H-08-36

AIR1362-75
30 April 1984

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Releasing Industry Group: Society of Automotive Engineers , Inc.

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Custodians:
Navy - AS
Army - AV
AF -99

Reviewer Activities
Army - AV
AF - 11 ,71

Military Coordinating Activity:
Navy - AS
(Project No. 1650-0393)

FSC 1650

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H-08-36

LAND SEA AIR SPACE

Society of Automotive Engineers, Inc.
400 COMMONWEALTH DRIVE, WARRENDALE, PA. 15096

AEROSPACE INFORMATION REPORT

AIR 1362

Issued May 1975
Revised

PHYSICAL PROPERTIES OF HYDRAULIC FLUIDS

1. SCOPE

This report presents data on hydraulic fluids which are of interest to detail designers of hydraulic systems and components for military flight vehicles. The data pertain to fluids conforming to specifications MIL-H-5606, MIL-H-8446, MIL-H-27601, and MIL-H-83282.

2. INTRODUCTION

2.1 Hydraulic fluids have many physical and chemical properties which must be considered in the design of a hydraulic system.

Fluid Property	Primary Influence
1. Bulk Modulus	System stiffness
2. Viscosity	Power losses
3. Density	System weight
4. Specific Heat	Thermal characteristics
5. Thermal Conductivity	Heat exchanger design
6. Thermal Expansion	Reservoir sizing
7. Chemical Stability	Formation of breakdown products
8. Thermal Stability	Deterioration of fluid properties
9. Shear Stability	Loss of lubricity and viscosity
10. Hydrolytic Stability	Corrosion
11. Lubricity	Component wear
12. Compatibility	System materials
13. Volatility	Cavitation and evaporation
14. Toxicity	Safety
15. Foaming	Cavitation and system stiffness
16. Fire Resistance	Safety

Note: The above listing sequence has no bearing on relative importance.

Properties 1 through 6 have specific numerical values which are required in detail design and analysis work; data covering these properties are given in this AIR. Properties 7 through 16 are important considerations in the selection of a hydraulic fluid for a specific application, but numerical values associated with these properties are not usually required in system design.

2.2 The types of hydraulic fluid considered to be most applicable to current and near future military air vehicles are:

Fluid Type	Operating Temperatures	Specification
Petroleum base with polymeric additives	-65 to +275°F	MIL-H-5606
Silicate ester, shear stable	-65 to +500°F	MIL-H-8446
Deep de-waxed super-refined mineral oil	-30 to +550°F	MIL-H-27601
Synthetic hydrocarbon, fire resistant	-40 to +400°F	MIL-H-83282

2.3 Operating conditions can cause changes in the physical properties of a hydraulic fluid. Temperature and pressure, in particular, have significant influences on fluid viscosity and bulk modulus. The detail designer requires data for specific operating conditions, but these data are often not readily available. This results in designers acquiring, through various means, a personal file of hydraulic fluid properties. The intent of this AIR is to encourage the use of standardized design information. Fluid specifications provide for variations in properties which can result from differences in manufacturing processes or base stock used. The data presented herein are considered to be nominal values.

3. HYDRAULIC FLUID PROPERTIES

3.1 Bulk Modulus: Bulk modulus is a term used to denote the ability of a fluid to resist volumetric reduction caused by applied pressure, and is an important parameter in the design of hydraulic servo systems. Interaction of fluid compressibility with the mass of the mechanical parts and load produces a natural frequency in most hydraulic systems. This resonance is often the chief limitation to dynamic performance and is approximately proportional to the square root of the fluid bulk modulus.

3.1.1 There are several different types of bulk moduli; selection of the proper modulus is based on the function being performed. Functions that occur rapidly, with little chance for heat transfer into or out of the system, require adiabatic moduli; examples include hydraulic pumps, motors, and rapidly oscillating servo actuators. Functions that occur slowly or with constant fluid temperature require isothermal moduli; this modulus has limited application to air vehicle hydraulic systems. Pressure excursion magnitude is also a factor in modulus selection. Large excursions, for example in pumps and motors, require the use of secant moduli; small pressure fluctuations around a quiescent level, as in oscillating servo actuators, require the use of tangent moduli. Bulk modulus is the reciprocal of fluid compressibility and is generally expressed in psi. The most commonly used moduli are summarized below:

Function	Pressure Excursion	Bulk Modulus	Application
Dynamic	* Small	Adiabatic tangent	Design of servo systems and actuators
Dynamic	** Large	Adiabatic secant	Design of hydraulic pumps and motors
Static	Small	Isothermal tanget	Limited use in air vehicle system design
Static	Large	Isothermal secant	Limited use in air vehicle systems design.

* Less than 10% of system pressure (approximately)
** More than 80% of system pressure (approximately)

3.1.2 Bulk modulus is defined by:

$$\beta_T = -V \frac{\partial P}{\partial V} \qquad \text{Eq. 1}$$

and,

$$\beta_s = V_o \frac{P - P_o}{V_o - V} \qquad \text{Eq. 2}$$

where,

β_T = tangent bulk modulus

β_s = secant bulk modulus

P = pressure

V = volume

P_o = reference pressure, usually atmospheric

V_o = volume at P_o

Equation 1 is the thermodynamic definition of bulk modulus and represents the true rate of volumetric change at the pressure of "interest". Equation 2 defines a "mean" bulk modulus and represents the volumetric change with pressure from atmospheric to the pressure of "interest". Both moduli can be determined under isothermal or adiabatic conditions.

Two methods used for measuring bulk modulus are the pressure-volume-temperature method, which gives isothermal secant information, and the sonic method, which yields adiabatic tangent data. Relationships between the moduli are:

$$\frac{\beta_{AT}}{\beta_{IT}} = \gamma$$

$$\beta_{ITp} \approx \beta_{IS2p}$$

$$\beta_{AT} = \rho C^2$$

where,

β_{AT}	=	adiabatic tangent bulk modulus
β_{IT}	=	isothermal tangent bulk modulus
β_{IS}	=	isothermal secant bulk modulus
γ	=	ratio of specific heats $\frac{c_p}{c_v}$
ρ	=	fluid mass density (Rho)
C	=	velocity of sound in fluid
p	=	pressure level of interest

Bulk modulus can be substantially lowered by the presence of entrained air (free bubbles) in the fluid. Dissolved air has a minor effect in reducing bulk modulus. The amount of air which can be dissolved in hydraulic fluids is approximately proportional to the pressure level. The time required to achieve equilibrium conditions may prevent complete dissolution in some cases. Generally, when the operating pressure exceed the saturation pressure, bulk modulus degradation due to air is small.

3.1.4 The bulk modulus data presented in this AIR cover temperatures from +100° to +300°F at pressures from 0 to 8000 psig.

Figure No.	Bulk Modulus	Hydraulic Fluid
1	adiabatic tangent	MIL-H-5606
2		MIL-H-8446
3		MIL-H-27601
4		MIL-H-83282
5	adiabatic secant	MIL-H-5606
6		MIL-H-8446
7		MIL-H-27601
8		MIL-H-83282
9	isothermal secant	MIL-H-5606
10		MIL-H-8446
11		MIL-H-27601
12		MIL-H-83282

3.2 Viscosity: Viscosity causes a fluid to resist flow, varies with ambient conditions, and contributes to characterizing flow as laminar or turbulent. Fluid viscosity nearly always limits the lowest operating temperature of a hydraulic system, and often limits the highest operating temperature. Fluid systems and components have conflicting viscosity requirements, i.e., good lubrication and low internal leakage require a moderately high viscosity while low line losses and fast control response dictate a low viscosity fluid. Good design requires a thorough consideration of the effects of operating conditions on viscosity and the effects of viscosity variations on system performance.

3.2.1 Fluid flow causes shear stresses within the fluid which are proportional (in laminar flow) to the velocity gradient across a given sheared section. The proportionality factor is the absolute viscosity. Thus,

$$\tau = \mu \frac{dv}{ds}$$

where, τ = shear stress

μ = absolute viscosity

$\frac{dv}{ds}$ = velocity gradient across sheared section of thickness ds

If the absolute viscosity at a given temperature is independent of shear rate, the fluid is called Newtonian; if it varies with shear rate, the fluid is termed non-Newtonian.

3.2.2 The ratio of absolute viscosity to fluid mass density occurs frequently in flow analyses. This ratio is, by definition, the kinematic viscosity of the fluid.

$$\nu = \frac{\mu}{\rho}$$

where, ν = kinematic viscosity

ρ = mass density

Kinematic viscosity at atmospheric pressure is easily measured with commercially available viscometers. In the metric system, kinematic viscosity has units of cm^2/sec called stokes. Because this unit is large, the term centistoke (cs) is often used. The conversion to the English system equivalent is:

$$.001552 \times \nu \quad (cs) = \nu \quad (in^2/sec)$$

The viscosity of hydraulic fluids decreases significantly as temperature is increased. This relationship can be approximated by,

$$\mu_T = \mu_o \, e^{-\lambda (T-T_o)}$$

where,

μ_T = absolute viscosity at temperature T

μ_o = viscosity at reference temperature T_o

λ = a constant which depends upon the fluid

T = temperature

Moderate viscosity increases occur as pressure is increased. This relationship can be approximated by,

$$\mu_p = \mu_o \, e^{\propto p}$$

where,

μ_p = absolute viscosity at pressure

μ_o = viscosity at atmospheric pressure

P = pressure

$\propto$ = pressure coefficient (varies with temperature)

3.2.3 Hydraulic fluids employing viscosity-index improvers, such as polymeric thickeners, have complex non-Newtonian viscosity behavior. Either temporary or permanent viscosity losses can take place when the fluid is subjected to high shear rates. Temporary loss occurs in laminar flow when the long chain polymeric molecules become aligned and stretched, and thus lose their thickening power. Removal of the shear stress permits the molecules to revert to their original random configuration, and the fluid regains its initial viscosity. This process is fully reversible. The temporary loss decreases as temperatures increase. Permanent viscosity loss results from severe turbulent flow, cavitation, large pressure drops across sharp edged orifices, and scission between mating parts. These conditions can stress molecular chains to the breaking point, creating shorter less viscous fractions. The rate of permanent viscosity loss is dependent upon the severity of operating conditions and the stability of the polymeric molecule. Sheared fluid has a greater viscosity-temperature dependence than new, unsheared fluid.

Generally accepted viscosity levels for military air vehicle hydraulic systems are:

Condition	Viscosity, cs	Remarks
Cold Start	2500 max.	Operation at reduced rate permitted
Maximum operating viscosity	500	Rated system performance required
Optimum Performance	6 to 12	Maximum component efficiency and life
Minimum operating viscosity	2	Degraded system performance and reduced component life

The viscosity data in this AIR cover temperatures from -50^{o} to $+400^{o}F$ at pressures from 0 to 8000 psig.

Figure No.	Plot	Hydraulic Fluid
13	Viscosity vs Pressure	MIL-H-5606
14		MIL-H-8446
15		MIL-H-27601
16		MIL-H-83282
17	Viscosity vs Temperature	MIL-H-5606
18		MIL-H-8446
19		MIL-H-27601
20		MIL-H-83282

3.3 Density: Fluid density is an important factor in calculations made to estimate hydraulic system weight, and is required in analyses involving Reynolds number, bulk modulus, and orifice flow. Line losses and heat generation are directly proportional to fluid density. Temperature and pressure have moderate affects on density. Fluid mass density and specific weight are related as follows:

$$\rho = \frac{\omega}{g}$$

where, ρ = mass density (mass per unit volume)

ω = specific weight (weight per unit volume)

g = acceleration due to gravity

The mass density data in this AIR cover temperatures from $+100^{o}$ to $+300^{o}F$ at pressures from 0 to 8000 psig.

Figure No.	Hydraulic Fluid
21	MIL-H-5606
22	MIL-H-8446
23	MIL-H-27601
24	MIL-H-83282

3.4 Specific Heat: Heat is generated in hydraulic systems principally by fluid compression, pump inefficiences, transmission line friction, pressure drops across orifices, and internal leakage in valves on output devices. Fluid specific heat is required in thermal analyses involving heat transfer, heating and cooling rates, and temperature build-up.

The specific heat of a liquid is the amount of heat required to raise the temperature of a unit mass by 1 degree, and is expressed in BTU/lb/^{o}F (=Cal/gm/^{o}C). The specific heat at constant pressure (c_p) increases with rise in temperature; pressures from 0 to 10,000 psig have little effect on c_p.

The specific heat ratio $\frac{Cp}{Cv}$ is useful in calculations related to bulk modulus. The specific heat ratio generally decreases with increasing temperature; pressures in the range of 0 to 10,000 psig have little effect on the ratio.

Specific heat data in this AIR are at atmospheric pressure and cover temperatures from 0 to $+400^{o}$ F.

Figure No.	Plot
25	Specific Heat of Hydraulic Fluids
26	Specific Heat Ratio of Hydraulic Fluids

3.5 Thermal Conductivity: Fluid thermal conductivity is required in conduction-convection problems involving calculation of the surface film coefficient for heat exchanger design. Thermal conductivity is a measure of the rate of heat flow through the fluid and in the English system is generally expressed as BTU/hr/ft^2/^{o}F/ft. The thermal conductivity of most liquids decreases with increases in temperature and changes only slightly with pressure. Thermal conductivity data in this AIR are at atmospheric pressure and cover tempreatures from 0 to +400^{o}F.

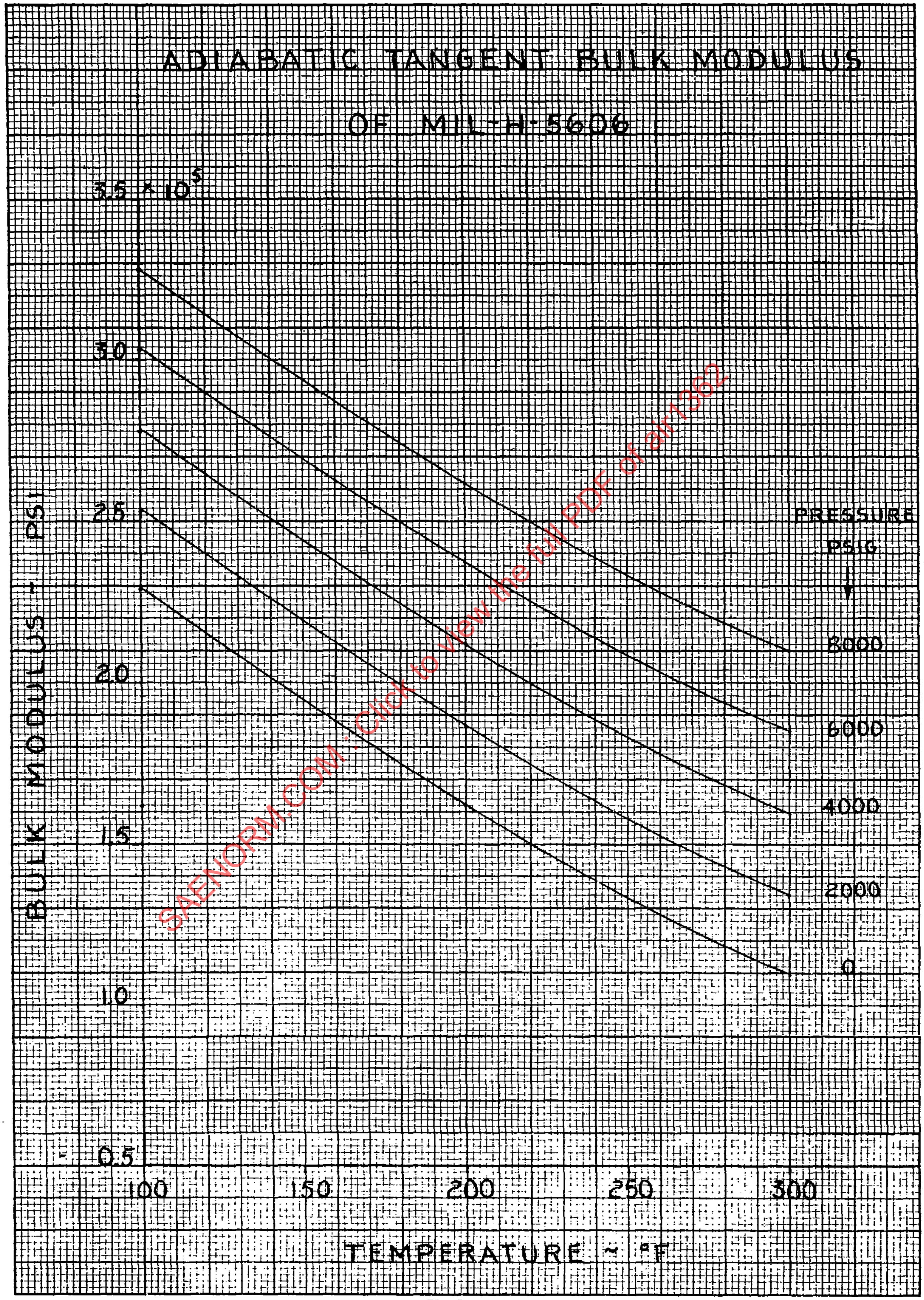
Figure No.	Plot
27	Thermal Conductivity of Hydraulic Fluids

3.6 Coefficient of Thermal Expansion: Hydraulic fluid expansion is of particular interest to the designer of a closed system which must operate over a wide temperature range. A low coefficient of expansion will minimize the capacity which must be added to accommodate increases in system fluid volume caused by rising temperatures. The coefficient of thermal expansion is related to fluid density. Temperature and pressure have relatively small effects on the coefficient. The coefficient of thermal expansion values listed below are at atmospheric pressure and cover a temperature range from +100^o to +300^{o}F.

Hydraulic Fluid	Coefficient of Thermal Expansion, in^3/in^3/^{o}F
MIL-H-5606	4.8×10^{-4}
MIL-H-8446	5.0×10^{-4}
MIL-H-27601	4.5×10^{-4}
MIL-H-83282	4.6×10^{-4}

PREPARED BY

SAE COMMITTEE A-6, AEROSPACE FLUID POWER & CONTROL TECHNOLOGIES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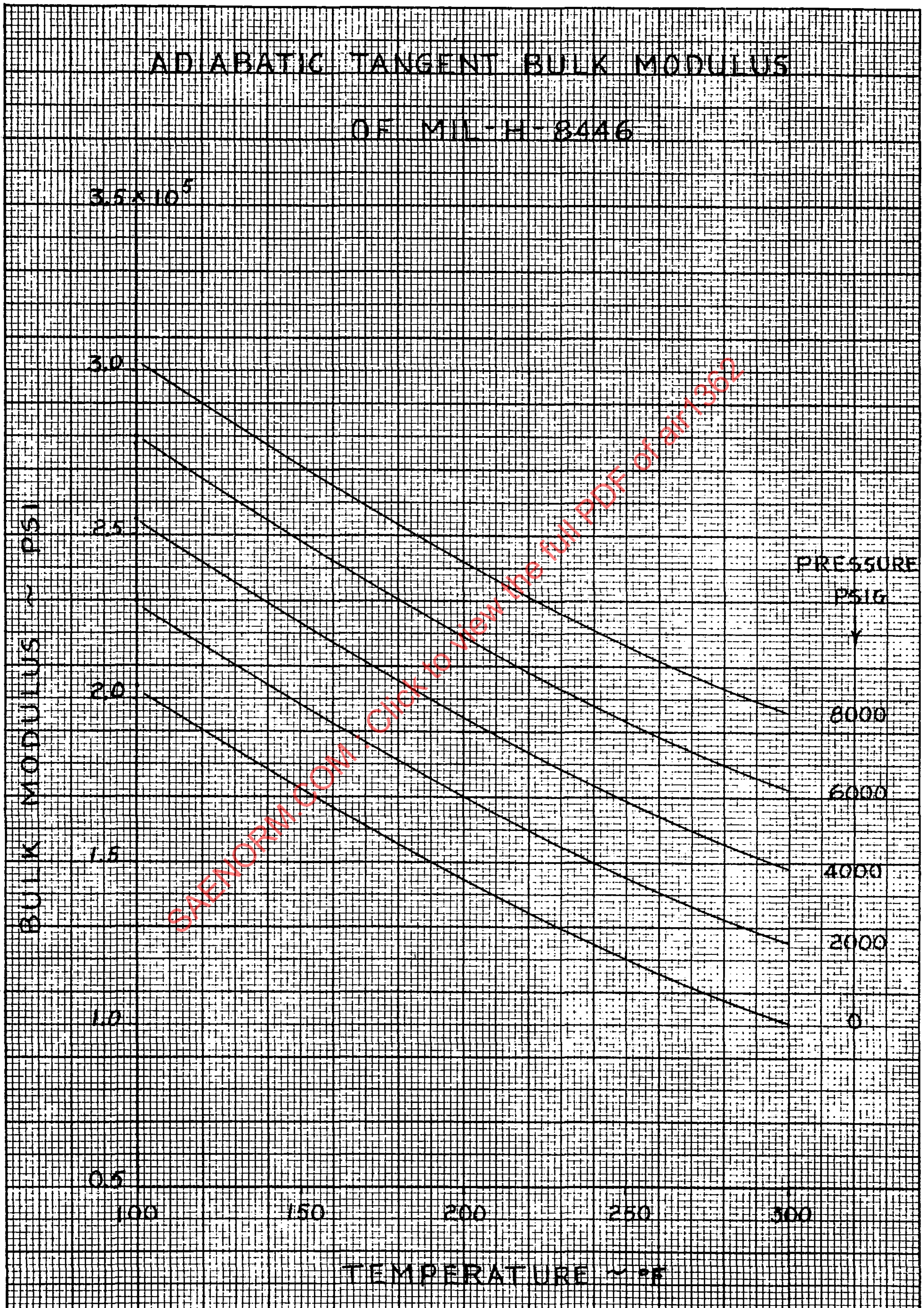
OF MIL-H-5606
3.5 × 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS - PSI
PRESSURE
PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 1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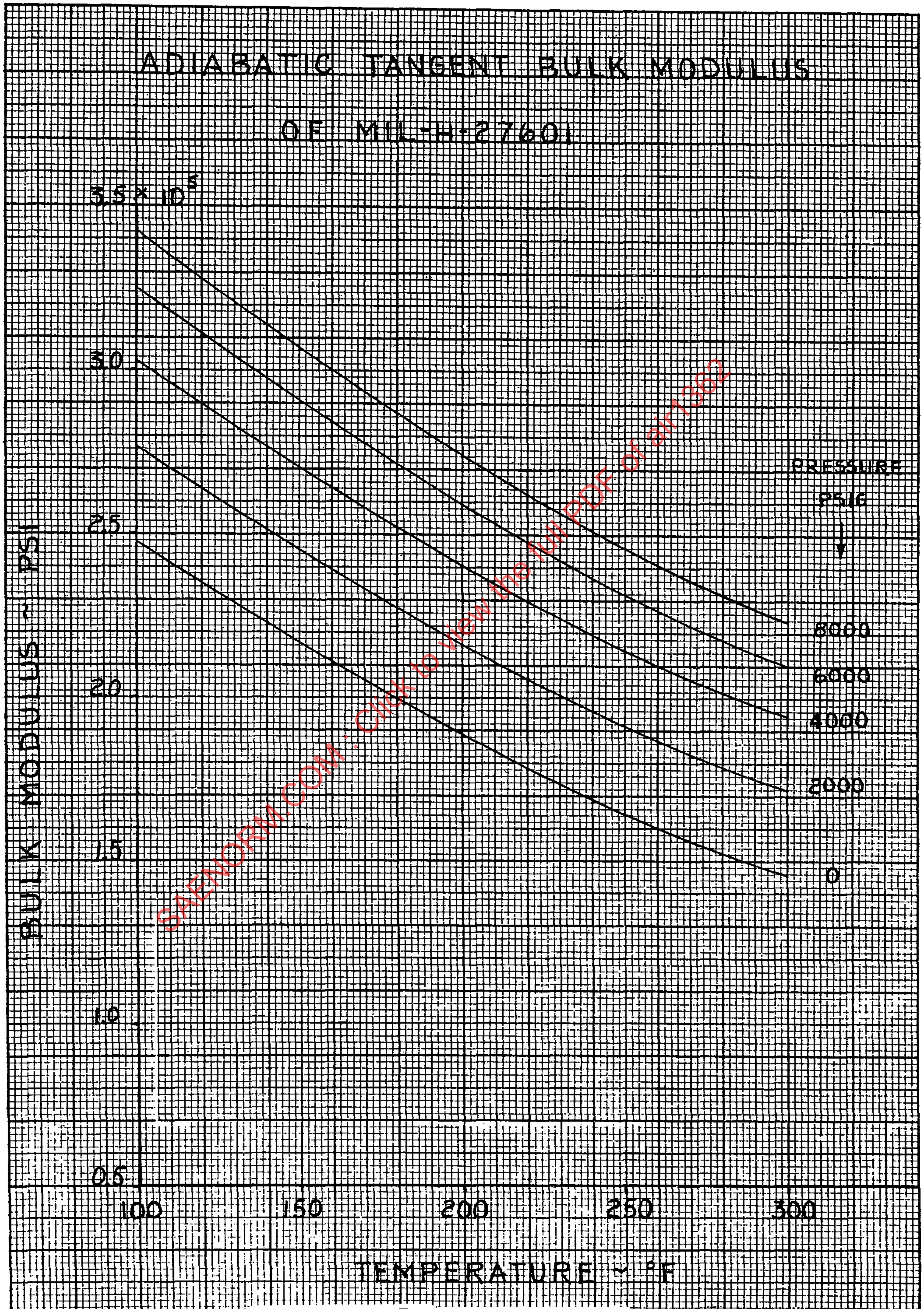
OF MIL-H-8446
3.5 × 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE
PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 2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OF MIL-H-27601
3.5 × 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE
PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 3

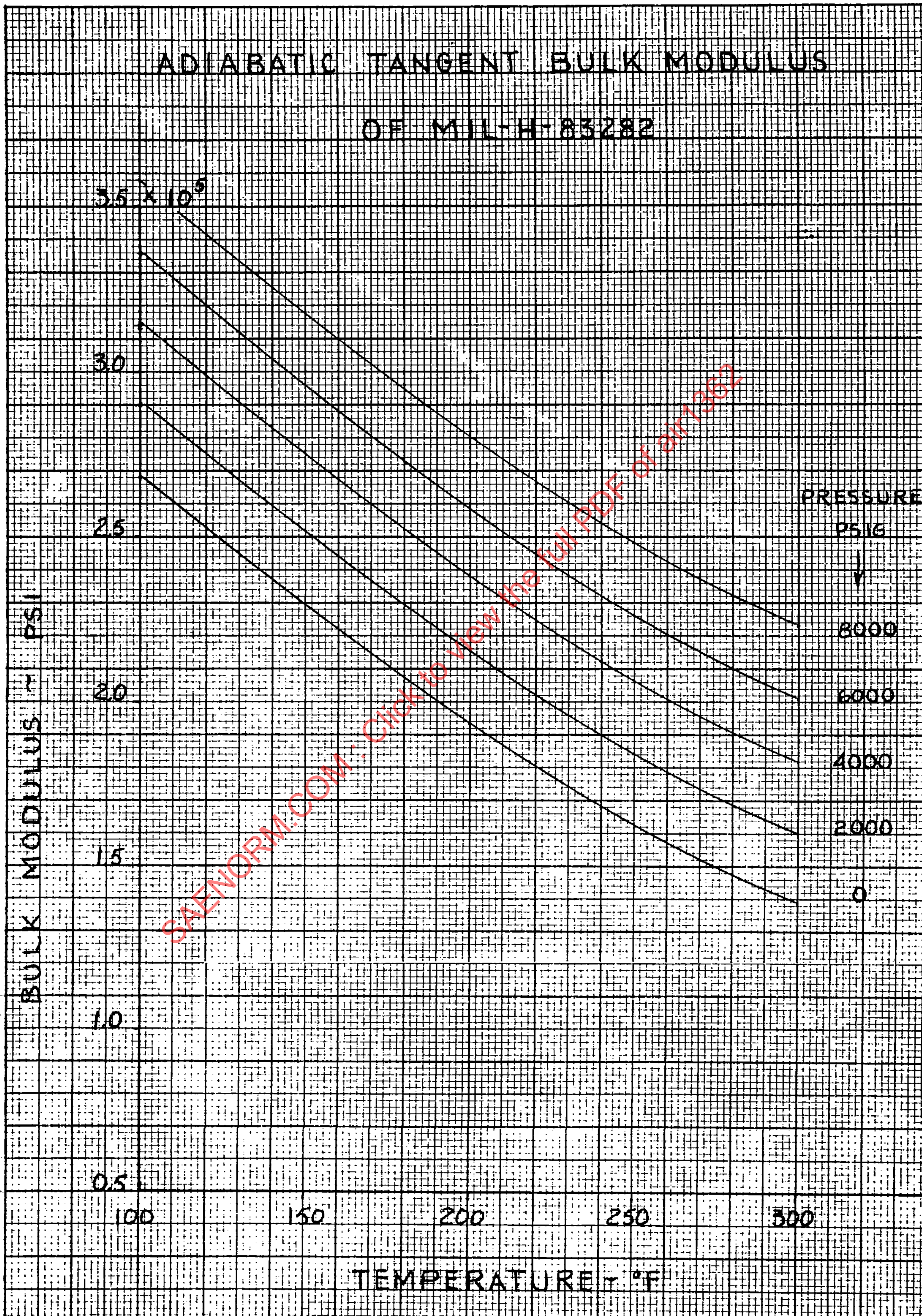

ADIABATIC TANGENT BULK MODULUS
OF MIL-H-83282
3.5 X 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
100
150
200
250
300
TEMPERATURE ~ °F
PRESSURE
PSIG
8000
6000
4000
2000
0

FIGURE 4

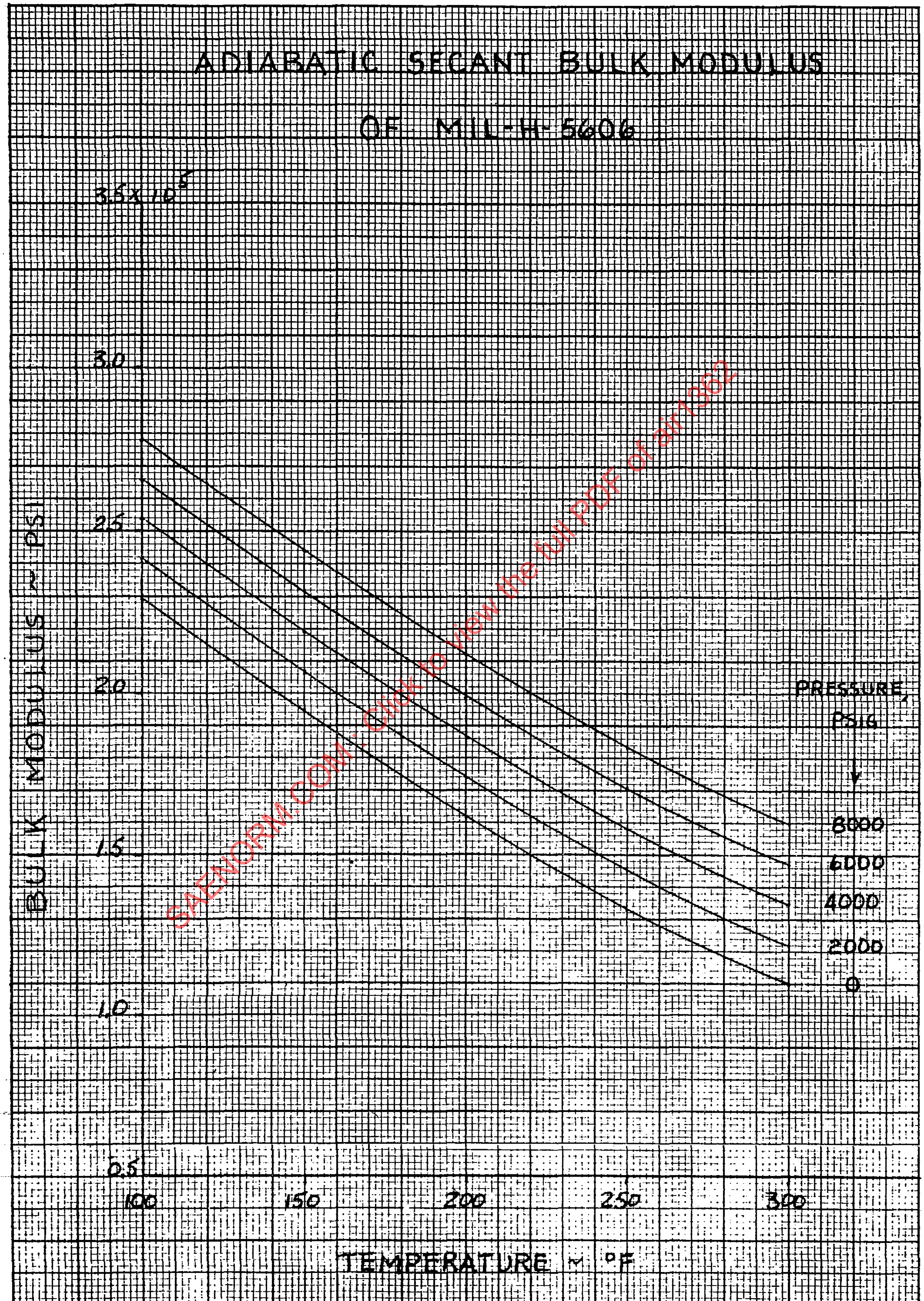

ADIABATIC SECANT BULK MODULUS
OF MIL-H-5606
3.5 X 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE, PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 5

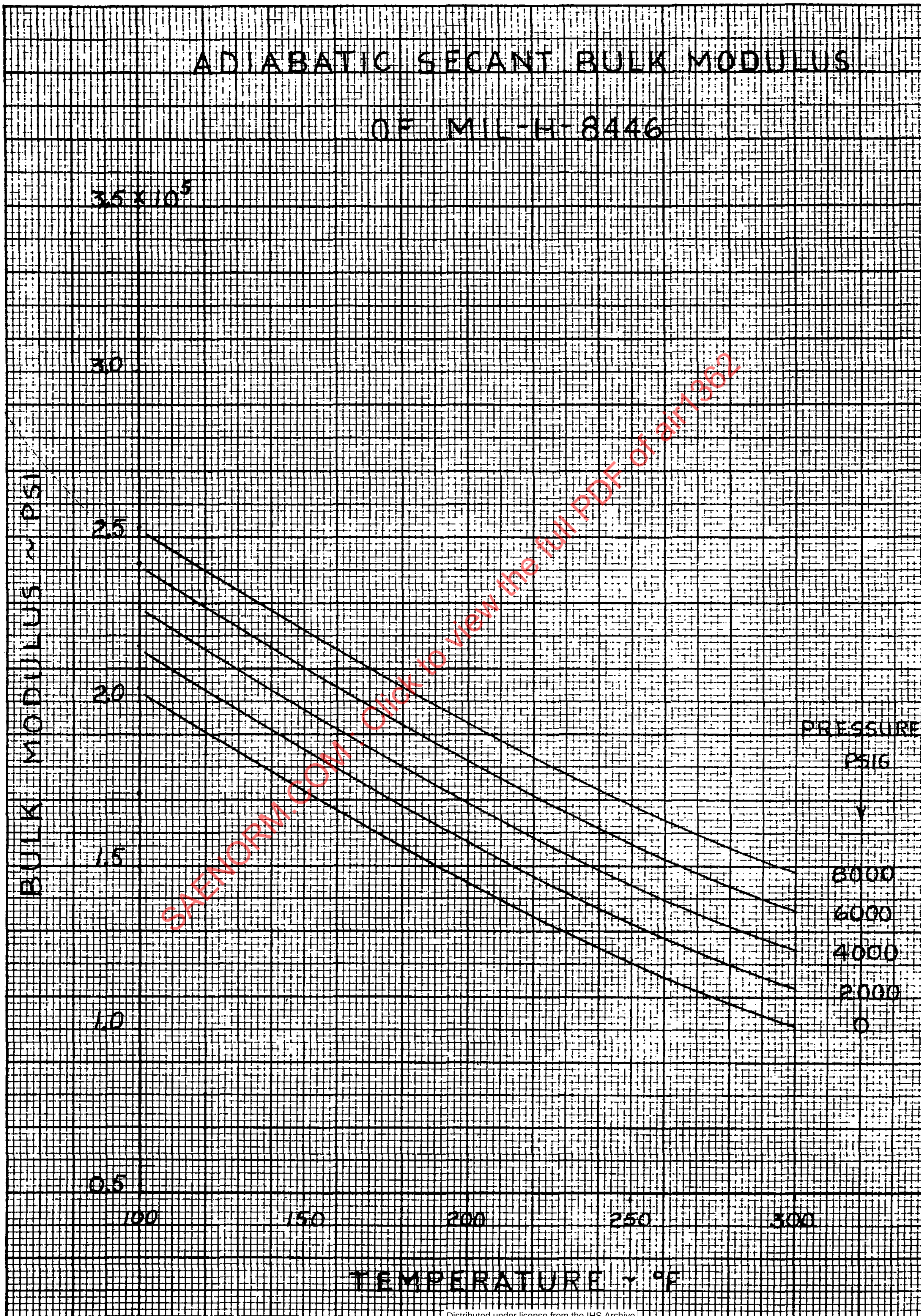

ADIABATIC SECANT BULK MODULUS
OF MIL-H-8446
3.5 x 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE, PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 6

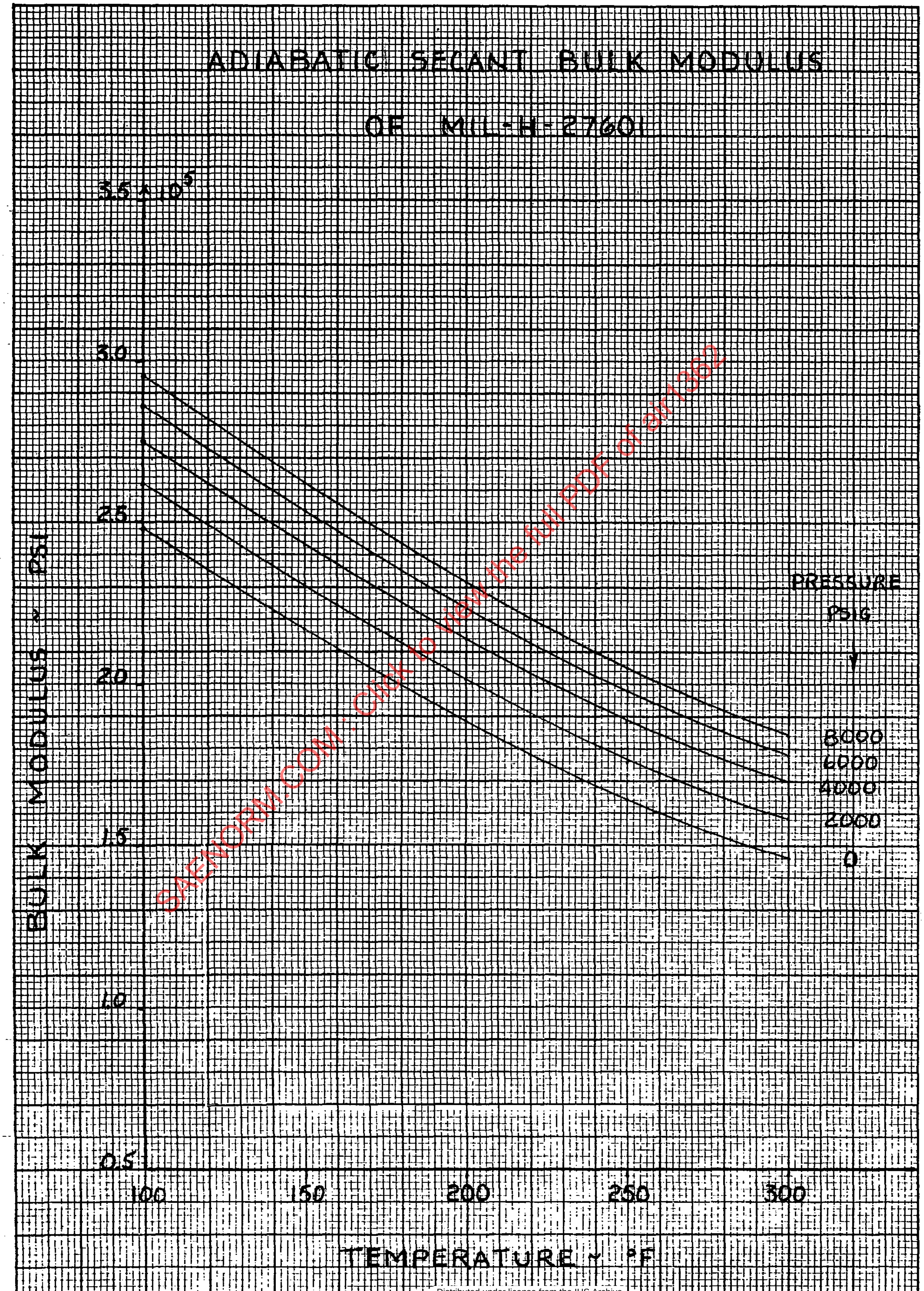
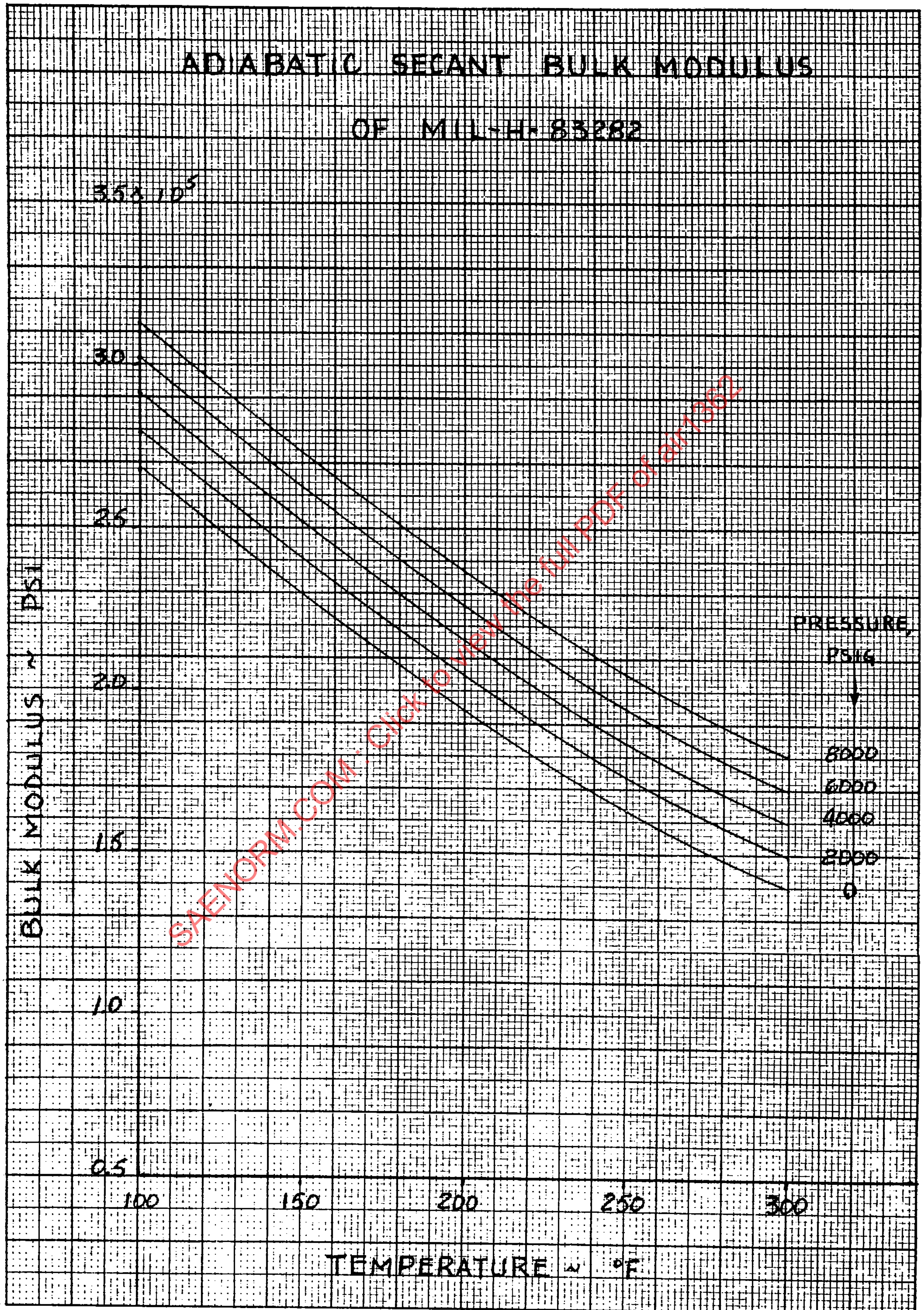

ADIABATIC SECANT BULK MODULUS
OF MIL-H-27601
BULK MODULUS ~ PSI
$\times 10^5$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
100
150
200
250
300
TEMPERATURE ~ °F
PRESSURE
PSIG
8000
6000
4000
2000
0

FIGURE 7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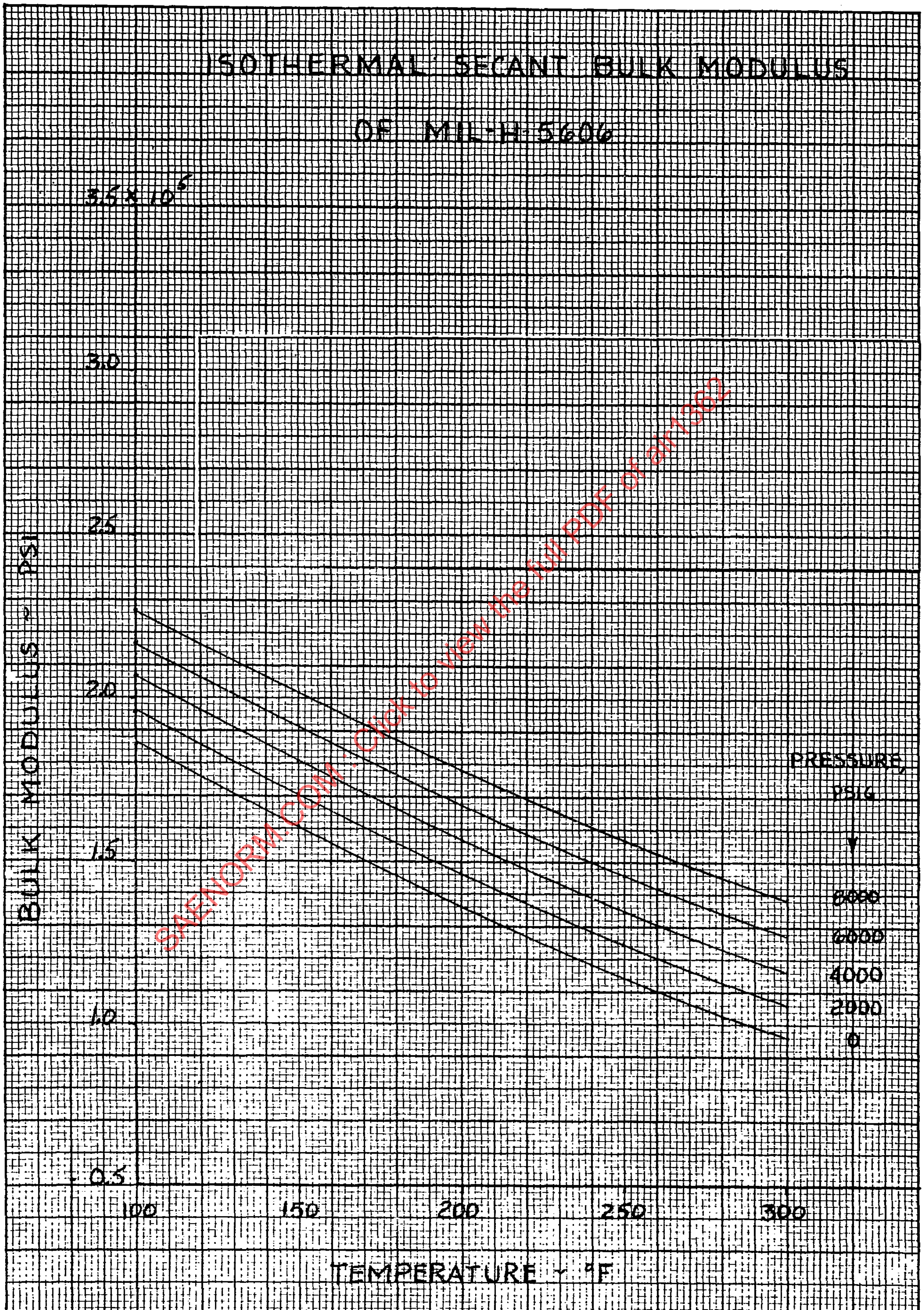
OF MIL-H-83282
3.5 x 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
100
150
200
250
300
TEMPERATURE ~ °F
PRESSURE, PSIG
8000
6000
4000
2000
0

FIGURE 8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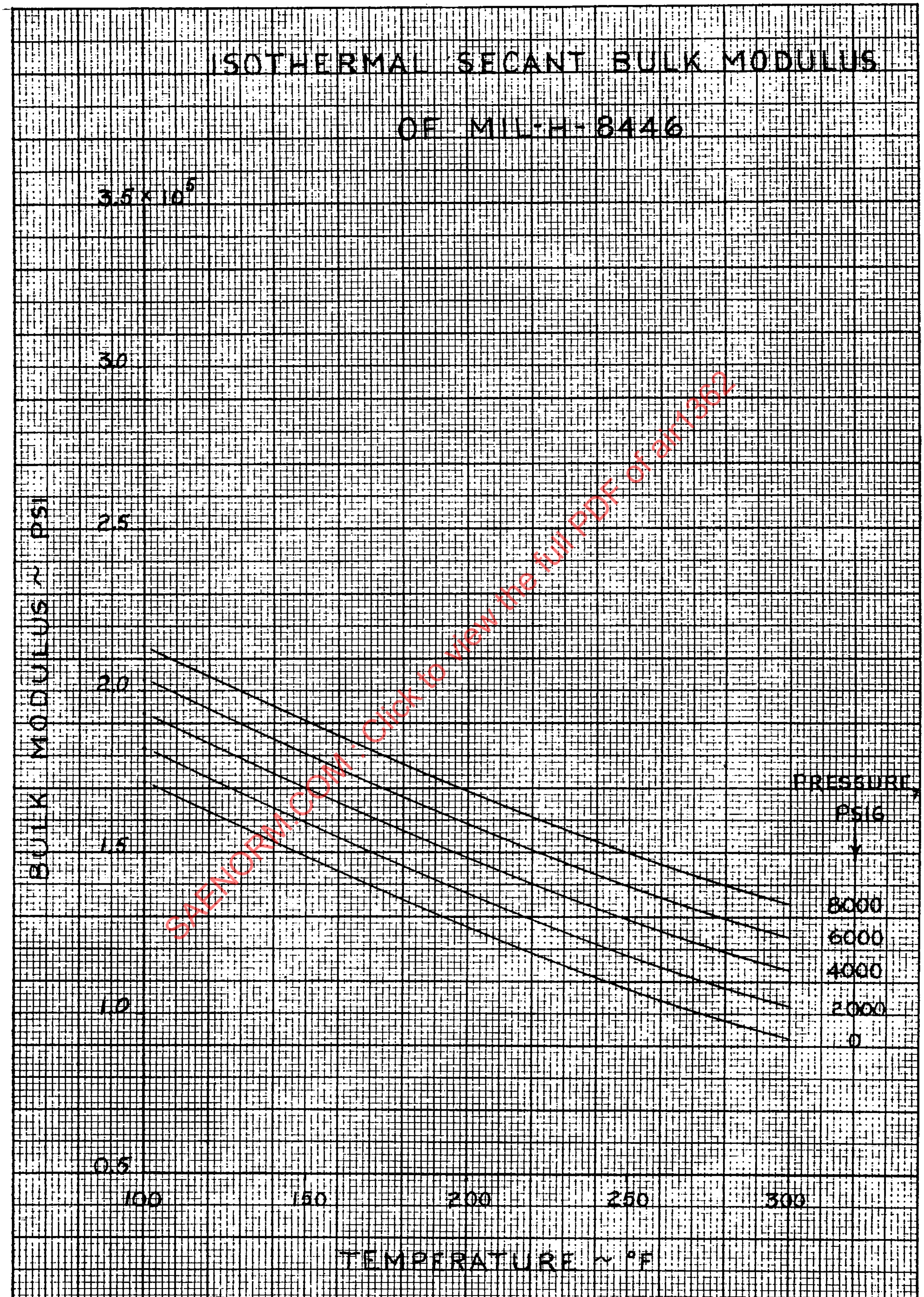
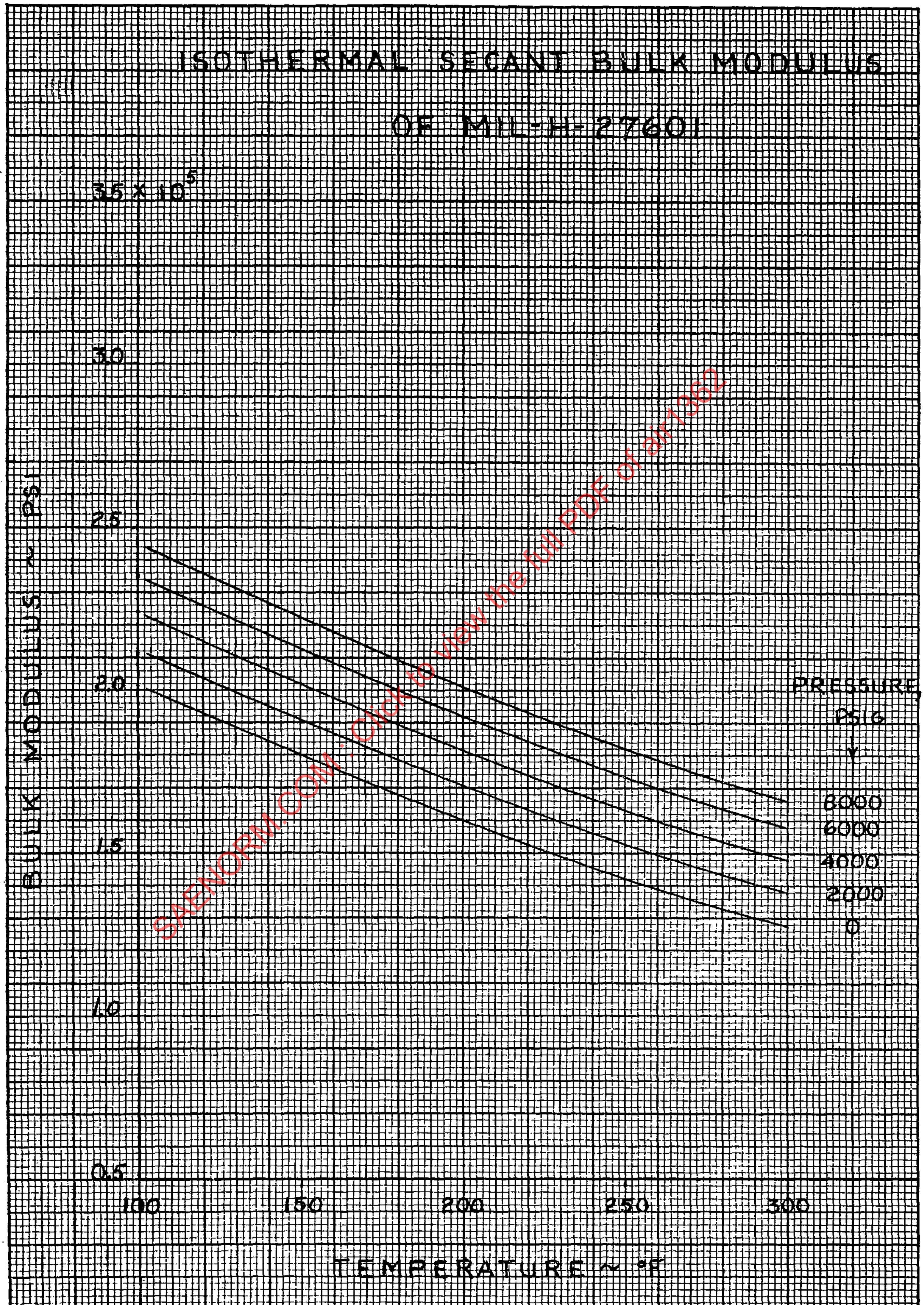
OF MIL-H-5606
3.5 x 10^6
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE, PSIG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 9


ISOTHERMAL SECANT BULK MODULUS
OF MIL-H-8446
BULK MODULUS ~ PSI
3.5 × 10^5
3.0
2.5
2.0
1.5
1.0
0.5
100
150
200
250
300
TEMPERATURE ~ °F
PRESSURE, PSIG
8000
6000
4000
2000
0

FI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OF MIL-H-27601
3.5 X 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
100
150
200
250
300
TEMPERATURE ~ °F
PRESSURE,
PSIG
8000
6000
4000
2000
0

F[illegible]

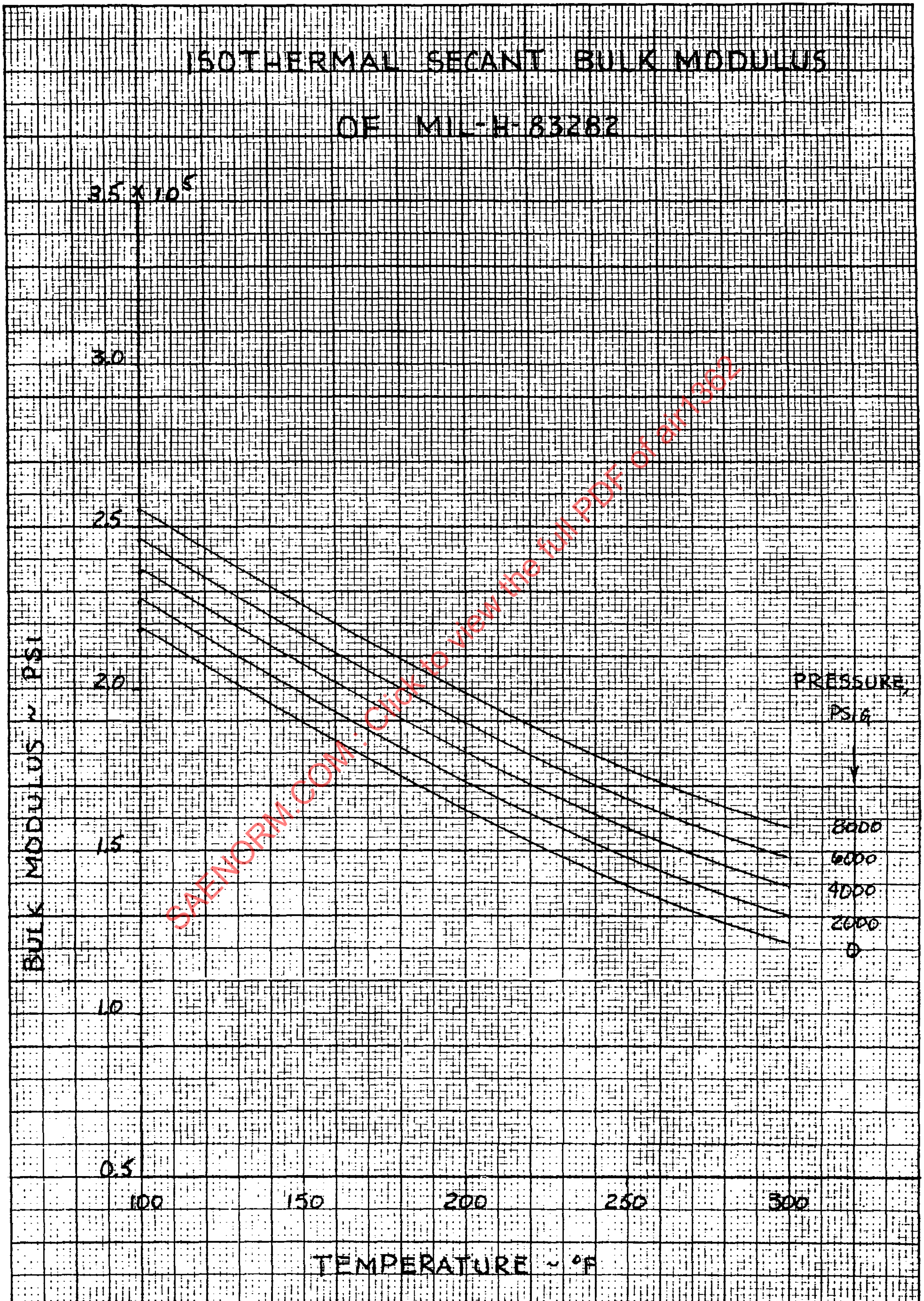
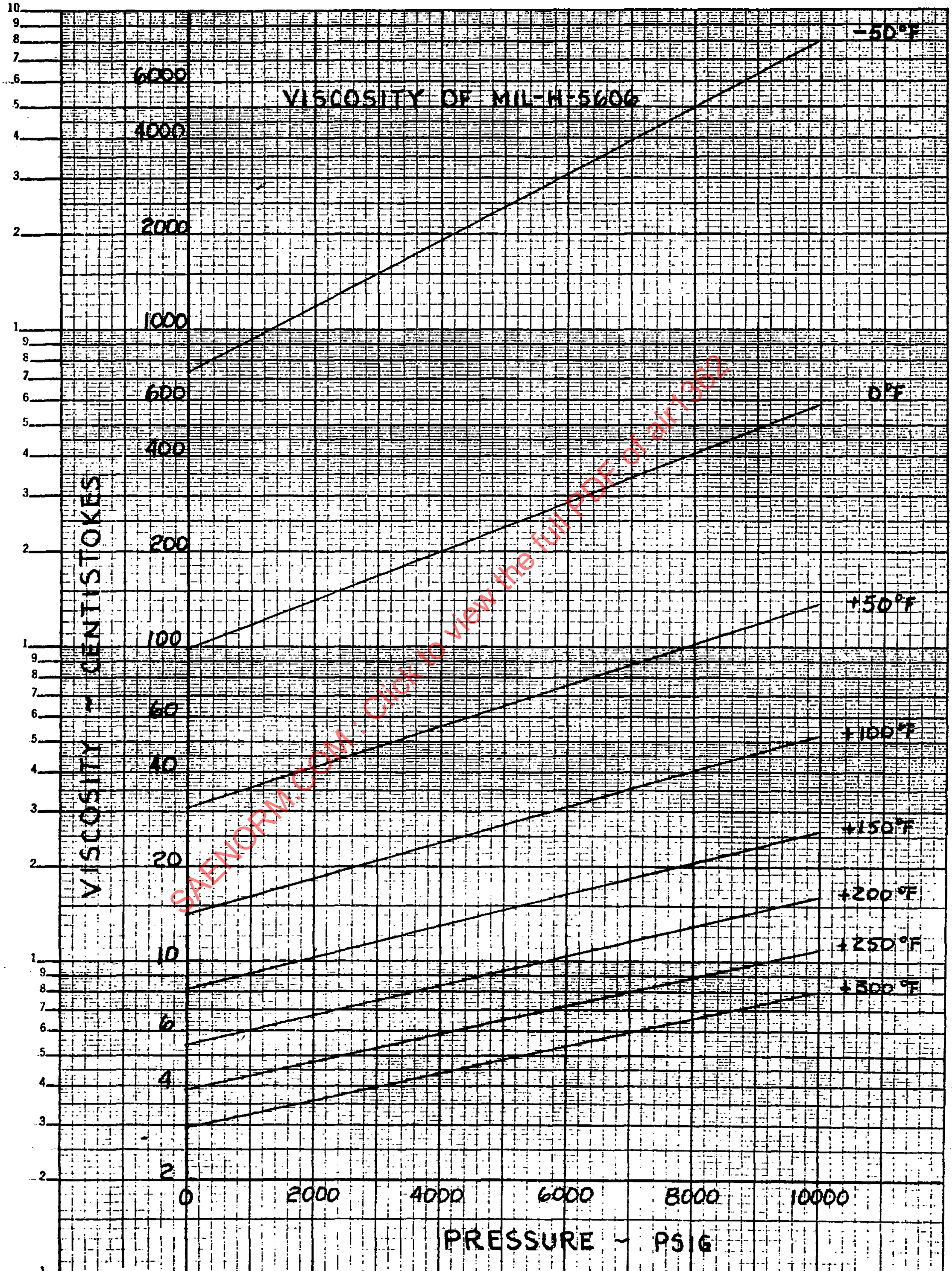
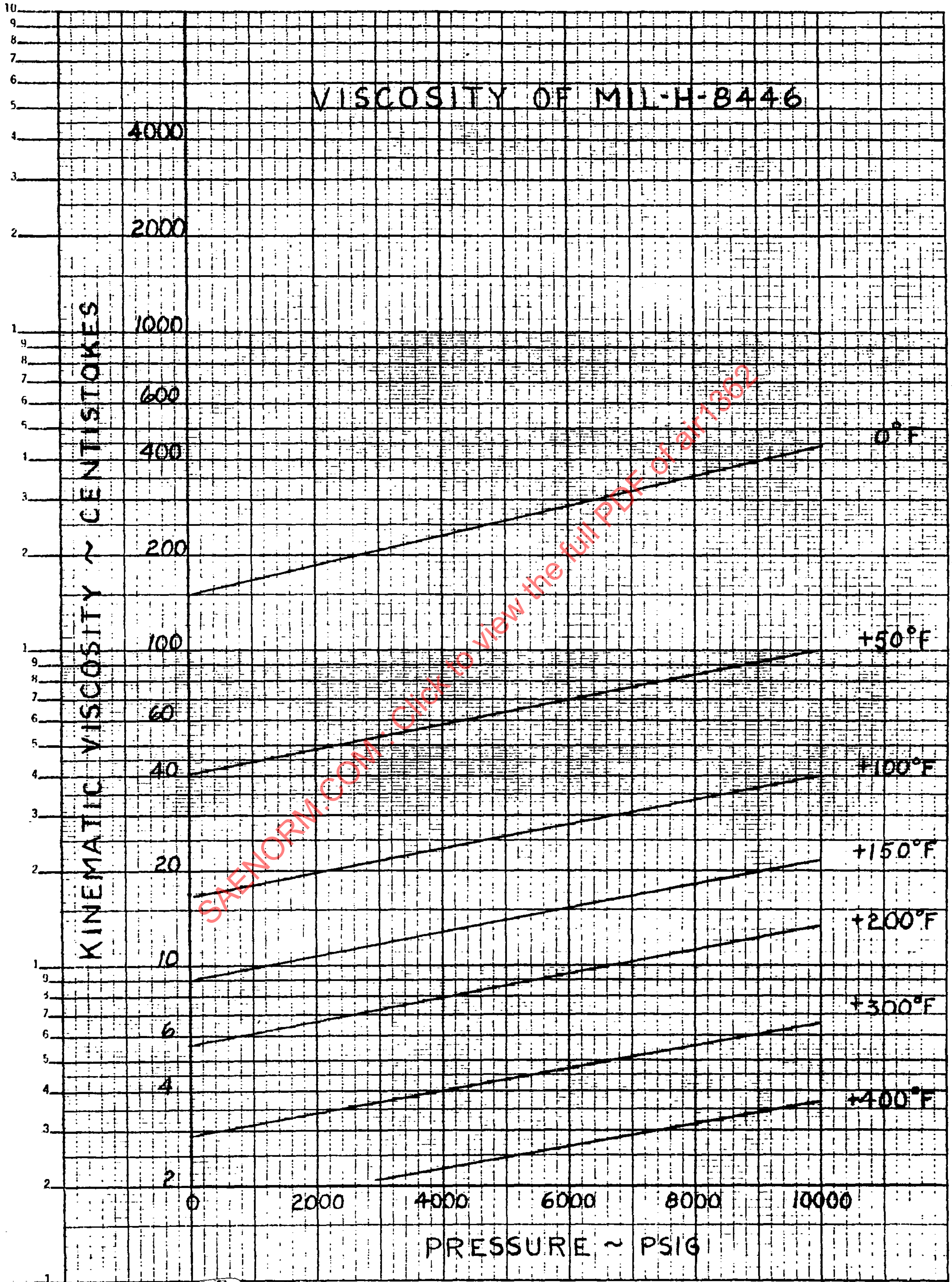
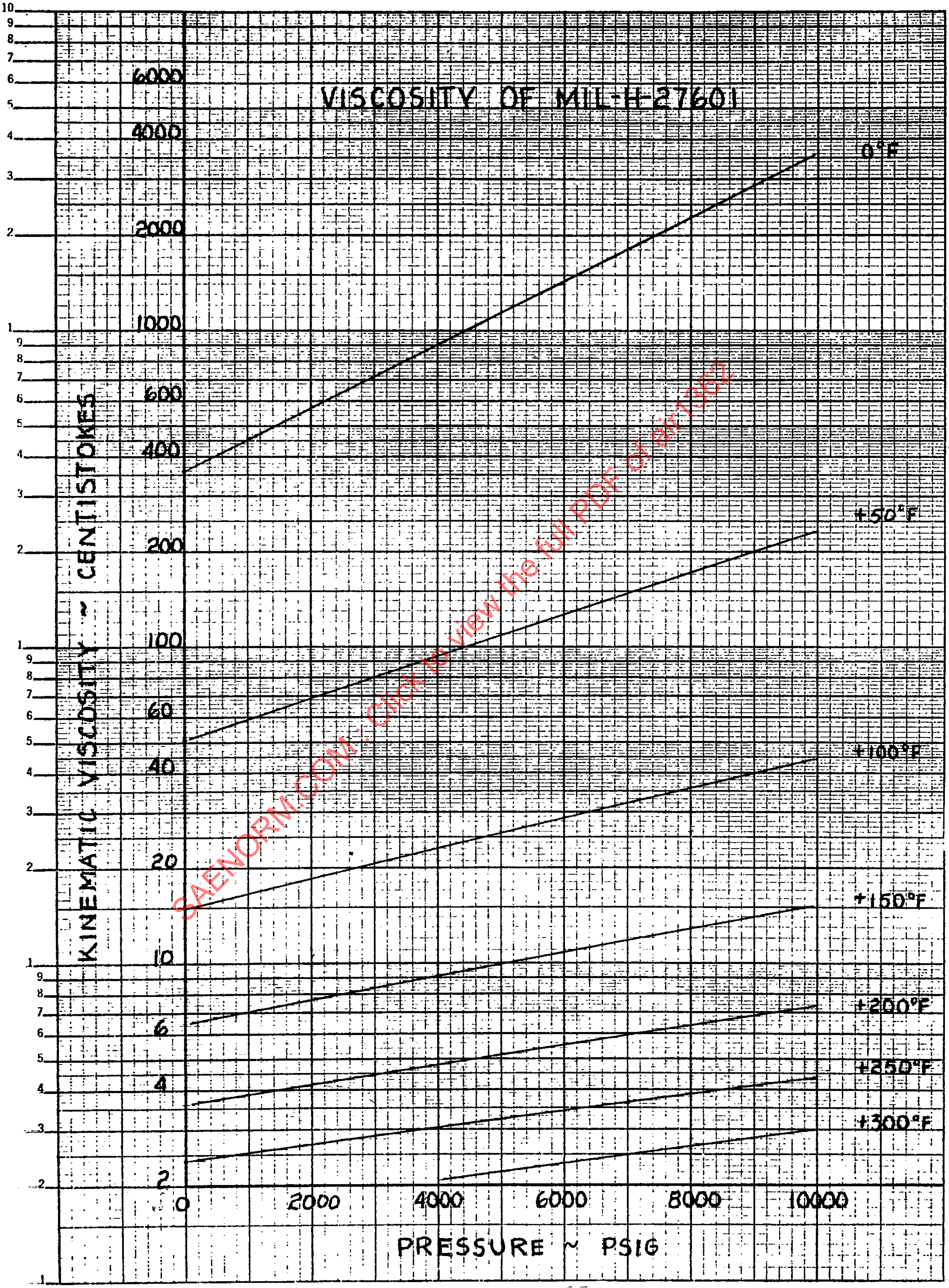
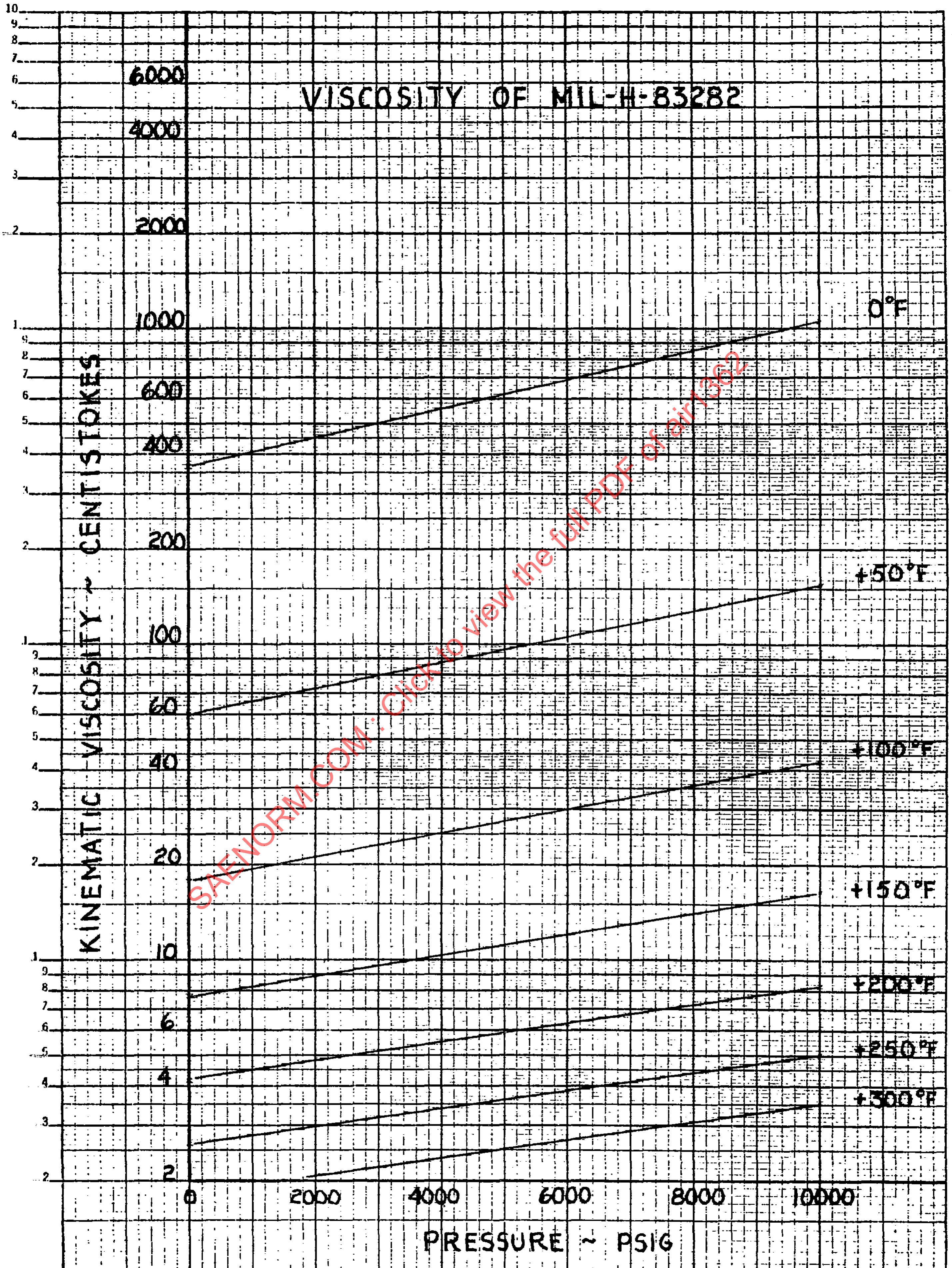

ISOTHERMAL SECANT BULK MODULUS
OF MIL-H-83282
3.5 X 10^5
3.0
2.5
2.0
1.5
1.0
0.5
BULK MODULUS ~ PSI
PRESSURE, PSG
8000
6000
4000
2000
0
100
150
200
250
300
TEMPERATURE ~ °F

FIGURE 12


VISCOSITY OF MIL-H-5606
VISCOSITY ~ CENTISTOKES
6000
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
-50°F
0°F
+50°F
+100°F
+150°F
+200°F
+250°F
+300°F
0
2000
4000
6000
8000
10000
PRESSURE ~ PSIG


VISCOSITY OF MIL-H-8446
KINEMATIC VISCOSITY ~ CENTISTOKES
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
0°F
+50°F
+100°F
+150°F
+200°F
+300°F
+400°F
0
2000
4000
6000
8000
10000
PRESSURE ~ PSIG


VISCOSITY OF MIL-H-27601
KINEMATIC VISCOSITY ~ CENTISTOKES
PRESSURE ~ PSIG
6000
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
0
2000
4000
6000
8000
10000
0°F
+50°F
+100°F
+150°F
+200°F
+250°F
+300°F


VISCOSITY OF MIL-H-83282
KINEMATIC VISCOSITY ~ CENTISTOKES
PRESSURE ~ PSIG
6000
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
0
2000
4000
6000
8000
10000
0°F
+50°F
+100°F
+150°F
+200°F
+250°F
+300°F

FIGURE

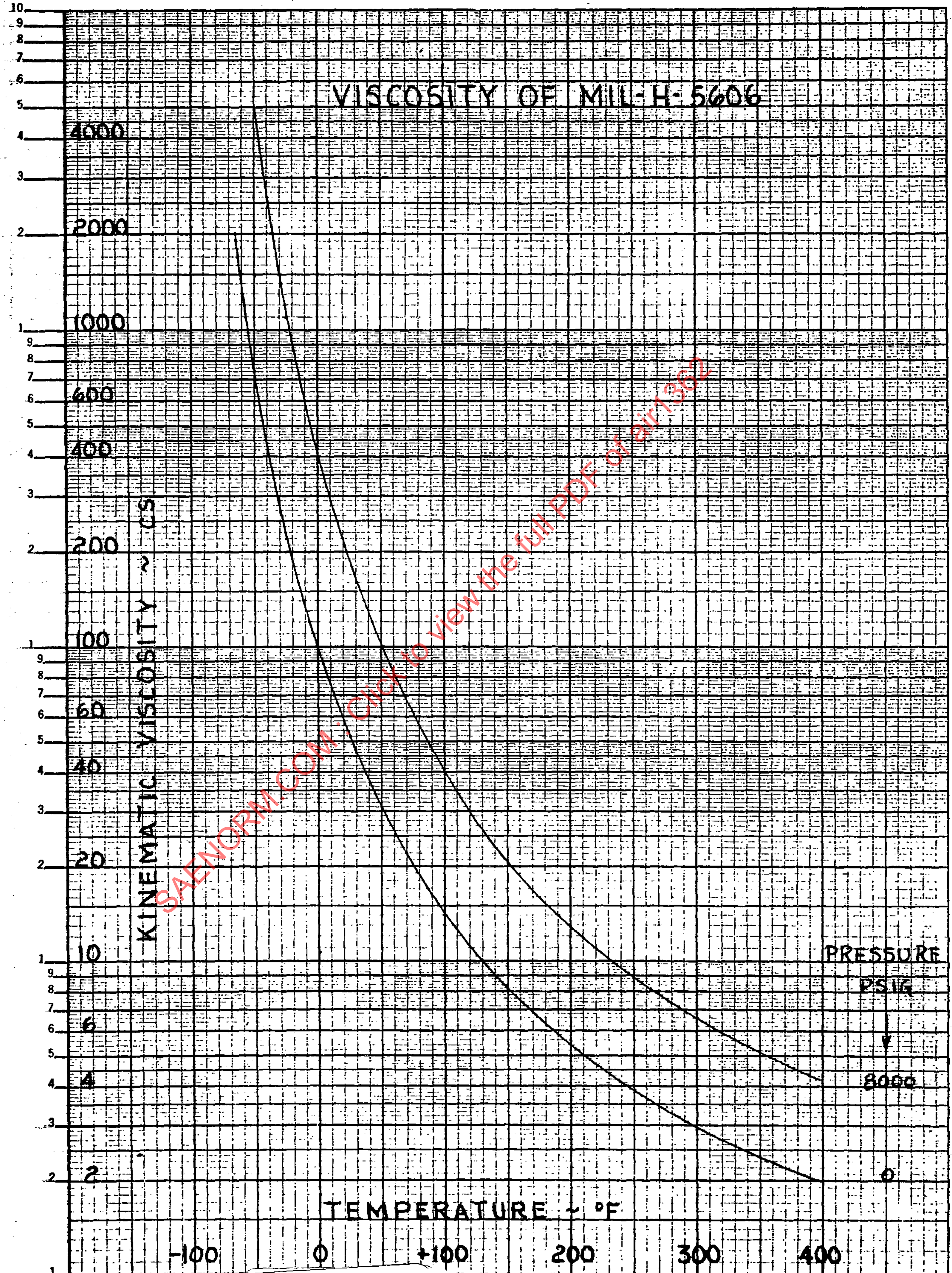

VISCOSITY OF MIL-H-5606
KINEMATIC VISCOSITY ~ CS
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
PRESSURE
PSIG
8000
0
TEMPERATURE ~ °F
-100
0
+100
200
300
400

FIGURE 17

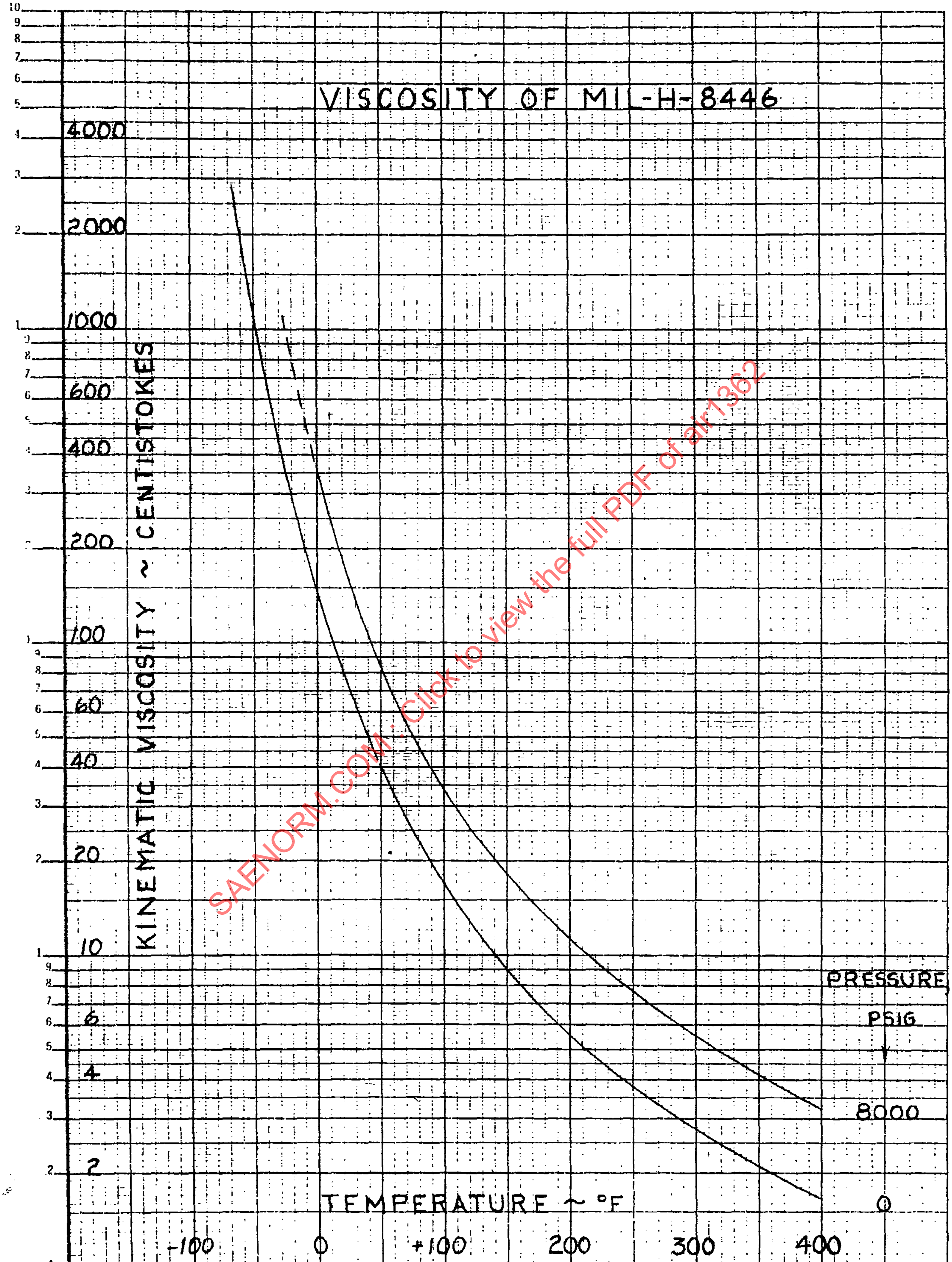

VISCOSITY OF MIL-H-8446
KINEMATIC VISCOSITY ~ CENTISTOKES
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
PRESSURE,
PSIG
8000
0
TEMPERATURE ~ °F
-100
0
+100
200
300
400

FIGURE 18

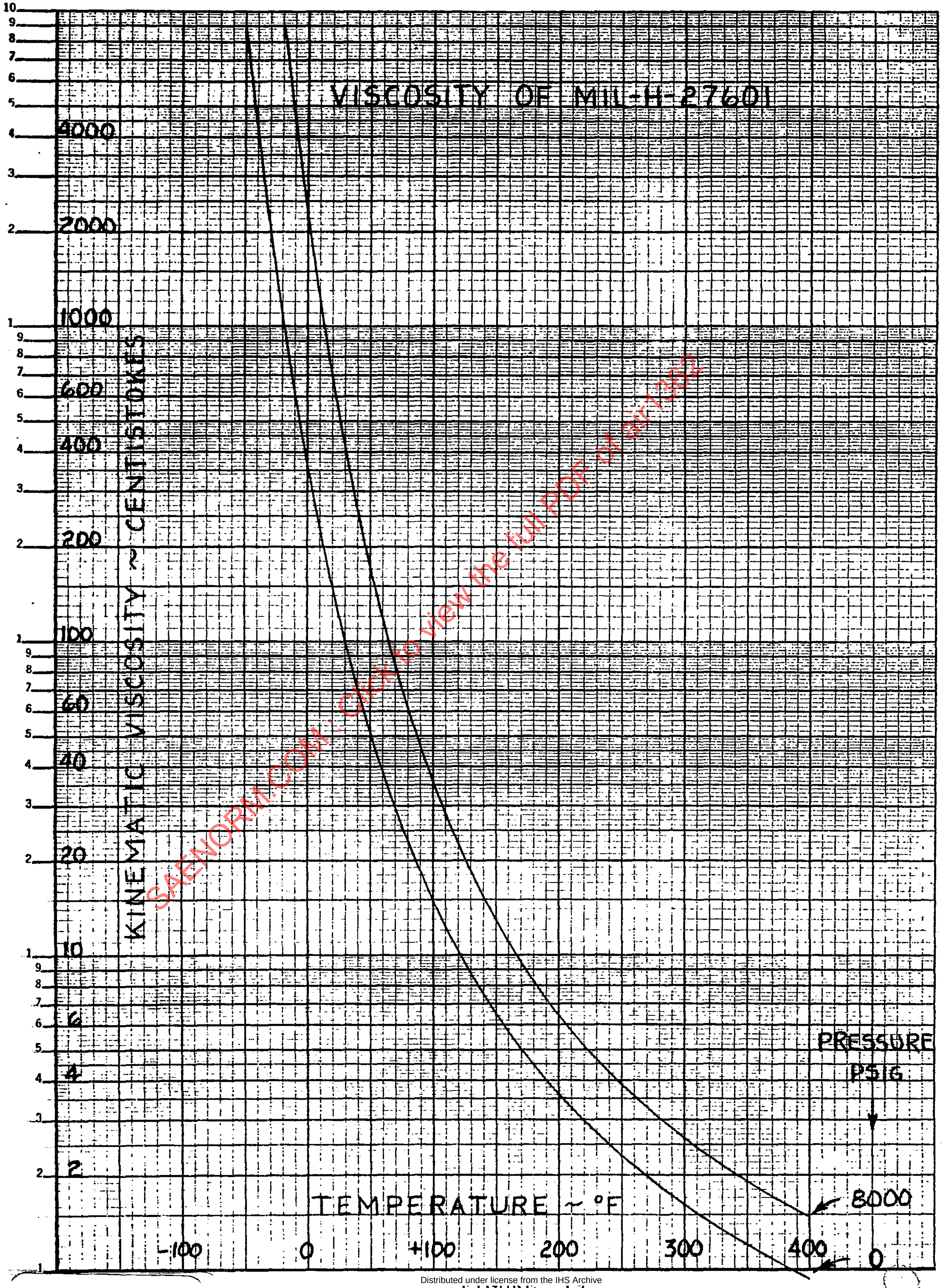

VISCOSITY OF MIL-H-27601
KINEMATIC VISCOSITY ~ CENTISTOKES
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
TEMPERATURE ~ °F
-100
0
+100
200
300
400
PRESSURE PSIG
8000
0

FIGURE 19

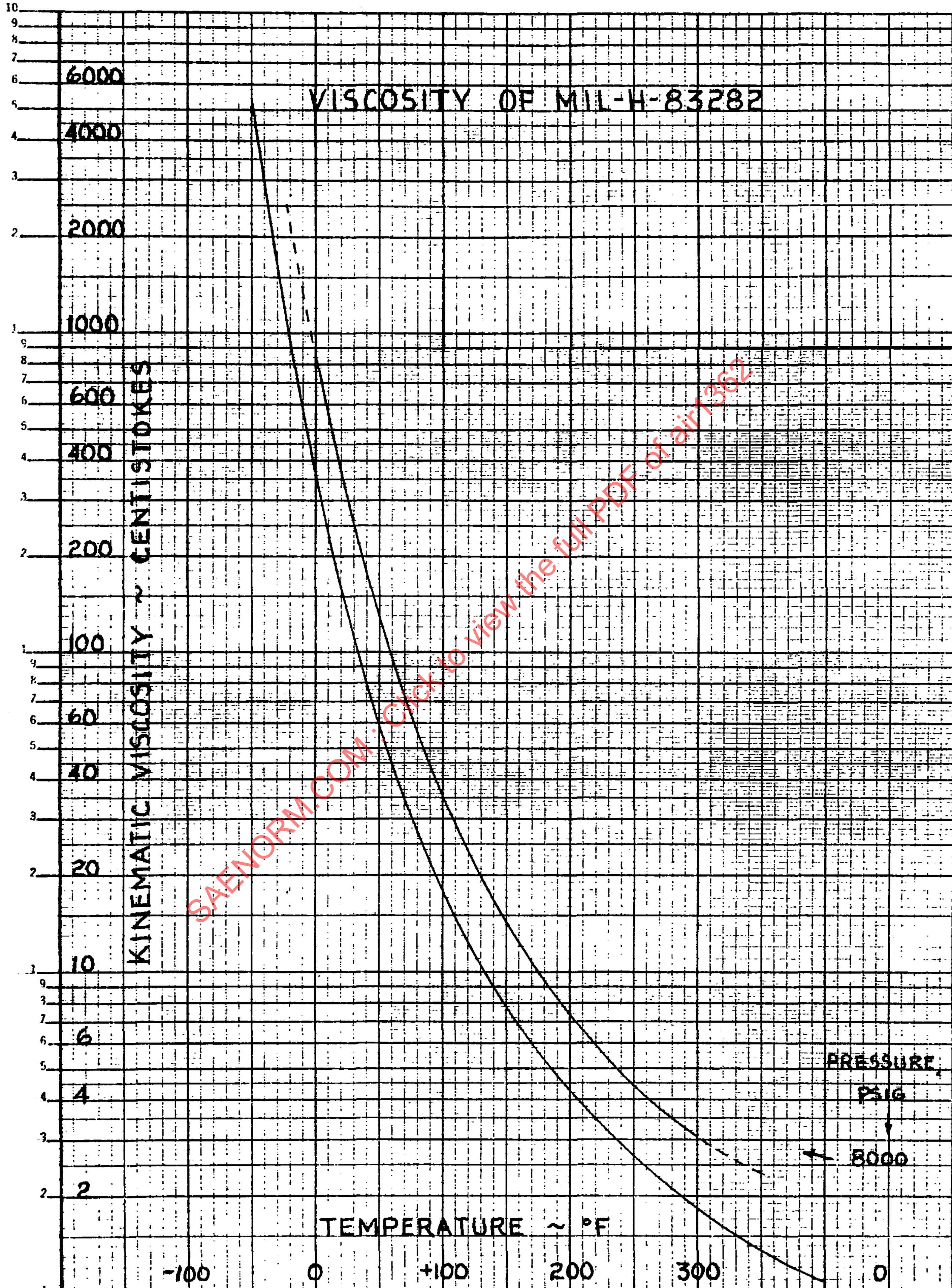

VISCOSITY OF MIL-H-83282
KINEMATIC VISCOSITY ~ CENTISTOKES
6000
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
TEMPERATURE ~ °F
-100
0
+100
200
300
PRESSURE, PSIG
8000
0

FIGURE 20