LEAK-BEFORE-BREAK CHARACTERIZATION AND DEMONSTRATION OF A HIGH-PRESSURANT HELIUM STORAGE VESSEL

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ABSTRACT

This storage vessel was designed to operate at a pressure of 41.37 MPa for a ten-year service life. Its specified mode of failure is leakage. For this application a combination of welded 304L and 301 cryogenically streched and aged stainless steel material was selected. A detailed stress analysis, followed by a linear elastic fracture mechanics analysis, was conducted. Using a CRACKS computer program, which incorporates the Paris and Forman equations with K_I test data, the predicted mode of failure was leakage rather than fragmentation.

Planned and designed tests to verify the mode of failure were not conducted; however, verification was established through an unexpected source when the vessel developed a through-crack and leaked in a saltwater test. Its failure was attributed to stress corrosion initiated by oxygen depletion in a crevice.

KEYWORDS

Fracture mechanics; stress analysis; leak before break; cryostreched stainless steel; stress intensity; threshold stress intensity; stress corrosion; crevice corrosion; oxygen depletion.

INTRODUCTION

Requirements were generated to develop a lightweight high-pressurant helium storage vessel operating at 41.37 MPa which would exhibit leakage rather than fracture as the mode of failure. Other stipulated objectives were a 10-year pressurized storage life with no degradation from immersion in salt water for 2-1/2 months.

After a detailed analysis, a cryoforming process using a type 301 (18-8 chrome-nickel) stainless steel was selected as best fulfilling all of the requirements. In order to accommodate valves and mounting arrangements, bosses were fabricated of type 304L stainless steel. This provided compatibility with the electron beam welding low heat input which was necessary to prevent degradation of the vessel's high strength and valve functions. Figure 1 shows the major components and dimensions of the welded pressure vessel.

DESIGN CONSIDERATIONS

The helium pressurant vessel is designed using conventional safety factors and stress analysis procedures. This involves conducting detailed stress analysis computations of primary membrane stresses along with secondary bending and discontinuity stresses using a finite difference computer program. Thicknesses

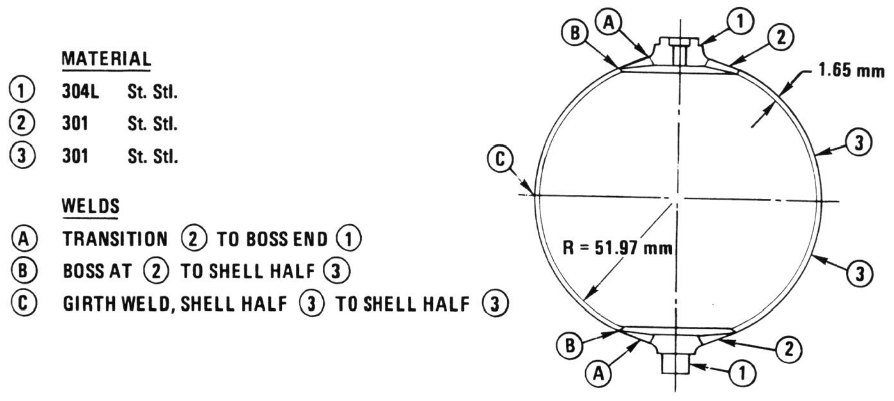

Fig. 1. Materials and construction.

throughout the spherical pressurant shell and its end bosses were optimized to assure that proofing the vessel at ambient temperature to 1.5 times operating pressure results in no detrimental or gross deformations and subjecting the tank to 2.0 times operating pressure assures no bursting or leakage. Additionally, the design limits burst failures to the membrane portion. Although shock and vibration formed an important portion of the requirements they did not contribute significantly to the design.

VESSEL FABRICATION

The vessels are manufactured by a patented cryoform process, which imparts reasonable ductility together with high mechanical properties and extremely high toughness. These consistently produced properties are dependent on precise process and dimensional control achieved by cryogenic forming, or stretching at low temperature and subsequently aging at a prescribed temperature and time.

Material allowable properties obtained from this process are depicted in Fig. 2. It will be noted that the properties are constant in the membrane area only, and considerable strength gradients exist in the boss areas.

DETAILED STRESS ANALYSIS

The detailed stress analysis program outputs were used to generate the stress distribution throughout the vessel geometry. Only the port boss data is depicted in Fig. 2 since the blind boss stress distribution is similar.

The maximum uniaxial stresses as computed by the Hencky von Mises equation occur in the membrane at $R_o = 33.93$ mm. Another significant fact derived from the analysis is that the bending stress contribution is only 2% and almost all of the stress in the membrane at the critical location is tensile. At the operating and proof pressures the maximum stresses are 766 MNm^{-2} and 1149 MNm^{-2}, respectively, which are used in the fracture mechanics analysis.

FRACTURE MECHANICS ANALYSIS

Approach

Fail-safe design is a means of safeguarding against those circumstances which are impractical or technically impossible to forestall. To assess the effectiveness of the design concepts in terms of reliability and safety, it is necessary to show analytically that a fail-safe, leak-before-burst, situation exists for this pressurant vessel.

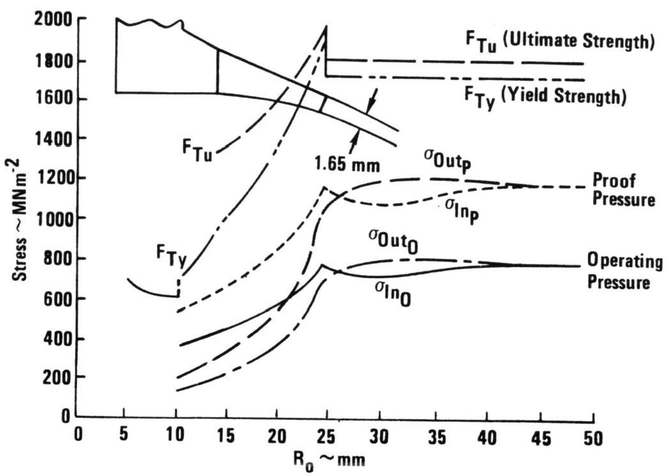

Fig. 2. Port boss pressure stresses.

To prevent service failures of metallic pressure vessels, the three basic considerations are:

(1) The initial flaw size (a_i).
(2) The critical flaw sizes (a_{cr}), the size to cause fracture at a given stress level.
(3) The subcritical flaw growth characteristics (da/dN).

To prevent proof-test failures, the actual initial flaw sizes must be less than the critical flaw sizes at the proof stress level.

To assure that the vessel will not fail in service, it must be shown that the largest possible initial flaw in the vessel cannot grow to critical size during the required life span of the vessel.

Leak-Before-Burst Analysis

Since the operating and proof stresses are well within the yield strength of the material, linear elastic fracture mechanics analysis is applicable. In elastic stress fields, the critical sizes for surface and internal flaws depend on the plane-strain critical stress intensity or fracture toughness values (K_{IC}) of the vessel materials, and the applied stress levels. Computational methods rely heavily on Forman (1975) and Tiffany (1970).

The critical flaw depth can be calculated for surface flaws from (Tiffany, 1970) using the following equation:

$$K_{IC} = 1.1\,\sigma_o\sqrt{\pi a_c/Q}\;M_K \qquad (1)$$

Rearranging terms to establish a_c (critical flaw depth)

$$a_c = K_{IC}^2\,Q/1.21\,\pi\,\sigma_o^2\,M_K^2 \qquad (2)$$

where: Q = 1.0 (flaw shape parameter conservatively assumed for long flaws where $a/2c$ is 0.20 or less, (Masters, 1969).

σ_o = 766 MNm^{-2} operating stress.

M_K = Kobayashi's stress intensity magnification factor (Masters, 1969).

K_{IC} = 104 $MN/m^{3/2}$, stress intensity at failure.

Review of several sources, primarily Forman (1975), led to the above estimate as the most realistic value. With a value of M_K = 1.6 the critical flaw size (a_c) is 1.92 mm. Therefore since 1.92 exceeds the thickness of 1.65, leakage is the predictable mode of failure by the criterion of Tiffany (1970) at the operating stress level of 766 MNm^{-2}.

Initial flaw depth screened (largest flaw which can survive without failing the vessel) is established by the cryoforming process with liquid nitrogen at (78°K) at the forming stress of 1770 MNm^{-2}. Bixler (1973) conducted tests at 78 and 295°K for two thicknesses: 0.71 and 2.6 mm. The results showed critical flaw sizes of 0.36 and 0.43 mm, respectively, with no apparent differences at room temperatures. Linear interpolation of the data resulted in a critical value of 0.395 mm for this vessel. The premise is that if the vessel does not fail under the cryogenic sizing conditions, flaws greater than 0.395 mm are not present. Attempts were made to verify this value by analysis. Data by Irvine (1970) was used to generate values of 0.51 and 0.635 mm, the latter being used in subsequent analyses as a conservative figure.

Sustained Pressure Flaw Growth

In the preceding analysis initial flaw sizes were established. This portion of the analysis shows that these flaws remain stable and will not grow as long as the threshold stress intensity (K_{TH}) value is not exceeded. The initial stress intensity (K_{Ii}) is calculated based on the depth of the largest flaws which could be present after a successful cryogenic sizing "proof" test.

Selecting equation (1), where a_i and K_{Ii} are substituted for a_{cr} and K_{IC}, with:

a_i = 0.635 mm, initial flaw size
M_K = 1.08 for $a_i/t = 0.37$ with $a/2c = 0.1$ from Forman (1975)
Q = 1.0 for long flaws
σ_o = 766 MNm^{-2} operating stress

results in a K_{Ii} value of 37.0 $MN/m^{3/2}$. The operating environment of helium is comparable to nitrogen for which data has been generated. K_{TH} is established by data presented by Forman (1975), where K_{Ii}/K_{IC} ratios of 0.70 to 0.86 are indicated, showing no growth for over 80 hr at flaw depths greater than 50% of the thickness and sustained stress levels as high as 1320 MNm^{-2}. On the basis of the 766-MNm^{-2} stress level and a 37% flaw depth, a value of K_{Ii}/K_{IC} of 0.80 was selected as being conservatively representative of the threshold ratio K_{TH}/K_{IC}. Since $K_{IC} = 104$ $MN/m^{3/2}$, K_{TH} becomes 0.80 x 104 = 83.2 $MN/m^{3/2}$. For a specific pressure vessel design environmental crack growth is prevented by selecting the proof pressure ratio or the material such that $K_{Ii}/K_{IC} < K_{TH}/K_{IC}$. The ratio of this material is $K_{Ii}/K_{IC} \ll K_{TH}/K_{IC} = 37/104 \ll 83.2/104$; thus the results indicate that no flaw growth should occur at sustained operating stress levels in a helium/air environment with initial flaws at $\leqslant 0.63$ mm.

Pressure Cycling Capability

A limited number of crack propagation tests are reported by Schwartzberg and associates (1970) as raw data for cryostretched 301 material. This data was used in conjunction with a CRACKS FORTRAN IV digital computer program reported by Engle (1970). The apparent best fit of crack growth rate (da/dN) as a function of change in stress intensity factor, (Δk) for parent and weld metal were computed using the Forman and Paris equations. Values for K_{IC} of 104 $MN/m^{3/2}$ in the parent metal and K_{IC} of 88 $MN/m^{3/2}$ for the weld with a stress cycled from 0 to 766 MNm^{-2} were used as computer inputs. A minimum thickness of 1.65 mm was used as the shell dimension. Both the interpolated and calculated initial flaw depths with lengths, a/2c = 0.20 were run. Results are presented in Tables 1 and 2.

TABLE 1 Number of Cycles to Propagate to a Through-Crack

		Cycles x 10^{-3}	
a_i (mm)	Equation	Parent Material	Weld Material
0.395	Paris	3.5	1.53
	Forman	5.0	1.62
0.635	Paris	1.65	0.73
	Forman	2.5	0.68

TABLE 2 Through-Crack Lengths at Instability

	Paris (mm)	Forman (mm)
Parent	5.92	7.87
Weld	4.14	4.16

Both methods show that leakage rather than catastrophic failure will occur with both flaw depths. Instability or rapid fracture is presented in Table 2 with the Paris equations providing the more conservative data.

TEST VERIFICATION OF MATERIAL TOUGHNESS

Attempts at Verification

Tiffany (1970) makes no distinction between liquid or gas pressurization in the presentation of the "leak-before-break" criterion. However, recognition must be given to the potential energy in a stored gas compared to a stored liquid pressurant.

Crack behavior modes in pressure vessels using gas as the pressurizing medium are practically nonexistent. Mostly all gas testing to date has been conducted by the Gas Research Institute on long commercial cylindrical pipelines, mainly to determine propagation rates and retardation lengths for through-the-thickness cracks.

To verify the analytical work on this pressure vessel, the customer requested a submittal of a proposal with a planned test program using helium or nitrogen as the pressurization medium. The plan revealed the numerous difficulties which would be encountered in cycling the flawed vessels to the working pressure of 41.37 MPa with gas. Consequently the test program was prohibitively expensive and was never authorized. During the test planning phase, literature searches were conducted which unearthed an attempt made by NASA during the Skylab program for leak-before-break demonstration.

Experimental Verification of Leak Before Break

Beck and Schwartzberg (1971) reported on tests conducted on flawed 301 cryostreched material in preparation for verification of a fail-safe design of a high-pressure helium vessel. This was a spherical backpack unit operating at 20.81 MPa carried by astronauts as part of the Skylab astronaut maneuvering unit. The vessel was 3.2-mm thick operating at a stress of 718 MNm^{-2}. After a material flaw characterization program, tests were conducted on flawed vessels using water as the pressurization medium. These were considered to have demonstrated the leak-before-break characteristics when they ceased to hold pressure and the cracks did not propagate. However, such a test leaves some doubt as to proof, since the potential energy of a compressed gas is far greater than that of a liquid. Upon breakthrough it would appear that failure modes may be governed by the kinetic energy release rate of the pressurant compared to the strain energy release rate of the material. Since no failures occurred in actual operation, neither argument was proven.

Confirmation From an Unsuspected Source

After apparently exhausting all available sources for confirmation of leak before break for our vessel, a breakthrough occurred through an unforeseen circumstance. As a part of the qualification process the vessel had to be immersed in sea water for 2-1/2 months without degradation of its burst pressure capability. A production vessel with bonded aluminum identification labels was pressurized with helium to its normal operating pressure of 37.75 MPa. The vessel was then immersed in a specially prepared sea water solution with an externally mounted gage to monitor the pressure. After two days a salt buildup was noticed on the aluminum label and was attributed to corrosion of the aluminum through breaks of the anodized surface. After 12 days a considerable amount of the label was dissolved with a substantial amount of salt buildup and the vessel was leaking. The monitor gage showed a pressure frop of 0.70 MPa/hour. When the pressure fell to 35.30 MPa, the test was discontinued so that the cause of failure could be determined.

After careful and exhaustive chemical and metallurgical tests, consisting of composition of sea water, labels, marking inks, label adhesives, microprobe and microsectioning, the cause of failure was attributed to stress corrosion induced by crevice corrosion. More specifically, crevice corrosion, whereby some portion of the inert adhesive, or more likely a segment of the inert material, became slightly displaced from the tank surface, and allowed an oxygen concentration gradient, and hence, an electrochemical cell, to form. This would cause rapid destruction of the protective oxide film in the oxygen-starved interior of the crevice, and subsequent pit formation. The pit formed a stress concentration which generated a surface crack propagating rapidly through the thickness by means of stress corrosion. Final geometry of the pit and crack was reconstructed after metalurgical sectioning and is depicted in Fig. 3. The crack occurred in the membrane midway between the girth weld and the boss weld.

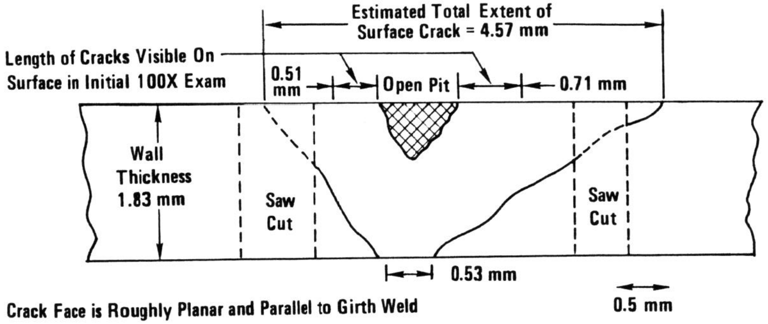

Fig. 3. Reconstruction of total extent of leaking crack.

The stress intensity (K_I) was calculated using equation (1); for crack length of 4.57 mm = 2c, crack depth, a = 1.83 mm full thickness, M_K = 1.22 from CRACKS computer program and a re-adjusted stress of 627 MNm^{-2} for the actual pressure and thickness. A value of $K_I = 45.5$ $MN/m^{3/2}$ was calculated. This is less than 1/2 of K_{IC} in the membrane parent metal. Forman (1975) reports no degradation of K_{IC} values in saltwater for this material. Allowing for uncertainty in both test and analysis, it is obvious that the crack produced in the fully pressurized vessel was quite stable, with no possibility of producing a catastrophic, unsafe fracture. It is also obvious that a pressure reduction, at a rate of 0.70 MPa/hr was occurring, therefore stress and stress intensity values were decreasing with no means of sustaining the load for further crack propagation.

It should be noted that another production vessel with all markings and identification labels removed successfully concluded the 2-1/2 month saltwater test with no degradation to subsequent burst tests.

CONCLUSIONS

Verification of leak-before-break analysis was established for the helium pressurized spherical vessel charged with 41.37 MPa. The vessel shows the high toughness and stress levels obtainable with 301 cryoformed stainless steel. Tests revealed that considerable care should be exercised in the manner of marking and type of identification labels applied when conducting saltwater immersion tests.

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REFERENCES

Beck, E.J., and F.R. Schwartzberg (1971). Fracture behavior of cryogenically streched 301 stainless steel used in the M509 pressure vessel. Report MCR71-53, Martin Marietta Corp.

Bixler, W.D. (1973). Development of a fracture control method for composite tanks with load sharing liners. Boeing Aerospace Co.

Colliprіest, J.E. Jr., and R.N. Ehret (1973). Computer modeling of part-through-crack growth. Report SD72-CE-0015B, North American Rockwell.

Engle, R.M. Jr. (1970). CRACKS, a FORTRAN IV digital computer program for crack propagation analysis. Report AFFDL-TR-70-107, Wright Patterson Air Force Base.

Forman, R.G. (1975). Environmental crack-growth behavior of high-strength pressure vessel alloys. Report TN D-7952, NASA.

Irvine, C.N. (1970). Cryoformed 301 stainless steel for pressure vessels. Report TM X-53978, NASA.

Masters, J.N., Haese, W.P., and R.W. Finger (1969). Final report investigation of deep flaw in thin walled tanks. Report CR-72606, NASA.

Schwartzberg, F.R., Keys, R.D., and T.F. Kiefer (1970).Cryogenic alloy screening. Report CR-72733, NASA.

Tiffany, C.F., (1970). Fracture control of metallic pressure vessels. Report SP-8040, NASA.