SOCIETY OF AUTOMOTIVE ENGINEERS, Inc.
485 LEXINGTON AVENUE
NEW YORK 17, N.Y.

AEROSPACE INFORMATION REPORT

AIR 728A

ELECTRONIC EQUIPMENT COOLING DESIGN CONCEPTS FOR HIGH MACH NUMBER AIRCRAFT

Issued 11-15-61
Revised 1-31-63

1. PURPOSE: The purpose of this information report is to provide a guide to the electronic manufacturer for the design approach to be used in producing equipment which can operate with satisfactory life and reliability when subjected to the environment associated with supersonic aircraft performance.

2. SCOPE: This publication outlines general design concepts considered the minimum acceptable standards for use in electrical and electronic equipment. The objective is increased reliability of the equipment without penalizing the aircraft performance.

3. GENERAL:

3.1 Background: Temperature problems with airborne electrical and electronic equipment are becoming more severe with each advance into higher flight speeds and altitudes. Improvement in aircraft performance, which results in higher environmental temperatures and reduced air density, also creates a need for electronic equipment with improved electrical performance, improved heat transfer design, decreased size, and greater reliability with a resulting complexity of function. These requirements for electronic equipment have been steadily increasing with no apparent change in the trend in the foreseeable future.

Figure (1) shows the free stream total temperature, which represents the heat sink for ram air cooling, versus Mach number. As a result of the increasing requirements, electronic design problems are multiplying in severity. It is necessary that these and associated problems be resolved in order to maintain and/or advance the state-of-the-art of electronic devices.

It has been concluded that it would be economical to pay more than twice the present cost for military electronic equipment if reliability could be improved by 50 per cent.(1)

Cooling techniques and electronic equipment design must be optimized in order to prevent the aircraft from being unduly penalized. Cooperation and coordination between the electrical equipment designer and the aircraft designer is essential to permit the equipment manufacturers to design equipment for use with different cooling systems, to save weight and space, and to achieve better cooling characteristics.

Some of the design philosophy noted in this document may be applied to electronic equipment used in missile and space vehicles.

(1) Reference: "Guide Manual of Cooling Methods for Electronic Equipment," NAVSHIPS 900, 190, Navy Department, Bureau of Ships, 31 March 1955

NOTE: "A" REVISION IS CORRECTION TO FIGURE 1 ONLY

 Printed in U. S. A.

3.2 Design Concepts:

3.2.1 Materials:

3.2.1.1 New developments in electronic equipment materials and components must be considered in raising allowable operating temperatures, and a continual development effort must be maintained to keep pace with the environmental temperatures associated with the increased flight speeds. It is important to have adequate knowledge of material or component life versus temperature, such as shown for electrical equipment insulation by Figure 2, in order to permit a more optimum overall design. Many of the known cooling problems can be alleviated if the operating temperatures for electronic equipment materials and components can be increased.

3.2.1.2 Acceptable standard heat transfer liquids should be used. These liquids can be divided into those that are used in (1) indirect contact cooling and (2) direct contact cooling.

3.2.1.2.1 Indirect contact liquids must be considered from their change in thermal and physical characteristics over the entire operating range as well as compatibility with the metals and materials of the heat exchangers, piping and pumps with which it comes in contact.

3.2.1.2.2 Direct contact liquids require the same considerations as indirect contact liquids in addition to the following properties: compatibility with electronic equipment and parts, dielectric constant, power factor, viscosity, vaporization temperature, flash point, toxicity, and coolant life.

3.2.1.3 When new materials and improved components become available, it is important that they be utilized in new equipment in order to provide as early as possible improved high temperature designs capable of operating over a wide temperature range.

3.2.1.4 Components should be designed to use the most efficient materials so less electrical power ends up as dissipated heat which has to be removed by the cooling system. Use of a higher overall efficiency can save weight not only by reducing the cooling loads, but by reducing the size of the air vehicle's generators and wiring systems as well. Designing electronic components to be compatible with less than ideal conditions may be necessary. Moisture proofing of circuits and wiring, for protection against condensation and against entrained moisture in the cooling air, should be given serious consideration.

3.2.2 Heat Transfer:

3.2.2.1 Arrangement: Effective heat removal is of prime importance in obtaining satisfactory life, reliability and electronic performance. To obtain the maximum benefits of forced air or liquid cooling, it is necessary to engineer the heat transfer paths carefully. Use of a cold plate design or a tabular passage with the components mounted directly on it are compact designs affording good heat transfer with a minimum pressure drop. Figure 3 illustrates an air cooled method utilizing potted construction with components finned to a cooling tube. The fin lengths can be as short or as long as necessary to provide the heat utilization of space and optimum heat transfer. Insulation, electrically and thermally, is provided between components by the potting material, and it provides heat lag during transients when low cooling airflow is available. The potting material can also provide necessary hermetic sealing of the components with good vibration free characteristics.

For the forced air cooling system, the air should be directed within the equipment to achieve maximum heat transfer coefficients from heat generating parts to the cooling air stream. Temperature sensitive components should be located on the cooler portions of the equipment to minimize their temperature rise and, insofar as possible, should be arranged in order of maximum operating temperature with the lower temperature components closest to the incoming cooling air. Other heat dissipating parts should be thermally separated from the more sensitive parts. Effective heat transfer design within the equipment itself should be given prime consideration since it is so vital to the overall cooling requirements. Leakage of cooling air from the equipment should be minimized in order to obtain the best use of the cooling air supplied.

Appendix B describes a suggested method for measuring leakage characteristics for forced air cooled equipment where specific supply and discharge connections are provided. Knowledge of the leakage from the equipment and the internal heat transfer arrangement will enable an evaluation of whether the cooling air is being used efficiently.

3.2.3 Cooling Method: The selection of the optimum cooling method should be integrated into the initial design and throughout the development of the electronic circuit. Where the electronic performance would be influenced by the cooling method, the circuit of the prototype should be modified during the breadboard tests. The heat transfer and electrical circuit designs should be compatible with each other. An investment of effort on the heat transfer design will return good interest in terms of improved electrical reliability.

3.2.3.1 Forced Air Cooling: There are many applications of forced air cooling for supersonic aircraft electronic equipment designs. Limitations of forced air cooling systems must be recognized and reflected in detail design of the system and the components. One of the primary problems encountered with forced air cooling is related to the density of air with altitude. At high altitudes the presently designed forced air cooling systems lose much of their cooling capability and electrical insulation fails through corona formation. One approach is the utilization of a heat exchanger case in which the electronic equipment is hermetically sealed at a pressure of one atmosphere. The heat exchanger arrangement can utilize a "cold plate," "liquid-to-air," or an "air-to-air" method of cooling. Figure 4* shows typical modes of heat transfer for both internal and external configurations. Other transfer modes are possible (radiation for example), but the modes presented are most generally applicable to normal problems encountered. For each mode the number of watts per cubic inch of volume which can be supported is shown. These numbers are very general and included only as a relative indicator of performance. An additional method that is used is a pressurized compartment accessible in flight and cooled by recirculating air or other forced air cooling methods.

3.2.3.1.1 Airflow and Pressure Drop: The cooling airflow and pressure drop requirements shall be optimized for the electronic equipment and the aircraft cooling system.

Low pressure recirculating air systems require that the airflow through the equipment be the minimum consistent with the maximum allowable discharge temperature over the equipment and a minimum of pressure drop through the equipment and the cooling system. An initial design goal for cooling airflow should be set at 2 lbs/min/KW of heat dissipation for an inlet temperature of 80°F which results in an allowable discharge temperature of 200°F. The pressure drop goal, under these conditions, should be a maximum $\sigma \Delta P$ of 0.5 inch of water. Appendix B describes a suggested method of measuring pressure drop and cooling airflow characteristics for forced air cooled equipment where specific supply and discharge connections are provided.

*Figure 4 - Reference: Design Manual, Electronic Equipment Environmental Conditioning, L-5909-R July 15, 1960, AiResearch Manufacturing Company, page 11 Figure 1.

Figure 5 shows the airflow requirements per KW heat dissipation from the equipment based on available supply cooling air temperatures and allowable discharge air temperatures.

Figure 6 illustrates the need for additional airflow when heat exchange effectiveness is decreased, based on an allowable temperature differential between the equipment supply temperature and discharge temperature.

3.2.3.2 Liquid or Vaporization Cooling: In many electronic equipment designs for supersonic aircraft, liquid or vaporization cooling is required because of high packaging densities which cannot be supported by forced air cooling. The mechanical features shown by Figure 7** illustrate one method of liquid cooling electronic equipment and emphasizes segregation of the equipment into cold, warm, and hot zones. Figure 7 shows a cross-sectional view of a cylindrical container housing temperature-sensitive and heat generating equipment. Cooling liquid enters the assembly through a large diameter common inlet at the lowest point in the front panel and branches out into 1/4 inch diameter copper tubing on either side. Heat is absorbed by intimate contact of the tube with the chassis and structural members. The heat transferred to the cooling liquid in the branches is carried along by the liquid to a common outlet at the upper part of the assembly where it discharged from the container.

3.2.3.3 Ratings: Present methods of equipment temperature ratings should be improved. The temperature rating method (surface temperature, thermal environment, heat removal rate, inlet air temperature, etc.) should be compatible with the cooling method used for the particular item of equipment. Techniques should be developed to obtain an analytical method of determining the rating and limits of each equipment type under given environmental conditions.

3.2.4 Transient Environmental Capabilities: Aircraft operation quite frequently involves some form of peak transient environment beyond the normal design requirements of the electronic equipment. These peak modes (which may consist of a temperature increase, altitude pressure decrease, decrease of cooling, or a combination of these) exist for relatively short time periods. The penalty for designing the cooling system for steady state capability of such transients is extreme, and consequently it is very important for the cooling system designer to know the transient capabilities of the equipment. The transient properties may be expressed in a plot of temperature, pressure altitude, or cooling (outside the steady state requirements) versus time. Knowledge of thermal lag or percentage of degradation of the electronic equipment during transient environmental conditions is necessary.

**Figure 7 - Reference: Liquid Cooling of Electronic Equipment by E. N. Shaw, Royal Radar Establishment, Malvern, England. Published in Product Engineering Design Digest Issue Mid-September 1959, page 466-469.

3.2.5 Reliability: The reliability of electronic equipment is of paramount importance and the improvement of its reliability should be a continual goal. Electrical circuit designs have been found to be excellent, but optimization of the mechanical and heat transfer designs with the electrical circuit design is required for maximum reliability.

3.2.5.1 Electronic equipment components have critical temperature limits which must not be exceeded if maximum reliability is to be obtained. The heat transfer design of electronic equipment is a relatively new science, and the mechanical complexity plus the limitations of heat transfer analysis methods contribute to the difficulty of adequate heat transfer designs. However, in order to provide adequate cooling for the components without penalizing the air vehicle, it is imperative that the science of heat transfer be applied.

3.2.5.2 The mechanical design of electronic equipment also contributes to the reliability of the equipment - in addition to its economy of production. Recognition of the advantages of hermetic sealing of minaturized electronic assemblies to eliminate the deleterious effects of corrosion and moisture is a contribution to improved reliability. Protective films have been used to alleviate corrosion problems, but this film is easily damaged leading to decreased reliability. The intimate relation between failures caused by corrosion or excessive temperature, or a combination thereof, should constantly be under consideration. Use of a hermetic sealing design makes inclusion of provisions for cooling mandatory since the sealants are basically heat insulators.

3.2.6 Specifications: The major factor permitting inadequate equipment design is the equipment specification which does not require design consistent with current material limits, current aircraft performance or improved types of cooling arrangements.

3.2.6.1 Figure 8 shows one method of presentation to define the natural external environmental temperatures encountered by the aircraft at various altitudes for a design mission on a specific type of day.

3.2.6.2 Figure 9 shows a method that can be used to present ram air temperatures for a particular design mission.

3.2.6.3 Figure 10 is a method of presentation for the highest aircraft skin temperatures and internal conditions to be used for the electronic equipment and cooling system design.

3.2.6.4 Specifications should include operating environment encountered when emergency conditions exist and the length of time that equipment is expected to operate under these conditions.

APPENDIX A - REFERENCES

1. J. Maxian, Jr., Problems Associated with Cooling of Electric Equipment in Future Aircraft (North American Aviation, Inc.)

2. E. W. Cornwall, Thermal Considerations in Electrical Accessory Design, Institute of the Aeronautical Sciences Preprint No. 489, June 21-24, 1954.

3. L. J. Lyons, High Temperature Problems of Airborne Electrical Equipment, American Society of Mechanical Engineers Paper No. 56-AV-25, March 14-16, 1956.

4. E. N. Shaw, Liquid Cooling of Electronic Equipment, Product Engineering Design Digest Issue, Mid-September 1959, Volume 30, No. 38.

5. Design Manual, Electronic Equipment Environmental Conditioning, L-5909-R July 15, 1960 AiResearch Manufacturing Company, page 11 Figure 1.

6. Heat Transfer in Miniaturized Electronic Equipment, NAVSHIPS 900, 189, Navy Department, Bureau of Ships, 1 February 1955.

7. Guide Manual of Cooling Methods for Electronic Equipment, NAVSHIPS 900, 190, Navy Department, Bureau of Ships, 31 March 1955.

8. Electronic Equipment, Aircraft, General Specification for, MIL-E-5400C (ASG) Amendment -1, 24 October 1958.

9. Electronic Modules, Aircraft, General Requirements for, MIL-E-19600A (WEP), 1 December 1959.

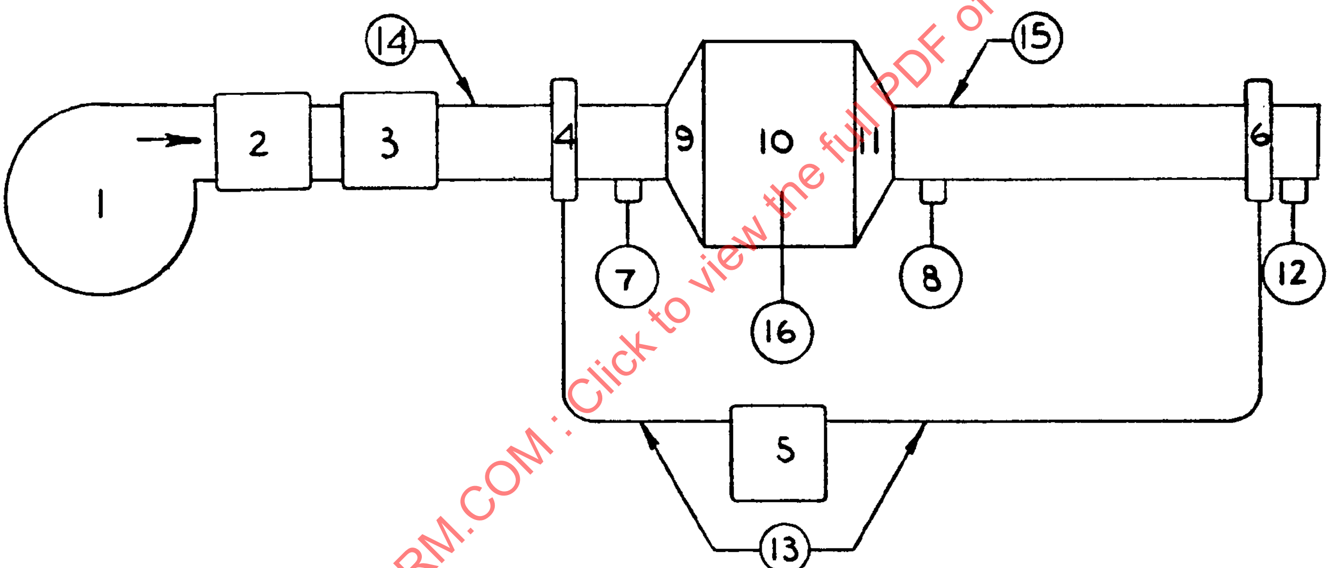
APPENDIX B

MEASUREMENT OF ELECTRONIC EQUIPMENT AIR PRESSURE DROP, COOLING AIRFLOW, AND AIR LEAKAGE CHARACTERISTICS

1. INTRODUCTION: The following information outlines a suggested method for obtaining the air pressure drop, cooling airflow, and air leakage characteristics of forced air cooled electronic equipment that has provisions for inlet and outlet air connections.

2. TEST SETUPS:

2.1 Pressure Drop and Cooling Airflow: A suggested test setup is shown below for obtaining air pressure drop and cooling airflow characteristics.



Item 1: Supply air source (blower, fan, etc.) of sufficient capacity to furnish maximum required airflow.

Item 2: Calibrated flow control and measuring device. (Suggested flow measuring devices are: Flowmeter, venturi, orifice plate, flow nozzle, or pitot-static.)

Item 3: Supply air heat exchanger.

Item 4: Supply air static pressure tap, located at least two inside duct diameters upstream of the equipment air inlet adapter duct and four inside duct diameters downstream of heat exchanger.

Item 5: Manometer of proper range to measure pressure drop with acceptable accuracy.

Item 6: Discharge air static pressure tap, located at least seven inside duct diameters downstream of the equipment air outlet adapter duct.

Item 7: Supply air temperature measuring device, such as a thermocouple, located downstream of static tap (item 4).

Item 8: Discharge air temperature measuring device located one inside duct diameter downstream of the equipment air outlet adapter duct.

Item 9: Equipment air inlet adapter duct.

Item 10: Electronic equipment under test.

Item 11: Equipment air outlet adapter duct.

Item 12: Equipment air outlet total pressure measuring device.

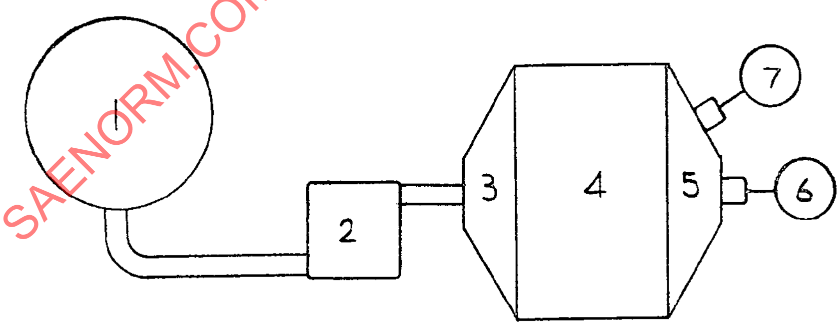
Item 13: Static air pressure lines between static pressure taps and manometer.

Item 14: Supply air ducting of adequate size to limit the duct Mach number to 0.1 or less at the maximum airflow.

Item 15: Discharge air ducting, the same size as the supply air ducting.

Item 16: Critical component temperature measuring device.

2.2 Equipment Leakage: The following sketch shows a suggested test setup for measuring cooling air external leakage from the electronic equipment.



Item 1: Pressure source.

Item 2: Direct reading flowmeter.

Item 3: Supply air inlet adapter.

Item 4: Electronic equipment under test.

Item 5: Discharge air outlet seal plate.

Item 6: Equipment internal air pressure measuring device.

Item 7: Equipment internal air temperature measuring device.

3. TEST PROCEDURES:

3.1 Pressure Drop and Airflow Characteristics:

3.1.1 Calibration of the test setup should be made by substituting an empty box for the electronic equipment to be tested, item 10. Measure the pressure drop over a range of airflows expected to be used in later testing of the equipment. The pressure drop obtained represents the pressure drop existing in the test setup and must be subtracted from the value obtained during actual testing of the equipment.

3.1.2 Pressure drop data should be obtained over a range of inlet air temperatures and a range of cooling airflows expected during actual operation of the equipment. Standard room pressure inlet conditions should be used. Caution must be exercised in selecting combinations of temperature and airflow so that the equipment "hot-spot" critical temperatures are not exceeded. A temperature measuring device, item 16, should be used to monitor the "hot-spot" temperature during testing so the equipment is not damaged. It is suggested that the initial airflow setting, for each supply temperature, be a maximum value. Reduction of the airflow can then be made until the critical "hot-spot" temperature is approached.

3.1.3 The cooling airflow Mach number should be limited to approximately 0.1 in order to reduce compressibility effects on the accuracy of determining σ and airflow.

3.2 Electronic Equipment Leakage:

3.2.1 The equipment should have the discharge opening sealed, and pressurized through the supply opening over a range of pressures expected during actual operation of the equipment. Leakage should be measured in lbs./min. at the various pressures.

4. TEST DATA REDUCTION:

4.1 Pressure Drop and Airflow Characteristics:

4.1.1 The final test data should result in two graphs as shown in Paragraph 4.1.2. The first graph should show $\sigma \Delta P$ (along the "Y" axis) versus W (along the "X" axis), where $\sigma \Delta P$ is the average density ratio σ times the pressure drop ΔP and W is the cooling air mass flow rate. $\sigma \Delta P$ should be in inches of water and W in lbs./min. The average density ratio σ can be determined by using the following relationship: $\sigma = 35.2Z$, where Z is equal to

$$\frac{\frac{P_o}{T_o} + \frac{P_1}{T_1}}{2}$$

P_o = Supply air pressure - psia

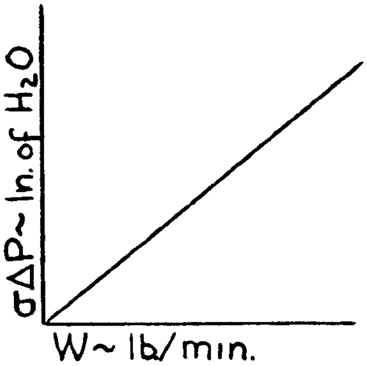
T_o = Supply air temperature - ^oR (460 + ^oF)

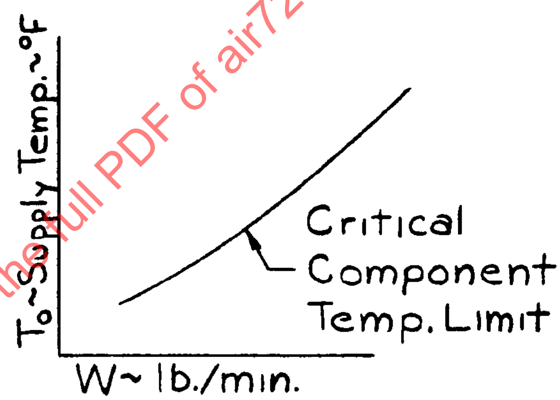
P_1 = Discharge air pressure - psia

T_1 = Discharge air temperature - ^oR (460 + ^oF)

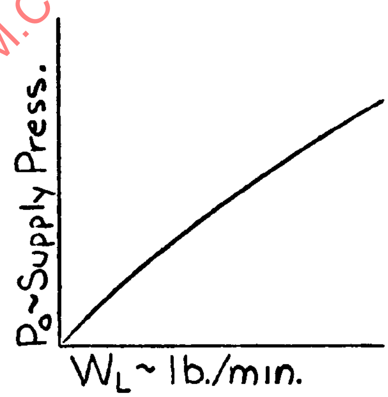
The second graph should show T_o (along the "Y" axis) versus W (along the "X" axis), where T_o is the supply air temperature and W is the cooling air mass flow rate. A curve should be drawn with these parameters indicating the minimum airflow that can be used for a particular supply temperature without exceeding the critical "hot-spot" temperature.

4.1.2 The following graphs show the final data desired for pressure drop and airflow characteristics.





4.2 <u>Electronic Equipment Leakage:</u> Plot a curve of P_o (along the "Y" axis) versus W_L (along the "X" axis) as shown below. P_o is supply air pressure in psia or inches of water and W_L is leakage in lbs./min.



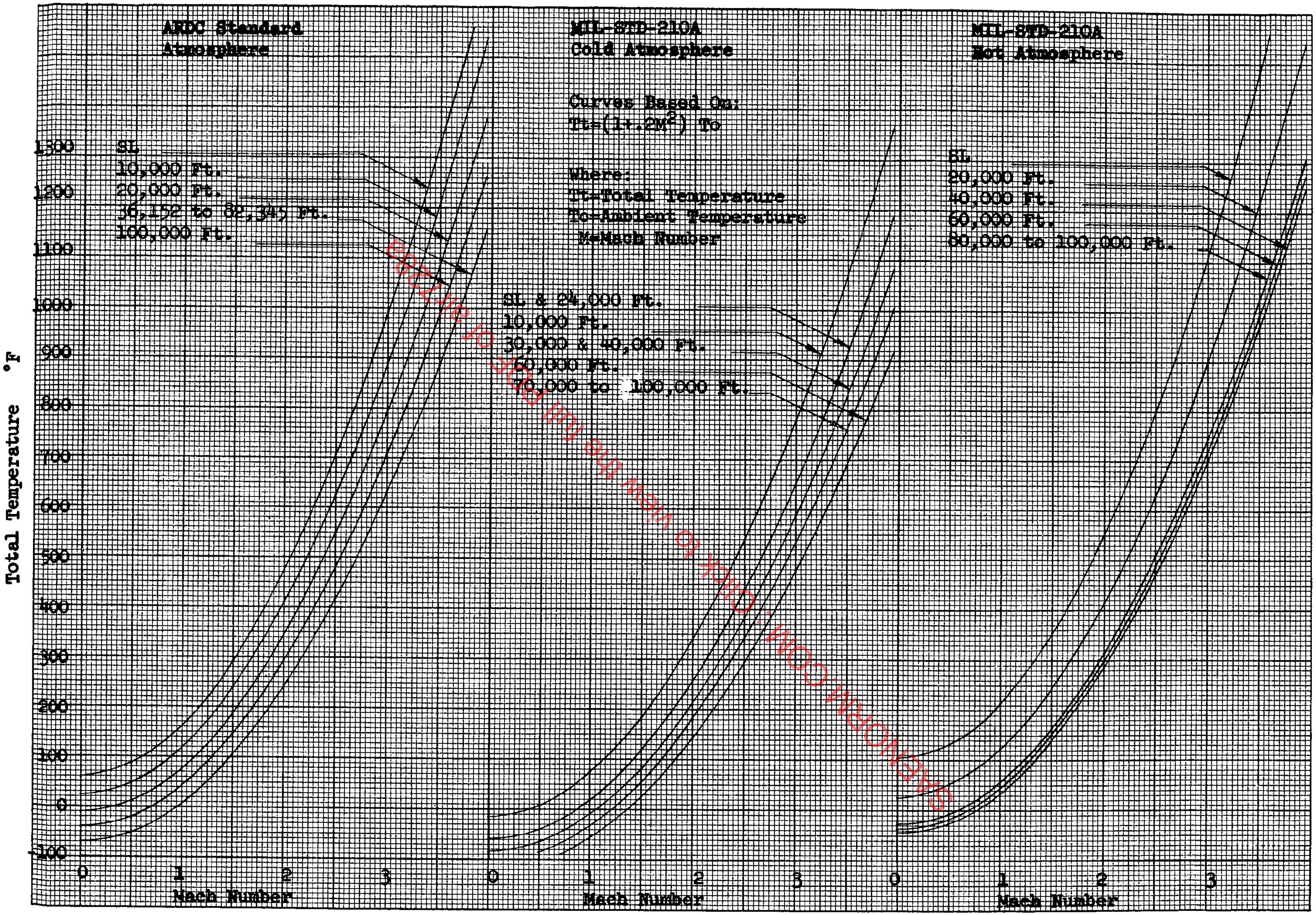

ARDC Standard
Atmosphere
SL
10,000 Ft.
20,000 Ft.
36,152 to 82,345 Ft.
100,000 Ft.
MIL-STD-210A
Cold Atmosphere
Curves Based On:
Tt=(1+.2M²) To
Where:
Tt-Total Temperature
To-Ambient Temperature
M=Mach Number
SL & 24,000 Ft.
10,000 Ft.
30,000 & 40,000 Ft.
60,000 Ft.
70,000 to 100,000 Ft.
MIL-STD-210A
Hot Atmosphere
SL
20,000 Ft.
40,000 Ft.
60,000 Ft.
80,000 to 100,000 Ft.
Total Temperature °F
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
1
2
3
Mach Number

Figure 1

Figure 2

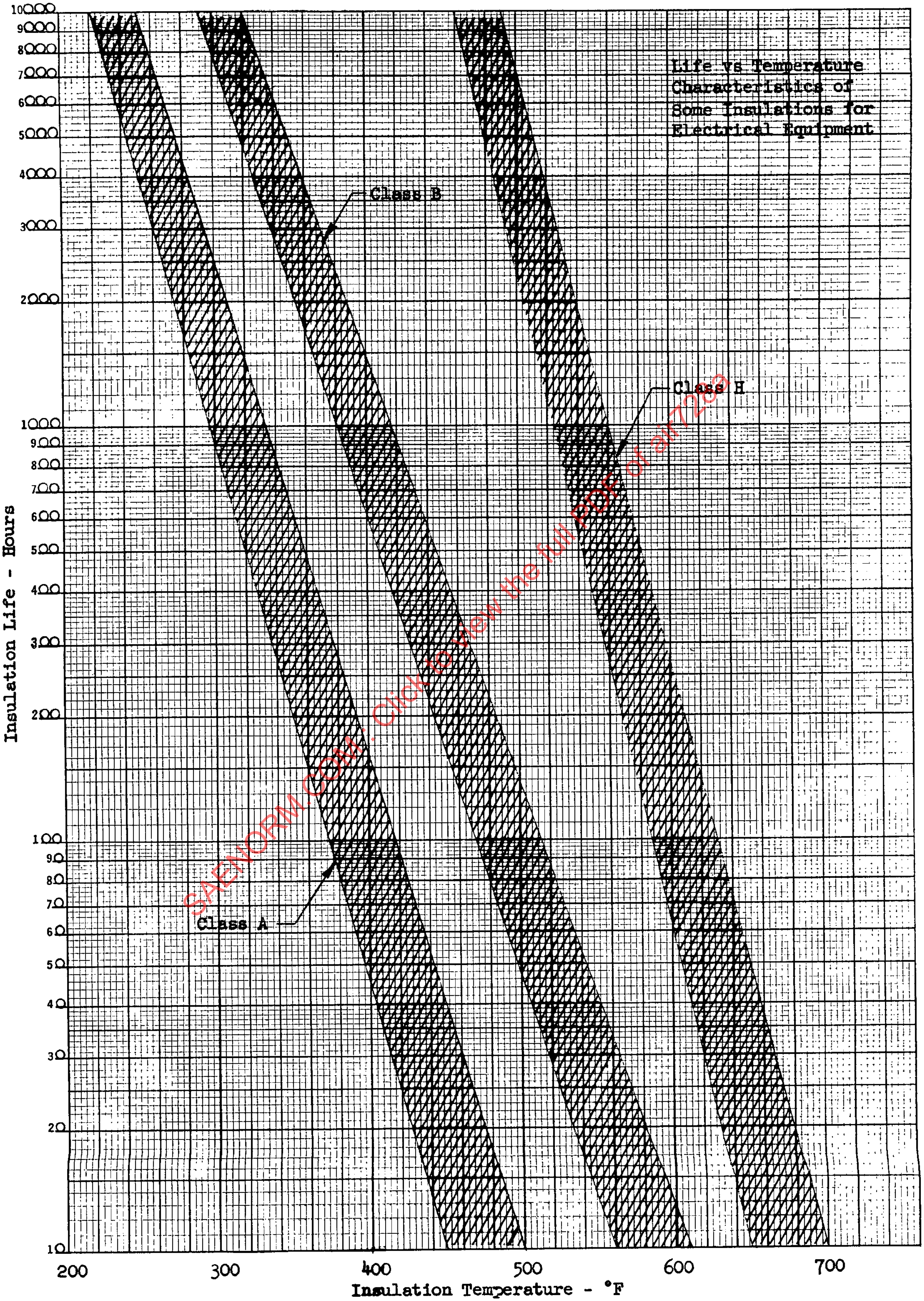
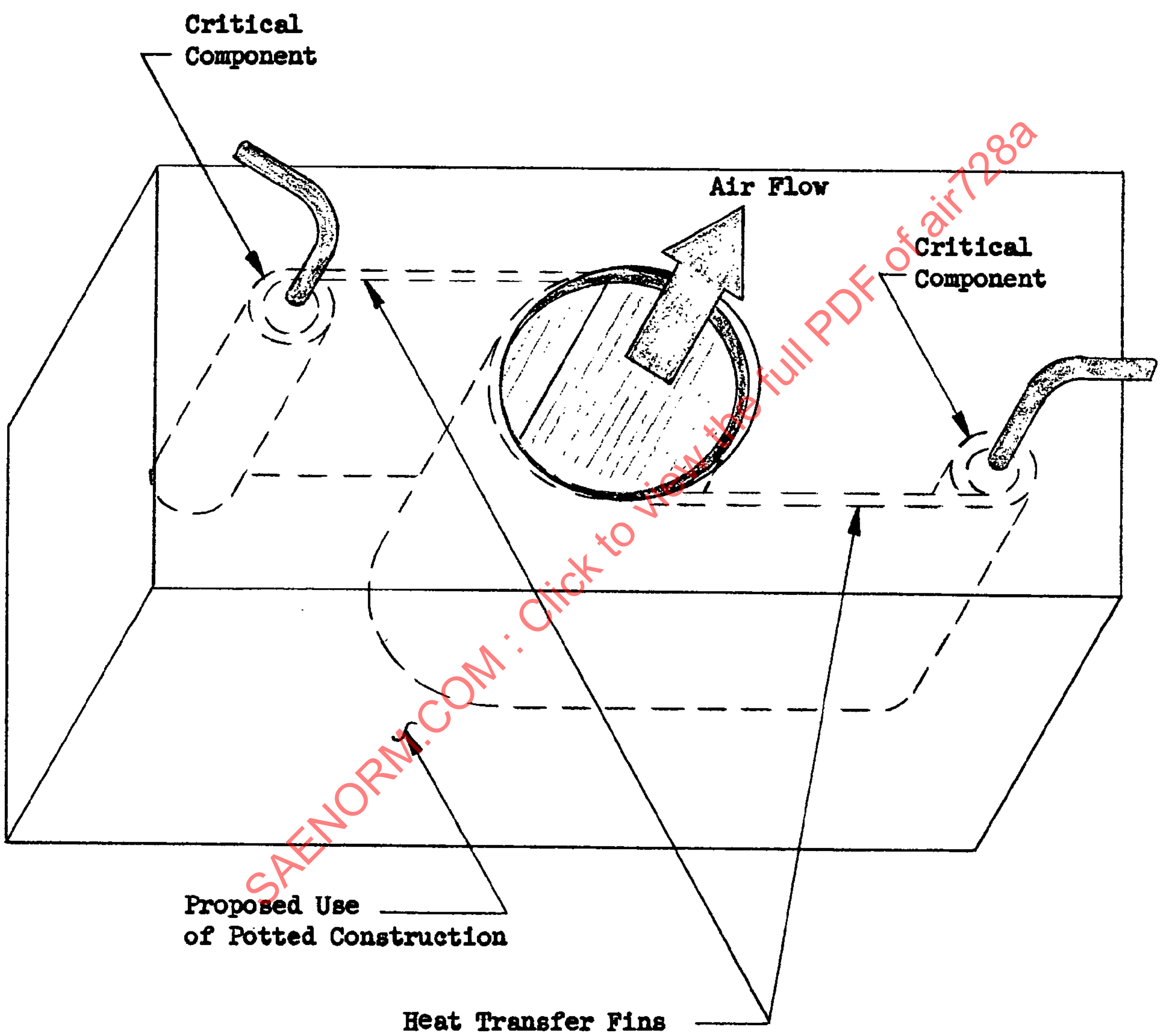

Life vs Temperature Characteristics of Some Insulations for Electrical Equipment
Class A
Class B
Class H
Insulation Life - Hours
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
200
300
400
500
600
700
Insulation Temperature - °F

Figure 3

Low Pressure Drop Design
With Good Heat Transfer



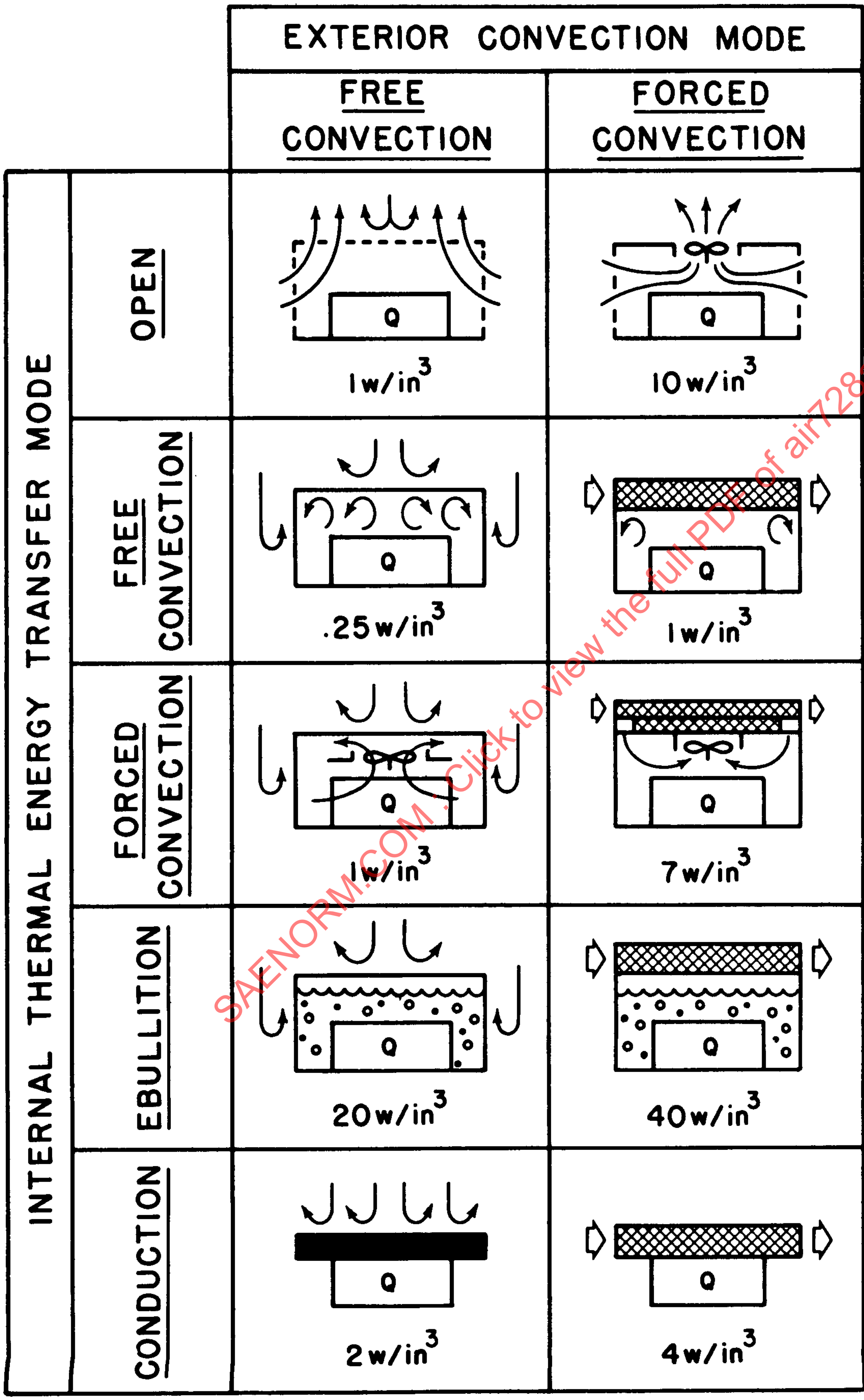

EXTERIOR CONVECTION MODE
FREE CONVECTION
FORCED CONVECTION
INTERNAL THERMAL ENERGY TRANSFER MODE
OPEN
FREE CONVECTION
FORCED CONVECTION
EBULLITION
CONDUCTION
Q
1 w/in3
10 w/in3
.25 w/in3
1 w/in3
1 w/in3
7 w/in3
20 w/in3
40 w/in3
2 w/in3
4 w/in3

FIG. 4

Figure 5

Curves Based On:
$Q = EWC_p (T_o - T_i)$

Where:
Q = Dissipated Heat
W = Cooling Airflow
Cp = Specific Heat
To = Outlet Air Temp.
Ti = Inlet Air Temp.
Tc = Component Temp.
E = Effectiveness

$$E = \frac{T_o - T_i}{T_c - T_i}$$

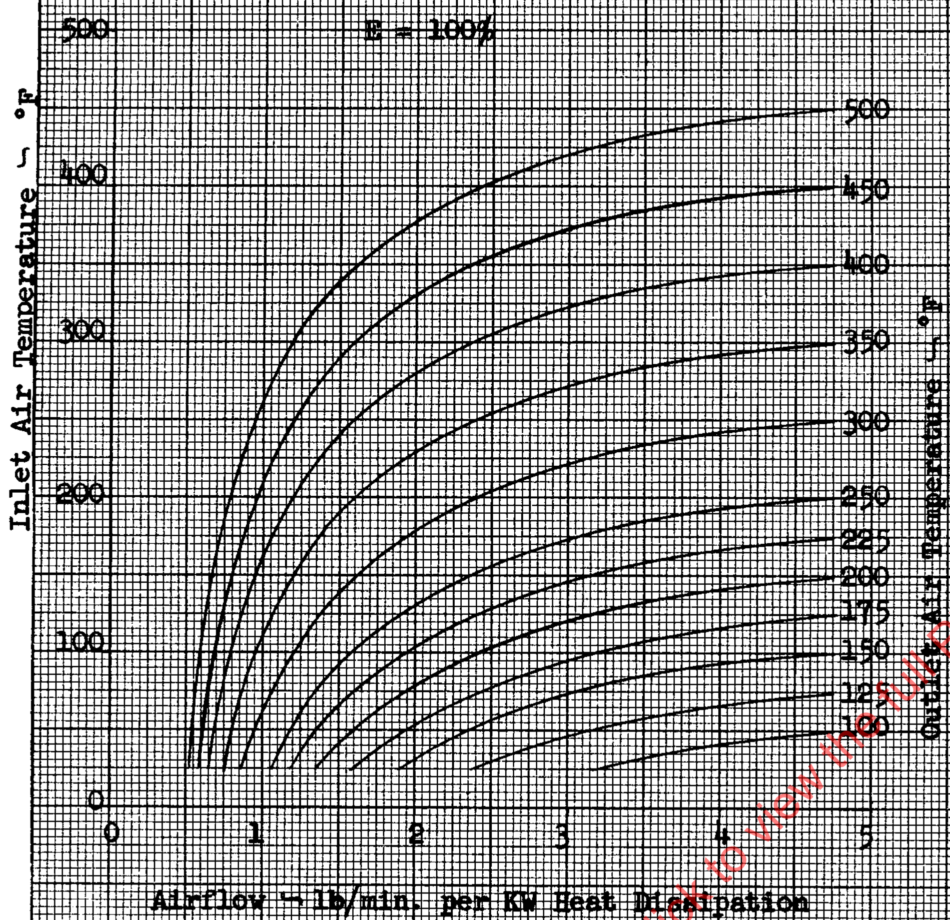


Figure 6

Curves Based On:
Same as Fig. 5