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AEROSPACE RECOMMENDED PRACTICE

ARP 735

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AEROSPACE VEHICLE CRYOGENIC DUCT SYSTEMS

PURPOSE AND SCOPE

This Aerospace Recommended Practice outlines the design, installation, testing and field maintenance criteria for aerospace vehicle cryogenic duct systems. These recommendations are considered currently applicable guides and are subject to revision due to the continuing development within industry.

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CREDIT PAGE

ARP 735 was prepared by the SC-9D Subcommittee of the SC-9, Spacecraft Environment Control and Life Support Systems Committee. The members of the subcommittee who contributed significantly to its content are listed below. They represent a wide spectrum of background and experience in the aerospace cryogenic ducting field, including government agencies, aerospace vehicle prime contractors, propulsion system prime contractors, ducting component contractors, and manufacturers of cryogens. The SAE is deeply indebted to them and their respective companies for their contributions.

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1. TERMINOLOGY

Absolute zero - Theoretical temperature at which all thermal motion or heat action ceases — approximately -273.16 C, -459.69 F, 0 K, and 0 R.

Actuating system - A system supplying and transmitting energy for operation of devices within a given system.

Adapter skirt - Flange or extension of a duct section providing a means of fitting another duct section to it.

Amagat - The ratio of the specific volume of a fluid at 0 C and one (1) atmosphere and the specific volume being considered (same fluid).

$$\text{Amagat} = \frac{V_o}{V} = \frac{\text{Specific Vol. (0 C and 1 atmosphere)}}{\text{Specific Vol. being considered}}$$

Attitude - Orientation of a vehicle or equipment as determined by the inclination of its axis to a frame of reference.

Bellows - A convoluted unit consisting of one or more convolutions used to obtain flexibility.

Boiloff - Vented vaporization of a saturated liquid as the fluid mass absorbs heat through the walls of the container.

Bracket - A support or structural part which attaches and holds a duct to the vehicle structure.

Bracket, adjustable - A bracket that allows some freedom in the location of the duct, which it supports, during installation. After the duct is located satisfactorily, the bracket is tightened and the duct is held fixed.

Bracket, anchor - A main duct support at a point on the duct system that remains fixed in respect to duct system expansions, contractions or deflections.

Bracket, guide - A support designed to provide for movement of a duct in a predetermined direction while supporting it in all other directions.

Bracket, sliding - A bracket which allows a duct to slide in a controlled direction while supporting it in all other directions.

Bracket, swing - A linkage which supports a duct and allows movement along the arc of the swinging bracket.

Braid - Woven wire sleeving used to limit the movements of a flex section.

Bulkhead seal - A fitting allowing the passage of a duct through a wall or bulkhead which prevents leakage through the bulkhead around the outer periphery of the duct.

By-pass - A duct that conveys fluid around a system or system component(s).

Cap, pressure - A part which can be used to cover tightly the end of a duct and sustain the internal pressure.

Cap, protective - A part used to cover an end or opening in a duct for the purpose of excluding foreign matter.

Cavitation - A localized reduction of pressure in a fluid system, below the vapor pressure of the fluid, causing the fluid to form cavities which are filled with vapor and dissolved gases.

Certified clean - A term used to specify that a component has been examined and cleaned in accordance with specific methods so that it does not contain foreign particles above a specified size and concentration.

Cold flow test - Test of a liquid rocket without firing to check efficiency of a propulsion subsystem that provides for the conditioning and flow of propellants, including tank pressurization, propellant loading, and propellant feeding.

Compression - Act of reducing the volume of the working fluid by the application of force.

Compression system - A duct system wherein the fluid column loads due to internal pressure are reacted by the support structure.

Cool-down - The process by which the temperature of cryogenic components is reduced to or below the saturation temperature of the contained cryogen.

Coupling - A fitting or clamping device that serves to join the mating ends of adjacent ducts or other components.

Critical constants - Values of pressure, temperature and volume corresponding to the "critical point" are called "critical constants".

Critical point - The point at which the slope of the saturated liquid-vapor line on a pressure-volume diagram or temperature-entropy diagram is zero.

Critical pressure - The saturation pressure at the critical temperature.

Critical temperature - The limiting temperature of a fluid, above which the liquid phase may not exist.

Cryogen - A member of a family of substances which are gases at "room temperature" and are liquids at temperatures below -150 C at sea level pressure.

Cryogenerator - An apparatus used to remove heat from gases so that they condense at cryogenic temperatures.

Cryogenic engineering - Engineering which is concerned with developing and improving low-temperature processes and equipment, determining physical properties of structural and other materials used in producing, maintaining, and using low temperatures; and the practical application of low-temperature techniques and processes.

Cryogenics - The science of low-temperature conditions; usually below 123 K (-150 C).

Cryogenists - Personnel associated with the science of refrigeration, especially with reference to methods, systems, and materials for producing very low temperatures.

Cryometer - A thermometer for the measurement of low temperature.

Cryopumping - The process whereby gas is "pumped" by being condensed at cryogenic temperatures. Similar to cryovoiding.

Cryoscopy - Determination of the freezing points of liquids.

Cryostat - An apparatus for maintaining a constant temperature in the cryogenic range with automatic regulation of temperature.

Cryotron (switch) - An electromagnetic type of switch which utilizes electrical conduction characteristics of materials at cryogenic conditions.

Cryovoiding - The process of evacuation whereby gas is condensed at cryogenic temperatures. Similar to cryopumping.

Deflection - A displacement of a duct or joint due to operating conditions.

Dewar - An insulated container for storing cryogenic liquid. Usually a multi-walled vessel with a vacuum between the walls for insulation or a combination of vacuum and insulating materials.

Duct - An enclosed passageway made of sheet metal or other suitable material for the conveyance of fluids.

Duct assembly - Detail parts fitted and joined together to form an integral part.

Expansion, thermal - Duct growth due to an increase in temperature.

Flex-section - These devices when incorporated in a duct system permit relative motion in one or more planes. The term Flex-section may include bellows, flexible sections and flexible joints which are devices possessing flexibility resulting from the method of construction or the utilization of flexible materials.

Flex-section, braided - A flexible device surrounded by a woven wire sleeve attached to the ends which restrict the movements of the unit.

Flex-section, free - A flexible device which does not incorporate any device or part for the purpose of preventing movement.

Flex-section, restrained - A flexible device incorporating a means of restraint, other than braid, to prevent axial motion.

Flow, single phase - With a cryogenic fluid flowing in a duct, single phase flow is characterized by being either all liquid or all gas.

Flow, two-phase - The simultaneous flow of a liquid and gas and/or vapor in a duct. The following are types of two-phase flow in a cryogenic system.

Annular - Annular flow is characterized by the flow of a continuous liquid layer along the duct wall while the gas flows in the central core at much higher velocity.

Bubble - Bubble flow is characterized by the formation of individual bubbles along the upper surface of the duct.

Froth - Froth flow is characterized by a foam-like mixture of small bubbles and liquid intimately mixed during turbulent flow through the duct.

Mist - Mist flow is characterized by fine liquid drops suspended by surface tension, with no significant relative velocity between the liquid and gas phase.

Plug - Plug flow is characterized by the flow of large plugs of liquid through the duct and is most likely to exist during the transition period from bubble to stratified flow.

Slug - Slug flow is characterized by alternate sections of gas and liquid along the duct.

Stratified - Stratified flow is characterized by the flow of the liquid phase along the bottom of the duct, while the gas phase occupies the upper portion of the duct. The gas phase flows at much higher velocity than the liquid at the bottom.

Wavy - Wavy flow is similar to stratified flow with the exception that waves are formed at the gas-liquid interface.

Fluid - A fluid is a substance which undergoes continuous deformation when subjected to a shear stress.

Freeze-out method - A method of controlling the composition of gases or liquids by freezing and separating frozen matter from the remaining liquids or fluids.

Getter - A substance which takes up gas at very low pressures and is used to improve or maintain a vacuum in a closed system.

Gox - Commonly used expression for gaseous oxygen.

Hose - Tubing, either flexible by construction or made of flexible material which is attached to the ends of adjacent ducts, tubes or fittings. The term generally implies flexible tubing with a length to diameter ratio (L/D) of three (3) or greater.

Ice frost - A thickness of ice that gathers on the outside of equipment over surfaces supercooled by cryogenic fluids.

Installation - A completed set of duct assemblies and duct supports incorporated in a vehicle.

Insulation - A material applied around the duct which is used to reduce heat exchange.

Insulation, super - High efficiency insulator used in extremely low temperature applications. The thermal conductivity range of super insulations is 1/10 to 1/50 that of the more common low-temperature insulations.

Interface, fluid system - The common boundary between fluids. In a cryogenic storage vehicle, the boundary between liquid and ullage.

Interface, vehicle system - The common boundary between one component and another.

Joint - A device or complete assembly which unites or establishes continuity between adjacent ducts or other components.

Joint, ball - A joint which permits relative angular movement and rotation of two adjacent ducts.

Joint, compensating - A pressure (thrust) compensated assembly allowing axial motion which maintains the duct walls in tension.

Joint, expansion - Any of many types of joints which can permit axial movement without failures and, therefore, permit the ducting system to expand or contract.

Joint, flexible - A non-rigid joint, convoluted tubing, hose or ball joint assembly which joins two ducts and permits relative motion of the ducts in one or more planes.

Joint, restrained - A flex-section assembly in which an angular deflection can occur with a tension load being transmitted by an external or internal device.

Joint, rotary - A joint which permits relative rotation of two adjacent ducts.

Joint, slip - A joint having sleeve assemblies, one sliding inside the other, to allow axial motion.

Line mounting - Refers to a component mounted on and supported by the duct, instead of direct attachment to a support or bracket.

Linear offset - Distance between the duct centerlines of two joining ducts.

Liner - A cylindrical part within a flex-section assembly.

Liquefaction - Cooling of gas until its condensation temperature is reached.

Liquefier - A device used in the process of condensation of gases.

Live length - The convoluted length of a flex-section assembly.

Load - The resultant force exerted upon restraining brackets (and structure) due to internal fluid static and dynamic pressures, thermal expansion or contraction, structural deflection, and component weight.

Load, limit - The maximum combined load due to all internal and external pressures and forces that a duct or duct system can encounter at any time in service.

Load, pre - The force imposed on a duct or duct system prior to, or during, installation.

Load, pressure - The force determined by the product of the internal differential pressure and the duct cross-sectional area.

Load, ultimate - The maximum load a duct or duct system can sustain without failure.

Lox clean - A component that has been examined and cleaned in accordance with specified methods so that it does not contain foreign particles of a specific size and concentration that could cause a malfunction.

Mass flow rate - The rate of fluid flow expressed in units of mass per units of time.

Misalignment - Error in alignment between the axes of two joining parts; the error may be linear, angular, or both.

Omega bend - A bend whose shape resembles the Greek letter omega and is used to accommodate contraction or expansion in a duct system.

Ortho-hydrogen - Molecular hydrogen in which two hydrogen nuclei are spinning in the same direction.

Oxidizer - A rocket propellant component, such as liquid oxygen, nitric acid, fluorine, and others, which supports combustion when in combination with a fuel.

Para-hydrogen - Molecular hydrogen in which the two hydrogen nuclei are spinning in opposite directions so that their contribution to the total angular momentum is zero.

Percolating - (Percolate) To cause (a liquid) to pass through interstices, as a porous substance; to filter; to strain; also formerly to sift through fine holes. Percolating can be evidenced by the rapid release of gas bubbles in excess of that rate which may occur as a normal function of bubble release.

Precooling - The first or initial cooling applied to a fluid involved in a process.

Pressure, burst - Maximum internal pressure above ambient which duct must withstand without rupture.

Pressure, design - The selected normal operating pressure.

Pressure, differential - The difference between the internal pressure at a point in a duct and a reference pressure (ambient) or, in a flowing system, the difference in pressure between two points due to pressure drop.

Pressure envelope - The range of pressures to which a part is subjected in normal operation.

Pressure, maximum operating - The maximum pressure a duct will experience under all possible operating conditions.

Pressure, proof - The maximum test pressure a duct or duct installation must sustain without permanent deformation.

Purge - To internally cleanse a component or system of undesirable fluids or contaminants by flowing a selected fluid, usually under pressure, through the component or system.

Regenerator - A device used in liquefaction systems to cool high pressure air and remove some impurities by condensation.

Reliability - (1) Dependability. (2) The probability that a component or system will operate for a specified period of time under specified conditions without failing.

Rupture - A break in a duct or duct assembly.

Saturation - The condition for coexistence in stable equilibrium of two or more distinct phases.

Scim - Abbreviation for "standard cubic inches per minute", used for measuring leakage rates.

Sloshing - The oscillation of a body of liquid in its tank or container.

Stratification - Temperature layering of a cryogenic fluid in its container due to the temperature of the liquid at the surface rising more rapidly than that of the bulk of the liquid.

Subcritical storage - Containment of a cryogen below its critical temperature and pressure so that a liquid-vapor interface exits.

Superconductivity - The condition where there is no measurable electrical resistance in certain materials below a specific low temperature for each of the materials.

Supercritical storage - Containment of cryogenic fluid initially stored above its critical pressure and generally below its critical temperature - used for supply systems under zero "G" or variable "G" conditions.

Symbols - Gaseous Hydrogen: GH_2 Liquid Nitrogen: LN_2
Gaseous Nitrogen: GN_2 Liquid Oxygen: LO_2
Gaseous Oxygen: GO_2 Liquid Hydrogen: LH_2

System - A combination of ducts, duct supports, duct joints and fluid control devices which will regulate and convey fluids from a source to a point or points of use.

Temperature, design - The selected normal operating temperature.

Temperature, differential - The difference between the internal temperature in a duct and a reference temperature, or in a flowing system, the difference in temperature between two points due to temperature drop.

Temperature, envelope - The range of temperatures to which a part is subjected in normal operation.

Temperature, maximum operating - The maximum temperature a duct will experience under all possible operating conditions.

Tension system - A ducting system wherein the fluid column or longitudinal forces due to internal pressure are not transmitted to the supporting structure. The fluid column loads of such a duct system are reacted by axial tension in the duct walls.

Transfer lines - In cryogenics, generally referred to vacuum jacketed or insulated piping.

Triple point - Triple line - A point or line on Pressure-Temperature or Pressure-Volume diagrams where all three phases of a substance may co-exist simultaneously in equilibrium; i.e., solid, liquid, and gas.

Ullage - The extra volume of a pressure vessel above the contained liquid level to allow for thermal expansion of liquid and for ejection of dissolved gases or the accumulation of gaseous products of slow reactions within the liquid.

Vehicle - Assembled structural and aero-dynamic components of an aircraft or missile.

White room (or clean room) - A cleaning facility designed to provide the necessary environmental conditions (temperature, dew-point and contaminant particle size) and equipment to accomplish certified cleaning.

2. SYSTEM DESIGN

2.1 SYSTEM ENVIRONMENT - Environment is here considered to be the sum of the influence applied by systems associated with the ducting and the influence applied by nature.

Three major conditions for consideration have been established: stand by or transportation, tanking and cool-down, and flight or static firing.

2.1.1 Stand-By or Transportation Condition

2.1.1.1 Vibration in Transportation - If a completed flight article must be transported by truck, trailer, or airplane, shipping vibration can be a problem.

Vibration at this time is generally of smaller magnitude than that during flight, but it may involve a large number of cycles.

Conditions are different than flight as the ducting does not contain propellants, or flight pressures. This condition may be included as part of duct qualification testing.

2.1.1.2 Two Valves or Closures in the Same Duct:

a. In a duct with both ends closed large positive pressures will develop when trapped residual cryogenic liquid boils off.

b. A duct closed at both ends may, if not internally pressurized, develop negative pressures with decrease in temperature.

c. This same arrangement may develop negative pressures due to leakage from the duct during altitude changes. The negative pressures become evident when altitude is decreased.

2.1.1.3 Corrosion:

a. Galvanic corrosion is an action that must be controlled. When two metals differing in electro-chemical potential are allowed to have electrical contact through some form of electrolyte, the less noble metal is consumed.

b. Coating of the less noble material is practiced, and is effective. On components exposed to the elements, however, coating may not be adequate. Hard particles, such as sand, can penetrate painted, or in the case of aluminum, anodized surfaces. This leaves the surface vulnerable.

c. Coated surfaces are more practical in a protected area, and can be practical even in particularly corrosive atmosphere.

d. Stored components, such as spares, must also be considered. The interior must be protected against corrosion and other contamination.

e. Some cryogenic propellants subject the interior of ducting to severe corrosive atmosphere. Detailed studies and tests of materials are then required.

f. Stress corrosion environments may exist in cryogenic ducts and should be considered in design.

2.1.1.4 Leakage:

a. Leakage at any time is not a desirable situation. The allowable leak-rate should be established based upon the criticality of leakage. In many systems, even small leak-rates are critical, because of:

(1) fire hazard
(2) explosion hazard
(3) depletion of supply

The result is loss of the mission, or even loss of the vehicle.

b. Seals should be designed to allow for collecting and measuring leakage throughout development, checkout, static test and flight phase of the system. Test programs should simulate flight conditions, particularly dynamic pressure and temperature, and should include long term storage.

c. Seals used for cryogenics may be subject to creeping at ambient temperatures. Test problems should include hot and cold cycling, and storage tests to check for this possibility.

2.1.1.5 Maintenance:

a. It is inevitable that components will be removed and replaced in the field.

b. Simplicity of design is important. The amount of required adjusting, aligning etc., should be minimized.

c. The possibility of installing components backwards or otherwise oriented incorrectly should be eliminated. This applies also to parts of components which are removable.

d. Good access is important for installation and for leak check after installation.

2.1.2 Tanking and Cool-Down Condition

2.1.2.1 High Rate Tanking - The requirement may exist for fluid flow to be greater during fill than during flight. Portions of the system may be sized to meet this, and this also may be the highest pressure condition. Since the fluid flow is in reverse direction, certain components must have particular consideration.

a. Poppet valves in the duct.

b. Reverse loading on supports as a consequence of valve sequencing, or pressure drop due to flow.

c. Impingement of fluid as it enters the tank.

2.1.2.2 Cool-Down Into a Hot Duct - When flow is initiated into a relatively hot duct, the rapid boiloff can be of concern.

a. If the ducts involved are long with considerable pressure drop, a high pressure will be the result.

b. If a pump is supplying the cool-down flow, cavitation and surging can be induced as the flow decreases to zero or even reverses.

Allowing boiloff from upstream lines to pass through the system prior to liquid flow minimizes the problem.

2.1.2.3 Tank Pressure Decay - If a quantity of cryogenic liquid is suddenly introduced into a large tank at ambient pressure and temperature, negative pressures can result in the tank. These may be in the order of 3 or 4 psi. Allowing childown gas flow through the tank prior to liquid entering, reduces this effect.

2.1.2.4 Low Flow Rates on Small Lines - Heat transfer rates and flow rate may be such that a steady state condition can develop in which the line never fully chills down. This results in a condition where liquid is introduced to the duct and vapor exits from the line.

2.1.2.5 Keeping the Liquid Cold - Heat input to a filled duct must be considered.

a. If a propellant is not sufficiently cold, but near boiling, the engine pump NPSH (net positive suction head) may not be supplied.

b. A duct may percolate or burp in the manner of a coffee pot. This endangers engine start conditions and introduces surges into the system.

c. Problems of this nature may be solved by injection of cold liquid, or allowing recirculation through branch lines. In either case, insulation on the duct may help.

d. Insulation:

(1) Analysis should be made to prove there is a net weight saving in the use of insulation. If the result is only a small net saving, then the problems of insulation will probably be of more concern than weight saving.

(2) Insulation is often difficult to install and inspect, and is easily damaged.

(3) The cryogenic fluid may be colder than the condensing temperature of oxygen in the air, as are LN_2 and LH_2. If the insulation can trap this condensation, then an explosive hazard can result. Another result can be damage to insulation as ducting warms to ambient.

2.1.3 Flight and Static Firing Condition

2.1.3.1 Influences Determining Duct Sizes - The objective is to make ducting as small as possible. Velocities should be as high as can be tolerated by allowable pressure drop.

a. Net pump suction head

(1) Start condition - From zero, the fluid must accelerate to a velocity as required by pump demand. The larger the diameter of the duct, the less the pressure drop during this acceleration. This is a transient condition, but still may be critical to a starting engine.

(2) Flight condition - To be considered is the fact that the liquid head is dropping due to consumption of propellant. Increase in acceleration may more than compensate for this liquid head loss.

(3) Static firing - If system is designed to flight conditions, then static firing may be limited to less than full duration because of head loss, with no compensating gain in acceleration.

b. Multi engine arrangements - There may be a requirement that each pump inlet have the same pressure. If all ducting is sized to the minimum, this condition is probably met.

The tendency, however, is to use the same flex joints, flanges, etc., for as many different ducting systems as possible. The requirement then is not so easily met.

c. Application of test data in respect to pressure drop - Caution should be exercised in directly converting test data to cryogenic applications when the test fluid was noncryogenic. Direct conversion does not necessarily agree with later test results when the correct fluid is used.

2.1.3.2 Pressure Transients Due to Valves - A system with quick closing valves is subject to pressure transients which may be the maximum pressure the system feels.

a. The magnitude of the surge is dependent on the weight flow and compressibility of the fluid, the valve closing time, and the ducting configuration, and material.

b. The length of time the surge exists is a function of the length of the duct upstream of the valve and the speed of sound through the fluid.

c. Surges that exist for short time periods, such as 15 milliseconds, must be considered as steady state.

2.1.3.3 Allowable Flange Loads - Equipment to which a duct is attached may have specified allowable load limitations. Problem areas are in ducting stiffness, weight, location of supports and vibration response. Calculations should be made to check this condition early in the lay-out stage.

2.1.3.4 Influences of Heat

a. Aerodynamic heating

(1) High velocity through atmosphere develops heating of surfaces where air impingement is allowed to exist.

(2) Ducting supports on the exterior of a flight article must be insulated or made of material that can withstand high temperatures.

(3) Cryogenic ducting generally will not experience trouble from impingement as long as fluid flow exists in the duct.

(4) An exposed flex section can experience trouble in that the cryo liquid flow is stagnant in the convolutions, heating causes gas to form, and at this time the heat transfer is so poor that the convolution can become overheated.

(5) Ballistic re-entry into the atmosphere may be required. Aerodynamic heating on any exposed ducting will be severe, and ablative covering for protection of ducting will probably be required. Since the covering would have to be replaced, it would be good design to keep ducting from being exposed.

b. Structural displacement due to temperature change

(1) As a duct system and or a large tank changes in temperature, such as ambient to cold, there is a change in length that the ducting must accommodate.

(2) During flight, the structure of the vehicle can become heated and make a surprisingly large displacement of attached ducting.

c. Base heating and flame attenuation

(1) Base heating may take place when vapor from fuel rich flames moves into the low pressure area at aft end of a vehicle. Combustion then takes place and all components in this area are subject to high temperatures.

(2) Flames from sources which are not well aft of the vehicle, will at high altitudes flare out or attenuate to the extent that the flame envelops much of the vehicle.

d. Ice formation - Cryogenic system valve actuators or other mechanisms near cryogenic ducting may become covered with ice. The condition is most severe when exposed to rain. Such mechanisms must be designed to operate with ice deposited, or have heaters to eliminate the problem.

e. Radiation

(1) Radiation from a rocket engine flame has an effect on base heating and all exposed components.

(2) Solar radiation in space, particularly during coast periods is a heat source that must be considered. Insulation in this case is simplified in that a vacuum already exists, and only shielding with proper absorbtivity-emissivity ratio is required.

(3) Nuclear radiation has an effect on the properties of some of the cryogenic ducting materials. A characteristic change to materials is a decrease in tensile and elongation properties. This effect appears more severe at cryogenic temperatures. An example of this property change is 27% tensile loss in 301 cres. (See reference 1.)

2.1.3.5 Acceleration

a. Structural deflections from acceleration - As flight articles are typically of optimum strength to weight ratio, they are also quite flexible under dynamic conditions. Thrust, gimbaling engines, buffeting etc., result in deflections of the basic structure. The ducting then must allow for these motions. In the case of duct attached to a gimbaling engine, considerably more motion must be designed for.

b. Pressure variations from acceleration effects - The pressure-time history may show considerable variation. As an example, a propellant duct may feel the following:

+ 70 psig after tanking
\- 10 psig at engine start
\+ 150 psig at max acceleration
\+ 180 psig at valve closure
\+ 40 psig at thrust decay

c. Zero G condition - A liquid system in a condition of no acceleration, presents interesting problems.

(1) Surface tension forces tend to dominate the shape of liquid gas interface. When the contact angle is small, then a tank tends to have liquid covering its surface, with the gas confined to the center.

(2) Attempts to pump either a liquid or a gas from the system may not be rewarded. Application of an acceleration prior to attempts to pump liquid is one solution.

(3) Heat transfer with gas formation at hot spots further complicates the situation.

d. Pressure pulse - During engine start, a pressure wave may be generated in the flame bucket. The pressure will be externally applied to ducting, and as a secondary effect, deflections and shock loads transmitted from supporting structure will be felt.

The pressure wave develops as a function of flame bucket dimensions, and thrust rise time. Pulse pressures in the order of 5 psi are known.

e. Touchdown after re-entry

(1) Water impact may be involved. There can be considerable spray and sea water impingement on ducting. This is particularly so if touchdown rockets are used, as the ground effect will result in a return flow of water and gases to the vehicle.

(2) In the case of ground touchdown the impact "G's" may be high, but of short duration.

2.1.3.6 Zero-Ambient Pressure

a. Substances that normally are solids or gels may change their properties thru sublimation. Insulation is subject to expanding.

b. Friction is a particular problem. In addition to grease or ordinary lubricants losing their properties, there may be change in friction coefficient on surfaces which were designed to operate without lubricant. Layers of gas or oxide on metal surfaces have an influence on coefficient of friction as measured at sea level conditions. These layers may disintegrate at zero pressure. Actuators, disconnects, braided hoses, etc., may be suspect here.

c. The existence of a nature supplied vacuum may be of advantage. Heat transfer through convection is eliminated.

2.1.3.7 Vibration

a. Ducting systems, being of flexible nature to allow for displacements, are resonant at low vibration frequencies. At these low frequencies, large energies may be encountered. An input of ± 3 G's may be magnified to 30 to 60 G's at various points in the duct system.

b. Ducting supports, and minimum gauges of ducting may be established by vibration requirements rather than pressure.

c. Components that have flat spots or odd intersections such as Y's or T's are especially susceptible to damage. Failures here are involved with oil canning and local fatigue.

d. A situation that should be avoided is the one where a component or length of ducting is mounted between two unrestrained flex sections. Damage of the flex sections may result when vibrating at the resonant frequency.

e. Strategic location and proper design of supports or dampeners to eliminate system damage without decreasing the required flexibility of the ducting is a real challenge to the designer.

f. Vibration requirement should be governed by actual or analytical spectrum and level for the particular duct location.

2.1.3.8 Particle Impingement - When out of the protective earth atmosphere the vehicle is subject to bombardment from dust particles. Wearing or pitting of the duct wall and actual penetration may result, as the particles may have large kinetic energy.

The length of time, and to some extent, the location in space are significant factors. As the need for protection of personnel and tanks is required, similar consideration must be given to ducting.

2.1.3.9 Influences Concerning Flow

a. Modes of failure from flow

(1) Seals in butterfly valves, even though they appear to be firmly in place, may become unseated during high rate flow.

(2) Duct walls are subject to buffeting particularly where diameters are large and there are elbows in the system. Oil canning and fatigue failures can take place.

(3) Turning vanes in elbows must be rugged. Instability of a vane leads to additional dynamic load which further

increases its deflection and possibility of failure.

(4) A convoluted flex whether free or restrained is subject to longitudinal cycling during flow. The flow rate and flex spring rate are important.

(5) As tank depletion nears, vortexing of liquid in the tank takes place allowing gas to be entrained in the flow. If this cannot be tolerated, large tank residuals will exist. Various forms of baffles and perforated diaphrams are employed to eliminate vortexing.

b. Flow test requirements - The hardware should be subject to the same safety factors under flow conditions as under any other conditions.

(1) A proof flow rate should be established which will apply dynamic forces with a certain margin over the dynamic forces applied at operating flow rates. As an example, a flow rate of 1.225 x operating flow rate results in dynamic forces of 1.50 for safety factor.

(2) In addition, some flow time should be spent at operating flow rates, as the flex joints may be critical at some points different from proof flow rate.

(3) A liberal use of instrumentation bosses on test hardware may save time in a test program. In development of a system, the test objectives may change to find more and different information than originally planned.

REFERENCE

1. Allen, J. W., J. L. Christian, and J. F. Watson. "A Study of the Effects of Nuclear Radiation on High-Strength Aerospace Vehicle Materials at the Boiling Point of Hydrogen," General Dynamics Research Program 111-9135, 111-9212, 27 September 1961.

2.2 SYSTEM ARRANGEMENT AND DESIGN

2.2.1 Types of Duct Systems - A duct system may be a tension, compression or combination tension-compression type. The type of system selected will depend on a number of factors, e.g., the duct configuration, provision for thermal movement, the type of or lack of insulation, the availability of structure for anchoring, etc. The following paragraphs give a brief description of the types. For further information see ARP 699.

2.2.1.1 Tension System - A tension system is one in which the internal fluid forces are reacted by the duct and are not transmitted to the vehicle structure through supports. Analysis of a tension system must include, but is not necessarily limited to, the following:

a. Duct guide supports (such as rollers, sliding, or hanger type)
b. Provision for thermal movement
c. Differential contraction during cooldown
d. Vehicle structural deflections
e. Duct end connections
f. Internal fluid dynamics
g. Acceleration loads
h. Heat leak mechanism
i. Thrust vector gimballing
j. Flex section motion limitation
k. Vibration

2.2.1.2 Compression System - A compression system is one in which the internal fluid and thermal contraction forces are reacted by the support structure. Analysis of a compression system includes the factors mentioned for the tension system and the following additional considerations.

a. Adequate vehicle structural supports
b. Duct strength to withstand bending and column loads

2.2.1.3 Tension-Compression System - A tension-compression-type system may be used in lieu of either a tension or compression system. It would consist of placing one section of the system in tension and the other section in compression as described above. The fixed point in the tension section will occur where it joins the duct section which is in compression. Design of the system will include all of the considerations mentioned in individual systems.

2.2.2 Optimum Arrangement - Arriving at an optimum duct arrangement involves engineering comparison studies including but not limited to the following factors:

a. Permissible pressure drop
b. Heat transfer to or from the fluid
c. Type or lack of insulation
d. Percolating or other cryogenic phenomena
e. Routing around or through structure
f. Cleaning and purging requirements
g. Compensation for duct and structural movements
h. Pumping system
i. Transferring, filling, purging, draining, venting, or test stand operation
j. Weight
k. Accessibility for maintenance

2.2.3 Quality Assurance - The costly problem of frequent maintenance, the logistics problem of low equipment operation time, and the problem of equipment failing to perform the required function dictate an active quality assurance program. During design, manufacture, and installation, quality and reliability can be assured by adhering to the following:

a. Careful consideration of requirements in design (temperature, pressure, deflections, insulation, materials, etc.)
b. Use standard, well developed components where possible
c. Select vendors whose performance is proven
d. Comprehensive qualification acceptance and production evaluation testing

e. Thorough inspection and proof test after manufacturing

f. Proven manufacturing methods

g. Package for protection during handling or shipment

h. Use only properly maintained and calibrated test equipment

i. Maintain cleanliness standards

j. Use proper tools and fixtures in assembly and installation

k. Initiate a training program in the handling, installation, and maintenance for shop and field personnel

l. Organize a system for reporting, investigating, and correcting malfunctions

2.2.4 Compatibility - The change in mechanical properties at cryogenic temperatures and the chemical reactions of cryogenic fluids with materials makes it necessary to consider the following:

a. The compatibility of materials with cryogenic fluids

b. The compatibility of the ducting location with the structure

c. The compatibility of manufacturing methods with materials

d. The suitability of the resulting duct to perform the intended function

e. Dissimilar metals

2.2.5 Maintainability - Design of low-maintenance duct systems involves consideration of reliability, accessibility, and replaceability. Durability during manufacturing, inspection, handling and installation must be inherent in the design or insured by the use of proper temporary reinforcing, packaging and handling procedures. Accessibility and replaceability requirements must be coordinated with the design of the structure, tankage and associated sub-systems to insure the capability of leak checking after installation.

2.2.6 Testing - A system test program should be initiated for qualification and production evaluation.

2.2.6.1 System Qualification - The qualification test must be performed on a production duct system. Support structure should duplicate that of the installed system as to rigidity, vibration characteristics, support points and strength. The test setup should include production or simulated production valves, pump, tanks and other related components with instrumentation and controls to be used in the production installation. Additional test instrumentation should be included to indicate operation under all conditions and to verify original system calculations. Actual testing should be conducted in the environment in which the system will operate including temperature, pressure, vibration, altitude, deflection, etc. The system tests should include:

a. Leak checking

b. Cold shocking

c. Flow characteristics

d. Proof pressure

e. Heat transfer characteristics

f. Temperature, pressure, and motion cycling

g. Installation methods

h. Cleaning and purging methods

2.2.6.2 Production Acceptance - Production acceptance testing verifies that the production system fulfills all pertinent requirements and should include as a minimum:

a. Examination of product

b. Leak check

c. Motion check if critical

d. Proof pressure

e. Heat transfer characteristics

f. Operational check of integrated components

2.2.7 Compensation for Movement

2.2.7.1 Methods - To prevent damage to the ducting, system components, tankage, or structure, a means must be incorporated in the system design to compensate for structural deflections and thermal movements. The methods include the use of flexible ducting, duct flexure, or a combination.

2.2.7.2 Use of Flexible Ducting - Flexible ducting consists of one or more flexible sections and is arranged to permit movement in one or more planes. For a detailed discussion of flexible joints refer to Section 3.4.

Care must be exercised in the placement, support and restraint of flex sections in a tension system to prevent damage to the flexible section during movement.

Misalignment of free flexible sections in a compression system can impose undesirable loads through the supports during movement.

Other factors to be considered in the use of flexible sections include:

a. The amount and type of movement

b. Suitable support points

c. Space limitations

d. System components

e. Fluid dynamics including fluid induced oscillation

f. Cleaning capability

g. Ease of assembly

h. Availability for inspection

i. Ease of maintenance

j. Life expectancy

2.2.7.3 Use of Duct Flexure - Absorbing movement by duct flexure is accomplished by a suitable length of duct or a special bend such as the "U" or Omega. Loads imposed by duct flexure can damage or cause malfunction in components if not reacted properly by supports. The factors listed under flexible ducting must also be considered in the design of a system using duct flexure.

2.2.7.4 Combination of Methods - The two methods can be combined in different sections of one system depending upon the system configuration.

2.2.8 Duct Supports - Duct supports fall into two general categories: those which anchor the ducts and those which permit and control motion. These latter are generally sliding- or swing-type brackets. Supports of this type used in the space vacuum environment must be designed to prevent cold welding of any friction surfaces. Insulation may be required to limit heat leak through a support.

The location of an anchoring duct support will be governed by design of the system. A tension system will require anchor supports on each major section. Intermediate guide supports may be needed to stabilize the duct. Individual components, such as valves or regulators, should be supported as necessary to prevent malfunction or damage.

Anchor supports in a compression system must be designed to carry the internal pressure loads and the loads due to thermal movement as well as those due to structural movement.

All supports should be accurately located to prevent preloading of the duct, including torsion. The need for adjustment during installation should be considered during bracket design.

2.3 HEAT TRANSFER AND FLUID FLOW

2.3.1 Heat Transfer - The temperature rise, due to heat leak, of a cryogenic fluid in a duct can be described by the equation:

$$\Delta T = \frac{q}{\dot{\omega}_f \, C_P} \qquad (1)$$

where

ΔT = fluid temperature rise, R

q = heat flux, Btu/sec

$\dot{\omega}_f$ = flow rate, lb/sec

C_P = specific heat, Btu/lb-R

This expression is valid only when no phase change is associated with the cryogen. For the condition of a saturated liquid within the duct, phase change will occur and the quantity of gas produced is given by the equation:

$$\dot{\omega}_g = \frac{q}{\Delta H_v} \qquad (2)$$

where

$\dot{\omega}_g$ = gas produced, flow rate, lbs/sec

q = heat flux, Btu/sec

ΔH_v = heat of vaporization, Btu/lb

The amount of heat leak into the duct will depend upon many environmental factors, including the use of insulation, type of insulation, supports and their configuration, the use of vacuum lines, radiation shields, etc. Depending upon the configuration, the heat may be transferred by radiation, convection, and/or conduction.

For a vacuum insulated line ($< 1 \times 10^{-4}$ torr), radiation is an important mode of heat transfer. The equation of heat transfer by radiation can be written:

$$Q = \sigma \, F_\epsilon \, A_1 \left[\left(\frac{T_2}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right] \qquad (3)$$

where

Q = heat flux, Btu/hr

σ = constant, 0.1714×10^{-8} Btu/hr-ft^2-R^4

F_ϵ = emissivity factor, dimensionless

A_1 = inside duct surface area, ft^2

T_1 = inside duct temperature, R

T_2 = outside duct temperature, R

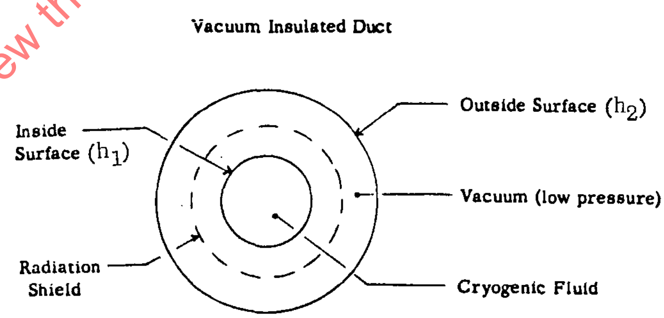


Figure 1

The emissivity factor for concentric cylinders can be expressed as:

$$F_\epsilon = \frac{1}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)} \quad \text{(See reference 1.)} \qquad (4)$$

ϵ_1 = emissivity of inside surface evaluated at T_1

ϵ_2 = emissivity of outside surface evaluated at T_2

A_1 = surface area of inside cylinder

A_2 = surface area of outside cylinder

It should also be pointed out that the heat leak for vacuum insulated ducts can be reduced by the use of one or more radiation shields as represented by the dotted line in Fig. 1. The heat leak for this condition can be evaluated by a simultaneous solution of a series of equations similar to equation (3) by writing a heat balance between all surfaces which "see" each other.

Heat transfer by convection is important for the case of non-insulated ducts. The heat addition to non-insulated ducts can be represented by equation (5).

$$Q = UA\,(T_2 - T_1) \qquad (5)$$

where

$$U = \frac{1}{1/h_1 + 1/h_2 + L/K} \qquad (6)$$

and

- Q = heat flux, Btu/hr
- A = duct surface area, ft^2
- T_2 = outside environmental temp., R
- T_1 = cryogen temp., R
- h_1 = cryogen heat transfer coefficient, Btu/hr-ft^2-R
- h_2 = environmental heat transfer coefficient, Btu/hr-ft^2-R
- L = duct thickness, ft
- K = thermal conductivity of duct, Btu/hr-ft^2-R/ft

Both h_1 and h_2 depend upon the configuration and physical properties of the fluids. Values of these heat transfer coefficients can be calculated by use of equations available in most heat transfer texts.

As a result of the very low pressure in vacuum insulated ducts ($< 1 \times 10^{-4}$ torr), the convection of heat is accomplished in the free molecule flow regime and can be expressed as:

$$Q = (.57)\, A_1 \frac{\alpha_1 \quad \alpha_2}{\alpha_1 + \frac{A_1}{A_2}(1 - \alpha_2)\,\alpha_1} \; \frac{\gamma + 1}{\gamma - 1} \; \frac{P}{\sqrt{MT}} \,(T_1 - T_2) \qquad (7)$$

(See reference 1.)

where

- Q = heat flux, Btu/hr
- A_1 = inner wall area, ft^2
- A_2 = outer wall area, ft^2
- P = pressure, microns of Hg.
- T = temperature, R
- α_1 = accommodation coefficient of inner surface
- α_2 = accommodation coefficient of outer surface
- γ = specific heat ratio
- M = molecular weight

Free molecular flow can be said to exist when the mean free path of the gas is greater than some characteristic dimension of the system. The characteristic dimension of the vacuum insulated duct is the distance between the inside and outside walls.

Conservative results can be obtained by letting the accommodation coefficient equal 1.0. Typical values of α are shown in Table I.

TABLE I

APPROXIMATE ACCOMMODATION COEFFICIENTS

T^o, K	He	H_2	Air
300	0.3	0.3	0.8-0.9
76	0.4	0.5	1.0
20	0.6	1.0	-

Conduction heat transfer through insulation, supports, and spacers can be a major mode of energy transfer and is represented by the equation:

$$Q = \frac{k}{L} \; A \; \Delta T \qquad (8)$$

where

- Q = heat flux, Btu/hr
- k = thermal conductivity, Btu/hr-ft-R
- A = cross sectional area in direction of heat flow, ft^2
- ΔT = temperature difference across the insulation, R
- L = insulation thickness, ft

2.3.2 Pressure Drop

2.3.2.1 Duct Losses - Whenever possible it is desirable to maintain single phase flow in the duct system, either all liquid or all gas. For this case the normal equation for hydraulic and thermodynamic analysis of fluids may be used. Pressure drop for a single phase fluid in a duct can be evaluated from the following equation:

$$\Delta P = \frac{2\, f\, L\, V^2 \;\; \rho_m}{g_o \; D} + \frac{G^2}{2\, g_o} \left(\frac{1}{\rho_2} - \frac{1}{\rho_1} \right) \qquad (9)$$

NOTE: When considering single phase gas systems the above equation has a general design limitation of Mach 0.2.

where

ΔP = pressure drop, psf

f = Fanning friction factor (see refs. 3 and 5)

V = fluid velocity, ft/sec

ρ_m = mean fluid density, lb/ft^3

L = duct length, ft

g_o = acceleration due to gravity, ft/sec^2

D = duct diameter, ft

G = mass flow rate, lb/sec-ft^2

ρ_1 = density of fluid at entrance, lb/ft^3

ρ_2 = density of fluid at exit, lb/ft^3

Note: Flow-induced vibrations may cause failure of flex sections in ducts carrying gases (for unsleeved bellows). For this reason limit internal duct Mach number to 0.3.

It is not always possible to design a duct system which will maintain single phase flow at all times. One example is the non-steady state case associated with duct "cool down" by a cryogenic fluid. For ducts of normal size, it is not unusual to have a cryogen enter a duct as a liquid and leave as a gas. Thus, for some length of the line two phase flow exists. No reliable equations have been developed for evaluating the pressure drop of fluid in two-phase flow. One difficulty lies in the large number of types of two-phase flow which can exist. The types of flow are indicated in Figure 2.

The following equations are used to establish the parameters for Figure 2, where

$$\lambda = \left[\left(\frac{\rho_g}{.075}\right)\left(\frac{\rho_L}{62.3}\right)\right]^{1/2} \qquad (10)$$

and

$$\Psi = 73/\gamma \left[\mu_L (62.3/\rho_L)^2\right]^{1/3} \qquad (11)$$

where

G = gas mass flow rate, lb/hr-ft^2

L = liquid mass flow rate, lb/hr-ft^2

ρ_g = density of gas, lb/ft^3

ρ_L = density of liquid, lb/ft^3

γ = surface tension, dynes/cm^2

μ_L = liquid viscosity, centipoise

One author has suggested evaluating pressure drop based on the homogeneous properties of the two-phase system, while another suggests assuming gas properties for the total two-phase regime. Whatever method is assumed, a generous safety factor should be used. Reference 2 has a series of two-phase pressure drop equations. They are somewhat tedious, however, and the small increased accuracy may not warrant their use.

To maintain single phase flow at the duct exit, P_{S_e} must be greater than P_{V_e} at T_e.

P_{V_e} will of necessity be > P_{V_i} because of the increase in fluid temperature (T) caused by the heat leak through the duct insulation and, in addition, to a much smaller degree, by friction.

P_{T_i} therefore must be > P_{V_i} by an amount equal to the ΔP of the duct plus the increase of P_{V_i} to P_{V_e} caused by the temperature increase of the fluid, where

P_{T_i} = total pressure at duct inlet

P_{V_i} = vapor pressure at duct inlet

P_{S_e} = fluid static pressure at exit

P_{V_e} = vapor pressure at exit

T_e = temperature of fluid at exit

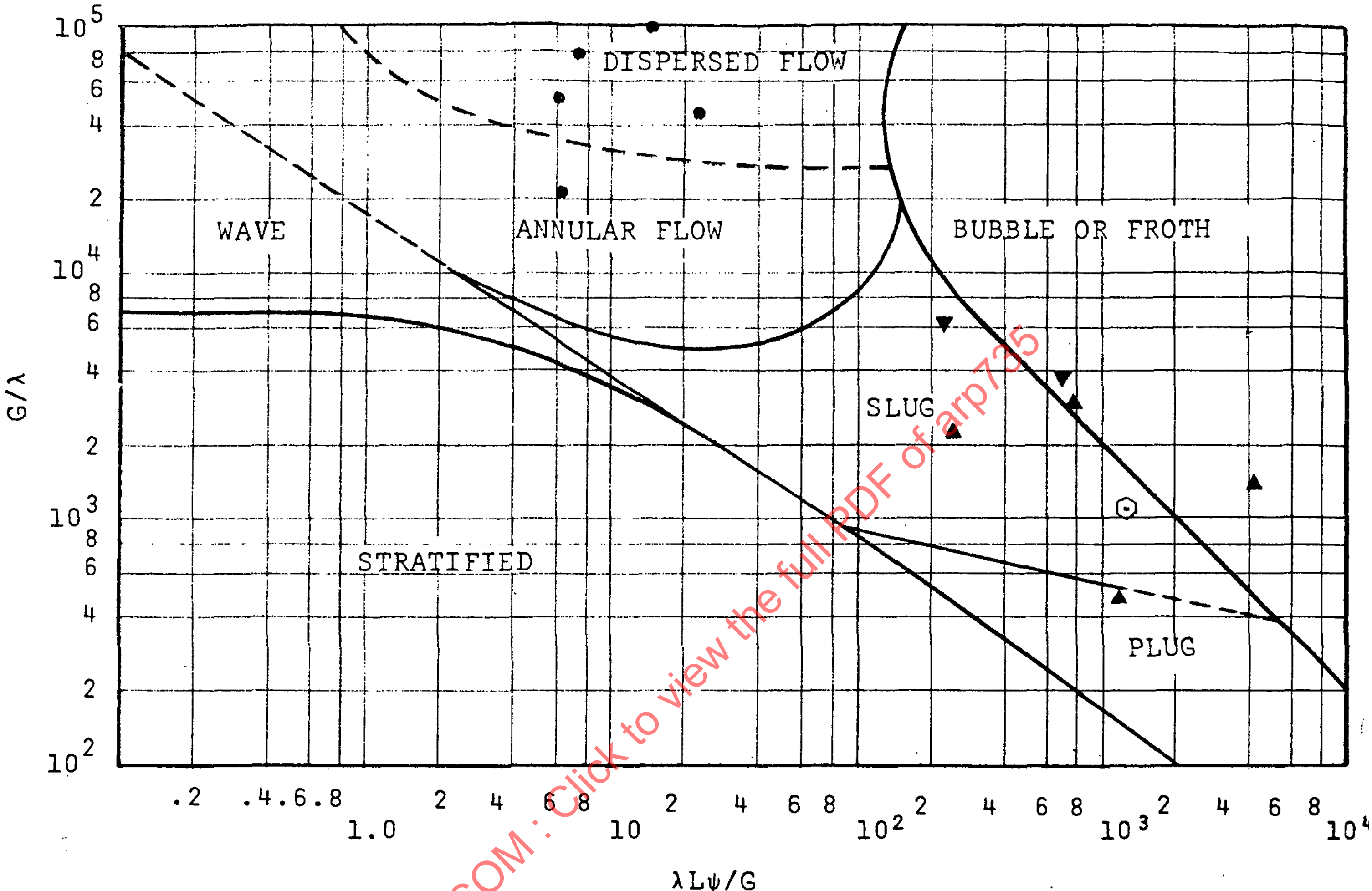
Also, fluid velocities must be kept low enough so that the static pressure in the duct does not fall below liquid vapor pressure.

2.3.2.2 Pressure Transients (Surges) - The designer should be aware of when pressure surges may occur. A typical case is during initial cool down. If a cryogenic liquid is forced too rapidly into a "hot" duct, flashing of the liquid may occur at such a rate that the gas produced may not be capable of venting, thus producing a pressure surge forcing the liquid back out of the duct. The cycle may then be repeated.

Note: Severe water hammer problems may occur in ducting of any size if modulating flow or rapid shut off or start of flow is introduced.

2.3.2.3 Elbow Flow Losses - Pressure drop for a single phase fluid in a duct can be evaluated from the following equation (see reference 4):

$$\Delta P = \left(\frac{4\,f\,L}{D} + CK_{T_{90}}\right)\left(\frac{V^2\,\rho_m}{2\,g_o}\right) + \frac{G_2}{2\,g_o}\left(\frac{1}{\rho_2} - \frac{1}{\rho_1}\right) \qquad (12)$$



Points determined from test data:

- ▼ SLUG FLOW
- ● ANNULAR FLOW
- ▲ BUBBLE FLOW
- ⊙ PLUG FLOW

$\lambda = [(\rho g/.075)(\rho_L/62.3)]^{1/2}$

$\psi = 73/\gamma[\mu_L(62.3/\rho_L)^2]^{1/3}$

L = LIQUID MASS VELOCITY, lb/hr-ft²

G = GAS MASS VELOCITY, lb/hr-ft²

γ = SURFACE TENSION, dynes/cm²

μ_L = LIQUID VISCOSITY, CENTIPOISE

ρ_g = GAS DENSITY, lb/ft³

ρ_L = LIQUID DENSITY, lb/ft³

FIGURE 2 (Reference 6)

FLOW PATTERN REGIONS FOR TWO PHASE FLOW

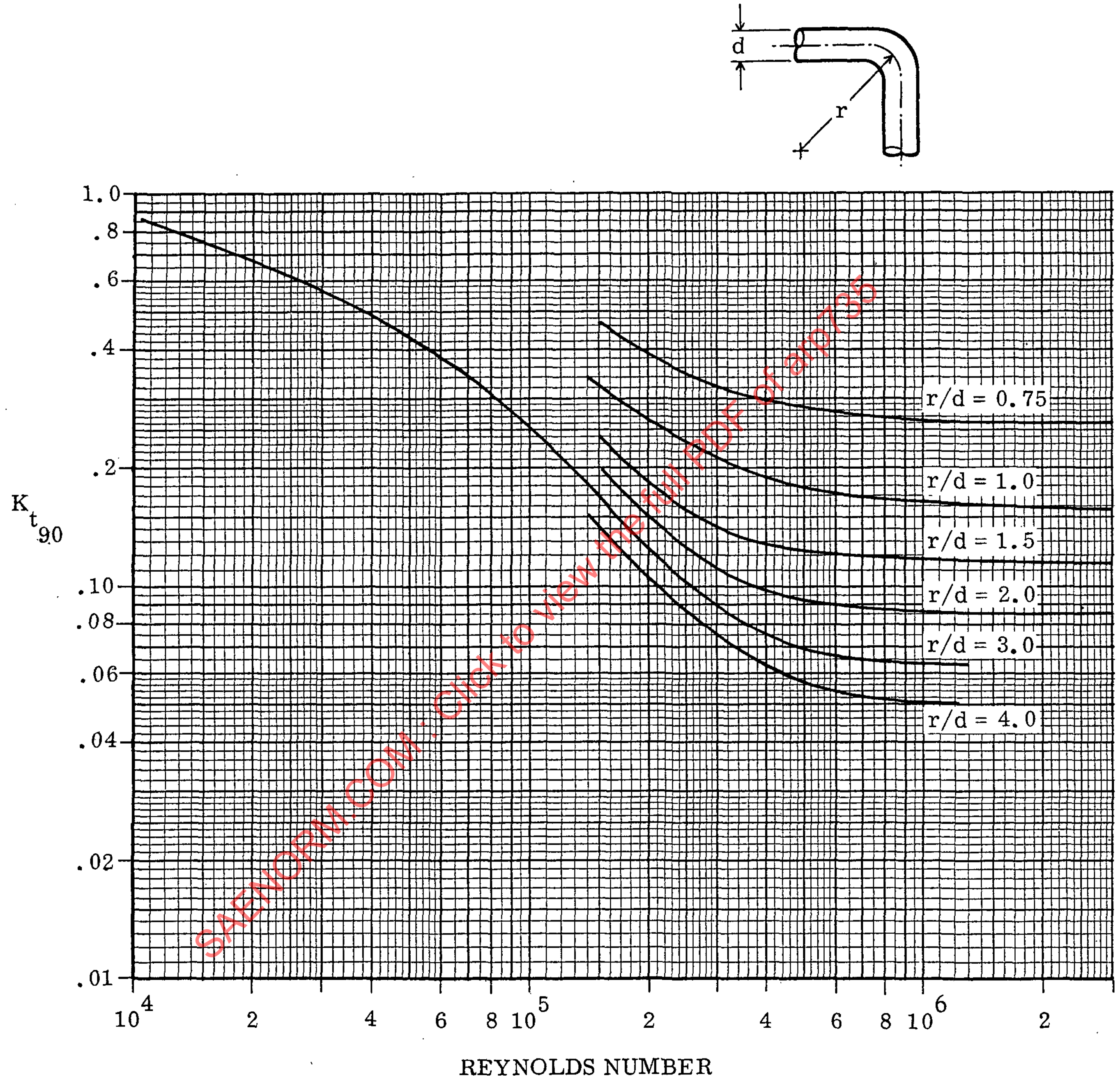


FIGURE 3 (Reference 4)

LOSS COEFFICIENT VS. REYNOLDS NUMBER FOR 90° RADIUS BENDS - CIRCULAR DUCTS

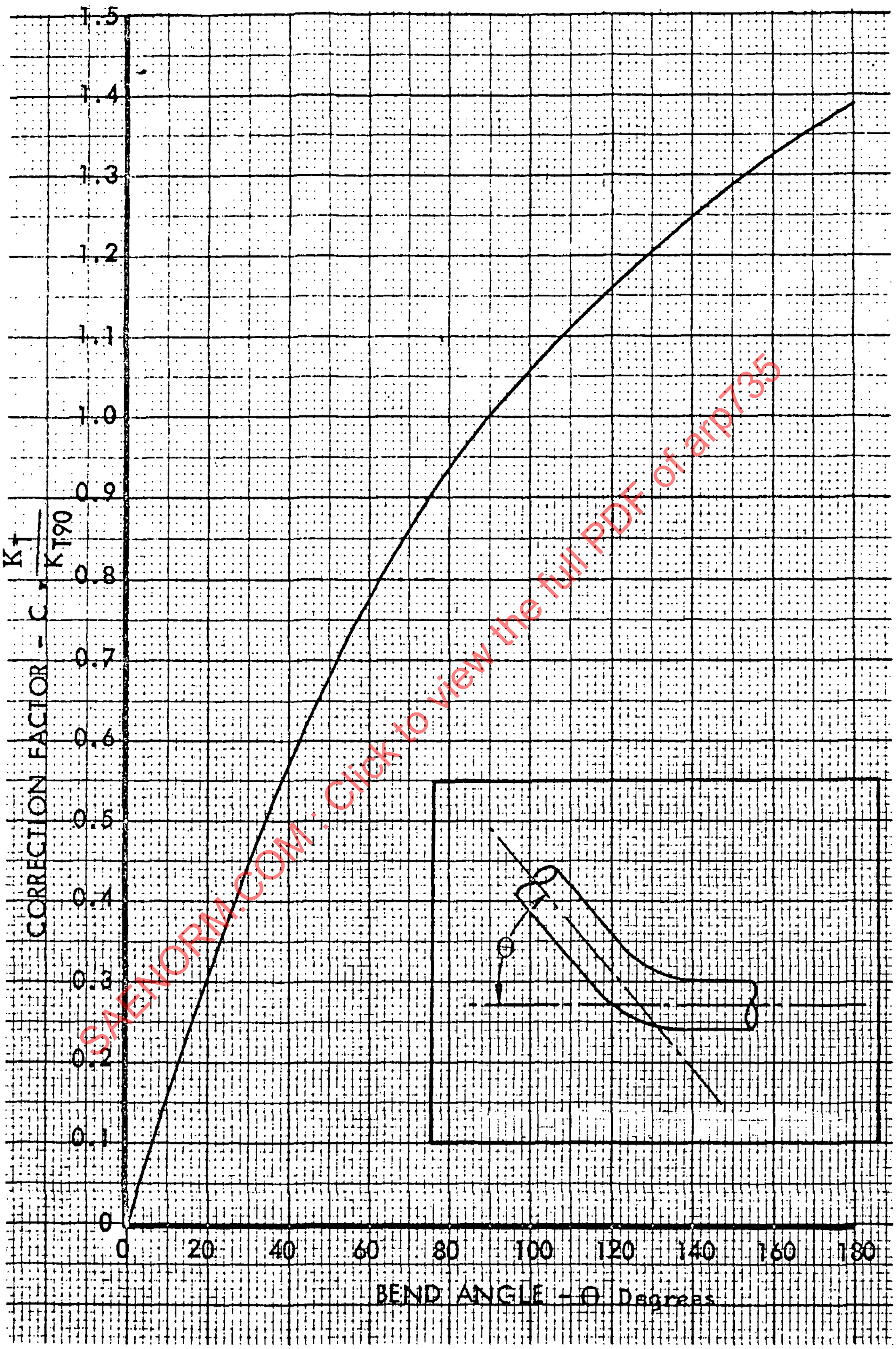


FIGURE 4 (Reference 4)
CORRECTION FACTOR FOR BENDS OTHER THAN 90° FOR ELLIPTICAL AND CIRCULAR DUCTS

where

ΔP = pressure drop, psf

f = Fanning friction factor (see refs. 3 and 5)

V = fluid velocity, ft/sec

ρ_m = mean fluid density, lb/ft^3

L = length along the center line of the duct

g_o = acceleration due to gravity, ft/sec^2

D = duct diameter, ft

G = mass flow rate, lb/sec-ft^2

ρ_1 = density of fluid at entrance, lb/ft^3

ρ_2 = density of fluid at exit, lb/ft^3

C = correction factor for bends other than 90 deg

$K_{T_{90}}$ = loss coefficient for a 90-deg elbow bend

Values for $K_{T_{90}}$ versus Reynolds number may be found from Figure 3, and Figure 4 shows values of C versus duct bend angle θ in degrees.

$$\text{Reynolds number} = DV \frac{\rho}{g_o \mu}$$

where

D = duct diameter, ft

V = velocity of fluid, ft/sec

ρ = density of fluid, lb/ft^3

μ = absolute viscosity of fluid, lb/sec/ft^2

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1. Scott, Russell B., Cryogenic Engineering, Van Norstrand, New York, 1960.

2. Ludwig, Ernest E., "Flow of Fluids," Chemical Engineering, June 13, 1960, p. 161.

3. McAdams, Heat Transmission.

4. SAE Aerospace Applied Thermodynamics Manual.

5. Resek, R. B., "Fluid Conversion Factors for Pressure Drop Calculations," Product Engineering, June 1954.

6. Baker, O., Multiphase Flow in Pipe Lines. Oil & Gas Journal, Nov. 10, 1958, pg. 156.

Section 2.3: "Additional References - refer to Bibliography publications 23 and 31."

2.4 CRYOGENIC FLUIDS - Cryogenic fluids are materials that move easily at temperatures below 123 K (-150 C) (see ref. 1). These fluids are in the gaseous state at higher temperatures, in the liquid state at lower temperatures, and become solids at very low temperatures. The exact temperature at which change of state occurs is a function of the specific material and the ambient pressure except in the case of helium, which can only be solidified at high pressure and very low temperature.

2.4.1 Applicable Cryogenic Fluids - This recommended practice discusses those cryogenic fluids which may reasonably be expected to be used in aerospace vehicles in sufficient quantities to require the use of ducting for their proper utilization. These fluids are:

a. Air
b. Oxygen
c. Fluorine
d. Nitrogen
e. Normal hydrogen
f. Parahydrogen
g. Helium

2.4.2 Important Physical Properties - Table I lists the important sea-level physical properties of these cryogenic fluids. Figures 1 through 6 are temperature-entropy curves for each of these fluids, except fluorine.

2.4.3 Fluid Handling - Cryogenic fluids require special handling because of their low temperature relative to ambient. The use of insulation may be desirable to minimize heat losses and resultant vaporization of the fluid. Ducting must be capable of maintaining leak-tight seals even during rapid chill down.

This transient cooling period produces loads on the ducting in addition to the normal external design loads. These transient loads are due to differential thermal contractions and to the high velocity gas flow caused by rapid boiling of the cryogenic fluid when it contacts the relatively warm ducting.

Ducting systems that handle cryogenic fluids should be maintained to standards of safety and cleanliness which depend on the specific fluid used. (See paragraph 2.5.)

REFERENCES

1. WADD Technical Report 60-56 Part I.

2. American Institute of Physics Handbook - 1957.

3. Ruheman, M. B., Low Temperature Physics

4. Marks Handbook - 1951, "Converted Units $\frac{\text{ft-lb}}{\text{lb K}} = \frac{273}{459.7} \times \frac{1}{30.48} - \frac{\text{cm-gm}}{\text{gm K}}$"

5. Scott, Russell B. Cryogenic Engineering, Van Norstrand, New York, 1960.

6. Handbook of Chemistry & Physics - 35th Edition - 1953-54.

7. Rocketdyne Report RR-59-48.

8. NBS Technical Note 130 - December, 1961.

9. Hydrogen Handbook - AFFTC TR60-19 - April, 1960.

10. [illegible]2 - November, 1948.

TABLE 1 - Physical Properties

Fluid / Characteristic	Air	Oxygen O_2	Fluorine F_2	Nitrogen N_2	Hydrogen - H_2 Normal	Hydrogen - H_2 Para.	Helium He^4
Boiling Temp. K *	(1) 78.8	(1) 90.19	(1) 85.21	(1) 77.35	(1) 20.39	(8) 20.268	(1) 4.2
Melting Temp. K *	(3) 50.1	(1) 54.9	(1) 53.51	(1) 63.1	(1) 13.95 at 54mm Hg	(1) 13.81 at 52.8 mm Hg	(3) 25 Atmos 1.0
Critical Temp. K	(4) 133.	(1) 154.7	(1) 132.88	(1) 126.1	(1) 33.19	(1) 32.99	(1) 5.2
Critical Press. Atmospheres	(4) 37.2	(1) 50.1	(1) 34.529	(1) 33.49	(1) 12.98	(1) 12.77	(1) 2.26
Liquid density at the boiling point Gms/Cm^3 *	(1) 0.8739	(1) 1.14	(6) 1.11	(1) 0.8084	(5) 0.071	(8) 0.0708	(1) 0.125
Gas density at 273°K - Gms/Liter *	(1) 1.269	(2) 1.4277	(6) 1.69	(2) 1.2568	(2)	(8) 0.08994	(2) 0.17847
Vapor density at the boiling point Gm/Cm^3 *	(1) .004485 at 81.8°K	(5) 0.00426	(7) 0.00573	(5) 0.00425	(5) 0.00122	(8) 0.00134	(5) 0.01135
Heat of Vaporization at the boiling point Cal/Gm *	(1) 49.04	(1) 50.18	(1) 39.728	(5) 47.6	(1) 105.5	(8) 107.65	(1) 4.995
Heat of fusion at the melting point Cal/Gm *		(5) 3.32	(1) 3.209	(5) 6.11	(5) 13.9	(10) 14.0 at 13.81°K & 52.8mmHg	(1) 1.72 at 4.2°K
Specific Heat at constant Press. at 273 K - Cp Cal/Gm K *	(6) 0.2398	(1) 0.2191	(1) 0.1953	(1) 0.249	(1) 3.3934	(10) 3.611	(2) 1.25
Specific Heat at constant Vol. at 273°K - Cv Cal/Gm K	(1) 0.1702	(1) 0.1566	approx. 0.143	(1) 0.178	(1) 2.4076		(2) 0.753
$K = \frac{Cp}{Cv}$ *	(6) 1.403	(1) 1.40	approx. 1.36	(2) 1.404	(1) 1.409		(2) 1.660
Gas constant - [R] $\frac{Cm\ Gm}{Gm\ K}$ (4)	(4) 2,924.	(6) 2,649.	2,231.	(6) 3,026.	(6) 42,055.	(10) 42,055.	(6) 21,180.
Gas sonic velocity at 273 K - meters/sec. *	(2) 331.45	(2) 317.2	approx. 276.	(2) 337.	(2) 1,269.5		(2) 970

See Ref. 1 for curves of viscosity vs. temp. and for thermal conductivity

*At Sea Level Atmospheric Pressure - unless otherwise noted.

( ) Indicates source (see references this section).

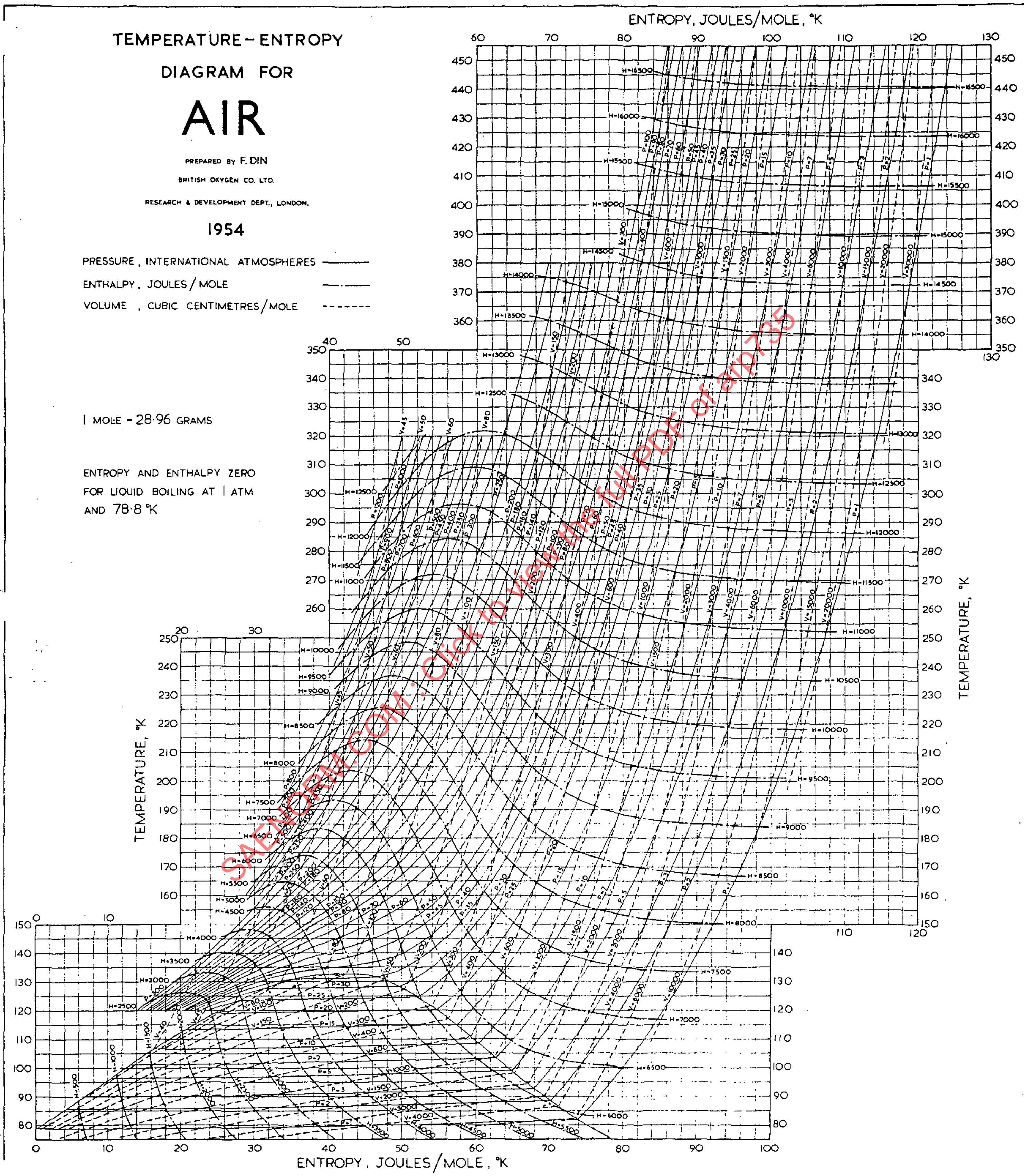

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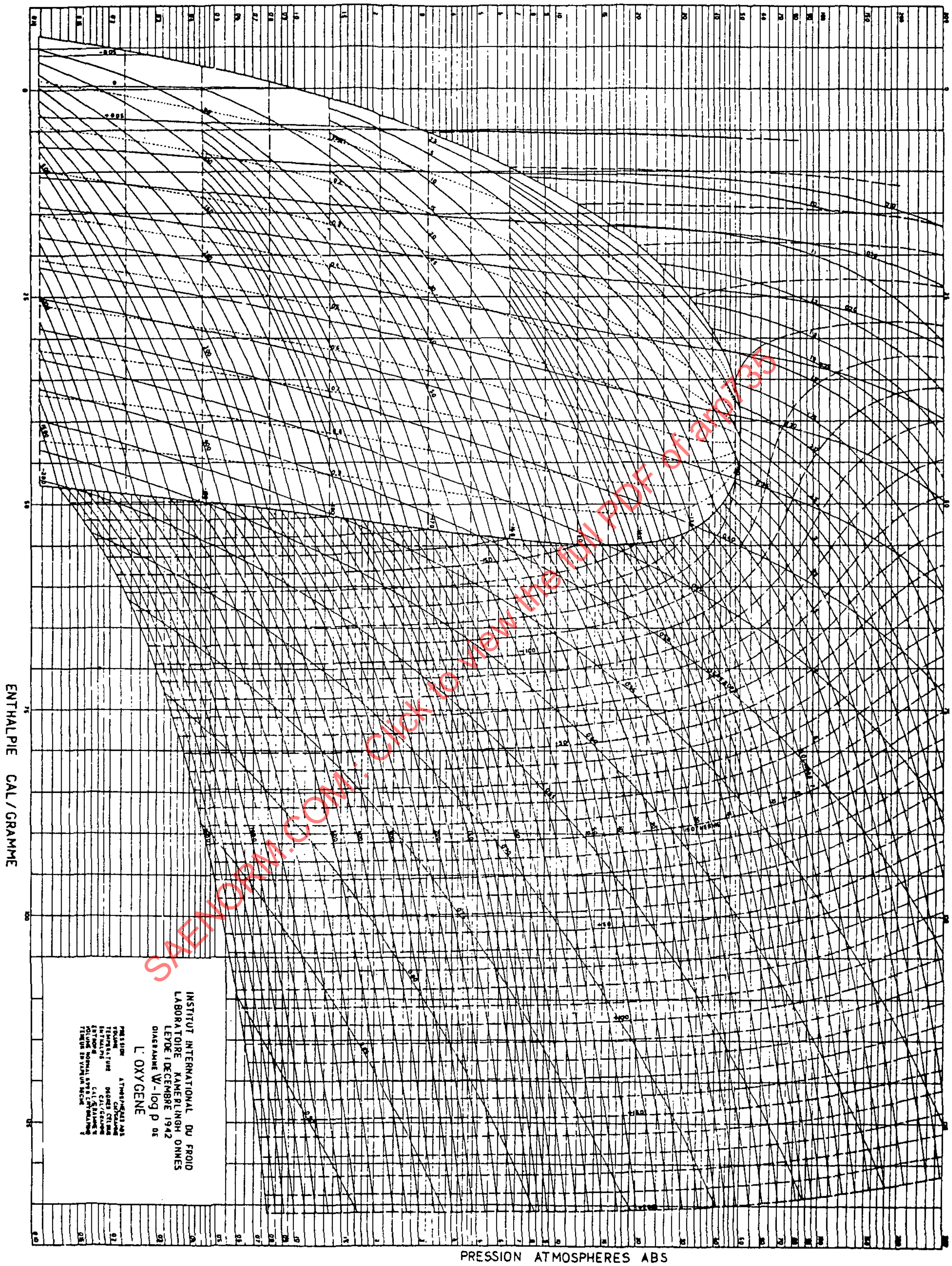
Fig. 1



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Log p - Enthalpy Diagrams of Carbon Monoxide and Oxygen (in French)
Communs. Kamerlingh Onnes Lab. Univ. Leiden Suppl. No. 112d (1955)
Translation Available from Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado

Fig. 2

Prepared from: National Bureau of Standards, Technical Note, TN 129 (PB 161630) January 1962, "The Thermodynamic Properties of Nitrogen from 64 to 300°K between 0.1 and 200 Atmospheres", Thomas R. Strobridge; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado.

R. D. McCarty, L. J. Ericks (January 1963)

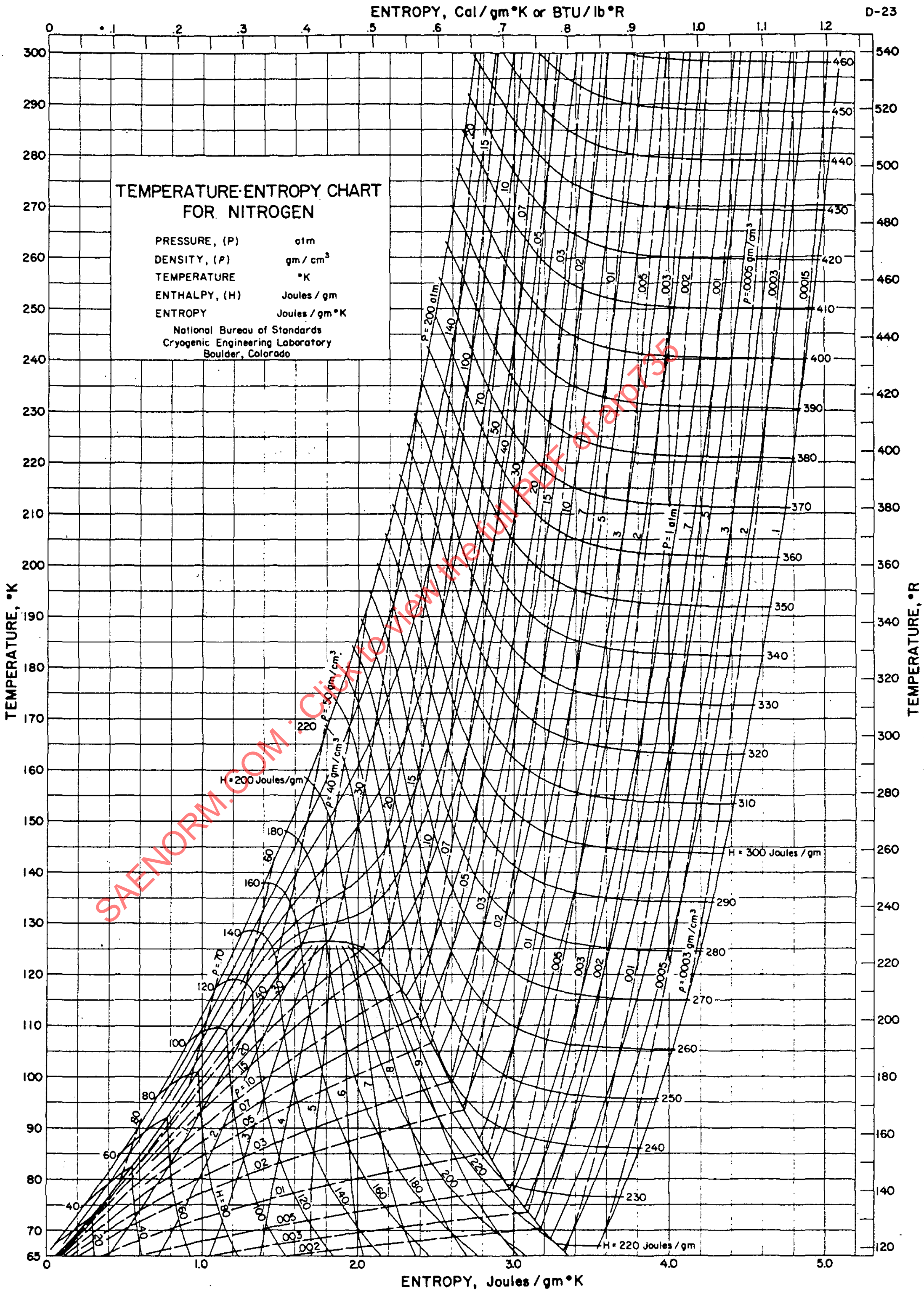


Fig. 3

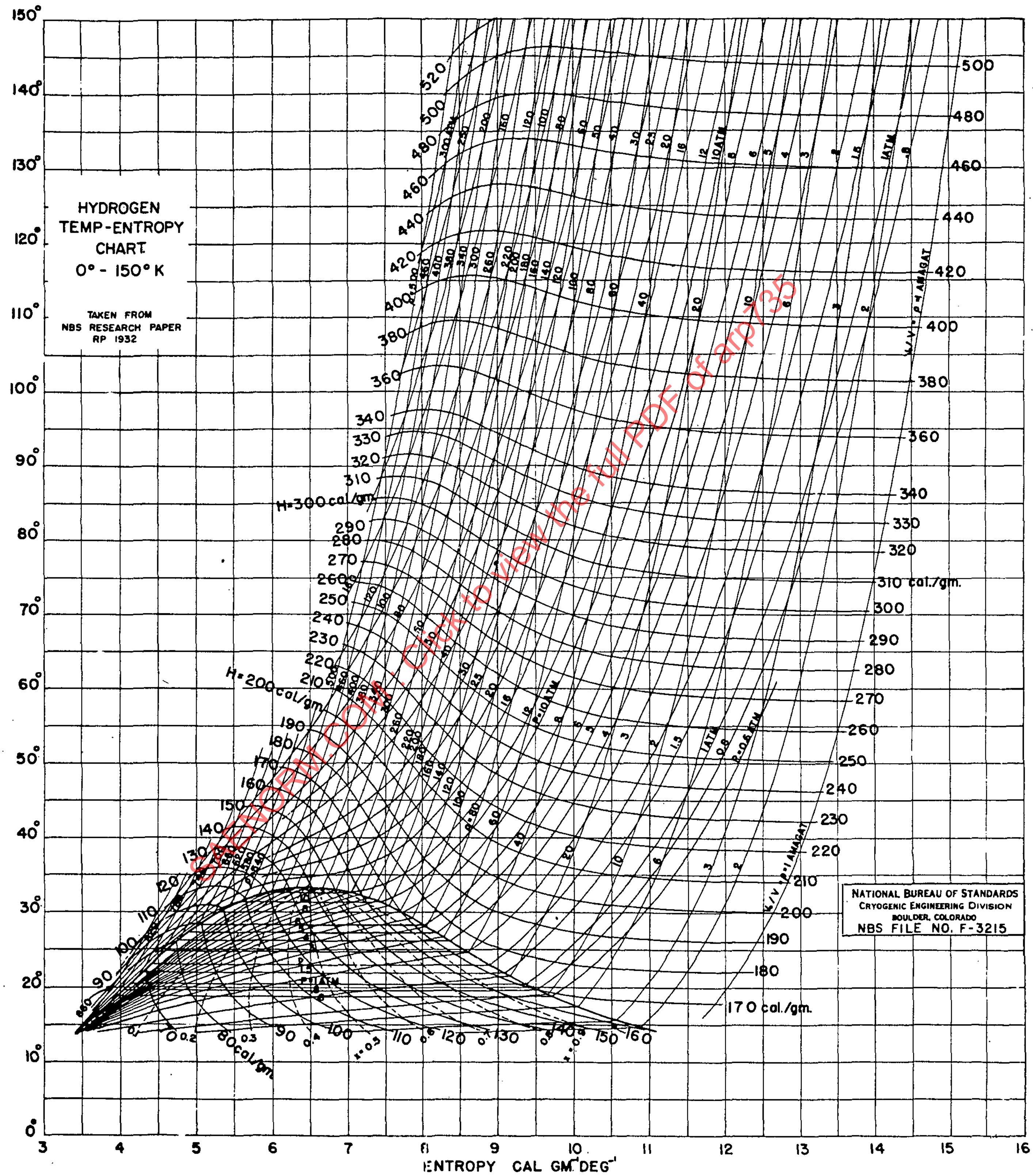

HYDROGEN
TEMP-ENTROPY
CHART
0° - 150° K
TAKEN FROM
NBS RESEARCH PAPER
RP 1932
NATIONAL BUREAU OF STANDARDS
CRYOGENIC ENGINEERING DIVISION
BOULDER, COLORADO
NBS FILE NO. F-3215
H=300 cal/gm.
H=200 cal/gm.
80 cal/gm.
310 cal./gm.
170 cal./gm.
ENTROPY CAL GM⁻¹DEG⁻¹
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Fig. 4

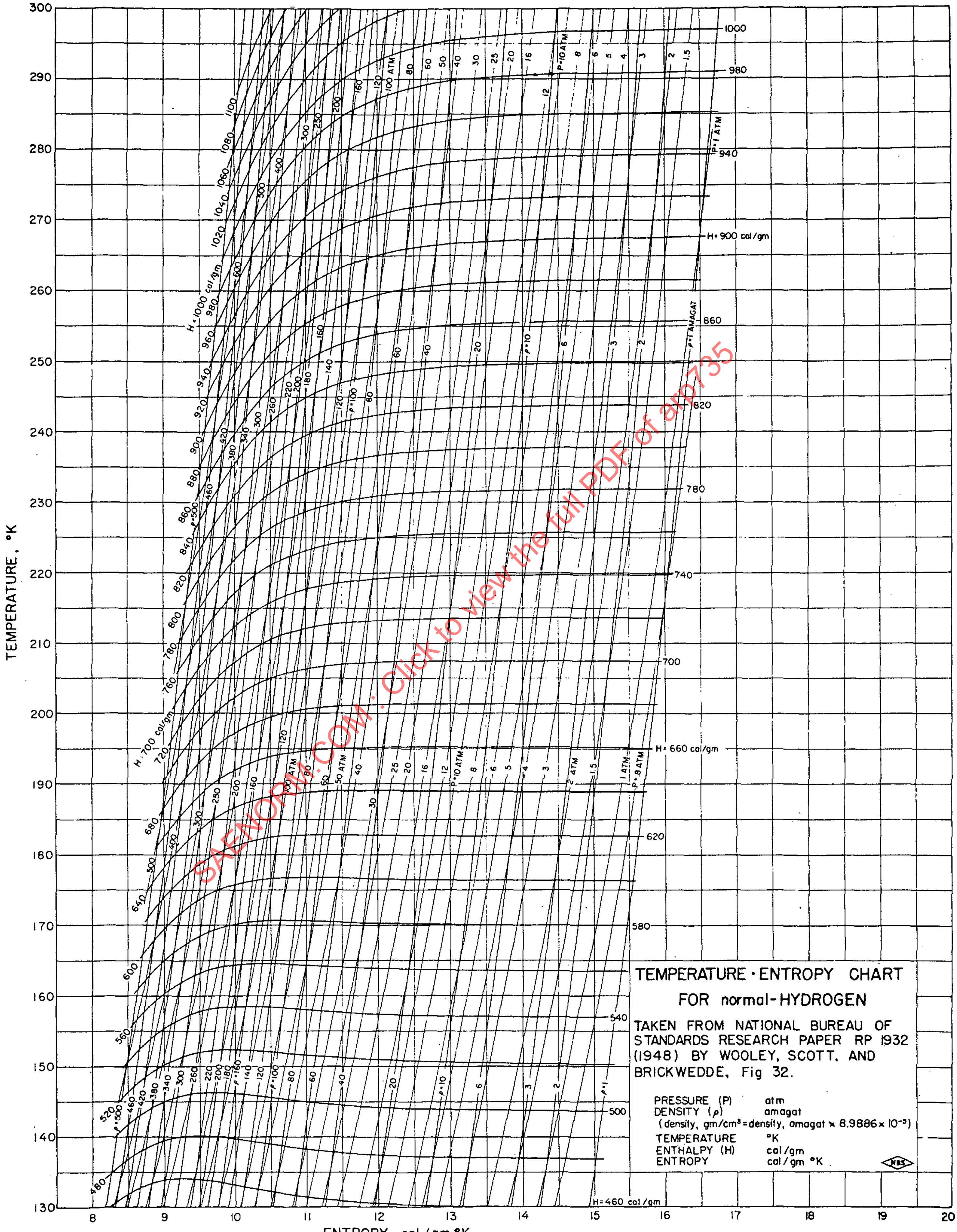
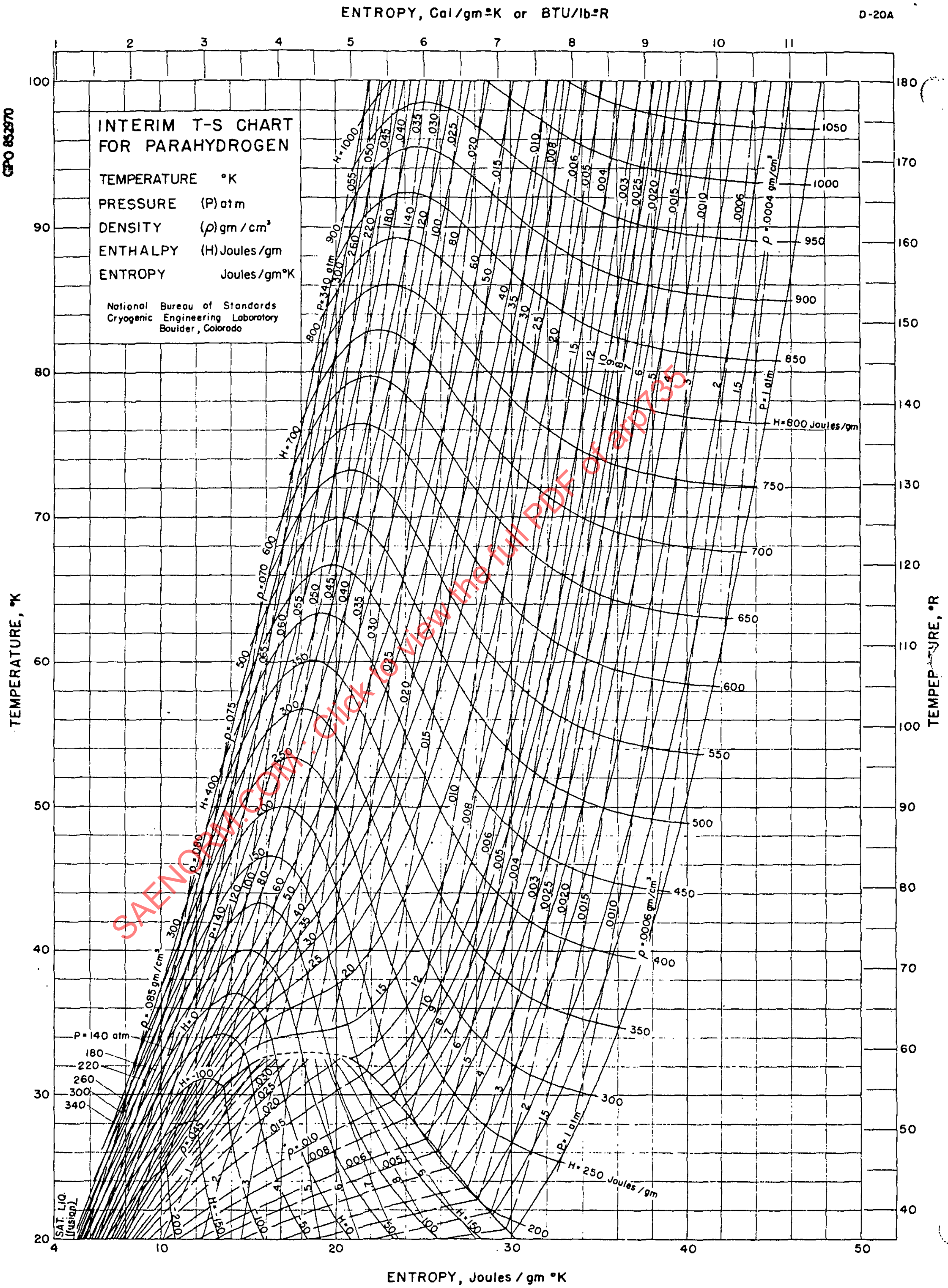

TEMPERATURE · ENTROPY CHART
FOR normal-HYDROGEN
TAKEN FROM NATIONAL BUREAU OF STANDARDS RESEARCH PAPER RP 1932 (1948) BY WOOLEY, SCOTT, AND BRICKWEDDE, Fig 32.
PRESSURE (P) atm
DENSITY (ρ) amagat
(density, gm/cm³ = density, amagat × 8.9886 × 10⁻³)
TEMPERATURE °K
ENTHALPY (H) cal/gm
ENTROPY cal/gm °K
TEMPERATURE, °K
ENTROPY, cal/gm °K
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
8
9
10
11
12
13
14
15
16
17
18
19
20
H = 1000 cal/gm
H = 900 cal/gm
H = 700 cal/gm
H = 660 cal/gm
H = 460 cal/gm
P = 1 ATM
P = 10 ATM
100 ATM
50 ATM
ρ = 1 AMAGAT
ρ = 500
ρ = 100
ρ = 10
ρ = 8 ATM

Fig. 4a



Prepared for: National Bureau of Standards, Technical Note, TN 130 (PB161631) December 1961, "Provisional Thermodynamic Functions for Parahydrogen", H. M. Roder and R. D. Goodwin; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado, from property functions reported in NBS TN 130. These functions were used to calculate temperature and entropy for all intersections of isobars and isenthalps and for intersections of isobars and isometric lines. Additional points were also calculated as necessary to complete the precise definition of the property lines.

R. B. Stewart, R. D. McCarty, T. W. Griffith (December 1961)

GPO 852970

Prepared for: National Bureau of Standards, Technical Note, TN 130 (PB161631) December 1961, "Provisional Thermodynamic Functions for Parahydrogen", H. M. Roder and R. D. Goodwin; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado, from property functions reported in NBS TN 130. These functions were used to calculate temperature and entropy for all intersections of isobars and isenthalps and for intersections of isobars and isometric lines. Additional points were also calculated as necessary to complete the precise definition of the property lines.

R. B. Stewart, R. D. McCarty, R. D. Weekley (December 1961)

GPO 852971

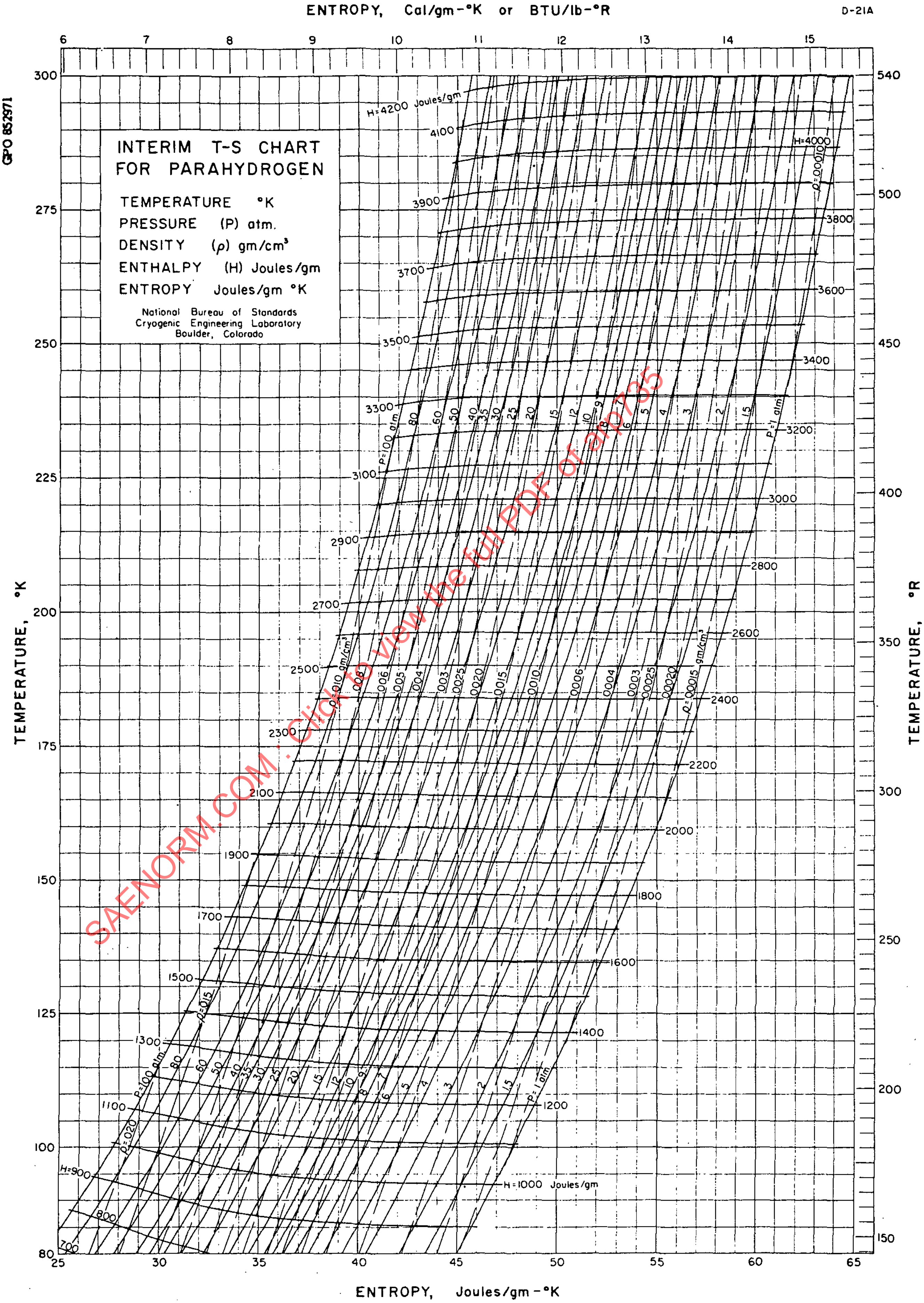
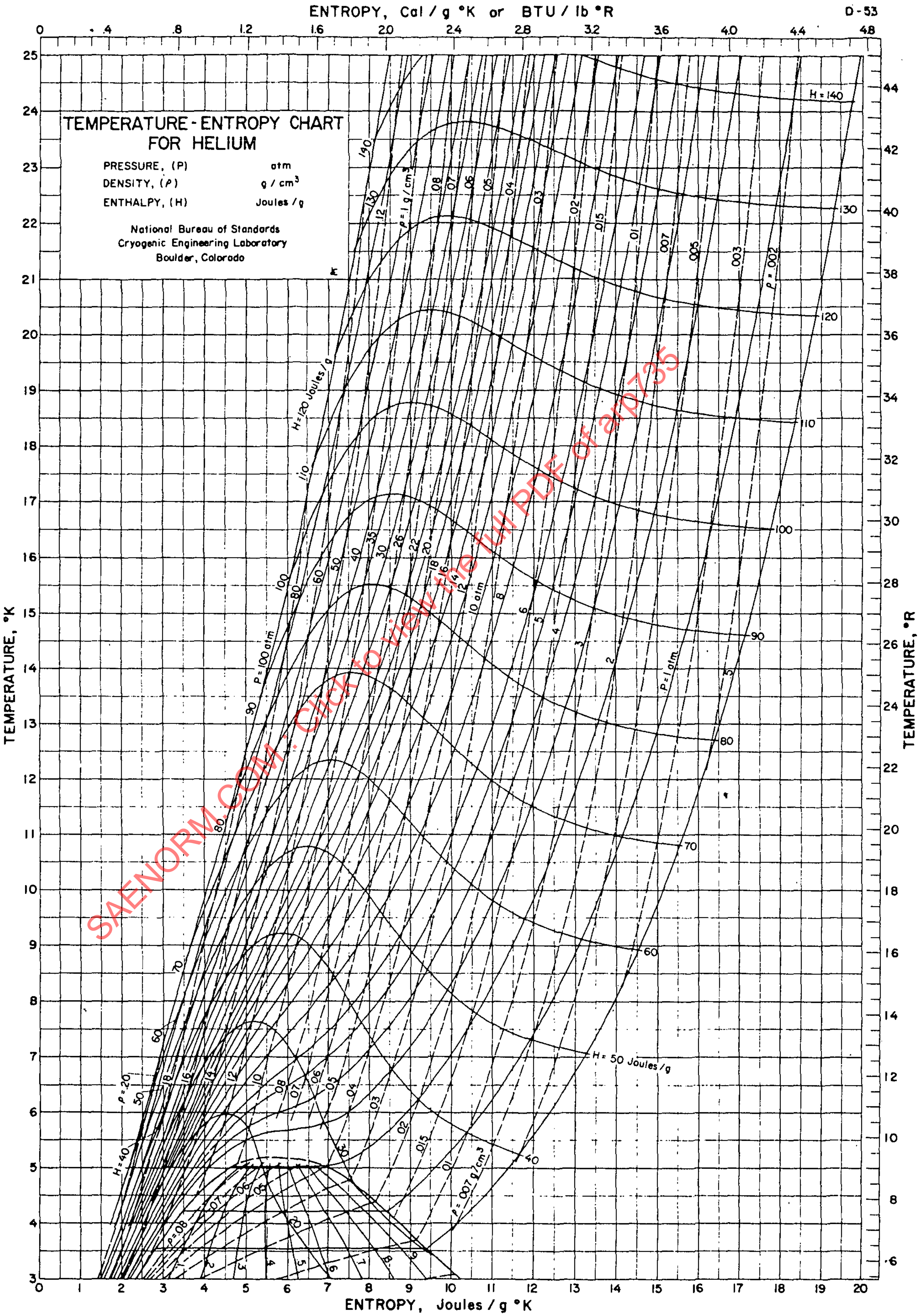


Fig. 5a

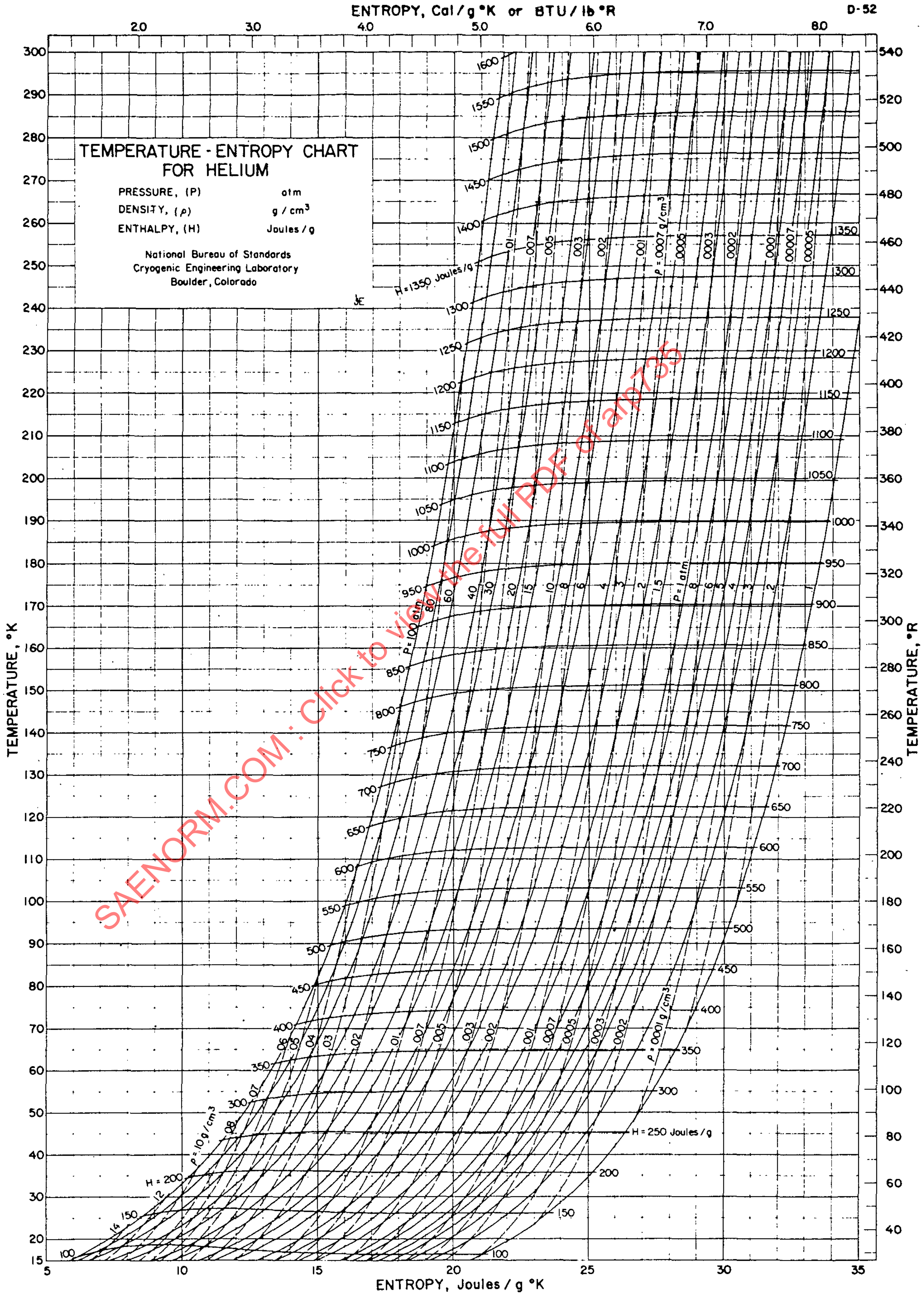
Prepared from: National Bureau of Standards, Technical Note, TN 154, January 1962, "The Thermodynamic Properties of Helium from 3 to 300°K between 0.5 and 100 Atmospheres", Douglas B. Mann; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado.

R. D. McCarty, L. J. Ericks (January 1964)



Prepared from: National Bureau of Standards, Technical Note, TN 154, January 1962, "The Thermodynamic Properties of Helium from 3 to 300°K between 0.5 and 100 Atmospheres", Douglas B. Mann; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado.

R. D. McCarty, L. J. Ericks (January 1964)



2.5 SAFETY

2.5.1 General Considerations - Considerable caution must be exercised in the use of cryogenic fluids. The hazards involved are due to four physical characteristics of these fluids:

a. Extreme cold
b. High pressure gas generation
c. Combustibility
d. Toxicity

Table I indicates the applicability of recommended safety rules to the handling of cryogenic fluids; the following paragraphs contain some amplification of these recommendations. Adequate first-aid equipment must be maintained in the area, and personnel must be properly trained in the use of this equipment.

2.5.2 Extreme Cold - Contact with materials at cryogenic temperatures can seriously harm human tissue. Personnel must be adequately protected by clothing, goggles, and gloves. Improperly insulated ducts, which handle liquid hydrogen, helium, or nitrogen, produce significant quantities of liquid oxygen on the outside of the duct by cooling of the ambient air. This liquid oxygen, if present, must be dissipated to prevent contact with personnel or any fuels.

Physical properties of construction materials are greatly affected by cryogenic temperatures (see paragraph 2.6 - Materials) and design consideration must be given to the cryogenic properties.

2.5.3 High Pressure Gas Generation - Cryogenic fluids are liquid because of their very low temperature. Atmospheric heat in time will convert these liquids to gases which, if contained, will develop dangerously high pressures. To avoid this hazard, the following rules should be observed:

a. Avoid fluid entrapment. Each section of duct between shut-off valves must be provided with an adequate relief valve or safety rupture disc. Direct flow of any escaping gases so as to avoid contact with personnel.

b. Pressure safety devices and vent ducts must be protected from accumulation of external moisture which will freeze and render these devices inoperative.

2.5.4 Combustibility

2.5.4.1 General Considerations - In order to prevent combustion, fuels and oxidizers must be kept separated and potential ignition sources must be eliminated. In addition, extra cleanliness precautions must be taken with the oxidizers since the presence of even small amounts of many materials in the presence of oxygen or fluorine constitute an explosive hazard. Use of demagnetizing techniques may be desirable to assist in removing small particles from ducting during the cleaning process.

2.5.4.2 Cleanliness - It is of utmost importance that all cryogenic systems be maintained at a high level of cleanliness. Components and systems which handle oxygen, fluorine and hydrogen must be cleaned in accordance with applicable references such as 1, 2, and 3. These procedures are applicable during assembly of components, installation into systems and in operational use (including related ground handling equipment).

The following design practices will give maximum assurance of duct cleanliness:

a. Eliminate crevices or joints that can hold contaminants. If unavoidable, these openings should be large enough to provide for adequate flushing and drainage to avoid retention of particles and to avoid etching during or after the cleaning operation.

b. Weld joints should be butt welds.

c. Flexible members should be designed so as to avoid entrapment of contaminants, and to provide adequate means of inspection and cleaning. Where feasible, convoluted bellows should be of open pitch construction. If a liner is required, the use of a removable liner is preferred. If a fixed liner is required, the liner should contain holes to permit adequate flushing.

d. Closures should be provided to protect ducts against recontamination after cleaning, prior to system installation; and during maintenance.

2.5.4.3 Operational Safety - Thorough knowledge of the applicable fluid characteristics is essential. All equipment should be electrically grounded. Smoking, open flames and other potential ignition sources should be prohibited in areas handling cryogenic fluids. This is particularly important when handling liquid hydrogen. (Reference 4)

Leakage, spillage and dumping of cryogenic fluids must be controlled. Wind condition and direction must be considered whenever handling large quantities of fluids to assure rapid dissipation of the spillage in a safe area. Vent and burn hydrogen in a vertical stack away from the supply or area of spillage. Purging of systems, ventilation of area, concrete run off channels and strictly enforced safety rules are important. Rigid control of valving procedures and operations, and a complete set of emergency procedures for use in case of an accident or malfunction are required.

2.5.5 Toxicity and Asphyxia - Fluorine is highly toxic even in moderate concentrations, and must be handled only by personnel attired in adequate protective clothing and using separate breathing equipment.

Non toxic gasses in some concentrations will cause asphyxiation, so adequate area ventilation must be provided.

REFERENCES

1. Handbook for Contamination Control of Liquid Rocket Propulsion Systems - Aerospace Industries Association.

2. NASA - Cleanliness of Components for Use in Liquid Oxygen, Fuel, and Pneumatic Systems - MSFC - Spec. - 164.

3. NASA - Testing of Materials Other than Sealants for Compatibility with Liquid Oxygen

4. Research on the Hazards Associated with the Production and Handling of Liquid Hydrogen - Bureau of Mines, RI-5707, Zabetakis and Burgess, 1961.

Section 2.5: "Additional References - refer to Bibliography publications 22, 44, 103, and 108."

TABLE I

APPLICABILITY OF SAFETY RULES

Safety Rule	N_2	O_2	F_2	H_2	H_e
Personnel: Protective clothing	x	x	x	x	x
Breathing equipment			x		
Fire fighting equipment Required:		x	x	x	
Ignition sources prohibited		x	x	x	
Spillage disposal and area ventilation required	x	x	x	x	x
Duct insulation	x*	x*	x*	x	x
Periodic leakage checks required	@	x	x	x	@
System purge required	x	x	x	x	x
Design must avoid entrapment of fluids and provide adequate means of pressure relief	x	x	x	x	x
Materials must be compatible with the applicable fluid and have adequate physical properties at cryogenic temperature	x	x	x	x	x
System must always be maintained clean per specification	x	x	x	x	x

@ Leak check if in enclosed area

* Insulation not always required for heat loss

2.6 METALLIC MATERIALS

2.6.1 General Characteristics of Metallic Materials - The selection of a suitable cryogenic duct material is generally a function of both quantitative and qualitative considerations. In general, strength and stiffness of metals increase with a decrease in temperature. Ductility is one of the main application parameters and may, or may not, be significantly affected by low temperatures. Many common materials are temperature-sensitive and do exhibit a lowering of ductility in the low temperature realm and are considered brittle. The transition from ductile to brittle behavior can occur sharply or gradually, and at relatively high temperatures. This transition is affected by both metallurgical and mechanical characteristics, and is the most limiting factor in material selection. In general, the metals and alloys having a face-centered-cubic crystal structure such as aluminum alloys, austenitic stainless steels, and nickel base alloys, and some with hexagonal-close-packed crystal structure such as the alpha titanium alloys and cobalt base alloys are ductile at cryogenic temperatures. Metals with a body-centered-cubic structure such as the beta titanium alloys and low-alloy steels have a relatively high ductile-brittle (D. B.) transition temperature, and are not suitable for cryogenic application.

2.6.1.1 Quantitative Data - The quantitative evaluation is based on one or more comparative figures of merit unique to the particular design requirements.

2.6.1.1.1 Strength-to-Weight Ratio - This is a frequently used figure of merit, and is commonly given as the ratio of tensile yield strength to density. Figure 3 shows this relationship for a group of materials suitable for cryogenic use.

2.6.1.1.2 Ductility - This parameter is difficult to specify in a straight-forward manner. In essence it is some comparative measure that determines to what extent the material will be brittle at service temperature. If brittleness is present, the hardware would be subject to catastrophic failure in the event of impact loads, complex stress fields or excessive vibratory loads where stress reduction through plastic flow is not possible.

Several laboratory tests have been devised to predict whether a material will behave in a ductile manner or brittle manner in service. The most popular of these tests are the various impact tests, the notched tensile test, and the tensile elongation or reduction in area test. The greatest amount of published literature to date has been on the tensile elongation and impact type. Comparative tests currently receiving much attention are the notch tensile test and fracture toughness measured by crack propagation. Care must be exercised in the use of any data of the above type to be sure that it was obtained under reasonably similar circumstances.

2.6.1.1.3 Impact Strength - Even though the effects of low temperature on tensile elongation properties of metals tend to show certain trends, the factors involved in specifying materials for low temperature service are far more complex than can be evaluated by such measurements alone. In most instances, cryogenic equipment should have minimum weight which leads to relatively high stresses. It should be possible to fabricate the metals by accepted methods. In certain applications, shock-loading will be experienced. Problems of toughness at very low temperatures ranging from -320 to -423 F become critical. A point to remember is that low notched to unnotched tensile ratios frequently occur at -423 F where elongation values are relatively high. Consequently, a material may exhibit a large amount of ductility, as measured by elongation or reduction of area, and yet have very poor toughness as measured by notched to unnotched tensile ratios, or Charpy notch tests. For example, aluminum alloy 7075-T6 has greater elongation at -423 F than does 2014-T6 alloy, but it has been noted that in sheet stock, it and others of the 7000 series aluminum alloys tend to become too brittle for use at -423 F. Without information on notched specimens to show the relative tendency for brittleness, it is possible to misjudge suitability of an alloy for use at very low temperatures. This is especially true where conditions favoring brittle failure are present. These include high strain rates, stress concentrations, high operating stresses, and low temperature. Variations in interstitial content resulting from commercial tolerances and/or processing often have a marked effect in material toughness at low temperature. Some typical values for Charpy impact tests on various materials are given in Table I.

2.6.1.1.4 Fatigue Strength - A good compilation of existing fatigue data of cryogenic materials is contained in reference 4, which is kept up to date by supplements as more data become available. These data, however, generally cover only the high cycle range, i.e. greater than 10^4 cycles, whereas the requirements of many ducting applications are below that value. In general, for a given stress level, fatigue life at cryogenic temperatures is greater than the room temperature value.

2.6.1.1.5 Thermal Movement - In cryogenic as well as high-temperature duct systems thermal movement effects are one of the principal design considerations. The total thermal movement in the cryogenic region for selected materials on which data are available is given in Figure 4.

2.6.1.1.6 Thermal Conductivity - Heat conduction through ducting and supports can be an important design problem. With the use of super insulations particular consideration must be given to all heat leaks which degrade system insulation performance. At the present time thermal conductivity values at cryogenic temperatures are not readily available for many of the materials suitable for ducting. Figure 5 gives conductivity values for various groups of materials which may be used as a general engineering selection guide. References 4 and 5 should be consulted for more specific values. Reference 4 in particular will have data added through supplements as it becomes available.

2.6.1.2 Qualitative Considerations - When the most suitable materials have been compared on a quantitative engineering basis, then the more qualitative aspects must be examined. In some cases, it may be desirable to assign arbitrary figures of merit to the qualitative factors to aid in the optimum selection.

2.6.1.2.1 Fabrication - Careful consideration must be given to the unique working characteristics of the many suitable materials. If severe forming is required, the fact that some materials work-harden very rapidly must be considered. Since for many materials, the mechanical properties at cryogenic temperatures are sensitive to contamination and interstitial content, care must be exercised in selecting the proper welding procedures.

2.6.1.2.2 Availability - Many materials are limited with respect to available gages. Also, where materials have limited usage, lead-time to obtain special mill runs must be considered. Since low temperature properties are often sensitive to variations in thermal and mechanical history as well as the chemical compositions which are allowable within commercial specifications, a special procurement specification may be required.

2.6.1.2.3 Compatibility - Ordinarily, most materials whose mechanical properties are suitable for cryogenic temperatures have good to excellent corrosion resistance. There are cases, however, where a material is specifically preferable, e.g., monel for use with liquid fluorine.

2.6.2 General Design Data - Table I gives a selection of materials which are suitable for use at cryogenic temperatures. The minimum temperature given indicates the region where ductile to brittle transition occurs. Comparative typical mechanical properties for some materials are given on Figures 1, 2, and 3. Materials whose strength is normally obtained by cold-working have not been included since in most ducting applications fusion welding is required which results in local weakening.

2.6.2.1 Aluminum Alloys - A considerable amount of information is presently available on aluminum alloys for cryogenic application. Aluminum alloys have many strong points in the low-temperature realm, mainly because:

a. At cryogenic temperatures, tensile, shear, and fatigue strengths increase
b. Fracture occurs in a ductile manner
c. There is no ductile-brittle transition
d. They are easily worked
e. Cost is low

Most of the published data on the mechanical properties of aluminum alloys do not provide a clear-cut indication of the preferred sheet aluminum alloy for cryogenic temperature applications. However, the 5000 series alloys are used with increasing frequency in cryogenic applications. The modern inert gas shielded arc welding technique has encouraged use of this alloy group because of the relatively high strength and toughness in the as-welded condition. This group of alloys exhibits an increase in tensile strength of about 80% between 80 and -423 F; the yield increases about 15% in this same range.

In the 3000 series, 3003 is the most popular. It is easiest to weld of all the aluminum alloys and is especially good where reliable vacuum sealing is essential. It is normally welded with 1100 wire. The low strength of this alloy is the chief limitation.

Alloys in the 6000 series show no evidence of ductile to brittle transition. They are all readily weldable in the annealed condition. The as-welded strength of the 6000 alloys is lower than the 5000 series.

The 7000 series normally have higher strengths than any of the other groups. However, they are not generally recommended where welding is a consideration. Welded joint strengths are too low to permit reasonable use of the high strength properties. The same is true for the 2000 series alloys with the exception of Alloy 2219.

2.6.2.2 Stainless Steels - The stainless steels are generally divided into four main categories:

a. Austenitic (300 series typical)
b. Ferritic (400 series, non-hardenable)
c. Martensitic (400 series, hardenable)
d. Precipitation Hardening (AM 350, 17-7PH, A-286, etc.)

The austenitic group of 300 series stainless is the only one with acceptable properties at cryogenic temperatures; the materials within the group are generally considered superior in this respect. However, in the annealed condition these steels have relatively low strength. The strength is considerably improved by cold-working, but when fusion welding is required, it is difficult to fully utilize this increased strength, since the property advantage developed through cold working is no longer valid at the welded zone.

Care must be taken to keep austenitic stainless stable. For example, sensitization (chromium carbide precipitation to grain boundaries) must be avoided since this stimulates intergranular or intercrystalline attack when in the presence of a corrosive medium.

2.6.2.3 Nickel Base Alloys - Nickel base alloys such as the Inconels, Rene' 41, Monel, and Hastelloys are of face-centered-cubic crystal structure and exhibit good cryogenic properties and are extensively used. These materials were originally developed for high-temperature applications. Some applications could have parameters involving both high and low temperatures which would suggest that these nickel base alloys would have extreme advantages.

2.6.2.4 Cobalt Base Alloys - Cobalt alloys such as L-605 (or Haynes Alloy #25) have a hexagonal-close-packed lattice and show good cryogenic properties similar to the titanium-base alloys. Again, these materials are principally used for high temperature applications and are usually considered for cryogenic use only in unique devices exposed to both temperature extremes.

2.6.2.5 Titanium Alloys - Titanium and its alloys are grouped in three general classes: alpha, alpha-beta, and beta. Only the alpha and alpha-beta alloys are suitable for cryogenic use. The most important alpha alloy is 5Al - 2.5Sn which has relatively better weldability, and is non-heat-treatable. The alpha-beta alloys such as 6Al - 4V, 7Al - 4Mo, 4Al - 4Mn, and 8Mn are weldable and may be heat treated. Of this latter group, 6Al - 4V is the more popular. There is much scatter in the cryogenic property data mainly because of the interstitial content within the alloys. Titanium is susceptable to pickup of C, H, N, and

O. Welding, for example, must be accomplished in an inert atmosphere or vacuum to preclude contaminating gases. Absorption of hydrogen through pickling acids, plating solutions, or just plain water vapor must also be guarded against. The interstitials affect the ductility significantly, and unless removed, as in ELI (extra low interstitial) grades, will lower the ductility to a great extent at cryogenic temperatures.

In 1959 it was discovered that under specific conditions titanium and its alloys were susceptible to violent, and often catastrophic, reactions in the presence of liquid oxygen. These reactions are associated with local impact, galling and stress rupture which promote the formation of a gaseous oxygen pocket, and thus, is said to be LOX impact sensitive. A thorough description of this phenomenon is beyond the scope of this report; however, an excellent description plus a list of references are contained in reference 6. (See also reference 10 for LOX compatibility of material.)

2.6.3 Non-Metallic Materials - Because of their light weight, low thermal conductivity, and adequate mechanical properties, a limited number of plastics can be considered for cryogenic ducting applications, such as insulating and sliding supports, gasketing material, and valve seats. The ductility of nearly all plastics decreases with decreasing temperature; however, unlike metallic materials the notched to unnotched tensile strength ratio increases slightly at lower temperatures. The tensile strength and modulus of elasticity of plastics increases as temperature decreases, which improves structural properties but makes contour conformance and sealing more difficult.

The most commonly specified plastics for cryogenic applications are Mylar, Nylon, and fluorocarbons. Outstanding among the fluorocarbons that retain some ductility at low temperature are Teflon and Kel-F. Glass sheet and reinforced plastics are sometimes applicable for non-structural applications, such as insulation. Mylar (except in very thin sheet form) and Nylon are considered brittle at low temperature; however, where ductility is not a primary consideration, these materials are considered suitable, except for LOX application, due to their low impact-sensitivity threshold.

Figure 6 shows the variation in tensile strength of some commonly used plastics at cryogenic temperatures. For design application in the cryogenic region the yield and ultimate strength are practically identical due to the drastic reduction in ductility.

For the fluorocarbon materials, such as Teflon and Kel-F, one of the most important features that must be considered in application is the dependence of mechanical properties at cryogenic temperatures upon the crystallinity of the material. The crystalline content is dependent on design shape and processing history. Consequently, design properties obtained from a tensile specimen of a controlled uniform crystalline content will not be necessarily indicative of the mechanical properties of a molded or extruded part with variable crystalline content throughout the section. This is illustrated in Figure 6, where the difference in tensile properties for controlled crystallinity content is shown.

REFERENCES

1. Schwartzberg, F., Agricola, K., and Hauser, R. "Properties of Missile Materials at Cryogenic Temperatures," Martin Co. Informal Report No. M1-60-24, Denver, Colorado, May, 1960.

2. McClintock, M. R., and Gibbons, H. P. "Mechanical Properties of Structural Materials at Low Temperatures," National Bureau of Standards Monograph 13, June 1, 1960.

3. Anonymous, "Engineering Properties of Monel and 'R' Monel," The International Nickel Company Technical Bulletin T-5, February, 1960.

4. Durham, T. F., McClintlock, M. R., and Reed, R. P. "Cryogenic Materials Data Handbook," National Bureau of Standards Report PB 171 809. (Obtainable from Office of Technical Services, U. S. Department of Commerce, Wash., D. C.)

5. Powell, R. L., and Blanpied, W. A. "Thermal Conductivity of Metals and Alloys at Low Temperature," National Bureau of Standards Circular 556, September, 1954.

6. Jackson, J. D., et. al. "A Study of the Mechanism of the Titanium-Liquid Oxygen Explosive Reaction," Aeronautical Systems Division Technical Report ASD-TR-61-479.

7. Christian, J. L. "Mechanical Properties of High-Strength Sheet Materials at Cryogenic Temperatures," General Dynamics/Astronautics Report ERR-AN-255, November 28, 1962.

8. "Lescalloy 718 Vac Arc," Latrobe Steel Company Brochure, July, 1963.

9. Aluminum Company of America data, November, 1963.

10. Curry, J. E., and Riehl, W. A. "Compatibility of Engineering Material with Liquid Oxygen," George C. Marshall Space Flight Center, MTP-M-S and M-61-7.

Section 2.6: "Additional References - refer to Bibliography publications 16, 17, 59, 77, and 99."

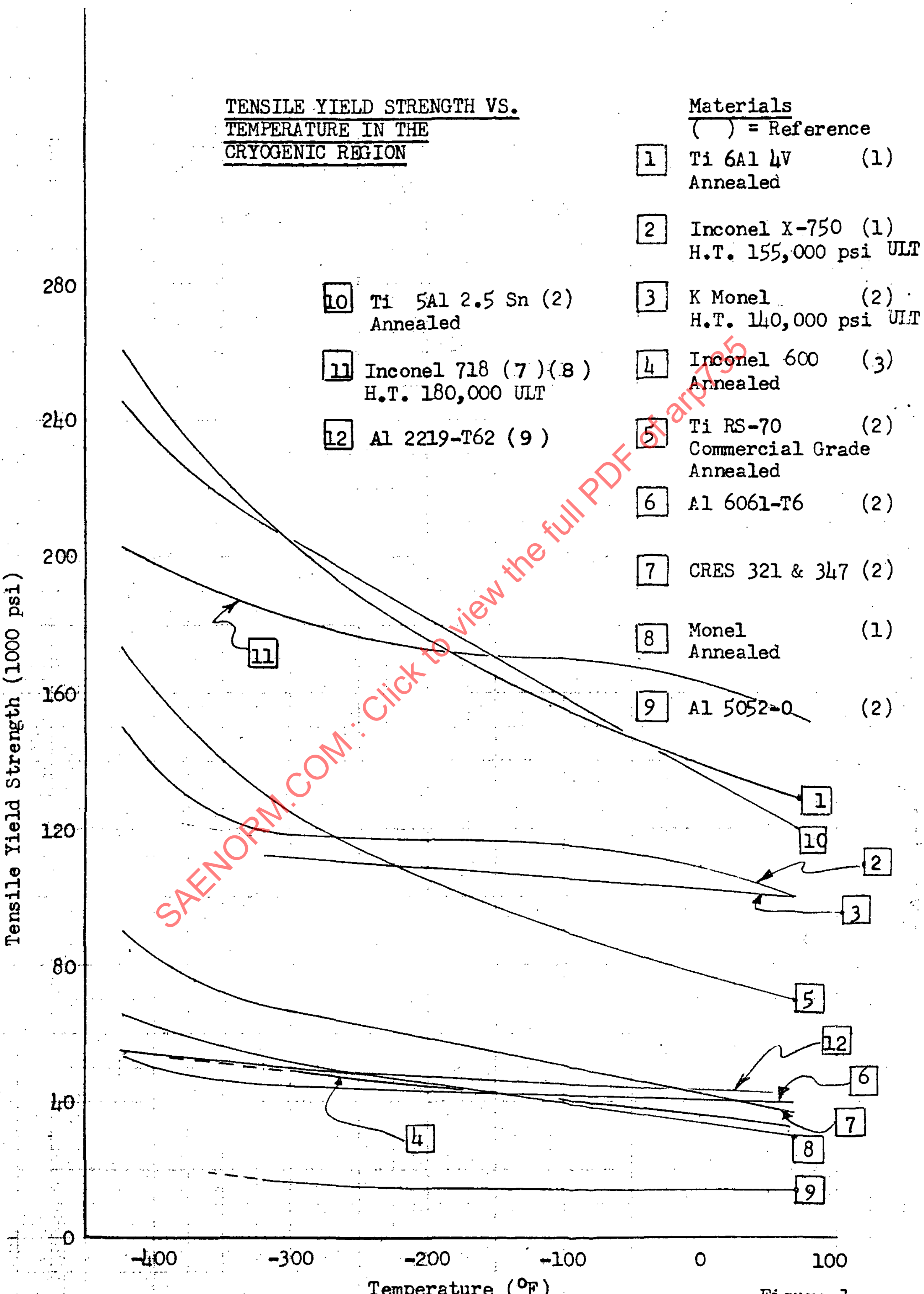

TENSILE YIELD STRENGTH VS. TEMPERATURE IN THE CRYOGENIC REGION
Materials
( ) = Reference
1 Ti 6Al 4V Annealed (1)
2 Inconel X-750 (1) H.T. 155,000 psi ULT
3 K Monel (2) H.T. 140,000 psi ULT
4 Inconel 600 Annealed (3)
5 Ti RS-70 Commercial Grade Annealed (2)
6 Al 6061-T6 (2)
7 CRES 321 & 347 (2)
8 Monel Annealed (1)
9 Al 5052-0 (2)
10 Ti 5Al 2.5 Sn (2) Annealed
11 Inconel 718 (7)(8) H.T. 180,000 ULT
12 Al 2219-T62 (9)
Tensile Yield Strength (1000 psi)
0
40
80
120
160
200
240
280
-400
-300
-200
-100
0
100
Temperature (°F)

Figure 1

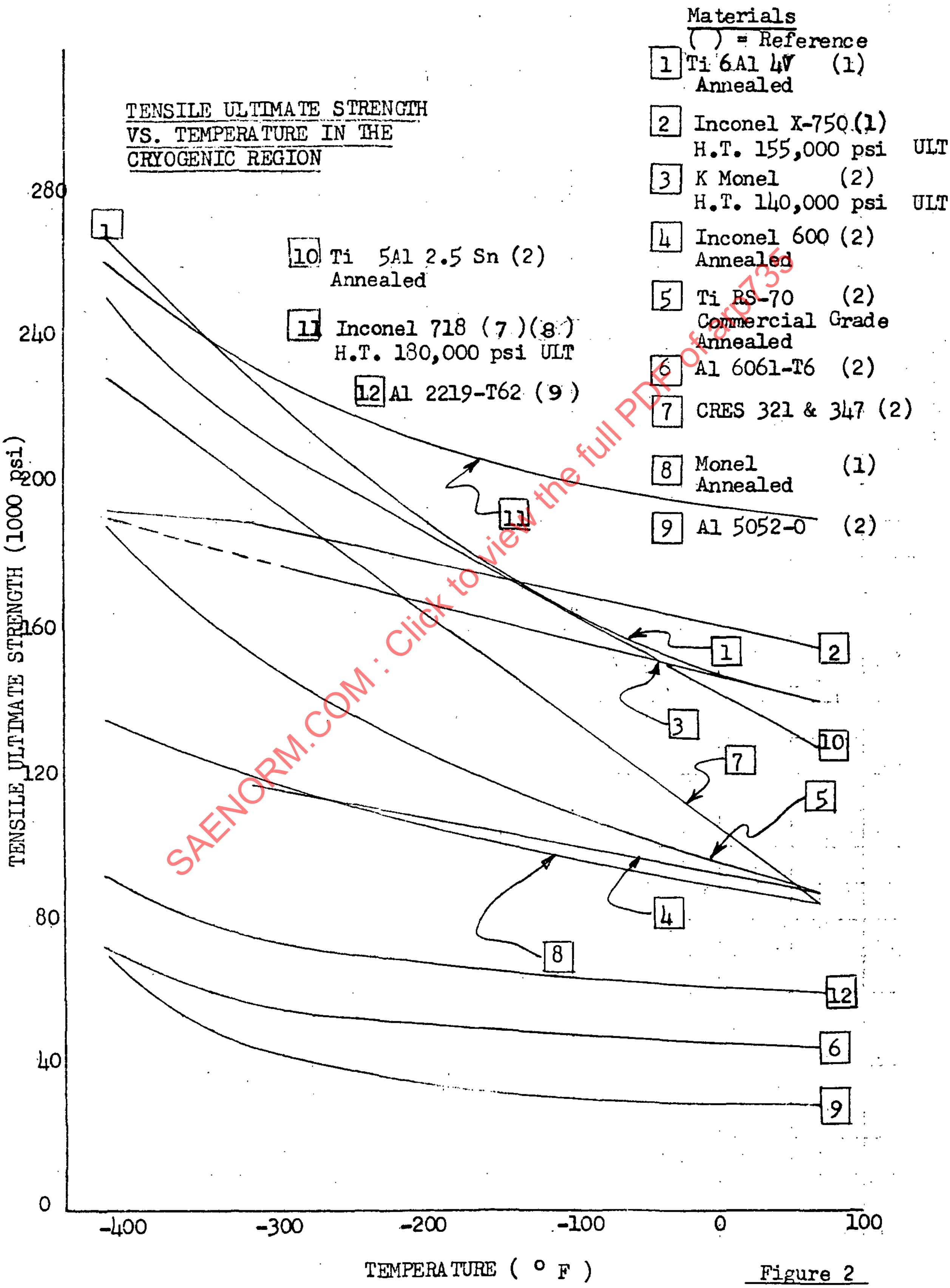

TENSILE ULTIMATE STRENGTH VS. TEMPERATURE IN THE CRYOGENIC REGION
Materials
( ) = Reference
1 Ti 6Al 4V (1) Annealed
2 Inconel X-750 (1) H.T. 155,000 psi ULT
3 K Monel (2) H.T. 140,000 psi ULT
4 Inconel 600 (2) Annealed
5 Ti RS-70 (2) Commercial Grade Annealed
6 Al 6061-T6 (2)
7 CRES 321 & 347 (2)
8 Monel (1) Annealed
9 Al 5052-0 (2)
10 Ti 5Al 2.5 Sn (2) Annealed
11 Inconel 718 (7)(8) H.T. 180,000 psi ULT
12 Al 2219-T62 (9)
TENSILE ULTIMATE STRENGTH (1000 psi)
280
240
200
160
120
80
40
0
-400
-300
-200
-100
0
100
TEMPERATURE (°F)

Figure 2

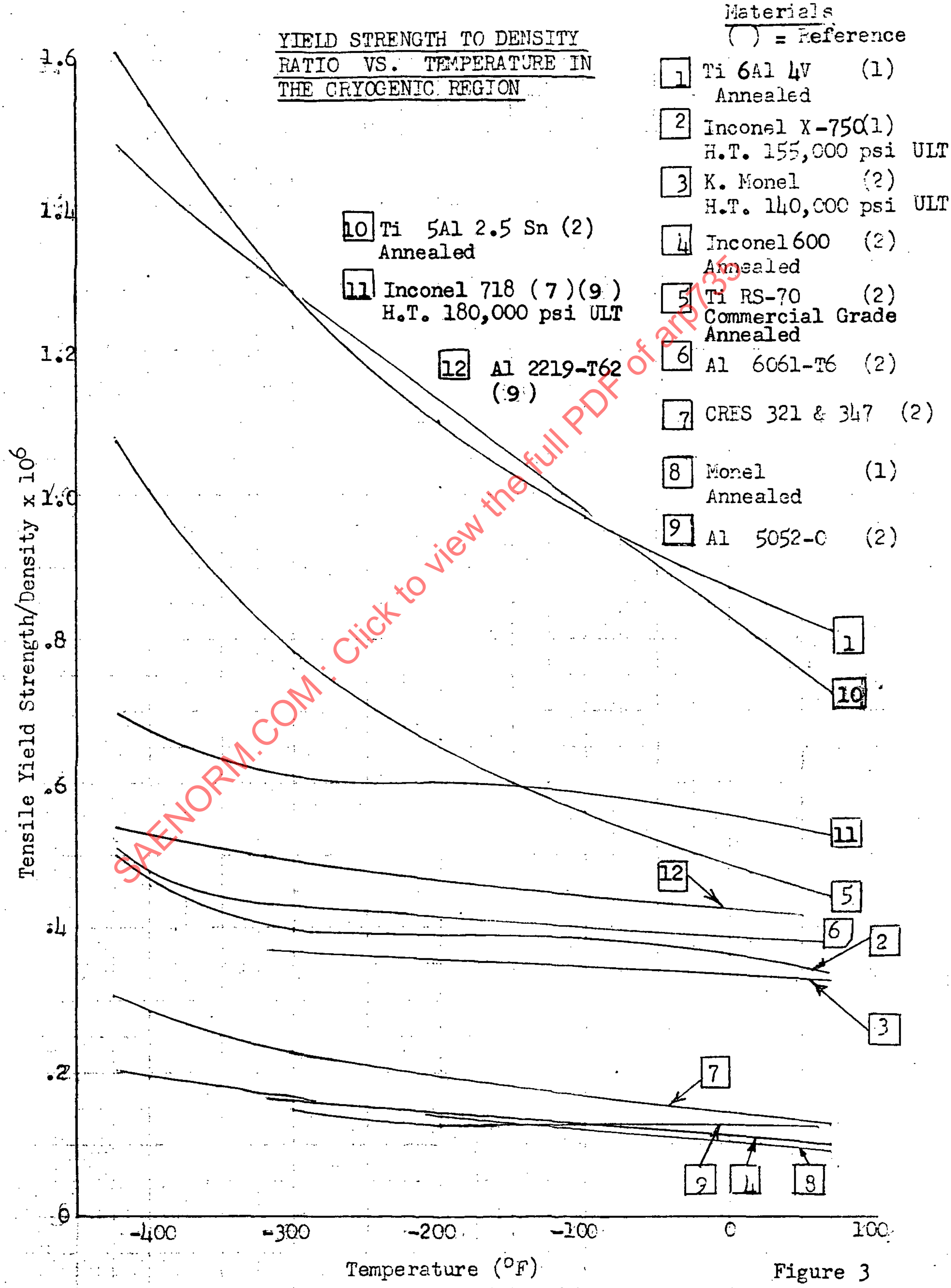

YIELD STRENGTH TO DENSITY RATIO VS. TEMPERATURE IN THE CRYOGENIC REGION
Materials
( ) = Reference
1 Ti 6Al 4V (1) Annealed
2 Inconel X-750 (1) H.T. 155,000 psi ULT
3 K. Monel (2) H.T. 140,000 psi ULT
4 Inconel 600 (2) Annealed
5 Ti RS-70 (2) Commercial Grade Annealed
6 Al 6061-T6 (2)
7 CRES 321 & 347 (2)
8 Monel (1) Annealed
9 Al 5052-O (2)
10 Ti 5Al 2.5 Sn (2) Annealed
11 Inconel 718 (7)(9) H.T. 180,000 psi ULT
12 Al 2219-T62 (9)
Tensile Yield Strength/Density x 10^6
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-400
-300
-200
-100
0
100
Temperature (°F)

Figure 3

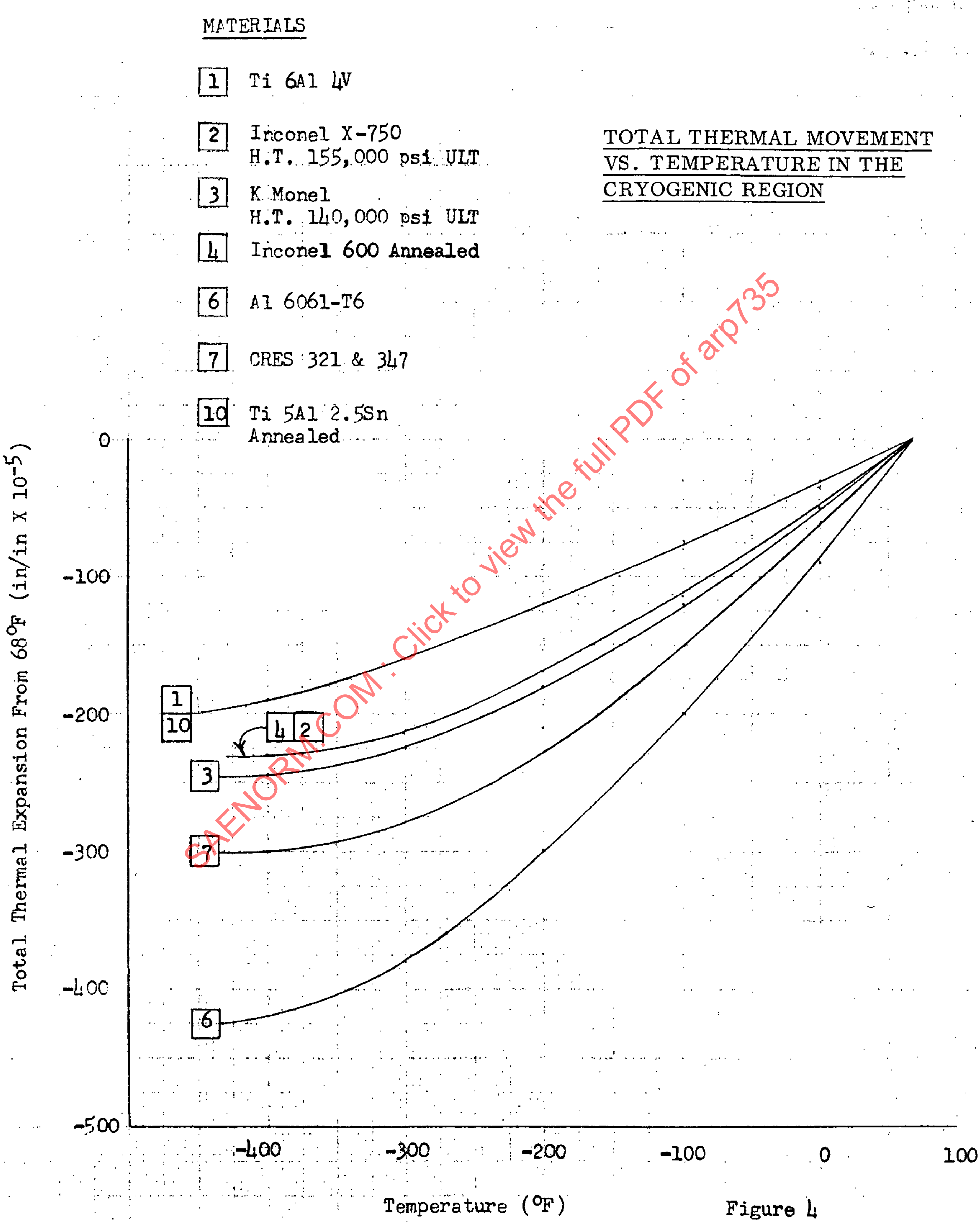

MATERIALS
1 Ti 6Al 4V
2 Inconel X-750 H.T. 155,000 psi ULT
3 K Monel H.T. 140,000 psi ULT
4 Inconel 600 Annealed
6 Al 6061-T6
7 CRES 321 & 347
10 Ti 5Al 2.5Sn Annealed
TOTAL THERMAL MOVEMENT VS. TEMPERATURE IN THE CRYOGENIC REGION
Total Thermal Expansion From 68°F (in/in X 10-5)
0
-100
-200
-300
-400
-500
-400
-300
-200
-100
0
100
Temperature (°F)

Figure 4

TYPICAL THERMAL CONDUCTIVITY VALUES VS TEMPERATURE FOR MATERIAL GROUPS IN THE CRYOGENIC REGION

(O⟶ indicates scale)

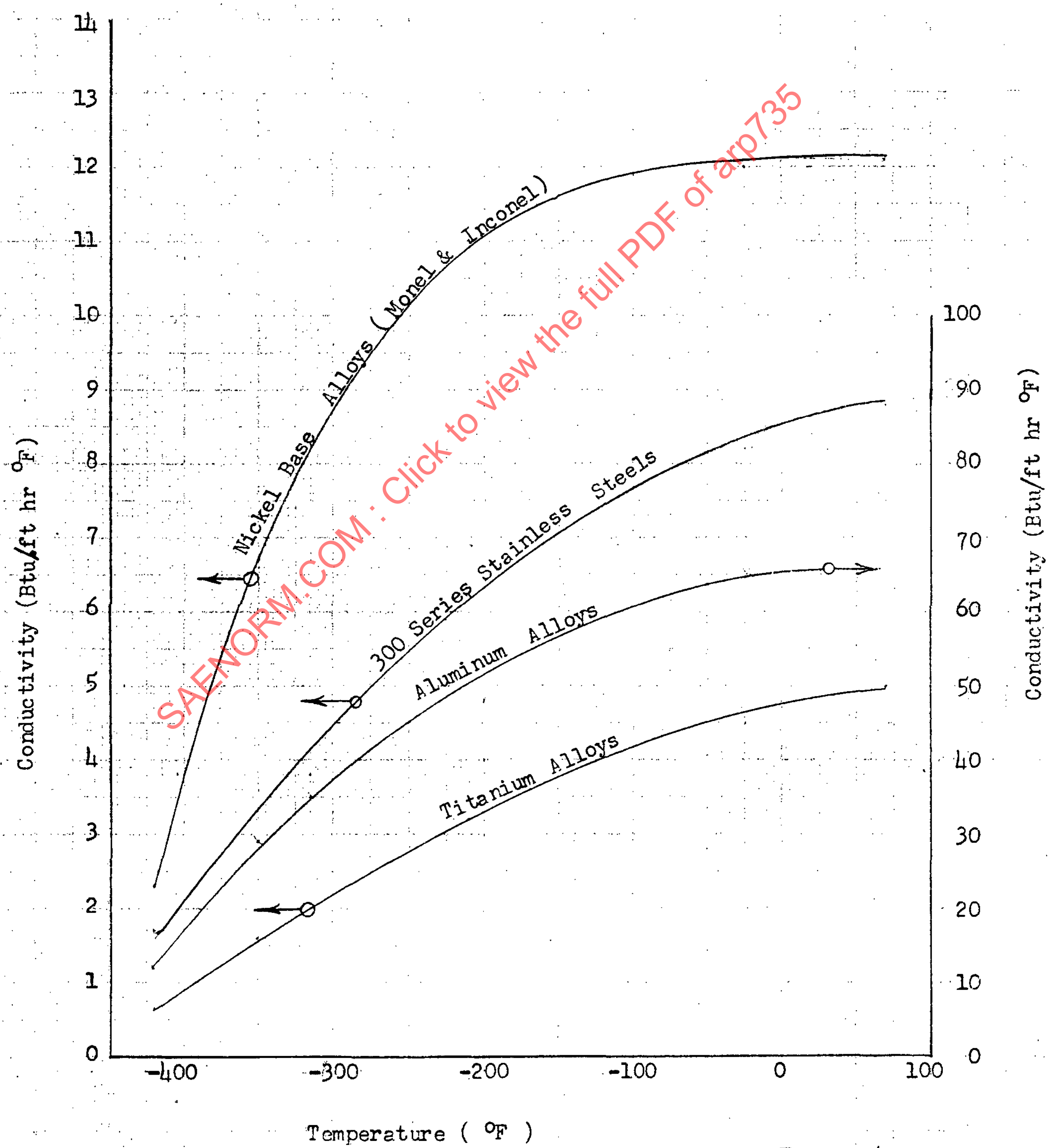


Figure 5

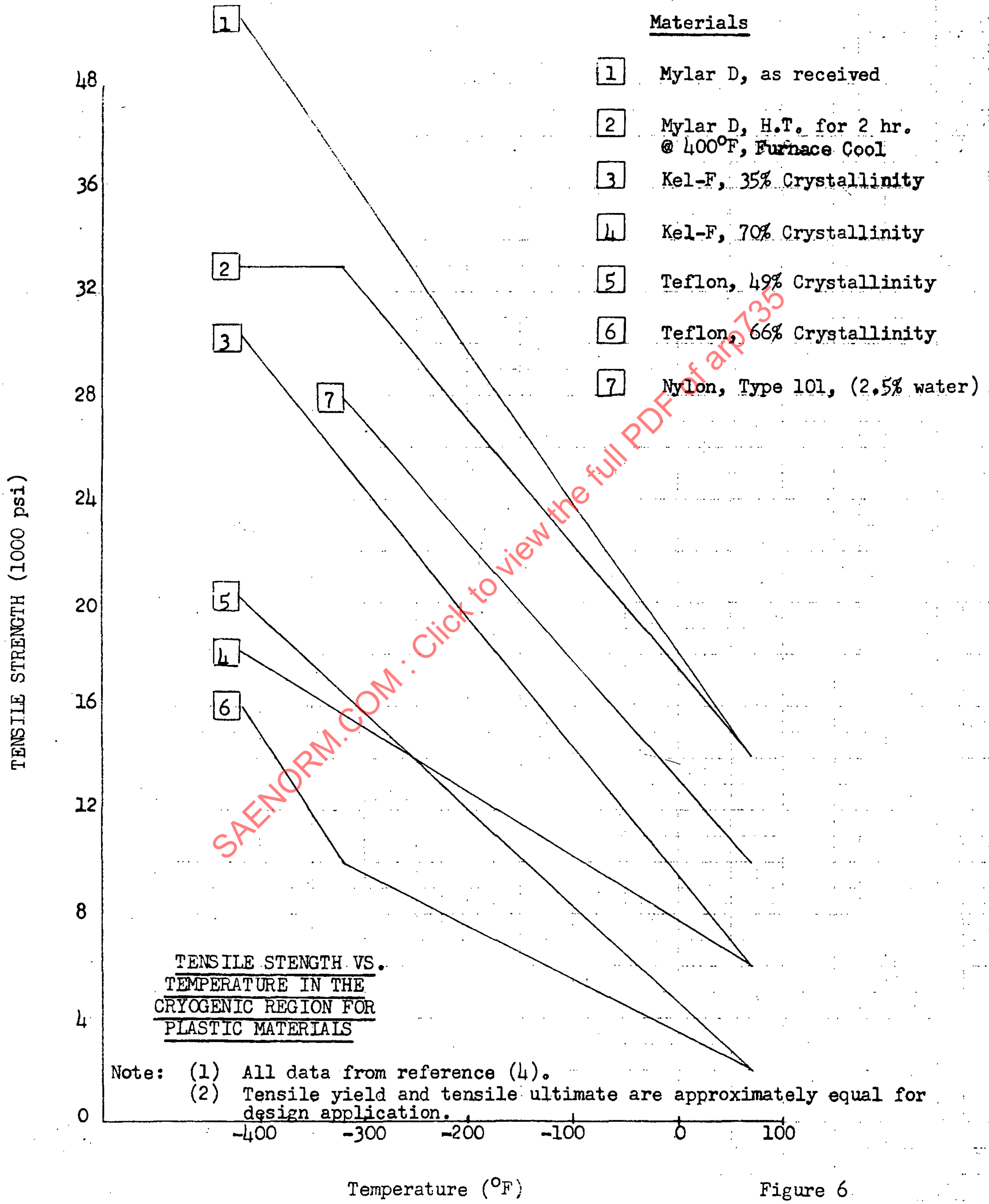

Materials
1 Mylar D, as received
2 Mylar D, H.T. for 2 hr. @ 400°F, Furnace Cool
3 Kel-F, 35% Crystallinity
4 Kel-F, 70% Crystallinity
5 Teflon, 49% Crystallinity
6 Teflon, 66% Crystallinity
7 Nylon, Type 101, (2.5% water)
TENSILE STRENGTH (1000 psi)
48
36
32
28
24
20
16
12
8
4
0
1
2
3
7
5
4
6
TENSILE STENGTH VS. TEMPERATURE IN THE CRYOGENIC REGION FOR PLASTIC MATERIALS
Note: (1) All data from reference (4).
(2) Tensile yield and tensile ultimate are approximately equal for design application.
-400
-300
-200
-100
0
100
Temperature (°F)

Figure 6

TABLE I

SELECTED MATERIALS SUITABLE FOR USE AT CRYOGENIC TEMPERATURES

Material	AMS Spec. (sheet)	Min. Temp. (F)	Condition	Corrosion Resistance	Weldability	Formability	Impact*** Strength (ft-lb)
304	5513	-455	Annealed	Excellent	Good*	Excellent	75K - 320T
304L	5647A	-455	Annealed	Excellent	Excellent	Excellent	65K - 423T
316	5524	-455	Annealed	Excellent	Good*	Excellent	
321	5510	-455	Annealed	Good	Excellent	Excellent	45K - 320T
347	5512	-455	Annealed	Good	Excellent	Excellent	55K - 320T
A-286	5525	-320	Aged	Excellent	Fair**	Good	53V - 320T 50V - 423T
Inconel 718	5596	-455	Aged	Excellent	Good	Good	
Inconel 600	5540	-455	Annealed	Excellent	Excellent	Excellent	
Monel	4544	-455	Annealed	Excellent	Excellent	Excellent	
Inconel-X-750	5542	-455	Aged	Excellent	Good**	Good	37V - 320T
K Monel	None	-320	Aged	Excellent	Good**	Good	34V - 320T 36V - 423T
Hastel-loy B	None	-455	Annealed	Excellent	Excellent	Good	
Hastel-loy C	5530	-455	Annealed	Excellent	Excellent	Good	
Hastel-loy X	5536	-455	Annealed	Excellent	Excellent	Excellent	Good
N-155	5532	-455	Annealed	Excellent	Fair	Good	
HS-25 (L-605)	5537	-455	Annealed	Good	Good	Good	

* Must be annealed (fast quench) after welding to maintain best corrosion resistance

** Welding must be accomplished before heat treatment

*** V = Charpy V, K = Charpy K, T = Temp F

TABLE I (Continued)

Material	AMS Spec. (sheet)	Min. Temp. (F)	Condition	Corrosion Resistance	Weldability	Formability	Impact*** Strength (ft-lb)
Invar	None	-320	Annealed	Excellent	Good	Good	
Al 6061	4027	-455	T6 Aged	Excellent	Excellent**	Poor	12K - 320T 12K - 423T
Al 5052	4015	-455	0	Excellent	Excellent	Excellent	
Al 5086	None	-455	0	Excellent	Excellent	Fair	
Al 5154	4018	-455	0	Excellent	Excellent**	Fair	
Al 2024	4037	-455	T3	Fair	Fair	Fair	6K - 320T 6K - 423T
Al 5083	4056	-455	0	Excellent	Good	Fair	
Ti-6Al4V	4911	-320	Annealed	Excellent	Fair	Poor	
Ti-5Al 2.5Sn	4910	-320	Annealed	Excellent	Good	Poor	10V - 320T
Ti-RS70	4901	-320	Annealed	Excellent	Good	Fair	
Al2219	None	-423	T62 Aged	Excellent	Excellent	Fair	

* Must be annealed (fast quench) after welding to maintain best corrosion resistance

** Welding must be accomplished before heat treatment

*** V = Charpy V, K = Charpy K, T = Temp F

2.7 RELIABILITY

2.7.1 Background - Historically, reliability disciplines were introduced in the 1920's when Bell Laboratories put quality control on a firm scientific basis, and still later when the government took action to improve reliability in design by developing the JAN standards during World War II. Another major step was taken in the 1951-1952 period when the Department of Defense established the "Advisory Group on Reliability of Electronic Equipment" (AGREE). The AGREE task force was established to "monitor and stimulate interest in reliability matters and recommend measures which would result in more reliable electronic equipment." The report (reference 1) issued by this group is still a valuable reference for designers and reliability engineers and is considered the origin of the technical reliability program as we know it today.

Today there are more than two hundred identifiable government specifications and documents related to the establishment and support of reliability requirements on all types of equipment. The most commonly applied specifications in current usage are: U.S. Air Force's MIL-R-27542, Reliability Program for Systems, Sub-Systems and Equipment; NASA's NPC 250-1, Reliability Program Provisions for Space Systems Contractors; and NAVY's WS-3250, General Specification for Reliability.

2.7.2 Designing for Reliability - When the design of a cryogenic ducting system(s) is included within the scope of any military or space agency contract, the submittal of a Reliability Program Plan will generally be required. Although many tasks, disciplines, and controls are contained within a Reliability Program Plan, the individual designer is initially concerned with designing his equipment to meet a designated or preapportioned reliability goal. This goal is a design objective and is a numerical expression of the probability that the design will perform, without failure, its specified function under given conditions for a specified period of time. In simplified terms, the reliability of a cryogenic ducting system, or any component within the system, is the probability that it will work as intended.

The reliability of a product is primarily determined in four basic areas of effort: (1) design and development (including testing), (2) manufacturing, (3) logistics, and (4) human factors (including operator effectiveness). Although all four factors must be given due consideration during the initial design and development states, the primary emphasis must be on design. If the design is good, but the other areas are deficient, correction of the deficient areas can be made later in the program; but if deficiencies exist in the basic design, they are often impossible to correct once the design has progressed beyond a certain point (see reference 2). It is important, therefore, for the designer to request and obtain reliability engineering information and services early in the design phase. The types of reliability information and assistance needed by the designer can be broadly classified into the following categories:

a. Interfaces with other design areas which would affect the designer's decisions and, in some instances, result in trade-off relationships

b. Reliability design techniques, parts selection, and data (such as mean-time-between-failures, de-rating factors, and the application of redundancy)

c. Periodic quantitative evaluation of design to determine progress towards reliability goals

d. Reliability and system test planning

e. Design reviews

The designer retains full authority and responsibility for product design and reliability throughout the life of the product. It is incumbent upon the designer to use the services of his reliability organization to assure that the reliability inherent in his design is not compromised by any reliability hazard associated with the fabrication, delivery, or end use of the product.

2.7.3 Reliability Testing - Plans for demonstrating the achieved reliability of a product at specified milestones are imposed on the contractor by one of the specifications noted in paragraph 2.7.1. Although these documents are generally applicable to major weapon systems or subsystems, the subcontractor usually receives a proportionate share of the reliability requirement which he must verify through demonstration and reliability tests.

Design, development, and testing are virtually synonymous and come under the general heading of "design." But what is reliability testing, and how does it fit into a company's established test program? Reliability testing has as its purpose the establishment of the length of time a product will operate satisfactorily under the specified conditions. In effect, reliability testing has evolved as a complement to, and not as a replacement for, the traditional development, qualification, environmental, and production tests.

Integrating and optimizing a test program on a cryogenic system or component, particularly when reliability commitments are involved, is a task requiring special training or experience. No attempt is made here to impart the "how" involved, but to strongly recommend that reliability specialists participate in the formulation of development, qualification, and reliability test plans to assure that the test results will yield the required data for the verification and improvement of product reliability.

2.7.4 Emphasizing Reliability - The objective of this brief section was not to treat in any depth the subject of reliability, but to alert the cryogenic ducting system designer to the ever increasing importance of reliability disciplines in the design of today's aerospace systems. While the growth in technology has made it easier to achieve reliability in the design of a part or a simple assembly, the increase in system complexity and technological requirements cause system reliability to become ever more difficult and costly to achieve. There is a point of diminishing returns, but the more effort spent on reliability considerations during the design, development, and test phases, the greater will be the savings during the operational phases.

Recommended reliability design and test standards, specifications, reports, and texts are provided for the benefit of the designer in the Bibliography.

REFERENCES

1. "Reliability of Military Electronic Equipment." AGREE Task Group 9 Report, Washington, D.C. U.S. Government Printing Office, June 1957.

2. "Reliability Control in Aerospace Equipment Development." Technical Progress Series, Volume 4, Society of Automotive Engineers, Inc., 1963.

Section 2.7: "Additional References - refer to Bibliography publications 8, 15, 33, 46, 50, 60, 68, 78, 80, 86, 87, 89, 92, 93, 94, 95, 96, 107."

3. COMPONENT DESIGN

3.1 DUCT - A duct, as here considered, is a complete unit from coupling to coupling. Design considerations for individual components, including flex sections and connectors, are handled in subsequent chapters.

3.1.1 Duct Types

3.1.1.1 Non-Insulated Ducts - A non-insulated duct is one in which no insulation means are provided.

3.1.1.2 Insulated Ducts

3.1.1.2.1 Integrally Insulated Duct - An integrally insulated duct is one in which the insulation is constructed as a part of the duct assembly and is not removable.

3.1.1.2.1.1 Vacuum Jacketed Duct - A vacuum jacketed duct is the most common form of integrally insulated assembly. It possesses the lowest heat gain but at some cost disadvantage. See further handling and manufacturing paragraphs for additional information. Insulation section, 3.2, deals with types of vacuum insulations commonly used.

3.1.1.2.1.2 Integral, Non-Vacuum Jacketed Duct - An integral, non-vacuum jacketed duct can utilize a metal or reinforced plastic outer shell which forms an annular volume containing a dead air space, foam, fiberglass or other insulating medium. The duct will usually contain standoffs, rings, or other means to support the outer shell.

3.1.1.2.2 Non-Integral, Insulated Duct - A non-integrally insulated duct assembly uses insulation which is removable and replaceable and does not form an integral part of the duct.

3.1.2 Criteria

3.1.2.1 The following considerations should be taken into account when designing cryogenic duct assemblies:

a. Maximum and minimum operating pressure
b. Maximum and minimum operating temperature
c. Most critical combination of pressure and temperature
d. Pressure impulse and "fluid hammer"
e. Vibration environment
f. External negative pressures caused by environment or by vacuum jacket insulation
g. Flow velocity and/or impingement
h. Internal load (i.e., momentum change at elbows)
i. Externally applied loads (i.e., vehicle deflection forces, weight of duct, installation loads, possibility of use as step, aerodynamic forces, etc.)
j. Shock and accelerations due to engine start, blast-off, stage separation
k. Movement due to structural deflections
l. Movement due to engine if gimballed
m. Thermal contraction or growth
n. Movement due to acceleration loads
o. Cleanliness requirements
p. Means for supporting duct
q. Shop handling limitations
r. Shop fabrication capabilities
s. Corrosion
t. Compatibility of materials and processes to the fluid used
u. Permissible flange loads
v. Insulation requirements

3.1.2.2 Vacuum jacketed ducts require additional considerations and precautions. These are as follows:

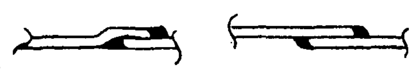
a. Cleanliness and elimination of outgassing materials
b. Means for evacuation of vacuum area (usually a pump-down valve in the jacket)
c. Means for measuring vacuum
d. Safety rupture disk or other devices for releasing pressure build-up in vacuum jacket due to leak in inner duct
e. Accommodation of differential growth between inner and outer ducts due to both temperature and pressure differences (usually by flex section)
f. Support points and jacket compatibility, particularly transmission of pressure reactions through elbows.

3.1.3 Design

3.1.3.1 Welding - Types of weld joints play an important part in successful cryogenic duct design. For oxidizer use, an additional requirement for ease of cleaning and elimination of dirt retaining areas has to be considered. Listed below are conventional weld joints with applicable comments:

Butt-Weld - Most ideal from both cleanliness and stress considerations but more difficult to make in thinner gauges.

Burn-Down Flange - Common for drop hammer halves and for joining thin gauge tubes. Care must be taken to assure full weld penetration to I.D. of duct. Radius at bend must be kept small and mating parts must match.



Overlap - Self-aligning. For oxidizer service, I.D. is usually welded in addition to O.D.

Combination Weld - For joining thin or multiple ply flex sections to adjacent component. Resistance seamweld is trimmed in center of nugget and this heavy section is welded to the next assembly. For oxidizer use I.D. would also be welded.

3.1.3.2 Brazing - Certain brazes can be used to join cryogenic ducts, but do not find widespread use due to resultant cleaning and inspection problems.

3.1.3.3 Die Formed Parts

3.1.3.3.1 Flat Areas - Special attention should be given to duct shapes such as tees or Y's that contain flat areas. The flats should be crowned and/or reinforced to guard against early fatigue from pressure pulsations or from flow-induced vibration. Reinforcement of the crotch area of Y sections is common practice and is often a necessity due to high loading in this area. This reinforcement is commonly accomplished by the addition of external saddles, tie bars through the duct or, in the case of Y sections, a splitter. The leading edge of the splitter will usually have to be reinforced.

3.1.3.3.2 Thinning - Whenever a duct design includes die-formed tees or elbows, an allowance in the form of reduced stress levels must be made for stretching of the metal over the die. Normally, the maximum thinning occurs at the inside bend radius near the duct half parting plane and can be as high as 50% in these areas.

Thinning is dependent on the ratio of duct diameter to wall thickness, forming techniques, radius of bend, and degrees of bend.

Increase in yield due to cold working will to some degree offset the amount of thinning and should be considered when establishing the minimum allowance wall thickness.

Consult available design and manufacturing manuals before establishing the wall thickness. Recommended practice is to specify a minimum permissible wall thickness after forming.

3.1.3.3.3 Ovality - Ovality in welded ducts can appreciably shorten fatigue life due to the breathing effect, or change in cross-sectional shape as pressure fluctuates. This can also result in a Bourdon tube effect in elbows. Care must be taken in allowing for this ovality by reducing design level, by reinforcing, or by secondary manufacturing processes to round the section.

3.1.3.4 Duct Reinforcements - When used, doublers, or other reinforcements should be welded all around, preferably by fusion welding, to the basic duct. If large temperature differentials are encountered, consideration should be given to venting the entrapped area.

3.1.3.5 External Pressure - Many ducts can experience external pressure during some phase of their use. If this is a possibility it must be taken into consideration in thin wall ducting since design procedures for internal pressure are often insufficient for external pressure.

3.1.3.6 Design Stress Factors - A duct should be structurally adequate to resist without rupture, pressures of at least 2.5 times the maximum operating pressure, including transients. The duct should be structurally adequate to resist without permanent deformation, pressures of at least 1.5 times the operating pressure or 1.2 times design pressure including transients, whichever is considered the most severe. The maximum operating pressure should be determined from the values resulting when any single system component malfunctions. Similar factors should be applied to dynamic forces resulting from fluid flow. Where combined loads occur, detail design of the ducting should be adequate to absorb loads from column action, structural or bracket deflection, and dynamic loads in addition to the internal pressure loads. A reduced allowable yield strength should be considered with respect to life-cycle expectancy. Normally, room temperature material properties are used unless special circumstances dictate otherwise.

3.1.3.7 Typical Basic Duct Design Formulas

The following symbols are used in this section:

A	=	Area
a	=	Mean radius of toroid or elbow bend
c	=	Coefficient of expansion
E	=	Modulus of elasticity
g	=	Gravitational constant (32.2 ft/sec^2)
ℓ	=	Duct length
M	=	Moment
m	=	Mass flow rate
p'	=	Buckling pressure
P	=	Pressure
r	=	Radius of duct
r'	=	Radius of elbow to O.D. of bend
Δt	=	Temperature differential
S'	=	Buckling Stress
S	=	Stress
t	=	Tube wall thickness
T	=	Torsion
v	=	Poisson's Ratio
V	=	Fluid velocity

3.1.3.7.1 Wall Stresses (Due to Internal Pressure)

Meridional

$$S_1 = \frac{pr}{2t}$$

Hoop

$$S_2 = \frac{pr}{t}$$

Ref: Roark p 268 Case 1

3.1.3.7.2 External Collapsing Pressure (Assumes Perfectly Round Thin Wall Duct and Infinite Stiffness at Support Point). Practical considerations can be met by applying an additional safety factor of 2.5 unless specifically varified by test.

For Long Duct with Free Ends of Length ℓ

Applicable when $\ell > 4.90r\sqrt{\frac{r}{t}}$

$$p' = 1/4 \cdot \frac{E}{1 - v^2} \cdot \frac{t^3}{r^3} \cdot 2.5 \text{ (safety factor)}$$

For Long Duct Reinforced at Intervals or Short Duct of Length ℓ

$$p' = 0.807 \frac{Et^2}{\ell r} \sqrt[4]{\left(\frac{1}{1 - v^2}\right)^3 \frac{t^2}{r^2}} \cdot 2.5 \text{ (safety factor)}$$

Ref: Roark p 318 Case 30 and 31

3.1.3.7.3 Column Buckling Stress-Ends not Constrained-Thin Wall Duct

$$S' = .3E \frac{t}{r}$$

Most accurate for long ducts, and tube is round.

Ref: Roark p 316 Case 25

3.1.3.7.4 Bending (Equal Moment Applied to Each End)

$$S = \frac{Mc}{I}$$

where:

$c = r =$ Radius of Duct

$I =$ Moment of Inertia of Thin Annulus

$\pi r^3 t$

$$S = \frac{Mr}{\pi r^3 t} = \frac{M}{\pi r^2 t}$$

3.1.3.7.5 Thermal Stress

Axial Length Change $\Delta = cl\,(\Delta t)$

$$S = \frac{\Delta E}{\ell} \text{ (Within the Proportional Limit)}$$

3.1.3.7.6 Torsion

$$S_s = \frac{T}{2\pi r^2 t}$$

Ref: Roark p 317 Ref: Case 27 and 28

3.1.3.7.7 External Reactions Due to Change in Direction

Assume Incompressible Flow

$$F = PA(1 - \cos\theta) + mV\,(1 - \cos\theta) \quad m = \frac{wQ}{g}$$

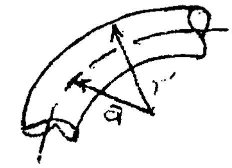
Where F is a combination of static pressure reaction and thrust due to fluid change in direction and θ is a complement of included elbow angle.

Ref: Marks V, pg. 262

3.1.3.7.8 Elbow - Stress in torus due to internal pressure may be used as an approximate method.

Tangential Stress

$$S_1 = \frac{pr}{t}\left(\frac{r' + a}{2r'}\right)$$



Maximum Tangential Stress (Occurs on Inside of Toroid)

$$\text{Max } S_1 = \frac{pr}{t}\left(\frac{2a - r}{2a - 2r}\right)$$

Meridional Stress

$$S_2 = \frac{pr}{2t} \text{ (Uniform Throughout)}$$

Ref: Roark p 274 Case 20

3.1.4 Special Considerations

3.1.4.1 Handling - Ducts for airborne use are typically light gage. This presents a problem wherein this factor will often constitute the governing criteria for design. Minimum wall thicknesses to minimize damage during fabrication and handling are suggested below. These figures are intended as a guide only and will vary with physical properties, handling practices and l/r ratio.

Duct Diameter (Inches)	Wall Thickness (Inches)
Under 1.5	.010
1.50 to 2.50	.012
2.50 to 4.00	.016
4.00 to 6.00	.020
6.00 to 9.00	.025
9.00 to 14.00	.032
14.00 to 20.00	.050
Above 20 Inches	As Dictated By Design

3.1.4.2 Entrapment Areas - Impurities can cause explosions with oxidizers. These contaminants can also cause malfunction in valves and other equipment. Ducts for special service such as liquid oxygen must be assembled and cleaned to applicable specifications.

3.1.4.3 Assembly Sequences for Cleaning - The designer must give due consideration to the assembly sequence. Proper cleaning, if required, can often be done only in specific subassembly stages. Cleaning sequence can be of such importance as to dictate choice of details influencing the most advantageous cleaning procedure.

3.1.4.4 Duct Support and Boss Provisions - Attention should be given to duct support points, adding the support load to other duct stresses. The effect of load reversals through supports must also be checked. The following general duct support provisions are recommended for considerations:

3.1.4.4.1 Doublers - Generally, doublers are one material gage heavier than the parent duct material, and are usually recommended under bosses and attach brackets on thin wall ducts (usually less than .060).

Boss doublers should be circular in shape, at least 1-inch larger in diameter, where possible, than the boss and fusion welded with full circumferential weld to the duct. The bosses should contain wrench flats if possible.

Attachment bracket doublers should be full circumferential doublers which may be roll seam welded or fusion welded to the duct. The doubler width should extend at least 1/2 in. beyond the support bracket and the gap between the ends of the doubler should be welded closed.

3.1.4.4.2 Slide Doublers - Doublers, as described under 3.1.4.4.1, should also be used on ducts for all sliding or rubbing areas.

3.1.4.4.3 External Duct Stiffeners - External duct stiffeners, or beading, should be used, if necessary, on ducts which may be subjected to collapsing or external pressure. It is wise practice that this particular design problem be verified by test.

3.1.5 Testing

3.1.5.1 Production Test - The following tests are normally performed by the duct manufacturer on each production unit.

3.1.5.1.1 Proof Pressure and Leak Test - The duct shall be pressurized to design proof pressure, at ambient temperature, using dry air or nitrogen and then submerging in water for a period of five minutes. During this time, the duct shall be visually examined for evidence of leakage as indicated by the emission of air bubbles. There shall be no leakage or evidence of permanent deformation. For more critical systems such as hydrogen, helium or vacuum, it will be necessary to use more sensitive leak detection methods such as a helium mass spectrometer. For safety considerations, a hydrostatic test may precede the gas test.

3.1.5.1.2 Examination of Product - The duct shall be:

a. Dimensionally inspected for conformance with the design drawing and applicable specifications with emphasis on critical dimensions.

b. Visually examined for quality of workmanship, use of correct materials, finishes and proper identification.

3.1.5.1.3 Movement Verification - Where deemed essential the design movements shall be verified by actual test.

3.1.5.2 Qualification Test - Qualification testing may be performed by the duct manufacturer or vehicle manufacturer. A certified copy of the test results shall be required. The following tests shall be performed on one production unit.

a. Examination of product
b. Proof pressure
c. Leakage
d. Vibration
e. Life cycle
f. Pressure impulse
g. Pressure drop
h. Flow fatigue
i. Burst pressure

3.1.5.2.1 Examination of Product (See 3.1.5.1.2 and 3.1.5.1.3.)

3.1.5.2.2 Proof Pressure and Leak Test - The duct shall be installed in a fixture simulating actual service installation and pressurized with the operating fluid, or a safe substitute, to proof pressure for a period of five minutes. Following this, the room temperature proof test of paragraph 3.1.5.1.1 shall be repeated. There shall be no evidence of leakage or permanent deformation as a result of these tests.

3.1.5.2.3 Vibration Test - The duct shall be installed in a fixture capable of reproducing the actual service dynamic environment (as closely as practical), and subjected to a resonance scan in each of three mutually perpendicular axes over the expected frequency range at the required displacement and/or accelerations. Both the fixture and the test specimen shall be monitored throughout the test by both instrumentation and visual observation with a strobe light.

Upon completion of the search for resonance, the duct shall be subjected to a vibration dwell for a period of five minutes at the one most severe resonant frequency noted for each axis (total dwell time, 15 minutes).

The duct shall be filled with the operating fluid, or a safe substitute, and pressurized to design pressure during vibration.

There shall be no evidence of leakage or damage as a result of this test.

3.1.5.2.4 Life Cycle Test - The life cycle test should be based on a statistical distribution of all anticipated movements throughout the unit's life and not on its maximum movement alone.

A cycle shall be a full excursion from a starting position to the extremes and back to the starting position. The designer must include the cycles encountered during vehicle manufacture and checkout, if these cycles form a measurable part of the limited life.

The unit shall be installed in a fixture capable of imparting the line deflections anticipated in actual service. The unit shall be pressurized to design pressure, using the operating fluid or a safe reasonable substitute, as a medium and operational deflection applied for the expected endurance life of the unit. Installation movements should be considered separately in the test program.

During this test, load cells or similar equipment may be placed between the specimen and fixture to determine spring rates, flange loading, etc. The unit shall be examined frequently during the testing for evidence of leakage or damage.

At the completion of testing, the proof test of paragraph 3.1.5.2.2 shall be repeated.

3.1.5.2.5 Pressure Impulse Test - The duct shall be installed in its maximum deflected position in a fixture simulating actual service installation. The duct shall be filled with an incompressible fluid and subjected to pressure impulses. The magnitude, duration, and number of surges will be the maximum anticipated in service. The surge will be monitored by pressure transducers on or immediately adjacent to the part and recorded on direct readout equipment Extreme caution must be exercised in the set-up to prevent over-pressurization of the specimen. A quick acting pressure relief valve set 5% above maximum pressure will be installed in the system.

Following this test the duct shall be examined and proof-tested at room temperature to check for leakage and/or damage.

3.1.5.2.6 Pressure Drop and Flow Test - When pressure drop is important the duct shall be subjected to the range of flow rates expected in service. Pressure drop shall be measured at a sufficient number of flows to establish a curve over the entire range. This test may be performed using water as a medium at conditions other than those of service with final results converted to service conditions. If pressure drop is critical, consideration shall be given to performing the flow test at both nominal and maximum deflected positions. If flow velocities are critical, a flow scan may be performed to search for any resonances in the duct.

3.1.5.2.7 Environmental Test - Salt spray, fungus, sand and other tests that may simulate the duct environment may be specified as deemed necessary by materials and design.

3.1.5.2.8 Burst Pressure Test - With the unit installed in a fixture simulating service installation and using LN_2 as a pressurizing medium, increase internal pressure to design burst pressure and hold for a period of two minutes. There shall be no rupture but deformation is permissible. At this point, the pressure shall be increased to rupture, or complete failure. The unit shall be returned to room temperature and pressure for examination. Entrapped air, or gas generated from the fluid, present a serious explosion hazard if failure occurs during test. Every effort should be made to maintain a liquid fill.

3.1.5.2.9 Cycle to Failure - When a cycle-to-failure test is desired, an additional duct will be required to go through vibration, impulse and life cycle to failure.

3.1.5.2.10 Sectioning and Examination - The test article may be sectioned or otherwise made ready for an examination to disclose types of wear, interferences, failure modes, quality defects, etc. The duct shall then be disposed of in accordance with customer requirements.

3.1.5.3 Sampling Test - As a check on subsequent manufacturing and processing, consideration should be given to specifying sampling tests. Normally a randomly selected duct from each production run shall be subjected to the following tests:

a. Examination of product
b. Proof pressure test
c. Vibration test
d. Life cycle test
e. Pressure impulse test
f. Burst test

Failure of the sample duct to comply with all test requirements will require detail analysis and may be cause for rejection of the entire lot.

3.1.5.4 Cross Reference for Test Procedures as Applied to Duct Assemblies

Test	Qualification Test	Sample Test	Production or Acceptance Test	Test Description
Examination	Yes	Yes	Yes	Para. 3.1.5.1.2
Leakage	Yes	Yes	Yes	Para. 3.1.5.1.1
Proof Pressure	Yes	Yes	Yes	Para. 3.1.5.2.2 and 3.1.5.1.1
Life Cycle	Yes	Yes	No	Para. 3.1.5.2.4
Vibration	Yes	Yes	No	Para. 3.1.5.2.3
Pressure Impulse	Yes	If critical	No	Para. 3.1.5.2.5
Pressure Drop	If critical	If critical	No	Para. 3.1.5.2.6
Flow Fatigue	If critical	If critical	No	Para. 3.1.5.2.6
Movement Verification	Yes	If critical	If critical	Para. 3.1.5.1.3
Burst Pressure	Yes	If critical	No	Para. 3.1.5.2.8
Cycle to Failure		No	No	Para. 3.1.5.2.9
Sectioning and Examination	Yes	If critical	No	Para. 3.1.5.2.10 May be desirable if minimum gage or thinning is critical

REFERENCE

1. Roark, R. J. Formulas for Stress and Strain, Third Edition, 1954. McGraw-Hill Book Co.

3.2 INSULATION

3.2.1 Design Considerations of the System

3.2.1.1 Fluids to be Contained - The discussions to follow will be concerned primarily with liquid oxygen and liquid hydrogen ducting insulation systems. These are the most common cryogenic fluids used in space applications and the problems of insulating these are similar to the other cryogenic fluids. Of prime consideration in designing an insulation system for oxygen (as with fluorine) is the oxidizing property of the contained fluid. Many materials which will not burn in air, for example, flame retardant foam insulations, will burn violently when ignited in an oxygen-rich atmosphere. Insulation of hydrogen systems, on the other hand, must consider the lower temperature boiling point of the cryogen, the effect of cryopumping within the insulation and the serious pressure drop associated with two-phase flow. These effects will be discussed in relation to specific types of insulation systems in the paragraphs to follow.

3. 2. 1. 2 Safety (See also 2.5) - The discussion in this section is devoted to safety as regards the insulation system only. Many of the subjects mentioned here have been discussed under paragraph 2.5, but are repeated here for emphasis. The general safety considerations applicable to all cryogenic systems as well as those specifically involving the fluid in question must always be borne in mind by the designer. Review of references 1 and 2 is appropriate for these considerations.

Any cryogenic fluid, unless it is subcooled below the saturation temperature corresponding to its pressure, will be subjected to boiling by heat in-leakage from the surroundings. Thus, if the liquid is contained in a closed system, a pressure rise with time is inevitable. The quality of the applied insulation system can only affect the time rate at which this pressure rise occurs; it cannot prevent it. Therefore, a relief device or a bursting disk, must be installed in any portion of a duct system which can be closed off.

When the duct is to contain an oxidizer, the materials used must therefore be compatible with the oxidizing fluid. A similar problem arises when the fluid contained is at a temperature below that of air liquefaction. If the insulation system is not sufficiently well sealed to prevent air permeation, the air will condense on the cold surfaces and within the colder portions of the insulation material. Then as this air is allowed to warm and reboil, any fibrous insulation system will serve as a rectification column causing saturation of the system with liquid oxygen. A number of severe fires have been caused by this action when the insulation materials were not compatible with oxygen.

Cryopumping creates a vacuum within the cells of the insulation material. If the material is not strong enough to withstand the 1 atmosphere bearing pressure, the cell walls will collapse and the insulation will be destroyed.

Any vacuum insulation system is subject to leakage of atmospheric air or the fluid contained in the duct. To preclude a dangerous situation in either event, a vacuum bursting disk or other safety device must be used when vacuum insulations are employed.

3. 2. 1. 3 Vacuum Technology - Many of the higher quality insulation systems depend for their performance on a very low interstitial pressure in the submicron range.

Utilization of vacuum insulation requires careful design and precise fabrication techniques. If the vacuum space has the structural duct walls as one of its boundaries, this wall must be tight enough at cryogenic temperatures to prevent leakage of evaporated gas into the insulation space. The other boundary of the insulation space is usually exposed to ambient temperature. This wall must be leak-tight under whatever environmental conditions to which it will be subjected. Means must be provided to maintain the vacuum integrity in spite of the differential contraction between the cold and warm boundaries.

Helium mass spectrometer leak detection techniques must be used during fabrication. The allowable leakage rate depends upon the degree of vacuum required for optimum insulation performance and the volume of the insulation space. However, leakage figures of 10^{-6} to 10^{-7} ccs of atmospheric helium per second are common and are attainable with commonly used materials and commonly used welding techniques. It should be pointed out, however, that mechanical joints such as screwed fittings or flanges are not desirable within the vacuum enclosure unless some provision is made to weld the joints so that they are leak tight.

3. 2. 1. 4 Cleanliness - Any material which has been exposed to air will have a layer of gas and vapor several molecules thick on its surface, and, in addition, the interior of metals contains dissolved or occluded gas which is trapped during solidification and an oxide layer which may be scaly or porous thus presenting trapped areas for gas. Adsorption on freshly exposed surfaces is very rapid and the adsorbed gas tends to reach an equilibrium pressure with the surrounding atmosphere. Removal of the adsorbed gases is both a time and temperature function. Since the gases tend to reach an equilibrium with the environmental pressure, evacuation for a long period of time will desorb the gases. Application of heat during evacuation will speed the process.

3. 2. 1. 5 Adsorption and Gettering - Complete elimination of adsorbed gases is very time consuming and expensive. In order to attain high vacuum for long periods of time, therefore, it is necessary to make use of adsorbents and getters in the vacuum system. An adsorbent such as metallic zeolites activated charcoal (not compatible with liquid oxygen) or silica gel are used to adsorb gasses near liquification at the temperature of the contained cryogen. For this reason the adsorbent package should be located in a low temperature area.

Hydrogen is often an important constituent of the adsorbed gases. Because of its low boiling point, it is less easily picked up by adsorbents and, therefore, even a very small quantity of hydrogen will preclude good vacuum performance. Getter materials are used to remove this hydrogen. The basic difference between a getter and an adsorbent is that a getter cleans up gases by chemical reaction whereas surface adhesion is the technique employed by adsorbents. Getters usually will produce very low pressure levels indepentent of temperature but the chemical-reaction rate is speeded up by elevated temperatures. It is, therefore, common to locate the getters in the warmest portion of the insulation system. Common getter materials include active metals, active zeolites and weak oxides.

3. 2. 2 Types of Insulation Systems - Cryogenic insulations can be divided into foams, straight vacuum, vacuum powders and vacuum Super Insulations. Uninsulated ducts are also employed in certain instances. These will be discussed in the separate sections which follow.

3. 2. 2. 1 Uninsulated - Uninsulated pipe lines may be used in temporary or experimental systems involving con-

tinuously high flow rates, or in systems where the usage is infrequent or of short duration. A duct which is warm during ground hold might well be left bare since in space it will have the benefit of the ambient vacuum. Heat is transferred from the ambient air to the outside surface of the pipe line through a film consisting of liquid and solid air, and from the inner surface of the transfer line to the cryogenic liquid by convection and boiling. Frost may form, providing some insulation. An idea of the heat flux into a bare duct may be obtained from review of Table I.

Table I

Heat Transfer to Uninsulated Ducts (References 3 and 4)

	Heat Flux Btu/hr-ft^2	Remarks
Uninsulated Liquid Hydrogen	3490	Still, ambient air
	6020	15 mph wind
Uninsulated Liquid Oxygen	575	No frost
	325	1/10 in. frost
	900	Bare pipe, 8 mph wind
Uninsulated Liquid Nitrogen	Use LO2 figures above provided no air condenses	

3.2.2.2 Straight Vacuum - High vacuum insulation consists of an evacuated space between two highly reflecting surfaces. Heat is transferred principally by radiation, but there may be some contribution due to gas conduction. The amount of heat transfer by radiation can be calculated from equation 3 of paragraph 2.3.1. The emissivity is dependent on many factors such as the material, any applied coating, surface condition, etc. The magnitude of the gas conduction can be established from the Knudsen equation (Equation 7 of paragraph 2.3.1). A cold state pressure rise above 1×10^{-5} mm Hg abs for high vacuum will increase the heat leak, but cryopumping effects of the cryogenic fluid can effect practical economies in the design.

Supports are required to maintain the outer shell of a vacuum line and to attach the ducting to the structure itself in all cases. The longest possible heat path with minimum contact area is desirable. Stainless steel is often used when both structural strength and comparatively low thermal conductivity are desired; several nonmetallic materials are applicable when the lower strength is acceptable in favor of improved thermal performance such as Teflon or Kel-F (see paragraph 2.6.3).

A range of performance for straight vacuum as an insulation is depicted on Figure 1 for comparison with the other cryogenic insulations. Obviously, no allowance can be included for density because the only weight is that of the vacuum enclosure which is entirely configuration dependent. Thickness and temperature difference to establish a thermal conductivity value have been arbitrarily chosen from representative cases. The range of values shown reflects the effect of degree of vacuum and surface emissivity of the system.

3.2.2.3 Foam Insulations

3.2.2.3.1 Types of Foams - It is important to note that organic foam materials are a fuel and will present an explosive hazard if they come in contact with oxygen or fluorine. There are a number of cellular foams available which have somewhat different properties. The overall conductivity is dependent upon the type of foam, e.g. foamed fiber glass, polystyrene, polyurethane, etc., as well as density, cell size, blowing agent and percentage of closed cells.

Foam insulation exists in two forms: open cell and closed cell. The latter type is exclusively used in cryogenic service to prevent vapor passage and to take advantage of cryopumping. When the insulation cools to cryogenic temperatures, gas which fills the closed cell decreases in volume, causing a partial vacuum inside the foam, thus decreasing the effective conductivity of the foam.

As an insulating foam ages, the above effect is decreased due to a slow diffusion of the surrounding atmosphere into the closed cells. When this happens, the insulation loses its usefulness and must be replaced. This generally happens in a period of one year and can be detected by the initiation of two phase flow or forming of condensate or frost on the outer ducts under conditions which previously did not cause either of these effects. To decrease the rate of this diffusion, a vapor barrier consisting of a tough, flexible material (usually a plastic) which is impermeable to air is often employed.

3.2.2.3.2 Properties of Foams - Most types of foam are available in densities which range from 1 to 15 lb/cu ft. The density, which is a direct function of foam cell size, affects both conductivity and compressive strength. Smaller cell size (greater density), results in higher compressive strength but also higher thermal conductivity. Conversely, lesser density means lower thermal conductivity but decreased loading capabilities. The optimum value of density for low thermal conductivity is 2 to 3.5 lb/cu ft. Any foam of lighter density will have a higher heat leak due to an increase in radiation. If the insulation must meet a loading requirement, higher density foams can be considered but it must be remembered that this is done at the expense of additional heat leak due to increased solid conduction.

Since the thermal expansion coefficient of an expanded foam is from 2 to 10 times that of most structural materials, application to a metal surface subject to rapid cooldown may crack the foam. Thus the foam insulation is applied in overlapping segments or slabs with expansion joints between segment ends filled with flexible insulating material. For smaller surface area applications such as around valves or fittings, solid foam, which is rigidly foamed in place, can be used without danger of cracking.

Table II lists the important properties for a number of representative foam insulations available currently. It should be emphasized that the insulation performance depends upon the materials used, the blowing agent, the density, and manufacture.

Table II

Properties of Representative Foam Insulations

Foam	Density lb/ft^3	Internal Pressure - Torr	Boundary Temperature, R	Thermal Conductivity Btu/hr-ft-R
Polyurethane	5.0-8.5	760	540-137	0.019
	5.0-8.5	1×10^{-3}	540-137	0.007
	2.0-5.0	760	540-137	0.014
	0.87	760 (hydrogen)	141-36	0.025
	0.87	760 (hydrogen)	365-142	0.07
	0.87	5×10^{-3}	365-142	0.0025
	0.87	5×10^{-3}	141-36	0.002
Polystyrene	2.9	760	540-139	0.015
	3.7	760	540-139	0.019
	2.9	10^{-5}	139-36	0.0047
	1.2	760	380-140	0.0135
Epoxy Resin	5	760	540-139	0.019
	5	10^{-2}	540-139	0.0097
	5	4×10^{-3}	540-139	0.0075
	5-8.75	760	540-139	0.019
	5-8.75	10^{-3}	540-139	0.007
	2	760	540-139	0.0166
	(Freon Blown)	10^{-3}	540-37	0.062
	(CO_2 Blown)	10^{-3}	540-37	0.004
	(CO_2 Blown)	10^{-3}	540-37	0.006
Foamglas	9.0	760	540-37	0.02
		$< 10^{-3}$	511-139	0.017
Rubber	5.0	760	540-139	0.021
Silica	10.0	760	540-139	0.032
Teflon	-	760	-	0.05

Notes

1. Coefficient of thermal expansion for most foams is approximately 4×10^{-5} in./in.-R.
2. Specific heat of foam (polystyrene:density 2.9 lbs/ft^3, 500 R) = 0.27 Btu/lb-R.
3. An approximate value for compressive strength = 25 ρ (psi) where ρ = density in lb/ft^3.
4. References 5, 6, 7, 8, 9, 10.

3.2.2.3.3 Application Methods - Insulation of flanges, valves and other fittings should consist of prefabricated or premolded covers of foam applied to the same thickness as specified for the adjacent duct insulation. If prefabricated fitting covers are not available, regular duct insulation may be formed to fit bends, tees, etc., closely enough not to reduce the efficiency of the insulation due to an excessive number of joints.

An increasingly popular method for insulating odd shaped duct arrangements is foamed-in-place insulation. This method involves construction of a mold around the equipment to be insulated. Foam materials and foaming agent are then mixed and poured into the mold. Inside the mold, the foam expands into shape and dries. Curing time is up to two hours, depending on curing temperature. A newer method involves spraying the foam mixture onto the component to be insulated with a spray gun. The foam then expands in place without use of a mold.

3.2.2.4 Vacuum Powders - As review of Table III and Figure 1 shows, vacuum powder insulation systems are an order of magnitude better on the basis of thermal conductivity times density than foam insulations. Representative materials which fall into this category include perlite, vermiculite, Microcel and Santocel.

In order to reduce the heat transport by radiation, small metallic flakes can be mixed with the vacuum powder. One proprietary compound has been developed which is composed of very fine copper flakes and a powder mixed together.

It should be pointed out that these powders are not load-bearing and, therefore, a rigid vacuum casing must be installed to enclose the powders. No provision is included in the density figures given below to account for this vacuum casing. Another disadvantage of powder insulations is their tendency to settle which deteriorates their performance.

Table III

Physical Properties of Representative Vacuum Insulations (Reference 11)

Designation	Thermal Conductivity Btu/hr-ft R Warm Side at 530 R Cold Side at 36 R	Density Lbs/Cu Ft	Approximate Layers/Inch
Vacuum Perlite	72×10^{-5}	6.0	Powder
Fiber Glass (Helium at Atmospheric Pressure)	5800×10^{-5}	0.5	
Fiber Glass (Vacuum)	32×10^{-5}	2.5	
CS-5	18×10^{-5}	8.0	Powder
Super Insulations*	6.5×10^{-5}	2.0	15 - 30
	9.0×10^{-5}	2.5	10 - 20
	2.0×10^{-5}	4.7	35 - 70
	1.8×10^{-5}	5.5	50 - 100
	1.0×10^{-5}	7.5	75 - 150
NRC-2**	2.0×10^{-5}	3.2	100 - 150

* Super Insulations and CS-5 refer to proprietary insulation systems developed by Union Carbide Corporation, Linde Division.

** NRC-2 is a proprietary insulation system developed by National Research Corp.

3.2.2.5 Super Insulation Systems - The concept of super insulation systems may be defined as a means to provide a large number of radiation shields in a small space and maintaining them under conditions of low interstitial pressure. Two types of super insulation have been developed to date. One is the concept of alternate layers of radiation shields separated by fibrous spacers. These radiation shields may take the form of aluminum or other reflecting foil material (or aluminimized polyester film). The fibrous spacer material is most often some form of unbonded fiberglass, although, again, a wide variety of materials is available and has been used in practice. Different performance values can be obtained by varying spacer and shield materials as is evident in Table III. It should be noted that a degradation up to 30% is not uncommon when the insulation systems are applied to small ducts or complicated shapes.

Another type of laminar insulation is formed of a number of layers of metalized plastic such as aluminized [illegible] is crinkled so that the layers touch only at numerous points. These points prevent the existence of large areas of planer contact between layers and hold the layers spaced apart to permit each layer to reach its own separate equilibrium temperature. This type has a thermal conductivity of about 2×10^{-5} Btu/hr-ft F and a density of about 3.2 lb/cu ft., at an optimum practical layer density. These values, too, are taken from calorimeter tests.

Discussions of super insulation for applications such as this should include consideration of insulation systems which are purged with a non-condensible gas such as helium. The concept here is to install the insulation system without an external rigid vacuum casing and maintain a purge of non-condensing gas in the interstitial space. During ground hold prior to launch of the vehicle while this gas pressure is maintained at slightly above one atmosphere, assuming helium is used as the purge gas, the thermal conductivity of the insulation will be 5800×10^{-5} Btu/hr-ft F. When the vehicle reaches the vacuum of space, ultimately the performance figures given above can be achieved.

Another concept which has been under evaluation includes encapsulating the insulation material within a flexible jacket and evacuating the interstitial space. During the ground hold this flexible jacket is compressed under the one atmosphere external pressure causing compression of the insulation by an approximate factor of four and increasing the solid conduction component of heat transfer. This concept is described more fully in references 11 and 12. A curve showing the effects of compression on the thermal performance of super insulation is shown in Figure 3. Here, as the spacecraft leaves the earth's atmosphere, the insulation recovers nearly its original thickness and thermal performance.

3.2.2.6 Tests and Maintenance - The most important overall test of an insulation system is its performance as measured by total heat in-leakage to the line. This is most often performed by conducting a normal evaporation rate test. Extreme caution must be exercised in setting up a normal evaporation rate test for a well insulated ducting system since heat in-leakage to the ends can very easily mask the true insulation performance. For example, if a duct is simply flanged at the ends, and filled with a liquid cryogen, the heat in-leakage at the ends will far surpass any heat entering the fluid through the insulation along the duct. Careful design, therefore, of end closures is essential in tooling for a normal evaporation rate test. Preferably, the end closures should be located above the liquid level during testing.

In order to conduct a good test, the duct system to be tested is installed in a test setup and suitable enclosures installed. The line is then filled with liquid cryogen and the effluent vapor piped through a bubbler chamber and a wet drum meter to measure flow quantities. If high flow rates are anticipated, an orifice type meter might be preferred. Visual inspection of the insulation while cold will reveal any cracking due to differential contraction (particularly with foams) or the formation of frost spots which will occur in faulty locations in any insulation material or system.

For vacuum insulations, the vacuum integrity is best determined by use of the thermocouple gauge and observation of its performance as the line cools and any cryopumping takes place. One would expect the pressure to drop as the inner line is cooled. Conversely, if the pressure in fact rises at this time, one would suspect a leak in the internal line such that noncondensing gas is permitted into the insulation space. Again, formation of frost or cold spots on the insulation is indicative of poor vacuum or other malfunction.

Frequent inspection of all lines prior to actual flight use is desirable to ensure that foams have not deteriorated or vacuum insulations lost their vacuum. Normally, vacuum insulated lines are sealed during manufacture and re-evacuation in the field is not necessary. However, re-evacuation can be performed if it is deemed desirable.

REFERENCES

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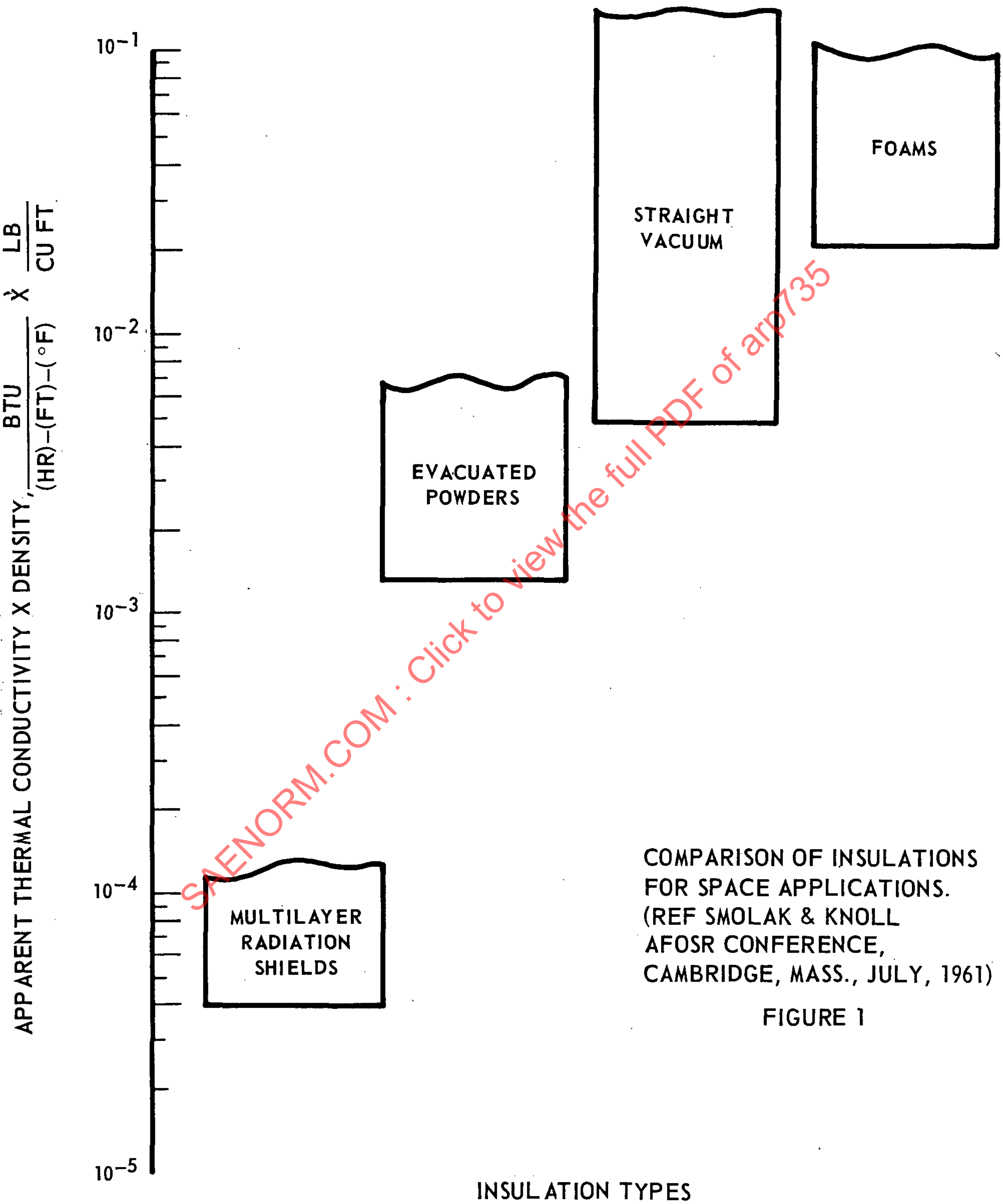
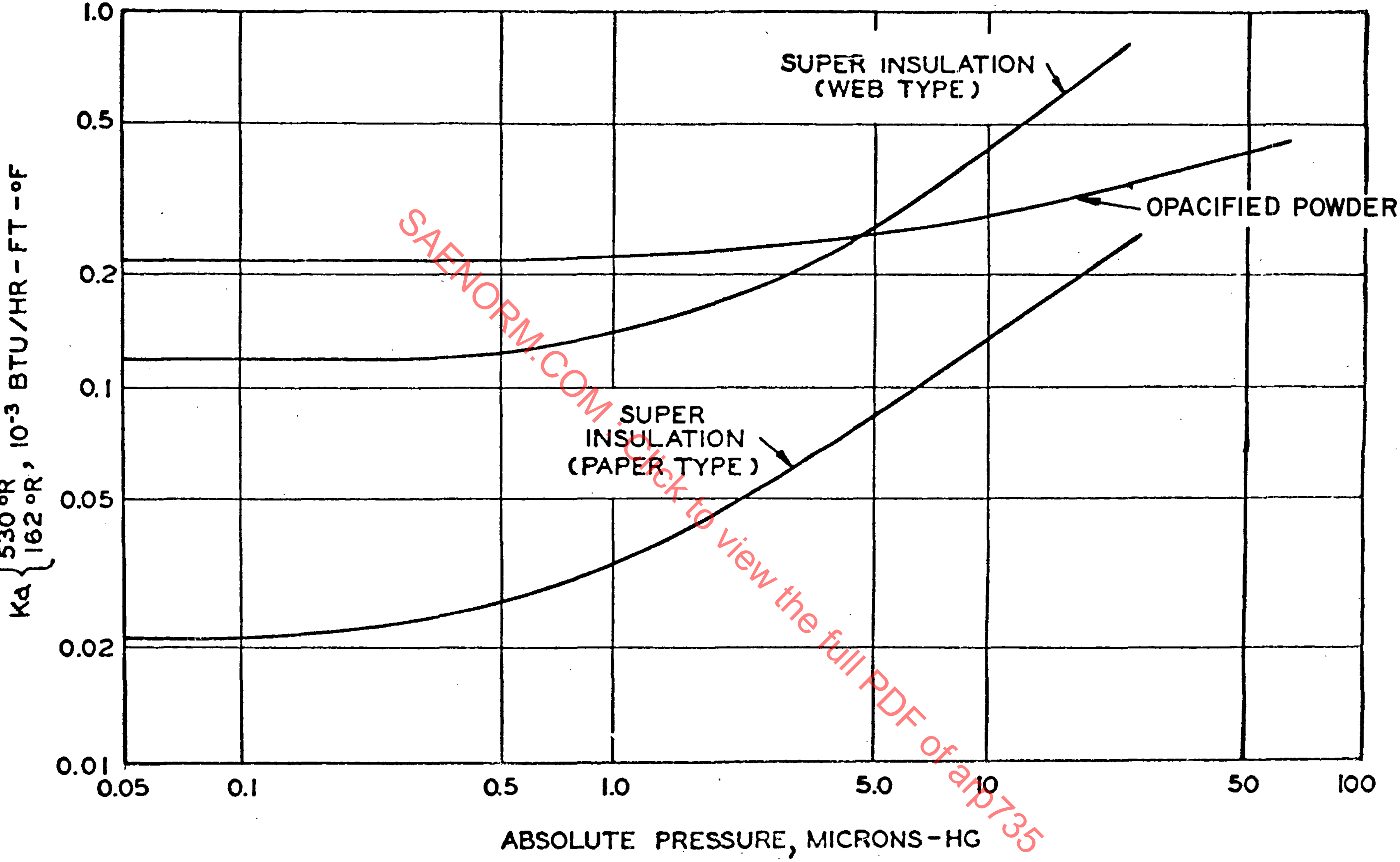
12. Perkins, P. J., N. A. Colaluca, and L. S. Smith. "Preliminary Test Results on a Compressed Multilayer Insulation System for a Liquid Hydrogen Fueled Rocket," Vol. 9, Advances in Cryogenic Engineering, Plenum Press, 1963.

Section 3.2: "Additional References - refer to Bibliography publications 19, 24, 32, 41, 43, 61, 62, 65, 72, 74, 106, and 112."



COMPARISON OF INSULATIONS FOR SPACE APPLICATIONS. (REF SMOLAK & KNOLL AFOSR CONFERENCE, CAMBRIDGE, MASS., JULY, 1961)

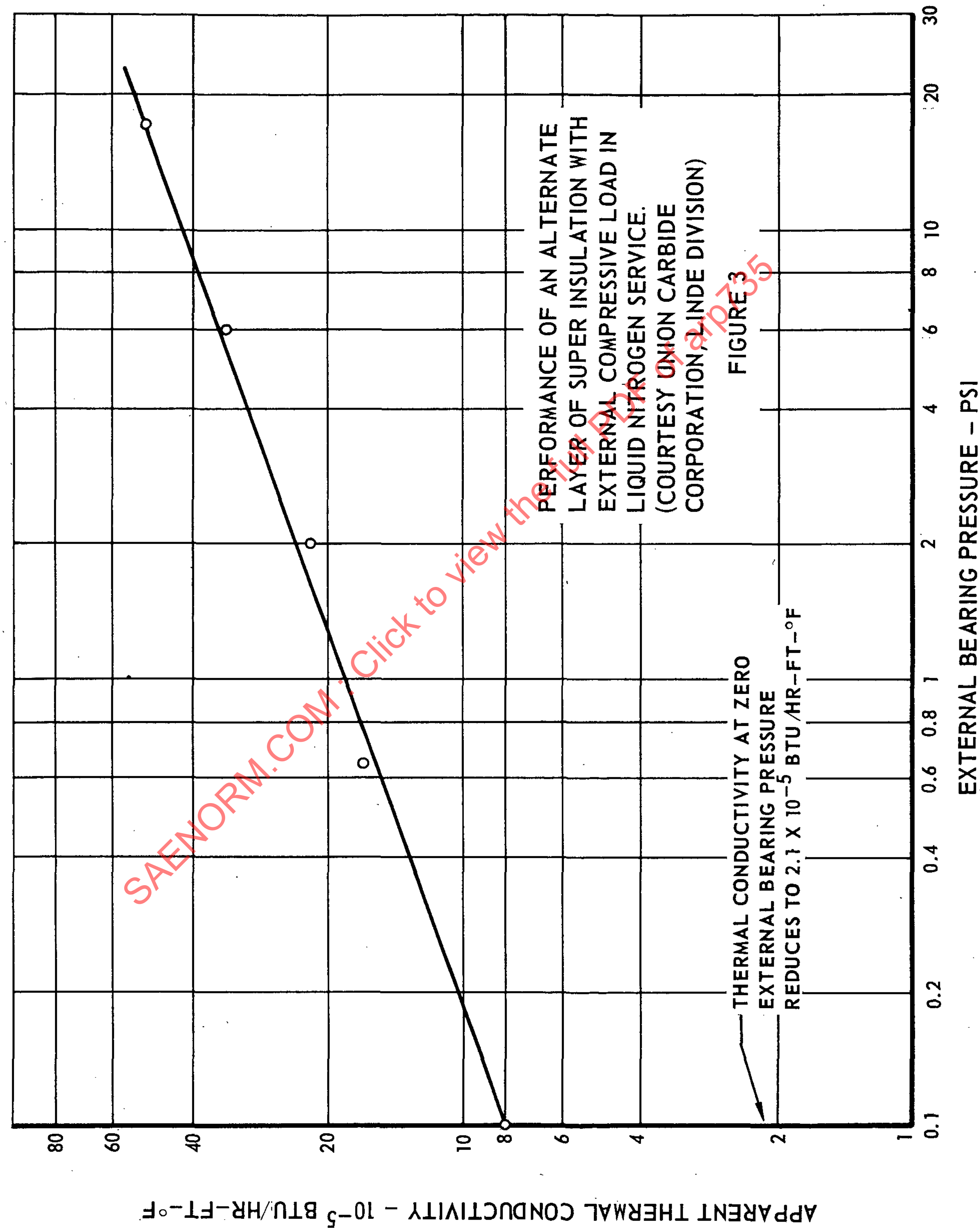
FIGURE 1



APPARENT THERMAL CONDUCTIVITY AS A FUNCTION OF VACUUM PRESSURE

Reference, Riede, P. M. and Wang D. I. - J. "Characteristics and Applications of some Super Insulations", Volume 5, Advances in Cryogenic Engineering, Plenum Press, 1959.

FIGURE 2



PERFORMANCE OF AN ALTERNATE LAYER OF SUPER INSULATION WITH EXTERNAL COMPRESSIVE LOAD IN LIQUID NITROGEN SERVICE. (COURTESY UNION CARBIDE CORPORATION, LINDE DIVISION)

FIGURE 3

3.3 COUPLINGS FOR CRYOGENIC DUCTING - The purpose of this section is to outline a recommended practice governing the design and test of couplings for cryogenic ducting. Generally, couplings for cryogenic ducting have requirements similar to couplings for pneumatic ducting as outlined in ARP 699, except that the allowable leakage rates are usually orders of magnitude lower, and except for the effects of cryogenic temperatures and material compatibility.

3.3.1 Design Requirements for Couplings - A duct coupling is herein considered to be a joint assembly of flanges, seals, clamps, bolts, and/or related devices comprising a fitting that serves to connect and disconnect the mating ends of adjacent ducts or components in a cryogenic system. Brazed or welded joints are not considered herein.

The following performance requirements should be considered:

3.3.1.1 Structural Loads - The coupling shall be capable of safely carrying the maximum possible combination of loads simultaneously applied, plus the fatigue cycles caused by the following factors, while maintaining system integrity.

a. Rigging load required to seal.

b. Mechanical duct system loads (maximum axial tension and axial compression, bending, and torsion loads) required to compensate for duct installation misalignment motion, vehicle deflections, etc.

c. Fluid pressure loads, positive and negative operating pressure, surge pressure, ambient pressure, fluid direction changes, etc.

d. System vibration.

e. Thermal loads covering the total temperature range (including transients).

Flanges and retaining members are usually analyzed separately for ability to withstand the applied loads. See MIL-C-27536 (reference 1) and ASME Boiler Code Section VIII (reference 2) for example. An improved analysis method which accounts for deflection is shown in reference 3. Special care should be taken to consider possible "hidden" loads, such as bending or axial loads due to thermal growth or misalignment and transient temperature effects. Special attention should be given to the selection of materials which are considered naturally resistant to stress corrosion.

3.3.1.2 Allowable Leakage - All couplings will exhibit some small elastic deflections in response to the applied loads of 3.3.1.1. Couplings must therefore not exceed maximum allowable leakage during and after such deflections. Considering the hazard of even slight leakage in most cryogenic systems, it is recommended that the best current state-of-the-art sealing be specified and tested with and without applied loading on sample couplings.

3.3.1.3 Safety Devices - The extreme danger that can result from a coupling failure in a cryogenic system makes it advisable to give consideration to redundant-load-path couplings. Examples are parallel bolts, safety straps and tangs, etc; also, double- or redundant-seal joint designs where the primary seal leakage can be monitored, or bled off, are worthy of note (see Figure 6).

3.3.1.4 Heat Leak - Heat transfer through couplings may be a problem in many cryogenic systems, particularly those using vacuum-jacketed ducting. Long-heat-path joint can be employed to solve this problem (see Figure 4).

3.3.1.5 Quick Disconnect - The ease of fastening feature of a duct coupling should be determined by a trade-off with weight, reliability, and the relative economy of its use in the duct system where definite advantages are gained by the use of a "quick disconnect" over the normal coupling; as an example, where the duct connects to a piece of equipment requiring frequent removal for inspection, filter replacement, or rapid attrition, etc. The time thus saved in removal and reinstallation of the equipment may justify the use of the "quick disconnect" coupler. "Quick disconnect" features will generally add some weight to the coupling.

3.3.1.6 Installation and Handling Requirement - The following requirements pertaining to the installation and handling of duct couplings should be given careful consideration:

a. Dimensional and damage inspection before and after attachment. This may include compatibility of the duct outside diameter with the inside diameter of the flange, angular relation of flange face to the duct axis, out-of-roundness, flatness and surface condition of the flange face, with special attention given to sealing surfaces. Look for tool marks, scratches, nicks, scaling, etc.

b. Handling precautions to prevent damage and contamination. (The manufacturer usually supplies protective media and instructions.)

c. Installation techniques.

d. Requirements for repeated assembly and disassembly, including seal replacement.

3.3.2 Qualification Tests - Suitable qualification testing, sampling testing, and acceptance testing should be specified for cryogenic duct system couplings and should be supplemented with testing of all or a portion of the duct system.

A suggested minimum test outline with typical procedures is outlined in Table I.

3.3.3 Duct Coupling Methods - This section illustrates a series of the more common duct coupling types and methods in current use. Specific information regarding the intended use, the leakage allowed, the temperature range, the pressure range, and the bending load or deflection requirements should be furnished to the coupling manufacturer. Torque wrenches are usually employed.

3.3.3.1 Clamping and Joining Methods - Figures 1 through 4 illustrate clamping and joining methods.

3.3.3.2 Joint Sealing Methods - Figures 5 through 14 illustrate the more common types of seals in current use. See also references 4 and 5 for additional types and limitations.

REFERENCES

1. "Coupling, Clamp, Grooved, V-Band," Military Specification MIL-C-27536, 15 October 1963.

2. "A.S.M.E. Boiler & Pressure Vessel Code," Section VIII, Unfired Pressure Vessels, 1962 Edition.

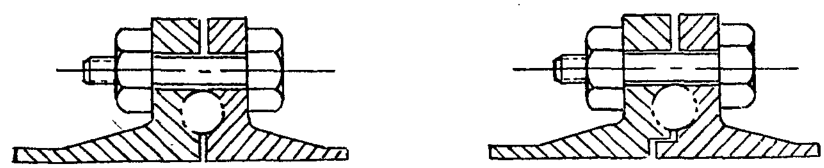
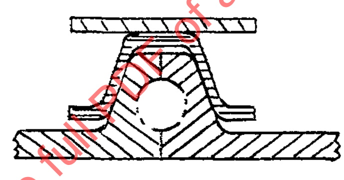
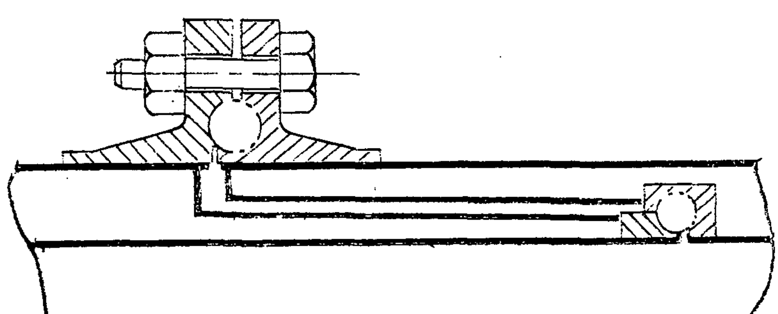
3. "Development of Mechanical Fittings," Air Force Flight Test Center Technical Documentary Report No. RTD-TDR-63-1115. Qualified requestors may obtain copies of this report from DDC.

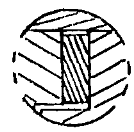
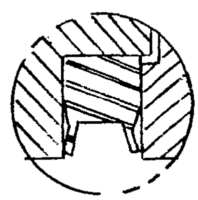
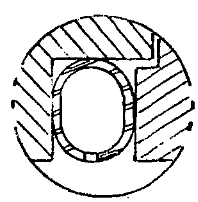
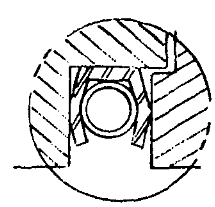
Table I

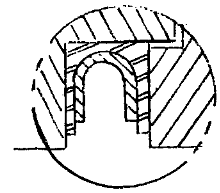
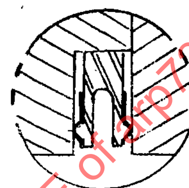
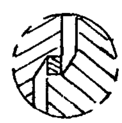
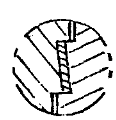
	Qualification Test	Sample Test	Acceptance Test	Test Description
Examination of Product	Yes	Yes	Yes	Examine coupling material, workmanship, dimensions, finish, identification marking, etc., to insure conformity to drawing and specification.
Assembly and Torque Deformation	Yes	Yes	No	Assemble coupling. Check for any interference, binding, misalignment, or other installation difficulty. Tighten to maximum torque and check for any galling or excessive deformation. Repeat assembly cycles per detail specification.
Proof Load and Leakage	Yes	Yes	No	Assemble coupling in test cell at recommended torque. Apply proof pressure at operating temperature and check for leakage or excessive deformation. Repeat with system bending load or other loads added. Leakage sensitivity to be 1 x 10^{-9} scc/sec helium or as stated in detail specification.
Leakage Test of Redundant Feature (if applicable)	Yes	Yes	No	Leakage test at operating conditions alternately with primary and secondary seal or latch element inoperative.
High-Temperature Test	Yes (If required)	No	No	Subject coupling to high-temperature test per paragraph 4.1.2 of MIL-E-5272 except use maximum operating or environmental temperature. Repeat proof load and leakage. Some specifications now require over temperature tests up to 50%
Low-Temperature Test	Yes	No	No	Subject coupling to low-temperature test per paragraph 4.2.2 of MIL-E-5272 except use minimum operating or environmental temperature or per detail specification. Repeat proof load and leakage.
Temperature Shock Test	Yes	No	No	Subject coupling to temperature shock test per paragraph 4.3.1 of MIL-E-5272 except initial and final temperature to be minimum and maximum operating temperature, respectively, or with measured thermal gradient per detail specification. Repeat cycle per detail specification (100 cycles suggested). Repeat proof load and leakage.

Table I (Cont'd)

	Qualification Test	Sample Test	Acceptance Test	Test Description
Corrosion-Resistance Test	Yes	Can if critical	No	Subject the coupling to Salt Spray Test per Procedure I of MIL-E-5272 or Strauss Test per Federal Test Method 151, Method 821.1, or suitable Stress-corrosion Test per detail specification. Repeat proof load and leakage.
Vibration	Yes	Can if critical	No	Assemble coupling in test cell at maximum torque. Perform Vibration Test per Procedure XII of MIL-E-5272 or per detail specification. Fixture and/or response acceleration to dynamically simulate application. Half of test at operating pressure and temperature. Half at room temperature without pressure unless otherwise specified in detail specification. Repeat proof load and leakage.
Endurance Test	Yes	Can if critical	No	Assemble coupling in test cell and apply ± cyclic bending loads for 100,000 cycles at 60-120 cpm or per detail specification. Simultaneously apply pressure cycles from 10-100% of operating pressure not in phase with bending cycles. Test at specified temperature.
Ultimate Load and/or Burst Pressure Test	Yes	Yes	No	Assemble coupling and apply 150% rated torque. Subject coupling to 150% of proof load and pressure at operating temperature for five minutes. Leakage is allowed, but separation or fracture shall constitute failure.

Description	Remarks	
Bolted Coupling	Conventional method. Generally heavy but light weight possible with special designs.	 Figure 1
V-band or clamp-type coupling	Often used in limited access areas or where frequent disassembly is required.	 Figure 2
Threaded or Union-type Coupling	Most common for small diameters	 Figure 3
Vacuum-jacketed "Bayonet" Coupling	Special design for low heat "leak"	 Figure 4

Description	Remarks	
Conventional Gaskets	Generally low resilience requiring high load. Sensitive to temp gradients, flange distortion & deflection.	 Figure 5
Redundant Seal	Combination primary and "O" ring secondary seal with leakage-monitoring port; used where high reliability is required.	 Figure 6
"K" shaped seal	Somewhat pressure actuated. Various platings available. Low tolerance to flange out-of-flat warpage and scratches.	 Figure 7
Metal "O" Ring	Holes added for some pressure actuation. Various platings available. Low allowable flange distortion & deflection. Scratch sensitive.	 Figure 8
Teflon seal with internal spiral wound spring	Pressure actuated. Good allowable flange distortion & deflection. Somewhat re-usable. Brittle at LH_2 temperature.	 Figure 9

Description	Remarks	
Teflon seal with formed metal spring	Similar to Figure 9.	 Figure 10
Machined spring seal	Pressure actuated. Various platings available. Spacer can be used with flat-face flanges. Low tolerance to flange out-of-flat warpage and scratches.	 Figure 11
Rectangular "Rocker" type metal radial seal	Special tight tolerance gland; good deformation. Not reusable.	 Figure 12
Wedge-type metal radial seal	Special gland, low roundness and concentricity tolerance.	 Figure 13
Conical metal radial seal	Allowable flange distortion & deflection very good. Special gland. Gasket cost low.	 Figure 14

3.4 FLEXIBLE SECTIONS - The accommodations of duct motions caused by thermal deflections, installation misalignment, and structural and gimbaling deflections is normally provided for with bellows-type joints or combinations thereof. These bellows type joints may be either free bellows, restrained bellows, or thrust-compensating bellows.

3.4.1 Bellows Design - A bellows accommodates duct movements by deflection of its convoluted portion. Bellows used in missile ducting are normally fabricated from stainless steel and may be of single or multi-ply wall construction. Caution should be used in the fabrication of multi-ply bellows in avoiding entrapment of contaminants or moisture between the plies during forming. Usually this entrapped material can be baked out of the assembly prior to making closure welds on the bellows necks. A bellows is composed of a number of working convolutions as shown in Figure 1. Our discussion here will be limited to the as-formed, straight-side wall, rounded crown and root, convolution type bellows, which is the type most commonly used. The nomenclature given in Figure 1 will be used throughout this specification. An internally pressurized bellows will tend to elongate axially because of the unbalanced pressure forces created by the pressure acting on the convolution shapes. The tendency can be reacted to by tension linkages tying axially across the bellows or by compressive forces in the bellows end support structure.*

3.4.1.1 Fundamental Design Parameters - Aircraft and/or missile manufacturers (prime contractors) as a rule do not fabricate the bellows themselves. They usually specify their requirements to a subcontractor who specializes in bellows design and fabrication. However, for the prime contractor to be able to write an intelligent and reasonable specification, he must be fairly familiar with the design limitations of bellows. The purpose for presenting the bellows design equations and references thereto is two fold: (1) to allow the prime contractor to be aware of bellows design limitations, and (2) to allow the prime contractor to at least make a cursory analysis of the designs submitted to him by the subcontractors. The fundamental parameters in bellows design are considered to be:

a. Material selection
b. Spring rate
c. Buckling stability
d. Stress analysis
(1) Bending stress
(2) Bulging stress
(3) Hoop stress
e. Fatigue life
f. Pressure loss
g. Vibration characteristics

*Note that linkages must be designed to resist full bellows pressure separating load; $\frac{\pi Dm^2}{4} \cdot p$.

The information on bellows design that is presented herein is intended to be used as a guide only. A practical, successful design, as in all engineering designs, may represent a compromise of these design parameters. Final design of the bellows should be left to the individual subcontractors involved in order to take advantage of their broad design, testing, service, and fabrication experience.

3.4.1.1.1 Material Selection - The most commonly used material for cryogenic applications is 321 corrosion-resistant steel. However, successful bellows have also been made of 347 CRES, Inconel-X, Inco 718, K-monel, Hastelloy B&C, A-286, René 41, and Haynes 25. Various aluminum alloys are also occasionally used, but they are usually limited to low stress or noncritical applications. These materials offer the added bonus of having their yield and ultimate strengths increase with decreasing temperature. Some materials such as 17-7PH and AM350 stainless steels become brittle at low temperature and should not be used.

3.4.1.1.2 Spring Rate - Figure 2 presents the various types of deflections which bellows are capable of accommodating and their respective equations for determining spring rates. Bellows nomenclature of Figure 1 is supplemented with that given in Figure 2. These equations are based on a consensus of the information presented in references 1 through 7.

3.4.1.1.3 Buckling Stability - Bellows can become unstable when pressurized internally and will buckle in a manner similar to that of column buckling. The equation given in Figure 3 may be used to determine the critical buckling pressure of straight bellows. Reference 8 (Haringx) may be used if a more sophisticated result -- taking into account different types of end restraint -- is desired. Theoretically, a bellows deflected in angular rotation does not have a lower critical buckling pressure than the same bellows in a straight position; however, a bent bellows has a lateral deflection for each pressure increment and those deflections may become excessive. Externally pressurized bellows do not buckle in the same sense as an internally pressurized bellows; their mode of failure is a crimping or oil canning of the walls inwardly. This usually occurs at a much higher pressure than the pressure at which internally pressurized buckling occurs. In design situations where a long bellows is needed to allow long axial strokes, preference should be given to external pressurization, i.e., pressure applied to outside diameter surface area.

3.4.1.1.4 Stress Analysis - Stress analysis of a given bellows can be made using equations presented in Figure 4. For bending stress analysis purposes, it is usually convenient to express all types of deflections in terms of equivalent axial deflections. The conversion factors to accomplish this are given in Figure 5. Design requirements such as spring rate and fatigue life usually cause the bellows to operate in the plastic stress range. It is not unusual to design a 321 CRES bellows for a working stress (as calculated with the equations in this document) of up to 150,000 psi, although the yield strength of the material in the annealed condition is only 35,000 psi. Cold working of the bellows material during forming operations can increase the yield strength considerably, and bellows designers sometimes take advantage of this fact.

3.4.1.1.5 Fatigue Life - Fatigue life of a bellows is mostly a function of the number of alternating stress cycles imposed and is relatively independent of steady state stresses. The number of cycles before failure is inversely proportional to the alternating stress raised to some exponential power:

$$N = \left(\frac{K}{\sigma_b}\right)^n \text{, where K is a constant}$$

The values of n and K are dependent on the properties of the particular material involved. An exponent of 3.5 and a K value of $1.6 \cdot 10^6$ have been determined from Type 321 CRES at room temperature (reference 4). Comparison of fatigue life conducted on identical bellows at room and cryogenic temperatures indicates much longer life at the cryogenic temperatures. For example, for 321 CRES, fatigue life at liquid nitrogen temperature is 2 to 4 times that at room temperature and at liquid hydrogen temperature limited test data indicates that it is at least 12 times greater than at room temperature.

3.4.1.1.6 Pressure Drop - Pressure drop in unsleeved bellows because of friction has been determined to be a function of the geometry of bellows. The friction factor in the turbulent regime is relatively independent of Reynolds number. See Figure 6 for losses in straight bellows, and Figure 7 for effect of 90 deg bends. Losses in internally restrained gimbal and internal tie-rod joints are given in Figures 8 and 9.

3.4.1.1.7 Vibration Characteristics - A bellows constitutes a spring-mass system with low-damping characteristics. Consequently, mechanically or flow induced vibrations near the resonant frequency of the bellows (and harmonics) can cause rapid deterioration and eventual fatigue failure. These failures can occur in what appears to be a fantastically short operating time, i.e., seconds. Equations for the fundamental resonant frequency for the two most common supporting and accelerating systems are:

1. For ends fixed and acceleration parallel to the bellows centerline

$$f = 9.85 \left(\frac{K_A}{\ell \cdot W}\right)^{1/2}$$

where

f = cps and W is weight in lb/in. of length

2. For ends fixed and acceleration perpendicular to the bellows centerline

$$f = 24.8 \, D_m \left(\frac{K_A}{\ell^3 \cdot W}\right)^{1/2}$$

3.4.1.2 Normal Design Practice - The following criteria should be observed for best results in the application of the bellows:

NORMAL DESIGN PRACTICE FOR BELLOWS USAGE

Proof Pressure - 1.2 x (Design Pressure Including Transients) or 1.5 x (Design Pressure) whichever is considered the most severe.

Burst Pressure - 2.5 x (Design Pressure Including Transients).

Compression Stroke - 10 to 15% of the flex section live length, although up to 40% has been successfully attained; however, fatigue life will be greatly reduced. See paragraph 3.4.1.1.5.

Extension Stroke - 10% of the flex-section live length, although up to 40% has been successfully attained; however, fatigue life will be greatly reduced. See paragraph 3.4.1.1.5.

Angular Deflection - ±5 deg maximum, although ±15 deg has been successfully attained.

Lateral Offset - $0.02\,\ell^2/D$ maximum although $0.25\,\ell^2/D$ has been successfully attained. Note that it is poor practice to have one joint accommodate two or more types of deflection simultaneously, although it is often dictated by other design considerations.

Torsional Deflection - Preferably none; however, small rotations can be accommodated by specific design.

Ratio of Flex-Section Length to Inside Diameter - Generally, 1/2 to 1-1/2; however, exceptions can be made. See Haringx's buckling analysis.

Convolution Height - 3 to 13% of the inside diameter, although up to 25% has been achieved.

Minimum Ratio of Convolution Inside Bend Radius to Total Wall Thickness - 2.0 for straight side wall convolutions, although 0.8 has been successfully achieved. (Based on inside ply in the case of multi-ply.)

Use of Internal Liners to Prevent Flow-Induced Vibration - Recommended in gas service when Mach number is in 0.3 to 0.4 or greater range and in liquid service where maximum velocity in velocity profile is 60 ft/sec or more. Liners should definitely be used in bellows located immediately downstream of sharp-turn elbows, valves, or other flow disturbances and for angular joints making large angulations.

Next Assembly Precaution - For bellows made of materials which utilize the forming, cold worked strength (such as 321 CRES), care should be exercised in next assembly to not weld too close to bellows or heat treat assembly so as to reduce cold worked strength. A good rule of the thumb is to keep the duct weld at least the $\sqrt{Rt}$ distance away from the end convolution disk, where R = Di/2 and t = total wall thickness.

Vibration - Bellows should be designed with natural frequencies different from known system inputs such as pump speeds, pump outlet pressure oscillations, etc.

3.4.1.3 Specification of Design Requirements - Because of the highly specialized nature of bellows design and fabrication, it is necessary that the design requirements and operating conditions be carefully specified. The following information should normally be called out:

a. Type of fluid service

b. Pressure (normal operating, proof, surge, and burst), temperature (maximum, minimum, and normal operating), and the most critical combination of temperature and pressure

c. Type of material

d. Deflections (axial, angular, and lateral offset)

e. Vibration requirements (frequency, amplitude, and acceleration)

f. Maximum flow velocity or Mach number and allowable pressure drop

g. Minimum life cycles (define cycle clearly in terms of deflections, pressures, and temperatures)

h. Space envelope (maximum outside diameter, minimum inside diameter, live length, overall length, nature of end couplings)

i. If a liner or sleeve is required, specify the minimum allowable inside diameter, minimum clearance between liner and convolutions, liner length, type of liner free end, the direction of normal flow, and the possibility of reverse flow.

j. Qualification test requirements (to include method of duct support)

k. Production test requirements

l. Optional requirements may include the spring rate, sectioning and measurement of wall thickness consistency, and buckling stability

3.4.2 Flexible Joint Design - A flexible joint design consists of a bellows pressure carrier and a mechanical linkage and/or a compensating bellows device to counteract the tendency of the bellows to elongate axially under the pressure-separating force. The restraint feature allows the joint to act as a tension-carrying member.

3.4.2.1 Restrained Joints - Some typical modes of restraint are shown in Figure 10. The most commonly used linkage types are the gimbal, tie rod, and braided.

3.4.2.1.1 Gimbal Type - These units can be made with either internal or external gimbal supports and will permit angular deflection in any plane. The primary advantage of this type is its ability to provide angular deflection with a small actuating force. It should be pointed out that a gimbal joint when deflected in two planes will result in a geometrical, torsional deflection and load being applied to the bellows. This is the Hooke's joint effect.

3.4.2.1.2 Tie Rod Type - Internal tie-rod flexible joints also permit angular deflection in any plane. They have the advantages of low cost, low weight, and lowest bending force. They have the disadvantage of presenting protuberances in the flow stream which can cause relatively high-pressure drop in high-velocity systems (Figure 8).

3.4.2.1.3 Braided Type - The use of an external, wire braid over a flex section has been a long accepted method of providing restraint. The primary advantages are low cost, simplicity of fabrication, and small space envelope. On the other hand, the braid restricts the angular deflection which results in a greater bending moment. The design of these units should be such as to minimize rubbing contact between the braid and the end convolutions.

3.4.2.2 Thrust Compensating Joints - This type of bellows assembly allows for axial deflection in the same manner as an unrestrained bellows. The particular design shown in Figure 10 utilizes a pressure balancing chamber installed external to and concentric with the main-duct bellows. This chamber is vented to internal duct pressure and, by use of proper cross sectional area, an axial force equal and opposite to the pressure separating force of the main duct bellows is thus created. There are many variations of this theme. The primary use of the compensating joint is to retain a tension type system in areas where limited space exists and axial travel cannot be absorbed by angulation. By proper selection of the cross sectional area, the thrust force may be under, fully, or overly compensated so that a compressive, balancing, or tensile load is imposed on the system.

3.4.2.2.1 Normal Design Practice - The following design criteria should be observed for compensating joints:

a. Compression stroke: 10 to 15% of the total bellows live length, although up to 40% has been successfully achieved; however, fatigue life will be greatly reduced. See paragraph 3.4.1.1.5.

b. Extension stroke: 10% of the total bellows live length, although up to 40% has been successfully achieved.

c. Angular deflection: ± 5 deg.

d. Lateral offset: None.

e. Torsional deflection: None, although small rotations can be accommodated by specific design.

f. Ratio of individual bellows length to duct outside diameter; unsupported length limitation same as unrestrained bellows.

3.4.2.2.2 Statement of Design Requirements - Applicable information from paragraph 3.4.1.3 should be specified as needed for compensating joints. The following additional requirements are usually necessary:

a. Spring rate at design compression stroke

b. Amount of pressure thrust unbalance which can be tolerated

c. Mounting details

3.4.3 Test Procedures - Testing is usually divided into two categories; one is the initial qualification testing which is later repeated on a sampling basis during production runs, and the other is acceptance testing which consists of nondestructive tests made on all production pieces. Typical tests conducted and categories they fall into are given in the following table:

	Qualification Test	Sample Test	Acceptance Test	Test Description
Proof Pressure	Yes	Yes	Yes	Hydrostatic or pneumostatic pressure applied to bellows for 5 minutes, no leakage or distortion allowed, normally 1.2 x design pressure including transients or 1.5 x design pressure, whichever is considered the most severe
Spring Rate	Yes	Yes	Can be if critical	Determine force vs axial (or lateral or angular) deflection characteristics
Dimensional Check	Yes	Yes	Yes	Micrometer, caliper sort of an inspection
Buckling Stability	Yes	Can be if critical	Can be if critical	Application of proof or design pressure with bellows in most extreme deflected position
Burst Pressure	Yes	Yes	No	Hydrostatic or pneumostatic pressure applied to bellows at up to 2.5 x design pressure. Yielding allowed but no leakage
Fatigue Cycling	Yes	Yes	No	Deflection and/or pressure cycling under normal operating conditions for a predetermined number of life cycles without failure
Vibration	Yes	Yes	No	Vibrating under normal operating conditions and end-use vibration environment conditions for a predetermined period of time without failure
Flow Calibration	Can be if critical	Can be if critical	No	Measurement of pressure loss through flex at rated flow conditions
Flow Fatigue	Can be if critical	Can be if critical	No	Flowing end-use fluid (water or air may sometimes be substituted) through part at rated velocity for a predetermined period of time without failure
Sectioning and Thickness	Yes	Yes	No	Cross sectioning of bellows after completion of fatigue test and measurement of consistency of wall thickness along length of convolution, ±10 percent tolerance usually allowed