlorodifluoromethane) for R-22 (HCFC, chlorodifluoromethane) freeze compound for the accuracy evaluations specified in the QAPP. R-12 and R-22 freeze compounds are available under the same Federal Stock Number; R-12 was the compound in stock when the Newark AFB Experiment Coordinator obtained freeze compound from the NAFB supply area. Because R-12 and R-22 freeze compounds generally are used interchangeably, the freeze compound substitution was not expected to affect accuracy evaluation results.

TABLE 12. REVISED QUANTITATIVE QA OBJECTIVES

Parameter	Measurement	Unit of Measure	MDL	Revised MDL	Accuracy	Revised Accuracy	Precision	Revised Precision	Completeness	Revised Completeness
Accuracy	Component Identification Confidence	% confidence	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	18	18
Electrostatic Discharge Risk	Nozzle Electrostatic Charge Buildup	volts	Not applicable	Not applicable	1%	1%	25%	25%	6	8
	Circuit Board Electrostatic Charge Buildup	volts	Not applicable	Not applicable	1%	1%	25%	25%	24	36
Cooling Rate and Absolute Temperature Drop	Cooling Rate	°F/sec	Not applicable	Not applicable	2%	2%	10%	10%	24	36
	Absolute Temperature Drop	°F	Not applicable	Not applicable	2%	2%	10%	10%	24	36
	Compressed Air Pressure	psi	Not applicable	Not applicable	3%	3%	Not applicable	Not applicable	12	12
	Compressed Air Temperature	°F	Not applicable	Not applicable	2%	2%	Not applicable	Not applicable	12	12
	Ambient Temperature	°F	Not applicable	Not applicable	2%	2%	Not applicable	Not applicable	24	24
Safety	Sound Level	dBA	Not applicable	Not applicable	± 2 dBA	± 2 dBA	10%	10%	30	30
Pollution Prevention Potential	CFC Released	grams	Not applicable	Not applicable	1%	1%	Not applicable	Not applicable	18	18
Estimate of Economics	Compressed Air Release Time	min/sec	Not applicable	Not applicable	5%	5%	Not applicable	Not applicable	18	18
	Liquid Nitrogen Released	grams		Not applicable		1%		Not applicable		18
	Compressed Air Pressure	psi	Not applicable	Not applicable	3%	3%	Not applicable	Not applicable	18	18

TABLE 13. PERFORMANCE AGAINST REVISED QUANTITATIVE QA OBJECTIVES

Parameter	Measurement	Unit of Measure	MDL Objective	Revised Accuracy Objective	Actual Accuracy Performance	Revised Precision Objective	Actual Precision Performance	Revised Completeness Objective	Actual Completeness Performance
Accuracy	Component Identification Confidence	% confidence	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	18	13
Electrostatic Discharge Risk	Nozzle Electrostatic Charge Buildup	volts	Not applicable	1%	2%	25%	Refer to Table 14	8	8
	Circuit Board Electrostatic Charge Buildup	volts	Not applicable	1%	2%	25%	Refer to Table 15	36	36
Cooling Rate and Absolute Temperature Drop	Cooling Rate	°F/sec	Not applicable	Refer to Table 17	2%	10%	Refer to Table 16	36	36
	Absolute Temperature Drop	°F	Not applicable	Refer to Table 19	2%	10%	Refer to Table 18	36	36
	Compressed Air Pressure	psi	Not applicable	3%	2%	Not applicable	Not applicable	12	12
	Compressed Air Temperature	°F	Not applicable	2%	See page 76	Not applicable	Not applicable	12	12
	Ambient Temperature	°F	Not applicable	2%	3.21%	Not applicable	Not applicable	24	24
Safety	Sound Level	dBA	Not applicable	±2 dBA	±1.5 dBA @ 1000 Hz	10%	See page 82	30	1
Pollution Prevention Potential	CFC Released	grams	Not applicable	1%	0.01 gram	Not applicable	Not applicable	18	13
Estimate of Economics	Compressed Air Release Time	min/sec	Not applicable	5%	5%	Not applicable	Not applicable	18	13
	Liquid Nitrogen Released	grams	Not applicable	1%	0.01 gram	Not applicable	Not applicable	18	13
	Compressed Air Pressure	psi	Not applicable	2%	3.00%	Not applicable	Not applicable	18	13

Completeness

The objective of the accuracy evaluation was to compare the effectiveness of the three cooling methods. The site for the evaluation was selected because the systems tested there contained a variety of circuit boards that, it was hoped, would provide a variety of test articles during the test period. Variety in the test articles would have allowed investigation of the possible effects of circuit board characteristics on cooling method effectiveness. At the end of the test period, however, the hoped-for variety had not occurred.

A total of 17 circuit boards with thermally intermittent failure modes were identified by test sets during the five-month test period. Of these circuit boards, only 13 were determined to have failure modes that could be tested using the three component cooling methods. Of the 13 test articles, 11 had high component density and component variety; one board (Sample #6) was of low density and one board (Sample #9) was of low variety. Six of the 13 test articles were the same model circuit board, an FMC Tank Processing Unit.

The impact of the actual quantity and variety of test articles was that conclusions would be more applicable for potential users who test similar high-component-density/high-component-variety circuit boards. Without samples of low-component-density or low-component-variety, it was not possible to determine how accuracy of alternative cooling materials might change with varying circuit board attributes.

ELECTROSTATIC DISCHARGE RISK EVALUATION

R-12 Substitution

R-22 freeze compound was not available through the base supply during the study period (see page 63). The Battelle Study Leader authorized the substitution of R-12 freeze compound for both nozzle and circuit board tests because the two compounds generally are used interchangeably.

Test Location and Nozzle Test Meter Change

The test location for measurement of electrostatic charge buildup on both nozzles and circuit boards was changed from the Newark AFB Electrostatic Discharge (ESD) Laboratory to the Carousel Shop. The change was authorized by the Battelle Study Leader because the compressed air supply in the ESD Lab could not provide the 90 psi specified for air-tool operation during tests.

As a result of the location change, the nozzle electrostatic charge buildup measurements could not be made with the Ion Systems monitor specified in the QAPP because the monitor was not portable.

The consensus of Newark AFB and Battelle staff was that a Monroe Electronics meter could be substituted if the component cooling tools were held so that dispensing nozzles were parallel to the meter platen. Charge buildup on the platen was measured as the cooling material (R-12, nitrogen, or cold air) was released. The Battelle Study Leader authorized the test meter substitution.

Nozzle Electrostatic Charge Buildup: Completeness

The completion of two measurements each for three cooling methods (R-12 aerosol with a steel nozzle, R-12 aerosol with a plastic nozzle, and compressed air) resulted in a completeness parameter of 100%. The additional testing of liquid nitrogen increased the number of measurements by two.

Nozzle Electrostatic Charge Buildup: Precision

The QAPP required a quantitative objective for measurement precision for electrostatic charge buildup. To satisfy this requirement, each measurement was repeated one time and a precision measure, RPD, was calculated using the following formula:

$$\text{Precision} = \text{RPD} = \frac{(A-B) \times 100\%}{(A+B)/2}$$

where A, B = Results from repeated tests.

Precision calculations for nozzle tests are included in Table 14.

No potential user-driver precision limit was identified during the study. Due to budget constraints, no preliminary testing was performed to gain experience with the precision capability of the measurement method. The QAPP objective for measurement precision, 25%, was based solely on the knowledge that electrostatic charge measurements were sensitive to many factors. Measurements were actually more sensitive than expected as evidenced by the calculations in Table 14. The measurement precision experienced does not indicate problems with measurement method but rather indicates that the electrostatic charge buildup is highly variable. This variability was caused by manual positioning of the cooling material dispenser. Because manual positioning of dispensers would be used in production, the variability experienced during the evaluations would occur in production also. Nozzle electrostatic charge buildup results would be directly applicable to all potential users.

TABLE 14. ELECTROSTATIC CHARGE BUILDUP — MEASUREMENT PRECISION FOR NOZZLE TESTS

Electrostatic Charge Buildup (volts)	Aerosol R-12 w/Plastic Nozzle	Aerosol R-12 w/Steel Nozzle	Compressed Air Tool	Liquid Nitrogen
Test 1	376	10	2	3
Test 2	1445	13	3	3
Measurement Precision (%)	117.4	26.1	40.0	0.0

Nozzle Electrostatic Charge Buildup: Accuracy

Because no potential user-driver accuracy objective was identified during the study, the QAPP objective was based on using measuring equipment typically found in testing laboratories such as that at Newark AFB. Preliminary information indicated that both the Ion Systems Model 200* and the Monroe Electronics Model 175* measurement devices provide measurement accuracy of ±1%. According to the manufacturer's specifications, the Monroe Electronics meter used for the nozzle electrostatic charge buildup evaluations (see discussion page 67) actually provides accuracy of 2% of full-scale measurement ±1 digit. The measurement accuracy of the Monroe Electronics meter should be acceptable to potential users of alternative cooling methods.

Circuit Board Electrostatic Charge Buildup: Steel Aerosol Nozzle Evaluation

Additional data were collected during the circuit board tests to confirm earlier Newark AFB tests, which had indicated that steel nozzles used with R-12 aerosol cans reduced electrostatic charge buildup when compared to plastic nozzles provided with the aerosol cans. The Battelle Study Leader authorized the additional data collection.

* Mention of trade names and products does not constitute endorsement for use.

Circuit Board Electrostatic Charge Buildup: Completeness

The completion of two measurements each for six circuit boards with R-12 and compressed-air cooling methods resulted in a completeness parameter of 100%. The additional testing of liquid nitrogen and R-12 with steel aerosol nozzles required an additional 24 measurements. The additional testing was suggested by the Battelle Technician and authorized by the Battelle Study Leader.

Circuit Board Electrostatic Charge Buildup: Precision

The QAPP required a quantitative objective for measurement precision for electrostatic charge buildup. To satisfy this requirement, each measurement was repeated one time and a precision measure, RPD, was calculated using the following formula:

$$\text{Precision} = \text{RPD} = \frac{(A-B) \times 100\%}{(A+B)/2}$$

where A, B = Results from repeated tests.

Precision calculations for nozzle tests are included in Table 15.

No potential user-driven precision limit was identified during the study. Due to budget constraints, preliminary testing to gain experience with the precision capability of the measurement method was not performed. The QAPP objective for measurement precision, 25%, was based solely on the knowledge that electrostatic charge measurements were sensitive to many factors. Measurements were actually more sensitive than expected, as evidenced by the calculations in Table 15. The measurement precision experienced does not indicate problems with measurement method but rather indicates that the electrostatic charge buildup is highly variable. This variability is caused by manual positioning of the cooling material dispenser. Because manual positioning of the dispensers would be used in production, the variability experienced during the evaluations would occur also in production. Nozzle electrostatic charge buildup results would be directly applicable to all potential users.

Circuit Board Electrostatic Charge Buildup: Accuracy

No potential user-driven accuracy objective was identified during the study. Therefore, the QAPP objective was based on using measuring equipment typically found in testing laboratories such as the one at Newark AFB. Preliminary information indicated that the Monroe Electronics Model 175 measurement device provided measurement accuracy of ±1%. The manufacturer's specifications for

TABLE 15. ELECTROSTATIC CHARGE BUILDUP — MEASUREMENT PRECISION FOR CIRCUIT BOARD TESTS

Electrostatic Charge Buildup (volts)		Aerosol R-12 w/Plastic Nozzle	Aerosol R-12 w/Steel Nozzle	Compressed Air Tool	Liquid Nitrogen
Test Board #1	Test 1	-251	623	-58	152
	Test 2	-341	110	-63	205
	Measurement Precision (%)	30.4	140.0	8.3	29.7
Test Board #2	Test 1	158	443	-1	28
	Test 2	1250	102	0	26
	Measurement Precision (%)	155.1	125.1	200.0	7.4
Test Board #3	Test 1	-411	-666	-6	133
	Test 2	162	-1380	-16	45
	Measurement Precision (%)	86.9	69.8	90.9	98.9
Test Board #4	Test 1	-1366	-900	-80	92
	Test 2	-1100	-470	-69	25
	Measurement Precision (%)	21.6	62.8	14.8	114.5
Test Board #5	Test 1	-143	-139	-80	300
	Test 2	-907	-165	-174	254
	Measurement Precision (%)	145.5	17.1	74.0	16.6
Test Board #6	Test 1	-138	-40	-45	174
	Test 2	-63	-19	-50	247
	Measurement Precision (%)	74.6	71.2	10.5	34.7

the Monroe Electronics meter used for the electrostatic charge buildup evaluations actually provides accuracy of 2% of full-scale measurement ± 1 digit. The measurement accuracy of the Monroe Electronics meter should be acceptable to potential users of alternative cooling methods.

COOLING RATE AND ABSOLUTE TEMPERATURE DROP EVALUATION

Unit of Measure Change

The QAPP (Table 2-1) specified all temperature measurements in Fahrenheit. This objective was not incorporated into the test plan, and staff performing the temperature measurements set the data logger to measure in degrees Celsius. Conversion of data could have been performed to comply with the QAPP, but another step would have been added to the trail from time/temperature plots to the final report data. The Battelle Study Leader approved the use of degrees Celsius as the unit of measure because it is interchangeable with Fahrenheit and because it avoids a conversion step.

R-12 Substitution

As described on page 63, only R-12 freeze compound was available at Newark AFB at the time of the cooling rate and absolute temperature drop experiments. Although R-22 is expected to cool components to lower temperatures than R-12, both materials are used commonly and are generally interchangeable. The substitution of R-12 for R-22 in the cooling rate and absolute temperature drop evaluations was authorized by the Battelle Study Leader.

Data Acquisition Methodology Description

Absolute temperature drop and cooling rates are determined from thermocouple time/temperature plots recorded by a four-channel data logger connected to thermocouples. Elapsed time was obtained by dividing the distance measured on the data logger strip chart by the feedrate of the log paper. A template with 1 second demarcations was used to obtain measurements. Elapsed times were determined for each thermocouple at 10°C intervals beginning at 20°C and descending until stabilization occurred at a minimum temperature. Elapsed times were measured from the initial dropoff of the target component temperature and were rounded to the nearest half second. During recording, the data logger was set so that the physical pen offsets were not reflected in the line plots. Temperature levels were read at the demarcation lines for 10°C increments; starting and minimum temperature levels were rounded to the nearest half degree.

Cooling Rate: Completeness

Twelve evaluations each were performed for the R-12 and for the compressed-air cooling methods, resulting in a completeness measure of 100%. An additional 12 evaluations of liquid nitrogen were performed, for a total of 36 evaluations.

Cooling Rate: Precision

The QAPP required a quantitative objective for cooling rate measurement precision. To satisfy this objective, each measurement was repeated once, and a precision measure, RPD, was calculated using the following formula:

$$\text{Precision} = \text{RPD} = \frac{(A-B) \times 100\%}{(A+B)/2}$$

where A, B = Results from repeated tests.

Precision calculations for cooling rates were included in Table 16. Cooling rates were calculated for the first half of the temperature drop range.. A temperature of −20°C was used as the minimum for R-12, −70°C for liquid nitrogen, and 0°C for compressed air (except in wound-film capacitor tests A-6-1 and A-6-2, where 10°C was used). The ranges were selected by the Battelle Study Leader because they are expected to be the area of most concern to potential users of the alternative cooling methods.

No potential user-driven objectives for precision were identified during the study, nor was preliminary testing performed to gain experience with the precision capability of the measurement method. The QAPP objective, 10%, was established solely on the knowledge that the compressed-air cooling method would be sensitive to application distance and direction. The data in Table 16 indicate that precision exceeded the objective in 11 of 18 evaluations.

The precision of the cooling rate measurements does not indicate problems with the measurement method, but rather it indicates that cooling rate was more sensitive to application distance and direction than expected. This was particularly true for the compressed air evaluations where the precision objectives were greatly exceeded in five of six evaluations. Because the variability of cooling rates was caused by manual positioning of the cooling material dispensers during material release and because the same positioning method is used in production, potential users of alternative cooling methods could expect comparable variability.

TABLE 16. RATE OF COOLING — MEASUREMENT PRECISION

Test	Start Temp (°C)	End Temp (°C)	Delta Temp (°C)	Elapsed Time (sec)	Cooling Rate (°C/sec)	Precision (%)
ICH31	24.5	-20.0	44.5	6.5	6.8	
ICH32	22.5	-20.0	42.5	6.0	7.1	4.3
ICH61	21.5	-20.0	41.5	1.5	27.7	
ICH62	22.0	-20.0	42.0	1.5	28.0	1.1
ICH91	21.0	-20.0	41.0	2.5	16.4	
ICH92	21.5	-20.0	41.5	4.0	10.4	44.8
ICN31	20.0	-70.0	90.0	25.5	3.5	
ICN32	21.0	-70.0	91.0	29.0	3.1	12.1
ICN61	23.0	-70.0	93.0	20.5	4.5	
ICN62	21.0	-70.0	91.0	20.5	4.4	2.2
ICN91	21.0	-70.0	91.0	25.5	3.6	
ICN92	25.0	-70.0	95.0	23.5	4.0	10.5
ICA31	19.0	0.0	19.0	5.5	3.5	
ICA32	21.0	0.0	21.0	3.0	7.0	66.7
ICA61	20.5	0.0	20.5	21.0	1.0	
ICA62	20.5	0.0	20.5	12.0	1.7	51.9
ICA91	23.0	0.0	23.0	21.0	1.1	
ICA92	19.0	0.0	19.0	12.0	1.6	37.0
CAPH31	24.5	-20.0	44.5	11.5	3.9	
CAPH32	20.5	-20.0	40.5	11.5	3.5	10.8
CAPH61	21.0	-20.0	41.0	11.5	3.6	
CAPH62	20.5	-20.0	40.5	11.5	3.5	2.8
CAPH91	20.0	-20.0	40.0	14.0	2.9	
CAPH92	22.0	-20.0	42.0	14.0	3.0	3.4
CAPN31	23.0	-70.0	93.0	24.5	3.8	
CAPN32	22.0	-70.0	92.0	27.0	3.4	11.1
CAPN61	20.0	-70.0	90.0	53.0	1.7	
CAPN62	19.0	-70.0	89.0	45.0	2.0	16.2
CAPN91	20.0	-70.0	90.0	25.5	3.5	
CAPN92	21.0	-70.0	91.0	27.5	3.3	5.9
CAPA31	20.5	0.0	20.5	22.0	0.9	
CAPA32	21.0	0.0	21.0	18.5	1.1	20.0
CAPA61	21.0	10.0	11.0	36.5	0.3	
CAPA62	21.0	10.0	11.0	16.0	0.7	80.0
CAPA91	21.0	0.0	21.0	20.5	1.0	
CAPA92	24.5	0.0	24.5	25.0	1.0	0.0

Cooling Rate: Accuracy

The data logger and type K thermocouples provided a calculated worst-case error of ±3.21°C at 20°C and ±4.59°C at −175°C (based on manufacturer data). Temperature measurement accuracy varies with temperature. Additional error can be introduced also by the method used to read temperature levels from the data chart or by chart paper alignment in the data logger. Because temperature levels for 10°C increments were read from chart demarcation lines, error should be negligible. Starting temperatures and minimum temperature levels that fell between chart demarcation lines were rounded to the nearest half degree. After chart paper loading, paper alignment was checked using the data logger routines; because pens stopped at the extreme chart ends, error from paper alignment can be ignored.

The accuracy of elapsed time data is determined by the accuracy of the chart feed and the accuracy of the measurement tool and method used to measure elapsed times data. Elapsed times were determined by measuring the distance from the beginning of cooling, using a template with 1-second demarcation lines; elapsed times were rounded to the nearest half second. Chart feed accuracy is specified at ±0.1% for recordings over 1 meter. Accuracy for recordings of less than 1 meter in length, which includes all recordings made during this experiment, is not specified but is presumably worse due to feed motor start characteristics. It is reasonable to expect that worst-case error of ±0.5 second for elapsed time data covers the combined error of chart feed and measurement error.

Cooling rate accuracy calculations are summarized in Table 17. The lower limit (slowest cooling rate) was calculated using the greatest temperature drop (start temperature at upper limit and end temperature at the lower limit) and the shortest elapsed time. The upper limit (fastest cooling rate) was calculated using the smallest temperature change and the longest elapsed time. Accuracy was expressed as a percentage of the calculated cooling rate by dividing the absolute difference between the calculated limit and the calculated cooling rate. The calculated accuracies represent the absolute worst case conditions.

No potential user-driven accuracy objectives were identified during the study. The QAPP accuracy objective was based solely on the 2% temperature measurement accuracy expected from the data logger and thermocouple. Calculated accuracies exceed the maximum accuracy objective because the temperature measurement accuracy actually was worse than anticipated and because accuracy of elapsed time measurement was included.

Although the cooling rate accuracy objectives were not met under worst case cooling conditions, conclusions that would be meaningful to potential users could still be made. Because all measurements were made using the same data logger on the same day and only two target component thermocouples were used (one for capacities and one for integrated circuits), the measurement accuracy should be much greater than worst case calculations indicate. Given these measurement conditions, comparisons based on cooling rates of alternative cooling methods should be acceptable to potential users.

TABLE 17. RATE OF COOLING — MEASUREMENT ACCURACY

Test	Start Temp (°C)	End Temp (°C)	Delta Temp (°C)	Elapsed Time (sec)	Cooling Rate (°C/sec)	Start Minimum	Start Maximum	End Minimum	End Maximum	Elapsed Time Minimum	Elapsed Time Maximum	Minimum Rate Limit	Lower Accuracy (%)	Maximum Rate Limit	Upper Accuracy (%)
ICH31	24.5	-20.0	44.5	6.5	6.8	21.3	27.7	-16.8	-23.2	6	7	5.4	20.5	8.5	23.9
ICH32	22.5	-20.0	42.5	6.0	7.1	19.3	25.7	-16.8	-23.2	5.5	6.5	5.6	21.6	8.9	25.5
ICH61	21.5	-20.0	41.5	1.5	27.7	18.3	24.7	-16.8	-23.2	1	2	17.5	36.6	47.9	73.1
ICH62	22.0	-20.0	42.0	1.5	28.0	18.8	25.2	-16.8	-23.2	1	2	17.8	36.4	48.4	72.9
ICH91	21.0	-20.0	41.0	2.5	16.4	17.8	24.2	-16.8	-23.2	2	3	11.5	29.7	23.7	44.5
ICH92	21.5	-20.0	41.5	4.0	10.4	18.3	24.7	-16.8	-23.2	3.5	4.5	7.8	24.8	13.7	31.9
ICN31	20.0	-70.0	90.0	25.5	3.5	16.8	23.2	-66.8	-73.2	25	26	3.2	8.9	3.9	9.2
ICN32	21.0	-70.0	91.0	29.0	3.1	17.8	24.2	-66.8	-73.2	28.5	29.5	2.9	8.6	3.4	8.9
ICN61	23.0	-70.0	93.0	20.5	4.5	19.8	26.2	-66.8	-73.2	20	21	4.1	9.1	5.0	9.5
ICN62	21.0	-70.0	91.0	20.5	4.4	17.8	24.2	-66.8	-73.2	20	21	4.0	9.2	4.9	9.7
ICN91	21.0	-70.0	91.0	25.5	3.6	17.8	24.2	-66.8	-73.2	25	26	3.3	8.8	3.9	9.1
ICN92	25.0	-70.0	95.0	23.5	4.0	21.8	28.2	-66.8	-73.2	23	24	3.7	8.7	4.4	9.0
ICA31	19.0	0.0	19.0	5.5	3.5	15.8	22.2	3.2	-3.2	5	6	2.1	39.3	5.1	47.1
ICA32	21.0	0.0	21.0	3.0	7.0	17.8	24.2	3.2	-3.2	2.5	3.5	4.2	40.5	11.0	56.6
ICA61	20.5	0.0	20.5	21.0	1.0	17.3	23.7	3.2	-3.2	20.5	21.5	0.7	32.9	1.3	34.5
ICA62	20.5	0.0	20.5	12.0	1.7	17.3	23.7	3.2	-3.2	11.5	12.5	1.1	34.0	2.3	37.0
ICA91	23.0	0.0	23.0	21.0	1.1	19.8	26.2	3.2	-3.2	20.5	21.5	0.8	29.6	1.4	31.0
ICA92	19.0	0.0	19.0	12.0	1.6	15.8	22.2	3.2	-3.2	11.5	12.5	1.0	36.4	2.2	39.5

TABLE 17. (CONTINUED)

Test	Start Temp (°C)	End Temp (°C)	Delta Temp (°C)	Elapsed Time (sec)	Cooling Rate (°C/sec)	Start Minimum	Start Maximum	End Minimum	End Maximum	Elapsed Time Minimum	Elapsed Time Maximum	Minimum Rate Limit	Lower Accuracy (%)	Maximum Rate Limit	Upper Accuracy (%)
CAPH31	24.5	-20.0	44.5	11.5	3.9	21.3	27.7	-16.8	-23.2	11	12	3.2	18.0	4.6	19.6
CAPH32	20.5	-20.0	40.5	11.5	3.5	17.3	23.7	-16.8	-23.2	11	12	2.8	19.3	4.3	21.1
CAPH61	21.0	-20.0	41.0	11.5	3.6	17.8	24.2	-16.8	-23.2	11	12	2.9	19.1	4.3	20.9
CAPH62	20.5	-20.0	40.5	11.5	3.5	17.3	23.7	-16.8	-23.2	11	12	2.8	19.3	4.3	21.1
CAPH91	20.0	-20.0	40.0	14.0	2.9	16.8	23.2	-16.8	-23.2	13.5	14.5	2.3	18.9	3.4	20.3
CAPH92	22.0	-20.0	42.0	14.0	3.0	18.8	25.2	-16.8	-23.2	13.5	14.5	2.5	18.2	3.6	19.5
CAPN31	23.0	-70.0	93.0	24.5	3.8	19.8	26.2	-66.8	-73.2	24	25	3.5	8.7	4.1	9.1
CAPN32	22.0	-70.0	92.0	27.0	3.4	18.8	25.2	-66.8	-73.2	26.5	27.5	3.1	8.6	3.7	8.9
CAPN61	20.0	-70.0	90.0	53.0	1.7	16.8	23.2	-66.8	-73.2	52.5	53.5	1.6	8.0	1.8	8.1
CAPN62	19.0	-70.0	89.0	45.0	2.0	15.8	22.2	-66.8	-73.2	44.5	45.5	1.8	8.2	2.1	8.4
CAPN91	20.0	-70.0	90.0	25.5	3.5	16.8	23.2	-66.8	-73.2	25	26	3.2	8.9	3.9	9.2
CAPN92	21.0	-70.0	91.0	27.5	3.3	17.8	24.2	-66.8	-73.2	27	28	3.0	8.7	3.6	9.0
CAPA31	20.5	0.0	20.5	22.0	0.9	17.3	23.7	3.2	-3.2	21.5	22.5	0.6	32.8	1.3	34.3
CAPA32	21.0	0.0	21.0	18.5	1.1	17.8	24.2	3.2	-3.2	18	19	0.8	32.4	1.5	34.2
CAPA61	21.0	10.0	11.0	36.5	0.3	17.8	24.2	13.2	6.8	36	37	0.1	58.9	0.5	60.5
CAPA62	21.0	10.0	11.0	16.0	0.7	17.8	24.2	13.2	6.8	15.5	16.5	0.3	59.6	1.1	63.4
CAPA91	21.0	0.0	21.0	20.5	1.0	17.8	24.2	3.2	-3.2	20	21	0.7	32.2	1.4	33.8
CAPA92	24.5	0.0	24.5	25.0	1.0	21.3	27.7	3.2	-3.2	24.5	25.5	0.7	27.6	1.3	28.7

Absolute Temperature Drop: Completeness

Twelve evaluations were performed for both the R-12 and the compressed-air cooling methods; therefore, absolute temperature drop parameter completeness was 100%. An additional 12 evaluations of liquid nitrogen were performed, for a total of 36. Of the twelve, temperature of the thermocouple fell below the minimum measurable temperature of −175°C.

Absolute Temperature Drop: Precision

The QAPP required a quantitative objective for cooling rate measurement precision. To satisfy this objective, each measurement was repeated once and a precision measure, RPD, was calculated using the following formula:

$$\text{Precision} = \text{RPD} = \frac{(A - B) \times 100\%}{(A + B)/2}$$

where A, B = Results from repeated tests.

Precision calculations for absolute temperature drop are included in Table 18. No potential user-driven objectives for precision were identified during the study. Due to budget constraints, preliminary testing to gain experience with the precision capability of the measurement method was not performed. The QAPP objective, 10%, was established solely on the knowledge that the compressed-air cooling method would be sensitive to application distance and direction. The data in Table 18 indicate that precision exceeded the objective in 7 of 16 evaluations.

The precision of the cooling rate measurements does not indicate problems with the measurement method but does indicate that cooling rate was more sensitive to application distance and direction than expected. This was particularly true for the five of six compressed air evaluations in which the precision objectives were greatly exceeded. The variability of cooling rates was caused by manual positioning of the cooling material dispensers during material release. Because the same positioning method is used in production, potential users of alternative cooling methods could expect similar variability in cooling rates.

TABLE 18. ABSOLUTE TEMPERATURE DROP — MEASUREMENT PRECISION

Test	Target Component: Minimum Temperature (°C)	Target Component: Precision (%)	Exposed Thermocouple: Minimum Temperature (°C)	Exposed Thermocouple: Precision (%)
ICH31	-45.0		-54.5	
ICH32	-50.0	10.5	-58.0	6.2
ICH61	-53.0		-55.0	
ICH62	-54.0	1.9	-55.0	0.0
ICH91	-51.0		-58.0	
ICH92	-55.0	7.5	-55.0	5.3
ICN31	-175.0		-175.0	
ICN32	-175.0	**	*	**
ICN61	-134.0		*	
ICN62	-151.0	11.9	*	**
ICN91	-175.0		*	
ICN92	-175.0	**	*	**
ICA31	-27.5		-35.5	
ICA32	-28.5	3.6	-34.5	2.9
ICA61	-6.0		-12.0	
ICA62	-7.0	15.4	-18.5	42.6
ICA91	-18.5		-36.0	
ICA92	-16.5	11.4	-35.5	1.4
CAPH31	-53.5		-59.5	
CAPH32	-53.0	0.9	-59.0	0.8
CAPH61	-57.5		-55.5	
CAPH62	-55.0	4.4	-55.0	0.9
CAPH91	-52.5		-57.5	
CAPH92	-51.5	1.9	-57.0	0.9
CAPN31	-134.0		-175.0	
CAPN32	-139.0	3.7	-175.0	**
CAPN61	-101.0		*	
CAPN62	-105.0	3.9	*	**
CAPN91	-150.0		*	
CAPN92	-152.0	1.3	*	**
CAPA31	-11.5		-35.0	
CAPA32	-14.0	19.6	-35.0	0.0
CAPA61	6.0		-22.0	
CAPA62	1.0	142.9	-14.0	44.4
CAPA91	-12.0		-35.0	
CAPA92	-14.0	15.4	-35.0	0.0

* Measurement not taken. Assumed to be −175°C.
** Precision not calculated — no measurement data or measurement method at minimum limit of −175°C.

Absolute Temperature Drop: Accuracy

Absolute temperature drop accuracies for each evaluation are summarized in Table 19. Measurement accuracy calculations are based on the additive (worst case) accuracy of the data logger and the type K thermocouple. Accuracy of both components of the measurement system are stated in terms of the measured temperature.

No potential user-driven accuracy objective for absolute temperature drop measurement was identified during the study. The QAPP accuracy objective of 2% was established based on planned use of

TABLE 19. ABSOLUTE TEMPERATURE DROP — MEASUREMENT ACCURACY

Test	Target Component Min. Temp. (°C)	Measurement Accuracy (%)	Exposed Thermocouple Min. Temp. (°C)	Measurement Accuracy (%)
ICH31	-45.0	7.2	-54.5	5.9
ICH32	-50.0	6.5	-58.0	5.6
ICH61	-53.0	6.1	-55.0	5.9
ICH62	-54.0	6.0	-55.0	5.9
ICH91	-51.0	6.3	-58.0	5.6
ICH92	-55.0	5.9	-55.0	5.9
ICN31	-175.0	2.6	-175.0	2.6
ICN32	-175.0	2.6	*	**
ICN61	-134.0	2.8	*	
ICN62	-151.0	2.7	*	**
ICN91	-175.0	2.6	*	
ICN92	-175.0	2.6	*	**
ICA31	-27.5	11.7	-35.5	9.1
ICA32	-28.5	11.3	-34.5	9.3
ICA61	-6.0	53.4	-12.0	26.7
ICA62	-7.0	45.8	-18.5	17.3
ICA91	-18.5	17.3	-36.0	8.9
ICA92	-16.5	19.4	-35.5	9.1
CAPH31	-53.5	6.0	-59.5	5.4
CAPH32	-53.0	6.1	-59.0	5.5
CAPH61	-57.5	5.6	-55.5	5.8
CAPH62	-55.0	5.9	-55.0	5.9
CAPH91	-52.5	6.1	-57.5	5.6
CAPH92	-51.5	6.3	-57.0	5.7
CAPN31	-134.0	2.8	-175.0	2.6
CAPN32	-139.0	2.8	-175.0	2.6
CAPN61	-101.0	3.0	*	
CAPN62	-105.0	3.0	*	**
CAPN91	-150.0	2.7	*	
CAPN92	-152.0	2.7	*	**
CAPA31	-11.5	27.9	-35.0	9.2
CAPA32	-14.0	22.9	-35.0	9.2
CAPA61	6.0	53.4	-22.0	14.6
CAPA62	1.0	320.1	-14.0	22.9
CAPA91	-12.0	26.7	-35.0	9.2
CAPA92	-14.0	22.9	-35.0	9.2

* Measurement not taken. Assumed to be −175°C

** Accuracy not calculated — no measurement data or measurement method at minimum limit of −175°C.

the data logger only. The accuracy of the type K thermocouple erroneously was not included. The accuracy provided by the temperature measurement system should be acceptable to potential users of alternative cooling methods because the same data logger was used for all measurements and the same thermocouples were used for capacitor and wound-film measurements (target component and exposed).

Compressed-Air Pressure: Completeness

All twelve planned measurements were taken; completeness of the parameter was 100%.

Compressed-Air Pressure: Accuracy

Air pressure was regulated so that the pressure at the work position gauge read 100 psi. The pressure gauge used provides an accuracy of ±2%, which is within the QAPP objective of ±3%. The gauge accuracy of ±2% is valid in the range from 40 to 120 psi.

Compressed-Air Temperature: Measurement Method Change

The QAPP specified that the exposed thermocouple would be used to measure the temperature of compressed air as it is released with a blowoff tool. Temperatures obtained using this measurement method are not representative of the temperature of the air before release. The compressed air used for the experiment includes an air chilling system to cool air as it is delivered from the compressor to the storage tank. The chiller reduces the temperature of the air to approximately 80°F. When the compressed air arrived at the air tool, it was assumed to be at or slightly above shop ambient temperature. This assumption is supported by the fact that temperatures achieved when cooling exposed thermocouples with compressed air are very close to advertised cooling capability; if the compressed air was significantly above ambient temperature, minimum thermocouple temperature would have been warmer as well.

Compressed-Air Temperature: Completeness and Accuracy

A method for measuring compressed-air temperature at the air tool was not available during the study; completeness of the parameter was 0%. Accuracy for the parameter is no longer applicable; compressed-air temperature was known to be close to the ambient shop temperature of approximately 20°C.

Ambient Air Temperature: Completeness

All 24 planned measurements were taken. Completeness of the parameter was 100%.

Ambient Air Temperature: Accuracy

Ambient air temperature was obtained using the data logger and the exposed thermocouple. As discussed in the accuracy discussion for absolute temperature drop, the QAPP accuracy objective of 2% was based on using the data logger and the effect of the type K thermocouple accuracy was omitted erroneously. At 20°C, the accuracy of the measurement system is calculated at 3.21%, assuming worst-case condition with the accuracy of both data logger and thermocouple added together.

TECHNICIAN SAFETY EVALUATION

Sound-Level Measurement Procedure Change

The QAPP specified an extensive test plan for evaluating sound levels during compressed-air tool operation. Before Newark AFB technicians were permitted to operate the compressed-air tool, Base bioenvironmental engineering personnel performed an evaluation that included sound-level measurement. TSgt Earl Matthews performed the measurement, following Air Force procedures, and determined that the sound levels were well below the threshold of 84 dBA, where more extensive measurements would be necessary to characterize operator exposure hazards. The Battelle Study Leader cancelled the extensive testing specified in the QAPP because it would add unneeded cost to the study while providing unneeded information. The measurement equipment and measurement techniques, and therefore the sound-level measurement data, should be acceptable to potential users of the compressed-air tools.

Sound Level: Accuracy

TSgt Matthews performed the measurements using a General Radio 1565B Sound-Level Meter* The meter was calibrated immediately before use with a General Radio 1562 Sound-Level Calibrator, which was calibrated on February 6, 1992. The calibrator provide measurement accuracy ±0.3 dB at 500 Hz and ±0.5 dB at other frequencies. The instructions for calibrating the sound-level meter are to ensure meter measurement is within 0.5 dB of the calibrator at 500 Hz, within 1.0 dB at 125, 250, and 1000 Hz, and within 2.0 dB at 2000 Hz. It is not necessary to convert available instrument accuracy information to a dBA error for comparison to the QAPP objective of ±2% dBA because the equipment used is standard for sound-level measurements and the accuracy is sufficient for potential users of this study.

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* Mention of trade names and products does not constitute endorsement for use.

Sound Level: Precision and Completeness

Following Air Force sound-level measurement procedures, TSgt Matthews measured sound levels at the work position during air tool operation. During a period of approximately 10 seconds, the peak sound level observed was 81 dBA. Because, as discussed above, the recorded sound level was below a threshold of 84 dBA, the extensive testing specified in the QAPP was not performed and the precision and completeness objectives no longer were applicable.

POLLUTION PREVENTION POTENTIAL

R-12 Substitution

As described on page 63, R-12 was used instead of the R-22 specified in the QAPP. With respect to the amount of cooling material used in circuit board evaluations, any difference between R-12 and R-22 is expected to be insignificant.

CFC Released: Completeness

As described on page 66, the 13 test articles evaluated represent a completeness of 72.2%. The impact of the actual quantity and variety of test articles on the Pollution Prevention Potential evaluation was similar to the impact on the accuracy evaluation.

CFC Released: Accuracy

The scale used to weigh aerosol cans of R-12 during accuracy circuit board evaluations was a Mettler PC440 Electronic Top Loading Balance*. For measurements in the range of 450 grams (the weight of a full can of R-12), the tolerance of the scale is 0.01 grams. This level of accuracy is within the QAPP objectives.

* Mention of trade names and products does not constitute endorsement for use.

ESTIMATION OF ECONOMICS

R-12 Substitution

The cooling material use rate differences between R-12 and R-22 are expected to be insignificant, as was discussed on page 66. The government procures both under one stock number at one price. Therefore, cooling material costs for R-12 and R-22 can be considered equivalent.

Compressed-Air Release Time: Completeness

As described on page 66, only 13 compressed-air release time measurements were obtained, representing a completeness measure of 72.2%. The impact of the actual quantity and variety of test articles on the Estimation of Economics evaluation was similar to the impact on the accuracy evaluation.

Compressed-Air Release Time: Accuracy

The stopwatch used to measure release time against a known standard was checked and found to gain 4 seconds per 24-hour period. The sum of stopwatch error and inaccuracy related to nonsimultaneous activation of the stopwatch and the air-tool switch by the operator are assumed to be within the 5% QAPP objective.

Compressed-Air Pressure: Completeness

As described on page 66, only 13 compressed-air release time measurements were obtained, representing a completeness measure of 72.2%. The impact of the actual quantity and variety of test articles on the Estimation of Economics evaluation was similar to the impact on the accuracy evaluation.

Compressed-Air Pressure: Accuracy

Air pressure was set at the pressure regulator so that pressure at the work position gauge read 100 psi. The pressure gauge utilized provides an accuracy of ±2%, which is within the QAPP objective of ±3%. The gauge accuracy of ±2% is valid in the range from 40 to 120 psi. The regulator was a new unit purchased by Newark AFB specifically for this study. It was not calibrated prior to the study, but that should not have affected the study results because the air pressure gauge at the work position was used to measure line pressure at the tool. Air-pressure gauge inaccuracy could affect the cooling characteristics of the air tool and the volume of air consumed during accuracy evaluations. The air-pressure gauge was not calibrated, but the fact that the absolute temperature drop temperatures for the exposed thermocouples (Tables 4, 5, and 6) were consistent with tool specifications indicates that excessive air pressure gauge inaccuracy did not exist during the evaluations.

SECTION 9

DISCUSSION

The objective of this study was to characterize aerosol cans of refrigerant, compressed air and liquid nitrogen as methods for cooling electronic component cooling during testing. Data obtained from testing were used to compare alternative cooling methods in terms of accuracy, electrostatic discharge risk, cooling performance, technician safety hazards, pollution prevention potential, and economics. Conclusions drawn from this study are as follow:

- The compressed-air tool evaluated during the study was unable to cool components to the temperature level that was obtained with either R-12 or liquid nitrogen. However, the results of the accuracy test indicate that during all but one test, temperatures achievable with the compressed-air tool were low enough to reproduce failures.

- Liquid nitrogen has the capability to readily cool components to below −175°C if dispensed closely enough. At such temperatures, components may fail from temporary changes in output signals or fail permanently from physical damage. Two methods to control the temperature of components are to maintain dispensing nozzle distance and to slow the cooling rate of the dispenser by adding heat exchangers or smaller orifices. Both methods rely on a technician to a greater extent than either compressed air or R-12. Further discussion of component temperature control with liquid nitrogen is provided in Appendix A.

- Neither alternative is expected to increase safety risks to technicians when compared to aerosol refrigerants. Noise levels are higher during compressed-air tool operation than with R-12 or liquid nitrogen, but they are not high enough to pose a health hazard to users. Handling of liquid nitrogen presents a safety risk in the form of exposure to low temperatures, but technician training and proper safety procedures and equipment are expected to minimize risk. As with any aerosol, release of refrigerants under pressure presents a safety risk that is controlled through training.

- Replacement of aerosol refrigerant prevents emissions of substances that deplete the stratospheric ozone layer as well as accumulation of empty aerosol cans requiring landfill disposal. With liquid nitrogen, only nitrogen is emitted and refillable bulk containers and dispensers are used. Compressed air generates a small amount of pollution in the forms of waste compressor oil and filter elements; however, the incremental increase in these wastestreams following adoption of the compressed-air method is not expected to be significant.

- Material costs of either alternative are expected to be lower than R-12 or R-22 at current prices. Prices of R-12 and R-22 will undoubtedly escalate. Eventually, these materials will be unavailable due to regulatory prohibition.

- Investment cost to implement liquid nitrogen is expected to consist of the price of dispensing Dewar flasks at approximately $500 each in the half-liter size. Compressed-air tools cost approximately $200 each. The cost of equipment to deliver compressed air that is clean, dry, and near room temperature in the volume and pressure required to achieve maximum cooling capability will depend on existing equipment and the number of tools to be utilized.

- The results of this study led Newark AFB personnel to conclude that either of the cooling methods tested were viable alternatives to aerosol cans of refrigerants, recognizing that control of electronic component temperatures when using liquid nitrogen required resolution.

SECTION 10

DATA REDUCTION

ACCURACY EVALUATION

Component identification confidence measurements were read directly from Accuracy Experiment Data Collection Packages, which were filled out by Newark AFB technicians during test article evaluations.

ELECTROSTATIC DISCHARGE RISK

Nozzle Electrostatic Charge Buildup measurements were transferred directly from data collection sheets to tables in this report. Comparisons of recorded voltage levels for four nozzle/cooling material combinations were made. Precision of repeated measurement was calculated as described on page 67.

Circuit board electrostatic charge buildup measurements were transferred directly from data collection sheers to tables in this report. Comparisons of recorded voltage levels for four nozzle/circuit board combinations and six circuit boards were then made. Precision of repeated measurements was calculated as described on page 69.

COOLING RATE AND ABSOLUTE TEMPERATURE DROP

Cooling rates were calculated from temperature change over time measured as cooling material was dispensed toward thermocouples embedded in target components. Elapsed time was obtained from data logger plots on plotter paper. A clear template demarcated in 0.5 second lines was laid over the plot with the start line (time = 0) located at the time where material release began and the template demarcation lines visually parallel with the time demarcation lines of the plotter paper. The elapsed time then was read from the template by finding the line closest to the point where the data logger plotter brown line crossed the temperature demarcation line on the plotter paper. Cooling rates were calculated by dividing the temperature change by the elapsed time.

Precision of cooling rates for repeated tests were calculated as described on page 72. Accuracy was estimated using worst case conditions. The upper limit of cooling rate was calculated using the longest temperature change (based on temperature measurement accuracy) and the shortest elapsed time (based on temperature measurement accuracy). The lower limit was calculated using the shortest temperature change and the longest elapsed time.

Absolute temperature drop was determined from data logger paper plots. The lowest point that the brown plotter pen traveled represented the lowest temperature reached by the target thermocouple during cooling material release. The temperature reached was determined using the demarcation lines of the plotter paper.

Precision of absolute temperature drop measurement was calculated as described on page 77. Accuracy of absolute temperature measurements was calculated by assuming worst-case conditions and adding the accuracy of the data logger and type K thermocouple. Data logger accuracy was calculated using the following formula:

$$\pm(.0005 \times \text{observed temperature } ^{\circ}\text{C}) + 1\,^{\circ}\text{C}$$

Thermocouple accuracy was calculated using the following formula:

$$\text{maximum of: } \pm 2.2\,^{\circ}\text{C or } .02 \times \text{observed temperature } ^{\circ}\text{C}$$

Figures 21 to 44 in this report were created using the following methodology:

(1) Starting temperatures for each thermocouple were read from the time temperature plots using the plotter paper demarcation lines. Elapsed times for each thermocouple to reach 10°C increments (as cooling materials were dispensed) were determined using the template described earlier in this section. The minimum temperature for each thermocouple was determined using the plotter paper demarcation lines, and elapsed time was determined using the template. All temperature and elapsed time data were recorded on worksheets along with appropriate test information.

(2) Temperature and elapsed time data were entered into a spreadsheet program (Cricket™) and plotted using the spreadsheet capabilities. The plot was then imported into a computer-aided design program (MacDraw™). Test descriptive information was then added and the plots were printed.

No data reduction was required for either the compressed-air pressure or the compressed- air temperature measurements. Ambient temperature measurements were read from data logger plots using the red pen plots, which represented the exposed thermocouples on test boards. Accuracy of the temperature measurements was calculated as described on page 74.

SAFETY

Sound-level measurements were read from the sound-level meter by TSgt Matthews of Newark AFB. The peak value observed was recorded in a letter, a copy of which was provided to the Battelle Study Leader. No data reduction was required.

POLLUTION PREVENTION POTENTIAL

CFC released during the accuracy evaluation of each test article was determined from beginning and ending aerosol can weights recorded by technicians in the Data Collection Packages. Weight in grams was converted to cans using a conversion factor of 328 grams per can. An average use per test article was obtained by dividing the total CFC released during the accuracy evaluation by the number of test articles.

ESTIMATION OF ECONOMICS

Compressed-air release time measurements were recorded by technicians in the Data Collection Packages during the accuracy evaluation. Release time was converted to compressed-air consumption using a factor of 15 scfm. The published specifications of the air tool used are 15 scfm at 100 psi, which was the air pressure used in the accuracy evaluation. Consumed compressed air was converted to cost using an estimate of $0.26 per 1000 scf. This estimate was provided by the air tool manufacturer; it is acknowledged that the cost will vary with geographic location and compressed-air system. An average cost per test article was determined by dividing total compressed-air cost by the number of test articles.

Liquid nitrogen released was determined from start and finish Dewar weights recorded by technicians in the Data Collection Packages for the accuracy evaluation. The weight of the liquid nitrogen was converted to volume using a chemical handbook factor of 814 grams/liter. An estimate of $0.25 per liter was used to convert liters of liquid nitrogen to cost. Liquid nitrogen cost will vary depending on numerous factors. An average cost per test article was determined by dividing total liquid nitrogen cost by the number of test articles.

Compressed-air pressure was recorded in the Data Collection packages during accuracy evaluations of test articles. No data reduction was performed.

APPENDIX A

COMPONENT TEMPERATURE CONTROL: LIQUID NITROGEN

All of the tested cooling methods will achieve a steady component temperature level if held in the same orientation and dispensed for a long enough time. With R-12 and compressed air, the coldest level a component will achieve is near −60°C and −40°C, respectively. However, liquid nitrogen dispensed towards a component eventually will reduce the temperature of the component to near that of liquid nitrogen, possibly degrading component performance temporarily or permanently. The minimum component temperature can be controlled by four techniques described in the following paragraphs.

Holding the nozzle away from the component will warm the stream of material somewhat before it reaches the component. The drawback is that the time required to cool the component to a given temperature level also increases. In the ideal process, the nozzle would be moved away from the component as the temperature of the material stream dropped, thus obtaining fast cooling without exceeding a desired minimum component temperature. It is conceivable that a technician could learn to operate the dispenser in such a manner, but it would remain an imprecise control method.

Limiting the length of time material is released will prevent the valve and nozzle, and therefore the material stream, from exceeding some minimum temperature level. The drawback to this approach is that the technician must control the release times and allow sufficient time between releases for the valve and nozzle to return to ambient temperature.

Orifices can be used to control the rate at which material is released so that the valve and nozzle never exceed a desired steady-state minimum temperature. The drawback to this approach is that the cooling rate is slowed as the volume of material released is reduced. Three orifices supplied by Brymill Corp. were evaluated using the data logger to record temperature levels over time. The integrated circuit test board described on page 11 was used with only the target component connected to the data logger. All tests were performed at an application distance of .25 inch. With the smallest orifice, size C, the minimum target component temperature stabilized at approximately −90°C after a 5-minute release time. Both of the larger orifices, sizes A and B, allowed the target component to achieve the lowest recordable temperature (approximately −140°C) after 1.5 and 2.5 minutes, respectively. When compared to data in Table 4, which show that without a restrictive orifice liquid nitrogen cooled the target component to −175°C in 51 seconds, these results demonstrate that all three orifices reduce the cooling rate.

A heat exchanger can be attached to the nozzle to slow the cooling rate of the liquid nitrogen. Eventually the stream will approach liquid nitrogen temperatures unless an orifice is also used to restrict flow of material. The drawbacks are the same as with the reduced release rate alternative. Two heat exchangers were evaluated using the test method described above. One was the standard unit provided by Brymill, and the other was a standard unit that had been modified by removing approximately half its length. When used with the A, B, or C orifices, the heat exchangers slowed the cooling rate. However, in the case of the A and B sizes, the target component temperature still reached the minimum recordable temperature. The standard heat exchanger slowed the cooling rate more than the modified unit. When the standard heat exchanger was used without an orifice, approximately 90 seconds were required to reduce the target component from the ambient temperature of approximately 20°C to 0°C. Without the heat exchanger, as shown in Figure 30, the elapsed time for a similar temperature reduction was about 5 seconds.

In conclusion, restrictive orifices or a mechanical standoff are the only control methods for liquid nitrogen that can ensure that some desired minimum temperature is not exceeded. With experimentation, an orifice or a standoff could be sized to the minimum temperature required. As noted above, the drawback to these approaches is a slowed cooling rate. All other control techniques will rely on the technician to control the component temperature level using only knowledge of the cooling characteristics of liquid nitrogen with a specific dispenser apparatus and visual cues, such as frost buildup on the dispenser. This may be a viable approach if a heat exchanger is used that slows the cooling rate so that long dispense times are required before unacceptable temperatures are achieved. As with the first two control methods, slowing the cooling rate is a drawback that may reduce the effectiveness of liquid nitrogen as a trouble-shooting tool to identify electronic components with thermally intermittent failure modes.

APPENDIX B

MEASUREMENT PRECISION OBJECTIVES

Measurement precision objectives were established in the QAPP for five parameters:

- Nozzle electrostatic charge buildup
- Circuit board electrostatic charge buildup
- Cooling rate
- Absolute temperature drop
- Sound level

Precision of sound-level data was not calculated because a single measurement was performed (see the discussion on page 82). Measurement precision calculations for the other four parameters are summarized in Tables 14, 15, 16, and 18.

Precision was calculated using the following formula:

$$\text{Precision} = \text{RPD} = \frac{(A-B) \times 100\%}{(A+B)/2}$$

where A, B = measurements from repeated tests.