Spray Cooling Technologies Market Investigation

Prepared for:
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This market investigation is primarily directed at the identification of commercially available Spray cooling technologies which could be used or adapted for use in cooling and/or heating Commercial Off the Shelf (COTS) Electronic assemblies. Additionally, this investigation provides a comparison of the various alternative cooling technologies and assesses their applicability to the use of COTS in a military environment. The scope of this investigation was general in nature due to cost and schedule limitations.

Task 1 *Conduct a market investigation of existing spray cooling technologies.*

The market survey was conducted using the following three approaches:

1. Discussions with experts in the field regarding the use of dielectric liquids to cool electronics

2. A literature and file search for related information

3. A detailed WEB search for information related to spray cooling of electronics using dielectric liquids

Expert Knowledge

Discussions with experts in cooling research in the academic community and experienced designers of cooling systems revealed that significant basic research has been done in the area of dielectric liquid cooling. Transfer of the research technology to commercial products has been very limited. A recent SBIR (1996) effort involved comparison of dielectric liquid cooling techniques. That effort included high heat flux liquid flow through cooling, Spray Cooling and Jet Impingement cooling techniques applied to practical military thermal management examples. SDA attempted to obtain copies of the SBIR Phase II

(N92-136) report detailing results. Re-organization of SBIR offices and personnel has made it difficult to obtain the report. However, SDA subcontracted with a long time associate that was the cognizant Navy technical expert for that SBIR. His intimate knowledge of the SBIR efforts and 25 years plus experience in the electronics cooling area was tapped for this market survey. SDA also previously investigated dielectric liquid cooling research at Purdue University, with specific interest in developing practical applications. A foremost expert in the field at Purdue has been conducting research for over 15 years and has provided practical solutions to many commercial and government customers such as CRAY Research, AT&T, IBM, and the US Air Force. It is interesting to note that Purdue has been consulted numerous times regarding Spray Cooling technology included as part of a larger system or product. SDA refreshed the association with Purdue to obtain current research information.

Literature/ File Search

A literature/file search revealed some magazine references to spray cooling and to Isothermal Research Systems (ISR) technology development. It was also found that ISR previously received Phase I and II SBIR funding for Change of Phase (COP) Spray cooling technology development. More importantly, it was found that ISR was recently awarded a $35,000,000 contract by the Naval Air Warfare Center Aircraft Division for the development of airborne Spray Cooling systems.

Proceedings from the June 2000 DARPA sponsored HERETIC Program Principal Investigators' meeting were reviewed. The vision of the HERETIC Program is "to develop micro-scale solid state and fluidic heat removal devices that are integrable with dense electronics and optoelectronics in order to short circuit the thermal resistance between the heat sources in the electronics or optoelectronics devices and the thermal sinks." Review of the HERETIC material indicated a great deal of basic research is being conducted in this area at Institutions such as MIT, Harvard, Stanford, and Carnegie Mellon just to name a few. Other organizations such as the Jet Propulsion Laboratory and Rockwell Science Center, LLC are participating. Virtually all of this work involves basic research aimed at integrating cooling technologies with semiconductor structures or subassemblies of semiconductors. Much of it is very esoteric in nature. For example, one of the papers reviewed is titled Heat Removal by Inverse Nottingham Effect with Heat Pipes. Practical applications resulting from HERETIC Program research are years away.

WEB Search

To complete the market survey, a WEB search for information on Spray Cooling technologies was conducted using a variety of search words and terms to improve the chances of finding as much related information as possible. The initial results of the search appeared to indicate that a considerable amount of research on spray cooling has been reported by academic sources such as Purdue University, the University of Kentucky, The University of Minnesota, and the University of Maryland. Information indicated that this research is basic in nature and that little or no commercial product development work is in progress. Upon closer investigation, it was discovered that no current web information could be found for University of Maryland efforts. The University of Minnesota research web site dealt with Spray Cooling techniques, but was very incomplete. A University of Kentucky web site did not refer to current work that might be applicable, although it is believed that Spray Cooling research was performed in recent years. ISR is known to have worked with the University of Kentucky in the past. The Purdue University web site was very complete and current, detailing extensive liquid cooling research efforts and published papers.

Only one corporate WEB site was found with significant spray cooling information, that of ISR. The ISR WEB site contained extensive information on COP Spray Cooling, the ISR design approach, and the firm's experience with cooling COTS in a military environment. ISR equipment has been under evaluation in the Marine Corp Advanced Amphibious Assault Vehicle (AAAV) for some time. Discussions with company personnel have confirmed that, at present, ISR is the only company known to be offering COP spray cooling enclosures for use with COTS in a military environment.

Market Investigation Conclusions

The market investigation led to the following conclusions:

1. The ISR technology is the only one known to be directed at the cooling of low to medium power COTS electronics in a military environment.

2. The ISR technology is the only one known to have been evaluated by the military.

3. The recent large contract award to ISR by the U.S. Navy indicates that ISR is the leader in commercially available spray cooling technology and may be the only near term supplier of this technology.

Task 2 *Provide a comparison of spray cooling to other cooling technologies.*

In conducting a comparison of the various other cooling techniques to Spray Cooling it was decided that SDA should identify potential COTS liquid cooling techniques and traditional methods listing the advantages and disadvantages of each. That data is summarized and included as Attachment 1.

A review of the advantages and disadvantages of the cooling techniques in Attachment 1 leads to the immediate conclusion that almost any of them could be the approach of choice in a particular situation. An example might be the direct immersion, forced convection method to cool very high power density COTS electronics even though this selection might be somewhat unique. It could very well be the only feasible technical approach for a particular situation. In many cases, typical forced air cooling will still be the method of choice. Based on the recognition that military applications are varied, selection of a particular technique as a single standard solution is not advisable. It would be highly desirable have available a complete arsenal of possible solutions and not focus on a “one size fits all” approach.

The SBIR efforts previously mentioned can be summarized by saying that each technique examined is appropriate in specific real world situations. Purdue University compared three dielectric liquid cooling techniques; Flow Through, Spray, and Jet Impingement. The Flow Through cooling technique demonstrated heat removal capability of over 3000 Watts from a Standard Electronic Module (SEM) Format E configuration (approx. 6” x 6”). The spray cooling technique demonstrated the capability to cool a circuit card of SEM E size dissipating over 1000 Watts. The Jet Impingement technique demonstrated cooling capability of over 5000 Watts on a SEM E clamshell style circuit card.

Of particular interest to this investigation are the Spray Cooling and Jet Impingement performance results demonstrated by Purdue. Spray Cooling offers good performance in applications with low to moderate heat removal requirements. The individual Spray Cooling components, such as nozzles, plumbing, pumps, filters, and heat exchangers are commercially producible. However, it should be noted that special machining capabilities are required to manufacture spray nozzles to the precision and tolerance required. Purdue research revealed variation in nozzle performance due to contamination, corrosion, and long-term wear. Placement of spray nozzles is fairly critical to assure adequate cooling. A simplified drawing of the Spray Cooling concept is shown in Figure 1.

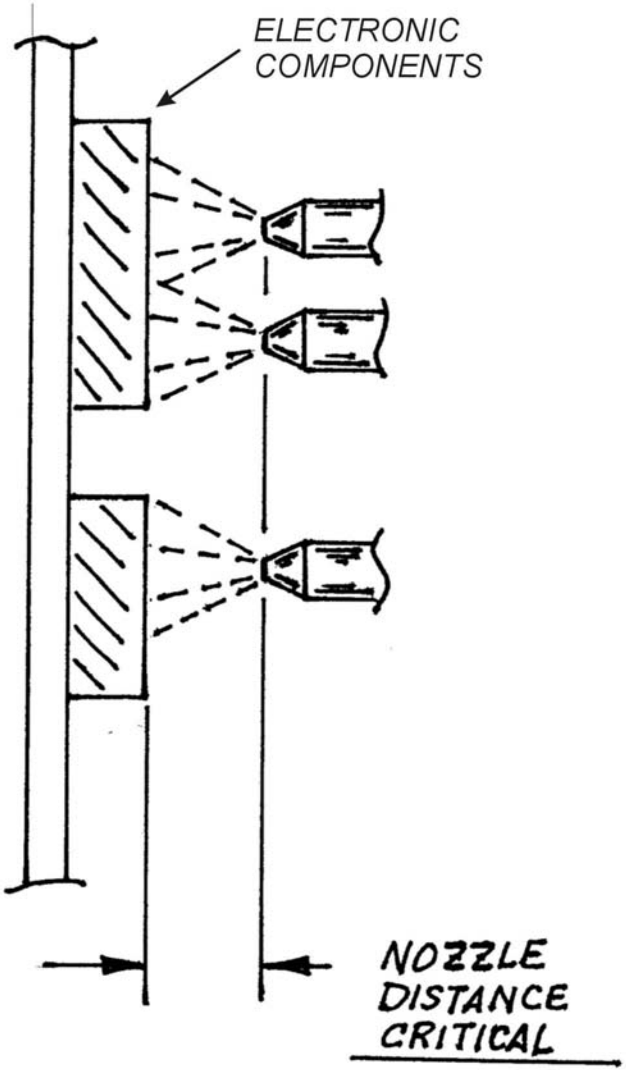


Figure 1. Spray Cooling Configuration Example

Jet Impingement offers excellent cooling performance in low to moderately high heat applications. Production of components is quite easy because precision manufacturing is not required. A simple Jet Impingement system could be constructed that delivers and directs dielectric liquid through holes (nozzles) in a plate. Rectangular or circular shapes can be used and tailored for size, flow rate, and velocity to match the heat dissipating components. Precise positioning is not required. Purdue research found that contamination, corrosion, and wear of Jet Impingement nozzles are of very little concern, even though the dielectric fluid should be filtered and conditioned in both Spray and Jet Impingement configurations. While no commercial product currently exists using the Jet Impingement technique, it should be relatively simple and low risk to develop and demonstrate a viable Jet Impingement cooling system. A simplified drawing of the Jet Impingement concept is shown in Figure 2.

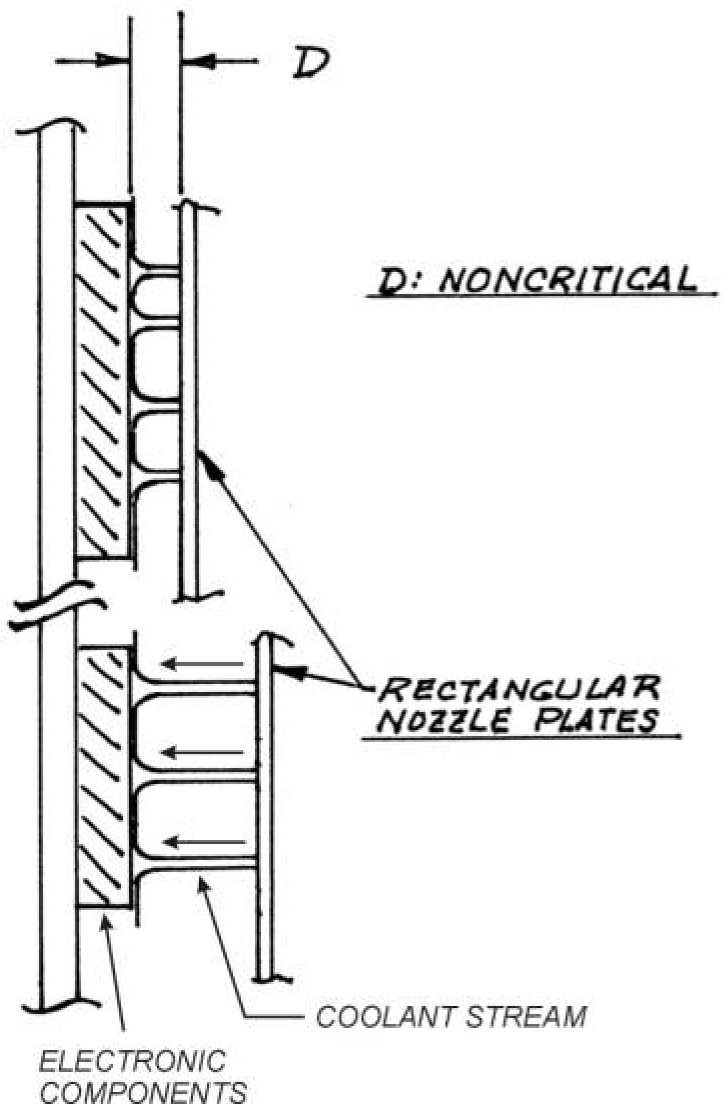


Figure 2. Jet Impingement Cooling Configuration

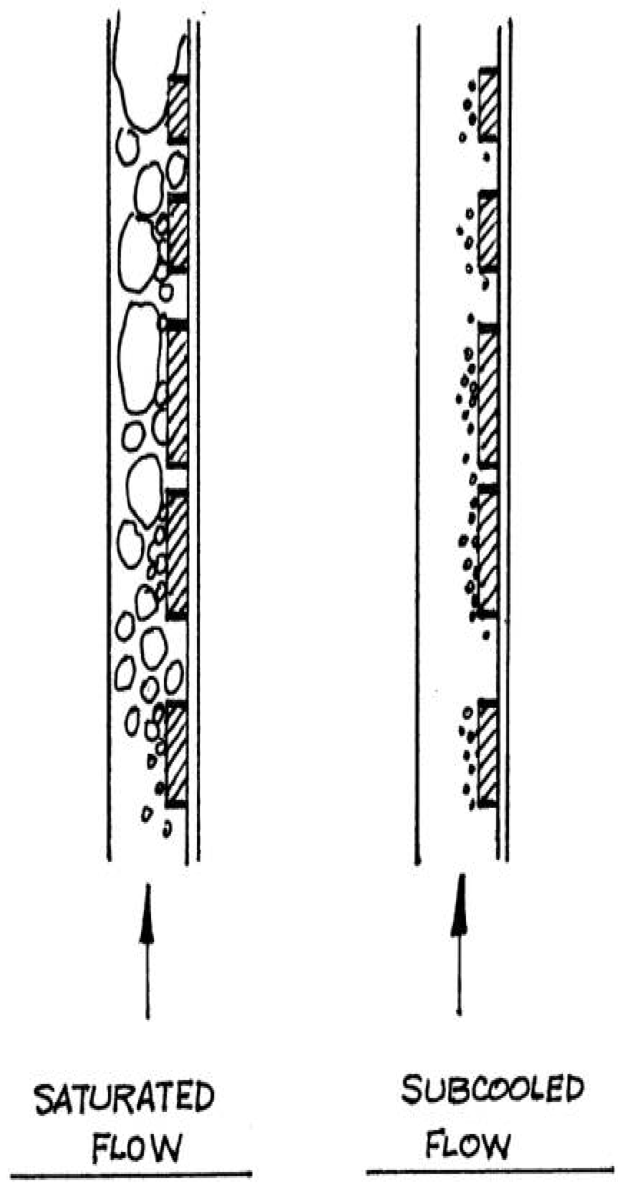


Figure 3. Direct Immersion and Flow Through/Channel Flow Cooling

Two other interesting dielectric liquid cooling concepts are presented here for information. Direct Immersion and Flow Through/Channel Flow liquid cooling are alternatives to Spray or Jet Impingement methods. An electronic package, such as a power supply, can be filled (Direct Immersion) with a dielectric fluid that transfers heat from electronic components to an external heat sink through conduction/convection. A larger volume of fluid may be required depending on the size of the flow channel(s); but nozzles, plumbing, a pump, and filter required by Spray or Jet impingement methods are eliminated. A variation of Direct Immersion is a Flow Through/Channel Flow configuration that directs coolant over the entire surface of an electronic circuit card and components. Nozzles are not needed, plumbing is minimized or eliminated, a pump circulates the coolant and a filter traps contamination. Figure 3 shows bubbles generated by the COP action as heat is transferred from components to the coolant. In the saturated flow example, large bubbles are generated. Large bubbles may inhibit liquid contact with electronic parts; therefore reducing heat transfer. This condition should be avoided. The subcooled flow example illustrates the preferred situation where very small bubbles (micro-bubbles) are produced by the COP actions that naturally condense back into the bulk coolant flow. Subcooling is achieved exactly as the term implies. The dielectric fluid is cooled some amount below the COP point based on the specific system requirements. An important fact to note is that a variety of dielectric fluids exist that can be mixed to achieve specific cooling performance.

Cooling COTS systems in military environments is a challenge that must be addressed by all military branches. COTS technology brings the benefits of high performance at a low initial cost. However, long-term cost of ownership may be high depending on reliability and supportability. Developing appropriate cooling techniques will be a major factor in the long-term viability of COTS technology in military applications.

This investigation confirmed that the only company known to be doing commercial development work on Spray Cooling for COTS in military applications and certainly the only company shipping operational Spray Cooling systems is ISR. The fact that a market investigation was commissioned indicates interest in liquid cooling technology exists within the Navy. SDA experience confirms that cooling COTS equipment is recognized as a significant part of successful development efforts. In the last 3 years SDA provided engineering support to a Navy project to develop a commercial replacement for a custom designed military system. Keeping the COTS electronics cool was a major part of that effort. SDA has also discussed liquid cooling of COTS in extreme environments with a military contractor. Other corporate or government development work on Spray Cooling systems or liquid cooling was not discovered; however, such work could be underway at firms under government contract with highly restricted public access.

There is a risk in having only one supplier of liquid cooling technology. Interruption of product supply, for any reason, can cause large problems for military customers. One supplier that produces only Spray Cooling equipment might not be able to handle peak demand periods or survive low demand periods. Certainly, proprietary technology should be avoided. While reliance on one technology or one supplier should be avoided, allowing a unique solution for each system must be avoided. A balance between a mandated single dielectric liquid cooling approach and many unique approaches should the goal of the Navy.

Recommendations

1. Proceed with the evaluation of spray COP for use as a general solution for cooling COTS. Spray COP is the most available advanced cooling technique at this time and is applicable to situations where the use of COTS is a necessity. It is the only technique with hardware available at this time.

2. Do a feasibility study on the development and demonstration of Jet Impingement COP cooling techniques to increase available cooling options, cooling capacity, and augment Spray COP capabilities. Jet impingement COP offers the potential for higher cooling capability and lower manufacturing cost. It is also not a proprietary technology at this time.

3. Do a feasibility study on the development and demonstration of Direct Immersion and Channel Flow COP cooling techniques to offer solutions not provided by Spray Cooling or Jet Impingement. It is also not a proprietary technology at this time.

4. Establish a second source for any liquid cooling technology used or purchase all design rights and manufacturing documentation.

5. Monitor liquid cooling technology developments on a regular basis.

	Complexity	Availability	Effectiveness	Cost
Liquid Flow Through				
Spray Cooling				
Jet Impingement				
Direct Immersion				
Channel Flow				

COMPARISON OF COOLING TECHNIQUES APPLIED TO COMMERCIAL PRODUCTS USED IN MILITARY ENVIRONMENTS

Introduction

Thermal Control, more commonly know as cooling, is a critical engineering discipline that must be successfully applied to ensure required performance and reliability in military electronic systems constructed using commercial-off-the-shelf (COTS) products. Studies performed during the last 40 years investigating military electronic system failures indicate that the majority were thermally related. Electronic parts fail catastrophically from simple overheating or due to a breakdown of components and attachment mechanisms brought on by thermal cycling that causes excessive expansion/contraction of internal parts and mounting substrates.

The prevention of catastrophic thermal failure must be the primary goal of all electronic thermal management schemes. Catastrophic failure can be defined as the immediate, thermally induced total loss of electronic function in a particular component or system. To avoid electronic equipment failure, it is therefore essential to minimize the thermally induced failure rates of each component comprising an electronic system. The two main problems that must be avoided are electronic components operating at elevated temperatures and excessive thermal cycling. Each can act independently to induce failure. In concert they can act synergistically to assure premature failures in electronic systems.

Mechanical/thermal engineers have spent untold hours developing highly sophisticated electronic packaging to protect against the effects of heat, cold, vibration, shock, electromagnetic radiation, electromagnetic noise, and, corrosion to ensure survivability in severe military environments. The requirement to use COTS in military electronic systems offers many technological and performance advantages but, in turn, causes incredible heartburn in packaging them in ruggedized schemes so as to survive the same harsh environments as "classic" military hardware did. While providing relatively low cost and high electronic performance, COTS hardware is basically fragile in environments other than relatively benign laboratory or industrial environments. Providing proper ruggedized protective packaging without turning enclosure systems into overweight, complicated, and expensive boxes is a challenging task.

Potential Thermal Control Techniques for use with COTS

Listed in ascending order of performance.

- Natural air convection
- Forced air convection
- Module thermal plane conduction to air or liquid convection heat exchangers

- Radiation
- Heat pipe technology (very difficult to attach to COTS modules, either as tubes or as "flat, shape-conforming plates")
- Dielectric liquids, e.g., non-CFC perfluorohexanes (3M Fluorocarbons), PAO (Coolanols), Silicone oils.

Note: "Fluorocarbons" are the much preferred dielectric liquids due to their safe performance properties.

- Direct immersion natural convection [sensible and Change of Phase (COP) mechanisms]
- Direct immersion forced convection (sensible and COP)
- Spray ("atomized mist") COP
- Jet impingement COP

Note: Sensible in this context is a thermal term defined as a non COP technique. It is not intended to convey a good or bad comparison.

NATURAL AIR CONVECTION: ADVANTAGES

- Abundant, free supply
- Requires no man-made pumping mechanisms.
- Minimal maintenance
- No weight and volume impacts on platform
- Can be an open system, i.e., once used it can be dumped
- Systems are inexpensive

NATURAL AIR CONVECTION: DISADVANTAGES

- Very low heat removal capacity
- Must have a gravity field present for buoyancy action
- May require cleaning [foreign object debris, e.g., dirt, chemicals, fuel, etc, foreign object debris (FOD)] and dehumidification
- Performance is adversely impacted by altitude. High altitudes severely reduce air molecular density and heat capacity of the coolant air.
- Equipment must be configured to enhance natural flow "updraft."
- Components must be arranged to keep the flow from absorbing excessive heat from "lower" components before reaching others that require substantial cooling.
- All components may not be reached by the air flow.

FORCED AIR CONVECTION: ADVANTAGES

- Abundant, free supply if taken from atmosphere
- Much more efficient in heat removal than natural air convection.

- May be taken from turbine engine bleed air or other source and conditioned to a low temperature.
- Can be used in open or closed systems.
- No atmospheric altitude impact if bleed air supplied

FORCED AIR CONVECTION: DISADVANTAGES

- Engine bleed air or other supply requires conditioning (throttling to lower temperature, filtering, etc.).
- Engine bleed air or other supply may be limited, depending on how supply is prioritized to other systems.
- Requires more complex pumping, ducting, and gasketing hardware. This adversely impacts platform weight, volume, and structural fatigue life of platform.
- Must be maintained
- Atmospheric or "cabin" air may require filtering to eliminate FOD.
- Added weight may require extra electronic system dynamics isolation if not hard mounted.
- Convection surfaces must be free from debris and corrosion, to maintain convection coefficients.

CONDUCTION: ADVANTAGES

- May utilize installation structures to reach an ultimate "heat sink" such as the ambient environment or a large system/platform heat exchanger.
- Module cards may use attached thermal planes of aluminum, copper, Invar (heavy), or polymer- or metal-matrix composite materials to transfer heat from components to other locations such as conduction/convection heat exchangers.
- Thermal planes may be double-walled to pass a coolant.
- Basic conduction mechanisms require no extra pumps, ducting, filters, collection reservoirs, etc.
- May be inexpensive unless more expensive materials are used. This in turn depends on cost of ownership and reliability.

CONDUCTION: DISADVANTAGES

- Requires high pressure, intimate contact between heat transfer surfaces. This may require extra machining and surface preparation, "thermal grease," other non-grease fillers.
- Material thermal conductivity dependant
- Thermal paths through multiple parts and surfaces will impose thermal resistances.
- Transfer surfaces must be maintained free of corrosion.

- Transfer surfaces must be free from vibration induced failures (separations leading to more thermal resistance.

HEAT PIPE TECHNOLOGY

- Heat pipes can provide great thermal transfer through their liquid to vapor COP action; much greater than conduction and air convection mechanisms. However, with respect to COTS electronics, unless the modules are designed specifically to incorporate tubular or flat, conforming hardware, they are not fiscally suitable.

RADIATION

- Radiation is not a good choice here either, as in a lot of "racked and stacked" electronic systems. The very fact of close proximity to other, equally dissipating (and receiving) units, will cause minimal, if any, "net losses" of thermal energy.

DIELECTRIC LIQUIDS: ADVANTAGES, IN GENERAL

- Can be used in direct contact with electronic components, eliminating thermal path resistances.
- Can deliver high heat transfer removal rates compared to air systems and conduction schemes with high path resistances.
- The perfluorohexanes, i.e., "fluorocarbons" such as 3M Company Fluorinerts, are very environmentally and "human" safe due to their inert, nontoxic, nonresidue, and nonflammable nature.
- Saturation temperatures can be somewhat tailored to match component environment requirements. this eliminates elevated temperatures.
- When used as COP, component temperatures can be maintained reasonably constant. This eliminates thermal cycling.
- Large quantities are not necessarily required, thus avoiding excessive weight (specific gravity for FC-72 = 1.62).

The following considerations must be balanced when using an existing liquid or tailoring one.

- Cost/availability
- Thermal transfer properties
    - Specific heat
    - Thermal conductivity
    - Saturation temperature and pressure (i.e., @ "boiling" COP)
    - Freezing temperature (pour point)
    - Viscosity
    - Density
- Circulation rates

- Dielectric strength
- Inertness and compatibility
- Toxicity
- Thermal decomposition and impurities
- Surface tension
- Moisture effects
- Pour and flash points
- Flammability
- Oxygen displacement

DIELECTRIC LIQUIDS: DISADVANTAGES, IN GENERAL

- Not as good as water for heat removal. At 70 - 80 F the specific heat of water at 70 - 80 F = 0.99Btu/LB while the specific heat of the fluorocarbons = approximately 0.25. However, water cannot be readily used as a dielectric direct contact fluid.
- Requires complex hardware (especially for sprays with very critical nozzle dimensioning and manufacture)
- Cost can be high, although continued use has caused reductions in cost.
- Are heavier than water. At specific gravity = 1.62 for FC-72, one gallon = approximately 13.2 pounds (assuming 8.2 lbs/gallon for water). However note that huge quantities are not necessarily required.
- COP action requires fluid reconditioning, i.e., temperature control, condensation, etc.

DIRECT IMMERSION: NATURAL CONVECTION, ADVANTAGES

- Natural convection requires no fluid moving hardware.
- Direct contact with parts
- Can be used in either sensible or COP methods.
- See above general advantages.
- Can provide close temperature control when used as COP.
- See dielectric liquid advantages.

DIRECT IMMERSION: NATURAL CONVECTION, DISADVANTAGES

- Lowest heat removal capability of the fluorocarbon mechanisms
- Can be heavy, depending on system volume.
- See dielectric liquid disadvantages.

DIRECT IMMERSION: FORCED CONVECTION, ADVANTAGES

- Greater thermal transfer than previous.
- Direct contact with parts.
- With COP and Channel Flow COP, heat removal begins to exceed other methods discussed previously and results in approximate constant part temperatures. See above advantages.

- When used as COP and Channel Flow COP, subcooled inlet liquid can cause complete condensation of the vapor micro bubbles within the bulk fluid flow, thus requiring conditioning only a single phase liquid. This leads to a more efficient mode of heat exchanger action and system operation.
- More simple method than spray and jet methods, yet affording high heat flux values.
- See dielectric liquid advantages.

DIRECT IMMERSION: FORCED CONVECTION, DISADVANTAGES

- Requires pumping hardware and associated maintenance/cost.
- Requires fluid reconditioning.
- Critical heat flux of the liquid coolant must be matched to the system requirements to avoid exceeding nucleate boiling regime and leading to overheating and catastrophic failure. This is not necessarily a "disadvantage," just a design requirement.
- See dielectric liquid disadvantages.

SPRAY COP: ADVANTAGES

Previous studies have indicated these advantages.

- Can provide high heat flux.
- Gives good coverage due to atomizing action.
- May use less fluid than forced convection, bulk flow mechanism.
- May use slightly less fluid than jet impingement.

SPRAY COP: DISADVANTAGES

Previous studies have indicated these concerns.

- Requires special spray nozzles.
- Requires complex fluid handling and reconditioning (condensation, heat exchanger with ultimate "sink", etc) equipment. This adds weight and associated penalties to platform systems.
- Quality control is critical. Studies have shown that the nozzles are very sensitive to manufacturing tolerances and quality.
- Nozzle action can change in time due to erosion, corrosion build up, and contaminants.
- Spray distance to components is critical for development of "spray cone."

- Spray velocity and momentum can be critical. If too great, it can lead to part erosion, and splashing away without proper wetting of the part surfaces, leading to poor cooling.
- Proper distance and some degree of confinement has been found necessary to avoid separation from surfaces, leading to poor wettability.
- Must be used only as COP. Has poor sensible cooling action
- High pressure required.

JET IMPINGEMENT COP: ADVANTAGES

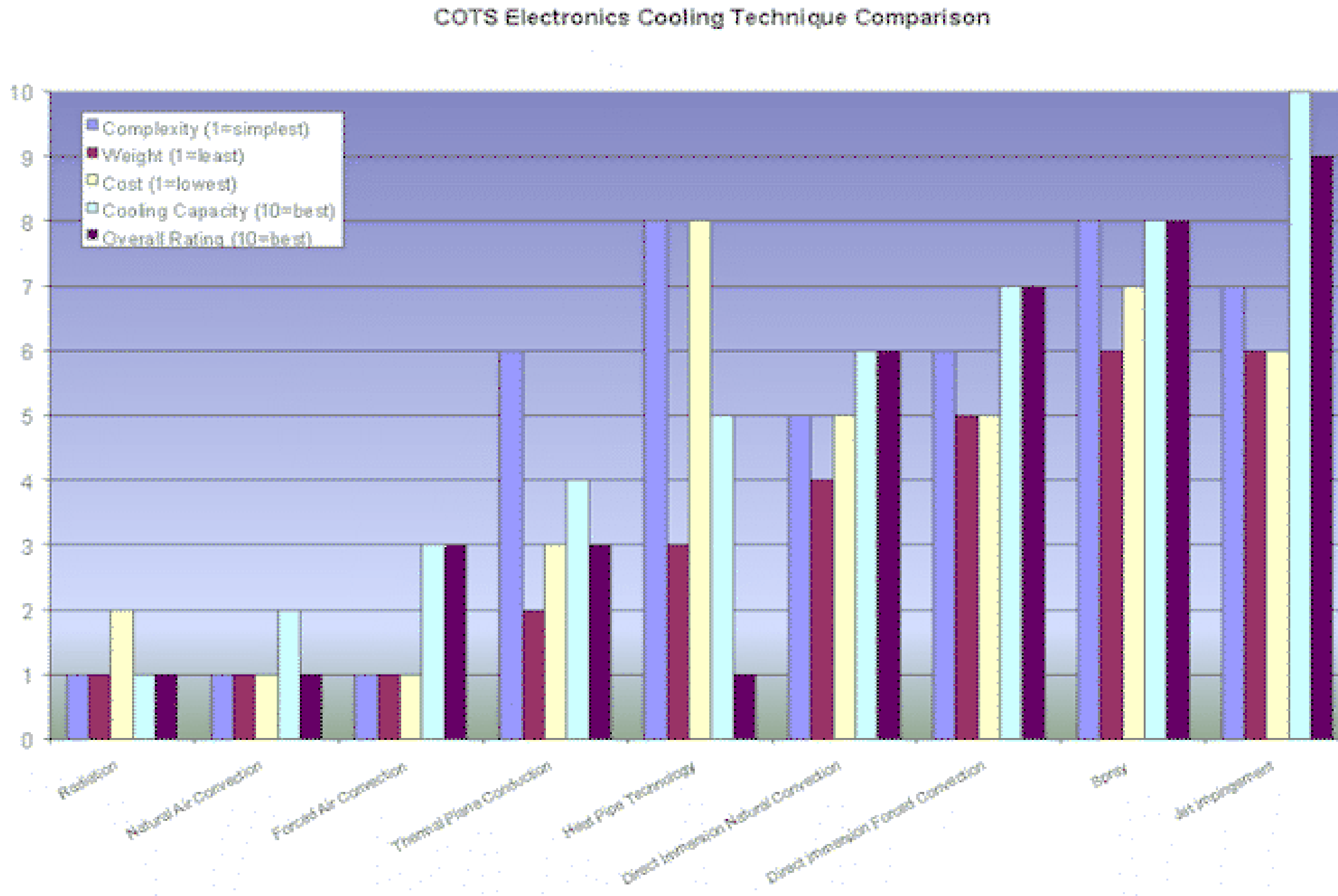
Previous studies have indicated these advantages.

- Very high heat fluxes can be achieved if desired.
- Critically designed/manufactured nozzles not required. Plates with machined openings can be used.
- Flow can be localized if only a single jet is used.
- Multiple jets placement is not as critical with respect to closeness to/from parts.
- Jet hardware is more repeatable and durable due to less precision required in jet openings.
- Will not splash and separate away from parts. There is no cone effect requiring specific locations with respect to parts.
- Thermal transfer can also take place in sensible regime better than with spray. This could benefit overall cooling and offer some redundancy.

JET IMPINGEMENT COP: DISADVANTAGES

Previous studies have indicated these concerns.

- Requires complex fluid handling and reconditioning (condensation, heat exchange with ultimate "sink," etc) hardware. This adds weight and associated penalties to platform systems.



Cooling Technique	Cooling Capacity	Complexity	Weight	Cost	Description/Comment	Overall Rating 1=poor 10=excel
Radiation	Low	Low	Low	Low	Does not allow dense COTS card packaging. Very low cooling capacity.	1
Natural Air Convection (1)	Low	Low	Low	Low	Low cooling capacity. Subjects COTS cards to heat, cold, humidity, salt, and contamination of military environment.	1
ed Air Convection (1)	Low	Low	Low	Low	Low to moderate cooling capacity. Can be used in open or closed systems. Subjects COTS cards to heat, cold, humidity, salt, and contamination of military environment.	3
ule Thermal Plane nduction to Heat Exchanger	Moderate	Moderate	Moderate	Moderate to High	Requires custom machined conduction planes for each COTS card. Moderate heat removal capacity. Can be used in closed system.	3
: Pipe Technology	Moderate	High	Moderate	Moderate to High	Expensive and very difficult to adapt to COTS cards. Normally designed into card frame and enclosure structure.	1

rect Immersion tural Convection	Low to Moderate	Low	Depends on type and quantity of coolant fluid	Depends on type and quantity of coolant fluid	Good heat removal capacity. Technically simple. Cost and weight of coolant may be problematic in some applications. Requires sealed enclosure. ILS issues may exist.	6
rect Immersion rced Convection	Moderate to High	Low to Moderate	Depends on type and quantity of coolant fluid	Depends on type and quantity of coolant fluid	Very good heat removal capacity. Cost and weight of coolant and fluid handling/reconditioning equipment may be problematic in some applications. Requires sealed enclosure. ILS issues may exist.	7
Spray hange of Phase (COP)	Moderate to High	Moderate to High	Depends on type and quantity of coolant fluid	Moderate to High	Very good heat removal capacity. System contains special spray nozzles, fluid handling /reconditioning equipment, and electronic controls. Requires sealed enclosure. Long term reliability unknown. ILS issues may exist. Most developed cooling technique for COTS at present.	8
et Impingement hange of Phase (COP)	Moderate to High	Moderate to High	Depends on type and quantity of coolant fluid	Low to Moderate	Excellent heat removal capacity. System contains simple spray nozzles, fluid handling/reconditioning equipment, and electronic controls. Requires sealed enclosure. Potentially lower cost than Spray. High reliability. ILS issues may exist. Potentially the best system when fully developed.	8-10