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APOLLO EXPERIENCE REPORT - THE PROBLEM OF STRESS-CORROSION CRACKING

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16. Abstract

Stress-corrosion cracking has been the most common cause of structural-material failures in the Apollo Program. The frequency of stress-corrosion cracking has been high and the magnitude of the problem, in terms of hardware lost and time and money expended, has been significant. In this report, the significant Apollo Program experiences with stress-corrosion cracking are discussed. The causes of stress-corrosion cracking and the corrective actions are discussed, in terminology familiar to design engineers and management personnel, to show how stress-corrosion cracking can be prevented.

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APOLLO EXPERIENCE REPORT

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SUMMARY

Stress-corrosion cracking has been the most common cause of structural-material failures in the Apollo Program. The frequency of stress-corrosion cracking has been high and the magnitude of the problem, in terms of hardware lost and time and money expended, has been significant. In this report, the significant Apollo Program experiences with stress-corrosion cracking are discussed. The causes of stress-corrosion cracking and the corrective actions are discussed, in terminology familiar to design engineers and management personnel, to show how stress-corrosion cracking can be prevented.

The basic conclusion of this report is that the environments and alloys used in the Apollo Program in which failures occurred were generally the same as those encountered in past aircraft and missile failures. Two exceptions to this conclusion are the methanol-titanium and the nitrogen tetroxide-titanium incompatibilities, which were combinations unique to the Apollo Program. Better communications are needed between designers and fabrication personnel, and a more thorough education on existing knowledge of stress-corrosion problems should significantly reduce problems in the construction of future spacecraft. A secondary conclusion presented in this report is that the use of certain aluminum alloys and high-strength steels and the use of certain heat-treatment procedures should be avoided.

INTRODUCTION

The following definition of stress-corrosion cracking is found in reference 1. "When certain metal alloys are exposed to a corrosive environment while at the same time they are subjected to an appreciable, continuously maintained, tensile stress, rapid structural failure can occur as a result of stress corrosion. This is known as stress-corrosion cracking and is characterized by a brittle type failure in a material that is otherwise ductile."

The stress-corrosion susceptibility of an alloy is affected by the temperature, the grain direction (in certain alloys), the grain size, and the distribution of phases or precipitates in the alloy, in addition to such obvious factors as alloy composition, environment, and stress level. Although the problem of preventing stress-corrosion cracking is difficult, the use of correct assembly procedures and the proper recognition during the design phase of the factors affecting structural sensitivity can be instrumental in avoiding this problem.

The structural materials used in the Apollo spacecraft hardware are high-strength alloys that are widely used in aircraft construction. The stress-corrosion behavior of these alloys is well established in certain environments. Therefore, it is important to examine some of the Apollo Program hardware failures to determine why they occurred and how they were overcome.

The photographs and much of the information in this report were supplied by two prime Apollo contractors, North American Rockwell and Grumman Aerospace Corporation. The help furnished by these organizations in preparing this report is acknowledged and appreciated.

DISCUSSION

Lunar Module Stress-Corrosion Failures

To provide a background for the discussion of lunar module (LM) stress-corrosion failures, a brief description of the LM structure and the design philosophy that affected the stress-corrosion susceptibility of the structure is presented. The LM structure (fig. 1) is constructed largely of high-strength aluminum alloys along with smaller amounts of titanium alloys and stainless steels. The evolution and design of the LM structure was based on a minimum-weight requirement. After the original design release, two additional weight-reduction programs were conducted to trim every possible ounce from all structural components. As a result, complex machining of components from bar stock or plate was combined with chemical milling to achieve a highly efficient structure from a weight standpoint. However, this approach led to undesirable stress-corrosion-resistance conditions because of the undesirable grain directions exposed to environments and the sustained high fabrication or residual stresses in the parts.

The first significant failure of an LM structural component was reported in October 1967 on an LM test article (LTA-3). A crack was found in a web splice plate made of type 7075-T651 aluminum alloy. The cause of the failure was listed as the high installation stresses to which the component was subjected because of the omission of a shim stock, contrary to the drawing requirements. The stresses, combined with the water used in the pressure testing of the ascent stage, led to stress-corrosion cracking of the component. Because the failure was attributed to a fabrication error that had been complicated by the nature of the test (hydrostatic), no serious thought was given at the time to the possibility that the failure was indicative of a general problem. Unfortunately, subsequent failures proved otherwise.

In December 1967, during the inspection of the same test article, numerous tubes that were used to support equipment racks were found to be cracked near fasteners or attachment points. This finding led to an examination of other vehicle parts that had a

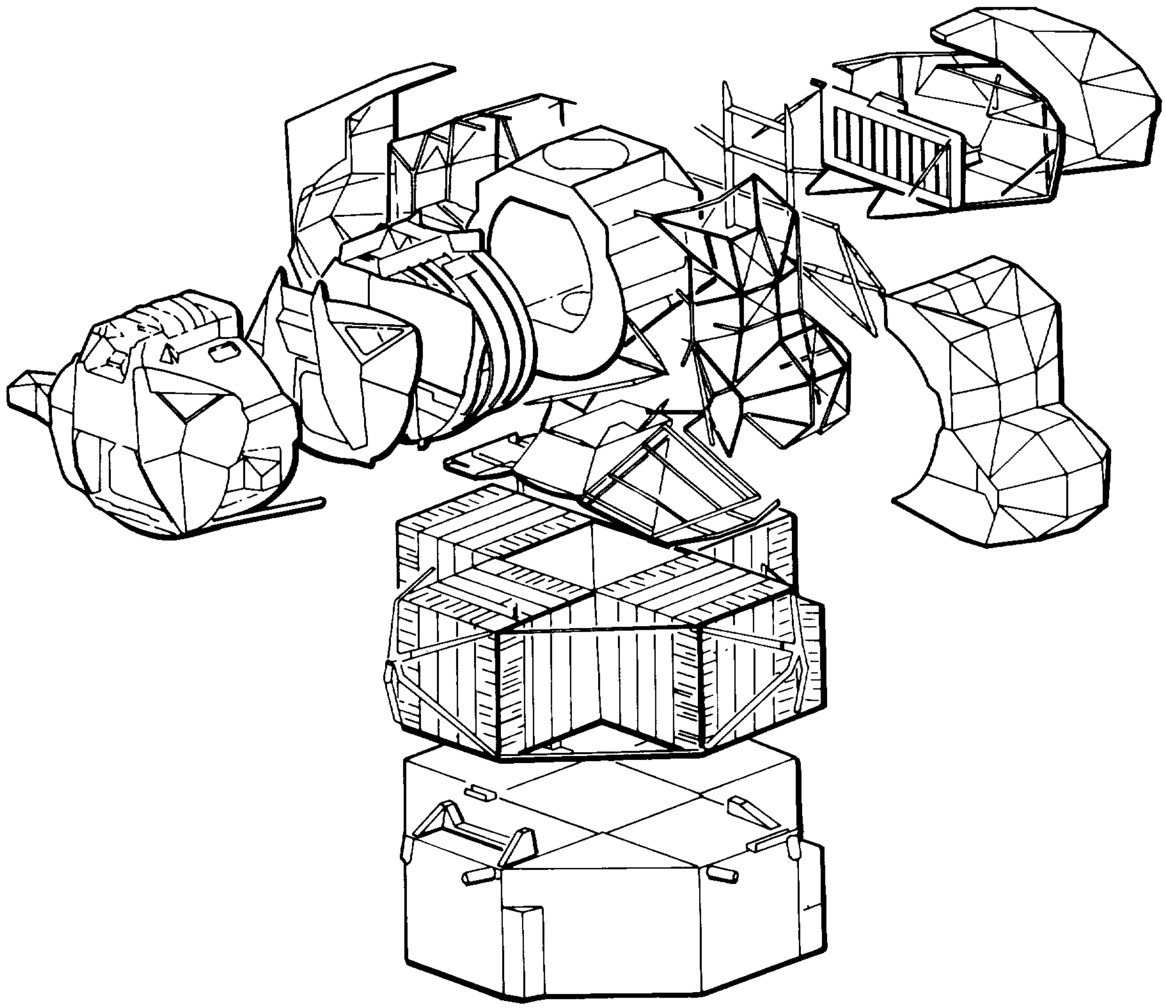


Figure 1. - Lunar module structure.

similar construction. Many components of assembled vehicles and subassemblies subsequently were found to be cracked. Because the failure modes and causes were similar, only one representative case will be described.

The support tubes in the LM aft-equipment-bay assembly (fig. 1) are made of type 7075-T6 aluminum alloy, and the ends of the tubes are reduced in diameter by swaging and are attached mechanically to end fittings. The incidence of cracks at the swaged ends of the tubes was high (over 20 cracked parts) and had resulted from a buildup of tolerances between the tube and the fitting. When the parts were assembled, sustained high tensile stresses were introduced in the tube, and cracks developed perpendicular to the direction of high residual stress. In this example and in many other cases, moist air was the environmental factor that caused stress-corrosion cracking. The type of cracking observed and the general locations of the cracks are shown in figures 2 to 8.

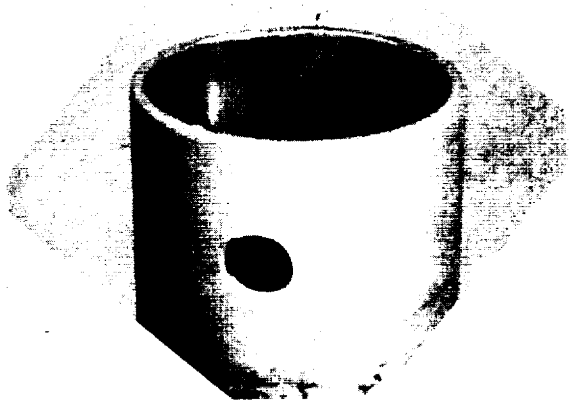


Figure 2. - Crack in a swaged type 7075-T6 aluminum tube found on LTA-3 (magnification: 3×).

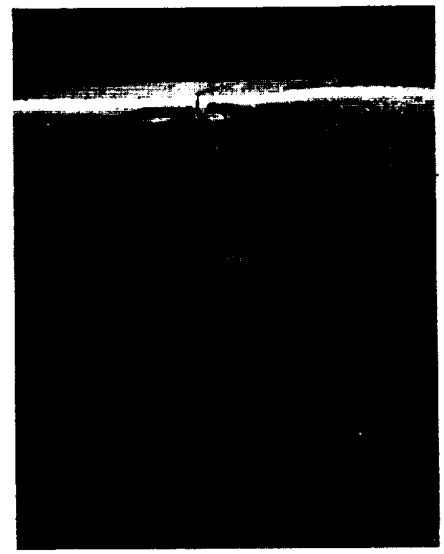


Figure 3. - Closeup of the crack shown in figure 2 (magnification: 7×).

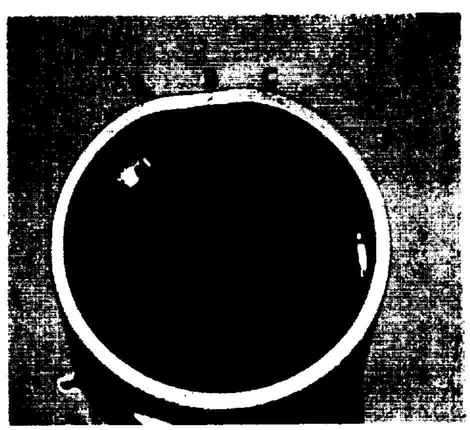
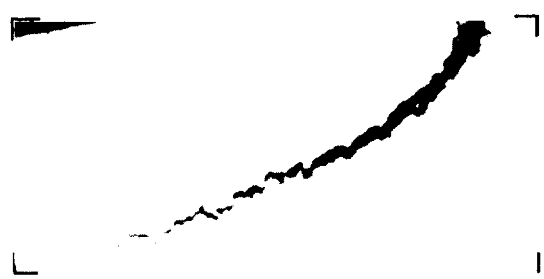


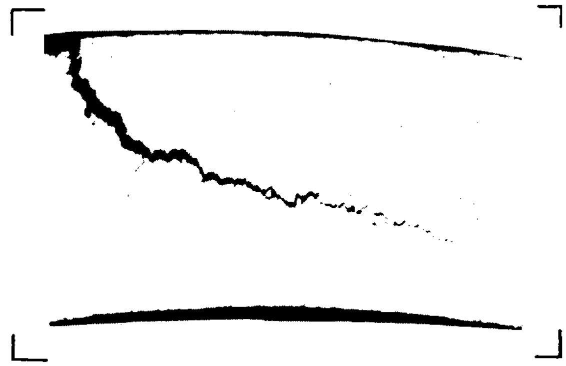
Figure 4.- Edge view of the crack shown in figures 2 and 3 (magnification: 3×). Cross sections of points A, B, and C are shown in figure 5.



(a) Cross-section point A.

Figure 5. - Closeups of the cross-section points indicated in figure 4.

(b) Cross-section point B.



(c) Cross-section point C.

Figure 5. - Concluded.

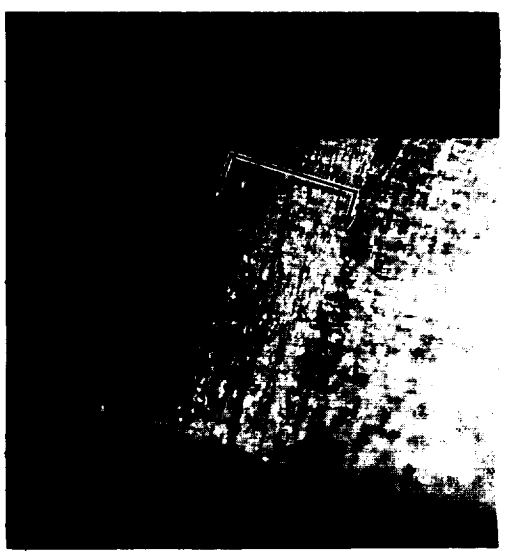


Figure 6. - Crack in a typical swaged type 7075-T6 aluminum tube (magnification: 10×).

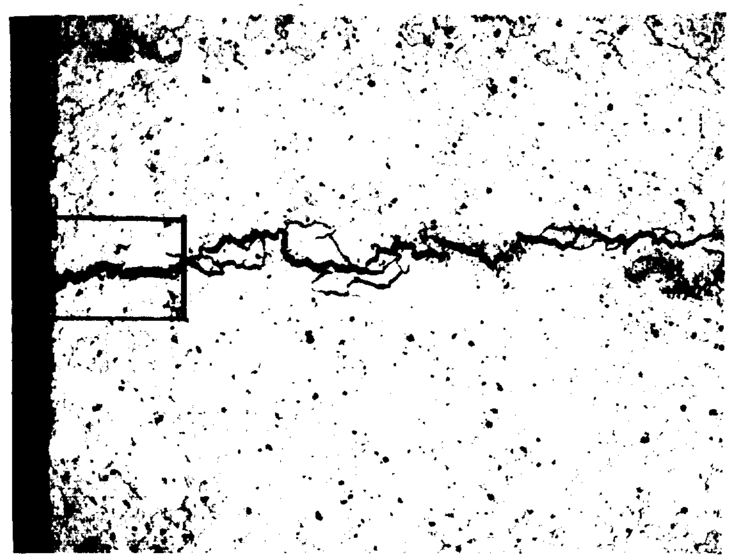


Figure 7. - Cross section of the crack shown in figure 6. The outlined area is thought to be a swaging lap. Closeup of the outlined area is shown in figure 8.

Figure 8. - Closeup of the outlined area shown in figure 7.

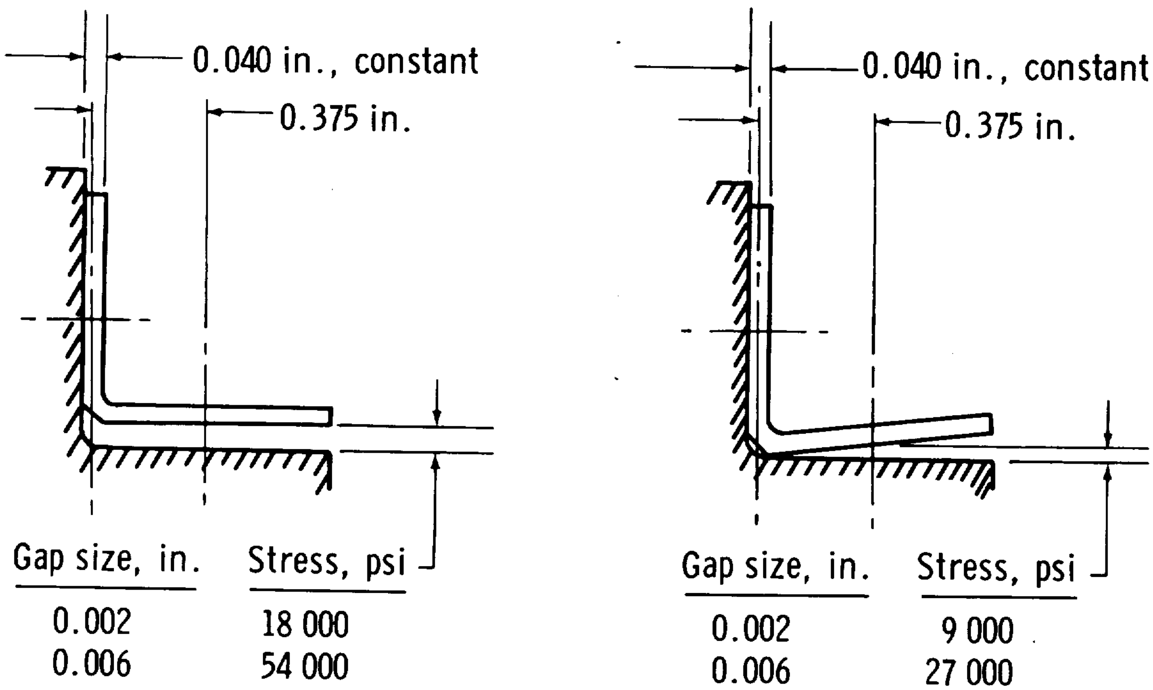
To eliminate the problem, all such fittings on assembled vehicles were disassembled; the gaps created by the tolerances in the mating parts were filled by means of liquid shimming, a technique by which a room-temperature-curing resin was introduced into the volume between the parts and allowed to harden before the parts were joined permanently by mechanical fasteners.

The discovery of the numerous failures alerted the contractors and NASA to the possibility that stresses introduced by the assembly techniques used by the contractor easily could cause stress-corrosion cracking on other parts of assembled vehicles. Because the time at which stress-corrosion cracking occurs can vary, often occurring after long periods of time, all susceptible alloys on all LM vehicles were suspect. Therefore, hardware designs that involved type 7075, 7079, 2014, 2024, and 7178 aluminum alloys were examined to evaluate the design and assembly stresses and to identify the locations at which sustained stresses were of a sufficient magnitude to cause stress-corrosion cracking. During the design review, approximately 1000 parts were judged to be susceptible to stress-corrosion cracking, approximately 500 design components were listed as probable problems that would require detailed analysis, and approximately 170 parts were found to constitute possible problems.

To examine these potential problems, representatives of the contractor, the NASA Manned Spacecraft Center and Marshall Space Flight Center, and the U.S. Air Force and Navy reviewed the acceptance criteria to be used in the detailed analyses. The contractor and NASA began a review of design drawings, and vehicle inspections were conducted that revealed additional cracked parts and other critical parts that required redesign.

During the investigation, it was noted that many cracked parts failed because of the improper fitting of mated parts, particularly where angles or channels nested together and were fastened by bolts or rivets. The process by which stresses can reach the threshold required for stress-corrosion cracking (8000 psi or higher, depending on the type of alloy and the alloy grain direction relative to the stress) is shown in figure 9. If proper precautions in the mating and shimming are not taken to eliminate the gap, high stresses can occur, particularly in the radius along the length of the parts. Examples of this type of problem are shown in figures 10 to 12.

Another type of cracking often observed was cracking between such fasteners as rivets or bolts. This type of cracking usually resulted from poor preparation of the holes (burrs, lips, etc.) and was aggravated by expanded rivets, which increased the stresses around the fastener holes. Examples of these failures are shown in figures 13 and 14.



(a) Linear offset.

(b) Angular offset.

Figure 9. - Significance of gap-dimension errors on the resulting stress.

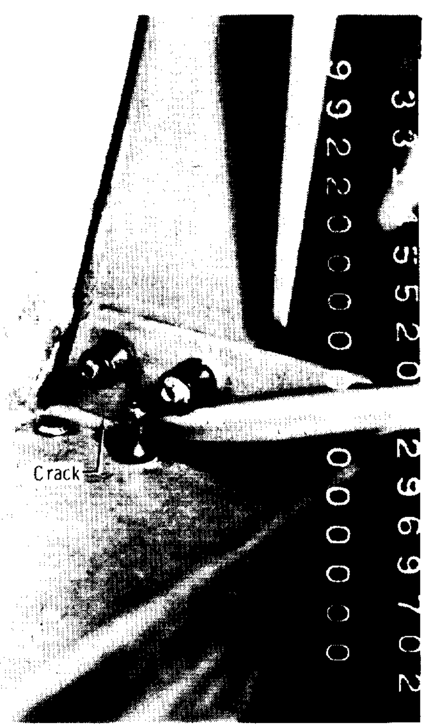


Figure 10. - Crack in the radius of a machined longeron made of type 7079-T652 aluminum alloy.

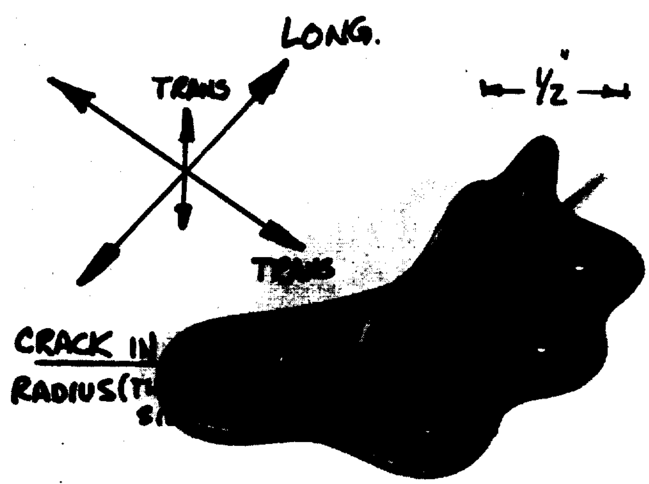
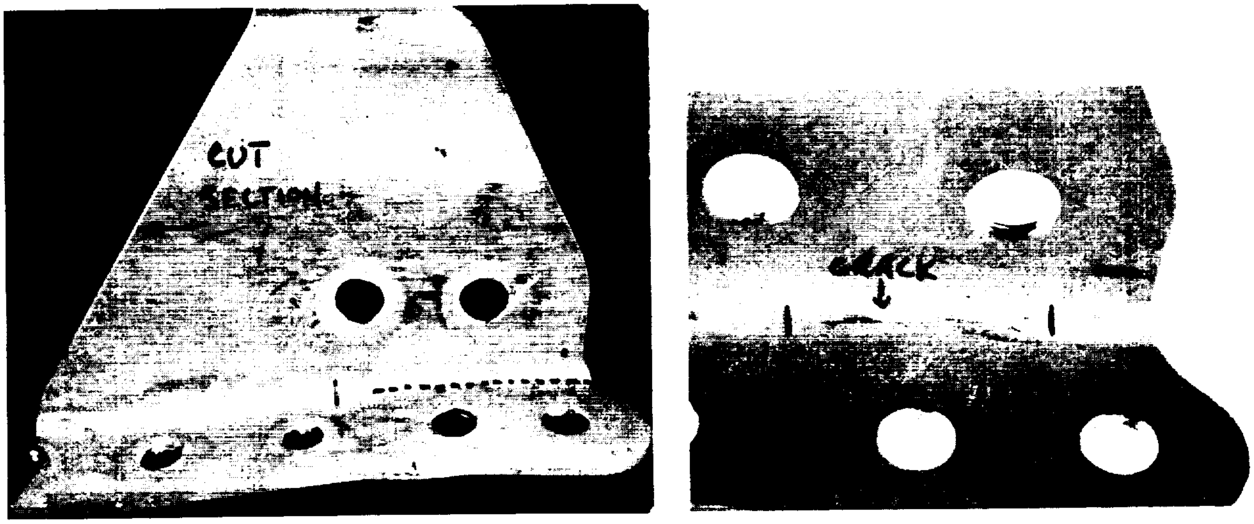


Figure 11. - Crack in the radius of a machined tank-truss fitting made of type 7075-T6511 aluminum alloy.



(a) Location of the crack in the radius of a stiffener (indicated by dashed line).

(b) Closeup of the crack shown in figure 12(a).

Figure 12. - Crack in the radius of a stiffener made of type 7075-T6 aluminum alloy.

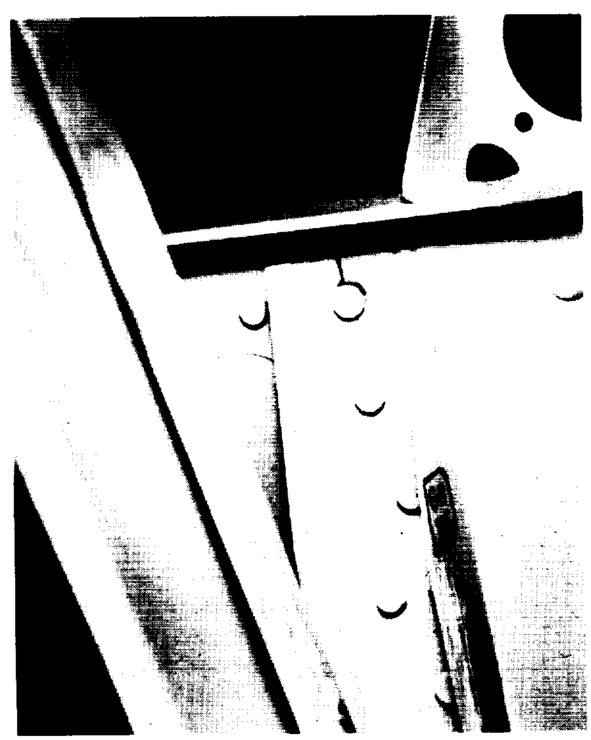


Figure 13. - Interrivet cracking on a channel made of type 7075-T651 aluminum alloy.

Still another type of failure involved straps. The clamping of parts resulted in sustained high stresses, which in some cases were quite close to the tensile yield strength. An example of this type of failure is shown in figures 15 and 16.

Complex parts that are machined from thick sections and in which short transverse loads are possible are particularly vulnerable to cracking because stress-corrosion-cracking threshold stresses are lowest in the transverse direction. An example is shown in figure 17.

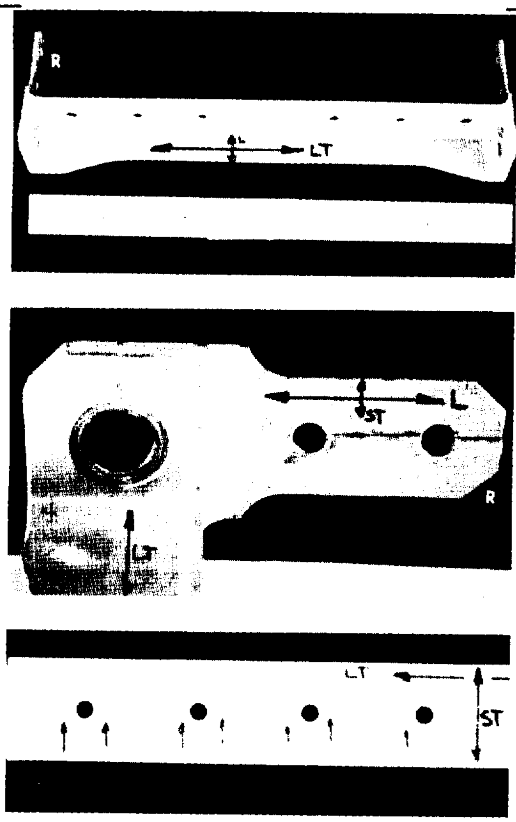


Figure 14. - Cracking around the fastener holes as a function of the alloy grain direction.

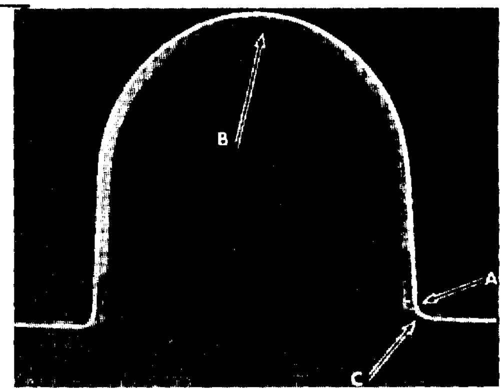


Figure 15.- Cracking on a strap made of type 7075-T6 aluminum alloy. The failure origin can be seen at point A, and secondary cracks can be seen at points B and C.

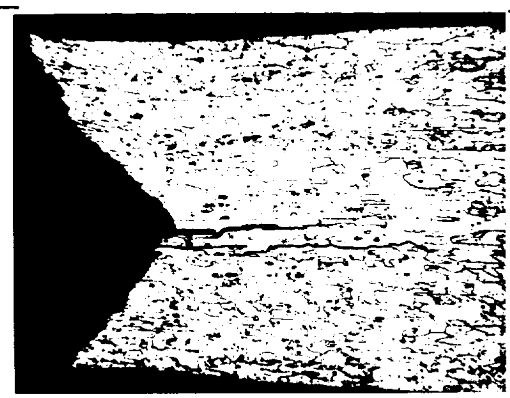


Figure 16. - Intergranular cracking at the midthickness from stress-corrosion cracking and transgranular cracking at surfaces, which indicates high tension loads (magnification: 100×).

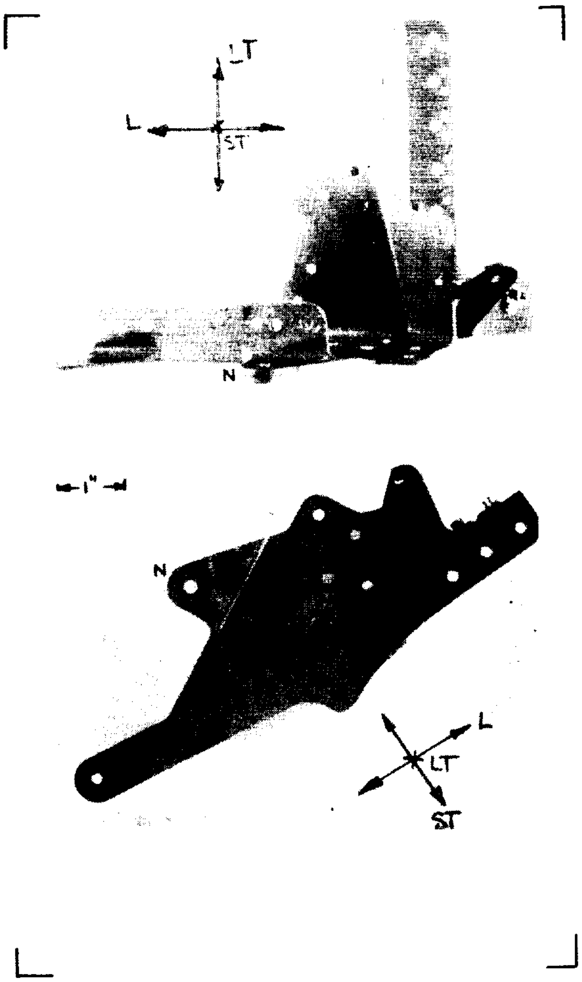


Figure 17. - Cracking on a machined part. (Note the relationship of the crack to the alloy grain direction.)

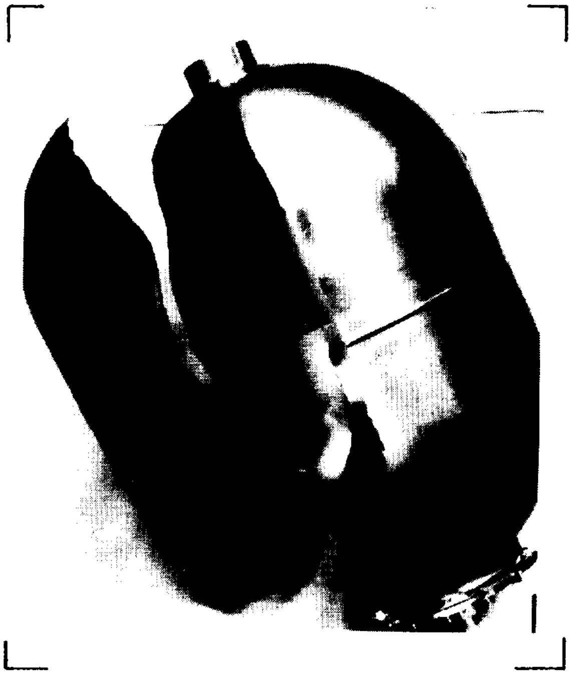
Over 130 parts in the LM program were found to be cracked as a result of stress corrosion. Many corrective actions were instituted. Among the solutions were component redesign, heat treatment to make the components less susceptible, shimming or otherwise relieving fabrication stresses, addition of corrosion-protection coatings to preclude as much of the corrosive environment as possible, and shot peening to introduce compressive surface stresses.

Pressure-Vessel Stress Corrosion

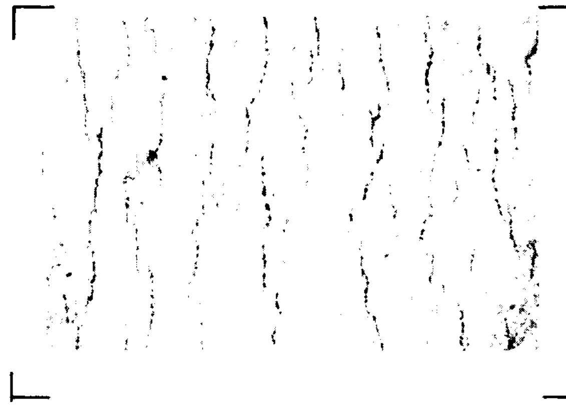
The problem of stress-corrosion cracking in pressure vessels is especially serious because the occurrence of this problem usually results in catastrophic failure of the vessel and associated damage to other hardware near the pressure vessel. Some of the significant Apollo Program pressure-vessel failures are described individually in the following sections.

Nitrogen tetroxide in titanium-alloy pressure vessels. - In all of the Apollo spacecraft propulsion systems, nitrogen tetroxide is used as the oxidizer. The storage of nitrogen tetroxide under pressure in titanium-alloy pressure vessels was a subject of concern because of known reactions between titanium and other oxidizers. Extensive test programs were conducted before 1964 to approve the use of type 6Al-4V titanium alloy as the standard Apollo spacecraft pressure-vessel material for this application. In 1964, qualification tests on the Apollo spacecraft main propellant tanks were completed. The tests included 30-day exposures of the pressure vessels to nitrogen tetroxide under the maximum wall stress of approximately 100 ksi.

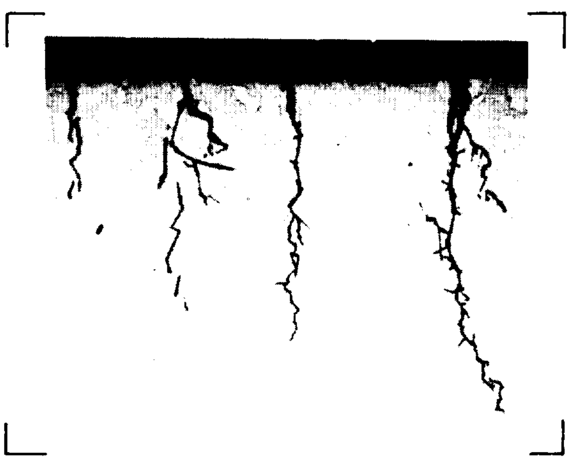
In 1965, a stress-corrosion failure of an Apollo reaction control system pressure vessel occurred. This failure could only have been caused by the nitrogen tetroxide reacting with the titanium-alloy pressure vessel. The failure analysis (refs. 2 and 3) showed that a change in the nitrogen tetroxide composition, within the limits of the procurement specification for the oxidizer, had eliminated one oxide of nitrogen and created a fluid that was causing serious stress-corrosion cracking of the titanium alloy. Details of the failed hardware are shown in figure 18.



(a) Failed pressure vessel.



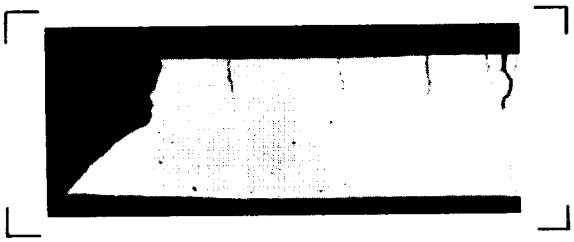
(b) Magnified view of the inside surface showing cracks.



(c) Transgranular cracks.

(d) Electron fractograph of the failed surface.

Figure 18. - Stress corrosion of type 6Al-4V titanium alloy from a failed nitrogen tetroxide pressure vessel.



(e) Cross section of the pressure-vessel wall showing a flat fracture with a shear lip.

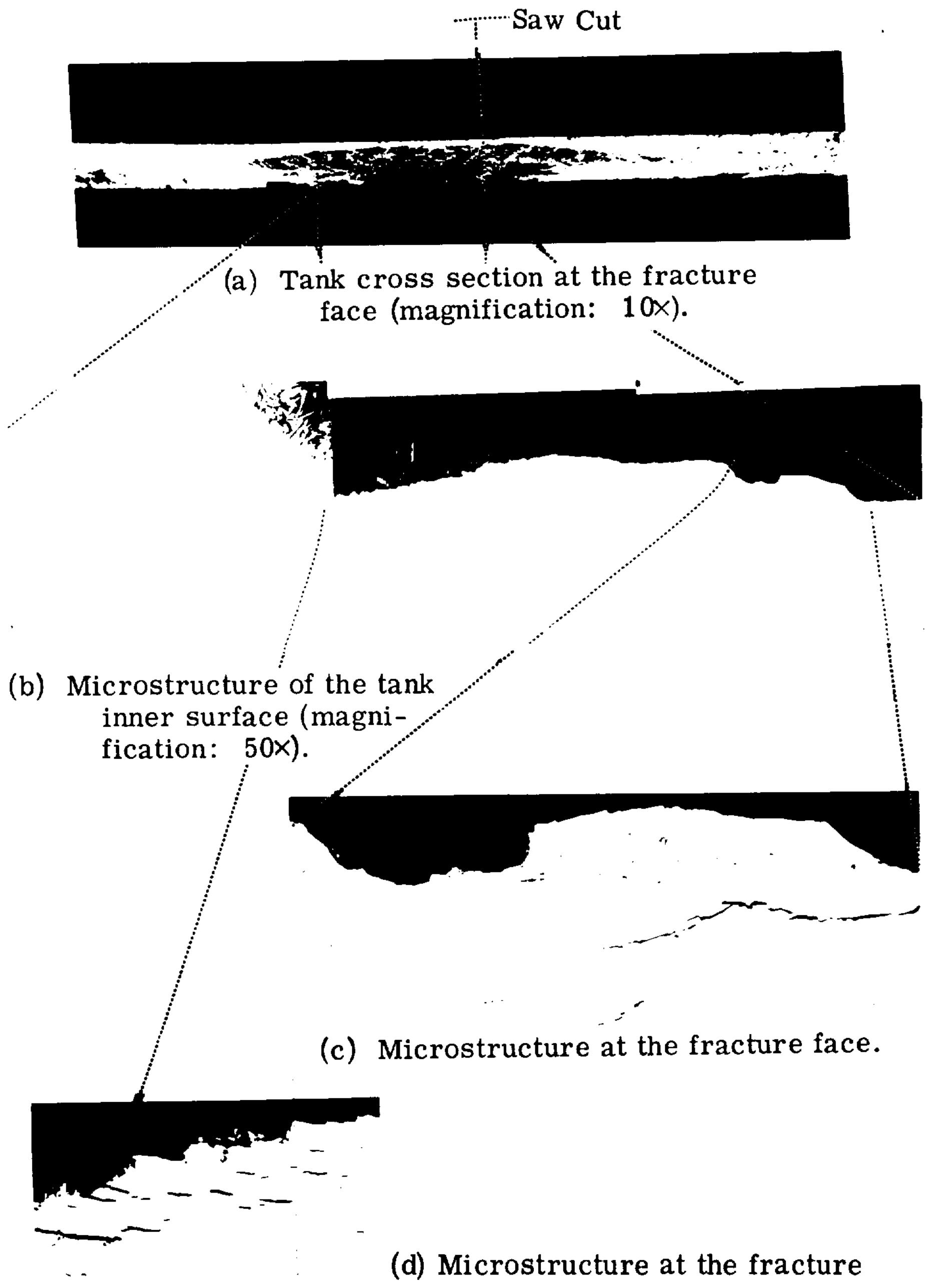
Figure 18. - Concluded.

To eliminate the problem, NASA generated a nitrogen tetroxide procurement specification that carefully controlled the oxidizer composition to maintain compatibility with the pressure-vessel titanium alloy. In addition, by taking samples of the oxidizer from the flight supply system before the oxidizer is loaded into the spacecraft and by testing the oxidizer in contact with stressed precracked samples of the pressure-vessel alloy, NASA continues to ensure that no fluid change has occurred that could cause aggressive reactions during a flight.

Methanol in titanium-alloy pressure vessels. - The most damaging failure of a pressure vessel in the Apollo Program occurred in October 1966 when a main propellant tank ruptured inside an Apollo service module and caused extensive damage and serious loss of hardware. The failure occurred while the pressure vessel, made of titanium alloy 6Al-4V, was filled with methanol and was pressurized. The failure mode was stress-corrosion cracking.

In this instance, methanol was used for safety reasons in the system checkout instead of the toxic propellant. Methanol was selected for its physical similarity (density, viscosity) to the propellant and because it could be removed from the system easily without leaving a residue or other contamination. The approval for the use of methanol was based on a literature search, which uncovered no data to indicate a potential problem. After the failure of the Apollo spacecraft hardware, numerous programs were initiated to investigate the problem, and the seriousness of the problem was defined in several technical papers (ref. 4). Examples of the metallography from the failed material are shown in figure 19. Additional information concerning the failure analysis is contained in references 3 and 5.

In retrospect, the lack of a test program to approve pressure-test fluids before they were used and a continuing check against contaminants during use caused a serious program problem. The Manned Spacecraft Center has corrected this situation by requiring compatibility testing before a new pressure-vessel material or a new test environment can be used in the Apollo Program.



(a) Tank cross section at the fracture face (magnification: 10×).

(b) Microstructure of the tank inner surface (magnification: 50×).

(c) Microstructure at the fracture face.

(d) Microstructure at the fracture face (different location from fig. 19(c)).

Figure 19. - Origin of the failure that resulted from methanol in a type 6Al-4V titanium-alloy pressure vessel.

Solid-fuel-rocket motor case made of type 4335V steel alloy. - Type 4335V steel alloy was heat treated to a minimum tensile strength of 210 000 psi. During hydrostatic acceptance testing, stress-corrosion cracking occurred that resulted in the rupture of two motor cases. The test fluid was water, and failure analysis showed that stress-corrosion cracking would occur if defects existed in the stressed alloy when it was brought into contact with water. The defects in the motor cases were identified as tight cracks that had resulted from the welding operation and that could not be detected by the postweld inspection. The corrective action for the problem was to change to a compatible test fluid, hydraulic fluid, and to make the inspection and quality-control procedures of the welding operation more thorough.

Oxygen-storage vessel made of type D6AC steel alloy. - Type D6AC steel alloy was heat treated to the 220 000- to 240 000-psi tensile-strength range and was used to store gaseous oxygen under pressure. The failure of one pressure vessel because of stress-corrosion cracking was caused by a small defect on the exterior surface of the pressure sphere. The corrosive medium was listed as water because the test consisted of immersing the vessel under water during hydrostatic testing. The vessel was nickel plated and the defect was found to contain nickel, which indicated the presence of the flaw before nickel plating. The corrective action taken was to change the test fluid to oil and to discontinue the immersion of the tank during pressure testing. Also, inspection procedures were tightened to enable detection of pressure-vessel defects before testing.

CONCLUSIONS

The Apollo spacecraft is constructed of high-strength alloys and is designed and fabricated to be a highly efficient, low-weight vehicle. Stress corrosion has been a serious problem in the Apollo Program and reflects the type of problem that can occur in a program requiring these characteristics. To illustrate the type of problem encountered, several examples are examined.

The examples discussed in this report are typical ones and do not represent all of the stress-corrosion cracking failures experienced in the Apollo Program. However, the examples discussed do represent the most significant problems encountered in the Apollo Program and allow the following general conclusions to be drawn concerning improvements that are needed to prevent the recurrence of similar problems in future programs.

1. With the exception of two environments, information on the stress-corrosion cracking behavior of the alloys used in Apollo spacecraft hardware was available and could have been used to avoid many of the stress-corrosion cracking failures if the information had been applied correctly during the design, fabrication, and test phases.

2. Without proper consideration of stress-corrosion cracking, such design changes as those for vehicle weight reduction can seriously affect the stress-corrosion sensitivity of the vehicle hardware by changing fabrication techniques, raw-material mill forms, and stress levels, and by eliminating corrosion-protection systems.

3. Specific alloys and alloys subjected to certain heat-treatment procedures are very susceptible to stress-corrosion cracking, and their use should be avoided wherever possible. Control should be exercised by the contractors and NASA over the use

of these alloys to ensure that adequate consideration of stress-corrosion cracking has been given to those applications in which the use of these materials is required.

4. New environment/alloy combinations must be examined experimentally before they are used in a program. The use of material forms, heat treatments, stresses, potential stress concentrations, and environments must be simulated if meaningful service data are to be obtained and program problems are to be avoided.

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National Aeronautics and Space Administration
Houston, Texas, July 10, 1972
914-13-20-06-72

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