Electronic Coolants for Laser Chillers and Direct Refrigerant Chillers for Electronic Systems

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Purpose and Motivation

Purpose:

1. Outline and review fluids used as electronic coolants, focusing on:
   - Primary fluids commonly used for commercial electronic systems
   - Fluids used and anticipated for vehicle electronics
   - Fluids used for military and aerospace electronic systems

2. Outline practical considerations for primary fluids:
   - Water is well-known but is not simple to use;
   - Certain market segments require extensive evaluation and understanding of characteristics of water and how water must be controlled.
   - *Practical* comparative data for applications.

3. Describe developments and trends:
   - Many types of liquids are available and/or under development.
   - New applications and concerns for performance and cost are developing.
   - Application parameters determine what is practical and effective as a coolant.

Liquid Cooling for Electronic Systems

A note on terminology:

"Water-based" in this presentation is intended to mean using water as the coolant. In general use, this can mean:

- Water contained in a closed system supplied from a cooling tower, chiller, city or utility supply, or other source.
- Water in some mixture with additives such as a glycol for frost protection, or with biocides and other treatments to control pH, corrosion, organic growth.
- Deionized water in a sealed system or supplied through a deionization system.

Water, while having excellent heat capacity and other properties, is not simple. Other coolants are also available and, in certain electronics industry market segments, widely used.

Liquid Cooling for Electronic Systems

Traditional path historically to liquid cooling applications for electronics:

- Considered and implemented when forced-air cooling capabilities have been exhausted for a given set of power dissipation, environmental, and application parameters.
- Single-phase water-based systems predominate as the first level decision:
  - Typically, using liquid cold plates for mounting and indirect contact cooling.
  - Typically single-phase water
  - In military and avionics applications, indirect contact is often through liquid flow-through (LFT) aluminum sidewalls for ruggedized enclosures
  - Circuit boards are mounted to conduction plates to carry heat load to the LFT wall.

Selective forms in specific market segments:

- Liquid immersion with dielectric fluids.
  - Most commonly found in semiconductor test and burn-in applications.
  - Variety of packaging concepts for immersion.
- Vapor-cycle refrigeration and air conditioning in several formats:
  - Most often found in semiconductor test and burn-in applications

Alternative concepts for electronics:

- Spray cooling in several forms, typically with dielectric fluids.
- Pumped liquid metal alloys (not explored here in detail).

Liquid Cooling System Performance

What performance improvements can be gained with different thermal management solutions (ignoring vapor cycle refrigeration for the moment)?

Type of IGBT Packaging and Thermal Management Scheme	Average Heat Flux Achieved (W/cm^2 of Silicon)
Standard IGBT Module/Natural Convection	11
Standard IGBT Module/Forced Convection	33
Press-Pack GTO/Pool Boiling	25
Standard IGBT Module/Thermogravity Heat Pipe	32
Standard IGBT Module/Oil cooling	60
Standard IGBT Module/Water Cooling	83
Direct Cooling/Minichannel Water/EG Cooling	120
Direct Cooling/Minichannel Double Sided Water Cooling	180
3D Silicon/Microchannel/Water Cooling	400

ALSTOM

Source: M. Mermet-Guyennet, Alstom Transport, "An Overview on Thermal Management for Power Chips", IMAPS France ATW Thermal 2006, La Rochelle, France, February 1-2, 2006

Liquid Cooling System Performance

Cooling System Type	Coolants	Primary Market Segments
Single-phase water	Tap water, chilled water Deionized water EGW, PGW (glycol, other antifreeze mixtures)	Industrial, commercial power electronics; electrical drives; laser systems; instrumentation; medical imaging systems; computing systems; ground vehicle systems; military/aerospace power systems
Single-phase mil/aerospace	Dielectric liquids (PAO, 3M Fluorinert™ liquids, Fluoroketones; silicate esters; oils)	Military airborne, shipboard, ground systems
Single-phase dielectric liquids	Dielectric liquids (3M Fluorinert and Solvay Galden™ liquids, HFCs, Fluoroketones)	Semiconductor test, semiconductor burn-in; Mil-Spec shock and environmental testing of semiconductor components; semiconductor fab; plasma generators.
Two-phase water	Tap, chilled, deionized water	Industrial power electronics (including heat pipes); laboratory use and evaluation
Two-phase dielectric liquids	Dielectric liquids (3M Fluorinert™ liquids, Fluoroketones, HFCs), R-134a refrigerant	Computing, industrial power electronics
Liquid spray cooling	Dielectric liquids (3M Fluorinert™ liquids, Fluroketones, HFCs), oils	Aerospace power supplies; computing
Liquid immersion	Dielectric liquids (3M Fluorinert™ liquids, Fluoroketones, HFCs); oils	Traction; Industrial mining vehicle powertrains; transformers; computing
Vapor cycle compression	Refrigerants, carbon dioxide	Military airborne electronics; semiconductor burn-in, test, validation; diode laser modules; CO_2 and other laser types; vehicle/HEV

Source: DS&A LLC

Properties of Typical Electronic Coolants

Coolant	Thermal Conductivity (W/m-K)	Thermal Expansion Coefficient (K^{-1})	Specific Heat (J/kg-K)	Boiling Point (°C)	Freezing Point (°C)	Reference Temperature (°C)
Water	0.600	0.0003	4279	100	0	25
Ethylene Glycol/Water (50%)	0.404	0.0016	3341	107.2	-34	25
Propylene Glycol/Water (50%)	0.382	0.0023	3640	222	-28	25
3M™ Novec™ HFE-7100 (HFE)	0.069	0.0018	1183	61	<-38	25
3M Novec HFE-7300 (HFE)	0.063	0.0013	1140	98	<-38	25
3M Novec 649 (FK)	0.059	0.0018	1103	49	<-100	25
3M Fluorinert FC-72 (PFC)	0.057	0.0016	1100	56	-90	25
Polyalphaolefin (2cSt) (PAO)	0.142	0.0008	2219	55	-73	26.67
Coolanol-20	0.120	0.0005	1907	232	<-73	26.67
R-134a	0.0824/0.0145 Liquid/vapor[1]	N/A	1400	-26.1[2]	-103	25
R-744	0.0146 Vapor[3]	N/A	N/A	-78	-56.5	0
Dynalene FC	0.325	N/A	3256	109	N/A	25

Note 1. Vapor at 1 atm (101.3kPa), 25°C. Note 2: Boiling point at 1 atm, 25°C. Note 3. Vapor at 101.3kPa, 0°C.

Properties of Typical Electronic Coolants

Coolant	GWP (GWP)	Flashpoint (°C)	Vapor Pressure (kPa)	Dielectric Constant (@1kHz)	Prandtl Number	Liquid Density (kg/m^3)	Reference Temperature (°C)
Water	0	None	3.2	78.5	6.2	997	25
Ethylene Glycol/Water (50%)	Low	111	2.3	N/A	29	1076	25
Propylene Glycol/Water (50%)	Low	99.1	N/A	N/A	46	1034	25
3M Novec HFE-7100	297	None	27	6.1	N/A	1510	25
3M™ Novec™ HFE-7300	210	None	5.9	7.4	N/A	1660	25
3M Novec 649 (FK)	1	None	40	1.8	N/A	1600	25
3M Fluorinert FC-72	>6000	None	30	1.8	14	1680	25
Polyalphaolefin (PAO)	N/A	163	<1	N/A	88	787	26.67
Coolanol-20	N/A	>230	5.3[1]	2.1	31	887	26.67
R-134a	1300	None 750[2]	661.9[3]	9.5	N/A	1210	25
R-744	1	None	7.80[4]	N/A	N/A	N/A	25
Dynalene FC	N/A	None	N/A	N/A	N/A	1044.8	25

Note 1: @150°C Note 2: Autoignition temperature shown. Flash point: None. Note 3: Vapor pressure, saturated liquid. Note 4: @20°C.*

Terminology - Refrigerants

Term	Definition
Bubble-point temperature	Temperature at which boiling begins, with bubble initiation.
Critical point	Point at which the properties of liquid and vapor phases of the refrigerant are identical, at a specific temperature and pressure.
Critical pressure	Pressure at the critical point of the refrigerant.
Critical temperature	Temperature at the critical point of the refrigerant.
Dew point	Temperature and pressure at which condensation forms as a fluid is cooled.
Normal boiling point (NBP)	Temperature at which refrigerant boils at standard atmospheric pressure [101.325 kPa (14.6969 PSIA)].

Source: DS&A LLC

Water-Based Coolants

Long recognized for high heat capacity as an electronic coolant. Water does not typically work alone for electronics cooling systems:

- Deionization is frequently required to eliminate chlorine and other ions and reduce risk of galvanic and other types of corrosion.
  - Leakage current in semiconductor devices is increasing with increased frequencies and power characteristics and further impacts electrical performance.
- Addition of ethylene glycol (EG) or propylene glycol (PG) for frost protection in mixtures to approximately 65%.
  - Ethylene glycol is more effective as a frostproofing additive than propylene glycol, but has a higher toxicity.
  - Propylene glycol is more effective as a heat transfer agent than ethylene glycol.
  - Low flammability for either EG or PG.
  - Increasing frostproofing additive percentage decreases fluid thermal performance.
- Other additives required based on fluid operating temperatures:
  - Corrosion inhibitors
  - Algaecides
  - Biocides
  - pH control

These are not insignificant factors in cooling system design.
-- Add significantly to complexity and maintenance
-- Replacement of corrosion inhibitors is required when exhausted
-- Strength of electric field can be critical to additive performance
-- Highly application-specific.

Water-Based Coolants

An example of where use of a deionized water/ethylene glycol mixture may present unsolvable difficulties for system operation in practice:

- Radome or RF module on UAV platform:
  - Closed-loop liquid cooling system required
  - Fuel is not an option as a coolant for an add-on system or for full flight envelope
  - High dielectric strength for fluid required to prevent galvanic action and corrosion or ion scavenging from electronic components.
  - Deionized water system for deionized water/ethylene glycol coolant mixture must require changeout of De-I canister every two months, on average, for fleet operation:
    - Cost of canister $\simeq$ USD 100.00.
    - Fluid required: 100-200ml
    - Logistical requirement for De-I canister changeout is not practical for 24/7 fleet operations in remote areas.

Dielectric Fluids

- A dielectric fluid is selected for one or more reasons:
  - Immersion or direct contact with electrically-live components, to eliminate packaging and thermal interface materials to achieve a best-possible (lowest) overall package thermal resistance value.
  - Safety, to prevent contact between electrically-conductive fluids and electronic components.
    - Critically important to prevent electrical arcing, for human safety for power electronic systems;
    - Prevent failure of electronics due to shorting.
  - Spray or impingement cooling system design
  - Minimize cost of packaging (dependent on packaging scheme employed).
  - A dielectric fluid, such as a refrigerant, may be selected for other reasons, for practicality *which may outweigh a significantly lower thermal conductivity of the fluid*:
    - Avoidance of need for additives such as frostproofing or corrosion control
    - Common availability at low cost, globally, with excellent vaporization properties
    - Availability in logistics and/or familiarity of global field service and maintenance technicians and installers
    - Compatibility with a wide range of known materials, components, tubings, sealants.

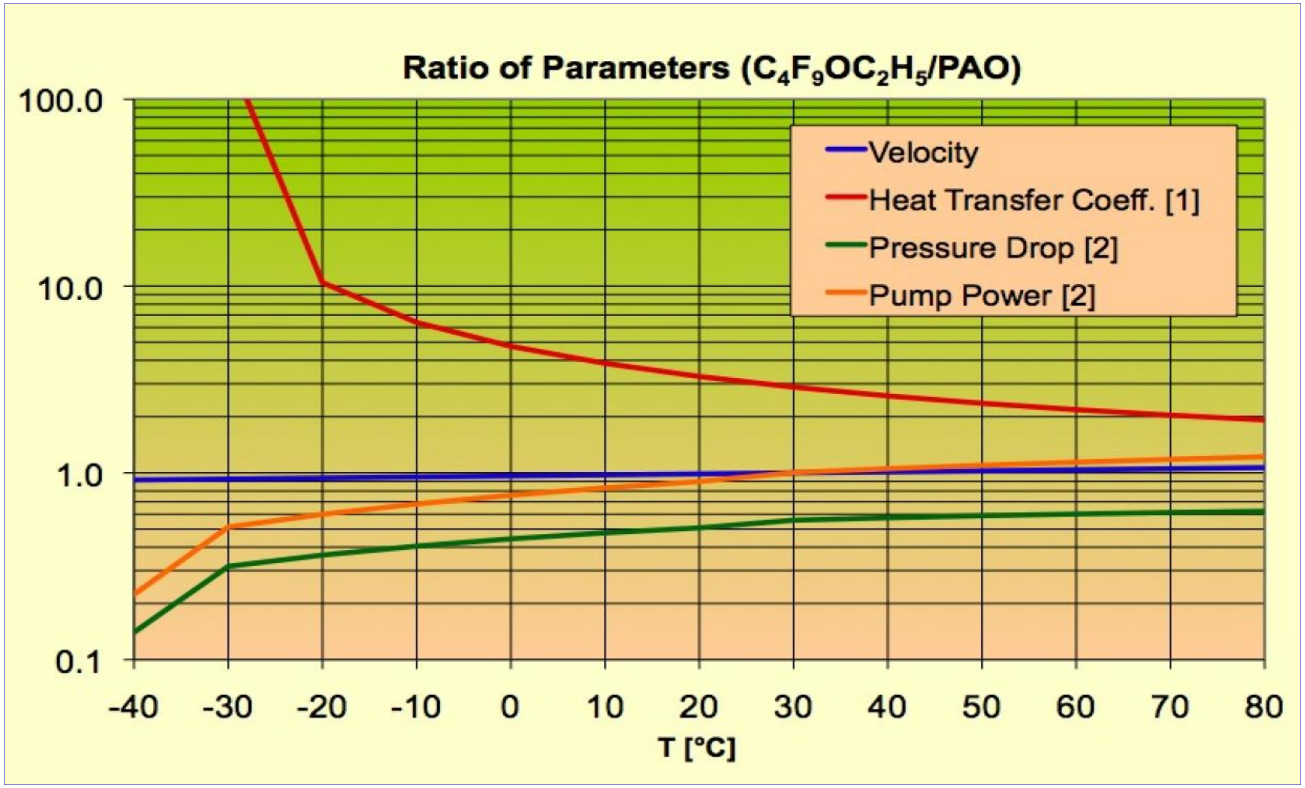
Refrigerant Fluids

- Properties of refrigerant fluids
  - Boiling point:
    - Single-compound refrigerants initiate boiling at a single temperature and pressure.
    - Blended-compound refrigerants initiate boiling over a range between bubble point and dewpoint temperatures, due to differing volatility of the components that cause mixture boiling.
    - Boiling (bubble) point is typically indicated as the Normal Boiling Point (NPB) for blended refrigerants.
- Selection of refrigerant fluids:
  - Initial selection of a particular refrigerant for a given set of application conditions may be made by examining the combination of NBP, Critical temperature, and Critical pressure.
- Naming conventions for refrigerant fluids have been devised by ASHRAE based on toxicity, flammability, and exposure under ASHRAE Safety Group 34.

Source: J. M . Calm, G. C. Hourahan, "Refrigerant Data Summary," Engineered Systems Magazine, November 2001, pp. 74-11.

Military and Aerospace Coolants

- Flow performance comparisons for a common PAO and HFE dielectric liquids:
  - Ratio comparisons for Polyalphaolefin and HFE for four critical parameters



Note: Flow calculations for 3M Novec™ 7200 (HFE) versus Polyalphaolefin (PAO). (1) Higher HTC is better; (2) A lower pressure drop value is better and a lower pump power requirement is better. Source: 3M Company.

Military and Aerospace Coolants

- Polyalphaolefins (PAO) have become the generally-accepted alternative to silicate ester fluids such as the Coolanol family for military electronic systems:
  - Synthetic oil-based, insoluble in water
  - Excellent thermal conductivity and good heat transfer characteristics
  - Good lubricity
  - Relatively inexpensive
  - Primary coolant for recent USAF platforms (e.g., F-22 Raptor)
  - High viscosities at low temperatures, a concern for certain applications and high altitudes, as required pumping power increases.
  - Low vapor pressures, making use for spray or evaporative cooling difficult in practice.
  - Flammable (flash point: 163°C).
- Silicate esters (Coolanol family), at one time a preferred coolant for mil/aero systems:
  - Excellent thermal conductivity, high boiling point, low freeze point.
  - Hygroscopic
  - Subject to decomposition in moisture and high electric field conditions, leading to reduced effectiveness and formation of flammable alcohols.
  - Therefore, no longer typically a candidate for evaluation for mil/aero applications.

Note: Statements are generalized for the family of PAO and silicate ester chemistries. Refer to manufacturer data for a specific chemistry.

Perfluorinated Fluorocarbon (PFC) Coolants

- Perfluorinated fluorocarbons are well-known and often viewed as an industry standard for many applications and for academic investigations.
  - Wide range of applications for commercial, military, and aerospace electronics:
    - Enterprise computing systems (Cray, ETA, others) utilizing liquid immersion
    - Semiconductor test and burn-in systems
    - Environmental testing standards for electronics (direct contact, shock, gross leak tests) as specified fluids:

      Mil-S-750

      MIL-S-883
    - PVD and plasma generator systems
    - Electronic component cleaning
    - Many major mil/aerospace systems:
      - Raytheon Patriot
      - Boeing AWACS
      - UAV (Global Hawk, Predator)
      - Others

Perfluorinated Fluorocarbon (PFC) Coolants

- Perfluorinated fluorocarbons are well-known and often viewed as an industry standard for many applications and for academic investigations.
  - Advantages:
    - Extremely stable
    - Highly stable dielectric properties over time, even in proximity to high electrical stresses and direct contact to electronic components.
    - Tailored boiling points (i.e., individual fluids tailored to a specific BP for major application requirements), with other properties remaining similar.
    - Mixtures may be used to tailor for a specific temperature range and BP.
    - Chemically inert and excellent toxicological properties.
    - Nonflammable
    - Extensive academic testing data and evaluation of properties in microchannels, spray cooling, and other relevant electronic thermal management technologies.
    - Ozone depletion potential (ODP): zero.
  - Primary product families: 3M Company Fluorinert™, Solvay Galden™ liquids.
  - Significant disadvantages:
    - Exceptionally high Global Warming Potential (GWP) value prevents consideration for most new applications.

Introducing New Fluids to Market

- Conservative nature of electronics market makes introducing new fluids more difficult
  - Regardless of theoretical improvements in performance on some scale
  - Long-term performance for system reliability must be examined
  - Research to identify potential failure mechanisms will be tested if performance warrants
- Many potential obstacles to evaluation and implementation:
  - Reliability
  - Toxicity
  - Flammability
  - Suspensions may be impacted by positive-displacement pump operation
  - Chemical constituents (chlorines, fluorines, et. al)
  - Approved known compatible sealants, tubings, container materials
  - Testing and regulatory approval for medical electronic systems applications
  - Logistical and practical obstacles for military/aerospace applications
  - Industrial logistical and safety requirements:
    - Uniform industry labeling standards (similar to established ASHRAE standards for containers for refrigerants) such as color coding of containers.
    - Service industry training and logistical requirements.

Nanofluids

- Developments of potential new coolants containing nanoparticles of some kind offer new opportunities for expanding the types of fluids available:
  - Typical materials considered for creating nano-sized constituent particles:

    Alumina (Al_2O_3)
    Carbon nanotubes
    Copper
    Copper oxide
    Silicas
    Titanium oxide
- The usual obstacles to evaluation and implementation:
  - Reliability over time, aggregation, pumping impact on dispersions, erosion
  - Toxicity and EU concerns for use of nanoparticles for workplace and human safety
  - Flammability
  - Chemical constituents (chlorines, fluorines, et. Al)
  - Approved known compatible materials as sealants, tubings, containers
  - Testing and regulatory approval for medical electronic systems applications
  - Logistical and practical obstacles for military/aerospace applications
  - Service industry training and logistical requirements.

Nanofluids

- What might characterize a "good" nanofluid (from a heat transfer perspective)?
  - High heat transfer rates
  - Low viscosity
  - Stability and compatibility
  - Inexpensive

Source: Theodore Bergman, "NSF Perspective on Nanofluids for Heat Transfer," INPBE Workshop (invited lecture), Beverly Hills CA USA, January 29-30, 2009

Nanofluids

Many academic investigations conducted to date, globally:

- Colloidal suspensions with particle sizes of approximately 10-40nm appear to yield significant increases in thermal conductivity of a water-based fluid.
- Highly stable, no significant settling observed in static (i.e., non-pumped) conditions
- Static conditions yield impressive results. Example:
  4.3% (vol.) Al_2O_3 nanoparticles (13nm): +30% increase in thermal conductivity of water under static conditions
- Larger (approaching 40nm and larger) particle sizes show an increase of $\leq$ 10% additional with an equal volume fraction.
- Apparent performance improvements with nanoparticle-containing fluids may in fact be due to changes in related and other factors:
  - *Induced* by particle presence (but not necessarily a change in fluid performance).
  - In some cases, may have a one-time impact on extending CHF.
- Development of an accurate analytical model to calculate the performance of a nanofluid is the subject of substantial academic research effort.

Sources:
P. Keblinski, Rensselaer Polytechnic Institute; S.R. Phillpot, S.U.S. Choi, J.A. Eastman, Argonne National Laboratory, "Mechanisms of Heat Flow in Suspensions of Nano-sized Particles (Nanofluids)," International Journal of Heat and Mass Transfer, Vol. 45, 2002, pp. 855-863.
S. Lee, S.U.S. Choi, S. Li, J.A. Eastman, "Measuring Thermal Conductivity of Fluids Containing Oxide Particles," ASME Journal of Heat Transfer, Vol. 121, 1999, pp. 280-289.

Commercialized Nanofluids: Future

Test and evaluation issues:

- Maintaining a colloidal suspension for periods of storage, shipment, and inventorying may prove to be difficult.
- Use in cooling systems with PD pumps may impact suspensions; maintaining a colloidal suspension may prove to be difficult.
- Impact of nanoparticles in fluid flow must be investigated.
- Aggressive particle materials are a concern within system components.
- Human health and safety factors are a consideration for nanoparticle use.
- For two-phase systems:
  - Vapors with a high boiling point require large component volumes
  - Larger diameter piping
  - Potentially larger volume required for reservoir, separator, other components

Typical barriers to introduction and implementation of a new coolant can be assumed to apply.

Refrigerants as Electronic Coolants

Common refrigerants such as R-134a and HFO-1234yf offer excellent properties for use as dielectric coolants for electronic systems:

- Compatible with a wide range of rubbers, polymers, and other sealant and tubing and insulating materials;
- Compatible with many engineered plastics
- Compatible with refrigerant oils typically used in HVAC industry or lubrication
- Improved viscosity (with lubricant) versus water and EGW for microchannel construction;
  - Less propensity for bubble and other potential blockages
  - Used in a sealed system, not requiring periodic refilling and therefore with no potential for particulate entrance;

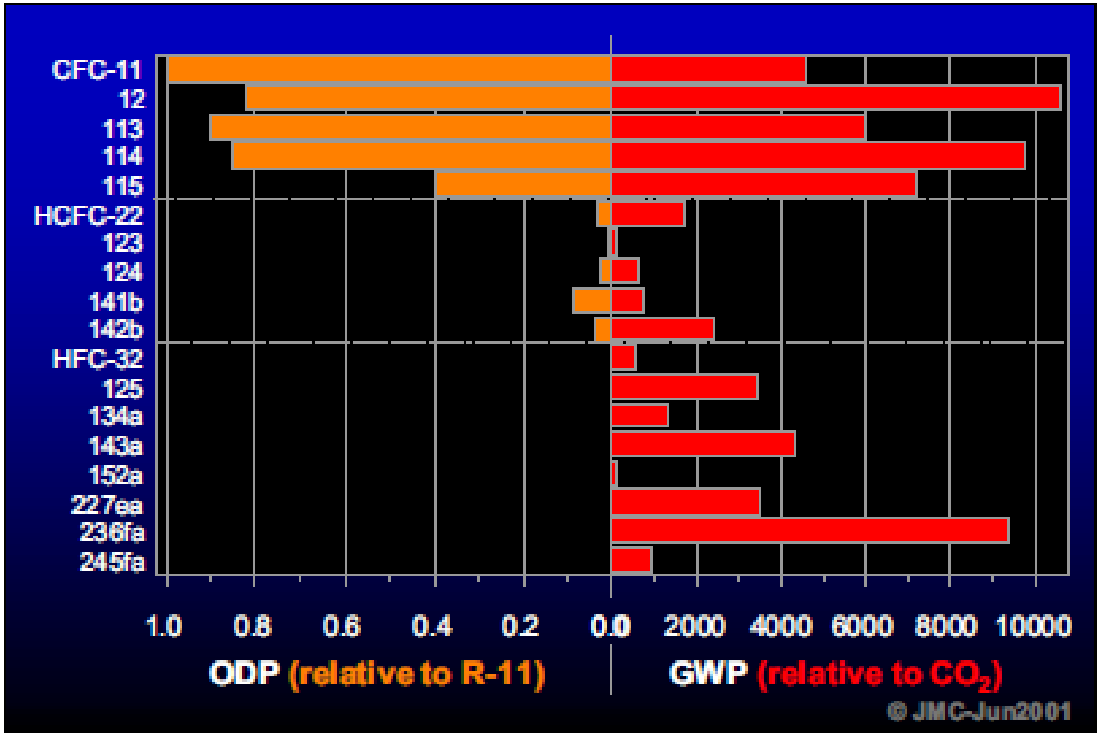
Practical characteristics of refrigerants:

- Non-toxic and evaporates at room temperature, with no damage to electronics
- Available globally from many suppliers at reasonable cost
- For military ground vehicle applications: already in the military logistics pipeline.
- Stable and inert across a wide temperature range, not requiring frostproofing.

Refrigerants as Electronic Coolants - Concerns for ODP and GWP

Environmental concerns for refrigerants:

- Oxygen Depletion Potential (ODP)
- Global Warming Potential (GWP)
- Primary target for change directives is mobile A/C for vehicles

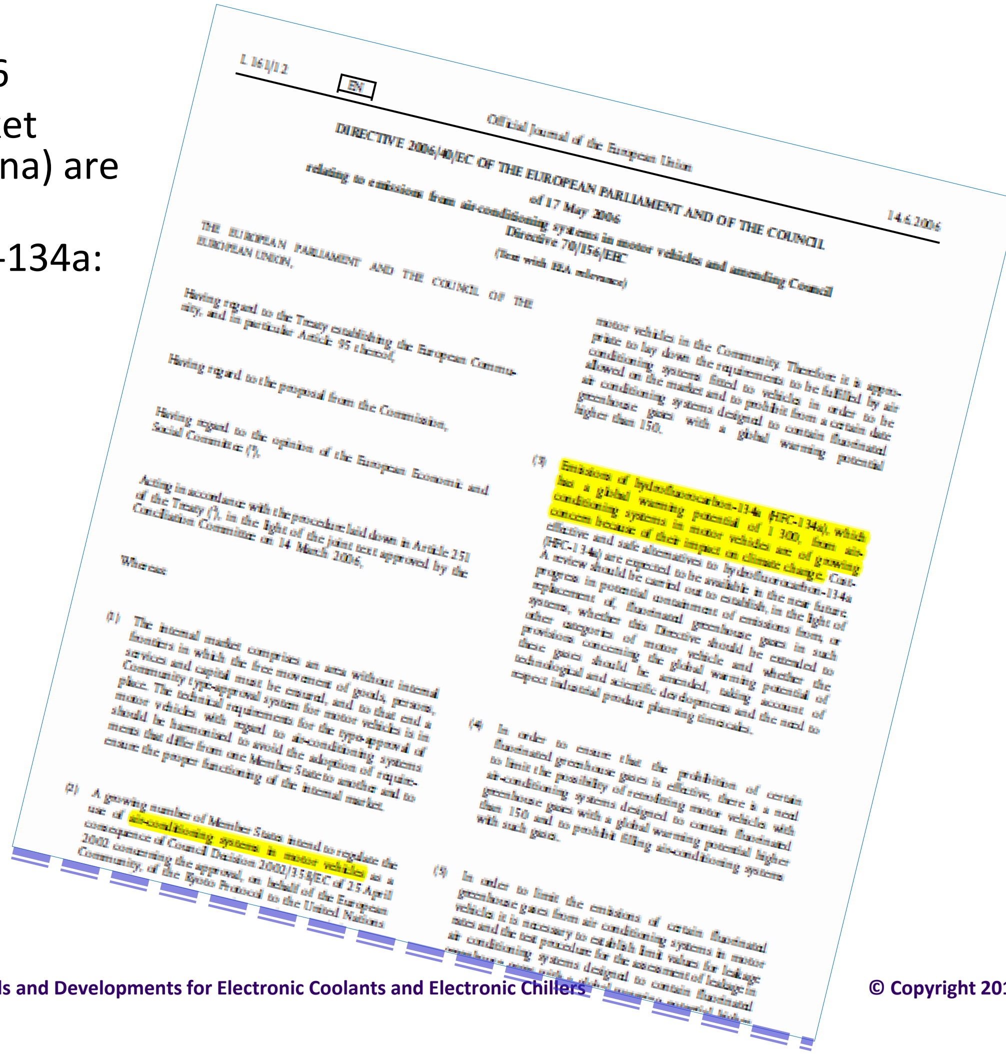


Source: J. M . Calm, G. C. Hourahan, "Refrigerant Data Summary," Engineered Systems Magazine, November 2001, pp. 74-11.

Refrigerants as Coolants - Concerns for ODP and GWP

An EU directive designates R-134a and similar refrigerants as a target for replacement:

- Eliminate the use of medium- and high-GWP fluids for mobile (vehicle) A/C systems
- Target: GWP = 1
- Published: 17 May 2006
- World automotive market associations (except China) are on board.
- Replacement fluid for R-134a: HFO-1234yf:



L 161/12 EN Official Journal of the European Union 14.6.2006

DIRECTIVE 2006/40/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 17 May 2006

relating to emissions from air-conditioning systems in motor vehicles and amending Council Directive 70/156/EEC

(Text with EEA relevance)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 95 thereof,

Having regard to the proposal from the Commission,

Having regard to the opinion of the European Economic and Social Committee (¹),

Acting in accordance with the procedure laid down in Article 251 of the Treaty (²), in the light of the joint text approved by the Conciliation Committee on 14 March 2006,

Whereas:

(1) The internal market comprises an area without internal frontiers in which the free movement of goods, persons, services and capital must be ensured, and to that end a Community type-approval system for motor vehicles is in place. The technical requirements for the type-approval of motor vehicles with regard to air-conditioning systems should be harmonised to avoid the adoption of requirements that differ from one Member State to another and to ensure the proper functioning of the internal market.

(2) A growing number of Member States intend to regulate the use of air-conditioning systems in motor vehicles as a consequence of Council Decision 2002/358/EC of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations

motor vehicles in the Community. Therefore it is appropriate to lay down the requirements to be fulfilled by air conditioning systems fitted to vehicles in order to be allowed on the market and to prohibit from a certain date air conditioning systems designed to contain fluorinated greenhouse gases with a global warming potential higher than 150.

(3) Emissions of hydrofluorocarbon-134a (HFC-134a), which has a global warming potential of 1 300, from air-conditioning systems in motor vehicles are of growing concern because of their impact on climate change. Cost-effective and safe alternatives to hydrofluorocarbon-134a (HFC-134a) are expected to be available in the near future. A review should be carried out to establish, in the light of progress in potential containment of emissions from, or replacement of, fluorinated greenhouse gases in such systems, whether this Directive should be extended to other categories of motor vehicle and whether the provisions concerning the global warming potential of these gases should be amended, taking account of technological and scientific developments and the need to respect industrial product planning timescales.

(4) In order to ensure that the prohibition of certain fluorinated greenhouse gases is effective, there is a need to limit the possibility of retrofitting motor vehicles with air-conditioning systems designed to contain fluorinated greenhouse gases with a global warming potential higher than 150 and to prohibit filling air-conditioning systems with such gases.

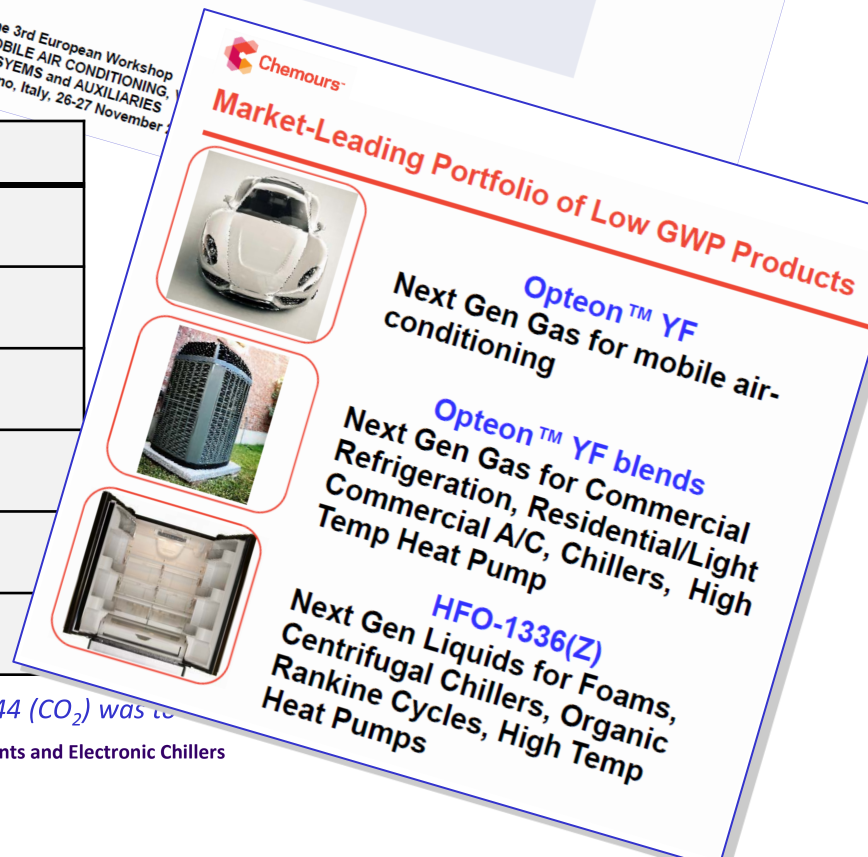
(5) In order to limit the emissions of certain fluorinated greenhouse gases from air conditioning systems in motor vehicles it is necessary to establish limit values for leakage rates and the test procedure for the assessment of leakage in air conditioning systems designed to contain fluorinated

Refrigerants as Coolants - Concerns for ODP and GWP

HFO-1234yf refrigerant replacement for R-134a:

- Joint development program: Dupont, Honeywell
- "Drop-in" replacement for R-134a
- GWP value: 4
- Pilot production availability: 2010
- Originally targeted for EU vehicles production
- Planned usage (in process):

Region or Country	Refrigerant
Asia (Except China)	HFO-1234yf
China	R-134a
European Union	HFO-1234yf
Germany	R-744*/HFO-1234yf
North America	HFO-1234yf
South America	HFO-1234yf



** German automotive manufacturers' association initially announced that R-744 (CO_2) was t*

Refrigerants for Electronics Cooling

Application areas for system development:

- Traditional vapor-cycle compression refrigeration
- *Pumped two-phase* systems which use a refrigerant as the working fluid:

Company	Coolant
Alcatel-Lucent (US)*	R-134a
Fujitsu (Japan)	R-134a
NEC System Research Laboratories (Japan)	3M Novec™ HFE-7100
USDOE Oak Ridge National Laboratory (US)	R-134a/HFO-1234yf
Parker Hannifin Precision Cooling Business Unit (US)*	R-134a/HFO-1234yf
Durbin Group/Thermal Form & Function Inc. (US)*	R-134a/HFO-1234yf

** Commercialized systems*

Refrigerants for Electronics Cooling

Pumped two-phase systems which use a refrigerant as the working fluid:

- Excellent examination of pumped refrigerant concept for applications for HEV/EV powertrain inverters:
  - C. Ayers, Oak Ridge National Laboratories (IEEE Semitherm 22, March 2006)
  - Illustrated use of a two-phase pumped R-134a refrigerant system in conjunction with an existing vehicle AC vapor-cycle compression system.
  - Purpose is to demonstrate a cooling solution for HEV/EV vehicle powertrain inverters.
  - Two-phase pumped loop may be used with or without AC VCC system, depending on the needs of the vehicle systems.

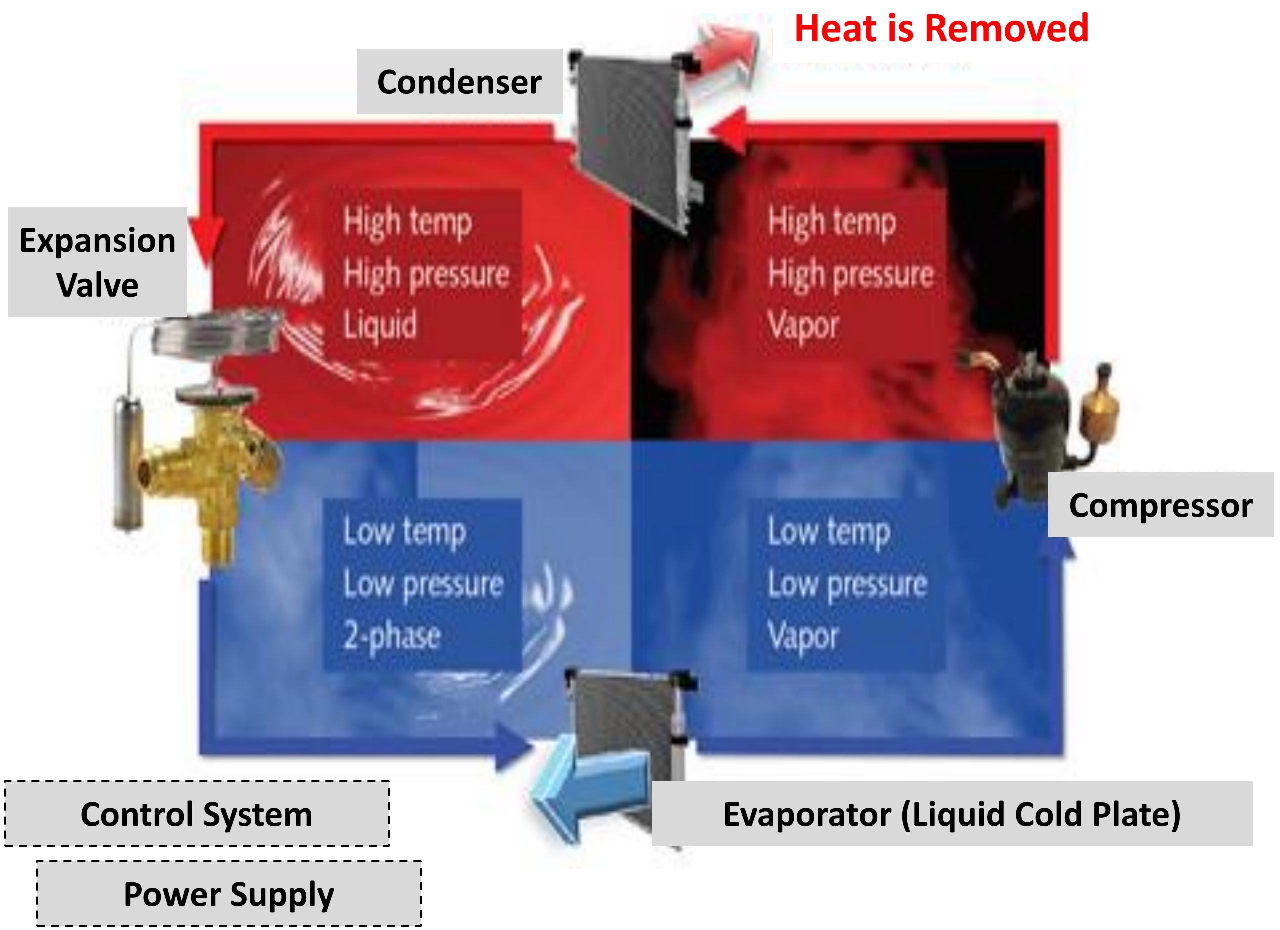
C. W. Ayers, J.S. Hsu, Oak Ridge National Laboratory; K.T. Lowe, University of Tennessee, "Fundamentals of a Floating Loop Concept Based on R-134a Refrigerant Cooling of High Heat Flux Electronics," IEEE Semitherm 22, March 2006, Dallas TX USA.

Future for Electronic Coolants

- Environmental requirements have had a major impact on some existing common electronic liquids used as coolants and refrigerants.
  - Traditional chemistries are being replaced with new, low-GWP fluids.
  - Opportunity for improvements is clear.
  - Drive to *energy efficiency in power electronics* is a large opportunity and the motivation for development of improved fluids for power electronics cooling.
- An "ideal fluid" recipe?
  - High heat transfer rates
  - Low viscosity
  - Stability and compatibility
  - Inexpensive
- For compatibility in many applications:
  - Excellent (or tailorable) dielectric properties over a wide temperature range.

Chiller Systems for Electronics Applications

Overview – Vapor Cycle Refrigeration



Major VCC System Components
Compressor
Evaporator/liquid cold plate
Expansion Valve
Condenser
Control System
Power Supply (standalone systems)

Source: Laser Focus World

Vapor Compression Cooling for Electronics

- VCC cooling may be in used in several ways for cooling electronics:
  - Conditioning recirculating air within a sealed electronic system
    - Temperature, humidity
  - Chilling recirculating air via heat exchanger and fan
  - Chilling recirculating secondary fluid, via liquid-to-liquid exchanger
  - Chilling recirculating fluid ported via couplings to a liquid cold plate

Vapor Compression Cycle Cooling -- Electronic Coolants

- Market segments and applications for vapor compression cycle (VCC) systems:

Market Segment	Typical Application
Semiconductor ATE (Automated Test Equipment)	Precise test head temperature control Precise test head contact probe control Test head heat dissipation
Semiconductor Burn-in and Thermal Cycling Chambers	Cold side temperature control for load and test head dwell
Computing Systems – Enterprise Servers	Processor and memory thermal management Rack internal ambient thermal management
Mil/Aerospace Electronics Operation – Ground Systems	Thermal management for aircraft on-board systems Thermal management for ground test and satellite systems
Military Airborne Electronics	On-board radar and detection systems On-board jamming and countermeasures systems Blood and plasma transport
Naval Shipboard Electronics Systems	Shipboard radar, detection, and jamming systems
Diode Laser and Laser Systems	Precise temperature control for specified laser output Precision thermal management (to minimize CTE-induced movement) for collimated multiple diode light output
Laboratory Test Equipment	Precise pharmaceutical, biological and medical temperature control Precision liquid cooling
Industrial Machine Tools, Packaging, Printing Equipment	Range of temperature control applications
Vacuum Deposition and Semiconductor Manufacturing	Range of temperature control applications
Medical Imaging and MRI Imaging	Range of temperature control across major system subsections

Vapor Compression Cycle Chiller System -- Electronic Coolants

- A range of fluids have been used for liquid cooling and VCC chiller systems:

Market Segment	Typical Application
Semiconductor ATE (Automated Test Equipment)	R-134a, HFO-1234yf
Semiconductor Burn-in and Thermal Cycling Chambers	R-134a, HFO-1234yf, water
Computing Systems – Enterprise Servers	R-134a, HFO-1234yf, water, 3M Novec 7300 HFE
Mil/Aerospace Electronics Operation – Ground Systems	PAO, R-134a, HFO-1234yf, EGW, PGW, 3M Novec 7300 HFE
Military Airborne Electronics	PAO, R-134a, HFO-1234yf, EGW, PGW, 3M Novec 7300 HFE
Naval Shipboard Electronics Systems	R-134a, HFO-1234yf
Diode Laser and Laser Systems	Deionized Water, 3M Novec 7300 HFE, R-134a, HFO-1234yf
Laboratory Test Equipment	R-134a, water
Industrial Machine Tools, Packaging, Printing Equipment	Deionized water, R-1341, HFO-1234yf
Vacuum Deposition and Semiconductor Manufacturing	3M Novec 7300 HFE, R-134a, HFO-1234yf, Deionized Water
Medical Imaging and MRI Imaging	Deionized Water, R-134a, HFO-1234yf, EGW

Vapor Compression Cycle Chiller System – Design Requirements

Selecting VCC chiller systems:

Specifications	Typical Values
Cooling capacity (W)	At rated operation conditions
Heating capacity (W)	At specified system ambient temperature
Refrigerant	As specified
Operating ambient temperature range	As specified (Example: -40°C to +60°C)
Storage temperature range	As specified (Example: -50°C to +70°C)
Maximum power draw (W)	At specified operating voltage, within operating temperature/condition range
Voltage (VAC or VDC)	(May be selectable, within AC))
Frequency (Hz)	Per country
Altitude (ft)	Range or maximum
Humidity control (%RH)	Within specified operating temperature range
Orientation (°)	Typ., ± 15°, any axis from vertical
Mil Standards, applicable	MIL-STD-810 (Environmental)
	MIL-STD-1461 (EMI protection)
	MIL-STD-1275 (Power supply)
Weight (kg)	As specified
Dimensions (cm)	As specified

Vapor Compression Cycle Chiller System – Design Requirements

Selecting VCC chiller systems for use in cooling electronic systems:

Specifications	Typical Values
Evaporator	Liquid cold plate, dimensions and performance; materials
Process coolant	As specified (e.g., water, EGW, deionized water, PAO synthetic oil, other)
Set point temperature (°)	As specified, coolant exit temperature from chiller to cold plate
Flow rate (LPM)	As specified
Connector/coupling (type)	As specified
Wetted materials	As specified, cooling component interior surfaces*

** Process coolant selected may affect component materials selection. Example: Stainless steel pump with graphite vanes or optional polypropylene pump. Coolant additives may also be selected (glycol, corrosion inhibitors, other).*

Chiller System Examples

- K-O Concepts Inc. liquid cooling and VCC systems – An example of a single manufacturer of chiller systems offering standard products for major electronic coolants:

Chiller Type	Coolant Fluid	Setpoint Temp Range (°C)	Cooling Capacity	Stability	Ambient Temp (°C)
LCR-8-G2 VCC (R-134a)	Water	5 - 35	800W@20°C	± 0.1°C	15 - 35
DMC-20 (R-134a)	PAO Deionized Water Steam Distilled Water	41 – 95	2,000W@20°C	± 0.1°C	59-95
Direct Refrigerant	R-134a/HFO-1234yf	As specified	As specified	As required	As specified

Summary

- Liquid cooling of electronics, widely used globally, is expanding for implementation into new market areas, including:
  - Many forms of energy efficiency and alternative energy development.
  - Electrification of vehicles
  - Data center and telcom efficiency improvements.
- Environmental requirements have lead to development of effective new coolant chemistries, with very low Global Warming Potential values:
  - Replacements for familiar coolants with very low GWP values.
  - Replacements for refrigerants which expand the selection of potential coolants.
  - Commercialization and adoption of new fluids must overcome market obstacles resulting from logistics, cost, compatibility, and other practical requirements.
- A range of electronic liquid and refrigeration cooling systems are available which are designed to handle a range of fluids, operating conditions, and system requirements.

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Market analysis and development, business strategy development, and product strategy development for electronics thermal management.

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Developer and manufacturer of standard and custom rack-mount and free-standing high-performance chiller systems for a range of refrigerants and coolants.

Chillers provide 800 to 3,200 W of continuous cooling. Water chillers, other coolants, and PAO coolers, as well as direct refrigerant coolers, are lightweight, compact, and offer precision temperature control with global input voltages.