THERMAL TEST REPORT

SPRAY COOLING COMPARITIVE ANALYSIS

21 June 2001

Prepared by:

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Goals

The main objective of this project is to evaluate the effectiveness of spray cooling technology for Commercial Off The Shelf (COTS) electronics in military applications. Positive results from this evaluation will provide the military with a COTS solution option to mitigate the environmental risks and allow the insertion of state-of-the-art high-power, high-density commercial electronics.

Background

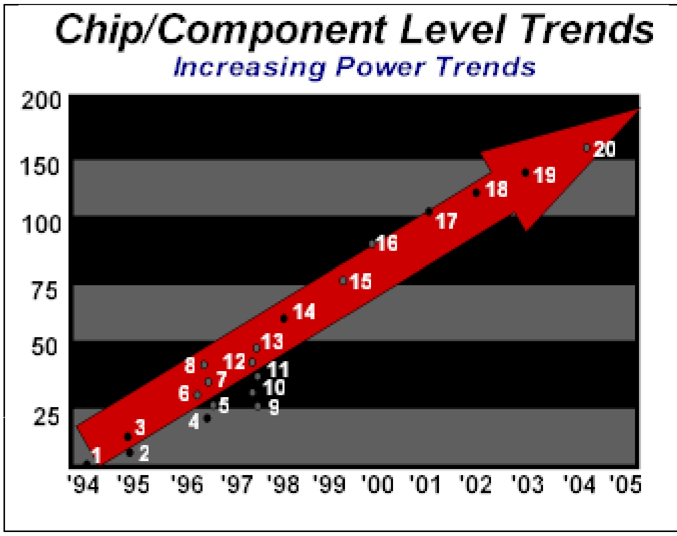
The use of COTS electronics in military systems has become a fact of life. Due to the shift toward use of commercially available off-the-shelf items, the military as a customer has become less of a driving force in the design of these products. There has been a large reduction in the number of manufacturers willing or able to supply "ruggedized" electronics that will meet the stringent environmental, reliability and space/size requirements of military programs, yet the military must still deploy the most capable systems possible in these harsh environments.

Military system designers use two basic techniques to deal with the problem. One is to seek out vendors who offer ruggedized products that are designed to meet the harsh requirements and build the system in a traditional enclosure. This approach often works, but there are many limiting problems, such as very few sources for critical parts, tight design tolerances, and mechanical/material issues. Enclosures for these systems offer some protection from the external environment, but are often limited to the level that the ruggedized components can tolerate.

The other approach is to design enclosure-based protection for the off-the-shelf products so that the demanding external environment doesn't affect the more delicate internal electronic parts. The enclosure, in this case, becomes more than just a box to hold the parts together and serve as a static heat sink. This enclosure functions as a key element of the total system solution.

One of the major challenges in designing such an enclosure is thermal management. As **FIGURE 1** shows, there is a trend for increasing power densities in emerging electronic technology. However, traditional cooling techniques greatly limit the choice of components available to the military system designer.

Spray cooling is a technique where a mist of inert liquid coolant is directed upon the components inside a sealed enclosure by pumps and nozzles. The vapor generated after the liquid contacts the hot components can be condensed on the chassis walls, or in a remote heat exchanger. Heat removed to the chassis walls is externally carried through natural or forced convection. In the case of a remote heat exchanger, air is forced over the heat exchanger core in order to reject the heat.



1	386 3 watts
2	Power PC 6 watts
3	486 8 watts
4	Pentium 13 watts
5	Cyrix 125 MHz 18 watts
6	Power PC 20 watts
7	Pentium Pro 25 watts
8	Alpha 500 MHz 45 watts
9	Power PC 266 MHz 25 watts
10	Pentium 233 MHz 27 watts
11	Pentium II 233 MHz 36 watts
12	Pentium II 300 MHz 43 watts
13	Ultra Sparc 50 watts
14	1998 CPU 50 watts
15	1999 CPU 75 watts
16	2000 CPU 85 watts
17	2001 CPU 125 watts
18	2002 CPU 140 watts
19	2003 CPU 175 watts
20	2004 CPU 200 watts

Figure 1-Chip/Component Level Trends.

Approach

This project focuses on comparing the cooling effects of a standard air-cooled, COTS electronic system to the cooling effects of a spray-cooled system manufactured by Isothermal Systems Research (ISR) (Clarkston, Washington).

The first phase of this evaluation consisted of establishing a baseline with an existing VME air-cooled card cage (**SEE FIGURE 2**) containing four heat load modules. The card cage is an air-cooled enclosure capable of housing up to 21, 6U X160 VME cards, with a 700 watt power supply containing 3 muffin fans for cooling. The test setup contained the four heat load modules and 17 blank cards to maintain a balanced air flow across each module (see figure 2). These load modules were VME bus slot load boards manufactured by Dawn VME Products. The load boards were used to simulate a working VME module and capable of producing a fifty watt heat load per module. Four modules were used in this test with one to four activated at various times. The center module was always activated and was populated with five thermocouples distributed throughout the board as follows:

- One on a resistor that was not powered
- Another on a resistor with a 3.1watt heat load
- A third on the board surface
- The fourth on a 3.1watt resistor that was powered on
- The fifth on another resistor that was not powered

The thermocouple locations were selected to measure temperatures of components across the module. In addition to the thermocouples placed on the module, others were used to measure the card cage inlet, exit and ambient fluid temperatures. The thermocouples were Omega T-type (Copper-constantan), with a 0.10 inch diameter and were attached to the resistive heaters using thermal epoxy.

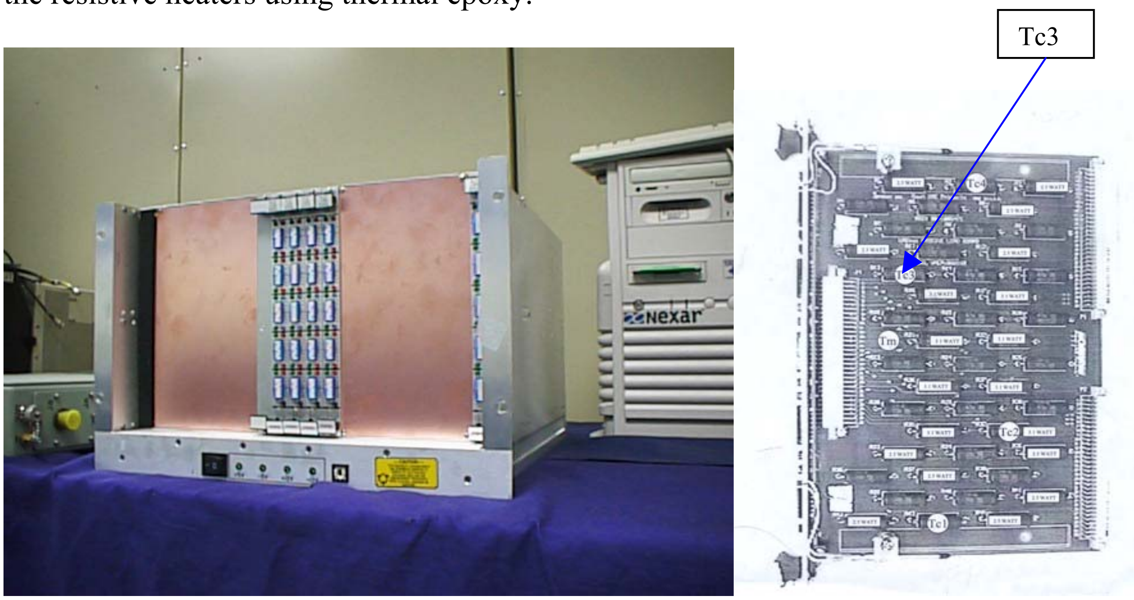


Figure 2-<u>VME Chassis & Load Board</u>

The spray-cooling phase consisted of utilizing a Portable Laboratory Support Unit (PLSU) and an Acrylic Test Chassis (ATC) purchased from ISR (**SEE FIGURES 3 & 4**).

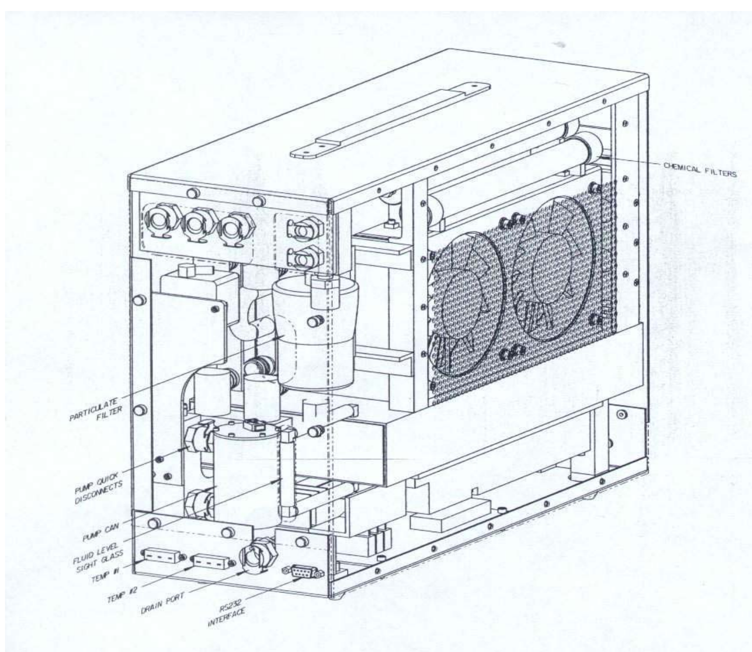
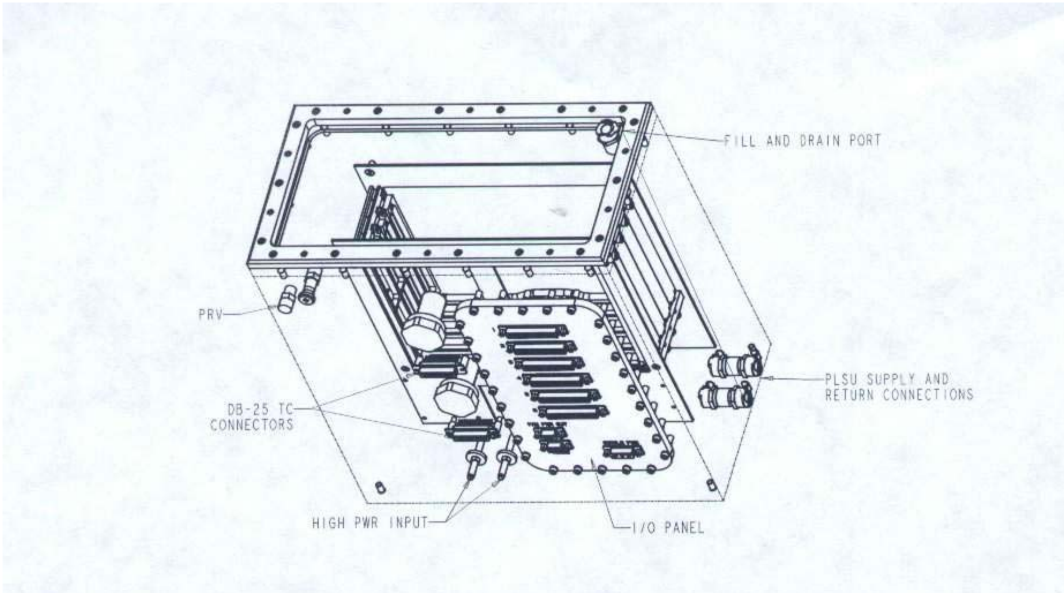


Figure 3-<u>Portable Laboratory Support Unit (PLSU)</u>
(with front and side panel removed)



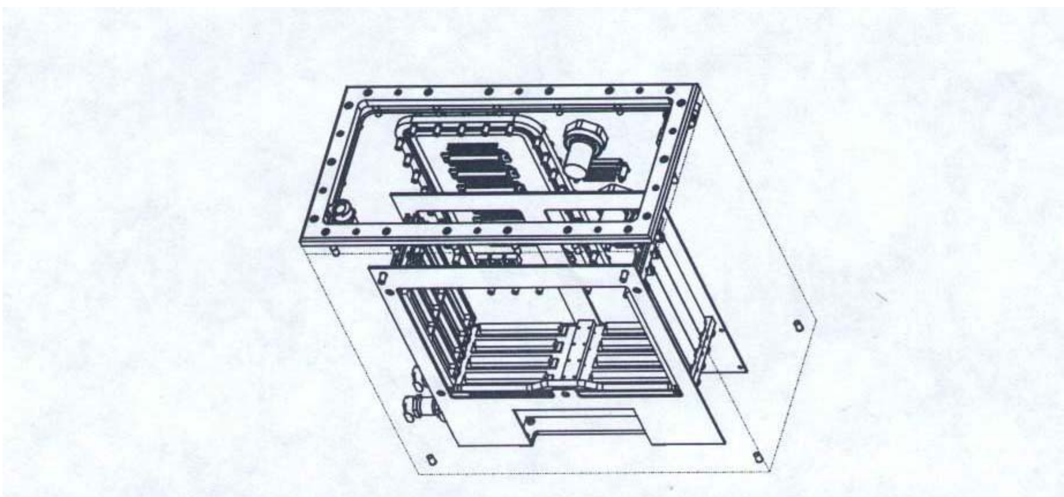


Figure 4-<u>Acrylic Test Chassis (ATC)</u>
Rear and Front Views

For consistency, the same set of heat load modules previously described in the air-cooled section were utilized for the spray-cooled evaluations. By keeping the power level on the heat load modules consistent in all of testing, the differences in the recorded temperatures were an actual result of the cooling methodology.

Test Procedure

The thermal testing was divided into four major parts:

1) Air cooling at ambient room temperature
2) Air cooling at elevated temperature
3) Spray cooling at ambient room temperature
4) Spray cooling at elevated temperature

1) Air Cooling at Ambient Room Temperature

This examination was performed at 25°C at four different power levels 50W, 100W, 150W, and 200W. The power levels were obtained by use of heat load modules see figure 2. Each module was setup for 50W. Four modules were placed in the VME air-cooled card cage. The test data was recorded on a Fluke data logger (see Appendix B for typical data recorded).

2) Air Cooling at an Elevated Temperature

This examination was performed at three different temperatures 35°C**,** 45 °C, and, 55°C as well as four different power levels 50W, 100W, 150W, and 200W. The test setup was similar to the air cooling at ambient room temperature test but the test unit was placed in the thermal chamber.

3) Spray Cool at Ambient Room Temperature

This examination was preformed using the spray cooling system (see figure 3 and 4) in the laboratory. The procedure is the same as the air cooling at ambient room temperature of 25°C but ran at four fluid flow rates, 890ml/min (15 psia), 1000ml/min (20 psia), 1300ml/min (25 psia), and 1500ml/min (30 psia) (see Appendix B for typical data). The data collection and evaluation remained constant throughout the evaluations.

4) Spray Cool at Elevated Temperature

This examination was performed at three different temperatures 35°C**,** 45 °C, and, 55°C, four different power levels 50W, 100W, 150W, and 200W and four different flow rates 890ml/min (15 psia), 1000ml/min (20 psia), 1300ml/min (25 psia), and 1500ml/min (30 psia). The test setup was similar to the spray cooling at ambient temperature but the test unit was placed in the thermal chamber.

Results/Accomplishments

The results of this thermal evaluation indicate that a significant heat removal gain is achieved by employing spray cooling heat transfer technology. As a result of all the testing, the spray cooling consistently out preformed the air-cooling. The amount of improvement ranged from 5 to 20 times the heat removal of a standard air-cooled chassis depending upon the surrounding temperature, heat load and liquid flow rate/pressure. See **TABLES 1 and 2** for test data from thermocouple #3 and **FIGURES 6 and 7** for graphical representations of the test results.

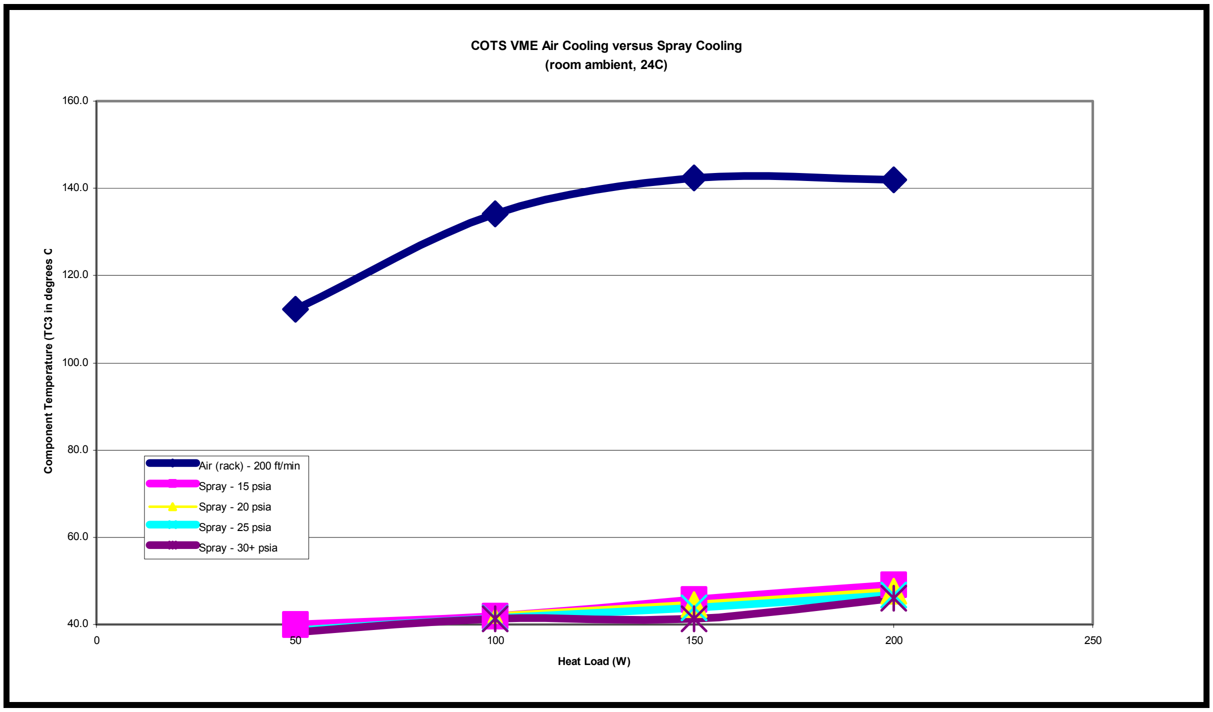


FIGURE 6-AIR/SPRAY AT ROOM AMBIENT

Air Cooling Air flow : **200 ft/min** All temps for **TC3** (See Fig 2)				
Heat load	**Air - 24.1C amb**	**Air - 37.8C amb**	**Air - 46.4C amb**	**Air - 57.7C amb**
Watts	**Temp. Deg. C**	**Temp. Deg. C**	**Temp. Deg. C**	**Temp. Deg. C**
50	112.3	123.3	131.0	142.3
100	134.2	124.0	138.8	150.0
150	142.4	132.6	140.9	152.4
200	142.0	133.1	141.7	152.8

TABLE 1 AIR FLOW TEST DATA Tc3

Spray cooling					
	15 psia (890 ml/min)	20 psia (1000 ml/min)	25 psia (1300 ml/min)	30+ psia (1300+ ml/min)	Boiling point
Heat load	Spray - 24C	Spray - 24C	Spray - 24C	Spray - 24C	(approx)
W					C
50	40.0	39.2	38.7	38.3	
100	41.9	41.9	41.4	41.3	
150	45.7	44.5	43.8	41.4	
200	49.1	47.7	46.8	46.1	57
	15 psia (890 ml/min)	20 psia (1000 ml/min)	25 psia (1300 ml/min)	30+ psia (1300+ ml/min)	
Heat load	Spray - 35C	Spray - 35C	Spray - 35C	Spray - 35C	
W					
50	52.4	51.5	51.6	51.2	66
100	52.4	52.5	50.7	49.8	65
150	53.3	52.9	51.4	50.4	60
200	56.1	56.3	53.9	52.1	65
	15 psia (890 ml/min)	20 psia (1000 ml/min)	25 psia (1300 ml/min)	30+ psia (1300+ ml/min)	
Heat load	Spray - 45C	Spray - 45C	Spray - 45C	Spray - 45C	
W					
50	57	57	53	55	66
100	58	57	54	55	65
150	60	58	55	57	66
200	61	58	57	56	65
	15 psia (890 ml/min)	20 psia (1000 ml/min)	25 psia (1300 ml/min)	30+ psia (1300+ ml/min)	
Heat load	Spray - 55C	Spray - 55C	Spray - 55C	Spray - 55C	
W					
50	59.6	57.0	54.5	54.4	66
100	60.5	59.8	57.5	57.9	65
150	63.0	59.9	57.7	59.6	65
200	63.9	62.6	60.7	55.2	65

TABLE 2 <u>SPRAY COOLING TEST DATA Tc3</u>

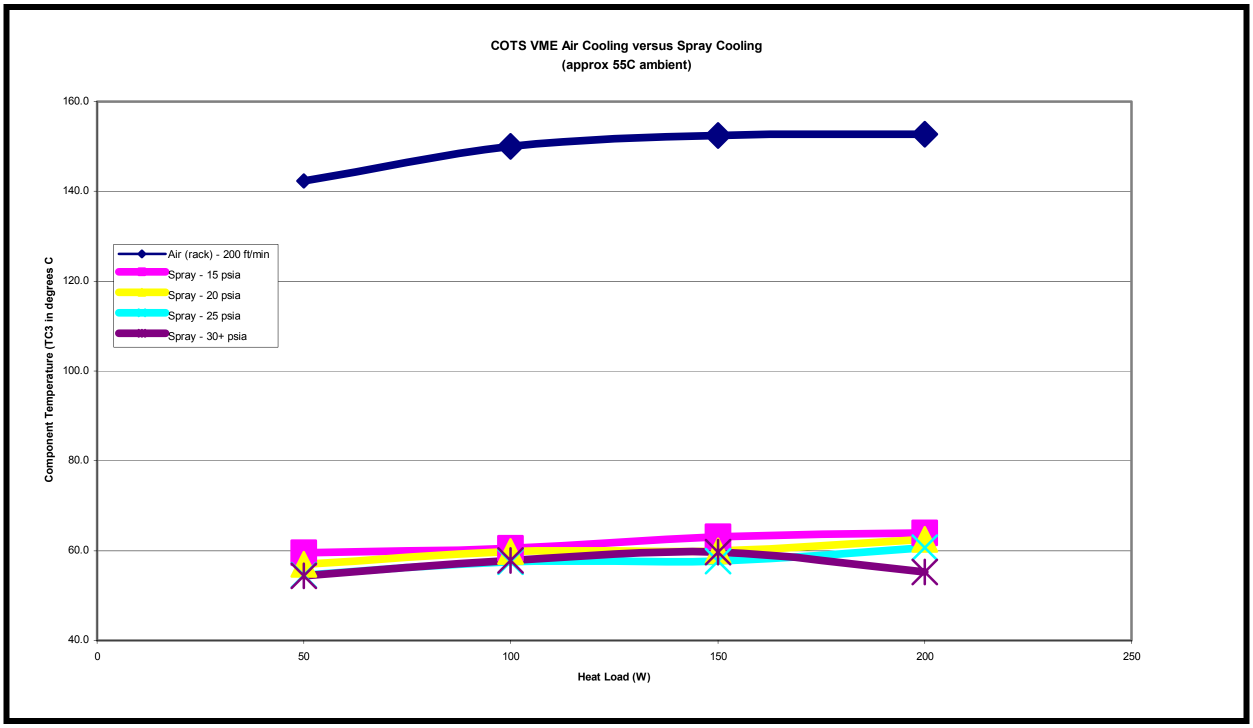


FIGURE 7-AIR/SPRAY AT 55 DEGREES C

The results of this investigation clearly indicate that the spray cooling system was not challenged at the stated temperatures, heat loads and flow rates/pressures. In order to more thoroughly evaluate spray cooling, NSWC Crane has identified a military system slated to utilize spray cooling in a harsh environment and are in the process of performing a reliability projection of the COTS electronics. This analysis will yield a reliability comparison (air vs. spray) at the system, sub-system, module and component level.

The next phase of evaluations will include:

- Reliability Verification
- Environmental Certification
  - Shock/Vibration
  - Toxicity/Flammability
  - Mechanical
  - Altitude
  - Humidity
- Material Compatibility Analysis
- High Power Component/Module Testing

For further information, contact Gerry Thomas (812) 854-1797 or Dan Quearry (812) 854-2443.

APPENDIX A
3M Fluorinert PF 5060

3M

Perfluorocarbon Liquid PF-5060

Dielectric Coolant for GE VaporTran™ Transformers

Application Information

A Non-Ozone Depleting FM-Approved Replacement for CFC-113

3M™ PF-5060 is a perfluorocarbon (PFC) liquid that effectively replaces CFC-113 as a dielectric coolant for GE VaporTran transformers. 3M PF-5060 is the only replacement available with a Factory Mutual Approval.

Although the use of CFCs in properly functioning equipment is still permitted by the U.S. EPA (Environmental Protection Agency), production and use of these materials, is severely restricted due to their harmful effect on the Earth's ozone layer. Many transformer owners, concerned about future supplies and rising costs of CFCs, are investigating the use of replacement coolants, such as 3M PF-5060.

An extensive series of factory tests to evaluate the performance of 3M PF-5060, performed according to applicable ANSI and NEMA standards by GE, show that the product meets or exceeds GE's performance and reliability requirements. 3M PF-5060 also demonstrates greater compatibility with the VaporTran transformer's materials of construction than CFC-113. 3M PF-5060 is the only CFC replacement that is Factory Mutual (FM) approved as a non-flammable transformer fluid.

PFCs offer many of the important performance properties of CFCs, but contain no chlorine or bromine in their chemical makeup. As such, they do not damage the Earth's ozone layer, and are not scheduled for phaseout by the EPA. PFCs are nonflammable, low in toxicity, chemically inert, thermally stable, electrically nonconductive and offer excellent materials compatibility. 3M PF-5060 is listed by the EPA as "acceptable" in existing designs and retrofits of heat transfer systems, including VaporTran transformers.

3M PF-5060 Material Description

C_6F_{14} .... 99.0% minimum

Appearance.................................... Clear, colorless

VaporTran is a registered trademark of General Electric Company.

Performance Properties

Properties @ 25°C	3M™ PF-5060	CFC-113*
Ozone depletion potential	0.0	0.8
Flash point, °C	None	None
Boiling point, °C @1 a+m	56	48
Pour point, °C	-90	-35
Liquid density, gm/ml	1.68	1.56
Viscosity, cp	0.67	0.68
Vapor pressure, mm Hg	232	334
Thermal conductivity, W/(cm)(°C) x 10^3	0.57	0.75
Specific heat, cal/(gm)(°C)	0.25	0.22
Heat of vaporization @ b.p., cal/gm	21	35
Coefficient of thermal expansion, ml/(ml)(°C) x 10^3	1.6	1.4
Surface tension, dynes/cm	12	17
Solubility of water, ppm	10	110
Hildebrand solubility parameter	5.6	7.3
Dielectric strength, 0.1 in. gap, KV(RMS)	38	35
Dielectric constant, 1 kHz	1.76	2.41
Volume resistivity, ohm-cm	1.0×10^{15}	1.2×10^{10}
Dissipation factor, 1 kHz	<0.0003	–

*Not a 3M product. Included for comparison purposes only.

Materials Compatibility

3M PF-5060 is compatible with most metals, plastics and elastomers used in GE VaporTran transformer construction.

Use Recommendations

3M PF-5060 has demonstrated excellent results as a dielectric coolant in GE VaporTran transformers. Unlike other liquid (oil) filled transformers, the GE VaporTran transformer uses boiling heat transfer to cool the transformer core and windings. The transformer must be designed specifically to accommodate this mode of heat transfer. Use of 3M PF-5060 for any transformer other than the GE VaporTran is not recommended. Consult the transformer manufacturer for suitable dielectric transformer coolants.

3M PF-5060 Toxicity Profile

3M PF-5060 is non-irritating to the eyes and skin, and is practically non-toxic orally. The product also demonstrates very low acute and sub-chronic inhalation toxicity. It is not a mutagen, or cardiac sensitizer.

Safety and Handling

3M™ PF-5060 is nonflammable, and is highly resistant to thermal breakdown and hydrolysis in storage and during use. Detailed recommended handling procedures are given in the Material Safety Data Sheet, which is available upon request.

Environmental

3M PF-5060 has zero ozone depletion potential. The material is not defined by the U.S. EPA, nor regulated as a volatile organic compound (VOC) and does not contribute to ground-level smog formation.

3M PF-5060, a perfluorocarbon (PFC), has a high global warming potential and a long atmospheric lifetime. As such, it should be carefully managed so as to minimize emissions and provide the necessary balance of safety and performance.

3M recommends that users of 3M PF-5060 further limit emissions by employing good conservation practices, and by implementing recovery, recycling and/or proper disposal procedures. 3M offers a program for used fluid return. Specific guidelines for the safe handling and use of 3M products are provided in the Material Safety Data Sheets.

Physical Properties Comparison Between 3M™ PF-5060 and CFC-113

Figure 1:

Vapor Pressure vs. Temperature

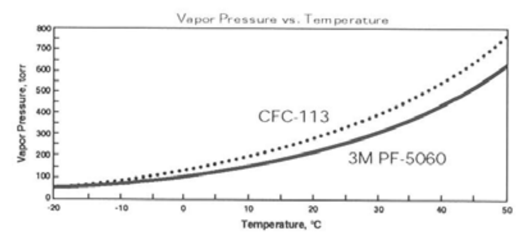


Figure 2:

Liquid Density vs. Temperature

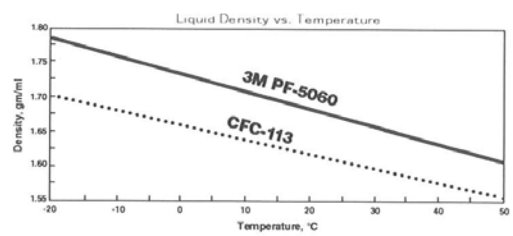
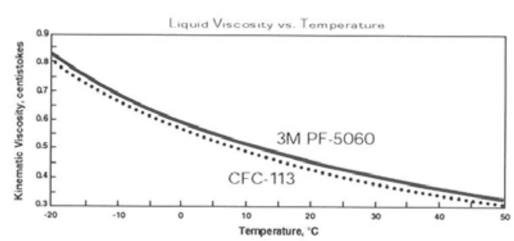


Figure 3:

Liquid Viscosity vs. Temperature



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Service and Support

3M can refer owners of GE VaporTran transformers to an authorized service contractor who can assist with converting equipment from CFC-113 to 3M™ PF-5060. For more information, contact 3M at 1(800)258-6930.

For information on additional 3M™ Specialty Fluids, visit our Web site at: **www.3m.com/fluids**

3M

Specialty Fluids
3M Chemicals

3M Center, Building 223-6S-04
St. Paul, MN 55144-1000

Issued: 11/98

98-0212-0496-5 (HB)

APPENDIX B
Test Data

For a copy of the actual test data (Excel File), please contact sd18poc@crane.navy.mil

APPENDIX C

One concern discovered during the testing was when an acrylic hose used to transfer the PF-5060 coolant from PLSU to the ATC failed (SEE FIGURE 5). Investigations led to the possibility of the hose having been previously contaminated with another refrigerant. The combination of PF-5060 and the other fluids yielded a acid-based byproduct and most likely caused the failure. See below for a preliminary report performed by NSWC Crane material analysis scientists. **Please note that this issue is not a major concern as it is a laboratory test unit and not designed for deployment**.

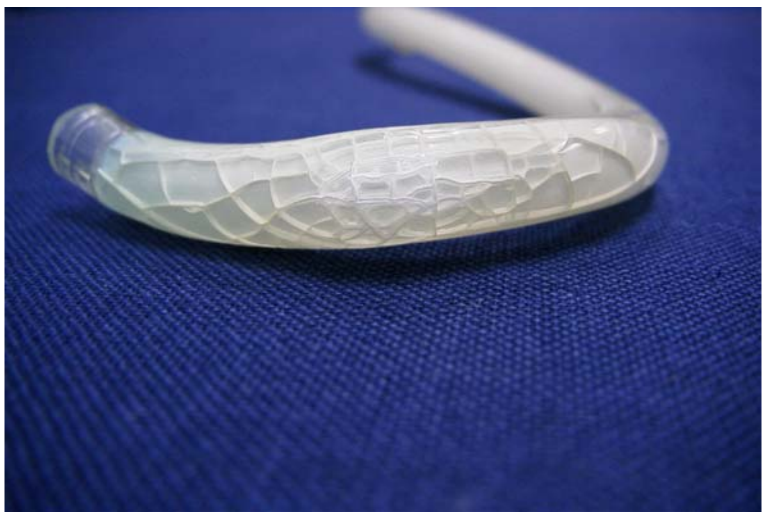

Figure 5-Acrylic Hose Failure

Subject: Spray Cooling Hose Failure Analysis

1. Samples of the two liquids and the hoses used in an experimental spray cooling system made by the ISR Company were received for testing from Code 6022. This system was acquired to allow Crane to evaluate the feasibility of the cooling technique. While testing, one of the hoses cracked and burst. Code 6051 was asked to assist in the failure analysis. The failed hose was analyzed by FTIR (Fourier Transform Infrared Spectroscopy) and found to be a polyurethane formulation. This was consistent with the company's information about the hose composition. The two liquids, a virgin PF-5060 fluorocarbon and the liquid being used in the ISR system when the hose failed (also PF-5060) were investigated by two techniques. First, an aliquot of the two liquids were examined by FTIR and no differences were noted. Secondly, samples were analyzed by GC-MS (Gas Chromatography Mass Spectrometry). Again, both samples appeared to be the

same with no contaminants.

2. In conversations with the personnel at ISR, it was suggested that the system had been inadvertently contaminated with R23 and/or R134a fluids prior to shipment to Crane and that these fluids could have decomposed and attacked the hose. In an attempt to verify this hypothesis, sections of the failed hose were opened and the interior walls of the hose were examined by SEM/EDS (Scanning Electron Microscopy/Energy Dispersive Spectroscopy). This analysis revealed Fluorine on the interior surface of the hose. This would be consistent with the hypothesis that the contaminating fluids (R23 and/or R134a) had broken down into hydrogen fluoride that then attacked the polyurethane hose. This could have weakened the hose sufficiently to cause it to burst under pressures used in the ISR system. All this is conjecture and should be considered as such. It would be a good idea to examine the new hoses after a similar operating time to test this scenario.

3. For information regarding this work, please call (812) 854-2287 at the Naval Surface Warfare Center Crane Division.