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Project Summary

Electronic Component Cooling Alternatives: Compressed Air and Liquid Nitrogen

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The goal of this study was to evaluate tools used to troubleshoot electronic circuit boards with known or suspected thermally intermittent failure modes. Aerosol cans of refrigerants, which are commonly used in electronics manufacturing and repair businesses for this purpose, served as the benchmark for the evaluation.

One promising alternative technology 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 comparing 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.

Newark Air Force Base (NAFB), in Ohio, was the site at which compressed-air and liquid-nitrogen technologies were evaluated. The electronic circuit boards that are tested and repaired daily at NAFB come from a variety of Air Force Systems, such as 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 these circuit boards demonstrate thermally intermittent failure modes and were used for comparison testing. Both alternative cooling technologies performed sufficiently well to be considered for use in trouble-shooting circuit boards. Both reduced pollution and cost less than aerosol refrigerants typically used.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

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 effect of implementation.

This study evaluated the use of cold compressed-air tools and liquid nitrogen as methods for cooling electronic circuits while searching for causes of thermally intermittent circuit failures. Aerosol cans of refrigerant (i.e., CFC R-12 and HCFC R-22), which commonly have been used in electronics manufacturing and repair businesses for this purpose, served as the benchmark for the evaluation. Six critical parameters were measured for each cooling method: accuracy, electrostatic discharge risk, cooling capability, technician safety, pollution prevention potential, and economics. The first three parameters are related to product quality, i.e., the accuracy with which circuit board failures can be located, and are discussed in that section. The remaining parameters are discussed independently.

Description of the Technology

Aerosol cans of refrigerant, such as R-12 and R-22, are commonly used in the electronics manufacturing and repair industries for trouble-shooting circuit boards that have known or suspected thermally intermittent failure modes. Thermally intermittent failures occur when temperature changes and material expansion or contraction aggravate the mechanical failure to create an electrical discontinuity condition. For example, if 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. The component that, when cooled, causes the failure mode to appear or disappear is replaced. If the circuit failure mode still exists, the troubleshooting process is repeated.

Aerosol cans of refrigerant are commonly used as trouble-shooting tools. They can be used easily to cool an entire circuit board or a single solder connection and are portable and relatively inexpensive. As recognized in the Montreal Protocol of 1987, however, 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. Hydrochlorofluoro-carbons (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. 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 1/2-L Dewar flask 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.

Description of the Site

Newark AFB (NAFB) was the site at which compressed-air and liquid-nitrogen alternative technologies were evaluated. Electronic circuit boards from a variety of Air Force systems, such as inertial guidance systems, are tested and repaired at NAFB daily. A percentage of the tested circuit boards 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. Because compressed air is not typically 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 because:

- The test stations included fixtures that were 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 troubleshooting capability since 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 used for the study are in close proximity.

The compressed-air system used 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 1/2-in. line with nonrestrictive couplings to three outlets. A filtration and drying system was installed approximately 20 ft from the test stations. A 5-hp compressor is the minimum requirement for continuous operation of an air tool.

Product Quality Evaluation

Three factors determine how well a given cooling method will work to identify failing circuit board components: accuracy, electrostatic discharge risk, and the cooling rate and absolute temperature drop. The procedures used to evaluate these factors and the conclusions reached during this study are described briefly below; additional detail is provided in the final report.

Accuracy

For this project, accuracy was defined as the capability of a technician using a cooling method to identify a specific component with a thermally intermittent failure mode causing a circuit board to have a thermally intermittent circuit failure mode. An accurate cooling method provides a high component identification confidence (CIC) level, which avoids the cost of erroneously replacing nondefective components, potential damage created during component replacement, and multiple iterations of testing and repair.

An experiment was performed to compare the capability of each cooling method to identify components with thermally intermittent failure modes. During the 5-month test period, 17 circuit boards were identified initially as having thermally intermittent failure modes. Four of these were subsequently removed from the evaluation because they were found not to be thermally intermittent or because the defective components were known from previous experience with a specific model circuit board. Each of the remaining 13 test articles were evaluated with the use of each of the three cooling methods. Three technicians, working independently of each other, evaluated the test articles following a randomized sequence of cooling methods. For each evaluation, the technicians assigned a CIC level which reflected their confidence that they had been able to isolate the cause of the circuit failure using the assigned cooling method.

The number and variety of test articles identified during the test period were not as great as hoped for. Also, the results of the test article evaluations do not support comparisons of the accuracy of the cooling methods. However, the results do indicate that the compressed-air method was able to reproduce circuit failures in 12 of 13 test articles. This is significant because it is known that the cooling capability of compressed air is less than either refrigerants or liquid nitrogen.

Also, a potential problem related to liquid nitrogen temperatures may have been identified — for one test article, the very low temperature apparently caused a RAM chip to fail temporarily, masking the diode that was the actual defective component. Potential users of liquid nitrogen may want to consider temperature control strategies to avoid excessively low temperatures that could temporarily change component functions or even damage components; possible strategies are discussed in an appendix to the report.

Detailed accuracy evaluation results are provided in the final report, including photographs of each test article and, if available, the results of the component replacement and retesting. This information is expected to help potential users of the alternative cooling materials determine the applicability of study results to their operations.

Electrostatic Discharge Risk

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 first experiment measured the electrostatic charge generated on the nozzle during release of cooling material. During a 10- to 12-sec material release, the nozzle was held parallel to and approximately 1 in. from the platen of an Ion Systems, Inc., Model 200 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 toward circuit boards placed on the platen of an Ion Systems Model 200 Charged Platen Monitor. The dispenser was held so that the nozzle was approximately 0.5 in. 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. 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.

Averages of each pair of measurements indicate that both the compressed air and the liquid nitrogen alternatives generated lower electrostatic charge buildup than did R-12 through either plastic or steel nozzles. Thus, the risk of electrostatic charge buildup is not increased by using either of the alternative component cooling technologies. If aerosol cans of R-12 have been used successfully, either compressed air or liquid nitrogen should be acceptable alternatives.

* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Cooling Rate and Absolute Temperature Drop

Cooling rate and absolute temperature drop were measured for each method. Understanding the characteristics of and differences between cooling methods will enable technicians to use the compressed-air and liquid nitrogen technologies effectively. For example, the distance between the applicator nozzle and the component does not significantly affect the cooling rate of aerosol cans of R-12; this distance is, however, expected to be a significant factor in the cooling rate provided by compressed air.

An experiment was designed to estimate the rate of change of component temperature. Two test boards were fabricated, one having integrated circuits and the other having wound-film capacitors. Each test board contained three components with thermocouples buried inside and one exposed thermocouple. 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, the cooling material was dispensed directly at 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. Table 1 shows the temperatures achieved under one set of conditions.

In all tests, the cooling material dispensers were positioned and aimed manually. By 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 undersprayed or oversprayed the 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

Table 1. *Minimum Temperature Achieved (at 1/4-in. Distance) and Elapsed Time for Three Cooling Points*

	Aerosol R-12		*Compressed Air*		*Liquid Nitrogen*	
Component Type/Test	*Temperature (°C)*	*Elapsed Time (sec)*	*Temperature (°C)*	*Elapsed Time (sec)*	*Temperature (°C)*	*Elapsed Time (sec)*
Integrated Circuit						
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						
Target Component	*-53.5*	*77.5*	*-11.5*	*121.0*	*-134.0*	*51.0*
Exposed Thermocouple	*-59.5*	*—*	*-35.0*	*—*	*-175.0**	*—*

** Minimum thermocouple temperature assumed to be — 175°C based on wound-film capacitor tests.*

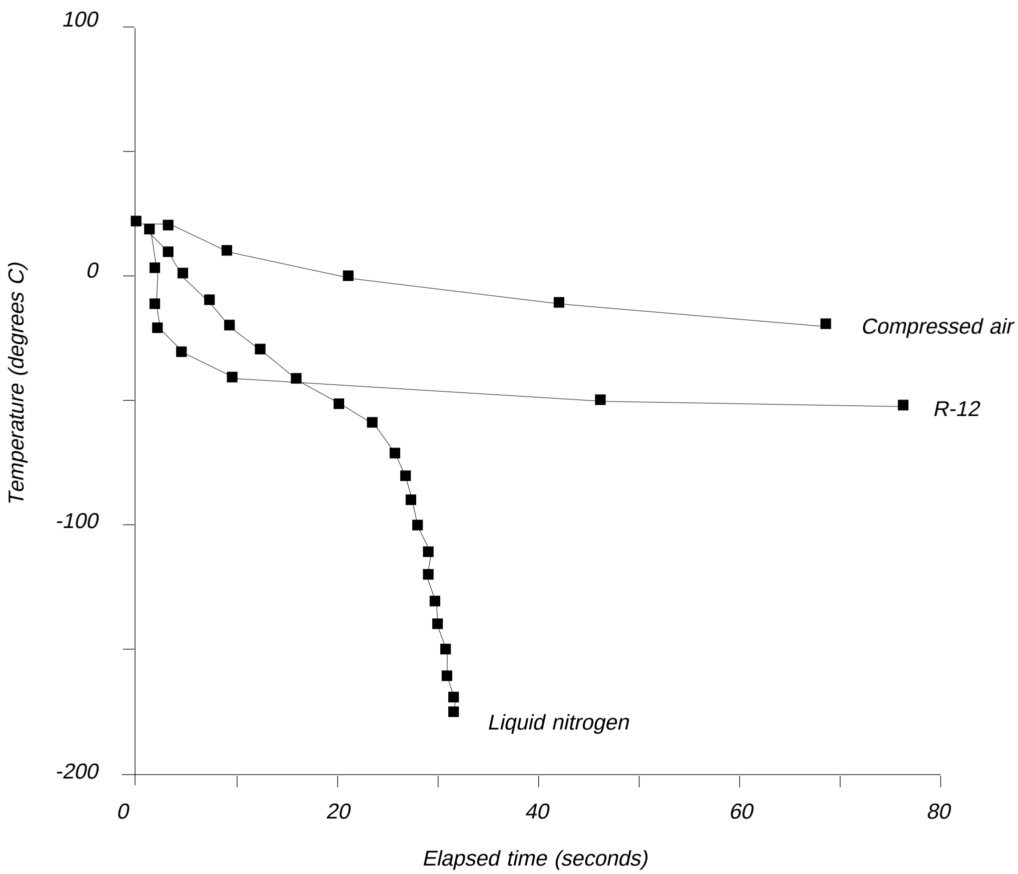

Figure 1. *Typical cooling rate comparison for integrated circuits: distance 1/4-in.*

cooling rate and temperature difference data, while they indicate performance that may be obtained in actual use, are not used for direct comparisons. The cooling rates of the three methods under one set of conditions are compared in Figure 1.

The three cooling materials differed in how they cooled components. 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. 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. 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.

The three cooling methods differed also in their sensitivity to such parameters as component type, application distance, and application direction. Evaluation of minimum target component temperature data indicates that:

- Component type is affected by the sensitivity of the liquid nitrogen and of the compressed air, both of which provided lower temperatures with integrated circuits than with the wound-film capacitors. R-12 was not significantly sensitive to the type of component and provided minimum temperatures for capacitors and integrated circuits that were not significantly different under each application distance/direction combination.
- Distance from the target component affects the component cooling capabilities of both compressed air and liquid nitrogen. An examination of the temperature data summarized in the final report reveals that, as the distance from the component to the nozzle increased from 0.25 in. to 1 in., 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.
- A comparison of component minimum temperature data for two different directions of application indicates that R-12 is not sensitive to application direction. In contrast, compressed air provided lower component temperatures for integrated circuits, 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.

Technician Safety

Exposure to sound created by operation of the compressed-air tool was a safety concern. To assess the potential safety hazard, 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.

The safety concerns related to handling liquid nitrogen and aerosols are well-known. Therefore, no technician safety testing was required.

Pollution Prevention Potential

The purpose of replacing aerosol cans of refrigerant is to reduce the amount of pollutants released into the atmosphere. During the accuracy experiments, the weight of R-12 released during evaluation of each circuit board with thermally intermittent failure modes was determined. The procedures for collecting these data are described in the project report.

These data provide a measure of the average pollution per circuit board that could be prevented if either of the alternative cooling methods were adopted in place of R-12. The average R-12 release/article was 232.65 g (0.51 lb). With the adoption of either alternative technology, release of R-12 would be eliminated along with the wastestream of empty aerosol cans. Neither usage nor production information for the United States was available when this report was written; quantities consumed vary by user, ranging from a few cans/ mo in repair shops to over a thousand cans/yr in production operations.

Economics Evaluation

To assess the economics of replacing R-12 use with either of the alternative technologies, operating costs and investment costs were examined.

The approach to estimating 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. It was beyond the scope of this study to measure all potential effects of alternative component-cooling materials 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 the defective component, a circuit board may be condemned unnecessarily. Comparisons of the ability of the various cooling materials to isolate thermally intermittent components was addressed in the discussions of accuracy and absolute temperature drop/cooling rate above.

Cooling Material Costs

Cooling material costs are based on the use data collected during the accuracy evaluation of the 13 test articles. The methodologies for collecting the data and calculating the use are described in detail in the project report. Use data were converted to cost data as follows:

- R-12 cost was based on a cost of $7.50/16-oz aerosol can. Purchase price of R-12 or R-22 freeze compound ranges from $6 to $15/ can; $7.50 was selected as a conservative estimate.
- Compressed-air cost was calculated by using an air tool consumption rate of 15 cfm at 100 psi and an estimated compressed-air generation cost of $0.26/1000 ft^3. 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/L was used as a typical cost. Potential users should obtain price quotations from local suppliers.

Investment Costs

The approach to estimating investment cost focused on the cost of dispensers.

There is no such investment cost for R-12. Costs for the alternative cooling material dispensing equipment are discussed below.

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 an existing air supply. Potential users will need to determine what, if any, investment is needed to obtain compressed air in the quantities and quality required. Implementation of compressed air requires, at a minimum, investment in the air tools at approximately $200/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. If no compressed air is available in a shop, the minimum equipment required to supply one air tool is a 5-hp 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 1/2-L Dewar flask. Heat exchangers or other accessories would be additional. 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.

Economics Assessment

Data presented in the project report indicate that a material cost savings of $5.28/circuit board can be projected if testing is done with liquid nitrogen instead of R-12. This would result in payback of a $500 dispenser investment after 95 circuit boards have been tested.

For a shop that has an existing adequate air supply, the average operating cost savings for compressed air is $5.26/board. This would pay back a $200 air-tool investment after 38 circuit boards have been tested. The payback period would be extended if additional investment were required to compress and deliver air to the work positions.

Table 2 summarizes investment and payback figures for each alternative technology.

Table 2. *Investment Cost and Payback*

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

Discussion

The objective of this study was to characterize and compare the use of aerosol cans of refrigerant, compressed air, and liquid nitrogen as methods to cool electronic circuits during troubleshooting. Data obtained from testing were used to compare the alternative cooling methods in terms of accuracy, electrostatic discharge risk, cooling performance, technician safety hazards, pollution prevention potential, and economics. Interpretation of the results of this study are:

- 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. The results of the accuracy test, however, indicate that during all but one test, temperatures achieved with the compressed-air tool were low enough to reproduce circuit 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 technician skill to a greater extent than do either compressed air or R-12. Further discussion of component temperature control with liquid nitrogen is provided in an appendix to the project report.
- The results of the accuracy experiment do not support conclusions regarding the relative effectiveness of alternative cooling methods and aerosol cans of refrigerant.
- Neither alternative is expected to increase safety risks to technicians when compared with those of 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 reduce risk to acceptable levels. As with any aerosol, release of refrigerants under pressure presents a safety risk that is minimized 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, but the incremental increase in these wastestreams that would follow adoption of the compressed-air method is not expected to be significant.
- Material costs of either alternative are expected to be lower than those of R-12 or R-22 at current prices. Prices of R-12 and R-22 will undoubtedly escalate and, eventually, these materials will be unavailable due to regulatory prohibition.
- Investment cost to implement liquid nitrogen is expected to consist of the price of Dewar flask dispensers at approximately $500 each in the 1/2-L 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 used.

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The complete report, entitled "Electronic Component Cooling Alternatives: Compressed Air and Liquid Nitrogen," (Order No. PB95-100087/AS; Cost: $27.00, subject to change) will be available only from:
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