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PRELIMINARY INVESTIGATION OF EFFECTS OF EXPOSURE TO SULFUR HEXAFLUORIDE ON TENSILE AND YIELD STRENGTHS OF ALUMINUM AND STEEL

by Cecil E. Kirby and Philip O. Ransone

Langley Research Center
Hampton, Va. 23365

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SUMMARY

Results are presented from an experimental investigation to determine the effects of sulfur hexafluoride (SF_6) on the tensile strength and yield strength of various metals. At present, data concerning the effects on metals exposed to SF_6 are available for temperatures up to approximately 375 K and pressures up to 1 atmosphere. Additional data at higher temperatures and pressures are necessary because of the recently suggested use of sulfur hexafluoride as a test gas for the simulation of exhaust gas products from solid-propellant rocket motors. Specimens of 2024-T6 and 6061-T6 aluminum alloys, cold-rolled AISI C-1020 steel, and annealed AISI type 304 and 316 stainless steels and AISI No. 4130 steel were exposed to SF_6 at a temperature of 500 K and a pressure of 3.62 MN/m^2 for 8, 16, and 24 hours. Results indicate that SF_6 does not degrade the tensile strengths of any of the metals tested for up to 24 hours exposure at 500 K and 3.62 MN/m^2. A discussion of the physical and chemical characteristics of sulfur hexafluoride which make it attractive as a test gas for solid-propellant rocket-motor exhaust-gas simulation is also included.

INTRODUCTION

Sulfur hexafluoride has recently been suggested as a test gas for use in investigating flow patterns of solid-propellant rocket-motor exhaust gases where exhaust gases have expanded and cooled to temperatures below its stability temperature (900 K). It is the only gas with a ratio of specific heats of approximately 1.1 at 500 K (ref. 1) which is available in sufficient quantities for flow-simulation tests. The flow values obtained are typical for the ratio of specific heats of solid-propellant exhaust gases. An appreciation for the significance of the ratio of specific heats of a gas in the simulation of a supersonic flow pattern can be gained from the discussion in the appendix and reference 2.

The effects of sulfur hexafluoride on metals at the high temperatures necessary for solid-propellant exhaust-gas simulation are not well documented. It has been shown to be nonreactive with copper, steel, and aluminum only for temperatures up to 373 K (refs. 3 and 4), which is adequate for present uses. Sulfur hexafluoride is primarily used as a coolant for industrial power transformers and capacitors because of its good dielectric strength and cooling properties. The presence of the sulfur in the molecule, however, can, under some conditions, yield a corrosivity which is of engineering significance even though the gas is chemically stable (ref. 3). Gaseous fluorine compounds can also have corrosive effects on metals (ref. 5).

The purpose of this investigation was to determine if SF_6, at a pressure and temperature typical of rocket-motor testing, would degrade the strength of metals which might be used in the construction of such test equipment.

MATERIALS AND SPECIMENS

The metals selected for testing were 2024-T6 and 6061-T6 aluminum alloys, cold-rolled AISI C-1020 steel, and annealed AISI type 304 and 316 stainless steels and AISI No. 4130 steel. These metals are representative of the materials which might typically be used with sulfur hexafluoride in solid-propellant rocket-motor nozzle tests. The nominal compositions of these metals are shown in tables I and II and reference 6.

TABLE I.- NOMINAL COMPOSITION LIMITS FOR ALUMINUM SPECIMENS[1]

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
2024	0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.25	---	0.15
6061	0.40-0.8	0.70	0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.25	0.15	0.15

[1]Values from reference 6 in percent.

TABLE II.- LADLE CHEMICAL COMPOSITION LIMITS FOR STEEL SPECIMENS[1]

	C	Mn	P	S	Si	Cr	Mo	Ni
4130	0.28-0.33	0.40-0.60	0.040	0.040	0.20-0.35	0.80-1.10	0.15-0.25	----------
304	0.08	2.00	----	----	1.00	18.00-20.00	--------	8.00-12.00
316	0.08	2.00	----	----	1.00	16.00-18.00	2.00-3.00	10.00-14.00
C-1020	0.17-0.24	0.30-0.60	0.040	0.050	--------	----------	--------	----------

[1]Values from reference 6 in percent.

Standard ASTM rectangular tension test specimens were used (fig. 1 of ref. 7). Nominal thicknesses were 0.238 cm for steel specimens and 0.318 cm for aluminum specimens. Holes of 0.254-cm diameter were drilled 1.27 cm from each end of the specimens to permit placement of spacers as shown in figure 1.

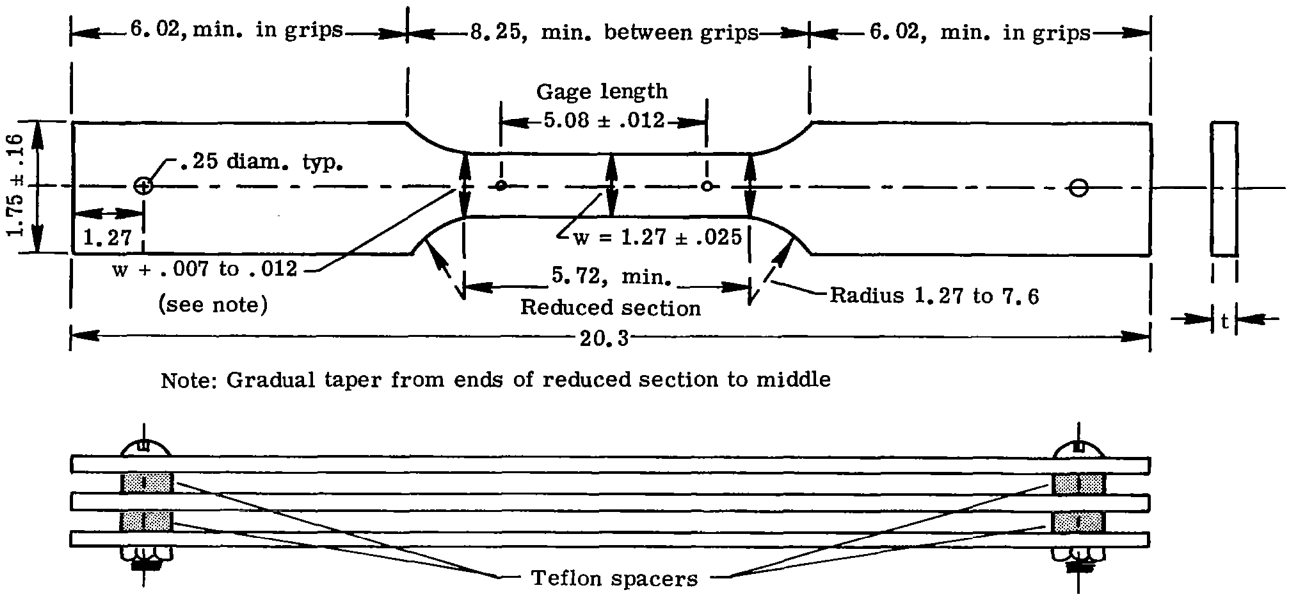

Figure 1.- Specimen dimensions and mounting scheme. All dimensions are in cm. (Symbols t and w represent thickness and width of material, respectively.)

Some representative properties of sulfur hexafluoride which indicate its applicability to solid-propellant exhaust-gas testing are shown in table III.

TABLE III.- SULFUR HEXAFLUORIDE PROPERTIES[1]

Formula	SF_6
Molecular weight	146.06
Melting point, K	323
Density of liquid at 223 K, g/ml	1.91
Density of gas at 760 mm and 298 K, g/l	6.093
Critical temperature, K	318.6
Critical pressure, MN/m^2	3.72
Specific heat at constant volume at 500 K, J/kg-K	795
Specific heat at constant pressure at 500 K, J/kg-K	878
Ratio of specific heats at 500 K	1.1
Surface tension, dynes/cm	11.63
Thermal conductivity, W/m^2-K	0.14
Viscosity of gas at 298°, poise	1.61
Boiling point, K	210
Relative density (air = 1)	5.1
Vapor pressure at 293 K, MN/m^2	1.04

[1]Property values from reference 3.

APPARATUS AND TEST PROCEDURE

Three specimens of each material were exposed to test conditions for 8, 16, and 24 hours. These times were selected as representative of times which might be encountered in a typical rocket-motor-nozzle test program. Specimens were installed in a cylindrical pressure vessel which was connected to a SF_6 supply. Three specimens were installed for each run. The pressure vessel was then mounted in a thermostatically controlled furnace as shown in figure 2. An iron-constantan thermocouple was inserted through the furnace wall and located adjacent to the pressure vessel. The pressure vessel and supply lines were evacuated to 1.33 kN/m^2 with a mechanical pump and backfilled with SF_6 to 1.72 MN/m^2. Pressure and temperature were adjusted to 3.62 MN/m^2 and 500 K and were recorded continuously during each run.

Three exposed specimens of each material and three specimens of the same material in the as-received condition were tension tested on an Instron testing machine. The cross-sectional area of each specimen was measured with a micrometer accurate to 0.01 mm. A strain-gage extensometer was used to measure tensile strain.

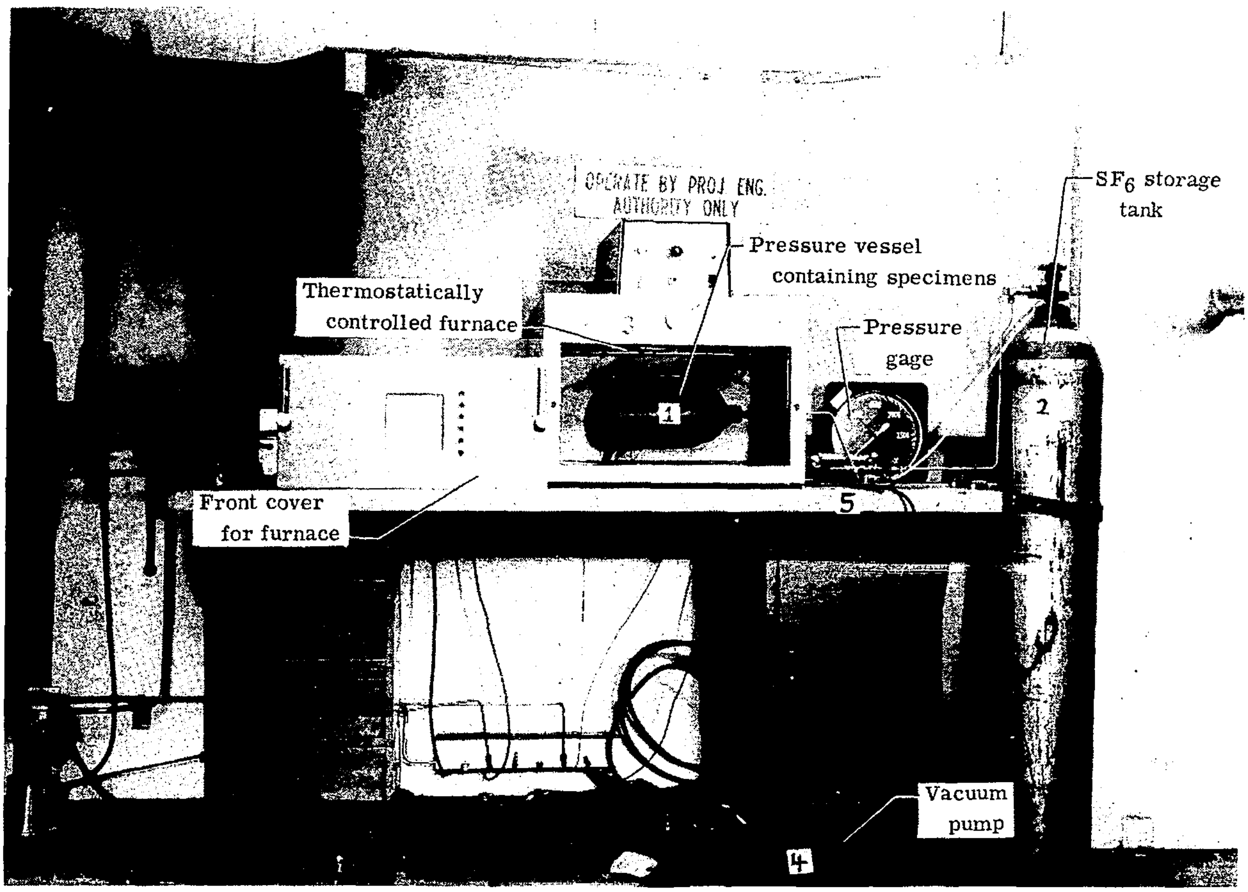

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Figure 2.- Experimental arrangement.

Since the tensile strength of aluminum decreases appreciably at relatively low temperatures (500 K), it was necessary to expose specimens of the 2024-T6 and 6061-T6 alloys to heating without exposure to SF_6. This exposure was to separate the effects of temperature from the effects of SF_6. For these tests, the specimens were mounted in the same manner as in the SF_6 tests with the air at 3.62 MN/m^2 as the test gas.

RESULTS AND DISCUSSION

Steel Specimens

Figures 3 to 6 show the effect of exposure time at test conditions on the tensile strength of C-1020, 304, 316, and 4130 steels. There was no variation in yield or ultimate strength for any of the steels tested except the C-1020 steel. After 8 hours exposure, the yield and ultimate strengths of the C-1020 steel increased by 2 percent and 3 percent, respectively. From 8 hours to 24 hours there was a very slight decrease in yield and tensile values which was termed insignificant. No effort was made in this investigation to determine the exact cause of the initial increase in tensile values; however, it is speculated that the increase was the result of one or more of the following reasons:

(1) Initial temperature effects

(2) Contamination of the specimen surfaces

(3) Reaction with SF_6 until surface layer inhibits further attack

Yield values of the 4130 steel showed a similar tendency although the ultimate strength seemed to be unaffected. The increase in yield strength after 8 hours was much less than 2 percent, however. A typical stress-strain curve is shown in figure 7. Since none of the steels tested showed a significant change in tensile strength or ductility, only the stress-strain curve for 304 stainless steel is included.

Some discoloration of the surface was observed on all specimens except the C-1020 steel. A brownish tint was barely detectable after 8 hours exposure to SF_6. The initially darker color of the C-1020 specimens could have prevented visual detection of such a discoloration. Further exposure resulted in darkening of the discoloration. No attempt was made to determine if the discoloration was a thin sulfide or fluoride layer or if it was an oxide layer formed by the presence of a trace of oxygen remaining in the test cylinder after initial evacuation.

Aluminum Specimens

The tensile strengths of the 6061-T6 and 2024-T6 aluminum specimens were lower after exposure to the SF_6 environment as shown in figures 8 and 9. The stress-strain curves in figures 10 and 11 show the results of exposure to SF_6 and air.

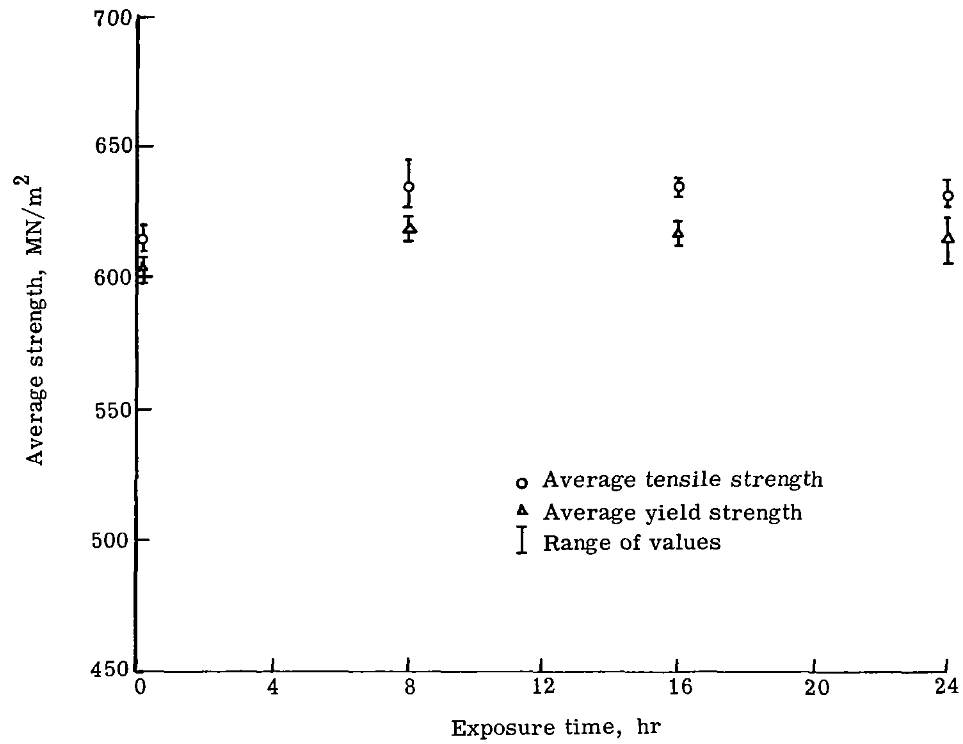

Figure 3.- Tensile and yield strengths of cold-rolled steel exposed to SF_6 at 500 K.

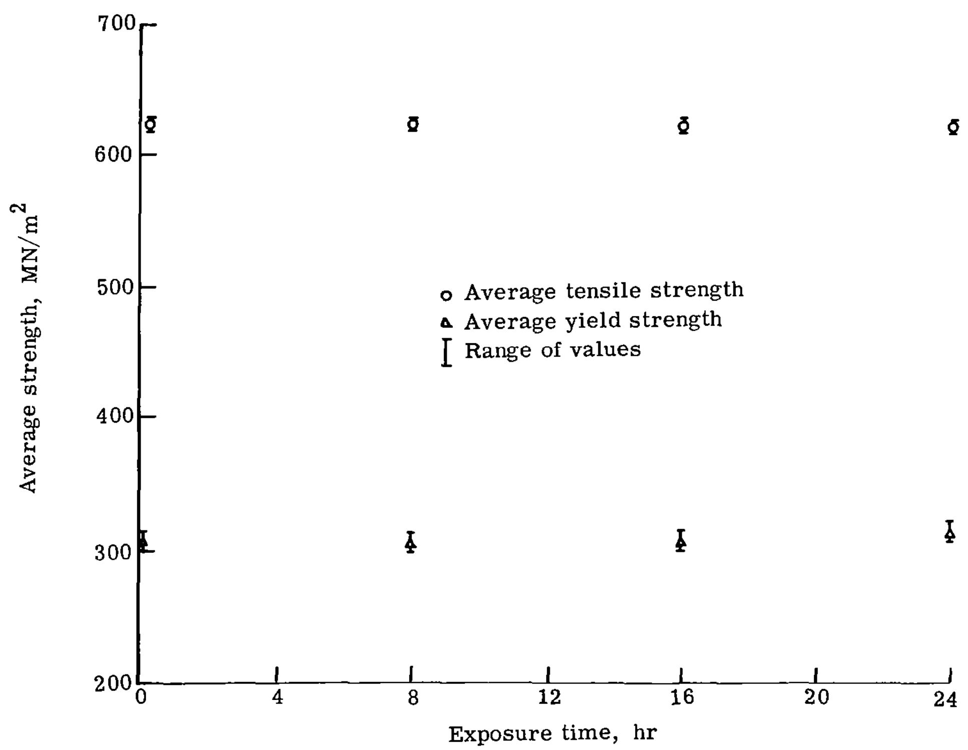

Figure 4.- Tensile and yield strengths of annealed 304 stainless steel exposed to SF_6 at 500 K.

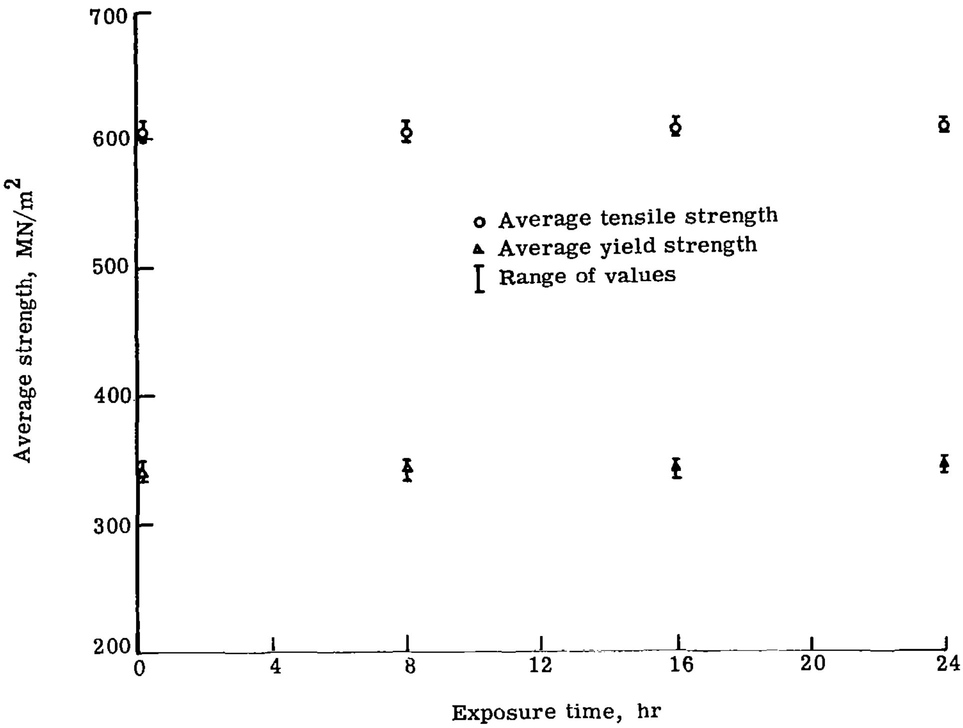

Figure 5.- Tensile and yield strengths of annealed 316 stainless steel exposed to SF_6 at 500 K.

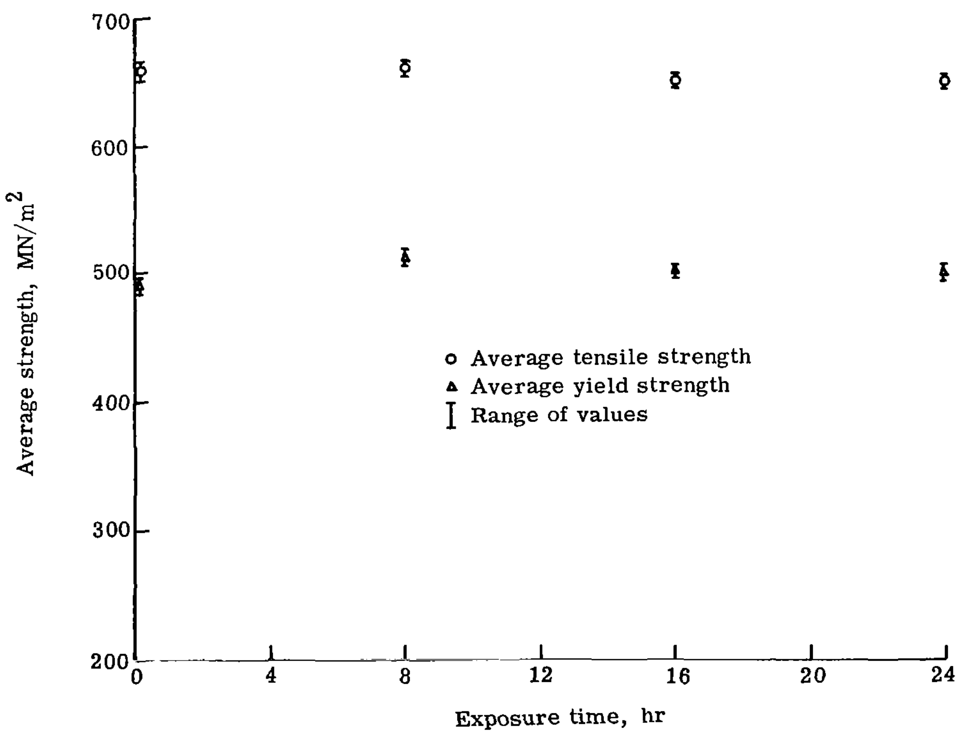

Figure 6.- Tensile and yield strengths of annealed 4130 steel exposed to SF_6 at 500 K.

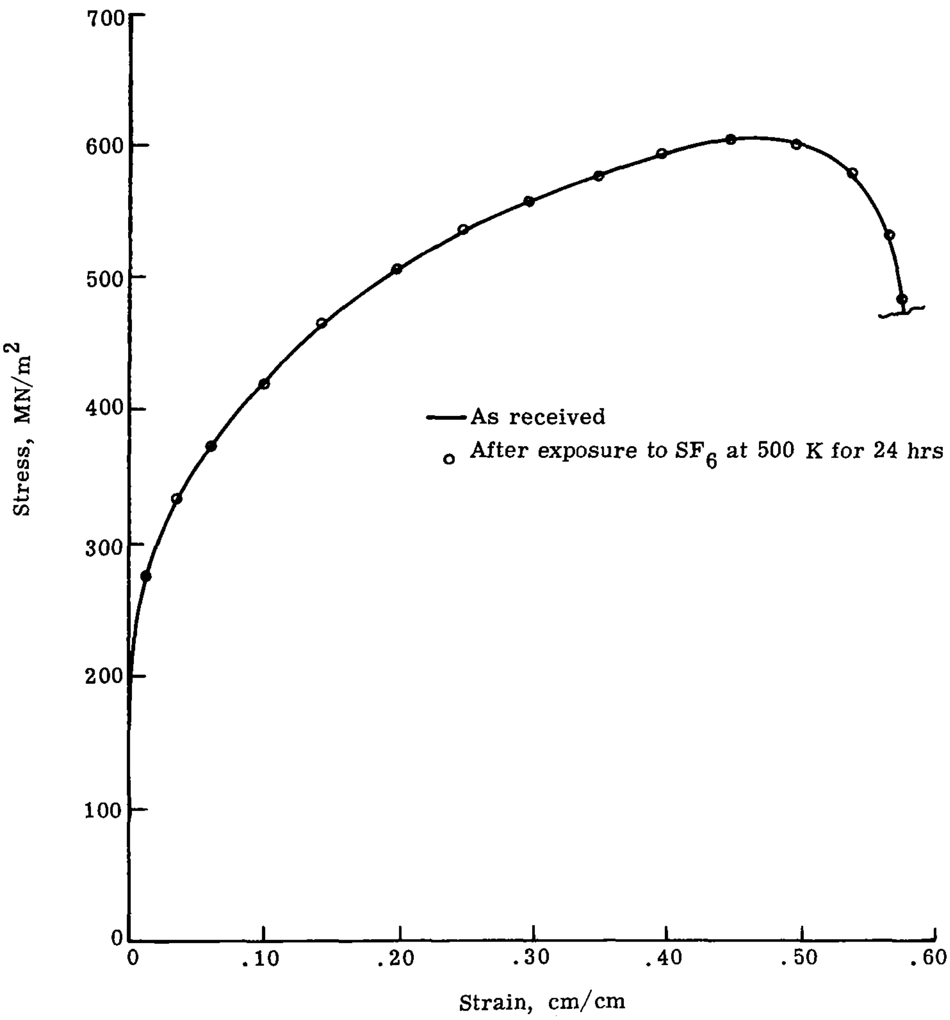

Figure 7.- Stress-strain curve for annealed 304 stainless steel.

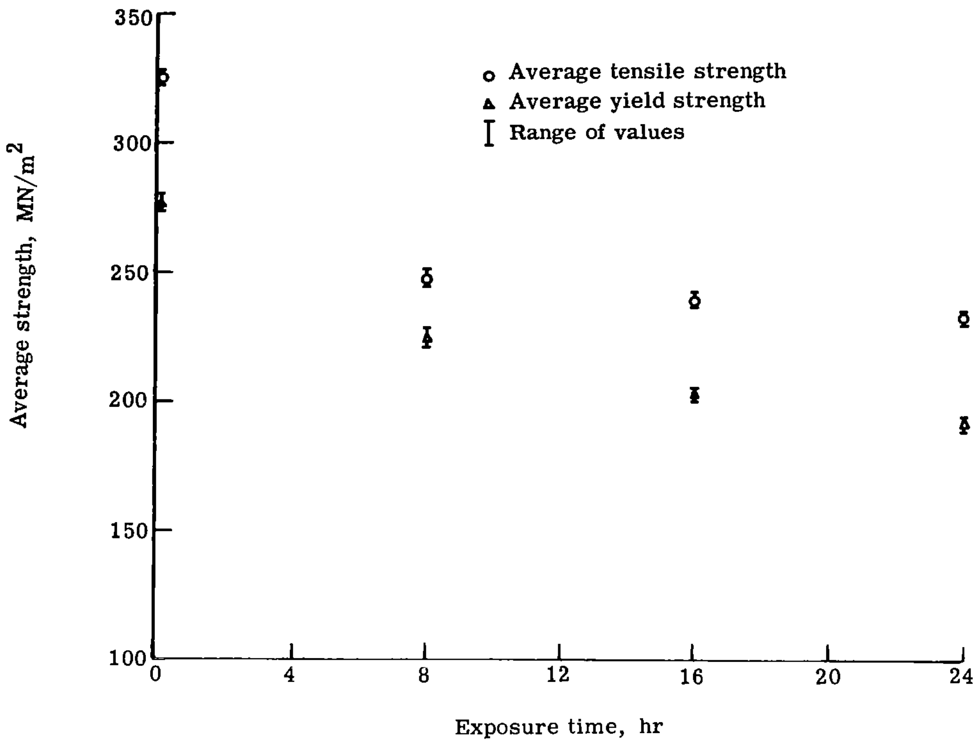

Figure 8.- Tensile and yield strengths of 6061-T6 aluminum alloy exposed to SF_6 at 500 K.

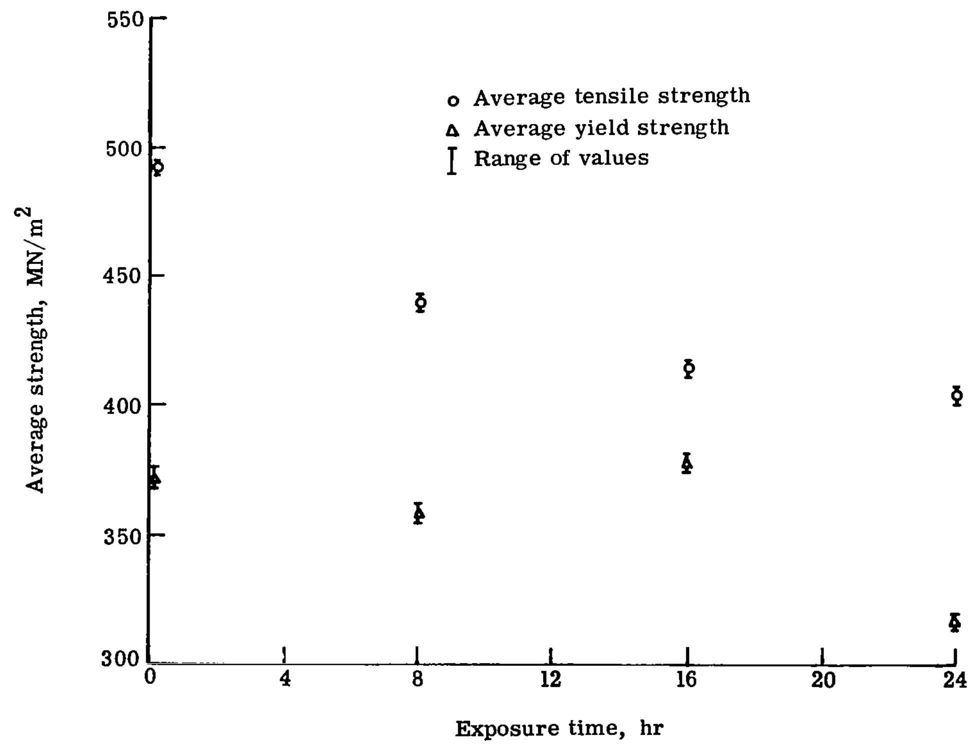

Figure 9.- Tensile and yield strengths of 2024-T6 aluminum alloy exposed to SF_6 at 500 K.

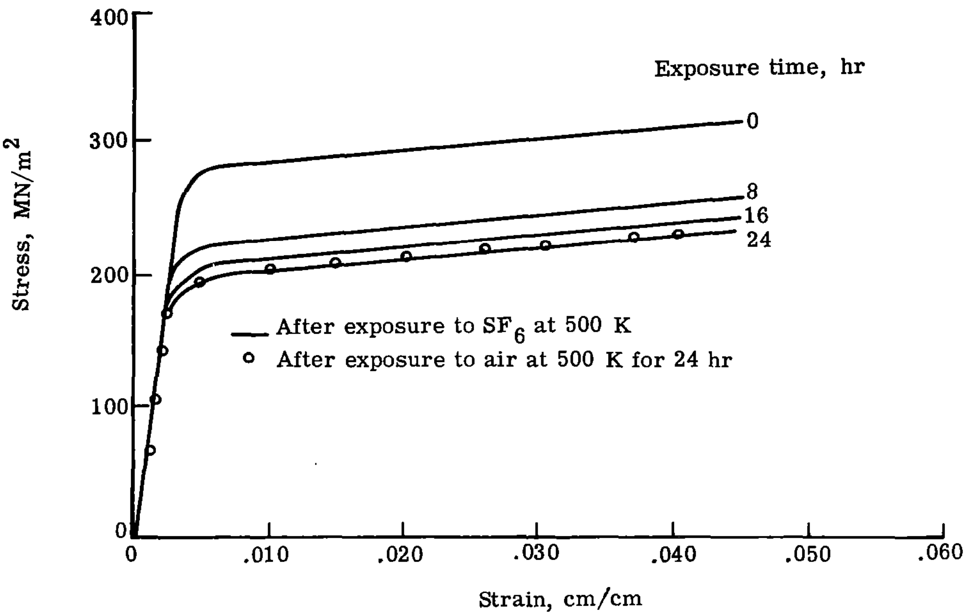

Figure 10.- Stress-strain curves for 6061-T6 aluminum alloy exposed to air and SF_6 at 500 K and 1.72 MN/m^2.

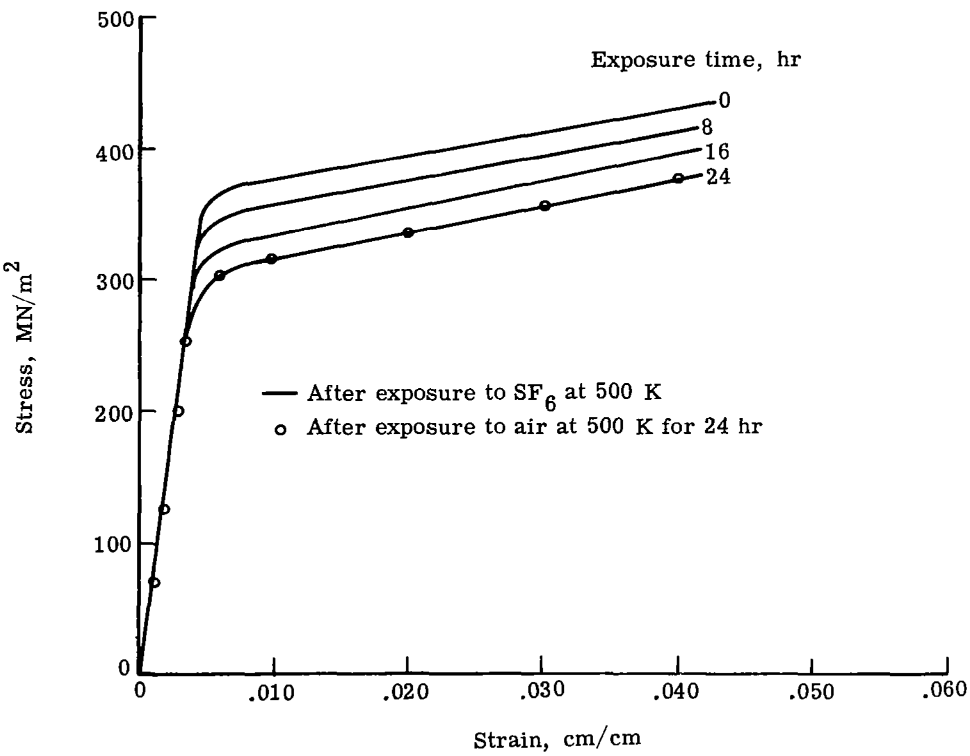

Figure 11.- Stress-strain curves for 2024-T6 aluminum alloy exposed to air and SF_6 at 500 K and 1.72 MN/m^2.

The reduction in strength for exposure to air at 500 K for 24 hours was the same as for exposure to SF_6 for 24 hours with both the 6061-T6 and the 2024-T6 alloys as shown by the agreement of the experimental value for both environments. The reduced values are, as expected, due to annealing of heat-treated aluminum (ref. 6).

Discoloration of the aluminum-alloy specimens was only visually detectable when a specimen heated in air was held next to a specimen heated in SF_6. Specimens heated in SF_6 had a barely discernible straw color, whereas specimens heated in air showed no change in color from as-received specimens. Although such a slight discoloration is apparently of little significance as far as strength of the aluminum alloys tested is concerned, it is an indication that a surface reaction with SF_6 may have taken place.

It was not deemed necessary to test specimens at temperatures below 500 K since chemical reactions would be slower at the lower temperatures; this can be seen by considering the Arrhenius expression for the reaction rate constant k, which is

$$k = A \exp\left(-\frac{E_a}{RT}\right)$$

where

A preexponential factor

E_a activation energy

R universal gas constant

T temperature

This equation shows that the reaction rate decreases exponentially as the temperature decreases, and any corrosion reaction effects would thus be less at lower temperatures.

CONCLUDING REMARKS

Sulfur hexafluoride (SF_6) does not significantly degrade the tensile or yield strength of cold-rolled AISI C-1020 steel and annealed AISI type 304 and 316 stainless steels and AISI No. 4130 steel or 6061-T6 and 2024-T6 aluminum alloys at temperatures up to 500 K and gas pressures up to 3.62 MN/m^2 for periods up to 24 hours.

Standard property values for tensile and yield strengths can be used for the aluminum alloys 2024-T6 and 6061-T6 and for 304, 316, and 4130 steels when designing pressure vessels for short term usage in sulfur hexafluoride applications. Further study is suggested for 1020 steel to separate temperature and other effects from the effects of SF_6.

Although the effects seem to be sufficiently negligible, there could be some problems associated with fracture toughness and fatigue properties as a result of the change in ductility.

Stress corrosion was not considered in this investigation and, therefore, appropriate caution should be exercised in designing pressure vessels for applications using SF_6 at pressures to 3.62 MN/m^2 and temperatures of 500 K.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 2, 1971.

APPENDIX

SIMILARITY PARAMETERS

Consider a prototype flow pattern and a model which is geometrically similar to the prototype. (See ref. 3.) Let L be a characteristic length for the prototype, and let $f_L L$ be the corresponding characteristic length for the model, where f_L is the scale factor for length. Similarly, the other properties of the prototype and model can be summarized as follows:

Property	Prototype	Model
Velocity	V	$f_V V$
Density	ρ	$f_\rho \rho$
Pressure	p	$f_p p$
Length	L	$f_L L$
Speed of sound	c	$f_c c$
Mach number	M	$f_M M$
Ratio of specific heats	k	$f_k k$

Euler's equation of motion must be satisfied for model and prototype; thus,

$$dp = -\rho V\, dV \tag{1}$$

and

$$d(f_p p) = -(f_\rho \rho)(f_V V)d(f_V V) \tag{2}$$

Since the scale factors are constant, both of these equations can be satisfied only if

$$f_p = f_\rho f_V^2 \tag{3}$$

Using the easily derived equation for the speed of sound in a perfect gas

$$c = \sqrt{\frac{kp}{\rho}} \tag{4}$$

shows that

$$f_c c = \sqrt{\frac{f_k f_p}{f_\rho}} \sqrt{\frac{kp}{\rho}} \tag{5}$$

and

$$f_c = \sqrt{\frac{f_k f_p}{f_\rho}} \tag{6}$$

Similarly using the defining equation for the Mach number

$$M = \frac{V}{c} \tag{7}$$

gives

$$f_M M = \frac{f_V V}{f_c c} \tag{8}$$

and

$$f_M = \frac{f_V}{f_c} \tag{9}$$

Combining equations (3), (6), and (9) gives

$$f_M = \frac{1}{\sqrt{f_k}} \tag{10}$$

By examining the energy equation, taking into account the effects of viscous work and thermal conductivity, it can be shown that k must be the same for both model and prototype – that is, $f_k = 1$ – in order to conclude that $f_M = 1$. Therefore similarity of the ratio of specific heats k is inherently required when the Mach number is used as a flow similarity parameter.

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