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Repr. from ~~Mag~~ Metals Eng. Quart.,
May 1963 ~~[illegible]~~

~~[illegible]~~ refs Presented at Natl. Metal
Congr., New York, Nov. 1, 1962

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Reprinted from

METALS ENGINEERING QUARTERLY
May, 1963

AMERICAN SOCIETY FOR METALS
Metals Park, Ohio

A Summary of the Behavior of Materials At Cryogenic Temperatures

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A summary is given of some of the pertinent results that have been obtained at the NASA Lewis Research Center relative to the behavior of materials for temperatures ranging from 75 to -423 F. The results were obtained with uniaxial, sheet-type test specimens. The strength characteristics of a number of engineering materials that might be employed in the fabrication of cryogenic propellant tanks for space vehicles are briefly discussed. The results of burst testing biaxially stressed model pressure vessels at 75 and -423 F are presented and preliminary attempts to correlate the biaxial burst strengths with uniaxial data through the use of Griffith-Irwin and Neuber concepts are discussed. ASM-SLA Classification: Q-general, 2-63; SS, Al-b, Ti-b.

Author

THE USE of hydrogen and oxygen as the fuel and oxidant in high-performance rocket motors for missiles and space vehicles results in the need to store these elements in their liquid state aboard the vehicle. This subjects some structural components of the vehicles to temperatures nearing that of absolute zero. For example, the walls of propellant tanks approach the boiling temperature of the contained fluid, which for liquid oxygen and liquid hydrogen is -297 and -423 F, respectively, at 1 atmosphere of pressure. Because the fuel and oxidant tanks of missiles and space vehicles are a significantly large portion of the total weight of the vehicles, every effort is made to reduce tank weights to an absolute minimum consistent with reliability. In order to design a tank for cryogenic applications the designer must have a knowledge of the behavior of materials at temperatures of the order of -300 F or lower. Until recent years there has been little need to know and understand the behavior of materials at temperatures much below about -60 F and, as a result, very little information on the behavior of engineering materials at temperatures of -300 F or lower has been available.

For the past several years the NASA Lewis Research Center, as well as other government agencies and industrial organizations, has been investigating numerous materials in order to determine their properties at cryogenic temperatures. Most of the investigations have been aimed at determining the mechanical properties of the most promising materials using sheet-type test specimens subjected to uniaxial stress. From the designer's standpoint, however, there is need to know the behavior of materials under the biaxial conditions that exist in a pressure vessel. In order to investigate the effects of biaxial stresses on materials at cryogenic temperatures, research is now in progress at the Lewis Research Center wherein model pressure vessels, made from materials that appear promising at cryogenic temperatures, are pressurized with cryogenic liquids to burst failure. This latter research permits the study of methods for correlating data from the relatively simple, low-cost uniaxial-type tests with that obtained with the more complex and expensive testing of pressure vessels. Hopefully, correlating methods will be achieved that will enable the designer to apply data obtained from uniaxial tests to his tank design in a more reliable manner than currently available.

It is the purpose of this paper to review the characteristics of a number of typical engineering materials as determined from uniaxial tensile data at room and cryogenic temperatures. In addition, results will be shown relative to methods for correlating the burst strength of pressure vessels with uniaxial tensile data at both room temperature and -423 F.

Uniaxial Tests

Materials. The sheet materials investigated at room and cryogenic temperatures within the past 3 years at the Lewis Research Center are listed in Table 1. Pertinent material and physical variables as well as references are included. Not all of the materials and tests indicated in Table 1 will be discussed herein; an attempt will be made, however, to generalize and indicate some of the significant results that have been obtained.

The authors are associated with the Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio. This paper was presented November 1, 1962 at the National Metal Congress, New York, N. Y.

Table 1. Materials Investigated

Material	Thickness, in.	Heat treatment	Remarks	Reference
AISI 301	0.025		Effect of rolling temperature investigated	6
AISI 301 (CEUM)	0.025		50, 60, 70, and 80% cold reduction	6
AISI 301	0.063		20, 40, 60, and 70% cold reduction	4
AISI 301	*0.031*		*70% cold reduction*	4
AISI 304L	0.063		40, 60, and 70% cold reduction	4
AISI 304L	0.031		70% cold reduction	4
AISI 310	0.020		75% cold reduction	6
Inconel-X	0.025		Effect of rolling temperature	6
V-36	0.025		50% cold reduction	6
TI-5 Al-2.5 Sn	0.025	Annealed	Low, normal, and high interstitial contents	6
Ti-6 Al-4 V	0.063	Annealed		5
Ti-6 Al-4 V	0.063	Solution treated		5
Ti-4 Al-3 Mo-1 V	0.040	Annealed		5
Ti-4 Al-3 Mo-1 V	0.063	Solution treated		5
Ti-16 V-2.5 Al	0.063	Annealed		5
Ti-16 V-2.5 Al	0.063	Solution treated		5
Ti-13 V-11 Cr-3 Al	0.063	Solution treated		5
Ti-5 Al-2.5 Sn	0.063	Annealed	High interstitial content	5
Ti-8 Mn	0.063	Annealed		5
Ti-6 Al-4 V	0.035	Annealed	Welded after heat treatment, welds were fusion butt welded using an inert-gas-shielded arc with a consumable electrode—no filler material used	7
Ti-6 Al-4 V	0.035	Solution treated		7
Ti-6 Al-4 V	0.030	Annealed		7
2014-T6	0.125		Welded with 4043 filler Welds made with a single pass using inert-gas-shielded arc-weld	3
2219-T62	0.125		Welded with 2319 filler	3
5456-H321	0.125		Welded with 5556 filler	3
6061-T6	0.125		Welded with 4043 filler	3
7075-T6	0.125		Welded with 4043 filler	3
7079-T6	0.125		Welded with 5556 filler	3
7178-T6	0.125		Welded with 5556 filler	3
AM-350	0.043	1710 F, ½ hr; air cool; —100 F, 3 hr; 850 F, 3 hr; air cool	Investigated in liquid fluorine	
AMS-6434	0.030	1600 F, ½ hr; oil quench; 500 F, 1 hr; air cool		
Inconel-X	0.031	Aged 1300 F, 21 hr		
AISI 301	0.031		70% cold reduced	
AISI 304L	0.031		70% cold reduced	
2014-T6	0.125			
6061-T6	0.125			
7075-T6	0.125			
Ti-6 Al-4 V	0.035	Annealed		
Ti-6 Al-4 V	0.035	Solution treated		

Specimens. Figure 1 shows a sketch of the smooth and sharp-notch sheet tensile specimens used throughout the investigations. The specimens were edge machined to the nominal dimensions shown in the figure. The sharply notched specimens had a notch radius less than 0.001 in. and, in general, complied with the specimen design specifications of the ASTM Committee on Fracture Testing of High Strength Sheet Materials (1). A detailed discussion relative to the selection of the sharp-notch tensile specimen is given by Espey, Jones and Brown (2). In the case of welded specimens, the weld was located in the longitudinal center of the specimen; the weld bead was not removed and any notches were located in the longitudinal center of the weld.

Apparatus. In all tests, the specimens were loaded through pins to ensure proper load alignment. Tests were made at three temperatures: room temperature, -320 F, and -423 F. The cryogenic temperatures represent the boiling points of liquid nitrogen and liquid hydrogen, respectively, at 1 atmosphere of pressure. The boiling point of liquid nitrogen is only 23 F lower than that for liquid oxygen, and inasmuch as liquid nitrogen is inert, nontoxic, and easy to handle, it was used throughout the investigations to obtain a temperature that closely approximated that of liquid oxygen. The tests at room temperature and -320 F were made in a universal testing machine. For safety reasons, the tests using liquid hydrogen were made in a remote area; these tests also involved the use of specially designed equipment for remotely controlling the loading of the specimens. In the tests made at -320 and -423 F, the specimens and the specimen holders were submerged in special cryostats that contained either liquid nitrogen or liquid hydrogen. A more detailed description of the loading apparatus and the cryostats is given in (3) and (4). The extensometer used for tests at -320 and -423 F was a mechanical strain transfer device that actuated a dial indicator located external of the cryostat.

Procedure. The tensile strength, yield strength (0.2% offset), elongation, and sharp-notch tensile

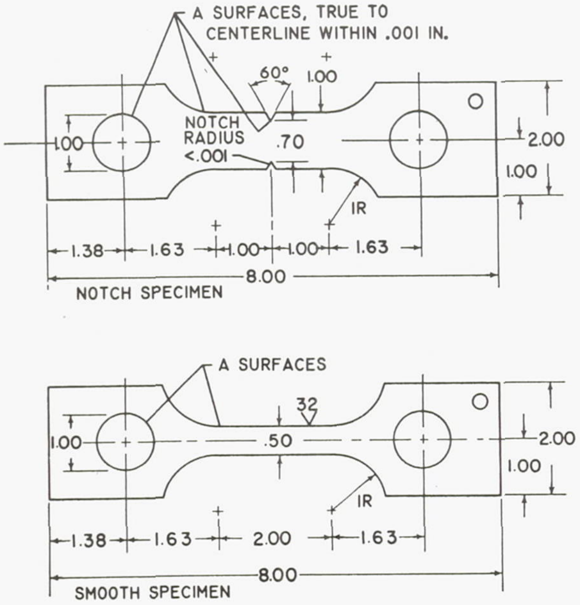


Fig. 1. Smooth and sharp edge notch sheet tensile specimens.

strength at each temperature and material condition were generally determined for a minimum of three test specimens. The strain rates for all tests were less than 0.005 in. per in. per min. Slight variations in the test procedures were sometimes required; the detailed procedures employed for each material can be found in the references listed in Table 1.

Discussion

Effect of Temperature. Figure 2 shows the variations in actual strength and elongation of four materials, namely V-36 (a cobalt-base alloy), AISI 304L stainless steel, titanium (5 Al-2.5 Sn), and 2014-T6 aluminum. For all of these materials it can be seen that the ultimate tensile and yield strengths increase as the temperature is decreased from 75 to -423 F. The V-36, 304L, and 2014-T6 materials show increases of ultimate tensile strength ranging from about 45 to 50%, while the Ti-5 Al-2.5 Sn material shows an increase of 125%. In most cases the yield strength closely parallels the behavior of the ultimate strength.

Although the ultimate and yield strengths are of considerable importance, the designer of cryogenic tanks for space applications will perhaps be more concerned with the sharp-notch tensile properties of the materials. This is because the tanks of space vehicles may be very large structures in which it will be impossible to eliminate or detect all flaws introduced during the various fabrication processes, in spite of the utmost care in fabrication, quality control, and inspection. This suggests that the design stresses in cryogenic tanks will probably be based upon the sharp-notch strength of the material rather than its yield strength. For this reason the sharp-notch tensile properties of materials that may be used in the fabrication of cryogenic pressure vessels are of considerable importance.

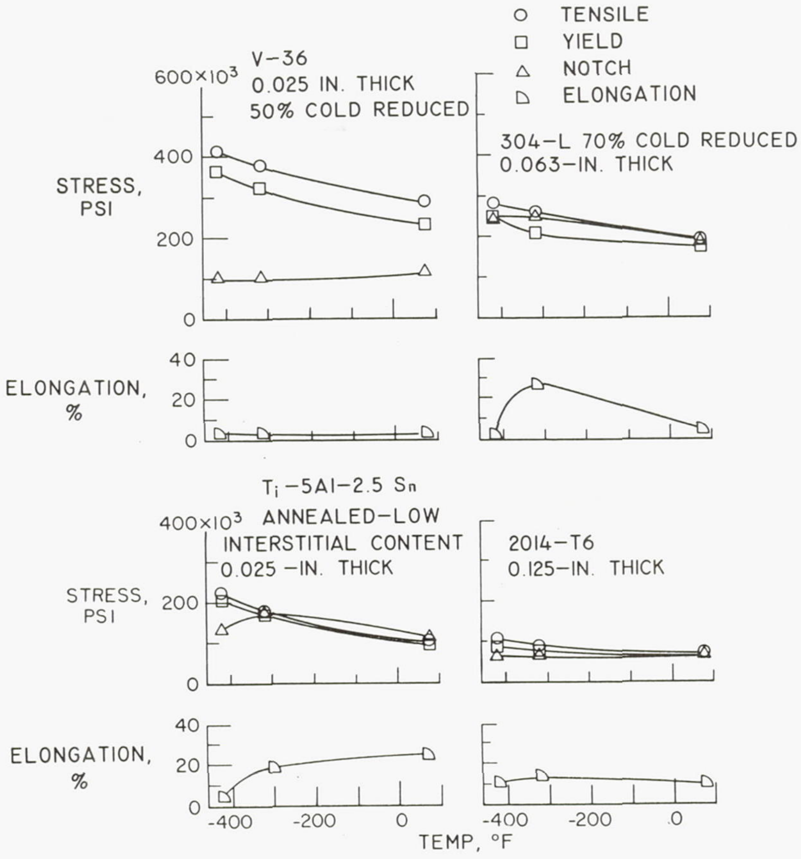


Fig. 2. Tensile characteristics of several sheet materials as a function of temperature.

It can be seen from Fig. 2 that the notch strength of V-36 is appreciably below that of the yield strength throughout the entire temperature range. The V-36 material exhibits a notch strength that is essentially constant at about 100,000 psi; this value is only about 28% of the yield strength at -423 F. This would, of course, be an unsuitable material for cryogenic use and is presented here primarily as an example of a material that has poor cryogenic properties.

Materials such as 304L (70% cold worked) and Ti-5 Al-2.5 Sn have excellent notch strength characteristics from room temperature to -320 F inasmuch as their notch strengths are above the yield strength for this temperature range. Even at -423 F the 304L exhibits a notch strength that is only slightly less than its yield strength. At -423 F, Ti-5 Al-2.5 Sn becomes notch sensitive and exhibits a notch strength of about 130,000 psi, which is 65% of the yield strength.

The notch strength of the 2014-T6 aluminum alloy shows a slight increase as temperature decreases and at -423 F its notch strength is about 78% of the yield strength. Thus the notch sensitivity of the aluminum alloy at -423 F is somewhat less than that of Ti-5 Al-2.5 Sn but its absolute notch strength level is only about ½ that of the titanium alloy. On the basis of notch-strength to density at -423 F, AISI 304L has the highest value (827,000 in.), Ti-5 Al-2.5 Sn next at 812,000 in., 2014-T6 next with 656,000 in., and V-36 last at 331,000 in. From this latter comparison it can be seen that 304L and Ti-5 Al-2.5 Sn compare favoraly to each other on a notch-strength-to-density basis and are definitely superior in this factor to 2014-T6 and V-36.

Another way to illustrate the behavior of materials at cryogenic temperatures is presented in Fig. 3 where the yield strength-to-density ratio and the notch-to-yield strength ratio is plotted in bar form for a number of materials for the three temperatures investigated. The materials included in Fig. 3 are those that were discussed previously in Fig. 2, as well as several additional materials including a filament-wound reinforced plastic sheet material.

The materials in Fig. 3 have been ranked according to their yield-strength-to-density ratios at -423 F. It can be seen that the best materials from the standpoint of yield strength-to-density at -423 F are the filament-wound reinforced plastic material and the Ti-6 Al-4 V and Ti-5 Al-2.5 Sn alloys. The actual yield strength-to-density ratios for these materials range from about 1.25 to 1.70 million in. at -423 F. For the room-temperature condition the reinforced plastic and the Ti-6 Al-4 V alloy also have the highest yield strength-to-density ratios of the materials shown; however, their superiority over the other

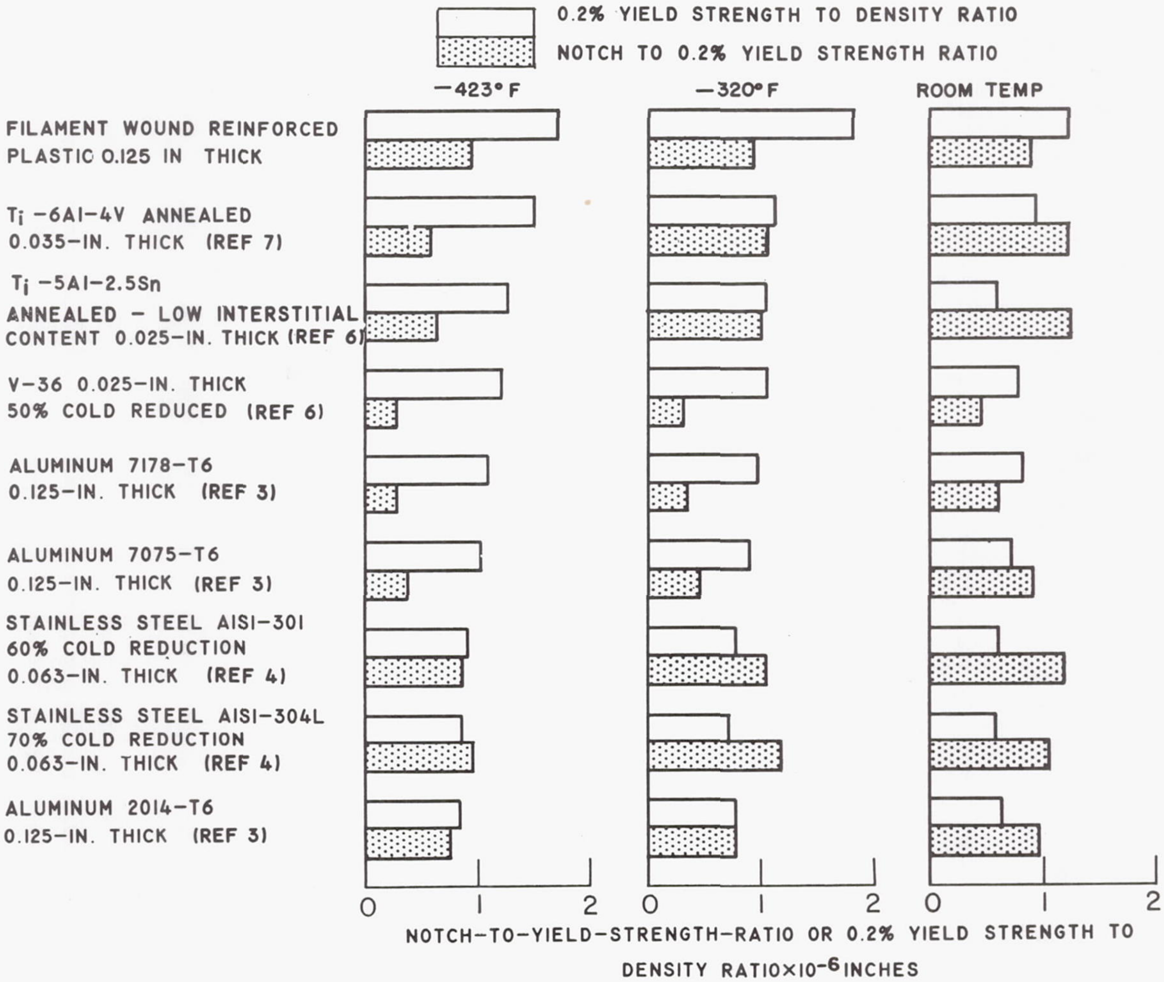


Fig. 3. Yield strength-to-density and notch-to-yield strength ratios for several materials at 75, —320 and —423 F.

materials in this factor is not as pronounced at room temperature as it is at the cryogenic temperatures.

As shown in Fig. 3 the metals, with the exception of Ti-5 Al-2.5 Sn, having the highest strength-to-density ratios at cryogenic temperatures also exhibit notch-to-yield strength ratios that are less than unity and, in some cases, values that are less than 0.5. This indicates that some materials are extremely notch sensitive and that the conventional design practice of basing working stresses on yield strength cannot safely be used. It infers that if a flaw or crack exists in the final structure, a failure could occur at a stress considerably below the yield strength. The use of notch-sensitive materials in the design of pressure vessels requires that "unconventional" design approaches be employed. Such approaches using uniaxial notch-strength data will be discussed in a later section of this paper. It should be noted in Fig. 3 that the Ti-5 Al-2.5 Sn alloy exhibits excellent notch properties at 75 and -320 F, having notch-to-yield strength ratios of 1.23 and 1.00, respectively, at these temperatures. Even at -423 F this alloy exhibits a notch-to-yield strength ratio of about 0.63, which is higher than for any of the metals shown in Fig. 3 except the AISI 301 and 304L and the 2014-T6 alloys which have relatively low yield strength-to-density ratios.

In general, the results presented in Fig. 3 indicate that as a metal becomes stronger (whether from temperature reduction, cold working, heat treatment, alloying, etc.) it becomes more brittle and notch sensitive. Some materials offer better combinations of strength and notch sensitivity than others, but in any event some compromise in material selection is required to obtain reasonably high strength without paying too severe a penalty in notch properties. Although only one filament-wound reinforced plastic material has been investigated, it would appear that this type of material shows considerable promise for use at cryogenic temperatures and may be superior to many metals for very low temperature use; its notch properties were excellent throughout the range of test temperatures investigated. The detailed behavior of the materials discussed in Fig. 2 and 3 as well as those listed in Table 1 (with the exception of the filament-wound reinforced plastic) can be found in references (3) through (7).

Effect of Cold Working. A typical example of the effect of cold working on the properties of a material are shown in Fig. 4 for AISI 301 sheet. The data for this figure were obtained from reference (4). The strength and elongation properties are plotted against Rockwell C hardness (or percent cold reduction) for a test temperature of -423 F. For the condition of 70% cold reduction, the data for two material thicknesses were available as indicated on the abscissa. A 70% reduction of the thin material (0.031 in. thick) resulted in a hardness Rockwell C-52, while the same reduction in the thicker material (0.063 in. thick) resulted in a Rockwell C-49.

The importance of results such as those shown in Fig. 4 is that cold working can be very beneficial in permitting higher working stresses up to a point, and then further cold working can have a serious degrading effect on the notch properties of the material. Figure 4 also shows that the directional effects that can be expected in any cold worked material are much more pronounced for the notch properties than for either the smooth or yield tensile properties. More complete discussion of the effects of cold working the 301 and 304L materials and their behavior at cryogenic temperatures is given in (4).

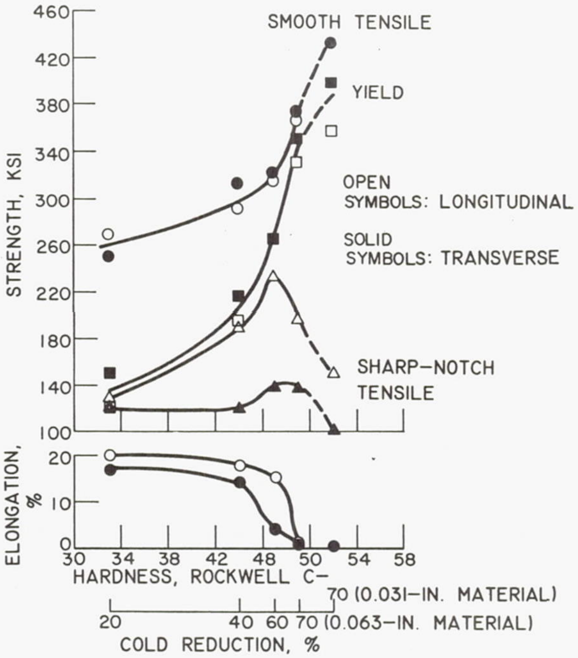
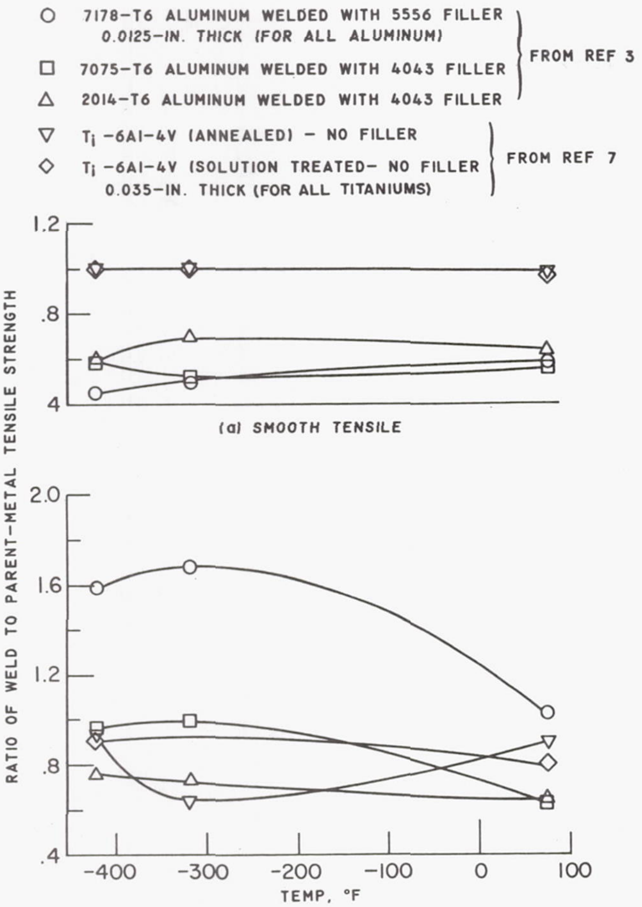


Fig. 4. The —423 F strength properties and elongations of AISI 301 sheet as functions of hardness and cold reduction. (Ref. 4).

Effect of Welding. An indication of the welded properties of several metals (three aluminum and one titanium alloy in two conditions) is presented in Fig. 5. The data for this figure are from references (3) and (7). In Fig. 5(a) the ratio of the welded strength to the parent metal strength is plotted against temperature for smooth specimens. Welding had essentially no effect on the smooth tensile properties of the Ti-6 Al-4 V material throughout the range of test temperatures.

The effect of welding on notch strength is illustrated in Fig. 5b. The annealed Ti-6 Al-4 V had notched weld properties that were about 0.9 that of the notched parent metal at 75 and -423 F, but at -320 F, its welded notch properties were only about 0.64 that of the notched parent metal. The actual values of the welded notch strength at temperatures of 75, -320, and -423 F were 130,000, 104,000, and 103,000 psi, respectively (7). The corresponding strength values of the notched parent material were 143,000, 163,000, and 110,000 psi. From these strength values it can be seen that the notched weld strengths were about equal at -320 and -423 F and about 26,000 psi less than the room-temperature strength. From the foregoing strength values it can be seen that the reason for the ratio of the notched weld strength to the notched parent metal strength of the annealed Ti-6 Al-4 V being low is the fact that the parent metal notch strength is relatively high at -320 F. An attempt to improve the -320 F welded and notched strength of the material by stress relieving the welded material at 1300 F for 1 hr offered no significant change in the welded notch strength at -320 F.

The welded and notched solution treated titanium alloy shows about a 20% loss in welded strength relative to the parent metal at 75 F, but improves as



(a) SMOOTH TENSILE

(b) NOTCH TENSILE

Fig. 5. Weld to parent metal strength ratios for several aluminum and titanium sheet materials as a function of temperature.

the temperature decreases and is degraded only about 10% at -320 and -423 F.

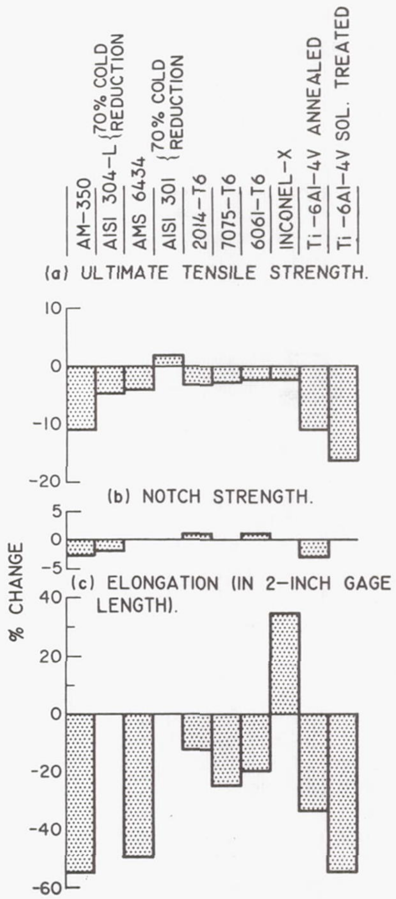
For the three aluminum alloys presented in Fig. 5, the welded notch properties vary considerably. The 7178-T6 alloy exhibits a marked improvement of its welded strength relative to parent metal strength at -320 and -423 F. The parent 7178-T6 metal is very notch sensitive at cryogenic temperatures as indicated in Fig. 3; apparently the welding of the material tends to anneal it and reduce its ultimate strength (as indicated in Fig. 5a) but improves its notch strength at the cryogenic temperatures.

There is a tendency for the 7075-T6 aluminum in the welded and notched condition to parallel the behavior of the 7178-T6 but at a reduced ratio of welded-to-parent material notch strength. At the cryogenic temperatures the 7075-T6 aluminum has welded notch-to-parent metal ratios that are nearly 1.0.

The notched 2014-T6 material was degraded considerably by welding throughout the test temperature range from 75 to -423 F, however, there was a steady increase of the notched welded-to-parent metal strength with decreasing temperature. It can be seen in Fig. 3 that the 2014-T6 aluminum was not nearly as notch sensitive as the 7000 series aluminum alloys; it appears, therefore, that welding may damage a material that is not initially notch sensitive and, conversely, may improve a material that is initially *notch sensitive*.

The data in Fig. 5 do not necessarily reflect the behavior that can be expected from all welded materials at cryogenic temperatures; they merely reflect the types of variations that can be anticipated. From the results shown in Fig. 5 it can be seen that the smooth and notched welded strength characteristics of materials can vary widely from material to material and also vary widely for a given material from room temperature to -423 F. It can also be seen that it would not be wise to extrapolate the behavior of a material to conditions other than for which test data are available.

Compatibility of Cryogenic Fluids with Materials. Generally cryogenic liquids such as liquid nitrogen, liquid oxygen and liquid hydrogen are considered to be compatible with most engineering materials as far as chemical reactions are concerned. One cryogenic liquid, however, that has been of concern to many people in the field of rocketry is liquid fluorine. Fluorine as an oxidant in chemical rocket propulsion systems can offer higher performance than oxygen, but the problems in handling and storing this toxic and reactive material, has in general limited its current use in rocketry to research purposes. An investigation has been made at the Lewis Research Center to determine whether liquid fluorine will adversely affect the strength characteristics of certain sheet metals.



(a) ULTIMATE TENSILE STRENGTH.

(b) NOTCH STRENGTH.

(c) ELONGATION (IN 2-INCH GAGE LENGTH).

Fig. 6. Effect of liquid fluorine on mechanical properties of several sheet materials. (Properties in liquid fluorine compared to those in liquid nitrogen; test temperature —320 F).

As a reference base for this determination, specimens of materials of the same parent sheet and same heat were first tested in liquid nitrogen at -320 F and then in liquid fluorine, also at -320 F. In this manner the test conditions were the same except that the relatively inert liquid nitrogen was replaced by liquid fluorine. The tensile specimens that were subjected to the liquid fluorine environment were "preloaded" prior to actual rupture. The preloading consisted of stressing the smooth specimens in liquid fluorine to a value equivalent to 90% of the 0.2% yield strength of the material in the liquid nitrogen environment. Notched specimens were also similarly preloaded in liquid fluorine to a value of 90% of the notch strength of the material in liquid nitrogen. The preloading was maintained for a period of 2 hr in the liquid fluorine environment before additional loading to rupture of the specimen.

Figure 6 summarizes the results that were obtained from the liquid fluorine tests of nine different sheet materials. The bars indicate the average percent change in strength properties in liquid fluorine as compared to those in liquid nitrogen. With the exception of AISI 301, all materials investigated showed a loss of ultimate tensile strength in liquid fluorine as shown in Fig. 6a. AM-350 and the Ti-6 Al-4 V alloy in the annealed and solution treated conditions had their ultimate strengths reduced 11, 11, and 16%, respectively. All of the other materials had their ultimate strengths reduced less than 5%. The elongation trends of the materials (Fig. 6c) are somewhat similar to the trends of ultimate strength with the exception of Inconel-X. The elongations for the 70% cold rolled 301 and 304L are not shown because the actual values are extremely low (less than 2%) even when they are investigated in liquid nitrogen. The AM-350 and the titanium materials that showed the greatest loss in smooth tensile strength in liquid fluorine also show the largest reduction in elongation along with that of AMS 6434. Although the tensile strength of AMS 6434 was only slightly affected by the fluorine environment, its elongation was severely reduced.

In Fig. 6b it can be seen that the effect of liquid fluorine on the notch properties of the various materials is very slight. Not all the alloys were tested for notch strength in fluorine since tests of the five alloys shown in Fig. 6b indicated a maximum of reduction of only 3% in the liquid fluorine environment as compared to the notch strength in liquid nitrogen. Since notch strength is the more important material characteristic in the design of cryogenic tanks, it was concluded that liquid fluorine did not damage those materials investigated to a serious extent.

It may be of interest to note that none of the tests conducted in a liquid fluorine environment showed any evidence of ignition during the fracturing process. It was felt that the very low temperature of the liquid fluorine might tend to make the material relatively inert, but that at a higher temperature (such as 75 F) ignition might occur. Hence, several notched specimens of AM 350 and Ti-6 Al-4 V were ruptured in the presence of a jet of gaseous fluorine impinging upon the notched area. Again no evidence of ignition was observed.

Comments on Uniaxial Test Results. In general the uniaxial test results shown herein indicate that cryogenic temperatures can influence considerably the strength characteristics of materials. The designer cannot necessarily select a material that exhibits good room-temperature properties and assume that the material will retain these properties at -320 or -423 F. Heat treatment, cold working, welding and other fabrication processes can affect markedly the strength properties of materials at cryogenic temperatures. In general it appears that any treatment that increases the strength of the material at cryogenic temperature also tends to embrittle the material and make it more notch sensitive. In any event the designer should have a complete and thorough knowledge of the behavior of the material he is considering for use for the complete temperature range through which the material is expected to operate.

The data from uniaxial specimen investigations are very helpful in selecting a suitable material for cryogenic application. However, in the final application, the material will be subjected to a biaxial stress field; furthermore, the fact that most of the materials that might be selected are notch sensitive at cryogenic temperatures, the design must be based upon the supposition that flaws or cracks will exist in the final structure. Therefore, a knowledge of the biaxial behavior of the material in the presence of defects is desirable. As a result, a study of the burst characteristics of scale-model pressure vessels is underway at the Lewis Research Center. The following section of this paper deals with the initial results obtained from these studies to correlate uniaxial properties with biaxially stressed vessels.

Correlation of Uniaxial Material Characteristics With Tank Performance

Design Considerations. The preceding portion of this paper has dealt with the problem of determining those characteristic properties that can be used in a screening procedure for selecting the most suitable materials for fabricating propellant tanks. These properties are concerned primarily with the strenght-to-density ratio and notch sensitivity of both the parent materials and the welds. Other factors that must be considered in the final selection include: ease of fabrication, difficulty of making high-quality welds, heat treatment problems, and compatibility with the contained fluid.

The next step after selecting a specific material is to determine the design criteria for assignment of working stresses. If the material is not notch sensitive (i.e., the notch strength is greater than the yield strength) the working stresses can be based on the yield strength and the problem resolves itself into a fairly simple solution. However, the high strength: density materials being considered for space flight applications are, in general, notch sensitive. This has been brought out previously by data showing the notch strength to be less than the yield strength for a number of sample materials. This infers that, if a flaw or crack exists in the completed structure, then catastrophic failure can occur at stresses considerably below the yield.

Several approaches based on uniaxial tensile specimen correlations have been proposed for designing with notch sensitive materials. These approaches, outlined in references (8) and (9), draw on the Griffith-Irwin and Neuber concepts. These concepts will be briefly outlined together with the modifications required for applying the uniaxial data to the biaxial stress field that exists in a propellant tank. To date, the Lewis experimental work for verifying these modifications has been limited to one material, the aluminum alloy 2014-T6.

Modified Griffith-Irwin Concept

The Griffith-Irwin concept relates the uniform gross tensile failure stress σ, normal to the crack length 2a *prior to instability crack growth*, with a critical plane stress intensity factor K_c. For a center crack in an infinite sheet, the relationship is as follows:

$$\sigma = \frac{K_c}{(\pi a)^{1/2}} \qquad \text{Eq 1}$$

The materials of interest are not completely brittle even though they exhibit brittle-fracture surface characteristics, and the laboratory test specimens are not necessarily equivalent to an infinite plate. Recognizing that there is a plastic zone in the region surrounding the tip of the crack for engineering materials, and the lack of confirmation of the invariability of the product of gross fracture stress and instability crack length, Irwin (10) postulated a correction to the instability crack growth based on an estimated plastic zone size From a modification of the Westergaard solution, the stress intensity factor in the vicinity of the crack tip is found to be:

$$K_C = \sigma\left(W \tan \frac{\pi a}{W}\right)^{1/2} \qquad \text{Eq 1a}$$

and correcting for the plastic zone size:

$$K_C = \sigma\left[W \tan \frac{\pi}{W}\left(a + \frac{K_C^2}{2\pi\sigma_{ys}^2}\right)\right]^{1/2} \qquad \text{Eq 2}$$

WHERE:

K_c = critical value of plane stress intensity, often referred to as the "fracture toughness" at the point of crack growth instability in the neighborhood of the crack
a = half-length of central crack at point of crack instability
W = specimen width
σ = gross section stress at onset of fracture
σ_{ys} = 0.2% offset tensile yield strength
$\frac{K_C^2}{2\pi\sigma_{ys}^2}$ = plastic zone correction to crack half-length at instability.

By use of Eq 2, it is possible to estimate the value of the fracture toughness parameter, K_C, from notched and smooth tensile specimens, for a given material. It is then desired to utilize this value of K_C and the material yield strength, σ_{ys}, to predict the failure stress that may occur in propellant tanks containing cracks. In applying Eq 1 to tanks, the cylinder radius-to-thickness ratio should be large and the crack length relatively small. Thus, it can be effectively considered that the region where the crack exists is equivalent to an infinite plate containing a center crack. Noting the different effect of a biaxial stress field on plastic zone size relative to that in the case of a uniaxial stress field, an empirical correction factor, b_G, is included in the equation. This term modifies the plastic zone correction term. For a crack normal to the direction of maximum principal stress, the effects of a biaxial field is to reduce the plastic zone size, based on the distortion energy criteria for plastic flow. The modified equation is as follows:

$$\sigma = \frac{K_C}{\left[\pi\left(a + \frac{b_G K_C^2}{2\pi\sigma_{ys}^2}\right)\right]^{1/2}} \qquad \text{Eq 3}$$

Should surface flaws exist, extending a small distance into the sheet thickness, the plane strain fracture toughness value, K_{Ic} is of importance. At a critical stress the flaw will enlarge to a crack extending through the sheet thickness. Should the plane stress fracture toughness, K_c, be of insufficient magnitude, the resulting crack will propagate catastrophically.

Modified Neuber Concept

The stress concentration factor, α_m, for mild, notches, according to Neuber (10) is given by the following expression for a central notch in a plate:

$$\alpha_m = 1 + 2\sqrt{\frac{a}{\rho}} \qquad \text{Eq 4}$$

where:

a = one-half notch length
ρ = notch root radius.

When ρ approaches values commensurate with a sharp notch or a crack, the expression must be modified to account for the effective notch radius introduced by the plastic zone at the tip of the notch. According to Neuber, ρ would approach a value of ρ' for a sharp notch that would be an effective radius and would be a constant for the material with a given heat treatment or condition. Thus, the stress concentration factor, α_s, for a sharp notch would be:

$$\alpha_s = 1 + 2\sqrt{\frac{a}{\rho'}}. \qquad \text{Eq 5}$$

A transition equation that holds for both conditions can be written as follows:

$$\alpha = 1 + \frac{\alpha_m - 1}{1 + \sqrt{\frac{\rho'}{\rho}}}. \qquad \text{Eq 6}$$

The value of α can be determined from the ratio of *the ultimate strength of smooth tensile specimens*, σ_{ult}, to the fracture strength of notched tensile specimens, based on the area away from the notch as follows:

$$\alpha = \frac{\sigma_{ult}}{\sigma}. \qquad \text{Eq 7}$$

By substituting in the previous equation and rearranging, the following expression can be written:

$$\frac{\rho'}{\rho} = \left[\frac{\alpha_m - 1}{\frac{\sigma_{ult}}{\sigma} - 1} - 1\right]^2. \qquad \text{Eq 8}$$

It is of interest to experimentally determine ρ'/ρ for both uniaxial tensile specimens and for tanks to determine a possible correlation. If the relation were a linear one, the following expression could be written for predicting tank failure stress:

$$\sigma = \sigma_{ult}\,\frac{1 + \sqrt{b_N\left(\frac{\rho'}{\rho}\right)}}{\alpha_m + \sqrt{b_N\left(\frac{\rho'}{\rho}\right)}} \qquad \text{Eq 9}$$

where:

σ = fracture hoop stress of the tank
σ_{ult} = smooth tensile ultimate of the material
ρ'/ρ = value determined from notched tensile specimens
b_N = proportionality factor expressing the relation of ρ'/ρ for notched tensile specimens with ρ'/ρ for notched tanks.

Experimental Correlation of Fracture Data Obtained in Uniaxial and Biaxial Stress Fields

Experimental Procedure. An attempt was made to obtain fracture data for 2014-T6 in both uniaxial and biaxial stress fields and to correlate these data through the use of the modified Griffith-Irwin and modified Neuber concepts described previously. The biaxial specimens were in the form of 6-in. diam cylinders, approximately 18 in. long and were machined from extruded tubing heat treated to the T-6 condition. The ends of the cylinders were capped with removable and reusable heads as described in reference (8) and were pressurized to the burst point at both room temperature and liquid hydrogen temperature (-423 F). The bursting procedure is also described in reference (8).

The uniaxial specimens were obtained from the same extruded tubing by slitting, flattening, machining and heat treating to the T-6 condition. Both the uniaxial and biaxial specimens are machined to a thickness of 0.060 in. in the test area. These specimens are illustrated in Fig. 7. Also shown in Fig. 7 is the notch configuration that was machined in both types of specimens. An 0.080 in. diam hole was drilled through the specimens and sharp notches introduced on both ends of a diameter of the hole by a hand broaching method. The orientation of the notches was such that they were perpendicular to the maximum principal stress, providing the maximum possible strength reduction. Notch root radii from 0.0002 to 0.005 in., with a total initial crack length of 0.10 in., were investigated. The tensile specimens were 1 in. wide at the test section, giving a crack length-to-width ratio of 0.10 and a width-to-thickness ratio of 16.4. As in the case of the biaxial tests, uniaxial tensile data were obtained at two temperature levels, room temperature and –423 F.

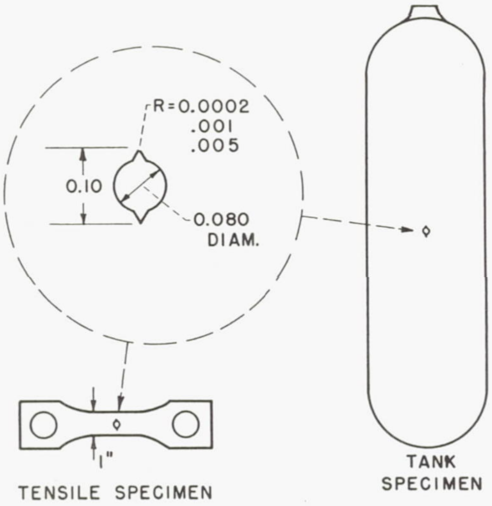


Fig. 7. Notch configuration and orientation in uniaxial and biaxial stress specimens.

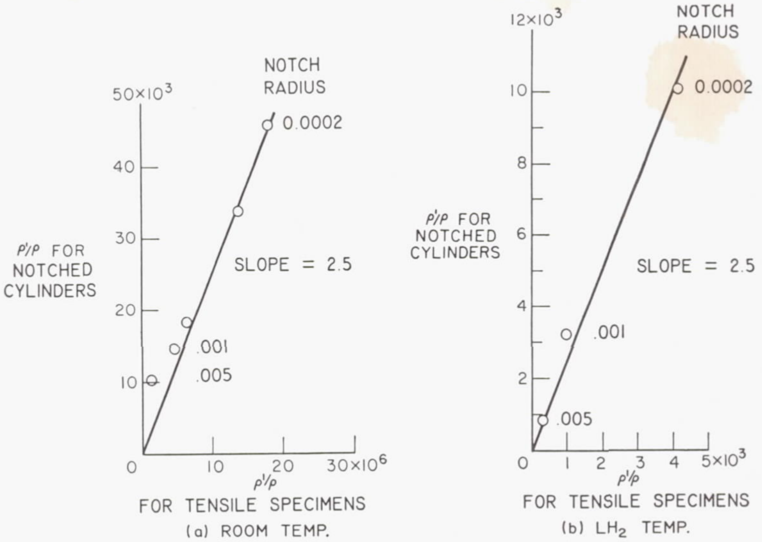
A photograph of the biaxial cylinder specimen (with heads removed) is shown in Fig. 8. A cylinder burst at –423 F is shown in this figure to indicate the type of fracture obtained.

Fig. 8. Typical biaxial cylinder specimen: (left) before burst; (right) after burst.

Correlation of Results with Theories. The values of ρ'/ρ for the notched cylinders plotted against ρ'/ρ for the notched tensile specimens are shown in Fig. 9 for both room temperature and –423 F. At both temperatures a straight line having a slope of 2.5 fits the data reasonably well. In other words, ρ'/ρ for the cylinders is 2.5 times ρ'/ρ for the tensile specimens. The absolute values of ρ'/ρ at room temperature are roughly 5 times the values at –423 F. The value of b_N for use in the modified Neuber equation (Eq 9) for predicting burst stress was therefore taken as 2.5.

Figure 10 shows the results obtained in comparing the actual hoop burst stresses for notched cylinders with the calculated values obtained from uniaxial tensile specimens by the modified Griffith-Irwin and modified Neuber theories for a range of notch root radii. Results for room temperature and –423 F are shown in the figure. The individual data points represent the experimental results and the curves describe the calculated results.

A general decrease in burst strength is noted with decreasing notch root radii, but it is believed that further sharpening of the notch would not lead to appreciably greater strength reduction. This is supported by the tests of various types of notches described in reference (12). The notch of 0.0002-in. radii, therefore, probably simulates the performance of specimens containing actual cracks. Correlation of the experimental data with the modified Griffith-Irwin equation in Fig. 10 was good at both –423 F and room temperature for the complete range of notch radii investigated if the proper plastic zone sizes were considered at the tip of the crack. It was found that at –423 F the plastic zone size correction in Eq 3 for tanks should be 46% of that required for uniaxial ten-



(a) ROOM TEMP.

(b) LH_2 TEMP.

Fig. 9. Correlation of notched cylinders with notched tensile specimens by Neuber concept.

sile specimens. In other words the value of b_G should be 0.46. At room temperature the value of b_G was found to be 0.68.

Figure 10 also shows the computed hoop stress where yielding would occur based on the equivalent stress being equal to the uniaxial yield stress. For a notch root radius of 0.0002 in. the failure stress was approximately 80% of the computed yield stress for both room temperature and liquid hydrogen temperature, which illustrates the danger of basing the design on yield strength for the case where there can be a small defect and the material shows a notch sensitivity.

Limitations of Burst Stress Predictions. It would be indicated, since the notch radius does not significantly affect the constants b_N or b_G, that these constants can be used in the prediction of tank failure from specimen data using natural cracks in addition to those employing sharp machined notches. Considerable caution must be observed, however, in the use of the specific values for b_N and b_G presented herein, because the data so far are for only one material and one heat treatment. Much more experimental evidence is required to determine the character of b_N and b_G.

Concluding Remarks

A number of materials that seemed to be logical choices have been studied at the Lewis Research Center to determine their strength characteristics for temperatures ranging from 75 to —423 F. It has been found that the strength properties of materials can vary considerably with temperature, and this is particularly true of the sharp notch strength characteristics of materials. Because of these variations in properties, considerable care is required in selecting a material for cryogenic application. For current application perhaps the most logical choice of materials for lightweight cryogenic tanks on a strength: density basis would be an aluminum alloy such as 2014-T6, a cold worked austenitic stainless steel such as AISI 301, or perhaps an alpha titanium alloy such as 5 Al-2.5 Sn-Ti. Glass-reinforced filament-wound materials show an interesting potential for use at cryogenic temperatures, but not enough data are available yet to provide a suitable background for the design of reliable cryogenic pressure vessels from material. One of the major problems that appears to be associated with the application of reinforced plastics to cryogenic

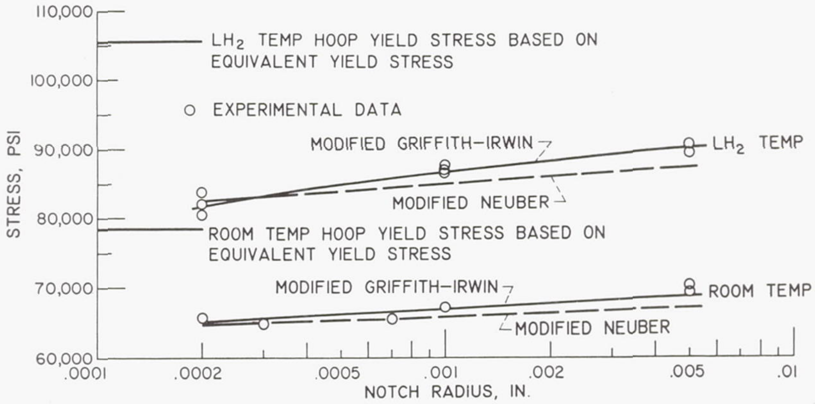


Fig. 10. Burst hoop stress for notched aluminum cylinders; notch length approximately two times thickness.

pressure vessels is that relative to providing some type of permeability barrier in the vessel to inhibit permeation of the contained liquids through the reinforced plastic walls.

The use of modified Griffith-Irwin or modified Neuber theories to predict the failure of biaxially stressed pressure vessels based upon strength properties of uniaxial test specimens has been encouraging to date. However, only a limited amount of data are available and much more experimental evidence and application must be made before the present methods can be proven reliable.

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