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AEROSPACE INFORMATION REPORT

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LIQUID COOLING SYSTEMS

TABLE OF CONTENTS

FIGURES

1. PURPOSE: The purpose of this Aerospace Information Report (AIR) is to provide guidelines for the selection and design of airborne liquid cooling systems.

2. SCOPE: This publication is applicable to liquid cooling systems of the closed loop type and the expendable coolant type in which the primary function is transporting of heat from its source to a heat sink. Most liquid cooling system applications are oriented toward the cooling of electronics. Liquid cooling techniques, heat sinks, design features, selection of coolants, corrosion control, and servicing requirements for these systems are presented. Information on vapor compression refrigeration systems, which are a type of cooling system, is found in Reference 1.

3. BACKGROUND: Liquid cooling systems offer many significant advantages over air cooling systems.

A major application of liquid cooling systems is for avionics in military aircraft. This use is the result of sophisticated, high performance electronic components in small packaging sizes, and the need for high reliability of avionic systems.

Liquid cooling can be accomplished by direct contact of the liquid with heat producing components, or indirectly via heat exchange devices.

In either case, the liquid transports heat to a heat sink. In airborne systems, the heat sink can be ambient or ram air, fuel, an expendable or heat storage material, or a refrigeration system.

Expendable systems are typically used in remotely piloted vehicles or drones, for avionics cooling and as a supplemental heat sink for a refrigeration system transport loop.

4. LIQUID COOLING TECHNIQUE: A major reason to use liquid for cooling is that it is more efficient than cooling with a gas, such as air. It may be used to remove heat directly or indirectly from the heat source and it may absorb heat as it changes phase and is expended.

4.1 Benefits: Liquid cooling systems provide superior localized cooling than either air or gas cooling. A larger heat transfer coefficient is obtainable with liquid versus air or gas, resulting in smaller differences between component temperatures and coolant supply temperatures. The smaller temperature difference allows components to operate at lower temperatures. This improves component reliability and reduces maintenance costs.

Relative heat transfer coefficients for two liquid cooling methods compared to two air cooling methods are presented in Fig. 1. (See Reference 2 or 3.) The higher heat transfer coefficients of liquid cooling systems permits larger power densities to be adequately cooled. Also, liquid cools low power density equipment more efficiently than air cooling. Heat transfer coefficients generally increase with increased fluid velocity. However, pressure losses increase with increased velocity.

4.1 (Cont'd)

The heat capacitance (mass flow rate times specific heat) of a cooling fluid is a significant factor. The large heat capacitance and high density of liquids results in smaller heat sink components and transport lines sizes. This generally reduces weight, therefore, lowers aircraft fuel penalties.

Disadvantages of liquid cooling systems also should be analyzed for each potential application. Major areas to be considered are maintenance, potential leaks, fluid contamination, logistics, and potential fire hazards.

4.2 Types of Liquid Cooling Systems: Direct, indirect, and expendable cooling systems are addressed in this AIR.

4.2.1 Direct: Liquid may be used to remove heat directly from the heat source. This provides the minimum thermal resistance from the heat source to the liquid. An example of direct liquid cooling of avionic components on circuit boards is shown in Fig. 2.

A major consideration of direct liquid cooling is compatibility of all parts being cooled with the liquid. Other design considerations are thermal expansion, liquid pressure, maintenance and servicing provisions, and controls for normal operation and failure conditions.

4.2.2 Indirect: In this method, heat is transferred to the liquid in a liquid cooled cold plate, via an intermediate device. Conduction is the common method for transferring heat from components and subassemblies to a liquid cooled cold plate. An advantage of indirect liquid cooling over direct cooling is that a heat producing component can be removed for servicing without disturbing (i.e., opening) the liquid loop.

The cold plate can be an integral part of the assembly being cooled, or it can be designed to readily separate from the assembly being cooled (i.e., a non-integral design). An example of an integral indirect cooling design is shown in Fig. 3 (from Reference 4). An example of a non-integral indirect cooling design is shown in Fig. 4 (from Reference 5).

Indirect cooling designs require an important thermal design consideration which is not necessary for direct cooling designs. Heat must be transferred from the heat source to the liquid. This heat should be transferred with a minimal total thermal resistance. There are two types of thermal resistances in this heat transfer path.

One thermal resistance is across one or more interfaces. An objective of the indirect design is to allow removal of a component subassembly (as in Fig. 3) or removal of an assembled unit (as in Fig. 4). It is important that mating surfaces of an interface are flat and are held together with sufficient pressure. A low thermal resistance design becomes more important as heat transfer rate increases per unit area of the interface. A thin, high thermal conductivity material (e.g., silver filled silicone

4.2.2 (Cont'd)

rubber) can be used between the two surfaces to fill the small asperities, thus decreasing overall thermal resistance.

The second thermal resistance is from the heat source to an interface or between interfaces (if more than one exists). Conductive heat transfer in copper or aluminum is most commonly used (see note in Fig. 3). Small heat pipes can transfer heat with a smaller thermal resistance than copper, and heat pipes weigh less. A heat pipe is a passive closed circuit heat transfer device which uses evaporation, condensation, and counter-current flow of liquid and vapor. Heat pipes can be used in avionic circuit boards or modules, and in assembly sidewalls (see Fig. 4) to reduce overall thermal resistance in non-integral indirect liquid cooling designs.

4.2.3 Expendable: Expendable cooling systems may be used with direct or indirect techniques of cooling equipment. Expendable systems may be used to handle temporary or peak loads. The quantity of heat to be removed determines the weight of expendable fluid required. Since liquid is used as heat is removed, expendable systems are time limited. These systems use the latent heat of evaporation, plus sensible heat, to absorb the heat load.

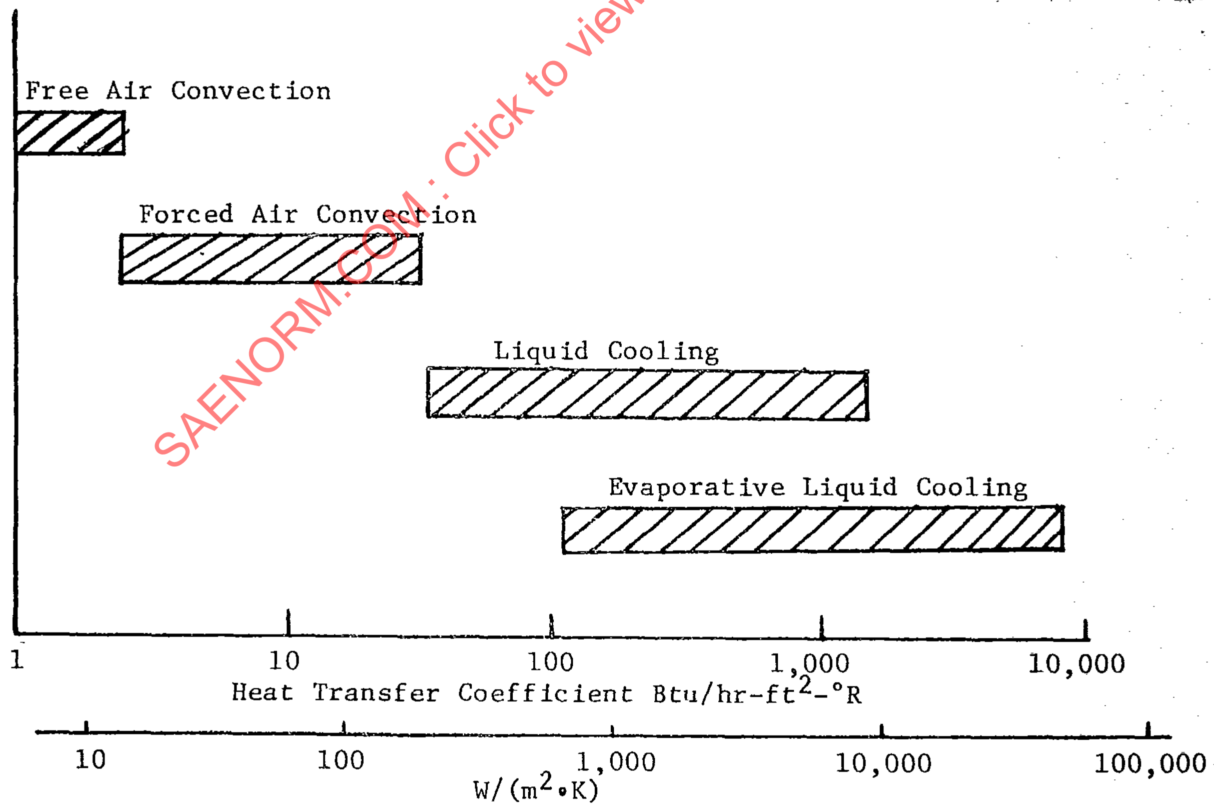

Fig. 1 - Cooling Methods versus Heat Transfer Coefficients

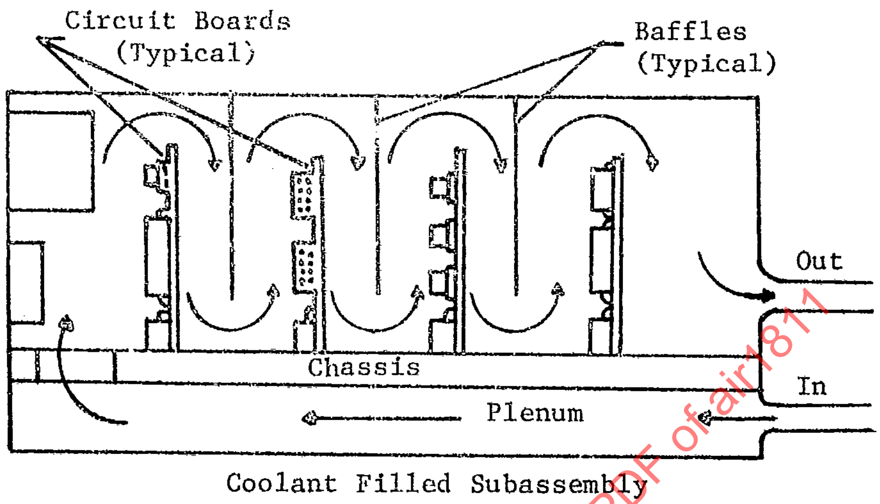

Fig. 2 - Direct Liquid Cooling

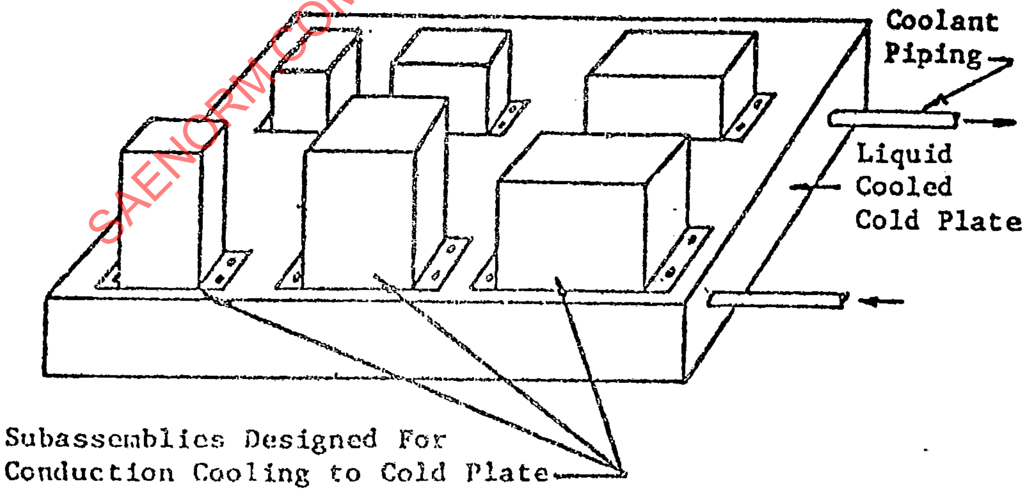

Fig. 3 - Indirect Liquid Cooling with Integral Cold Plate

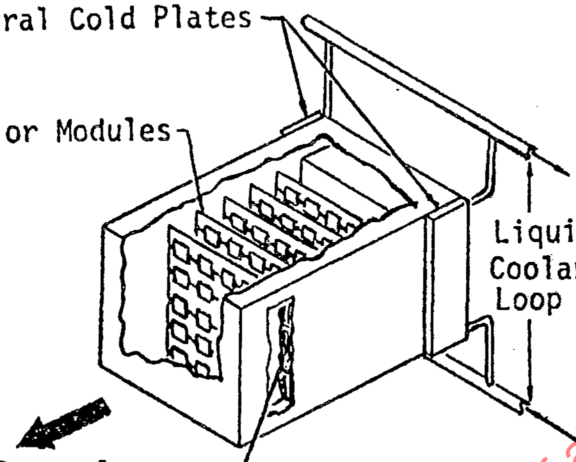

Fig. 4 - Indirect Liquid Cooling with Non-Integral Cold Plate

5. HEAT SINKS: Selection of the heat sink for a liquid cooling system depends on availability and temperature of heat sinks, and on other unique design factors.

Ambient or ram air, fuel, refrigeration system (such as an air cycle or vapor cycle), and expendables or heat storage materials are available types of heat sinks used for liquid cooling systems. A combination of different types may be required to optimize the system for different operating conditions. The cooling capacity of fuel and air heat sinks are related primarily to the flow rate and temperatures of these fluids. For a refrigeration system, its capacity is a function of system design. Cooling capacity of an expendable is the latent and sensible heat of the liquid and the liquid quantity. The capacity of a heat storage material is the latent heat of fusion and the quantity of the material.

5.1 Ambient or Ram Air: Heat from a liquid cooling system may be transferred to an ambient or ram air heat sink through an air-to-liquid heat exchanger, as shown in Fig. 5. Under most aircraft operating conditions, cooling load requirements can be met with ram air. For static and low speed aircraft operation, a fan or air driven ejector pump is used to provide adequate airflow. When a fan is used, consideration must be given to prevent potential fan overspeed. As aircraft speed increases, ram air temperature and pressure increases, and should be considered in the design. Increased airflow is required as ram air temperature increases. Other factors to be considered in the use of air as the heat sink are effectiveness of the heat exchanger in removing heat, and matching of available pressure head of the air and pressure losses of the heat exchanger design.

5.2 Fuel: Fuel, as a heat sink, may be pumped through a heat exchanger, installed in the liquid cooling system as shown in Fig. 5, or a natural convection heat exchanger may be installed within a fuel tank. If the amount and rate of heat added to the fuel causes fuel temperatures to rise above allowable limits, an auxiliary heat sink must be used or the fuel must be cooled. Fuel temperature limits are established by engine design and by the airframe design.

The advantage of a system with fuel pumped through a heat exchanger is high heat transfer rates, resulting in smaller and lighter heat exchangers. A major advantage of locating a heat exchanger in the fuel tank is that fuel is confined to the fuel tank, reducing the fire hazard. For a free convection heat exchanger located in a fuel tank the heat transfer rates are smaller since it is free rather than forced convection, hence, the heat exchanger is larger and heavier. Other disadvantages of this approach are servicing difficulty, loss of heat sink if fuel level falls below the heat exchanger, and the need for liquid lines which enter and leave the fuel tank. A forced cooled heat exchanger may be used within the fuel tanks by placing it in the engine feed line.

5.3 Expendables: Expendable systems require a supply of the liquid sufficient for the heat load. The latent heat of vaporization plus sensible heat is the means of absorbing heat. The expendable liquid is usually pressurized. Heaters may be needed to maintain a uniform pressure. If large changes in orientation normally occur, means of emptying the liquid container under these circumstances is required.

5.4 Heat Storage: A heat storage material may be used as a heat sink for a liquid cooling system during periods when the normal heat sink is inadequate. The heat storage material is normally a solid and changes to liquid during the time period it is serving as the heat sink. The latent heat of fusion is the means of absorbing heat and a constant temperature (melting point of the material) heat sink exists as long as the total heat capacity of the quantity of material provided is not exceeded.

5.5 Refrigeration System Transport Loop: Liquid cooling system heat may be dissipated to an air cycle or vapor cycle refrigeration system via a heat exchanger. A typical schematic of a vapor cycle loop for cooling a liquid system is shown in Fig. 6. An advantage for using the refrigeration system is that its controls can provide stable heat sink temperatures significantly less than the ambient temperature and is not time limited as are expendables or fuels. A probable disadvantage is greater weight compared to the less complex air or fuel heat sink designs. Vapor cycle systems are gravity sensitive and successful operation is dependent on aircraft orientation.

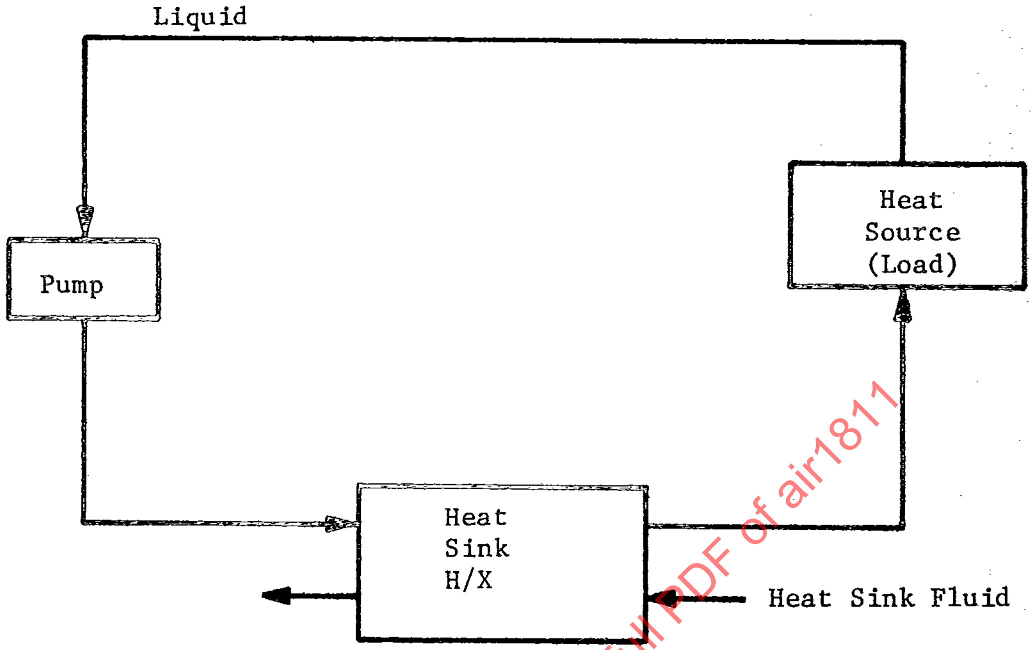

Fig. 5 - Liquid Loop/Heat Sink Schematic

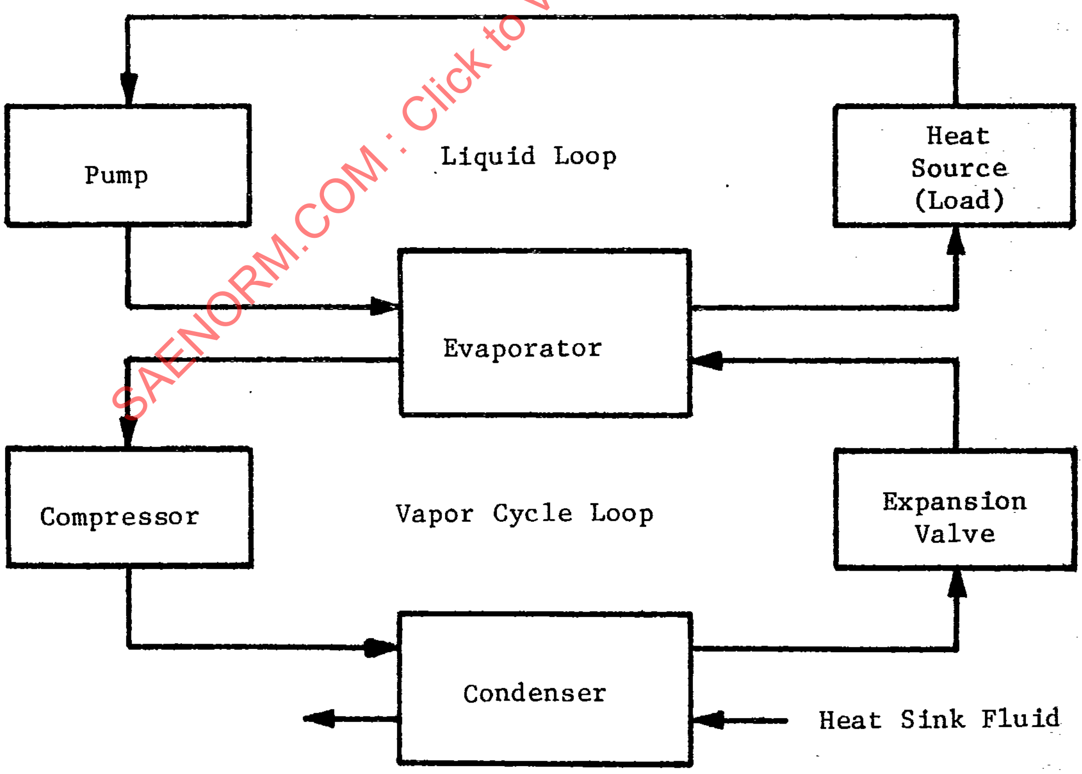

Fig. 6 - Refrigeration System Transport Loop

6. SYSTEM DESIGN: This section describes a typical Liquid Cooling System (LCS) and discusses system parameters that should be considered when specifying or designing a LCS.

6.1 Liquid Loop Cooling System, Description: Major elements in a LCS are the heat load being cooled by the liquid, a pump to circulate the liquid, a device to transfer heat from the liquid to the heat sink, and a temperature control system. LCS normally includes a filter, a liquid reservoir or accumulator, bypass provisions around the pump and filter, an overpressure relief valve, fill and drain valves, and a heater. A representative system flow arrangement is shown schematically in Fig. 7. Section 8 of this AIR discusses components used in a LCS.

6.2 Review of Liquid Cooling System Design Features: A liquid cooling system must transfer heat from source to sink. It must meet volume, weight, and structure requirements; and operate in the aircraft or missile environment. It should be reliable and easily maintained. Tests to verify these design features are required.

6.2.1 Thermodynamic Performance: Thermodynamic performance defines the capability of the LCS to transfer heat from where it is added to the system to where it is removed. The following factors should be included:

- Heat rejection rate and temperature at which the heat source is to be maintained;
- Temperature, capacity, and availability of heat sinks;
- Selection of a liquid;
- Compatibility of the liquid with the heat source and heat sink;
- Duty cycle or mission profile through which the system must operate, including time variations of heat load, source temperature, and availability and temperature of the heat sink (in flight and on the ground);
- Type and quantity of power available to operate the system;
- Allowable excess heat transport capacity (growth).

6.2.2 Package Configuration and Weight: The available or allowable space and weight for system components must be defined. All LCS components may be mounted in a single package; or they may be distributed throughout the aircraft or missile, with some components packaged together. For example, the reservoir, pump and motor, and valves may be packaged as a single assembly, with other components located elsewhere.

Packaging requirements may determine arrangement and types of components to be used more than the thermodynamic performance, resulting in lower thermodynamic efficiency. Allowable leakage rates of fittings and components should also be defined.

6.2.3 Structure: Aircraft vibration, acceleration, and aerodynamic maneuver loads (including inverted operation) to which the system will be exposed to must be considered. Vibration loads transferred to structure by the LCS components also need to be defined.

6.2.3 (Cont'd)

Normal and extreme operating fluid pressure in the LCS must be established. Normal practice is to design for a proof pressure factor (no deformation when load is removed) of 1.5, and a burst pressure factor of 2 (ultimate stress and no failure) relative to maximum system operating pressure. Other design approaches include bypass valves and lines around the pump and filter, to minimize pressure spikes and to limit maximum system operating pressure, and system overpressure relief valve to limit maximum system pressure in the event of a fluid line blockage or system overfill. Fatigue of liquid loop components due to cyclic pressurization resulting from system start and stop cycles, control valve operation, or pump output pressure ripple, should also be considered.

6.2.4 Reliability: Failure rates for the system components should be determined, and an overall system "Mean-Time-Between-Failure" (MTBF) analysis prepared. Useful operating life and storage life requirements for the system should be defined.

Redundancy may be required for critical components with relatively high failure rates to enhance mission completion probability or flight safety. The need for redundancy is determined by evaluating system functions needed for successful system operation. This evaluation identifies potentially poor design, such as a feature which produces a single point failure, which can prevent mission completion.

6.2.5 Maintainability: Overall system design should include provisions for ease of maintenance, such as readily accessible components (e.g., fill and drain ports, fluid level indicators). Quick disconnects, with disconnect and seal features, should be considered where frequent servicing is anticipated. Method and ease of ground operation should be considered. Test points may be added to the system to allow rapid fault isolation of key components.

Provision for Built-In Test (BIT) and fault isolation are desirable, to indicate impending failures and out-of-tolerance performance, or to isolate failures that have occured so maintenance effort is minimal. Sensing of temperature, pressure, flow, filter pressure drop, current, and fluid level should be considered. The number and location of sensors depends on the degree of failure detection and fault isolation desired. BIT requirements are usually specified as the percentage of possible malfunctions and out-of-tolerance conditions to be detected (i.e., 95%), with the allowable false alarm rate specified as a percentage of the detected failures (i.e., 10% of failure indications may be false alarms). BIT capability increases the complexity of the system's electronic controller.

Maintenance requirements for the system are often given as mean corrective maintenance times or maintenance manhours per flight hour.

6.2.6 Environment: Design and test environment factors include external pressures, temperature extremes, humidity, solar radiation, rain, fungus, salt, sand, dust, temperature shock, exposure to aircraft fluids, and explosive atmosphere. Reference 6 may be used to specify environmental test requirements.

6.2.7 Electromagnetic Interference: Electromagnetic Interference (EMI) must be considered if the LCS is for cooling electronic systems. EMI includes emissions conducted and radiated by the LCS, susceptibility of the LCS to emissions from the aircraft, and electrical bonding and shielding requirements. Systems with electronic controls may be subject to nuclear hardening requirements.

6.2.8 Corrosion Protection: Corrosion can occur both internally and externally. Careful selection of the liquid cooling system fluids, materials, and protective coatings, coupled with an adequately planned maintenance philosophy will minimize corrosion problems and ensure a satisfactory service life. Types of corrosion commonly encountered in liquid cooling systems are: atmospheric, galvanic, electrolytic, and chemical. (See Section 9 for corrosion prevention and control.)

6.2.9 Testing: Testing of system components and of the complete system is necessary to verify adequacy of the design, and to modify and improve the design as appropriate.

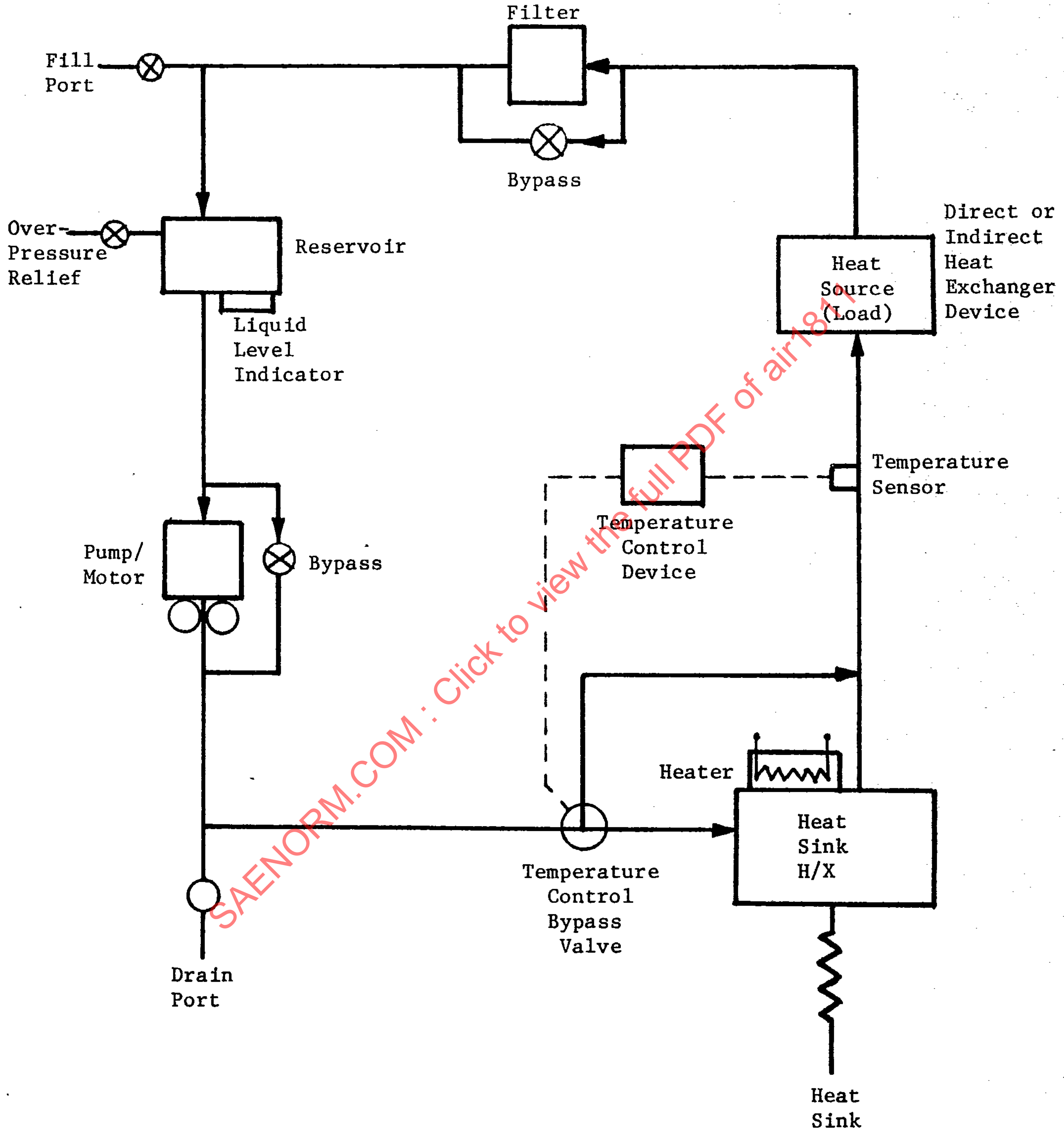

Fig. 7 - Representative Liquid Cooling System Schematic

7. COOLANT SELECTION: There are many factors to be considered in choosing a liquid coolant, and there is normally not a single best choice. Many factors influencing the selection of a coolant must be evaluated subjectively.

This section provides general information about important liquid coolant properties, and references information about a number of specific liquid coolants. Analyses of heat transfer and power requirements are integral steps in the selection of a coolant.

7.1 Fluid Properties: The selection of a liquid coolant should relate liquid properties to the system in which they are to be used. (Also see Reference 7.)

7.1.1 Heat Transfer: Heat transfer related properties are specific heat, latent heat of evaporation, density, thermal conductivity, and viscosity. Specific heat defines the ability of the liquid to store heat relative to its mass and temperature. Density defines the amount of mass per unit volume. Thermal conductivity defines the ability of the liquid to conduct heat between adjacent liquid layers. Viscosity is the physical property that characterizes the flow resistance of simple fluids. Latent heat of evaporation is the amount of heat a fluid absorbs when it changes from a liquid to a gaseous phase at a constant temperature and pressure. A liquid with a high heat transfer effectiveness (i.e., an ideal liquid loop heat transport fluid) will have high specific heat, density, thermal conductivity; and low viscosity.

7.1.2 Thermal Expansion: The coefficient of thermal expansion describes the volumetric expansion per unit change in temperature. A low value is desired. Thermal expansion must be considered when designing a closed system to operate over a large temperature range.

7.1.3 Surface Tension: Surface tension is a measure of the cohesive force between a liquid and a surface which it contacts. A liquid with a low surface tension adheres or covers ("wets") the surface more readily, thus enhancing heat transfer effectiveness. Liquids having a low surface tension are more likely to leak, such as at seals, gaskets, cracks, or connectors.

7.1.4 Flash Point: The flash point is the lowest temperature at which enough vapor is generated to cause a flash, or small explosion, when brought into contact with a flame or spark. A liquid should not be considered if it has a flash point lower than the highest temperature it will contact during normal use or due to leakage.

7.1.5 Flammability: Flammability indicates the tendency of a liquid to burn. A low flash point liquid will normally be more flammable. Flammable liquids could be used for systems which are always sealed; however, filling, maintenance, and the potential for leakage should be considered.

7.1.6 Pour or Freezing Point: The temperature at which the liquid will just begin to pour is defined as the pour point. Pure liquids (i.e., water) do not have a pour point, thus the freezing point is considered. The pour and freezing points define the lower end of the useful coolant operating temperature range. The pour and freeze points are of concern where the requirements for low temperature startup exist.

7.1.7 Viscosity: Viscosity is an indication of the shear force required to cause liquid deformation, and thus liquid movement. A high (coefficient of) viscosity means more force and power is required to cause liquid flow. Most liquids become more viscous as temperature is lowered, thus the largest amount of power to pump a liquid is at its lowest operating temperature.

7.1.8 Vapor Pressure: The vapor pressure must be sufficiently low at operating temperatures to prevent boiling within the cooling system and cavitation in the pump. If evaporation cooling in a closed loop is desired, sufficient heat removal in the condenser, and a reservoir, must be provided to prevent vapor from reaching the coolant pump if it has only been designed to pump liquids.

7.1.9 Thermal Decomposition: Many liquids decompose into more basic elements or chemical compositions at high temperatures. This decomposition can occur at lower temperatures due to reactions with other compounds in the system. A coolant must be used in accordance with manufacturer's recommendations for service temperature and operating pressure. Some liquids have to be purified and deionized to prevent thermal decomposition.

7.1.10 Dielectric Strength: Dielectric strength is important if the coolant should contact electronic or electrical components. A high dielectric strength is required to prevent electrical breakdown.

7.1.11 Moisture Absorption: Absorption of moisture by a liquid can degrade dielectric properties, enhance hydrolysis, and form acids and salts which cause corrosion. Many good coolants have an affinity for moisture. When using these, cost and weight penalties of added design features for preventing moisture into the system should be included.

7.1.12 Toxicity: Toxicity is of concern to maintenance and flight personnel. Contact with the liquid or its vapor may cause temporary discomfort or injury.

7.1.13 Compatibility: Coolants must be chemically compatible with the materials which they contact within the cooling loop. Particular attention must be paid to the selection of seals, gaskets, and adhesives used in the cooling system. Reference 8 gives the relative compatibility of a number of common compounds with fluids which might be used as coolants.

7.1.14 Lubricity: Lubricity is the quality of a fluid to reduce friction. The fluid used should have sufficient lubricity to reduce friction, thus reducing wear on any movable components (e.g., pumps) compatible with required life.

7.1.15 Optical Clarity: Optical clarity is the degree of transparency and must be considered when LCS are used in laser systems.

7.2 General Liquid Properties: Most manufacturers of liquids used in airborne liquid cooling systems provide brochures and pamphlets containing properties of their liquids. Numerous references also summarize selected properties. For example, Reference 8 includes heat transfer properties for silicate ester, dimethyl silicone, fluorochemical liquids, and aqueous ethylene glycol. Further information about these liquids and others may be obtained from liquid manufacturers (e.g., Bray Oil Company, Chevron Chemical Company, Dow Corning Corporation, E. I. duPont de Nemours and Company, General Electric Company, Minnesota Mining and Manufacturing Company, Monsanto Company, Union Carbide Corporation, etc.).

7.2.1 Glycol-Water or Methanol-Water: Glycol-water or methanol-water offer the best thermal properties (except pure water) of the liquids considered. These two liquids have limited temperature range, and are not as compatible with other materials, compared to silicate esters or silicones. A half percent (0.5%) by weight benzotriazole (BZT) silver chelating agent should be added to glycol-water when it is adjacent to or in contact with electrical circuitry containing silver to eliminate potentially hazardous chemical reaction.

7.2.2 Silicate Ester: Silicate esters are commonly used to cool avionics, because of their good dielectric properties and moderately good thermal properties. Elastomeric and fabric coated materials for use in the system should be compatible with the liquid. Silicate esters are somewhat hygroscopic. This can produce a sludge if too much water is absorbed. Silicate esters have relatively good low temperature and high temperature characteristics.

7.2.3 Silicone: Silicone liquids have good thermal properties, although they are lower than those of silicate esters. Silicones are very compatible with other materials. They seldom are used in airborne cooling systems.

7.2.4 Halogenated-Hydrocarbon: Flourinated and chlorinated hydrocarbons are not flammable and have low toxicity. This liquid class includes those commonly used as refrigerants and most have low boiling points. They have moderately good thermal properties, but are less compatible with elastomers and fabrics than are silicate esters. The liquids have good dielectric properties.

Some varieties are possible choices if evaporation of the liquid is needed (e.g., an expendable). Typical examples: CCl_2F_2 (R-12) and $CHClF_2$ (R-22), although all have relatively low latent heat.

7.2.5 Synthetic Hydrocarbon (Polyalphaolefin): Synthetic hydrocarbons, although not currently used in airborne liquid cooling systems, are being considered as an acceptable fluid. They are non-hygroscopic and possess good dielectric, heat transfer and thermal stability properties. These fluids are more resistant to ignition than their petroleum counterparts.

7.2.6 Water: Water is the best heat transfer liquid available, but it is not used in liquid cooling systems because of its limited temperature range. Water is also the best expendable liquid, because of its very high latent heat compared to other liquids. Distilled and deionized water must be used to prevent corrosion. Water may need to be heated to prevent freezing.

7.2.7 Ammonia: More properly, an aqua-ammonia solution may be considered as an expendable liquid. Its latent heat is less than that of water, but it offers a reduced boiling point. Use of an ammonia solution should be considered very carefully because of its toxicity.

7.2.8 Cryogenic: Cryogenic liquids, such as nitrogen or helium, may be required to achieve very low heat sink temperatures as expendables. These liquids must be stored in a very well insulated tank, with adequate venting and flow controls provided.

8. COMPONENTS: General characteristics and design criteria for components used in airborne liquid cooling systems are discussed in this section.

8.1 Heat Exchanger: A heat exchanger transfers heat from hot to a cold fluid without mixing of the fluids. In a heat exchanger, heat is transferred from a hot fluid to a solid interface between fluids by convection, through the solid by conduction, and from the solid to the cold fluid by convection. As a fluid travels through the heat exchanger, its temperature (or enthalpy) changes and its pressure decreases due to friction with heat exchanger surfaces. Hence, the heat exchanger design affects the power required to pump fluids through the system. Objectives are the desired fluid outlet temperature by transfer of heat, with minimum fluid pressure losses, and to be small and light in weight.

The performance of a heat exchanger is determined by its effectiveness. See References 9 and 10 for detail explanation. The greater the effectiveness, the more heat it will transfer. A heat exchanger performance is commonly related to the inlet and outlet fluid temperatures. The term "temperature effectiveness" refers to the ratio of the temperature change of one fluid to the inlet temperature difference of the two fluids.

Relative flow directions of fluid through a heat exchanger affect its performance. Counterflow designs are best, followed by crossflow, then parallel-flow. Counterflow and parallel-flow designs in a plate and fin configuration have more complex fluid routing into and out of the basic heat transfer surfaces (the heat exchanger core). Crossflow heat exchanger performance may be increased by designs in which either fluid makes more

8.1 (Cont'd)

than one-pass across the other fluid. Heat exchanger performance also can be increased by using staggered or interrupted surfaces in the heat exchanger to prevent boundary layer growth along the flow passages. This is generally at the expense of increased pressure losses.

A simple heat exchanger design has one fluid in a series of tubes with this tubing immersed in the other fluid. Heat transfer rates with this design can be increased by adding fins to the tubing, either internally or externally. These designs are referred to as "shell and tube" and "finned tube".

Plate and fin heat exchanger designs are most common in airborne cooling systems. They consist of thin corrugated metal (fins) between thin plates, stacked one after another. The liquid sides of plate-fin heat exchangers usually have small fin heights, a high number of fins per inch, and often are multi-pass designs. If the other side is air or gas, larger fin heights are usually used.

Common heat exchanger materials are aluminum alloys and stainless steel. Aluminum is light, has a high thermal conductivity, and is generally used unless the temperatures are too high. Some heat exchangers used for higher temperature fluids may use nickel or nickel alloy fins with the remainder stainless steel. Nickel provides greater thermal conductivity while stainless steel is used for those parts requiring higher strength.

Brazing is common for the fabrication of plate-fin heat exchanger cores, while external closure parts (i.e., headers, tubing, duct connections to the core) are welded to the core. Care is required to ensure that brazing fluxes are not present in the final product as they can cause severe corrosion (and leakage) problems in the heat exchanger and other system components. The potential problem is eliminated if the assembly is brazed in a vacuum or an inert atmosphere. Design of the heat exchanger as a pressure vessel and structural member must be considered. Tube-fin or shell and tube heat exchangers are better suited to high pressure applications than are plate-fin heat exchangers.

Methods of ensuring proper fluid distribution into the various passages of a plate-fin heat exchanger should be considered. This is especially critical for air or gas or whenever very low pressure drops through the core are anticipated. Poor distribution may result in significantly lowered heat exchanger performance.

8.2 Pump: The pump in a liquid cooling system moves the liquid through the system, providing the energy (pressure head) to overcome flow losses in the system. Normally, electric motors are used to drive the pump.

8.2 (Cont'd)

Positive displacement (gear or vane) and dynamic (centrifugal) pump designs are most common. Gear or vane pumps can easily provide the required head, and provide high efficiency for the low to intermediate flow rates of airborne cooling systems. Centrifugal designs, which operate at higher speeds, are better for higher flow rates. Reciprocating pumps provide high pressures at low flow rates, are generally more complex (costly), and larger in size and weight.

In gear or vane pumps, variation of flow with pressure head is minimal, with flow decreasing more rapidly at higher heads. In centrifugal pumps, the flow decreases much more rapidly as head is increased. Vane or gear pumps generally require the use of a pressure relief and bypass provision to prevent overloading of the motor, while centrifugal pumps generally do not require relief valve provisions.

Air in a liquid system can have a strong adverse effect on pump performance. The formation of vapor at the pump inlet can reduce pump performance and may damage the pump. Vapor formation is prevented by maintaining a minimum system pressure at the pump inlet above the vapor pressure for any expected temperature.

The pump design should consider fluid lubricity to assure compatibility of pump materials.

The electric motor for driving the pump generally is an integral part of the pump housing. Then, liquid is available to cool the motor, if motor materials and the liquid are compatible.

8.3 Reservoir and Accumulator: Additional liquid is needed to compensate for liquid volume variations in the system due to temperature changes. This may be an accumulator incorporated into the pump housing, or a separate accumulator and reservoir. The accumulator maintains system pressures (i.e., at pump inlet, to prevent formation of vapor) under all operating attitudes and temperature extremes. If only system pressurization is required, a simple reservoir, pressurized by air or a gas, can be used. An accumulator mounted in the pump outlet line can reduce pressure pulsations of the pump supply.

A movable piston type of accumulator, using either seal rings, a rolling diaphragm, or metal bellows as the piston sealing device, is typical for airborne liquid cooling systems. These accumulators may be a flow-through configuration (in-line) or a non-flow through configuration (T-line). Compatibility of the sealing material with the liquid is required. Allowable leakage rates versus desired requirements must be considered.

8.3 (Cont'd)

A piston type accumulator creates a pressure that is proportional to the force imposed on the back side of the piston. This force is usually a sealed air or gas pressure, a spring, or the spring rate of the metal bellows piston seal. The piston loading device is selected to yield the desired pressure versus volume relationship on the liquid side, with a minimum desired pressure when the piston bottoms at the minimum accumulator volume position.

An alternate method of loading the piston is the "boot-strap" approach, in which pressurized liquid from the pump outlet is used to load the piston. An advantage of this configuration is that it can minimize system external leakage (i.e., past piston seals). The pressurizing source can also be controlled to yield a nearly constant accumulator volume versus liquid system pressure.

8.4 Flow Control Valve: Valves are generally used to control flow in various parts of a LCS (e.g., to bypass the heat exchanger) and thereby to provide temperature control. The valves are commonly actuated by electrical solenoids, but may be actuated by fluids whose expansion or pressure is proportional to temperature. The valves need not have stringent minimum leakage requirements when closed, as they are usually only flow directing devices. Thermal or pressure relief values may be required on individual high pressure loss components to permit cold start up.

8.5 Filter and Bypass Valve: Dirt or sludge in the liquid loop can clog valves or the pump. A filter, to remove the dirt, may be located at several places in the loop. Need for a filter, and the filter size, is generally determined by the system cleanliness at time of assembly, contamination introduced during servicing (adding liquid), and the propensity of the liquid to sludge or gum up at extreme temperature conditions encountered during operation. Filtration rating is controlled so that particles which can block orifices or cause damage to the pump are not allowed to pass through the filter. "Paper" filters of 25 micron rating are sufficient for most liquid cooling systems.

A bypass valve around the filter normally is required. In addition, a pressure sensing device may be used to indicate when the filter is starting to become plugged with contaminants (i.e., increased pressure drop across the filter). The pressure sensing device is set to indicate at a filter differential pressure that is somewhat below the filter bypass valve setting. If periodic filter replacement is required, provisions to isolate the filter from the rest of the liquid system are desirable.