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ANALYSIS OF LIQUID ROCKET TANKAGE

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Bell Aerospace Company

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The objective of this program was the assessment of storage container compatibility with N_2O_4, and ClF_5, for periods of time up to and including 6 years of pressurized exposure. Tankage materials were aluminum alloys 2021, 2014, 2024, 2219, 6061, 7039, X7007, and 5456, as well as Arde 301 stainless steel, A-286 and Inconel 718. Two types of N_2O_4 were evaluated for compatibility, namely oxygenated and unoxygenated.

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The evaluation of the storage containers revealed that the major source of degradation was external. The primary cause of corrosion was the dilute acid, high humidity storage area environment. Internal corrosion observed in a very limited number of containers was attributable to a lack of thorough rinsing after exposure. The majority of internal surfaces showed little or no degradation from either oxidizer.

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FOREWORD

This report was submitted by the Bell Aerospace Company, Division of Textron, Inc., P. O. Box One, Buffalo, New York 14240, under Contract No. F04611-74-C-0007, Job Order No. 305811TR with the Air Force Rocket Propulsion Laboratory, Edwards, CA 93523.

The Project Manager was E. J. King; the Project Metallurgical Engineers were John Salvaggi and H. G. Kammerer. The in-depth analyses were conducted by John Salvaggi. Analysis of corrosion products was performed by D. G. Roberts.

This report has been reviewed by the Information Office/DOZ and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

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PREFACE

This report covers the examination and metallurgical evaluation of a number of liquid propellant system storage vessels and associated components used for the storage of liquid rocket oxidizers. The primary purpose of this effort was to assess the degree of damage sustained by various alloys used in liquid system construction, after exposure to a storage environment of +85°F and 85 percent relative humidity, while storing the propellant oxidizers ClF_5 or N_2O_4.

The results of long-term storage up to six years indicate that oxidizer leakage can occur as a result of inadequate quality control of manifold tubing welds. Corrosion effects of the stored propellants on the internal metal surfaces of the various alloys studied, including aluminum and stainless steels, were negligible, with no serious degradation of strength or structural integrity occurring.

Corrosion occurred primarily on the external surfaces exposed to the ambient storage environment, particularly at manifold tubing welds in which 4043 aluminum filler wire was used to join 6061 aluminum tubing by the manual TIG weld process. Most of the propellant leakage observed was traced to weld metal penetration in this area.

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SECTION I

INTRODUCTION

The advent of long-term Air Force Weapon System Missions has made it necessary to evaluate long-term storability of liquid rocket propellant systems. This contract was concerned with the Metallurgical evaluation of simulated aerospace tankage after storage for various time periods, the maximum being six years, in unique environmental exposure areas at the Air Force Rocket Propulsion Laboratory (AFRPL). The storability program was designed to demonstrate compatibility of tankage alloys with rocket engine propellants, thereby providing fundamental information on tankage materials to be used over long storage periods.

The program conducted by BAC consisted of:

1. Documentation of as-received exposure vessels and components.

2. Definition of anomalies and defects that altered the functional capability of the components and exposure vessels.

3. Defining and obtaining approval of a Metallurgical Procedure Report.

4. In-depth metallurgical analysis of nine component/tanks.

5. Confirmation analysis of fourteen component/tanks.

The evaluation program conducted by BAC was divided into two Phases. The first Phase included steps 1 through 3 above while the second Phase dealt with the in-depth and confirmation analysis of areas where the degree of corrosion found would have eventually led to failure. The first shipment of tanks was received in October 1973; the second group of tanks was received July 1974. The tanks received are tabulated in Tables I and II.

Metallurgical examination of the exposure vessels/ components identified the nature and extent of corrosion that had occurred over the various time periods of interest. An effort was made to build a comprehensive matrix of positive and negative observations resulting from the analysis. Anomalies and failure modes were related to exposure conditions and when applicable to the mechanical characteristics that were deteriorated by the types of corrosion taking place. Processing and environmental effects were analyzed to determine their role in the abnormality or defect observed.

Mechanical properties of specimens machined from the test hardware were determined and include base metal properties as well as weld properties. These mechanical tests were necessary to verify heat treatments and to establish the extent, if any, of degradation from exposure, as well as verifying the integrity of weld joint or explosive bonded joints.

SECTION II
PROGRAM STRUCTURE

This contract continued the storability program initiated by the Air Force Propulsion Laboratory (AFRPL) in its effort to bridge the gap between laboratory coupon tests and austere evaluation of tankage materials that have endured long-term exposure to earth-storable fuels and oxidizers. Tankage materials investigated were those common to the aerospace industry, where strength to density requirements are a vital economic factor in the design of advance space systems. They included aluminum alloys, cryogenic formed austenitic stainless steel, and an age hardenable stainless steel. This program dealt with the evaluation and demonstration of long-term storage (up to 6 years), of tankage, components and integrated feed systems. The internal environment of these components was the oxidizers nitrogen tetroxide (N_2O_4) and chlorine pentafluoride (ClF_5) and the hydrazine fuel monohydrazine pentafluoride (MHF-5). The nitrogen tetroxide (N_2O_4) for some of the tests met specification MIL-P-2639, and is commonly referred to as brown N_2O_4. Other tests were conducted with MSC-PPD 2A specification N_2O_4, which contains NO. The external environment was a high humidity (85%) storage building. Leakage of the earth storable propellants from fittings or exposure vessels during the storage period, transformed this to a moist, acid fume environment.

The systems under evaluation in this program may be divided into three basic groups: (1) small containers, (2) representative type tankage and (3) tankage systems with associated expulsion devices and/or feed system components.

A brief description of each group follows.

A. GROUP I - SMALL CONTAINERS

All simulated tankage containers in this group have a capacity of one quart or less. The three types of containers evaluated during this program were as follows:

1. 2014-T6 Aluminum Alloy - 3" x 6" Containers

2. Alcoa One-Quart Containers - Fabricated of various Aluminum Alloys.

3. Arde One-Pint Cylinders - AISI 301 Stainless Steel.

B. GROUP II - REPRESENTATIVE TANKAGE

The exposure vessels in this group vary in size, with the largest having a capacity of 15 gallons. The range of fabrication and quality control problems encountered in manufacturing these vessels simulate those likely to be encountered during the manufacture of an operational liquid rocket system. There were two basic types of tanks in this group.

1. Storability Test Articles

Tanks of 10 to 15 gallon capacity fabricated of various aluminum alloys, one steel base alloy (A-286) and one nickel base alloy (Inconel 718).

2. Solid State Bonded Tank

Explosively bonded Alclad 2024 aluminum alloy material.

C. GROUP III - STORABLE PREPACKAGED FEED SYSTEMS (SPPS)

These systems, containing N_2O_4 or MHF-5 fuel, were manufactured by the General Dynamics Corp./Convair Division and consist of EB welded 2219-T62 aluminum alloy propellant tanks with a 15-gallon capacity.

SECTION III
TEST FACILITIES

A. LONG-TERM STORAGE PROGRAM - AFRPL

Two distinct test facilities, one for oxidizer tankage and one for fuel, located at the Air Force Rocket Propulsion Laboratory, were used for the propellant exposure of hardware evaluated in this program. The facilities were similar in design, incorporating safety provisions applicable to an oxidizer environment.

The exposure building was a Metal Quonset hut equipped to provide a constant controlled temperature environment of 85 ± 5°F and a relative humidity of 85 ± 5 percent. A Firex water deluge system, large water drain piping, fire detector, continuous toxic vapor detector incorporated into an automatic conditioner and a shutdown and scrubbing system which operates when an excess of oxidizer vapor is detected, constitute the safety system. The oxidizer vapor detector also minimizes the damage that would result when a leak develops in a test article.

B. POST-STORAGE TANKAGE ANALYSIS - BAC

The destructive examination of all tanks was conducted in the Bell Aerospace Company's Metallurgical Laboratories. All facilities required to conduct a complete metallurgical evaluation of the tanks were available and utilized within these Laboratories. The evaluation procedures used are outlined in Section (IV).

The equipment used in this work is described below.

After visual examination and photographic documentation of the as-received and as-sectioned vessels, they were examined in detail for corrosion, anomalies or defects using both binocular microscopes at low magnification and a higher magnification research microscope, such as the one shown in Figure 1. Photomacrographs of local corrosion and other anomalies were taken on view cameras, as seen in Figure 2. Cross sections of leaks, corroded areas, welds, etc., were prepared using the automatic rotary and vibratory metallographic polishing equipment shown in Figure 3. Photomicrographs of these metallographic sections, in the as-polished condition and after etching to reveal the microstructure, were taken on the research microscope shown in Figure 1. It was occasionally necessary to use radiographic inspection equipment, shown in Figure 4, to determine the exact location of corrosion penetration through the walls of the tubes and similar heavily corroded regions of the tanks. X-ray diffraction equipment, Figure 5, was used wherever a significant volume of corrosion product was available for analysis, by a powder diffraction pattern. Heat treatment facilities were available including a very high temperature vacuum furnace, Figure 6.

Mechanical properties were determined on most types of tanks evaluated, to establish the heat treatment condition or presence of degradation due to corrosion or other long-term storage effects. A wide range of universal testing machines and electrohydraulic closed loop testing systems were available and used to determine these mechanical properties, depending on the load range and any special loading conditions required. A typical tensile test specimen taken across a weld from one of these tanks is shown in Figure 7, with examples of fractured and unfractured mechanical test specimens. A tensile test in progress is shown in Figure 8, utilizing one of the universal testing machines with a load range of 3,000 to 300,000 pounds.

Other facilities and equipment were used in an auxiliary or routine manner during various portions of this evaluation program. These included hardness testing equipment such as conventional Rockwell or Vickers, Leitz micro-hardness and a Sonodour for automatic micro-hardness traverses. Tank sectioning was performed on abrasive cutoff saws, lathes and bandsaws.

SECTION IV

PROCEDURES

The procurement of test hardware and the environmental testing of this hardware with earth-storable propellants has remained essentially unchanged, since initiation of this long-term compatibility program, Reference (1). Although these procedures have been previously documented they are also presented here to maintain completeness of the presentation and to provide a convenient reference for the post-test evaluations of exposed hardware being reported on.

Test articles evaluated in this program were procured from aerospace contractors, where primary responsibility for quality control and quality assurance of the test articles was vested. This hardware was fabricated according to specific procedural specifications encompassing detailed inspection and cleaning procedures, as dictated by the alloy used.

Helim leak testing of all individual tankage in the as-received condition was performed to ensure against the development of leaks and the introduction of contamination during shipment of the test articles from the manufacturer. Upon completion of the leak test, the tanks were loaded with propellant and placed in the appropriate storage facility for storability testing. The oxidizer tanks were monitored for leakage while fuel tanks were monitored for excessive pressure rise.

Oxidizer tankage was removed when evidence of leakage was found. Leakage was determined through observation of an actual liquid leak, or the detection and location of a vapor leak by means of the facility toxic vapor detector. This instrument was also used as a "sniffer" to pinpoint leakage.

Following the above exposure test procedures, tanks were selected for destructive examination to ascertain the cause of failure or other observed anomalies. The metallurgical procedures used in the assessment of corrosive damage consisted of an examination of external and internal surfaces of the storage vessels with an in-depth analysis following the procedure outlined below. This procedure was submitted for approval of the project officer prior to initiation of these analyses.

A. APPEARANCE DOCUMENTATION

1. Those anomalies which are in large components will have the anomaly and surrounding materials segment cut down for ease of handling.

2. Take photomacrographs of anomaly surfaces; remove for analysis any corrosion products or deposits, and take additional photomacrographs if surface changes or new features are involved.

3. If not already visible, section away from defect to reveal inside surface of anomaly area and take photographs of this inside surface.

B. EXAMINATION OF LEAK SURFACES

(Those components being analyzed for surface pitting, etc., where no leak or deep corrosion is involved, will be examined per C. below).

1. If leak is suspected but not pinpointed, radiograph to verify location and extent.

2. Carefully trim leak area to remove surrounding metal.

3. Break open leak area by hand bending or tensile fracturing, to expose corrosion surfaces.

4. After microscopic examination at 10X to 60X, take photomacrographs of exposed corrosion surfaces.

5. Perform high magnification microscope examination of one half of exposed corrosion surface, to determine topography and significant features of surface.

C. EXAMINATION OF PITTED SURFACES

(For those analyses where no leak is involved).

1. Section through pitted region in a careful manner (usually with jeweler's saw) so that at least two segments of essentially equal pitting are available, assuming pit is of sufficient size.

2. Perform high magnification microscope examination of one half of pitted surface to determine topography and significant features of surface.

D. MICROSTRUCTURE AND RELATION TO CORROSION, LEAK OR ANOMALY

1. Mount a cross section through critical area of anomaly.

2. Polish using conventional metallographic techniques.

3. Examine in unetched condition for corrosion penetration of grain boundaries or similar effects and take photomicrographs.

4. Etch with appropriate reagents to bring out microstructure of weld and/or parent metal.

5. Examine and take photomicrographs of microstructure, both as it relates to corrosion effects and also to determine matrix microstructure and material effects.

E. CHEMICAL ANALYSIS OF CORROSION PRODUCTS AND CORRODED MATERIAL

1. If corrosion products were removed in Step A. 2., analyze by X-ray diffraction or other analysis techniques.

2. If there is any suspicion that tank materials or weld filler metal is not of the alloy expected (based on

microstructure or other observations), spectrographic analysis of component material will be performed.

F. CONFIRMATORY ANALYSIS OF RELATED ANOMALIES

1. Anomalies in other components which appear to be closely related to one which is being subjected to detailed analysis will have been identified.

2. These anomalies will be photographed to show surface appearances only to the extent necessary to establish similarity/difference to detailed analysis subject.

3. These anomalies will then be sectioned, mounted and metallographically polished. They will then be examined and photographed in both unetched and etched condition in same manner as detailed analysis Steps D.3 thru D.5.

G. METALLURGICAL ANALYSIS AND PREPARATION OF REPORT

The foregoing test results will be reviewed in detail, correlated with prior fabrication and test history of the storage vessel, and presented as a final metallurgical failure analysis report. This report will follow the format outlined in MIL-STD-847D. The report will include glossy print reproductions of all applicable photographs showing surface appearance, corrosion products, leak progression and microstructure.

SECTION V

FABRICATION HISTORY OF TANKS

A. GENERAL

In the analysis of corrosion behavior of any component it is instructive, and often necessary to know the methods of fabrication and the processing details involved, in order to arrive at meaningful conclusions to the cause and significance of observed corrosion effects. Thus in this program of analysis of a wide variety of tanks, after various propellant exposures, it was necessary to collect as much fabrication history as possible to aid in the evaluation. This history is summarized in this section, and is then referred to in detail and confirmatory analyses discussed in Section VI on tank failure analysis. The reports and references from which this fabrication history was obtained are tabulated in the References (Section VIII), with the specific reports from the manufacturer listed, where applicable, in the Tables which accompany this section. None of the tanks evaluated were fabricated at Bell Aerospace Company; therefore, all of this section presents information obtained from reports, or observations on the tanks themselves by investigators experienced in many phases of aerospace hardware fabrication.

B. GROUP I - SMALL CONTAINERS

All simulated tankage containers in this group have a capacity of one quart or less. These containers were designed to evaluate a particular problem, a promising alloy or a fabrication procedure. The tanks offer an economical approach to storability testing compared to full scale tank testing and serve as excellent "screening" exposure vessels. Although they do not duplicate the manufacturing and quality control problems associated with larger size tanks, they do provide a realistic assessment of potential compatibility problems.

1. <u>2014-T6 Aluminum Alloy - 3"x6" Containers</u>

Four (4) of these containers were included in this examination. The containers were from a group of 28, produced by four manufacturers: McDonnell Douglas, General Dynamics-Convair, North American Rockwell and Martin, during a study of Titan II missile system leakage problems involving aluminum 2014-T6 tanks and N_2O_4 propellant oxidizer. Since these containers did not have serial numbers or any other identification, it was not possible to identify the specific manufacturer. The containers represent two different configurations of end plate to cylinder welds, and were therefore probably fabricated by two manufacturers. The other features of tank fabrication are quite similar, with sheet aluminum having been rolled into semi-cylinders and welded longitudinally. The short cylinders thus obtained were welded together and end caps, machined from plate stock, were then welded to the cylinder. From the appearance of some welds, it seemed that different filler alloys may have been used on some of the containers. All welds except some of the end plate to outlet fitting welds were obviously machine welded, possessing a smooth, relatively narrow and uniform geometry and appearance.

2. <u>Alcoa One-Quart Containers</u>

These containers are sometimes referred to as "Guinea Pig Tanks". A variety of aluminum alloys (2014, 2219, 5456, 6061, M825 or 7007) were fabricated into one quart vessels of a square ended cylinder shape, to provide small, relatively low cost containers which could be used for compatibility tests. No specific report was available to provide details of the fabrication process. However, inspection of the hardware, and a series of mechanical tests and other examinations provided sufficient information for an explanation of the fabrication process.

The containers consist of two spun cups, each with a square end and cylindrical sides. After the girth weld was made, joining the two tank halves, weld deposits were placed on the parent metal so that "crossed welds" would be produced in the finished tank. This configuration of a later weld crossing a previous weld is often encountered in large scale flight tankage and is therefore of great interest. In addition to these welds, machined fittings were welded into each end of the tank. All of these welds were manual welds, generally of very good quality, but not perfectly uniform.

In order to verify the heat treatment and welding sequence, and also provide insight into possible degradation of the materials during the course of exposure, tensile tests were performed on parent metal and weld samples of selected tanks, one of each alloy from this group. The results are considered in detail in Section VI.C.1. The only tank which departs significantly from the expected properties of the T6, fully heat treated condition, is the 7007 (M826) experimental alloy tank. The properties reported in the Alcoa report on the development of this alloy (Ref. 2) were used to provide the typical properties. The non-heat treatable, work hardening alloy 5456 produced properties which correspond to either the H117 temper as-worked condition or the H321 temper, a worked plus stabilized condition. These seem reasonable for this non-heat treatable alloy.

3. Arde One-Pint Cylinders

These tanks are small, elongated cylinder shapes developed by Arde, Inc., as a production quantity vessel for storing high pressure gases (CO_2 for raft inflation or O_2 for life support). Since they are a production item no individual cylinder information is available, but the fabrication process is well established. The material used is a controlled chemistry version of AISI 301 stainless steel, a "lean" grade of stainless steel, which readily transforms to martensite during low temperature straining. This transformation to martensite produces a very large increase in strength, making the cylinder capable of withstanding very high pressures.

The cylinder is fabricated by rolling and welding sheet to form the cylinder section, then welding on end caps spun from sheet metal. The closed cylinder is fabricated undersize, and is solution annealed before being placed in a cryogenic chamber where it can be stretched to final size by internal hydrostatic pressurization, at liquid nitrogen temperature. This stretch is accomplished in a die cavity, which controls the stretching, allowing shaping of the finished bottle, and results in a removal of weld mismatch or any eccentricities in the fabricated parts.

The cryogenic stretching results in the desired austenite to martensite transformation and a high strength level. The strength can be further increased by an aging treatment, 20 hours at 800°F, which results in precipitation along the transformed martensite boundaries. These effects and the properties obtained are presented in detail in Section VI.B.9.

C. GROUP II - REPRESENTATIVE TANKAGE

The tankage in this group included 15-gallon capacity vessels fabricated solely for use as test articles in this program. The tankage was fabricated by current or advanced state-of-the-art methods. Fabrication and quality control problems encountered during the course of manufacture of this tankage group are likely to be encountered during the manufacture of an operational liquid rocket system.

1. Storability Test Articles

These are tanks of 10 to 15-gallon capacity procured especially for use in this program. They were manufactured either by Convair or Martin, as a part of procurements made over the course of several years. The tankage was manufactured from aluminum, steel or nickel alloys, using large-scale production methods, and includes dome, girth, cylindrical, and longitudinal welds characteristic of large tankage design. Manufacturing process records, X-ray, photographs, inspection logs and metallurgical samples of welded and unwelded materials were delivered to AFRPL with the tanks to serve as documentation. For the prupose of this evaluation program, the Convair or Martin reports documenting these tank fabrication programs have generally provided all information needed to understand the fabrication process involved. These reports are included in the reference listing for this section. (References 3, 4 and 5). Based on these reports and inspection of the tanks, tabulations of the significant characteristics of fabrication are given in Tables III and IV.

2. Solid State Bonded Tank

The experimental solid state bonded tank was fabricated by the Martin Company, using explosive bonding techniques. The fabrication of this 2024 aluminum tank is discussed in greater detail in the corrosion analysis Sections VI.B.5 and 7 since the fabrication aspects (Alclad sheet, annealing, etc.) were quite important in understanding the corrosion effects observed.

D. GROUP III - STORABLE PREPACKAGED FEED SYSTEMS (SPPS)

These systems, procured especially for the storage compatibility program, consisted of a complete set of hardware for the storage, positive expulsion and control of propellant delivery under flight conditions. They were designed, fabricated and filled with propellant by the General Dynamics Corp./Convair Division. Their fabrication history is outlined in Table V. The systems contained either a surface force orientation (SFO) device or a Rolling Diaphragm (RD) for positive expulsion of the propellant, combined with either a liquid propellant gas generator (LPGG), solid propellant gas generator (SPGG) or high pressure stored gas device (SGD) pressurization sub-system. Metal discs, welded into the tank inlet and outlet, ruptured for propellant discharge when they were pressurized by the sub-system.

The SPPS evaluated in this program simulate operational systems, where an expulsion device is often integrated into the tankage to insure that single phase liquid is fed to the engine. Further fabrication details are given in Reference 6 which documented the Convair effort in building these systems.

SECTION VI
DISCUSSION OF RESULTS

A. OVERALL EXAMINATION OF EXTERNAL AND INTERNAL SURFACES

The first stage in any examination of hardware for corrosion effects is a thorough examination and documentation of the surface appearance. This examination must be done by trained and experienced observers who will pay careful attention to preferential attack of welds, crevices and other susceptible regions. The initial examination of these tanks, after exposure to various propellants and storage room environments, was done in this manner, with complete photographic documentation of the external and, after preliminary sectioning, internal surfaces. The primary purpose of this initial examination (Phase I of metallurgical effort) was to identify those failures, anomalies or unusual conditions which would warrant a more detailed examination and analysis in the Phase II portion of the metallurgical effort. Accordingly, this section of the report documents the surface condition of the tanks as received from their various test exposures, and identifies those anomalies, failures or other corrosion and service effects, which will be considered in the succeeding Section VI.B, Metallurgical Examination of Failures and Anomalies.

As was discussed in Section II on Program Structure, there were three main classes of tanks examined in this program: Small Containers, designed primarily for compatibility testing; Representative Tankage, 10-15 gallon tanks incorporating full scale tank fabrication methods; and Prepackaged Systems which contained all hardware necessary for storage, expulsion and control of propellants. These main classes are treated separately in the following sub-sections.

1. Small Containers

a. Arde One-Pint Cylinders

A total of 15 of these AISI 301 stainless steel cylinders, was examined. All of the cylinders included a valve and related fittings at each end. None of the attached valves or lines showed any significant corrosion effects. Therefore, these components were not examined further. One-half of the tanks were in the unaged (as-cryo-stretched) condition and the other half in the aged condition (20 hours at 800°F). In each group one-half of the tanks were filled with ClF_5 and the other half with N_2O_4. All were exposed for a period of five years. A listing of these cylinders, their condition, stored propellant and brief summary of their external and internal appearance, is given in Table VI.

The unaged cylinders loaded with ClF_5 are shown in Figure 9. The exteriors of all three of these cylinders were clean and smooth with no corrosion. After sectioning, the interiors were found to have a light straw colored stain appearance, but no corrosion or attack was visible.

The unaged cylinders loaded with N_2O_4 are shown in Figure 10. Two of them, S/N's 4 and 7, had a small amount of minor pitting on exterior welds at one end, but this was not considered significant. The other two were completely clean with no corrosion. The interiors of these cylinders were very clean and untarnished with only the faintest indication of a "waterline" to show the level of propellant stored in them.

The aged cylinders loaded with ClF_5 are shown in Figure 11. As with the last group, some very minor pitting was visible on welds and end fittings of S/N's 16 and 17, while the other two were clean and unattacked. The interiors of these aged cylinders were significantly different from the unaged cylinders previously discussed. The surfaces were dulled and uniformly stained to a light medium brown. There was no evidence of any corrosive attack. These cylinders had either been filled completely, or the partial filling with ClF_5 did not cause any change in the internal stain, as it did with the N_2O_4. This internal dulling and staining was therefore associated with the aging rather than with the propellant exposure.

The aged tanks loaded with N_2O_4 are shown in Figure 12. The exteriors of these cylinders showed no attack or corrosion. As with the other aged tanks, the interiors were dull and stained a light brown. The N_2O_4 exposure had left a "waterline" about 2/3 up the sides of the cylinder, with the liquid phase surface slightly darker than the vapor phase. There was no corrosion or attack visible.

The dulling or staining of the aged cylinders and the apparent slight effect of the N_2O_4 was considered worthy of metallurgical evaluation, even though it obviously did not represent a degrading condition. In addition, the sectioning of these Arde cylinders offered an excellent opportunity to further examine the strength and metallurgical characteristics of this tank material, with its extreme toughness and strength. Therefore, a detail analysis of cylinders S/N's 10 and 23 was performed and is included in Section VI.B.9.

The exposure and compatibility performance of these cylinders over a five-year period was excellent in all three environments: ClF_5, N_2O_4 and a humid, sometimes acid vapor laden, storage room environment. This material would certainly seem to be an excellent choice for long-term storage of these propellants.

b. 2014-T6 Aluminum Alloy 3"x6" Containers

Four containers, loaded with N_2O_4 (Specification MIL-P-26539) for over four years, were examined and are tabulated in Table VII. Their exterior and interior surface appearance is shown in Figure 13.

The external surfaces of these containers were lightly etched with scattered, very shallow pitting, particularly on the welds and along the edge of weld areas. The welds were generally darkened, but none of these external, mild corrosion effects were considered significant. They do indicate the moderately corrosive nature of the humid, sometimes acid fume containing, storage room environment.

The internal surfaces of these four cylinders showed some light surface attack and some pitting, varying from definite, though shallow pits in S/N 1 to the suggestion of the start of pitting in S/N 3. A small quantity of white corrosion product was usually found in areas where definite pits had formed. As indicated in Table VII, these containers had remained empty, drained and purged, but not flushed, for 2½ years before sectioning and evaluation. Past experience at BAC, with hardware tankage, has shown that flushing must be carried out with care if corrosion is to be prevented. It is therefore believed that the pitting observed is directly attributable to the lack of flushing. The localized appearance of discoloration along a strip which would represent a residual liquid location can be seen in the S/N 4 cylinder in Figure 13 and supports this conclusion.

This internal pitting, although not considered serious, does correspond to pitting in other 2014 or 2024 aluminum tanks. Therefore, S/N 1 from this group was examined in greater detail as a confirmatory analysis in Section VI.B.5.

Other than this internal pitting, which was believed due to post-propellant exposure, these containers showed no serious degradation, and they verify the conclusions drawn earlier in the Long Term Storage Testing Program (Ref. 7) that any leakage problems in Titan II tankage were the result of tank design and fabrication problems rather than material/propellant compatibility problems.

c. Alcoa One-Quart Containers

A total of 27 aluminum alloy tanks were loaded with ClF_5 or N_2O_4 and stored for $3\frac{1}{2}$ years. In addition, some of these tanks had previously been used in exposure tests with other interhalogen propellants such as ClF_3 or Compound A. Before use in this series of tests, the reused containers had been inspected and cleaned, so that any current corrosion effects are assumed to be the product of the current test exposure.

A tabulation of all tanks, their known history and brief description of their external and internal appearance is given in Table VII.

Two X7007 (M-825) alloy tanks loaded with ClF_5 are shown in Figure 14. The external surfaces of these tanks were heavily etched or corroded, with attack along the edge of weld and in heat affected zones even more pronounced. This was particularly true around the welded fittings at the tank ends. The interior surfaces were quite clean with only a slight suggestion of some spots which might eventually become pits. The external surface pitting of one of these tanks, S/N 105, was subjected to additional evaluation as a confirmatory analysis under the External Surface Pitting Study, Section VI.B.7.

Three 6061 alloy tanks loaded with ClF_5 are shown in Figure 15. The external surfaces of these tanks were generally clean with only a few pits on the tank ends, particularly on S/N 40. None of these pits were deep or serious and none were associated with the welds as had been the case with the 7007 alloy tanks. The internal surfaces were very clean and shiny showing no corrosive attack. This very good resistance to corrosion from both the propellant and atmosphere is to be expected for this 6061 alloy and no additional analysis was performed on these tanks.

The four 2219 alloy tanks loaded with ClF_5 are shown in Figure 16. These tanks showed some etching and pitting, particularly at edge of weld areas and at the ends, but it was much less pronounced than the 7007 alloy tanks. The interiors were dulled, with some very shallow pitting of the base metal in isolated areas, but no attack of the weld or heat affected zones. In general these tanks were unaffected by the propellant exposure and only lightly affected by the humid, environmental exposure, so no further analysis was performed on this group.

The four 5456 alloy tanks loaded with ClF_5 are shown in Figure 17. The external surfaces were generally clean with only a slight amount of pitting. There was some checking or very shallow cracking associated with the welds on two of the tanks, S/N's 92 and 96, but these were neither caused by nor aggravated by any corrosion and were therefore not considered significant to this program. The internal surfaces were clean and generally bright with no evidence of any corrosion effects, much the same as the 6061 alloy. No further analysis was necessary on this group of tanks.

The seven 2014 alloy tanks, loaded with ClF_5, are shown in Figure 18. The external surfaces of these tanks showed a general etching with pitting of the weld heat affected zones, particularly along the edge of weld lines. This etching and pitting was not deep but does indicate the poorer corrosion resistance of 2014 as compared to 6061, 5456, 7007 and 2219. Tank S/N 81 had a small hole extending inward a short distance at the edge of one weld. This appeared to be a weld induced anomaly, and no local corrosion occurred in or near the hole, so it was not considered further for this program. The internal surfaces of these tanks were dull and discolored, with severe pitting in S/N 19, lesser pitting in S/N 24 and some shallow pits or the start of pi's in most tanks. There were several checks, fissures or very shallow cracks on internal weld surfaces of several tanks which were considered primarily welding anomalies. The internal condition of tanks S/N's 19 and 24 are considered in detail in Section VII.B. The 2014 alloy, as expected, showed poorer corrosion performance externally than the other aluminum alloys. Internal corrosion resistance was also significantly less than that of the other aluminum alloys.

The three X7007 (M-825) alloy tanks loaded with N_2O_4 are shown in Figure 19. As with the ClF_5 loaded tanks, these showed general external surface etching or attack, with some pitting and heavier attack along the edge of weld lines. The interior surfaces were clean but with the start of pitting evident in some locations. The internal attack was much less than with the ClF_5 loaded, X7007 alloy tanks which were subjected to additional analysis. The N_2O_4 exposure and post test storage with N_2O_4 residues was evidently less severe on the alloy than the ClF_5 and ClF_5 residue exposure.

One 2219 alloy tank loaded with N_2O_4 is shown in Figure 20. The external surface of this tank was lightly etched with some edge of weld attack, particularly in the weld overlap or weld stop areas. The internal surface was stained somewhat, particularly at one end, where a residue had evaporated, but no corrosion or pitting was observed.

Three 2014 alloy tanks loaded with N_2O_4 are shown in Figure 21. The external surfaces showed heat affected zone and edge of weld attack but no serious pitting and essentially no attack of the base metal. The internal surfaces showed some shallow pitting and discoloration which were less severe than the 2014 alloy tanks loaded with ClF_5 and previously discussed. Since the attack in this group was much less than the other 2014 tanks selected for additional metallurgical analysis, no further analysis of these tanks was performed.

The surface evaluation of these Alcoa aluminum tanks can be summarized with these "ranking" comments:

(1) Propellant exposure effects were not severe in any alloy, with the ClF_5 causing slightly more attack than the N_2O_4.

(2) The internal attack that did occur is likely to have been caused primarily after draining, in the 1½ - 2 year period before evaluation.

(3) External surface attack, caused by a humid, acid vapor, room environment caused extensive, although not deep, attack of the 2014 and X7007 aluminum alloys, lesser attack of the 2219 and almost no attack of the 6061 and 5456 alloys. This same general ranking applies to the attack observed in the tank interiors, except that the X7007 alloy would fall between the 2219 and 6061 alloys.

2. Representative Tankage

All of the tanks of this type received and examined are tabulated in Table VIII along with their exposure history and a brief description of their external and internal surface appearances. The second set of these tanks received had been selected because of more serious corrosion effects and a separate tabulation of weld corrosion effects in these tanks is presented in Table IX.

A group of five 2021 aluminum tanks from Martin-Denver, loaded and stored with ClF_5, are shown in Figures 22, 23 and 24. The exteriors of the tanks, all painted blue, were clean and unaffected by the environment even in those areas where the paint film was scraped off. The internal surfaces of all five tanks were very bright and shiny, with no corrosion effects visible. In all cases the tank shell was completely unaffected by the propellant or environment exposure. On all of these tanks, however, the inlet tubes leading to the flange cover had been corroded or damaged. On Tank S/N 1, the tube to fitting weld was corroded and broken off. On Tank S/N 2, the fitting to tube weld was mechanically fractured with no evidence of corrosion. On tank S/N 3, the weld was corroded and leaking. On Tank S/N 4, two of the tubing welds were corroded with the tube broken off at one of these corroded welds. On Tank S/N 5, one weld was corroded and leaking. All of these corrosion effects occurred in welds made with 4043 alloy joining the tubing, which was 6061 aluminum. All of these corroded welds (excluding Tank S/N 2, where fracture appeared simply to be mechanical in origin) were subjected to detail or confirmatory analyses in Section VI.B.2 or 4.

The Inconel 718 tank, fabricated by Martin and loaded with ClF_5, is shown in Figure 25. This tank had been in test for only two days when leakage was noted at the flange cover plate seal. This seal consists of a soft aluminum gasket compressed by the adjacent sealing surfaces which have concentric ribs machined in them. The gasket had been deformed by the ribs, indicating that the cover plate bolts were torqued up. There was considerable local corrosion and corrosion product deposit outside the sealing ribs, verifying the reported leakage. No gross defects were visible on the gasket or sealing ribs. The manufacturer, Martin Company, had reported difficulty in sealing all the Inconel 718 tanks fabricated (Reference 4). Tool chatter, aggravated by the poor machinability of the Inconel, had been observed on the flange sealing ribs, presumably resulting in the inability to seal perfectly. The flange and cover were therefore remachined, and the tanks were then able to pass helium leak test. Some areas of fine chatter, scratches and other imperfections were observed on the rib surfaces of this flange assembly.

Away from the flange area, exterior and interior surfaces of this tank were clean and unaffected by exposure, with no evidence of corrosion or attack. The tank shell was slightly dulled from the post-weld aging used to develop the desired heat treatment condition. Because of the complete lack of any corrosion effects, and the very short exposure time, no further evaluation was performed on this tank, except for the mechanical property tests to be discussed in Section VI.C.

Two 6061 aluminum tanks from General Dynamics-Convair were in storage test for 5¾ years. The one loaded with ClF_5 is shown in Figure 26, and the one loaded with N_2O_4 is shown in Figure 27. The exterior surfaces of these tanks were slightly etched, with somewhat more attack along weld heat affected zones, but with none of the attack serious. The interiors of both tanks were bright and clean with occasional light stains and spots but no pitting. One outlet tube was mechanically broken off, but there was no evidence of corrosion in that tube or any other on these tanks. No further analysis was performed on these two 6061 tanks because of the absence of any corrosion effects.

A 2014 aluminum tank from Convair, loaded and stored with N_2O_4, is shown in Figure 28. The external surface was heavily etched throughout, with even more pronounced etching of the weld heat affected zones. The interior was dull and tarnished, with some spots that may be the onset of pit formation. One outlet tube was heavily corroded at a point where it was sharply bent but that corrosion appeared to have started at an adjacent mechanical fitting which may have loosened. Since the corrosion effects in this tank were less severe than in another 2014 Convair tank to be discussed below (and later analyzed in detail) no further evaluation was performed on this tank.

Three 2014 aluminum tanks manufactured by Martin and loaded with ClF_5 are shown in Figures 36 and 37. All of these tanks were painted with a blue protective paint on their exterior. Tank Nos. 1 and 2 (Figure 36) were free of any corrosion effects on the tank shell itself. On both of these tanks, the inlet tubing at the flange cover was corroded and leaked with the result that there was extensive corrosion of the exterior of the flange and adjacent tubing. On Tank No. 3 (Figure 37), acid from some external source (probably leakage of an adjacent tank or line) had severely corroded one side of the dome, flange end and upper portion of the cylinder section. The wall thickness was reduced considerably in a local region close to the flange boss attachment, and perforation or leakage of the tank occurred. The interiors of these three tanks were quite clean, and generally shiny, but with some minor discoloration. There was some minor edge of weld attack but no significant corrosion was noted in any of these interiors. The severe corrosion and leakage on the tubes of Tank Nos. 1 and 2 are considered in detail in Section VI.B.3 and 4, while the corrosion of the shell exterior of No. 3 was subjected to a detail analysis presented in Section VI.B.7.

Two 7039 aluminum tanks, also manufactured by Martin and loaded with ClF_5, are shown in Figure 38. As with the 2014 tanks just discussed, these were also painted and had small, insignificant spots of corrosion evident on the external tank shell. The internal surfaces were very clean and bright with no evidence of corrosion. The tubes welded to the flange cover were corroded. On Tank No. 4, the tube to fitting weld was corroded and then mechanically fractured. The flange cover to tube weld on Tank No. 5 was corroded, while the tube to fitting weld was fractured with no corrosion observed. It is likely that many of these broken tubing welds represent situations where the disassembly of adjacent fittings after lengthy exposure required considerable torque and mechanical effort, far beyond the normal assembly and disassembly forces expected. These tubing corrosion failures are examined as detail and confirmatory analyses in Section VI.B.4.

An experimental solid state bonded tank from Martin, fabricated of 2024 Alclad aluminum and loaded with N_2O_4, is shown in Figure 39. This relatively small tank, consisting of two domes explosively bonded at an overlap joint, showed extensive etching and corrosion with white powdery corrosion product over the entire exterior. The tank was fabricated from Alclad sheet, and additional corrosion was present on the exposed edge of the overlap joint where the 2024 core was bared to the environment. The interior of the tank was discolored and lightly etched.

Numerous very deep pits were found in the interior, particularly at the dome end opposite the inlet/outlet port. This interior pitting appeared to be the result of residual propellant left in the tank after draining and purging. A small crack was found on the inlet/outlet port to shell weld but it was not associated with any corrosion effect. A rust colored deposit of foreign material was found along a portion of the interior bond overlap. As described in this paragraph, it is evident that several of the features of this tank warranted additional examination. The most serious, the deep interior surface pitting, was examined as a detail analysis in Section VI.B.5. The external surface attack was examined as a confirmatory analysis in Section VI.B.7. The opportunity to study both mechanical properties and metallurgical behavior of the experimental solid state bond, after several years exposure, was also taken, and that evaluation is included in Section VI.C.

A 2014 aluminum tank, manufactured by Martin and loaded with N_2O_4 is shown in Figure 40. The exterior of this tank was etched and lightly pitted over the entire surface, with pitting heavier along heat affected zones and edge of weld lines. This pitting was not deep in any location, but was general over the surface, although slightly less under the support band where the surface is somewhat protected. The interior was very clean and bright except for some minor discoloration of welds and small spots. No significant corrosion occurred on the interior. The corrosion and pitting of the exterior was evaluated as a confirmatory analysis, in Section VI.B.7. Tensile tests to show strength degradation, if any are also included.

A 7039 aluminum tank from Martin, loaded and stored with N_2O_4, is shown in Figure 41. The exterior of this tank was uniformly and lightly etched to a light gray, matte finish. There was no pronounced exterior corrosion. The interior was very clean and bright, with a distinct "waterline" showing that the tank had been half-full of propellant. There were no corrosion effects visible in the interior. With only slight external corrosion and no interior corrosion, this tank was not subjected to any additional analysis.

A 6061 aluminum tank, manufactured by Convair and loaded with N_2O_4, is shown in Figure 42. The exterior was uniformly etched to a light gray, matte finish, with some welds darkened and a minor amount of edge of weld attack, but no pitting or other significant corrosion. The interior was bright and shiny, unaffected by the propellant exposure. No further analysis was performed on this 6061 tank, which again demonstrated the generally good corrosion resistance of this alloy. Two 2014 aluminum tanks made by Convair, one loaded with N_2O_4 (No. 10) and one with ClF_5 (No. 11) are shown in Figure 43. The exterior surfaces of both tanks were etched and corroded with a white, powdery corrosion product present on portions of the surface. There was some preferential attack along the weld edges, with occasional pitting. Exfoliation attack, (lifting up of surface layers of the sheet by subsurface corrosion along rolling planes) was observed in local areas near the bosses of Tank No. 11. The interior of the No. 10 tank, loaded with N_2O_4, contained significant discoloration and pitting, particularly in a band where residual propellant probably remained after draining. Other areas, particularly on and near welds, show shallower pits and spotted discoloration.

This No. 10 tank was subjected to metallurgical evaluation as a confirmatory analysis in Section VI.B.5. The No. 11 tank, loaded with ClF_5, showed much less corrosion effect, with the internal surface being generally clean and bright, with only shallow pitting. This tank, which did not receive additional analysis, represents a somewhat unusual condition, since throughout this program the ClF_5 propellant produced more severe attack than N_2O_4. This pair of essentially identical 2014 tanks, however, showed more pronounced corrosion in the N_2O_4 loaded unit. One possible explanation could be that pitting corrosion in the N_2O_4 tank may have been caused by incomplete draining and purging, developing during post-propellant storage period; whereas the ClF_5 tank was more thoroughly purged, so that less acid residue remained.

An A-286 stainless steel tank, manufactured by Martin and loaded with ClF_5, is shown in Figure 44. The exterior of this tank was painted blue, and the paint was intact and unaffected over most of the surface, with no evidence of any general corrosion. There was a relatively small, localized rust-like spot on the weld joining the dome to the flange. Although relatively small and appearing minor, later evaluation showed this spot of corrosion to have perforated through the weld. The interior of the tank showed no corrosion, only a dull film, probably from the post-weld aging of the tank. A "waterline" was visible near the mid-plane of the tank but there was no corrosion above or below the line. The localized attack of the weld was evaluated in detail and reported in Section VI.B.8.

The results of the visual examination of these Representative Tankage articles can be summarized as follows:

a. The welds between tubes, fittings and flanges at the inlet/outlet ports of the aluminum tanks were the most prevalent sources of leakage and corrosion damage. Most of these represent corrosion of 4043 filler alloy used on 6061 aluminum tubing. As will be discussed in the detail analyses which follow, the manual welds produced were often large and irregular, containing cold shuts and fissures for relatively easy initiation of corrosion.

b. Exterior, general corrosion occurred on the bare aluminum tanks, 2014 aluminum especially; but 2024, 6061 and 7039 alloy tanks also showed considerable etching. None of the external general corrosion was serious or degrading to tank performance in the degree observed, but it was indicative of the generally corrosive atmosphere to be expected in a storage area where occasional oxidizer leaks or spills occur.

c. The painted aluminum tanks were well protected from the general environmental corrosion.

d. Direct impingement of leaking oxidizer from adjacent tanks and systems can be quite damaging even to painted tanks.

e. No internal corrosion was found, as a direct result of the N_2O_4 or ClF_5 exposure. In general, tank interiors were in excellent condition.

f. Where interior pitting did occur, it appeared to be caused by residues of propellant left after tank draining and purging. If tanks are to sit for extended times after draining (many of these tanks sat for 2-4 years after draining) and they are intended for eventual re-use, they must be purged and cleaned of acid residues to a much greater degree than these tanks were.

g. The A-286 stainless steel tank examined had developed a leak through a weld, apparently from external corrosion. The Inconel 718 tank had such a short exposure before flange leakage that no assessment can be made of its propellant compatibility.

All of the corrosion effects noted above are examined in detail in Section VI.B.

3. Storable Prepackaged Feed Systems

As previously described, these systems are complete units, with the propellant storage tank containing a positive expulsion device, pressurizing gas source, isolation valves, pressure regulator valves, burst disks and necessary plumbing, all assembled within a support frame. The propellant tanks were the primary object of evaluation in this program. The other components were examined as the systems were disassembled, and in some cases these components were sectioned for internal evaluation. The results of that evaluation of auxiliary components are summarized below.

a. Pressurizing Gas Sources

(1) Stored Gas Devices

Three of the systems contained high pressure gas bottles as a gas source. These were very thick wall (0.75 inch) AISI 304 stainless steel spheres. No corrosion was found on the exterior of any of these spheres. A one-inch diameter hole was drilled into the spheres to allow Borescope examination of the interior. No corrosion or other anomalies were found, and no further evaluation of these bottles was performed.

(2) Liquid Propellant Gas Generator

Four of the systems contained a quantity of hydrazine/water mixture in a bellows tank, under pressure, which was fed through a catalyst bed reactor/gas generator to provide the pressurizing gas. The bellows tank was a very heavy wall (1 inch) AISI 347 stainless steel cylinder enclosing a welded leaf bellows. These tanks were sectioned to view both the exterior and interior of the bellows. No corrosion or other anomalies were found on either the exterior or interior of the tank or bellows. The gas generator and adjacent lines were discolored from the heat of decomposition, but no corrosion or anomalies were observed. No further analysis was performed.

(3) Solid Propellant Gas Generator

Six of the systems contained a solid propellant gas source consisting of a pair of ammonium nitrate/thermoplastic binder propellant grains in AISI 347 stainless steel cylinders, feeding through a nozzle orifice into the pressurizing line. As would be expected, the cylinders and lines were blackened and discolored by the propellant firing, but there was no evidence of any corrosion or anomalies in these components and they were not evaluated further.

b. Explosively Actuated Isolation Valves

The stored gas and liquid propellant generator systems contained explosively actuated isolation valves.

These were examined visually and no evidence of corrosion, anomalies or unusual firing behavior was found. No further examination was performed.

c. Pressure Regulators

The gas pressure regulators from the systems were removed and examined. A series of crack-like linear indications were found on several of the stainless steel valve bodies of these regulators. These were verified by dye penetrant examination as being true indications of some type of defect. They are considered in detail in Section VI.B.11. It should be pointed out that these indications were found not to be corrosion induced, but rather inclusions in the stainless steel material.

d. Relief Valves

On most of the systems, the burst disk on the relief side of the valve was found to be ruptured, indicating that these valves had operated during some high pressure portion of the pressurization cycle. This was a normal occurrence according to the available design information. The valves in high temperature gas lines were discolored and oxidized but otherwise undamaged. There was no evidence of corrosion attack in any of the valves, and no further analysis was performed on any of these components.

e. Summary of Auxiliary Component Examination

The observations on these auxiliary components indicated that all possessed very good corrosion resistance for the storage and propellant environments involved.

This is due at least partly to the very conservative designs, off-the-shelf hardware, and low strength, but very good corrosion resistant stainless steel used for all high pressure components. This resulted in components that were perhaps heavier than normally expected for flight systems, but of excellent corrosion resistance for long-term storage under corroding conditions.

f. Tank Shell-Expulsion Device Examination

As previously indicated, the propellant storage tanks were the primary object of examination in these systems. After examination of the tank shell exteriors, all tanks were sectioned to reveal the interior condition, taking care to section in locations and manners that would preserve and reveal the positive expulsion device within the tank, either rolling diaphragm or surface force orientation screen. Because all of these tanks were identical in basic construction, and were affected by common conditions, either environment or other factors in the systems, they are not discussed below as individual units but rather in groups, emphasizing their similarities and contrasts. All tanks and their characteristics are summarized in Table X.

The external surface appearance of the tanks could be divided into two categories. The tanks loaded with N_2O_4, Systems 7, 9, and 14, shown in Figures 29, 31 and 32, had an etched and lightly frosted external surface. The other tanks, all loaded with MHF-5 were unattacked on their exteriors. This observation correlates well with the observations on individual tanks evaluated in this program, all containing oxidizer, that the oxidizer storage room environment was at times quite corrosive to aluminum components when leaking N_2O_4 or ClF_5

would come in contact with the 85% humidity air and hydrolize to produce moist acid fumes. Systems containing fuel, and stored only with other fuel components, would not be exposed to the oxidizer environment and the surfaces therefore remain clean and unattacked. Tensile tests, performed to determine whether this corrosion had any effect on mechanical properties, are discussed in Section VI.C.3.

The propellant wetted surfaces of the tanks, interior of the rolling diaphragm or shell interior of the SFO units, displayed no corrosion or corrosive effects from the propellant. Neither the N_2O_4 nor the MHF-5 had any observable effect on the interior surfaces, other than some minor dulling.

The rolling diaphragm positive expulsion devices exhibited a range of behavior during the expulsion cycle. The tank in System S/N 7, shown in Figure 31, traveled less than one-half its desired expulsion distance. The piston had cocked during its travel, jamming on the center post and preventing proper travel. This problem had been encountered by the manufacturer. An RTV silicone rubber layer was cast between the shell inner surface and the diaphragm. This RTV layer was designed to seal that space and prevent pressurizing gas from acting around the periphery to collapse the O.D. of the diaphragm before normal expulsion could roll the diaphragm completely down from the gas end toward the liquid end. In contrast to this unit, the tank in System S/N 5, Figure 30, showed excellent expulsion, the most uniform and complete diaphragm movement of all systems examined. As can be seen in Figure 30, the RTV rubber layer remained adherent to the lower half of the diaphragm even after sectioning and removal, and must have contributed substantially to proper expulsion by preventing any premature collapse of the diaphragm O. D. Also shown in Figure 30 is tank S/N 1, where the collapse of the diaphragm exterior is quite visible, causing poor expulsion and eventual tearing of the diaphragm to shell joint. This tearing can cause undesirable two-phase flow in the propellant outlet line as the positive expulsion device fails. Other systems with rolling diaphragms shown in Figures 29 and 32, had reasonably good expulsion behavior, with full travel of the piston, but some general buckling of the diaphragm, which reduces the expulsion efficiency. As pointed out above, the role of RTV silicone rubber in providing a seal of the annulus, without restraining the normal travel of the diaphragm, is quite important. The tearing behavior of the rubber layer was noted to be quite non-uniform in the initial examination of the tanks. This anistropic behavior of the RTV was considered important and therefore the material was subjected to a detail analysis, which is reported in Section VI.B.10. No other aspect of the rolling diaphragms was found which would warrant additional analysis.

The other type of positive expulsion device was the Surface Force Orientation Screen, a fine mesh, aluminum screen placed at the outlet end of the tank to prevent gas bubbles from passing into the outlet line, and thereby prevent undesirable two-phase flow. At the time of tank design and fabrication, 1966/1967, screens were not readily available with sufficiently fine mesh to insure positive expulsion in a negative gravity field, so all expulsion testing was performed with the screen end down. The six screen units are shown with their respective tanks in Figures 33, 34 and 35. Their appearance and behavior were closely related to the pressurizing subsystem used on the tank. All of the screens were in MHF-5 fuel propellant, and there was no evidence of any corrosion or anomalies from the propellant storage. The screens in tanks pressurized with cold, stored gas, S/N 15 and 18 in Figure 33, were in reasonably good shape after expulsion, with the exception that the screen in S/N 15 was partially torn, starting along the circumference where it is resistance seam welded to the supporting "waffle plate". The screens in tanks pressurized with hot, decomposed hydrazine, S/N 19 and 23 shown in Figure 34, are clean and only slightly bulged, but are separated from the tank. The screen in S/N 19 is torn loose around its entire circumference at the resistance seam weld, while in S/N 23 the screen plus backup ring are loose because of failure of the electron beam weld joining them to the tank dome. The screens in tanks pressurized with solid propellant, S/N 17 and 22, shown in Figure 35, were badly discolored, torn on the screen face and around the periphery. Deposits and residues from the solid propellant firing covered most of the screen in S/N 17, indicating that it must have been uncovered (all of the fuel expelled) before the solid propellant firing was completed. The screen in S/N 22 shows only a small amount of residue, and must not have been uncovered for long. It would appear in reviewing the condition of these screen units, that there were moments of significant back pressure on the screen, probably when the pressurizing gas was interrupted. If this were to occur in a flight system, and positive expulsion needed again later in the mission, the usefulness of the screen would be destroyed. Either these screens must be mechanically supported for pressure differentials in both directions, or some system device should be available to prevent any "back pressure". The screens from the solid propellant units 17 and 22 were badly distorted and no longer useful. The other four screens were still in reasonable shape, and therefore, bubble point measurements could be made, although not on the entire, intact screen. The results of this more detailed analysis of the screens are presented in Section VI.A.4.

The varying degree of "harshness" of the pressurizing gas sources is evident in the examination of these screened tanks, with the cold, stored gas causing no discoloration of the tank interior and only minimal damage of the screen. The hot, decomposed hydrazine produced a slight discoloration of the tank shell interior, and moderate damage of the screen. The solid propellant gas generator produced extensive discoloration and blackening of the interior and serious damage of the screen. In the case of the screened tanks, these varying gas types acted directly on the shell wall, once most of the propellant had been expelled. This could have had an effect on the shell material, and therefore tensile tests were performed on three tank shells representing each of these conditions. The results of this detailed examination are presented in Section VI.C.3.

In the rolling diaphragm tanks, the layer of RTV silicone rubber isolates and insulates the tank shell from the pressurizing gas. Thus, although the RTV was blackened and discolored by the solid propellant gas, it was satisfactorily protecting the shell. The layer of RTV in tanks fired with decomposed hydrazine was loosened and more readily fell away from the shell wall (tank S/N 5 and 6 in Figures 30 and 31), but still prevented the formation of a discolored surface on the tank wall.

Although there were some problems and deficiencies in these tanks from a standpoint of positive expulsion behavior, most of these are related to the auxiliary components and their behavior in the system. It should be emphasized that from a standpoint of long-term propellant storability and compatibility, these propellant storage tanks performed excellently, with no evidence of any corrosion degradation or other anomalies.

4. Bubble Point Determination on Surface Force Orientation Screens

As was discussed in the preceding subsection, four of the six prepackaged system tanks had surface force orientation screens which were still sufficiently clean and undistorted to allow a meaningful measurement of bubble point. However, even these four units were partially or completely torn from the waffle backup plate, so that it was not possible to measure bubble point on the entire screen assembly. Four one-inch diameter samples were therefore punched from each of these four tanks and bubble point measured on these individual specimens.

The samples were taken on a mid-radius circumference of the screen at 90° increments. Four determinations were made on each sample, according to the procedures outlined in the specification ARP901 "Bubble Point Test Methods". The results are recorded in Table XI. A significant increase (to 140-150 micron) from the reported value of 100 for the as-fabricated screens occurred as a result of the expulsion cycle performed on these units. Apparently the expulsion force was sufficient to distort the screen weave and increase the micron rating. There was no difference in final bubble point rating between screens in the cold gas pressurized tanks (S/N 15 and 18) versus the hot hydrazine tanks (S/N 19 and 23). Since the overall change is not large, it is probable that it is merely the distortion occurring in rapid expulsion, and especially the back pressure distortion, which caused this change. Compared to the mechanical damage and complete separation of the screens which generally occurred (discussed in (3) above), this change in bubble point rating would not be significant.

B. METALLURGICAL ANALYSIS OF FAILURES AND ANOMALIES

1. GENERAL

The specific anomalies selected for detailed and confirmatory analyses were based on the initial visual examinations performed on all tanks and described in Section VI.A. A number of detailed analyses of the second group of tanks submitted to BAC were pre-selected by the AFRPL Program Management Office.

A total of 9 detailed and 14 confirmatory analyses were required and are presented in this section in their entirety. Seven detailed analyses, in which corrosion was a factor, were performed. Three selected studies were also performed to supplement the detail analyses and thus satisfy contractual requirements. An analysis matrix defining the overall program is presented in Table XII.

2. INLET TUBE WELD FAILURES OR CORROSION

a. Detail Analysis of Corrosion and Leakage Occurring on Inlet Tube Weld (4043 Filler Alloy) of 2021-T6 Aluminum Alloy Martin 10-Gallon Tank S/N 005 Used for ClF_5 Propellant Storage

(1) Test History

As was previously described in Section VI.A.2, five 10-gallon storage tanks fabricated of 2021-T6 aluminum alloy were exposed to a ClF_5 propellant environment for a period of two (2) years. No corrosion or degradation of the tank shells proper occurred. The inlet tubes of all five vessels were corroded in one of the welds joining the manifold tube to the bolt-on-flange or valve, and either cracked or broken off, with subsequent leakage occurring at this point. Tubing from tank S/N 005 was selected for an in-depth analysis and verification studies subsequently made on tubing welds from tanks S/N 001 (2021-T6), S/N 003, (2021-T6), No. 2 (2014) and No. 4 (S/N 003) (7039). Overall views of these leaks and corrosion are shown in Figures 22, 23 and 24.

(2) Observations

Welds in the 6061 aluminum alloy tubing were made manually by the Heliarc process using 4043 filler wire. The area of corrosive damage was confined to the 4043 weld alloy, with no corrosion of the 6061 tube alloy noted. Corrosion was observed in the center of the upper weld, joining the extension tube to the valve assembly tube. The white, fluffy appearing corrosion product can be seen in the photomacrograph of view (a) in Figure 45, which shows the external surface of the manifo tube weld joint.

The inside surface, which was apparently reamed out to remove the weld bead root, is shown in view (b), Figure 45. Note the absence of corrosion products, indicating that corrosion was initiated on the external surface, with incipient penetration occurring.

A cross section of the leak area, showing the interdendritic path of corrosion, and a number of large welding pores, is shown in Figure 46.

(3) Metallurgical Analysis

The corrosion observed on the subject weld joint was believed to be the result of atmospheric conditions existing in the storage hut. Propellant vapors emanating from leaks developed in this or other systems react with moisture to produce dilute acid vapors. These vapors then act as the corrosion agent, causing the general surface corrosion of bare aluminum containers. The dilute acid formed by this hydrolysis, probably HF, is very corrosive towards aluminum alloys, particularly the 4043 weld wire composition. This alloy is known to corrode 20 to 30 times faster in an acid environment than the adjacent parent metal.

Only one localized area of corrosion was observed on the external surface of the subject weld joint. This corrosion proceeded inward through the interdendritic boundaries until penetration and leakage occurred. This weld also contained a localized cold shut region on the I.D. surface, approximately 0.010 inch deep, which can be seen in the photomacrographs of Figure 45. The weld itself therefore becomes suspect as a source of initial propellant vapor leakage, due to crevice or stress corrosion occurring over the two-year storage period. Combined with the inter-dendritic corrosion network, the potential for leakage is thus greatly increased.

Only localized superficial pitting and blackening of the other manifold tubing welds were noted.

b. Four Confirmatory Analyses

The examination of all tanks yielded four similar tube weld anomalies which are discussed in this section.

Failure of manifold tube weld joints at the flange end of Tanks S/N 001 and 003 had also occurred during the two-year storage of this group of tanks. The appearance of these corroded welds was identical to that of Tank S/N 005.

Photomacrographs of each weld are shown in Figures 47 and 48. The tube interiors were reamed out, apparently to remove excess weld metal drop-thru. A white, voluminous corrosion product is common to all the tube weld leaks examined. This corrosion product has been identified as a hydrated aluminum hydroxy fluoride. This reaction product is formed when dilute HF acid comes in contact with aluminum. The dilute acid was probably formed by the hydrolysis of leaking ClF_5 vapors. Corrosion in all cases was initiated on the external surfaces.

Photomicrographs of sections cut through the corroded weld area are presented in Figures 47 and 48 with their respective surface views. The mechanism of corrosion and mode of failure are identical to those noted for the Tank S/N 005 tube weld.

In addition to the foregoing tanks, two tanks from the second group of storage vessels received for analysis contained similar appearing corroded tube welds. These two tanks had also been filled with ClF_5 propellant and had remained in storage for a period of six years. Tank No. 2, a 15-gallon tank fabricated of 2014 aluminum alloy, had developed severe corrosion of the tube to tube weld at the flange end of the vessel. Abrasion and cracking of the bottom, outlet tube weld on Tank No. 4 (S/N 003), a 10-gallon container fabricated of 7039 aluminum alloy, was also examined. Although no corrosion product was observed on the external surface, the abrasion probably having removed it, subsequent sectioning and examination disclosed the similarity between this tube weld leak and those discussed previously.

As with other tube leaks of this type, surface attack and eventual perforation of the 4043 weld metal was believed due to the hydrolysis of leaking propellant vapors. There is strong evidence to suggest that the possible source of the propellant vapors was the affected containment vessel, with leakage occurring through a network of fine microcracks produced during welding of the tube. Multiple passes at the start-stop area produced a heavy, uneven drop-thru, with a centerline fold or crevice, voids and porosity. These conditions are shown in the photomacrographs of Figure 49 and the cross section view of Figure 50. A similar condition for the bottom outlet weld from No. 4 (S/N 003) is shown in Figure 51. This weld was apparently reamed out, indicating that the original weld drop-thru may have been excessive.

The local nature of the observed corrosion, which was concentrated on one side of the weld joint, usually at the start-stop area, further indicates that vapor leakage may well have originated within the subject tube. Very heavy weld drop-thru in this area could have resulted in the formation of microcracks, which combined with a crevice-like fold in the weld root would eventually lead to the postulated vapor leakage. For this series of events to occur, a certain amount of crevice corrosion by the ClF_5 propellant would be necessary. Since the 4043 weld alloy is known to be far less corrosion resistant than wrought aluminum alloys, penetration of ClF_5 vapors through a partially formed leak network, over a period of several years, is within the realm of possibility. Another possibility is the rapid corrosion and volatilization of any tungsten inclusions picked up in the weld from the electrode. The irregular, manual weld, with excessive drop-thru could easily be expected to contain occasional tungsten particles, which would be rapidly attacked by the fluorine compound. The subsequent, reverse corrosion process propagating from the external surface, induced by HF acid formed by hydrolysis of the leaking vapors, then occurs in a relatively short time. The entire chain of events therefore becomes dependent on the overall soundness and integrity of the weld joint.

3. INLET FLANGE TUBE LEAKAGE BY CORROSION

a. Detail Analysis of Corrosion and Leakage Occurring on Inlet Tube Weld (4043 Filler Alloy) of a 2024 Aluminum Alloy 15-Gallon Tank No. 1 (S/N 9) Fabricated by the Martin Company for ClF_5 Propellant Storage

(1) Test History

A fifteen gallon capacity cylindrical container fabricated of 2024 aluminum alloy and designated as Tank No. 1 (S/N 9), was used for the storage of ClF_5 propellant for a period of six years. No corrosion or degradation of the tank shell proper occurred and no leakage of the cylinder was reported. The flange and flange tube end, which are at the top during storage, contained areas where the paint film had been perforated and metal corrosion initiated. One area of the flange tube weld was severely corroded on the external surface and had reportedly developed a leak. Overall views of this corrosion are shown in Figure 36. This anomaly was selected for a detailed analysis.

(2) Observations

As with all test containers in this program, the manifold tubing was fabricated of 6061 aluminum alloy. Welds were made manually by the Heliarc process, using 4043 filler wire. Detailed fabrication and heat treat procedures are described in Table VIII of Section V.

Considerable corrosion was observed on one segment of the flange tube weld, as shown in the photomacrograph of Figure 52. A heavy, uneven drop-thru of the weld bead was noted. Figure 53 indicates that corrosion was externally originated. Spectrographic analysis of the weld deposit and the adjacent tube material verified the alloys as 4043 and 6061 repsectively. X-ray diffraction analysis of the corrosion product associated with the weld leak was also performed. The compound was identified as a hydrated aluminum fluoride.

Cross sections of the leak area, illustrating the intergranular path of corrosion, are shown in Figure 53. Localized corrosion of the 6061 aluminum alloy tube, on the interior surface, is shown in Figure 54. This is believed to be a secondary effect occurring after weld perforation. The generally porous nature of the heavy weld root drop-thru and associated microcracks are displayed in Figure 55.

(3) Metallurgical Analysis

All indications and observations made on the subject failure suggest that the external environment initiated the observed weld bead and tube metal corrosion, with the weld bead displaying far greater susceptibility. Localized attack was also noted on the I.D. tube surface, with edge-of-weld penetration apparently linking up with the more pronounced external corrosion and causing leakage of the tube. In view of the cleanliness of the internal surface of the 2024 aluminum alloy, it is doubtful that corrosion of the internal 6061 alloy tube surface was caused by propellant alone. Rather it is more probable that the externally induced corrosion created a path inward through the tube weld, allowing moisture vapor to enter and react with the propellant vapors within the tube, producing highly corrosive, dilute hydrofluoric acid, which then attacked the tube I.D. surface.

The appearance and mechanism of corrosion were identical to those observed on similar welds in other tanks examined. The corrosion product, identified as a hydrated aluminum fluoride compound, was located on the external surface of the tube weld. No significant corrosion was observed on the I.D. tube surface. Reaction of the external, atmospheric environment with the tube weld surface is the most probable cause of the observed corrosion. Propellant vapors escaping into the atmosphere can be converted to dilute acids by hydrolysis. The source of these vapors is generally a nearby leaking container, tube or valve. However, it is also possible that these vapors may have emanated from the subject vessel, escaping from the inlet tube through a fine network of microcracks and porosity produced during welding of the flange tube. The extremely heavy weld deposit, presence of shrinkage cracks in the weld and leak path geometry shown in Figure 54 tend to substantiate this possibility. Regardless of the actual source of these vapors, the dilute acids formed by the hydrolysis reaction, usually HF or HCl, are very corrosive with respect to aluminum resulting in the severe pitting observed on bare, unprotected aluminum storage vessels, particularly those fabricated of the 2000 series aluminum alloys.

Pitting corrosion of the type observed on these vessels is typical for heat treatable aluminum alloys. It is produced by a penetration of the naturally protective, passive oxide barrier, by halogen ions present in the corrosive medium. This breakdown exposes fresh aluminum surfaces to a concentration cell action and subsequent, localized pitting attack.

4. FLANGE TRANSITION TUBE TO FITTING FAILURE

a. Detail analysis of corrosion and rupture of flange transition tube to RPL fitting tube weld (4043 filler alloy) on a 7039 aluminum alloy 10-gallon cylindrical Tank No. 4 (S/N 003) fabricated by the Martin Company

(1) Test History

A ten gallon capacity cylindrical container, fabricated of 7039 aluminum alloy material by the Martin Company and designated as Tank No. 4 (S/N 003), was used for the storage of ClF_5 propellant for a period of approximately six months. No corrosion or degradation of the tank shell proper occurred and no leakage of the cylinder was reported.

Fracture through the first tube to tube weld joint at the flange end, which is at the top of the tank during storage, had occurred. Only the transition section of tubing, which was welded directly to the flange remained. The longer portion extending from the RPL fitting was missing. Severe corrosion of this fractured weld was noted. Analysis of the corrosion mechanism and subsequent related fracture constitute the main portion of this detailed analysis.

All manifold systems attached to these storage vessels were made of 6061 aluminum alloy tubing welded with 4043 weld wire, using the manual Heliarc process. A majority of leaks developed during storage have been traced to the tubing welds. The pattern of leakage observed and the appearance of corroded welds disclosed a marked similarity, regardless of their location in the manifold system. Therefore several other pressure vessels used to store ClF_5 propellant, containing tube welds which displayed varying degrees of corrosion and one identical weld corrosion failure, were selected for confirmatory analyses. These are also discussed below.

(2) Observations

Detailed fabrication and heat treat procedures for the subject storage vessel are presented in Table VIII and an overall view of tube and tank is shown in Figure 38. The corroded area of interest, shown in the photomacrograph of Figure 56, is the tube weld connecting the bare inlet tube extension to the short, transition tube segment welded to the flange. This short section is painted blue. Severe corrosion of this weld is apparent in the photomacrographs of Figure 56. Corrosion product deposits can be seen in the higher magnification view of Figure 56, initiating on the O. D. surface of the tube. Corrosion and subsequent tube fracture occurred through the weld metal deposit, with no edge-of-weld or heat affected zone corrosion occurring. The fracture path is clearly illustrated in Figure 57. Porosity and micro-cracking in the weld deposit are also apparent.

(3) Metallurgical Analysis

Corrosion of the subject tube weld originated on the external surface and was confined primarily to the weld metal, with only minor pitting occurring on the 6061 aluminum alloy tube surface. No corrosion was noted on the I.D. surfaces. The atmospheric environment existing in the storage building contains sufficient moisture to hydrolize escaping propellant vapors, producing dilute acids which deposited on the tube weld O.D. surface, inititating the observed corrosion. The mechanism of corrosion and physical appearance of the corrosion product are identical to those observed on the majority of tube weld failures investigated in this program. Again, the source of propellant vapors entering the hydrolysis reaction is not precisely known. They may be emanating from nearby leaking vessels or hardware, or they may be leaking through a fine network of welding microcracks within the failed tube. In either case, subsequent hydrolysis then produces dilute acids which deposit back on the surface, resulting in corrosion which proceeds inward through dendrite boundaries and through already present microcracks, widening them in the process.

The weakening effect of this interdendritic corrosion combined with weld micro-cracking resulted in greatly reduced resistance to bending stresses. Subsequent failure through the weld joint was brittle in nature and easily related to the prior history of this tube weld.

b. Four Confirmatory Analyses

Two identical cases of severe tube weld corrosion combined with fracturing of the tube through the weld were observed on Tanks S/N 003 and S/N 004, both of which are 10-gallon Martin tanks fabricated of 2021-T6 aluminum alloy and used for the 6-month storage of ClF_5 propellant. The S/N 003 tube failure discussion was included in Section VI.B.2 as confirmation of a detailed analysis of the tube weld corrosion observed in 2021-T6 alloy tank S/N 005.

Photomacrographs of the S/N 004 tube weld joint area of interest are shown in Figure 58. Note the severe corrosion concentrated on one side of the tube weld and the corresponding reduction of wall thickness at this point. Ultimate fracture propagated through the weld joint. A cross section view of the corroded area presented in Figure 59, demonstrates interdendritic attack similar to that observed in the Tank No. 4 (S/N 003) tube weld. Corrosion in both cases was externally initiated.

Additional welds selected for confirmatory analyses include the flange to tube welds from the above S/N 004 storage system and from a 15-gallon cylindrical Tank No. 2, a 2014 aluminum alloy vessel received with the second shipment of corroded storage tanks. These welds displayed considerable surface attack, although not as severe as noted for the tube to tube weld failures described above. Corrosion was more pronounced on the No. 2 tank, which had been in storage for six months as compared to four months for the S/N 004 tank. These flange to tube welds are also made with the 4043 weld alloy and thus provide additional confirmation that the same corrosion mechanism, which is dependent on the corrosion behavior of this alloy, is operative throughout these manifold systems. In effect, the manifold tube welds become the limiting factor in long term storage of the aluminum tanks. Photomacrographs of these two welds are presented in Figures 60 and 61. Cross section views in Figures 60 and 61 indicate that corrosion was externally initiated, by the surrounding atmospheric environment. No corrosion was observed on the internal surfaces. Although the degree of corrosion noted on these two welds was relatively slight, it was sufficient to establish the direction of corrosion and to verify the corrosion mechanism involved in these manifold system tube welds.

Additional evidence to establish the corrosion mechanism and eventual failure mode is provided by the bottom, outlet tube weld from Tank No. 5 (S/N 001), a 10-gallon, 7039 aluminum alloy vessel exposed to ClF_5 for six months. This weld, representing a more advanced stage of localized external corrosion attack, is shown in the photomacrograph of Figure 62. The section view in Figure 62 shows the same interdendritic attack of the 4043 weld alloy observed on practically all manifold tube welds examined.

5. INTERNAL SURFACE PITTING

a. Corrosion observed on 2024 Alclad aluminum solid state bonded tank fabricated by the Martin Company

(1) Test History

An experimental, solid state bonded aluminum tank produced by the Martin Marietta Company was metalluegically evaluated after five (5) years storage with (brown) N_2O_4 propellant (MIL-P-26539 Specification). The tank had experienced no leakage or failure but did show general corrosion on the exterior and some severe pitting on the interior surface. The interior pitting is considered in detail in this section, while the exterior corrosion was studied with other tanks showing similar effects in Section VI. B. 7.

Two other containers, also used for the storage of brown N_2O_4 propellant displayed similar internal pitting and corrosion effects. These units, both fabricated of the 2C14 aluminum alloy, were selected for confirmatory analyses. One unit was a 15-gallon capacity round tank fabricated by the General Dynamics-Convair Company. The other was a small 3" x 6" container whose manufacturer, one of four aerospace companies, could not be determined.

(2) Observations

The interior of the solid state bonded tank was etched and discolored. The bottom pole (opposite inlet/outlet port) showed many pits of a generally semi-spherical shape There were a few of these spherical pits on the upper surfaces and other more shallow pits scattered around the entire interior. In addition one streak of a brownish film was found on the inner lap surface of the solid state bonded joint. These effects are shown in Figure 39.

The inner surface of the weld attaching the inlet port to the shell contained a small crack. However, since this crack occurred at an apparent interruption in the manual welding of the port and with no evidence of corrosion associated with the crack, the crack can be categorized as a welding crack and ignored for this investigation.

Hardness and tensile tests of this tank verified that it was in an annealed condition.

The severe pitting of the internal surface is shown in Figure 63. The pits were deep and roughly spherical, with cracking or micro fissures around and in the pits. A cross section of one of the pits is shown in Figure 63. It can be seen that attack was progressing by selective corrosion of grain boundaries, which lead to the complete removal of grains to form the pit. The enlargement of the pit occurred by continual corroding of the grain boundaries and release of individual grains.

The microstructure of the Alclad shell in Figure 63 shows that the cladding contains enlarged grain boundaries with a second phase, the copper aluminide phase, concentrated in the boundaries. This had occurred because of significant diffusion time at elevated temperature (probably during the anneal of the shell halves or finished tank), which allowed copper to diffuse from the core alloy into the cladding. The grain boundaries of the cladding provided the easiest path for the alloy element copper to follow, so it is in these grain boundaries that the copper concentrates.

The presence of this copper prevents formation of a uniform, protective oxide film over the grain boundaries and also promotes electro-chemical attack due to potential differences between the aluminum grain interior and the $CuAl_2$ grain boundary film.

One additional corrosion effect was noted on the interior surface of this tank. There was a brownish or rust colored stain extending a short distance on the inner surface of the solid state bond overlap, (visible in Figure 39, Section VI). This stain had no appreciable thickness and did not cover any abnormal corrosion on the aluminum surface. X-ray diffraction scans of the surface with the stain produced no detectable peaks other than the aluminum substrate, nor was it possible to scrape off any of the discoloration to perform a powder pattern X-ray diffraction analysis.

It is believed that this stain may represent residue from a striker or backing plate used in the solid state explosive bonding process which would have been mechanically or chemically removed after bonding. The steel strip was probably etched away with minor adhering residue producing the observed stain. This stain was not detrimental to the tank.

(3) Metallurgical Analysis

This tank was fabricated from Alclad 2024 sheet which should have provided it with excellent corrosion protection. However, the protection of the pure aluminum cladding was largely lost through diffusion of the copper alloying element from the core into the cladding at some stage in processing. Therefore, the cladding could corrode intergranularly along copper rich grain boundaries to allow the corrosive storage building environment to reach the 2024 alloy core. This core material was in the annealed condition, which is especially prone to intergranular attack.

The location of the pits, their orientation and arragement, primarily in a zone near the bottom pole, makes it quite probable that they were formed in the drained tank, after the five year storage with N_2O_4 propellant, during the almost two years (Sept. 1972 to July 1974) the tank was stored before evaluation. The pits are concentrated in the area quite likely to contain propellant liquid residue. The pitting would thus be initiated by local attack of the copper enriched grain boundaries of the cladding in contact with the acidic residues of propellant. The deep, roughly spherical nature of the pits results from the partially protective nature of the cladding, which tends to confine the attack after a small area of the cladding has been penetrated. This more localized corroding medium or local electromechanical cell effect promoted pitting, by corrosion of grain boundaries of both the cladding with copper diffused into it and the annealed core material with the copper aluminide concentrated along grain boundaries.

b. Two Confirmatory Analyses

The general, interior surface condition of the large capacity vessel selected for confirmatory analysis, S/N N-10, is shown in Figure 43 of Section VI. Discoloration and staining of parent metal and weld deposits are clearly visible. Scattered corrosion deposits were observed on the welds and parent metal, at sites of incipient pit formation. Close-up views of two areas containing a fairly large number of pits are shown in Figure 64. The early stages of pit formation and a well-defined pit are shown in the cross section views of Figure 65. Note the similarity in appearance of intergranular penetration occurring in this tank with that shown in Figure 63 for the solid state bonded tank. The mechanism of corrosion is identical.

A small capacity 3" x 6" tank, S/N 1, which also contained N_2O_4 propellant, displayed the same type of internal pitting corrosion. This condition, shown in Figure 66, is almost identical to that shown in Figure 63.

At first glance, it would appear that problems could arise from the use of aluminum alloys of the 2000 series for N_2O_4 propellant storage vessels. The fairly severe pitting observed in the three tanks discussed above is a typical form of corrosion which occurs on aluminum alloys when exposed to dilute acid solutions containing halogen ions. If continued over a sufficiently long period of time such pitting could eventually penetrate the shell wall resulting in vessel leakage. However, as concluded for the S/N 6 solid state bonded vessel discussed previously, the six year N_2O_4 propellant exposure did not cause the pitting observed on the interior surfaces of these two vessels. It is believed that corrosion effects on the interior surfaces were caused after the storage test had been completed and the vessel drained of propellant. Insufficient draining and flushing could have resulted in a subsequent reaction of N_2O_4 residue with moisture in the air. This hydrolysis produced a dilute acid, probably HNO_3, which then initiated the pitting attack.

It is recommended that more thorough draining and flushing operations be performed on propellant tanks after long-term storage tests. Complete drying and sealing of the vessel in a dry, relatively air tight container should preclude such post-storage occurrences.

6. INTERNAL SURFACE WELD CRACKING AND PITTING

a. Detail analysis of corrosion observed on a 2014-T6 aluminum alloy Alcoa one-quart container exposed to ClF_5 propellant

(1) Test History

A one-quart capacity container fabricated of 2014-T6 aluminum alloy material and designated as S/N 19 was used to store ClF_5 propellant for a period of 42 months. No leakage of the container occurred during this storage period.

A second 2014-T6 one-quart container with the same fabrication and test history, S/N 24, was selected for a confirmatory analysis. In addition to a similarity in corrosion behavior this tank had developed cracks in the root of the longitudinal weld bead, in an area where a multiple weld pass had been made.

(2) Observations

The subject container represents an exercise in welding the 2014 aluminum alloy. Two longitudinal welds, intersecting the girth weld are deposited 180° apart. The fabrication and heat treat history are described in Section V.C.

General corrosion attack of the external surface was noted. A white, powdery corrosion product was uniformly scattered over the surface. Examination of the internal surface disclosed a gray to dark gray discoloration, with isolated mounds of a white corrosion product marking the locations of pit formation. A photomacrograph showing this internal surface pitting is displayed in Figure 67. Note that the pits are contained within a larger discolored area which indicates the location of propellant residue remaining after draining. Cross sections of two of the deepest pits are shown in Figures 68 and 69. Note the intergranular nature of the progressive pitting attack.

(3) Metallurgical Analysis

The pitting observed on the interior surface of the S/N 19 tank is characteristic of the type of corrosion usually associated with aluminum and its alloys. Penetration of the naturally protective, passive oxide barrier, usually by halogen ions, exposes fresh aluminum surfaces to a concentration cell action and subsequent, localized pitting attack. The maximum depth of pitting noted was approximately 0.022 inch, representing 35% of the wall thickness.

The other one-quart containers in this group (S/N 11, 24, 25, 81, 83 and 85) which were also exposed to ClF_5 propellant for 42 months, were generally similar in appearance with internal pitting of varying degree. The subject tank contained the greatest number and maximum depth of pits observed on the interior surfaces of these tanks.

b. <u>One Confirmatory Analysis</u>

Pitting type corrosion very similar to that observed on the interior surface of the subject container was also visible in the S/N 24 container. This tank was also used to store ClF_5 propellant for a 42 month period. The general overall appearance, both externally and internally was also similar. Pit depth and frequency however were much less than those noted in S/N 19. White deposits of a corrosion product associated with the pits are shown in the photomacrograph of Figure 70. Cross sections of a fully developed pit and one in the early stages of development are shown in Figure 71. The pitting attack is intergranular in nature and identical to that observed previously for the S/N 19 container.

Several cracks were also noted at one end of the longer of two longitudinal welds where a double weld pass had been made. These are shown in Figure 72. A cross section of these cracks, shown in Figure 72, indicates the presence of interdendritic cracking, probably caused by a hot shrinkage condition which is characteristic of the high strength, heat treatable 2014 aluminum alloy. This characteristic is further aggravated by the longer exposure to weld temperature during multiple weld passes, combined with a subsequently reduced cooling rate.

There was no corrosion associated with the open cracks or the network of interdendritic cracks exposed by sectioning and polishing. The possibility of a stress corrosion mechanism being operative appears remote since the orientation of the cracks is circumferential i.e., transverse to the weld bead. Thus, the principal hoop stress generated by pressurization during storage would not significantly affect the crack tip.

c. Discussion of Internal Pitting Anomaly

With respect to the apparent lack of compatibility between the ClF_5 propellant and the 2014-T6 one-quart containers, it is interesting to compare their internal appearance with that of a 15-gallon Martin Tank No. 3 (S/N 6) shown in Figure 37 of Section VI.A. This large tank, also fabricated of 2014-T6 aluminum alloy, contained the ClF_5 propellant for a period of six months and retained its original, bright, as-fabricated appearance. Based on this appearance, attempts to relate the pitting observed in the one-quart containers to the stored ClF_5 propellant cannot be justified. Considerable time had elapsed between removal of the small containers from storage test and the initiation of metallurgical analysis ($1\frac{1}{2}$ - 2 years). As with the other internal surface analyses, this analysis has confirmed that the pitting corrosion was caused by propellant residues and associated hydrolysis during extended storage after draining. This conclusion further substantiates the need for thorough purging, cleaning and sealing of vessels after propellant drainage, if reuse is contemplated.

7. EXTERNAL SURFACE CORROSION

a. Detail Analysis of External Corrosion on Flange to Hemisphere Attachment Weld of Martin 15-Gallon Tank No. 3 (S/N 6)

(1) Test History

A fifteen gallon capacity cylindrical container fabricated of 2014 aluminum alloy material by the Martin Company and designated as Tank No. 3 (S/N 6) was used for the storage of ClF_5 propellant for a period of approximately six years. Although this vessel was painted, the paint film was not sufficiently protective to prevent corrosion for a six-year period. One area of the external surface, on the hemispherical segment adjacent to the flange opening, was very severely corroded. It is in this area where leakage of the vessel probably occurred, with the weld joint deposit almost completely eroded.

The bare, unpainted storage tanks examined in this program had experienced general surface corrosion of varying degree, depending on the corrosive severity of the immediate environment. However, none had developed leaks in the tank shell proper. Three such vessels, of varying capacity, which had displayed extensive, overall corrosion of the exterior surface, were selected for confirmatory analyses.

(2) Observations

Corrosion of the subject vessel originated on the external surface, as shown in the overall view of Figure 37 in Section VI.A. The weld alloy deposit was attacked at a much greater rate than the surrounding wrought material, as can be seen in Figure 73. Heat affected zone areas were also attacked but not as severely. The pitting corrosion which occurred produced a number of perforations in the tank wall and resulted in an extreme reduction of wall thickness, also shown in Figure 73. A section taken through one of the perforations is presented in Figure 74. Note that the penetration occurred immediately at the edge of weld. The other edge of the corroded weld cross section from Figure 74 is shown in Figure 75. This photomicrograph clearly illustrates the origin of attack on the external surface of the tank shell. The corrosion attack has occurred preferentially in the weld metal but near the weld fusion line or edge of weld. Based on overall views of other weld cross sections of this corroded weld, it is quite possible that this local corrosion shown in Figure 73 is promoted by the multiple pass nature of the weld. The heat effects of subsequent passes would have made this portion of the weld particularly susceptible to corrosion. A cross section of the weld, slightly removed from the perforated area is presented as a composite photomicrograph in Figure 78. The appearance of the weld structure indicates that more than one pass was made in completing this joint.

Some very fine cracking at the edge of weld was also noted on the internal surface, as shown in Figure 76. This cracking is probably related to the initial fabrication of the storage vessel and may well have been caused by double pass welding. Such cracking is not uncommon in this alloy, particularly when welded in the fully heat treated -T6 temper. The cracks did not propagate through the shell wall. General, intergranular corrosion of the parent metal external surface is shown in the photomicrographs of Figure 79. The interior of the tank shell was very clean, with buffed areas adjacent to dome welds remaining bright and shiny, as can be seen in Figure 37.

Mechanical properties of the flange attachment weld through the heavily corroded area were determined and compared with the properties of material removed from a non-corroded area. Properties of parent metal shell material were also determined as a base-line reference. These results are discussed in detail in Section VI.C. with all data presented in Table XVII.

Spectrographic analysis of the eroded weld joint and X-ray diffraction analysis of the corrosion product were also performed in order to complete the investigation.

(3) Metallurgical Analysis

The type of corrosion observed on the external surface of the subject vessel is characteristic of that associated with heat treatable aluminum alloys exposed to an acid environment containing halogen ions. Observed corrosion effects were intensified by an erosion or washing effect believed to have been produced by the impingement of a corrosive stream of liquid/vapor emanating from a nearby leaking vessel. Reaction of the propellant liquid/vapor, probably ClF_5, with moisture in the atmosphere produces very corrosive, dilute acids which readily attack aluminum and its alloys. This erosion effect, combined with initial pitting corrosion, reduced the tank wall thickness to the point where complete perforation occurred, with several holes developing immediately adjacent to the weld bead, in the heat affected zone. All corrosion observed progressed from the exterior of the vessel inward, with no corrosion occurring on the interior surfaces.

The fabrication history, detailed in Section V, indicates the 2014 alloy was in the -T6 temper when welded. No subsequent heat treatment was employed. Ultimate corrosion resistance of this alloy is determined by the rate of cooling from welding temperatures. This is readily apparent from the variation in degree of corrosion observed in heat affected zone areas versus parent metal. Although some intergranular attack of the parent metal had occurred on the external surface, it was much less severe and of itself would be of little consequence in terms of storage vessel reliability.

Mechanical properties of the corroded weld joint, a noncorroded area and the parent 2014-T6 shell alloy are presented in Table XVII. Base metal properties indicate the 2014 shell alloy was in the -T6 temper prior to welding. After welding in the -T6 condition, tensile properties across the weld joint are reduced by overaging, with failure occurring in the heat affected zone or at the edge of weld. A loss in yield strength of approximately 15% was noted in the weld specimens from the corroded area relative to those specimens cut from the non-corroded area. However, only an insignificant loss in ultimate tensile strength was noted. Some variation in weld joint strength of the flange attachment welds at each end of the tank was also noted.

These tests results are based on the actual thickness of specimens, which in the corroded areas was somewhat reduced (6-7% below uncorroded areas). The lower yield strengths in these areas reflect the irregular surface produced by this corrosion. If strengths were based on the nominal area they would show reduced values, reflecting the 6-7% loss in thickness.

Spectrographic analysis of the weld alloy used to join the flange assembly to the shell identified the alloy as 4043 aluminum. X-ray diffraction analysis identified the corrosion product as a hydrated aluminum hydroxyfluoride with the approximate composition of 16 $AlF_2(OH)6H_2O$. This composition indicates a reaction between aluminum and hydrofluoric acid, the HF most probably having been formed by hydrolysis of ClF_5 vapors.

b. Three Confirmatory Analyses

The three vessels selected for confirmatory analyses and their histories are as follows:

S/N	DESCRIPTION	STORED PROPELLANT	TERM OF STORAGE
105	1 quart Alcoa Tank X7007-T6	ClF_5	42 mos.
6	Martin diffusion bonded round tank 2024 Al	N_2O_4	6 years
7	Martin 15-gallon cylinder 2014 Al	N_2O_4	6 years

Although these vessels represent different aluminum alloys, fabrication methods and internal storage environments, their resulting surface appearances are quite similar. This is not totally unexpected inasmuch as the predominant mechanism of corrosion observed in aluminum and its alloys is one of pitting. Corrosion of this type is generally initiated by a breakdown of the passive oxide film which is normally formed on aluminum surfaces. Halogen ions are generally responsible for this breakdown, followed by localized pitting attack. As discussed in other detailed analyses performed during this program, hydrolysis of escaping propellant vapors, resulting in the formation of dilute acids, is believed to be the source of the corroding environment.

The appearance of the surfaces of these three vessels is almost identical, with a slightly coarser texture visible on those vessels exposed to an N_2O_4 environment. This can be seen in the photomacrographs of Figure 80. Physical appearance of the corrosion product, a white, crystalline compound, was very similar in all cases. At higher magnification the S/N 105 tank displayed a greater frequency of pitting, more localized in nature. As with the Tank No. 3 (S/N 6) discussed in detail, corrosion at the edge-of-weld and in the heat affected zone was more pronounced. This is readily apparent in the views presented in Figure 80.

The solid state bonded tank was uniformly etched to a grayish-white color over the entire external surface. No unusual or localized effects were noted on the exterior, except for the overlapped, exposed edge of the joint being more heavily corroded, with the overlap corroded away in spots. These effects are shown in Figure 39, Section VI.

On the external surface of the solid state bonded tank, corrosion penetrated through the cladding by the attack of grain boundaries containing diffused copper. A cross section of the external surface attack is shown in Figure 81, and consisted of selective attack of the grain boundaries of the 2024 core alloy over a relatively large area around corrosion penetration of the cladding. This penetration and undermining of the cladding produced the "powdery" appearance of the surface, since it promoted the progressive powdering off of individual grains of the cladding and outer layers of the core. In no areas had this process progressed deeply or catastrophically, but it does indicate the onset of degradation of the tank.

The corrosion of the external surfaces appears to have been caused by the same atmospheric environment which attacked the other tanks evaluated in this program - a humid, enclosed atmosphere occasionally contaminated with acid fumes from leaking tanks or lines in the same room. The highly acidic fumes and liquids are generated when N_2O_4 or ClF_5 come in contact with moist air. The nitric, hydrochloric or hydrofluoric acid subsequently formed can be expected to easily attack the surface of this tank.

The alloy from which the tank halves were fabricated was Alclad 2024 aluminum sheet. The pure aluminum cladding layer provides good corrosion resistance as long as it is unbroken, and the copper alloying element in the core material has not diffused to the surface. In this tank both instances had occurred. There was extensive corrosion of the exposed, unbonded outer rim of the overlap in the solid state bonded joint. This outer rim contained exposed core alloy along the cut edge and evidently corroded away all of the overlap, as seen in the general view of Figure 39, Section VI.

8. LOCALIZED EXTERNAL PITTING OF WELD

a. Detail Analysis of External Corrosion and Leakage Occurring on Flange Assembly Attachment Weld of Martin 10-Gallon A-286 Alloy Tank No. 12 (S/N 003) Exposed to ClF_5 Propellant for Six Months

(1) Test History

A ten-gallon capacity cylindrical container was fabricated by the Martin Company using A-286 stainless steel, a heat and corrosion resistant alloy. This vessel, designated as Tank No. 12 (S/N 003) was used for the storage of ClF_5 propellant for a period of approximately six months. A leak had apparently developed in the flange assembly to dome weld region, with some corrosion build-up visible on the external surface. Removal of the corrosion product from this surface disclosed the presence of two pin-holes at the edge of the weld bead. This anomaly was selected for a detailed analysis.

(2) Observations

The corrosion leading to perforation of the subject tank shell wall was externally initiated. Location of the corroded and perforated area is shown in Figure 44 of Section VI. Close-up views of the corrosion and perforation are shown in Figure 82. The actual perforations can be seen in Figures 82 and 83. A view of the internal surface, showing severe abrasion of the weld root and the perforations at the edge of the weld, is presented in Figure 83. The natural step formed by the transition from a heavier flange assembly wall thickness, is accentuated by this clean-up, as shown in the Figure 83 cross section. Note the start of a pit on the external surface of the weld bead.

Figure 84 presents a cross section view of one of the perforations. Note the location of the perforation, immediately at the edge of the weld. Attack of the A-286 base metal in this area was primarily transgranular in nature.

Mechanical properties of the base metal and circumferential girth weld were determined and are included in Table XVII.

(3) Metallurgical Analysis

The corrosion leading to the observed perforation of the A-286 shell wall was initiated by penetration of the paint film and passiveoxide layer by the corroding agent. A concentration cell was then established, with the corroded area becoming anodic to the larger, surrounding area and resulting in a highly localized, pitting type attack. As described in other failure analyses conducted in this program, the corroding agent was most probably a dilute acid, produced by the hydrolysis of leaking propellant vapors.

Combined with this probable occurrence was a severe reduction in thickness of the shell wall in this area due to excessive grinding of the weld drop-thru, probably to remove oxides or to correct a mismatch condition. Thicknesses in this area were reduced to less than half of the 0.040 inch nominal thickness of the dome segment, thus considerably reducing the time span required to complete penetration of the wall by localized pitting corrosion. No other corrosion on either the exterior or interior surfaces of this vessel was noted.

The pitting type corrosion noted here is characteristic for austenitic alloys such as A-286 and various stainless steels of the 300 Series. It is dependent upon penetration of the passive oxide layer normally present on these alloys. Halogen ions, believed present in the dilute acid environment developed by the hydrolysis reaction with propellant vapors (probably HF in this instance) are particularly effective in breaking through the naturally protective oxide barrier. Once this penetration is achieved, the localized active metal area becomes anodic to the large, surrounding cathodic area. Active corrosion at the anode then causes rapid pitting to occur.

The mechanical properties determined for the shell material and weld joint indicate that the vessel was in the solution treated and aged condition when placed in storage. Records indicate that welding was performed with material in the solution treated condition, and the fabricated shell then aged.

9. METALLURGICAL CHARACTERIZATION OF CRYOFORMED AISI 301 STAINLESS STEEL ONE-PINT CYLINDERS, EXPOSED TO N_2O_4 AND ClF_5 ENVIRONMENTS

a. Test History

Fifteen one-pint cylinders, fabricated of AISI 301 stainless steel and subsequently cryogenically stretch formed to size, were used for the long-term storage of N_2O_4 and ClF_5 propellants. Each propellant was stored in both aged and unaged containers. No failures, leakage or stress corrosion cracking occurred in any of the containers during the five-year storage period.

Two of the containers, one used to store N_2O_4 and one to store ClF_5, were selected for a more detailed examination and material property characterization. These units are identified as S/N 010 (aged) and S/N 023 (unaged) respectively. Both cylinders were clean and free of corrosion on the external surfaces. A light brown stain, approximately straw color, was observed on the internal surfaces. A line of demarcation was also visible on the inside of both cylinders, indicating only partial filling, or evaporation of some of the liquid had occurred. These effects are visible in Figures 9 and 12.

b. Observations

The subject containers are fabricated of AISI 301 stainless steel formed and welded into a cylinder, with hemispherical ends then welded to the cylinder. The AISI 301 stainless steel is a specially produced, lean grade of corrosion resistant stainless steel. Fittings are welded to each end to facilitate propellant loading. The containers are then stretched at liquid nitrogen temperature (-320°F) by a patented process which cold works and strengthens the cylinder walls.

This cryogenic stretching, involving only modest total biaxial strain, achieves very high strength due to the austenite to martensite transformation in the stainless steel. The stretching also smooths out any mismatch or other irregularity in the welds to insure that the welds are not a degrading factor in the tanks.

One container, S/N 010, was loaded with N_2O_4 oxidizer on 8 June 1967 and removed from storage on 18 September 1972, for a total of 63 months exposure. The other container examined, S/N 023, was loaded with the ClF_5 oxidizer and placed in storage on 23 August 1967. It was removed from storage on 18 September 1972, for a total of 60 months exposure.

External surfaces of the two containers discussed in this report were very clean, with no evidence of corrosion. Welds were sound and continuous as shown in Figure 85. Internal surfaces were lightly stained, to approximately a straw color. The film on cylinder S/N 023, which had contained ClF_5, was somewhat powdery and could be scraped off. It appeared to be a residue and not a surface reaction product. The film on S/N 010, which had contained N_2O_4, was completely different in character. It was hard, dense, very thin and could not be scraped off. This would indicate it to be a surface reaction product rather than a residue.

Mechanical properties were determined for both the unaged and aged cylinders in both parent metal and weld regions. These tests are discussed in detail in Section VI.C.1 with results tabulated in Table XVI. The strengths obtained can be briefly summerized as follows.

	YIELD STRENGTH	ULTIMATE STRENGTH
Unaged parent metal	191.4	216.1
(S/N 23) across weld	191.2	214.4
Across weld with weld ground flush	166.6	180.2
Aged parent metal	221.7	259.9
(S/N 10) across weld	223.7	258.2
Across weld with weld ground flush	196.2	225.2
Annealed AISI 301 Stainless Steel	40.0	110.0

These properties demonstrate the tremendous increase in strength obtained by this process, compared to annealed stainless steel. The strengths obtained are slightly lower than strengths reported by Arde based on burst testing of cylinders and spheres. This would be expected because of biaxial strengthening effects. However, there is no indication of degradation of the strength properties from propellant or environment exposure over the extended exposure time.

c. Metallurgical Analysis

No deleterious effects of the propellants on surface or microstructure were detected in either cylinder. A loosely adhering, easily removed deposit was observed on the cylinder which had contained ClF_5. The surface film observed on the cylinder which had been exposed to N_2O_4 was tightly adhering and could not be rubbed off. Both films were very thin and could not be identified by X-ray diffraction analysis of the surface. A powder sample prepared from scrapings removed from the cylinder containing ClF_5 failed to yield a pattern, indicating it to be amorphous in nature.

Parent metal microstructures of both vessels, shown in Figure 86, were very similar, displaying evidence of the stretching and transformation of the stainless steel. The grains are only slightly deformed, indicative of the modest total biaxial strain imposed during the stretching. However, the grains can be seen to be heavily "peppered". This is evidence of martensitic transformation and carbide precipitation in the material due to the cryogenic straining. The "peppering" is carbide precipitation induced by the strain and subsequent return to room temperature. In the aged microstructure, view (a) of Figure 86, further precipitation has taken place along the strain lines, making them more visible. This additional precipitation during aging is responsible for the increased strength of aged bottles.

The Arde, Inc., AISI 301 stainless steel cylinders have demonstrated excellent compatibility with ClF_5 and N_2O_4 propellants and with the corrosive storage room environment for a five year period. No base metal or weld zone corrosion or stress cracking occurred in any of the fifteen containers examined in this program. The very high strengths obtained with this process, and verified with tests in this program are achieved without serious loss in ductility and with substantial toughness remaining. The material appears to be an excellent choice for pressurized propellant tankage.

10. MECHANICAL PROPERTY DETERMINATION OF RTV-634 SILICONE RUBBER LINER IN ROLLING DIAPHRAGM PROPELLANT TANKS OF PREPACKAGED SYSTEMS

a. Test History

An RTV-634 silicone rubber liner was formed in the annulus between the rolling diaphragm and shell interior of the tanks, in order to seal the outside of the diaphragm and prevent its collapse. During disassembly of the systems, the liners were found to tear or rip quite readily, with some tendency for easier tearing in one direction than the other. Five of the tanks were evaluated for tensile properties of the liner material in both directions. These tanks represented both the solid propellant and decomposed hydrazine, gas fired systems.

b. Observations

Sections of the silicone rubber liner were stripped out of the tank shells to obtain specimen material. In some areas the liner would adhere to the wall and tear away unevenly. These areas were not included in the analysis. Tests of the RTV-634 silicone rubber liner material were performed according to the procedures outlined in the ASTM Specification D412. An Instron automatic testing machine, with an area compensator and automatic elongation counter, was used. At least three specimens per lot, in the circumferential and axial directions, were tested although some tests had to be discarded because of failure at material defects. Results were averaged for tank comparison, and are presented in their entirety in Table XIII. All specimens were made in the same manner, according to the procedure outlined in para. 4.1 of the ASTM D412 specification.

This material is a General Electric product and their trade literature (CLS-852) shows a typical strength of 400 psi, elongation of 220% and a Shore A Durometer hardness of 35. This material is subject to significant variation in properties due to mixing, casting and curing variables, and other General Electric literature (Technical Data Book S-29B) shows a typical strength of 550 psi.

The tensile test data did not indicate the directionality observed in handling and from "hand tear" tests of the material. It was postulated that surface flaws or discontinuities could possibly contribute to the apparent directionality observed. To probe this possibility further, random sections of this material were taken from the same unit sample, cut into approximately 2" x 2" sections and stretched by hand in both directions. Some pieces could be stretched a considerable amount in both directions, without failure. Others failed on the first stretching, with little or no ductility. Samples of each type were then examined carefully under the microscope, to determine surface condition and origin of failure of the low-stretch material. Photomacrographs of each type of material are shown in Figure 87 and 88. Note the uniform, continuous surface of the high-stretch material as compared to the mottled, layered appearance of the low-stretch material. The failure origin can be seen at the edge of one of the round, surface flaw depressions. This edge, of reduced cross section, acts as a sharp stress concentration point, leading to a low-stress failure with very little ductility.

c. Discussion and Technical Analysis

The direct measurement of tensile strength and elongation in the two principal directions of the tank did not show any consistent variation in properties that would explain the apparent difference in behavior. The tensile strengths, Table I, do show a rather large variation with much of the data being above the reported typical strength properties of 400-500 psi. The strength variations are too great (minimum/maximum readings of 347/800 psi respectively) to be explained simply as the expected variation due to mixing, pouring and curing inconsistencies. When the tensile data were analyzed as a function of thickness of the layer, a definite trend and correlation was found, with the thin liner samples showing generally higher strength than the thicker material. The data are shown graphically as strength versus thickness in Figure 89. The annulus between diaphragm and shell will inevitably have some variation in thickness, and it appears that this variation produced variations in cure behavior or other effects controlling the strength. These variations are probably not significant to the performance of the liner, particularly since liner failure will almost always be by a tearing mode, as discussed below.

In analyzing the directionality behavior it was evident that the observation which indicated directionality was a tearing test. The tear resistance of this material is very low, only 20 lbs., per inch, when measured using the ASTM die B, tear test. This very low tear resistance, coupled with the pattern of circumferential lathe turning ridges of the shell, which are faithfully reproduced on the liner, will give a definite lowered tear behavior along that direction.

When minor discontinuities and surface defects are also encountered, even more pronounced directionality will result. In preparation of the tensile test specimens, the usual precautions were observed not to take specimens from any of these defect containing areas, or to disregard the data if a tensile specimen failed prematurely through a previously unnoticed defect. For these reasons it is not surprising that the tensile data did not show directionality. It is the low tear strength, accentuated by the occasional surface defect, such as shown in Figure 88, which produced the apparent directionality.

11. METALLURGICAL EXAMINATION OF LINEAR DISCONTINUITIES OBSERVED ON SURFACES OF REGULATOR VALVES FROM STORABLE PREPACKAGED FEED SYSTEMS

a. Background

A number of regulator valves which had been removed from the SPPS frames were examined at the request of the AFRPL project office. The presence of stress-corrosion cracks on the valve body surfaces was suspected and it was considered desirable to ascertain the true nature of crack-like, linear indications which had been observed on several of the valves.

b. Conclusions

The linear discontinuities observed, oriented parallel to the long edge of the regulator body, were not caused by a stress-corrosion mechanism. These discontinuities were determined to be gross slag inclusions, a condition not found in vacuum melted, aerospace quality stainless steel.

c. Observations

A group of eight regulator valve bodies were dye penetrant inspected. Three of the bodies displayed line-type indications oriented parallel to the long dimension of the body as shown in Figure 90. One valve body was sectioned and mounted in a manner to permit polishing of the face containing the discontinuities.

Random grinding and polishing disclosed similar indications, as shown in Figures 91 and 92. These discontinuities are heavy slag stringers, fairly prevalent in air-melted, commercial grade stainless steel. They are considered gross indications according to aerospace standards, but present no problem in this particular application. A cross section of two of the larger indications is shown in Figure 93. Note the depth of the large surface stringer, which measures approximately 0.005 inches deep. This far exceeds the heavy inclusion rating as defined by the ASTM specification E45. The cross section of the large inclusion located totally within the body is also shown in Figure 93. This inclusion appears to be a complex mixture of several compounds, probably including oxides, silicides and alumina.

C. MECHANICAL PROPERTIES OF TANK SHELL MATERIALS AND WELDS

1. General

Tensile tests were performed on the wall material of selected tanks from this program. These tests were performed for a dual purpose, to verify the material heat treatment condition and to determine whether any degradation of strength properties had occurred. The tanks selected for mechanical property testing represented all of the different types of alloy and tank configurations involved in this post-test analysis contract. In all cases the mechanical property determination included both the parent metal and at least one of the welds. Where the configuration allowed, as many welds as possible were evaluated. The parent metal was evaluated in the cylindrical section of all tanks; the dome section was evaluated when the configuration allowed a reasonable length of shell material. All welds were tested in the metallurgical condition used in the tank. Thus, almost all of the welds were tested with weld crown and drop-thru intact, just as they appeared in the tank. In the prepackaged feed systems, the welds had been heat treated and machined flush, so they were tested in that condition.

The tensile properties obtained from the various tanks are tabulated in Tables XIV thru XIX. A discussion of the significance of the test results follows, from the standpoints of both original tank fabrication, and effect of long term exposure.

2. Small Containers

a. 2014-T6 Alummnum Alloy 3"x6" Containers

The tensile properties of the parent metal (Table XIV) from this type of container are typical for 2014 aluminum alloy sheet in the -T6 temper. The tensile properties across the weld, shown in the same Table XIV, indicate properties higher than would be expected for as-welded joints, being in the range of properties for post weld aged or reheat-treated material. Although these tanks showed visual evidence of some slight pitting, there was no indication of degradation of strength properties due to corrosion.

b. Alcoa One-Quart Containers

The data from tensile tests of six tanks, representing all of the alloys involved, is presented in Table XV. The properties of the standard, production alloys, (all but X7007) show close correspondence to the typical handbook values for the heat treated, -T6, condition. In some instances the yield strength values were somewhat low, but this is likely to be the result of the difficulties caused by testing of curved and straightened specimens.

The weld joint specimens of the same production alloy tanks, indicated that some of the tanks had been aged after welding while others were used in the as-welded condition. The 2014 and 2219 aluminum tanks exhibited weld strengths that indicate post-weld aging, while the 6061 and 5456 tanks have as-welded strengths. In none of these tanks was there any indication of corrosion effects, either external or internal, degrading the strength properties.

The experimental alloy, X7007 (identified as M825 in test plans), is difficult to evaluate because of the uncertainty in the typical, reference properties expected of the alloy. The reference values are taken from the Alcoa report on the development of the alloy. There appears to be a significant reduction in properties as compared to the reported typical properties. There are three possibilities to explain this reduction in strength. (1) The reported typical properties are not representative of the alloy behavior in this set of tanks. (2) Surface corrosion effects have degraded the strength properties. (3) Degradation of strength has occurred during the extremely long natural aging time (tanks were first loaded over 7 years ago in 1967).

Of these possibilities, overaging during long term storage is the least likely. There was some pitting corrosion of the external surface of the X7007 tank, and this is covered in more detail in Section VI.B.7. One of these tanks was examined for a confirmatory analysis of the external corrosion observed on many of the tanks in this program. That analysis showed corrosion to be present. However, the light pitting and surface etching observed should not be expected to produce an 18% loss in tensile strength compared to the reported properties. There is corrosion, and some loss in strength could certainly be expected, but not the degree of loss apparent from this data.

The most likely explanation for the apparent reduction in properties is that the reported typical properties are quite optimistic, and were probably not achieved in the sheet used for these tanks. This alloy was being developed for maximum strength while maintaining weldability, and it may be that the experimental trial material which gave the desired properties, did not produce similar properties when containers were spun or stamped from sheet.

c. Arde One-Pint Cylinders

Tensile tests were performed on two bottles from this group of cryo-formed 301 stainless steel containers, one in the aged condition, the other unaged. The properties obtained are presented in Table XVI. As has already been discussed, the cryogenic stretching of this material induces a martensitic transformation and substantial strength increase, which is borne out by the properties observed. Aging of the tank (20 hours at 800°F) produces additional strengthening, over 40 KSI in these tests. The strengths obtained are slightly lower than strengths reported by Arde based on burst testing of cylinders and spheres. This would be expected however, because of biaxial strengthening effects. There was no indication of degradation of the strength properties from propellant or environment exposure over the extended exposure time.

3. <u>Representative Tankage</u>

a. Storability Test Articles

Tensile tests were performed on six aluminum tanks, representing each of the material/fabricator combinations, and on the corrosion resistant steel/nickel alloy tanks, A-286 and Inconel 718. The results are shown in Table XVII. As with the other tensile evaluations, typical literature values of the expected base metal and transverse weld joint strengths are included in Table XVII.

The data show that the tanks in all instances possessed normal and typical properties for the materials and heat treatments involved. The 2014 tanks developed intermediate weld strengths, higher than those expected for as-welded joints but not high enough to represent fully reheat-treated joints. The properties are in the range for welds aged after welding and it is likely this represents the fabrication process used.

The tensile tests on two of the tanks involved areas which could have had corrosion effects. Aluminum 2014 Tank No. 3 (S/N 6) shown in Figure 37, had considerable corrosion on the external surface, from dripping or spraying of propellant from a neighboring tank or line. Tensile tests were taken across the girth weld in this corroded area and also in uncorroded areas. A significant loss in yield strengths and lesser loss in ultimate tensile strengths were noted in the corroded areas. These test results are based on the actual thickness of specimens, which in the corroded areas was somewhat reduced (6-7% below uncorroded areas). The lower yield strengths in these areas reflect the irregular surface produced by this corrosion. This corroded region is discussed in detail in Section VI.B.7.

The other tank in which corrosion effects were observed which might have affected tensile properties was 2014 aluminum alloy Tank No. 7, shown in Figure 40. The surface attack or etching was more pronounced along the heat affected zones. However, there was no thickness loss, only a rather general pitting. Tensile properties showed no observable degradation due to this pitting. The mechanical properties are within the range found for other 2014 aluminum tanks. This tank is also considered in more detail in Section VI.B.7.

b. Solid State Bonded Tank

One of the tanks included in this evaluation was an experimental solid state bonded Alclad 2024 aluminum tank from the Martin Company. Various aspects of the corrosion effects in this tank have already been discussed in Sections VI.B.5. and 7. Since the evaluation of this tank provided an opportunity to examine the solid state bond after extended exposure, both tensile and metallographic specimens were prepared from this joint, even though no evidence of gross corrosion damage was apparent.

The experimental solid state bond in this tank was formed as a lap joint between two ellipsoidal halves. The joint is shown in cross section in Figure 94, and a very satisfactory metallurgical bond was obtained in the parallel lap portion of the joint, views (b) and (c) of Figure 94. The bond region shows good diffusion across the joint line in the central portion of the joint.

The bonded portion of the joint line shows some rippling, indicative of an explosively formed joint. The bonding action had broken any oxide film layer on the faying surfaces and allowed intimate contact and formation of a good metallurgical bond. The bonding action had also caused significant deformation of the components at the joint region. This is shown in view (a) of Figure 94. The extent to which the underlying component had been impressed into the overlying component of the lap joint is quite obvious. The external surface of the overlying component at the edge of the underlying component showed a decided ribbed effect. In some portions of the circumference of the tank the surface was sufficiently corroded at this point to produce a definite groove in the surface. One of these regions is shown in Figure 94. Other portions of the tank show a smoother transition up onto the lap joint. The difference in detail configuration of this portion of the joint caused slight variation in joint performance in a transverse tensile test. The data obtained, both from 6 tests of the joint and 4 tests of the parent metal, are presented in Table XVIII. Based on nominal shell thickness, all joint tensile tests fractured at strength levels 3-11 KSI below the parent metal. However since all fractures occurred in the overlying shell portion at the reduced thickness point already described, this does not represent a weakness in the bond itself, but rather a deficiency in the joint configuration. When the properties were calculated on a basis of the minimum cross section area, the properties were essentially equivalent to the parent metal.

As is discussed in Section VI.B.5 on corrosion effects, this tank is in the annealed condition, and the properties obtained bear this out, with yield strengths of 1[illegible] KSI and ultimate strengths of 25 KSI. This level of strength is not practical for any tank holding pressurized fluids. The tank did provide a good evaluation of the solid state bond performance under corroding conditions, however, illustrating that there was no localized adverse corrosion of the bond even when the tank shell itself was being subjected to significant corrosion.

4. Storable Prepackaged Feed Systems

Tensile properties were determined on the aluminum 2219 cylindrical shell and across the longitudinal weld in the cylinder portion of the propellant storage tanks from several of these systems. All tanks for these systems were reported to be processed identically. The systems selected for evaluation represented two different observed characteristics, one being the difference in external surface appearance of the N_2O_4 tanks (frosted or etched from slight environmental corrosion) versus fuel tanks (bright and unattacked); the other being the difference produced by pressuring the tank with three different pressurizing sources; stored gas bottle (cold gas), stored liquid (hot decomposed hydrazine) products, and solid propellant gas generator (products of combustion of solid charge).

The tensile results are presented in Table XIX. No difference in properties, either of the 2219-T62 shell material or across the electron beam welded (and fully reheat treated) joint was found between shells whose exterior was unattacked or lightly etched. The slightly etched surface effect was obviously insignificant for the tank shell, with its wall thickness of 0.375". This surface appearance had been discussed in detail in Section VI-A on Internal and External Surface Observations.

The set of three tanks, all containing MHF-5 fuel and the Surface Force Orientation (screen) expulsion device, and pressurized with the three different gas sources, did show a slight but interesting mechanical property effect. In all three of these tanks there was no diaphragm or RTV rubber liner to shield the tank wall, so that during expulsion the pressurizing gas could act directly on the shell wall, once the bulk of the liquid had been expelled. The tensile properties of the shell show a slight but consistent and significant loss in strength, with an increasingly severe pressurizing source. The cold gas pressurized tank (-18) developed properties which very closely duplicate the expected 2219-T62 properties (41 KSI yield and 60 KSI ultimate strengths), based on an average of three tests. The tank exposed to decomposed hydrazine (-23) showed a slight (1 KSI) drop in the average yield and ultimate strengths, while the tank exposed to the products of combustion of the solid propellant (-17) displayed a greater drop (4 KSI). All of these changes are within 10% of the reference strengths (cold gas fired tank) and hence are not large. The changes reported are averages of three tests, where the individual data in all cases are very closely grouped around the average. Based on this evaluation of the test data, the changes are considered significant. According to the Convair report on these systems (Reference 6) the hydrazine decomposition gas generator produces a gas temperature of 1150°F in the line before the propellant tank, while the solid propellant produces a gas temperature of 1600°F at the propellant tank inlet. Although these temperatures are substantially reduced by expansion into the propellant tank and contact with the cool tank walls and propellant, they do indicate some strength degradation can be expected during expulsion with hot gases. This effect should be considered in designing these types of expulsion systems, particularly units of larger size or slower expulsion rate, where the time for shell wall softening may be considerably extended and therefore could be more significant than the maximum loss of 10% in yield strength encountered in these tanks.

SECTION VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL SUMMARY OF CORROSION EFFECTS

The cleanest interior surfaces were displayed by the 5456 aluminum alloy containers, which retained a bright, shiny luster even after twelve months had elapsed from the time Alcoa one-quart containers of this material were sectioned for examination. Those tanks fabricated of the 6061 aluminum alloy were also very clean, rivaling the 5456 containers in brightness and lack of any visible, corrosion effects. The 7007 alloy (M-825) remained relatively clean and free of corrosion, but had been dulled and spotted, indicating less corrosion resistance than noted for the 5456 and 6061 alloys. The 2000 series aluminum alloys displayed the poorest resistance to corrosion of any tank alloy material examined during this program. The internal corrosion observed on various containers was generally a post-storage test phenomenon not related to propellant exposure. Residues left in tanks which were incompletely drained, flushed or dried would become highly acidic and corrosive towards the aluminum surface, initiating the pitting type corrosion observed. In effect, observations made of the internal surfaces reflect the relative corrosion resistance of these aluminum alloys when exposed to a dilute acid environment. Their relative order of corrosion resistance coincides with that documented in the literature.

The external surfaces were corroded to a far greater degree than the interior surfaces, indicating the relative severity of the surrounding atmospheric environment. This atmosphere was a highly acidic one, produced by the hydrolysis of leaking propellant vapors, and was active throughout the length of the storage period. Deposition and condensation of these acid vapors on the aluminum surfaces result in penetration of the passive, natural oxide layer and subsequent pitting attack. The painted tanks displayed a far greater resistance to surface attack except in those areas where extremely concentrated vapor deposition occurred, resulting in destruction of the paint film and accelerated attack of the exposed metal surface.

With respect to corrosion and failure in aluminum containers, the most vulnerable area proved to be the manifold tube welds. These welds, made by the manual heliarc welding process, using 4043 filler alloy, were quite heavy and irregular. Evidence of porosity and microcracks developed in the heavier start and stop areas produced a condition where the probability of weld penetration by external pitting corrosion was greatly increased. The possibility of vapor leakage through this network, by a crevice or stress-induced corrosion action could also be considered as a possible source of propellant vapors entering the external hydrolysis reactions. Corrosion susceptibility of the 4043 weld alloy is far greater than that of the wrought aluminum alloys used to fabricate these pressure vessels, so the observed behavior should not be unexpected.

Arde cryoformed 301 stainless steel displayed excellent corrosion resistance and compatibility performance over a five-year period in all three environments: ClF_5, N_2O_4 and the humid, sometimes acid vapor laden, storage room environment. This material would certainly seem to be an excellent choice for long-term storage of these propellants.

Only two other tank shell alloys were tested and examined during this program. These were the iron-base, austenitic alloy A-286 and Inconel 718, a nickel-base alloy. Both materials were unaffected by the ClF_5 propellant environment to which they were exposed. The A-286 storage tank did sustain some pitting attack on the external surface, adjacent to a hemisphere closure weld. This anomaly is discussed in detail in Section VI.B. The Inconel 718 alloy tank was removed from storage after only two days because of a flange seal leak. Consequently, no assessment of long-term compatibility with ClF_5 could be made.

The storable prepackaged feed systems were evaluated primarily in the propellant storage tanks only. Although there were some problems and deficiencies in these tanks from a standpoint of positive expulsion behavior, most of these are related to auxiliary components and their behavior in the system. From a standpoint of long-term propellant storability and compatibility, these propellant storage tanks performed excellently with no evidence of corrosion degradation or other anomalies.

The gas pressurization sources used to expel them did have significant effects on the positive expulsion tanks. The solid propellant gas generator with its hot, dirty and rather violent gas stream, caused ripping and clogging of the surface force orientation screen, and a slight but significant 5-10% loss in strength properties of the 2219 aluminum tank shell. The liquid propellant gas generator (decomposed hydrazine) produced similar effects but of a lesser magnitude.

The rolling diaphragm performed reasonably well, but with some of the same problems noted during design and acceptance testing i.e., premature collapse causing only partial expulsion, usually followed by rupturing of the diaphragm or cocking of the piston on the central shaft.

B. CONCLUSIONS

The overall interpretation of the detailed anlyses performed during this program can be summarized briefly in the following conclusions:

1. Little evidence of basic incompatibility between any of the materials used to fabricate the storage vessels and the stored propellants, ClF_5 or N_2O_4, was found.

2. The major corrosive effects observed were confined to the external surfaces of the tank shells i.e., manifold tubing; tubing welds, which appeared to be particularly susceptible to attack; and some tank shell weldments.

3. The appearance of the corroded surfaces and the corrosion products formed were very similar in all cases examined.

4. The composition of the corrosion products formed indicate that dilute acids deposited on the surface, generally HF or HNO_3, were the corrosive agent most responsible for the corrosion observed.

5. These dilute acids were the product of a reaction occurring between propellant vapors and moisture in the high humidity storage building atmosphere.

6. The source of the propellant vapors are not precisely known. However, the following areas can be considered suspect:

6. a. Leaking valves or fittings.

b. Leakage through microcrack/porosity networks in tubing welds.

c. Hot cracks in difficult to weld alloys.

7. Annealing of 2000 series aluminum tank shell material left grain boundary films of copper aluminide, which were quite susceptible to attack under the conditions described above. This same annealing results in diffusion of copper into a normally protective pure aluminum cladding, causing pitting and general surface corrosion to proceed more readily.

8. Recognizing that the specific difficulties described above are confined to auxiliary tubing or unique features of some tanks, basic compatibility has been verified for the tank shell materials examined in this program and the stored propellants ClF_5 and N_2O_4, for long-term storage periods up to six years.

C. RECOMMENDATIONS

Based on the foregoing summary of observations and conclusions, the following recommendations are presented for future programs, both long-term propellant storage programs and Air Force production systems utilizing these types of tanks.

1. Automate the welding of manifold tubes in order to reduce weld bead size and to improve weld bead geometry and uniformity.

2. If storage temperatures are sufficiently low, consider using a 5000 series weld alloy for the tube joints. Preliminary corrosion tests are advised.

3. Thoroughly inspect all welds in the storage system to verify quality. Pressurize system with helium gas and use leak detector equipment to establish pressure tightness of system prior to propellant loading and storage.

4. Isolate each storage system to prevent externally induced corrosion effects produced by hydrolysis of leaking propellant vapors.

5. Monitor the storage building environment to detect presence of leaking propellant vapors; or install liquid level gages on each storage tank to detect propellant liquid loss.

6. Thorough draining and flushing operations should be performed on propellant tanks after long-term storage if they are to be reused. Complete drying and sealing of the vessel in a dry, relatively air-tight container should preclude post-storage corrosion effects.

7. Caution should be exercised in utilizing solid propellant gas generators as pressurizing devices for storage tanks with fragile positive expulsion devices, such as screens; or where the shell wall design would be degraded by some loss in strength. To a lesser extent, the same caution aplies to liquid propellant gas generators.

8. Tank fabrication steps should be controlled when dealing with 2000 series aluminum alloys, to insure that continuous films of copper aluminde are not allowed to form along grain boundaries.

SECTION VIII

REFERENCES

1. Technical Report AFRPL-TR-69-82
"Long-Term Storability of Propellant Tankage and Components"
J. E. Branigan, April 1969

2. "Development of a High Strength Aluminum Alloy, Readily Weldable in Plate Thicknesses, and Suitable for Application at -423°F (-253°C)
Alcoa Report-Contract NAS8-5452
R. Westerlund, W. Anderson, H. Hunsicker,
October 1967

3. Technical Report AFRPL-TR-65-194
"Design, Fabrication and Test of Small-Scale Storable Propellant Vessels"
Martin-Denver Company,
L. D. Berman
January 1966

4. Technical Report AFRPL-TR-71-6
"ClF_5 Storability Test Article"
Martin-Denver Company,
C. Caudill, R. Kirlin,
December 1970

5. Technical Report AFRPL-66-35
"Design and Manufacture of 15-Gallon Propellant Vessels for Tank Storability Program"
General Dynamics-Convair,
A. Hucknall
March 1966

6. Technical Report AFRPL-TR-67-252
"Storability Demonstration Propellant Feed Systems"
General Dynamics-Convair,
A. Schuler, R. White, D. E. Lawrence,
October 1967

7. Technical Report AFRPL-TR-72-126
"Long-Term Storage Testing of Propellant Tankage"
H. M. White, Capt. USAF,
December 1972.

TABLE I

SUMMARY OF FIRST GROUP OF TANKS EVALUATED

ITEM NUMBER	DESCRIPTION	TOTAL SUPPLIED
1	Alcoa one-quart Aluminum Containers 6 with N_2O_4 21 with ClF_5	27
2	Arde 301 SS One-pint Cylinders 8 with N_2O_4 7 with ClF_5	15
2A	2014-T6 Aluminum Alloy 3" x 6" Containers used for N_2O_4 Storage	4
3	2014-T6 and 6061 Aluminum 15-gallon Tanks 1 - ClF_5 2 - N_2O_4	3
5	2021-T6 Aluminum 10-gallon Storability Test Articles - ClF_5	5
6	Prepackaged Liquid Propellant Feed Systems 10 - MHF-5 3 - N_2O_4	13
7	Storability Test Article Inconel 718 ClF_5	1

TABLE II

SUMMARY OF SECOND GROUP OF TANKS EVALUATED

ITEM NO.	CAPACITY	DESCRIPTION: TANK MATERIAL	DESCRIPTION: PROPELLANT STORED	DESCRIPTION: MANUFACTURER	CODE NUMBERS	
8	15-gallon	2014 Al	ClF_5	Martin-Denver	1	0
9	15-gallon	2014 Al	ClF_5	Martin-Denver	2	0
10	15-gallon	2014 Al	ClF_5	Martin-Denver	3	*
11	15-gallon	7039 Al	ClF_5	Martin-Denver	4	*
12	10-gallon	7039 Al	ClF_5	Martin-Denver	5	0
13		2024 Al	N_2O_4	Martin-Denver (Diffusion bonded)	6	0
14	15-gallon	2014 Al	N_2O_4	Martin-Denver	7	0
15	15-gallon	7039 Al	N_2O_4	Martin-Denver	8	0
16	15-gallon	6061 Al	N_2O_4	General Dynamics-Convair	9	0
17	15-gallon	2014 Al	N_2O_4	General Dynamics-Convair	10	0
18	15-gallon	2014 Al	ClF_5	General Dynamics-Convair	11	0
19	10-gallon	A-286 St.Steel	ClF_5	Martin-Denver	12	*

NOTES: (1) One tank per item

(2) *Under code numbers denotes items selected for detailed analysis.

0 denotes items for possible confirmatory analysis.

TABLE III SUMMARY OF SIGNIFICANT FABRICATION CHARACTERISTICS OF TANKS EVALUATED

REPRESENTATIVE TANKAGE-FIRST GROUP

TANK MATERIAL	SERIAL NUMBER	MANUFACTURER	GENERAL TANK DESCRIPTION	COMPONENTS	TYPE OF WELD & FILLER WIRE	HEAT TREATMENT AFTER WELDING	SOURCE OF MATERIAL	FORMING	HEAT TREATMENT	REFERENCES
2221-T6 Aluminum	1 thru 5	Martin Marietta-Denver	10-gallon cylinder with domed ends - flanged at one end, outlet port at other end	Barrel	Machine TIG AC current 25A 75 He gas 2319 filler wire	none	.063 inch sheet	Roll form, single longit. weld	Soln treat & age(T6) after forming	RPL-TR-71-6 "ClF_5 storability test article
				Dome	" "	none	.063 inch sheet	explosi-vely formed	" "	
				Outlet fitting flange	" "		3 inch forged bar	Machining	As-received heat treat	
				Outlet tube	Tube to flange or fitting-manual weld					
					Tube to tube-manual weld					
Inconel 718		Martin Marietta-Denver	10-gallon cylinder with domed ends-flanged at one end, outlet port at other end	Barrel	Machine TIG DC-SP current Argon torch & backup gas	Aged after welding	.050 inch sheet	Roll form, single longit. weld	Aged after welding	RPL-TR-71-6 "ClF_5 storability test article"
				Dome	718 Filler wire	Aged after welding	.050 inch sheet	Explosi-vely formed	Aged after welding	
				Outlet fitting and flange	718 Filler wire		Bar	Machining		
				Outlet tubes	Tube to flange plate or fitting-manual weld					
					Tube to tube-Astro Arc weld					

TABLE III SUMMARY OF SIGNIFICANT FABRICATION CHARACTERISTICS OF TANKS EVALUATED

continued

REPRESENTATIVE TANKAGE-FIRST GROUP

TANK MATERIAL	SERIAL NUMBER	MANUFACTURER	GENERAL TANK DESCRIPTION	COMPONENTS	TYPE OF WELD & FILLER WIRE	HEAT TREATMENT AFTER WELDING	SOURCE OF MATERIAL	FORMING	HEAT TREATMENT	REFERENCES
6061-T6 Aluminum	N-12 Plus Un-numbered one	General Dynamics-Convair	15-gallon capacity approximately spherical, used multiple segments to simulate large tankage	Dome - 8 gore segments	Machine TIG AC current helium gas 5356 filler wire	None	0.1 inch thick sheet	Stretch form 8 individual gore segments	Soln treat & age to T6 after forming	RPL-TR-66-35 "Design & manufacture of 15 gal. prop. vessel for tank storability program"
				Barrel- 2 semi cylinders	Machine TIG DC current helium gas 5356 filler wire	None	0.1 inch thick sheet	Roll form 2 semi cylinders	Soln treat & age to T6 after forming	
				Girth weld	Machine TIG AC - 5356 filler wire					
				End fittings-fill/vent	Manual TIG 4043 filler wire	None	Plate	Machined		
				Support lugs	Manual TIG 4043 filler	None	Sheet	Machined		
2014-T6 Aluminum	N-9	General Dynamics-Convair	Same as above	Dome- 8 gore segments	Machine TIG DC current helium gas 2319 filler wire	None	0.08 inch thick sheet	Stretch form 8 individual gore segments	Soln treat & age to T6 after forming but before final sizing	Same as above
				Barrel- 2 semi cylinders	Machine TIG DC current helium gas 2319 filler wire	None	0.08 inch thick sheet	Roll form 2 semi cylinders	Soln treat & age to T6 after forming	
				Girth weld	Machine TIG AC - 2319 filler					
				End fittings-fill/vent	Manual TIG 4043 filler wire	None	Plate	Machined		
				Support lugs	Manual TIG 4043 filler wire	None	Sheet	Machined		

TABLE IV SUMMARY OF SIGNIFICANT FABRICATION CHARACTERISTICS OF TANKS EVALUATED

REPRESENTATIVE TANKAGE-SECOND GROUP

TANK MATERIAL	SERIAL NUMBER	MANUFACTURER	GENERAL TANK DESCRIPTION	COMPONENTS	TYPE OF WELD & FILLER WIRE	HEAT TREATMENT AFTER WELDING	SOURCE OF MATERIAL	FORMING	HEAT TREATMENT	REFERENCES
[illegible] ALUMINUM		MARTIN MARIETTA-DENVER	15-GALLON CAPACITY CYLINDER WITH DOMED ENDS - FLANGED AT ONE END, OUTLET PORT AT OTHER END	BARREL (3 PARTIAL CYLINDER SEGMENTS)	MACHINE TIG AC CURRENT	NONE	0.071 INCH SHEET	ROLL FORM	SOLN TREAT AGE TO T6 AFTER FORMING	RPL-TR-65-194 "DESIGN, FAB. & TEST OF SMALL SCALE STORABLE PROPELLANT VESSELS"
				DOME	MACHINE TIG AC CURRENT	NONE	0.071 INCH SHEET	EXPLOSIVE FORM DOME, CUT INTO 4 GORE SEGMENTS	SOLN TREAT & AGE TO T6 AFTER EXPLOSIVE FORMING	
				GIRTH WELD	MACHINE TIG AC CURRENT	NONE				
				END FITTING	MACHINE TIG AC CURRENT	NONE	-T651 PLATE STOCK 1.5" OR 2.5" THICK.	MACHINED	NONE	
				INLET/OUTLET TUBES	MANUAL TIG WELD		6061 TUBING			
[illegible] ALUMINUM		MARTIN MARIETTA-DENVER	15-GALLON CAPACITY CYLINDER WITH DOMED ENDS-FLANGED AT ONE END, OUTLET PORT AT OTHER END	BARREL (3 PARTIAL CYLINDER SEGMENTS)	MACHINE TIG AC CURRENT 5039 FILLER WIRE	NONE	0.180" SHEET CHEM-MILLED TO 0.071" BEFORE FORMING	ROLL FORM	SOLN TREAT & AGE TO T64 AFTER FORMING	SAME AS ABOVE
				DOME	MACHINE TIG AC CURRENT	NONE	SAME AS ABOVE	EXPLOSIVE FORM DOME, CUT INTO 4 GORE SEGMENTS	SOLN TREAT & AGE TO T64 AFTER EXPLOSIVE FORMING	
				GIRTH WELD	MACHINE TIG AC CURRENT	NONE				
				END FITTINGS	MACHINE TIG AC CURRENT	NONE	-T6 PLATE STOCK	MACHINED	NONE	
				INLET/OUTLET TUBES	MANUAL TIG WELD		6061 TUBING			

TABLE IV SUMMARY OF SIGNIFICANT FABRICATION CHARACTERISTICS OF TANKS EVALUATED

continued

REPRESENTATIVE TANKAGE-SECOND GROUP

TANK MATERIAL	SERIAL NUMBER	MANUFACTURER	GENERAL TANK DESCRIPTION	COMPONENTS	TYPE OF WELD & FILLER WIRE	HEAT TREATMENT AFTER WELDING	SOURCE OF MATERIAL	FORMING	TREATMENT	REFERENCES
6061 and 2014 ALUMINUM AL OYS		GENERAL DYNAMICS-CONVAIR	15-GALLON CAPACITY-ROUND TYPE	THESE TANKS WERE DESCRIBED IN TABLE III						
A-286 SS		MARTIN-DENVER	15-GALLON CAPACITY CYLINDER WITH DOMED END-FLANGED AT ONE END, OUTLET PORT AT OTHER END	BARREL	MACHINE TIG DC-SP CURRENT ARGON TORCH BACK-UP GAS A-286 FILLER	AGED AFTER WELDING	0.050 INCH SHEET	ROLL FORM, SINGLE LONGIT. WELD	AGED AFTER WELDING	ClF_5 STORABILITY TEST ARTICLE" AFRPL-TR-71-6
				DOME	SAME AS ABOVE	SAME AS ABOVE	0.50 INCH SHEET	EXPLOSIVE FORM	AGED AFTER WELDING	
				OUTLET/ FITTING AND FLANGE	SAME AS ABOVE	SAME AS ABOVE	PLATE	MACHINED		
				OUTLET TUBES	TUBE TO FLANGE PLATE OR FITTING-MANUAL WELD					
					TUBE TO TUBE-ASTRO ARC WELD					
2024 ALUMINUM		MARTIN-DENVER	ROUGHLY SPHERICAL TANK WITH TWO ELLIPSOIDAL HALVES. EXPERIMENTAL SOLID STATE BONDED	DOME	EXPLOSIVE BONDED LAP JOINT BETWEEN TWO DOMES		0.065 INCH AlClad SHEET	SPUN OR EXPLOSIVE FORMED	ANNEALED	

TABLE V SUMMARY OF SIGNIFICANT FABRICATION CHARACTERISTICS OF TANKS EVALUATED

PREPACKAGED SYSTEMS

TANK MATERIAL	SERIAL NUMBER	MANUFACTURER	GENERAL TANK DESCRIPTION	COMPONENTS	TYPE OF WELD & FILLER WIRE	HEAT TREATMENT AFTER WELDING	SOURCE OF MATERIAL	FORMING	HEAT TREATMENT	REFERENCES
2219 ALUMI-NUM	All	GENERAL DYNAMICS-CONVAIR	CYLINDRICAL TANK	BULKHEAD (END DOMES)	ELECTRON BEAM WELD RUPTURE DISC INTO OUTLET PORT	NONE	BILLET IN 2219-T852 CONDITION	MACHINED	AS-RECEIVED	"STORABILITY DEMONSTRATION PROPELLANT FEED SYSTEMS" AFRPL-TP-67-252
				CYLINDER (FORMED FROM 2 SEMI CYLINDERS)	ELECTRON BEAM IN 2 PASSES-2319 FILLER ADDED TO SECOND PASS	MACHINE OVER-ALL AND SOLN TREAT PLUS AGE TO -T62	1/2 INCH PLATE	BRAKE FORM TO SEMI-CYLINDER	ONLY AFTER WELDING	
				GIRTH WELDS JOINING BULKHEADS TO CYLINDER	ELECTRON BEAM IN 2 PASSES-2319 FILLER ADDED TO SECOND PASS	NONE				
	15,17, 18,19, 22,23		SURFACE FORCE ORIENTATION (SFO) EXPULSION DEVICE	SCREEN-30x250 DUTCH TWILL	RESISTANCE WELD AROUND PERIPHERY TO BACKUP PLATE	NONE	5056 WIRE	STD SCREEN WEAVING		
				BACKUP PLATE	EBW TO TANK HEAD BEFORE GIRTH WELDING	NONE	2219-T81 PLATE	MACHINED	AS-RECEIVED	
	1,5,6, 7,9, 11,14		ROLLING DIAPHRAGM (RD) EXPULSION DEVICE	SHELL	TIG-DC St. POLARITY	ANNEALED	1100 Al SHEET	ROLL FORM TO CYLINDER	AFTER WELD	
				TUBE	ELECTRON BEAM WELD	ANNEALED	1100 Al TUBE	SPUN FORM TO CONVOLUTE	AFTER WELD	
				POST, GUIDE & PISTON END	ELECTRON BEAM WELD	NONE	1100 BAR	MACHINED		
				ASSEMBLY INTO TANK	MANUAL TIG-2319 FILLER ROD	NONE				

TABLE VI

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE
ARDE ONE-PINT CYLINDERS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACE IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N (1)	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
UNAGED PINT CYLINDERS	301 STAINLESS STEEL	ClF_5	ARDE INC.	23 AUG 1967	18 SEPT 1972	NO ANOMALIES	018	CLEAN SMOOTH SURFACE; NO CORROSION	LIGHT STAINING APPROX. STRAW COLOR-ALL THREE CYLINDERS HAVE SAME APPEARANCE.
							020	SAME AS S/N 018	
							023	SAME AS S/N 018	
UNAGED PINT CYLINDERS	301 STAINLESS STEEL	N_2O_4	ARDE INC.	8 JUNE 1967	18 SEPT 1972	NO ANOMALIES	004	FEW SMALL PITS IN ONE HEMISPHERE, OTHERWISE CLEAN	VERY CLEAN, UNTARNISHED SURFACES, VERY FAINT LINE OF DEMARCATION VISIBLE.
							005	CLEAN SURFACE-NO CORROSION	
							007	A FEW PITS IN ONE WELD BEAD	SAME AS S/N 004 AND 005.
							009	CLEAN SURFACE-NO CORROSION	SAME AS S/N 004 AND 005.
AGED PINT CYLINDERS	301 STAINLESS STEEL	ClF_5	ARDE INC.	23 AUG 1967	18 SEPT 1972	NO ANOMALIES	014	GENERALLY CLEAN, SMOOTH SURFACE-NO CORROSION	SLIGHTLY DULLED SURFACE.
							015	SAME AS S/N 014	LIGHT BROWN STAIN.
							016	SOME PITTING PROBABLY CAUSED BY A LEAKING FITTING	LIGHT BROWN STAIN.
							017	SOME PITTING AT WELD INTER-SECTION-ONE END	MEDIUM BROWN STAIN.
AGED PINT CYLINDERS	301 STAINLESS STEEL	N_2O_4	ARDE INC.	8 JUNE 1967	18 SEPT 1972	NO ANOMALIES	006	CLEAN, SMOOTH SURFACES ON ALL FOUR TANKS	VERY LIGHT STAIN SOME SPOTTING. LINE OF DEMARCATION DUE TO PARTIAL FILLING.
							008	NO CORROSION VISIBLE	LIGHT BROWN STAIN. SOME SPOTTING. LINE OF DEMARCATION DUE TO PARTIAL FILLING.
							010	SAME AS S/N 006	SAME AS S/N 006.
							012	SAME AS S/N 006	SAME AS S/N 008.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACE IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
3 in. x 6 in. CONTAINERS	2014-T6	N_2O_4	DOUGLAS, GENERAL DYNAMICS, MARTIN NORTH AMERICAN	5 DEC 1966	5 MAR 1971	S/N's OF TANKS DESTROYED BY EXPOSURE S/N's ARBITRARILY ASSIGNED (1-4)	1	GENERALLY GOOD, LIGHT OVERALL ETCH, ENDS MORE SO THAN CYLINDER. WELDS DARKENED.	LIGHT SURFACE ATTACK. BLACKENING OF SOME WELDS. WHITE DEPOSITS IN SOME AREAS WHERE SHALLOW PITTING OCCURRED.
							2	GENERAL LIGHT ETCH. NUMEROUS EDGE OF WELD PITS.	SHALLOW PITTING, SCATTERED WHITE DEPOSITS, BLACKENED WELDS; OTHERWISE CLEAN AND SHINY.
							3	OVERALL ETCH, ONE END MORE SO THAN OTHER. FITTINGS CORRODED AND WELDS DARKENED. A FEW PITS ON ONE END WELD.	COMPARATIVELY CLEAN SURFACE. SOME SCATTERED WELD DARKENING. START OF SCATTERED PITTING ATTACK.
							4	SIMILAR TO S/N 3. SCATTERED PITTING IN WELD AND EDGE OF WELD.	SOME SCATTERED SURFACE STAINING. START OF SCATTERED PITTING. SOME WELD DARKENING.
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	M-825 T6 (7007)	ClF_5	ALCOA	28 NOV 1968	6 JUN 1972	TANKS ORIGINALLY LOADED WITH COMPOUND A (INTERHALOGEN PROPELLANT FOR 1-1/3 YRS. (3/67-7/68). CLEANED, LEAK TESTED AND PREPARED FOR ClF_5 EXPOSURE 10/68.	103* (A-10)	VERY SEVERE E.O.W. ATTACK ON CYLINDER SIDE OF CAP WELDS. SOME LOCALIZED PITTING AT E.O.W. OR GIRTH WELD. OVERALL ATTACK LESS SEVERE THAN OBSERVED ON S/N 105.	CLEAN SURFACE. SOME SCATTERED SPOTTING, THE FIRST STAGE OF PIT FORMATION.
							105 (A-9)	HEAVY, OVERALL SURFACE ETCHING. THREADS CORRODED. HEAVY ETCHING AT EDGE OF WELD AND IN HEAT AFFECTED ZONES.	SAME AS S/N 103.
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	6061-T6	ClF_5	ALCOA	28 NOV 1968	6 JUN 1972	TANKS ORIGINALLY LOADED WITH ClF_3 FOR TWO YEARS. (7/66-7/68). CLEANED, LEAK TESTED AND PREPARED FOR ClF_5 EXPOSURE 10/68.	40 (C-7)	SOME PITTING, PARTICULARLY^2 AREAS OF APPROX. 1-1/2 in. AT ONE END RADIUS.	CLEAN, SHINY SURFACE.
							41 (A-11)	GENERALLY CLEAN, NON-CORRODED SURFACE.	CLEAN, SHINY SURFACE.
							43 (C-17)	GENERALLY CLEAN SURFACE, A FEW ISOLATED PITS ON THE END MARKED WITH THE S/N.	CLEAN SURFACE, SOME SCATTERED LIGHT TAN STAINING.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACED IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	2219-T62	ClF_5	ALCOA	28 NOV 1968	6 JUN 1972	TANKS ORIGINALLY LOADED WITH COMPOUND A OR ClF_3 FOR ONE TO TWO YEARS. CLEANED LEAK TESTED AND PREPARED FOR ClF_5 10/68.	59* (C-18)	SCATTERED E.O.W. ATTACK, MORE PRONOUNCED ON CAP WELDS AND AT WELD OVER-LAPS. FITTINGS PITTED. WELD HAZ AND TANK ENDS MORE SEVERELY ATTACKED THAN CYLIND-RICAL SECTION.	DULLED SURFACE. SOME SCATTERED SHALLOW PITTING OF BASE METAL.
							60 (C-8)	YELLOW-BROWN DISCOLOR-ATION AT ONE END, WITH MORE PRONOUNCED ETCHING ATTACK THAN BALANCE OF TANK. SOME MODERATE TO HEAVY E.O.W. ATTACK.	DULLED, DISCOLORED SURFACE. SCATTERED, SHALLOW PITTING OF BASE METAL.
							62* (A-14)	OVERALL ATTACK WITH PRONOUNCED PITTING OF HAZ IN SOME AREAS. PARENT MATERIAL OF TANK ENDS MORE SEVERELY ATTACKED THAN CYLINDER SECTION. PURPLE STAIN AT ONE END WITH HEAVY PITTING.	DULLED, BUT CLEAN SURFACE. SOME SPOTTED AREAS WITH WHITE SALT DEPOSITS.
							65 (A-13)	OVERALL SURFACE ETCH, MORE PRONOUNCED ON ENDS AND IN SOME AREAS OF E.O.W.	SAME AS S/N 62.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACED IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	5456-F	ClF_5	ALCOA	28 NOV 1968	6 JUN 1972	TANKS ORIGINALLY LOADED WITH COMPOUND A OR ClF_3 FOR ONE TO TWO YEARS. CLEANED, LEAK TESTED AND PREPARED FOR ClF_5 10/68.	92 (A-8)	VERY LIGHT ETCH EFFECT. YELLOW-BROWN STAIN LENGTH OF TANK-WHERE STAIN TERMINATES SOME CORROSION NOTED. SOME ISOLATED REGIONS (SMALL) AT FITTING EDGE OF WELD-ONE END ONLY. LINEAR INCLUSION NEAR GIRTH WELD AND SEVERAL CHECKS PARALLEL TO WELD.	CLEAN, BRIGHT SURFACES.
							93 (C-4)	GENERALLY CLEAN SURFACE - A FEW ISOLATED PITS.	CLEAN, BRIGHT SURFACES.
							96 (A-7)	VERY CLEAN SURFACE. TWO AREAS OF SLIGHT PITTING NEAR CENTER ON 1/2 OF TANK, WITH SOME CORROSION PRODUCT. SLIGHT PITTING IN TWO INCH WIDE STAINED BAND. SMALL CRACK PARALLEL TO GIRTH WELD, APPROX. 0.025 INCH LONG.	CLEAN, SLIGHTLY DULLED SURFACE. SOME SCATTERED WHITE DEPOSITS.
							97 (C-14)	FINE PITS OVERALL, MORE SEVERE ON ONE HALF OF TANK. TWO LOCALIZED AREAS OF HEAVIER CORROSION, ONE ADJACENT TO GIRTH WELD AND ONE AT TANK END RADIUS.	CLEAN, BRIGHT SURFACES.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACED IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG. EXTERNAL SURFACE	VISUAL EXAMINATION-6X MAG. INTERNAL SURFACE
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	2014-T6	ClF_5	ALCOA	28 NOV 1968	6 JUN 1972	TANKS ORIGINALLY LOADED WITH COMPOUND A(INTER-HALOGEN PROPEL-LANT FOR 1 1/3 YRS. 3/67-7/68). CLEANED, LEAK TESTED AND PRE-PARED FOR ClF_5 EXPOSURE 10/68.	11	OVERALL SURFACE ETCH-MORE PRONOUNCED AT ENDS. WELD EDGES DARKENED AT WELD OVERLAPS AND AT ENDS OF LONGITUDINAL WELDS.	DULLED, GRAYISH DIS-COLORED SURFACES. SCATTERED SPOTTING WITH WHITE RESIDUE EARLY STAGE OF PITTING ATTACK.
							19* (A-15)	SLIGHT ATTACK OF WELD HAZ PARTICULARLY END FITTINGS. POSSIBLE FITTING LEAK WITH SOME CORROSION EVIDENT.	GRAY TO DARK GRAY DISCOLORATION. SCATTERED WHITE CORROSION PRODUCTS. LOCALIZED PITTING, IN DARKEST GRAY AREAS, APPROX. 50% THROUGH WALL IN SOME CASES.
							24* (C-2)	OVERALL SURFACE ETCH. SOME ATTACK AT EDGE OF WELDS - HEAVIEST IN HAZ OF END FITTINGS.	DULLED SURFACES. SOME SCATTERED SHALLOW PITTING. SEVERAL CRACKS AT END OF ONE WELD. NOT AS CORRODED AS S/N 19.
							25 (C-19)	SOME PITTING-MORE PRO-NOUNCED IN WELD HAZ, PARTICULARLY IN END FITTING WELDS.	GRAY TO DARK GRAY DISCOLORATION. SOME SCATTERED, SHALLOW PITTING.
							81* (A-2)	EDGE OF WELD ATTACK. END FITTINGS PITTED. ONE HOLE ADJACENT TO LONGITUDINAL WELD.	CLEAN, DULLED SURFACE. SCATTERED WHITE RESIDUE. SOME LOCALIZED SPOTTING, SOME BLACK-ENING ALONG E.O.W. CRACK-LIKE FISSURE AT END OF ONE WELD.
							83 (A-1)	OVERALL SURFACE ETCH. PITTING TYPE ATTACK IN HAZ OF END FITTING WELDS.	SURFACE APPEARANCE ABOUT SAME AS S/N 81, NO CRACKS NOTED.
							85 (C-12)	CORROSIVE ATTACK AT EDGE OF WELDS AND IN HAZ.	DULLER, GRAYER SURFACE THAN S/N81 & 83, OTHER-WISE APPEARANCE IS THE SAME. NO CRACKS NOTED.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACED IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG. EXTERNAL SURFACE	VISUAL EXAMINATION-6X MAG. INTERNAL SURFACE
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS (SHOULD BE INCLUDED WITH S/N 103 & S/N 105, EXPOSED TO ClF_5)	M-825-T6 (X7007)	ClF_5	ALCOA	28 NOV 1968	11 AUG 1970	THIS TANK INCORRECTLY TAGGED ACCORDING TO TEST LOG. IT WAS THEREFORE INCLUDED WITH N_2O_4 EXPOSURE GROUP IN PHOTOGRAPHS. TANK ORIGINALLY LOADED WITH ClF_3 FOR TWO YEARS. (7/66-7/68). CLEANED, LEAK TESTED AND PREPARED FOR ClF_5 EXPOSURE 10/68.	101 (C-15)	GENERAL, OVERALL SURFACE ETCH. INTERMITTENT, E.O.W. ATTACK ON ALL WELDS. LOCALIZED PITTING ON END FITTINGS.	RELATIVELY CLEAN SURFACES. SCATTERED SPOTTING WITH WHITE SALT RESIDUES. VERAL DARKER GRAY SPOTS WITH START OF SHALLOW PITTING ATTACK. BROWN STAIN AT ONE END CAUSED BY EVAPORATION OF LAST REMAINING LIQUID.
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	M-825-T6 (X7007)	N_2O_4	ALCOA	5 DEC 1966	5 MAR 1971	NO ANOMALIES	102	SCATTERED ATTACK AT EDGE OF WELD, HEAVIER AT END FITTING TO SHELL WELDS. FITTING THREADS CORRODED.	CLEAN, DULLED SURFACES. SCATTERED WHITE DEPOSITS CORRESPONDING TO EARLY STAGE OF PITTING ATTACK COMMON TO ALUMINUM ALLOYS.
							115	VERY CLEAN, WITH ONLY SLIGHT SURFACE ETCHING. BROAD, DARKENED WELD HAZ.	CLEAN, FAIRLY BRIGHT SURFACE. SOME SCATTERED SPOTTING AND EDGE OF WELD STAINING.

TABLE VII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS - SMALL ALUMINUM TANKS

TANK DESCRIPTION	TANK MATERIAL	PRO-PELLANT STORED	MANUF.	DATE PLACED IN STORAGE	DATE REMOVED FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	2014-T6	N_2O_4	ALCOA	5 DEC 1966	5 MAR 1971	NO ANOMALIES	20 (N-9)	GENERALLY CLEAN, SOME HAZ ATTACK ADJACENT TO END FITTING WELD. SLIGHT EDGE OF WELD ATTACK AT END OF ONE LONGITUDINAL WELD.	RELATIVELY CLEAN. SOME SCATTERED, WHITE SPOTLIKE DEPOSITS, START OF SHALLOW PITTING OBSERVED.
							84* (N-12)	GENERALLY CLEAN. INTERMITTENT ATTACK AT WELD EDGES.	SAME AS S/N 20.
							88 (N-11)	GENERALLY CLEAN. HAZ ATTACK AT BOTH END FITTING WELDS (ON TANK SIDE) + LONGITUDINAL WELDS.	THE SAME AS S/N 20 AND S/N 84, BUT SLIGHTLY DULLER IN APPEARANCE.
ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS	2219-T62	N_2O_4	ALCOA	5 DEC 1966	5 MAR 1971	NO ANOMALIES	64 (N-14)	GENERALLY CLEAN, ETCHED SURFACE. INTERMITTENT EDGE OF WELD ATTACK CONCENTRATED IN AREAS OF WELD OVERLAPS AND STOPS.	THE SAME AS PREVIOUS THREE TANKS. BROWN STAIN AT ONE END CAUSED BY EVAPORATION OF RESIDUAL LIQUID.

TABLE VIII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS-REPRESENTATIVE TANKAGE

TANK DESCRIPTION	TANK MATERIAL	PROPELLANT STORED	MANUFACTURER	DATE PLACED IN STORAGE	DATE REMV'D FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG. EXTERNAL SURFACE	VISUAL EXAMINATION-6X MAG. INTERNAL SURFACE
10-GAL. TANK	2021-T6 ALUMINUM	ClF_5	MARTIN	2/1/72	6/23/72	ALL 5 TANKS (S/N 001-005 LOADED WITH HYDRAZINE FEB. 69-MAY 70. THEN CLEANED FOR ClF_5 TEST. S/N 001 FAILED AT TUBING WELD IN ClF_5 STORAGE TEST.	001*	INLET TUBE BROKEN IN WELD. SOME CORROSION AT END OF TANK, OPPOSITE FLANGE END.	VERY CLEAN, BRIGHT SURFACES. SOME SCATTERED SPOTTING CAUSED BY WHITE SALT DEPOSITS, THE VERY EARLY STAGE OF PIT FORMATION. SOME BLACKENING AT E.O.W. PROBABLY FORMED DURING WELDING. TUBE INTERIOR CLEAN.
10-GAL TANK	2021-T6	ClF_5	MARTIN	2/1/72	8/31/72	FAILED AT TUBING WELD.	002	SOME AREAS OF CORROSION ON FLANGE. CORROSION OBSERVED ON OPPOSITE END OF TANK. INLET TUBE MECHANICALLY BROKEN AT WELD (PART OF TUBE NOT LOCATED).	SAME OBSERVATIONS AS S/N 001.
10-GAL TANK	2021-T6	ClF_5	MARTIN	2/1/72	5/19/72	FAILED AT TUBING WELD.	003*	SOME CORROSION ON FLANGE CLOSURE PLATE. INLET TUBE WELD CONTAINS LEAK AREA.	SAME OBSERVATIONS AS S/N 001.
10-GAL. TANK	2021-T6	ClF_5	MARTIN	2/1/72	7/31/72	LEAKED AT TUBING WELD.	004*	INLET TUBE BROKEN AT WELD. CORROSION ON INLET TUBE AND FLANGE CLOSURE PLATE. CORROSION AROUND TUBE INLET LEAK AT OPPOSITE END OF TANK.	SAME OBSERVATION AS S/N 001. ONE SMALL AREA CONTAINS SUPERFICIAL BROWN STAIN.
10-GAL. TANK	2021-T6	ClF_5	MARTIN	2/1/72 5/19/72	3/1/72 8/31/72	FAILED AT TUBING WELD.	005*	CRACK AND LEAK MARKED ON INLET TUBE WELD. SOME CORROSION AROUND EDGES OF FLANGE CLOSURE PLATE. BALANCE OF TANK CLEAN.	SAME OBSERVATIONS AS S/N 001. SMALL AREA CONTAINS SUPERFICIAL BROWN STAIN.
10-GAL. TANK	INCONEL 718	ClF_5	MARTIN	2/2/72	2/4/72	LEAK AT FLANGE SEALING SURFACE.		TANK RECEIVED WITH CLOSURE FLANGE REMOVED. NO EVIDENCE OF CORROSION EXCEPT AROUND FLANGE.	CLEAN, UNTARNISHED INTERIOR. NO EVIDENCE OF CORROSION.
15-GAL. TANK (ROUND TYPE)	6061-T6 ALUMINUM	ClF_5	GENERAL DYNAMICS CONVAIR	12/16/66	6/5/72	NO ANOMALIES	NO S/N	ETCHED OVERALL WITH MORE PRONOUNCED ATTACK IN WELD HAZ OF PIE SECTIONS, END FITTING WELDS AND ADJACENT AREA.	CLEAN SURFACE. SOME SCATTERED SPOTTING. SMALL AREA WITH SURFACE STAIN.

TABLE VIII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS-REPRESENTATIVE TANKAGE

TANK DESC-RIPTION	TANK MATERIAL	PROPEL-LANT STORED	MANU-FACT-URER	DATE PLACED IN STORAGE	DATE REMV'D FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								EXTERNAL SURFACE	INTERNAL SURFACE
15-GAL. TANK (ROUND TYPE)	6061-T6	N_2O_4	GENERAL DYNAMICS CONVAIR	12/8/66	9/14/72	NO ANOMALIES	N-12	ETCHED OVERALL WITH MORE PRONOUNCED ATTACK IN WELD HAZ OF PIE SECTIONS. ONE OF THE 1/4" TUBES WAS BROKEN OFF AT EDGE OF SLEEVE.	CLEAN, BRIGHT SURFACE. SOME PIE SECTIONS AND END BOSSES CONTAIN TAN SURFACE STAIN.
15-GAL. TANK (ROUND TYPE)	2014-T6 ALUMI-NUM	N_2O_4	GENERAL DYNAMICS CONVAIR	12/8/66	9/14/72	NO ANOMALIES	N-9	HEAVILY ETCHED OVERALL - MORE PRONOUNCED IN WELD HAZ AREAS. ONE VALVE TUBE ASSEMBLY BENT TOWARD TANK. HEAVY LOCALIZED CORROSION ADJACENT TO BENT TUBE DUE TO LEAK IN THE FITTING.	WELDS DARKENED. DULLED TARNISHED SURFACE. SCATTERED SPOTTING, WITH SPOTS OUTLINED BY WHITE DEPOSITS.
15-GAL. CYLIN-DRICAL TANK NO. 1 PAINTED BLUE	2024 ALUMI-NUM	ClF_5	MARTIN	3/72 - 11/20/72 (8 MOS.)		CRACK IN FLANGE TUBE WELD (TOP OF TANK DURING STORAGE)	S/N 9	BLUE PAINT FILM INTACT AND PROTECTIVE. NO EVIDENCE OF CORROSION ON TANK PROPER. FLANGE AND FLANGE TUBE HAVE AREAS WHERE PAINT FILM HAS BEEN PERFORATED AND CORROSION OF METAL STARTED. ONE AREA OF TUBE WELD SEVERELY CORRODED, TO BE EXAMINED IN DETAIL.	CLEAN, BUT DULLED TO A GRAYISH COLOR. SOME SCATTERED AREAS OF DISCOLORATION WITH GRAYISH-WHITE POWDERY DEPOSITS. BUFFED AREAS ADJACENT TO WELDS STILL FAIRLY SHINY.
15-GAL. CYLIN-DRICAL TANK NO. 2 PAINTED BLUE	2014-T6	ClF_5	MARTIN	3/72 - 8/8/72 (5 MOS.)		NONE		BLUE PAINT FILM INTACT AND PROTECTIVE WITH EXCEPTION OF ONE AREA IN SMALL CIR-CUMFERENTIAL WELD AT FLANGE END WHERE FILM WAS BROKEN AND LOCALIZED CORRO-SION HAD STARTED. FLANGE FACE AND FLANGE TUBE PAINT FILM ALMOST COMPLETELY REMOVED, WITH EVIDENCE OF CORROSION. TUBE AND WELD HEAVILY CORRODED.	RELATIVELY CLEAN BUT WITH CONSIDERABLE SPOTTING IN LOWER HEMISPHERE END, THE EARLY STAGE OF PIT FORMATION. SOME EDGE-OF-WELD ATTACK OF LOWER GIRTH WELD. POLISHED AREAS ADJACENT TO WELDS STILL SHINY.

TABLE VIII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS-REPRESENTATIVE TANKAGE

TANK DESC-RIPTION	TANK MATERIAL	PROPEL-LANT STORED	MANU-FACT-URER	DATE PLACED IN STORAGE	REM'D FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG. EXTERNAL SURFACE	VISUAL EXAMINATION-6X MAG. INTERNAL SURFACE
15-GAL. CYLIN-DRICAL TANK NO. 3 PAINTED BLUE	2014-T6	ClF_5	MARTIN	3/72 - 10/23/73 (20 MOS.)		EXTERNAL CORROSION OF SMALLER CIRCUMFERENTIAL WELD.	S/N 6	PAINT FILM DESTROYED WITH MARKED CORROSION OF BASE METAL AND SMALL CIRCUM-FERENTIAL WELD AT FLANGE END, APPARENTLY CAUSED BY IMPINGEMENT OF CORRO-SIVE LIQUID STREAM, CONCENTRATED AT WELD. PAINT FILM ON FLANGE FACE LOOSENED AND COMPLETELY REMOVED FROM EDGE WHERE IMPINGEMENT HAD OCCURRED. TO BE EXAMINED IN DETAIL.	VERY CLEAN, WITH ONLY SOME MINOR DISCOLORATION VISIBLE. POLISHED AREAS ADJACENT TO WELDS STILL SHINY.
10-GAL. CYLIND-RICAL TANK NO. 4 PAINTED BLUE	7039 ALUMI-NUM	ClF_5	MARTIN	3/72 - 7/20/72 (5 MOS.)		FLANGE TUBE EDGE OF WELD FAILURE.	S/N 003	PAINT FILM INTACT AND PROTECTIVE. ONE SMALL SPOT OF CORROSION AT EDGE OF GIRTH WELD. PER-FORATION OF PAINT FILM AND CORROSION OF FLANGE TUBE WELD, WITH SUBSE-QUENT MECHANICAL FAILURE. TO BE EXAMINED IN DETAIL.	VERY CLEAN AND STILL BRIGHT. ONLY SOME SCATTERED SPOTS OF DISCOLORATION.
SOLID STATE BONDED TANK NO. 6 BARE METAL	2024 ALUMI-NUM ALCLAD	N_2O_4	MARTIN	10/4/67 THRU 9/14/72 (5 YRS.)			NONE	UNIFORMLY ETCHED TO A GRAYISH WHITE COLOR. WHITE, POWDERY CORROSION PRODUCT.	DISCOLORED TO A DULL, GRAYISH-WHITE COLOR. AREAS OF DARKER DISCOLORATION CONTAIN EXTENSIVE PITS, SOME QUITE DEEP. RUST COLOR DEPOSIT OF FOREIGN MATERIAL ON ONE SEGMENT OF WELD. SMALL TRANSVERSE CRACK IN BOSS ATTACH-MENT WELD.
15-GAL CYLIND-RICAL TANK NO. 7 BARE METAL	2014-T6	N_2O_4	MARTIN	12/8/66 THRU 9/14/72 (5-3/4 YRS.)			NONE	ETCHED AND LIGHTLY PITTED OVERALL. WHITE POWDERY CORROSION PRODUCT. PITTING AT EDGE-OF-WELD ON LONGIT-UDINAL WELD. EXFOLIATION TYPE ATTACK AT EDGE OF WELD ON CIRCUMFERENTIAL WELDS.	VERY CLEAN AND STILL BRIGHT IN CYLINDER PORTION, WITH ONE SMALL, ISOLATED AREA CONTAINING WHITE ALUMINUM CORROSION PRODUCT MOUND, PROBABLY A HYDROXIDE. HEMISHPERE ENDS SLIGHTLY DULLED AND SPOTTED, MORE SO AT FLANGE END. CIRCUMFEREN-TIAL WELD AT FLANGE END DISCOLORED TO A DARK GRAY COLOR. FLANGE ATTACH-MENT SEGMENT SHOWS EVIDENCE OF EARLY STAGES OF PIT FORMATION.

TABLE VIII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS-REPRESENTATIVE TANKAGE

TANK DESC-RIPTION	TANK MATERIAL	PROPEL-LANT STORED	MANU-FACT-URER	DATE PLACED IN STORAGE	DATE REMV'D FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG. EXTERNAL SURFACE	INTERNAL SURFACE
15-GAL. CYLIND-RICAL TANK NO. 8 BARE METAL	7039 ALUMI-NUM	N_2O_4	MARTIN	12/8/66 THRU 9/14/72 (5-3/4 YRS.)			S/N N-4	UNIFORMLY ETCHED, LIGHT GRAY, MATTE FINISH. NO PRONOUNCED CORROSION.	VERY CLEAN AND BRIGHT. AS-FABRICATED APPEARANCE. SOME SCATTERED SPOTTING OF HEMI-SPHERE END. LINE OF DEMAR-CATION AT CENTER, INDICATING VESSEL ONLY HALF FULL DURING STORAGE TEST.
15-GAL. ROUND TANK NO. 9 BARE METAL	6061-T6	N_2O_4	GENERAL DYNAMIC CONVAIR	12/8/66 THRU 9/14/72 (5-3/4 YRS.)			S/N 11	UNIFORMLY ETCHED, LIGHT GRAY, MATTE FINISH. WHITE, POWDERY CORRO-SION PRODUCT IN SOME MORE HEAVILY ETCHED AREAS. ONE CIRCUMFERENTIAL END WELD AND TAB ATTACHMENT WELDS BLACKENED. OTHER WELDS REMAINED GRAY. SOME EDGE-OF-WELD ATTACK NOTED. NO EVIDENCE OF PITTING.	VERY CLEAN AND BRIGHT. HAS AS-FABRICATED APPEARANCE. LINE OF DEMARCATION VISIBLE AT CENTER, INDICATING VESSEL HALF FULL. TOP HALF OF VESSEL HAS SLIGHTLY DULLER FINISH AND ONE SMALL STAINED AREA. BOTTOM HALF, WHICH CONTAINED LIQUID, STILL HAS BRIGHT, ABRADED AREAS VISIBLE.
10-GAL. CYLIND-RICAL TANK NO. 5 PAINTED BLUE	7039 ALUMI-NUM	ClF_5	MARTIN	3/72 THRU 9/72 (6 MOS.)			S/N 001	PAINT FILM INTACT AND PROTECTIVE. PERFORATION OF PAINT FILM ON INNER DIAMETER OF FLANGE, WITH SPOT OF CORROSION ON TUBE ATTACHMENT WELD. BOTTOM TUBE WELD HAS ONE SPOT WHERE PAINT WAS PERFOR-ATED WITH CORROSION OBSERVED AT EDGE OF WELD.	VERY CLEAN AND BRIGHT. NO EVIDENCE OF CORROSION.
15-GAL. ROUND TANK NO. 10 BARE METAL	.014-T6	N_2O_4	GENERAL DYNAMICS CONVAIR	12/8/66 THRU 9/14/72 (5-3/4 YRS.)			S/N N-10	ETCHED, GRAY MATTE FINISH. ONE HALF DARKER THAN OTHER. AREAS OF GREATER CORROSION CONTAIN WHITE POWDER DEPOSITS. BANDS OF ATTACK VISIBLE ALONG EDGES OF WELDS. SMALL CIRCUMFERENTIAL FITTING WELD BLACKENED.	TWO HALVES HAVE DIFFERENT APPEAR-ANCE. ONE HALF (VAPOR PHASE) HAS SCATTERED, DARK GRAY SPOTS CONTAINING SMALL, SHALLOW PITS. WELDS ALSO SPOTTED. CLEAN AREAS ARE DULLED. OTHER HALF OF VESSEL (LIQUID PHASE) MORE EXTENSIVELY SPOTTED AND GENERALLY ATTACKED. ONE AREA NEAR BOSS WELD SHOWS DEEPER DISCOLORATION AND APPARENT CORROSION. BOSS AND FITTING WELDS VERY CLEAN, WITH LIGHT GOLDEN COLOR. ONE 3" WIDE BAND IN CYLIND-RICAL PORTION WITH HEAVY SPOTTING AND SHALLOW PITTING, DUE TO RESIDUAL LIQUID IN TANK AFTER DRAINING.

TABLE VIII

EFFECT OF LONG-TERM STORABILITY ON PROPELLANT TANKAGE AND RELATED COMPONENTS-REPRESENTATIVE TANKAGE

5

TANK DESC-RIPTION	TANK MATERIAL	PROPEL-LANT STORED	MANU-FACT-URER	DATE PLACED IN STORAGE	DATE REMV'D FROM STORAGE	TEST LOG HISTORY	TANK S/N	VISUAL EXAMINATION-6X MAG.	
								LXTERNAL SURFACE	INTERNAL SURFACE
15-GAL. ROUND TANK NO. 11 BARE METAL	2014-T6	ClF_5	GENERAL DYNAMICS CONVAIR	12/15/66 THRU 6/6/72 MINUS 13 MOS. (4½ YRS.)			S/N 11	UNIFORMLY ETCHED, GRAY MATTE FINISH. TOP HALF LIGHTER IN COLOR, WITH SOME POWDERY, WHITE CORROSION PRODUCT VISIBLE AND FINE, SHALLOW PITTING BAND OF ATTACK ALONG EDGES OF WELDS. ONE AREA OF EXFOLIATION ATTACK IN CYLINDRICAL PORTION, NEXT TO GIRTH WELD. EXFOLIATION TYPE ATTACK ON BOSS PLATES.	CLEAN, AND FAIRLY BRIGHT. SCATTERED SMALL SHALLOW PITS THROUGHOUT. UPPER, VAPCR PHASE HALF SLIGHTLY DULLER AND DARKER. GIRTH WELD IN UPPER, VAPOR PHASE HALF IS DARKENED, TO DEEP GRAY COLOR.
10-GAL. CYLINDRICAL TANK NO. 12 PAINTED BLUE	A-286 SS	ClF_5	MARTIN	3/72 - 2/73 (PREVIOUSLY HELD HYDRAZINE FOR ONE YR.)		RUST SPOT ON CIRCUMFERENTIAL FLANGE ATTACHMENT WELD.	S/N 003	PAINT FILM PROTECTIVE AND INTACT. ONE RUST-LIKE SPOT OBSERVED ON FLANGE BOSS WELD, TO BE EXAMINED IN DETAIL.	NO CORROSION VISIBLE. LINE OF DEMARCATION ABOUT 1.5 INCHES BELOW TANK CENTERLINE. DULL GRAY APPEARANCE. SCATTERED SPOTS CAUSED BY SURFACE STAINING.

NOTES: (1) FIRST S/N IS TAG IDENTIFICATION NUMBER. THE NUMBER IN PARENTHESES IS FROM THE TEST LOG.

* THESE UNITS TENTATIVELY SELECTED FOR IN-DEPTH ANALYSIS.

TABLE IX

EXAMINATION OF WELDS ON LIQUID ROCKET TANKAGE EXPOSED TO LONG-TERM PROPELLANT STORAGE FOR SIX YEARS

TANK DESCRIPTION	TANK MATERIAL	MANUFACTURER	PROPELLANT STORED	TANK S/N	VISUAL EXAMINATION-6X AND 40X MAG. EXTERNAL SURFACE	VISUAL EXAMINATION-6X AND 40X MAG. INTERNAL SURFACE
15 Gal. Cylindrical Tank No. 1 Painted Blue	2024 Aluminum	Martin	ClF_5	S/N 9	Upper tubing weld heavily corroded on one side at E.O.W. Bottom tubing weld is clean, uniform, sound with no corrosion.	Clean, uniform, sound welds. Fully penetrated with no cracks or corrosion.
15 Gal. Cylindrical Tank No. 2 Painted Blue	2014 Aluminum	Martin	ClF_5	----	Sound welds with one spot of corrosion at break in film. Lower tube welds clean. Flange tube welds corroded extensivly.	Clean, bright, shiny welds. Some minor E.O.W. discoloration and powdery deposit.
15 Gal. Cylindrical Tank No. 3 Painted Blue	2014 Aluminum	Martin	ClF_5	S/N 6	Sound, clean, uniform weld beads. Heavy corrosion in impingment area on dome and weld. Tube welds clean with no corrosion.	Clean, sound fully penetrated welds with no corrosion. Some E.O.W. staining and light powdery deposit.
10 Gal Cylindrical Tank No. 4 Painted Blue	7039 Aluminum	Martin	ClF_5	S/N 003	Clean, uniform welds with no corrosion. Tube to Tube welds clean with little or no corrosion. Bare tube weld discolored gray, with small crack visible in abraded area. Corrosion related to flange to tube failure.	Very clear, bright, shiny welds. No corrosion or cracking.
10 Gal. Cylindrical Tank No. 5 Painted Blue	7039 Aluminum	Martin	ClF_5	S/N 001	Clean, uniform welds with no corrosion. Lower, bare tube weld discolored to dark gray. Flange to tube weld has E.O.W. corrosion where paint film is broken.	Very clean, bright, shiny welds. No corrosion or cracking. Some minor, scattered deposit at E.O.W.
Solid State Bonded Tank No. 6 Bare Metal	2024 Aluminum	Martin	N_2O_4	------	General corrosion of external bond line. No cracking.	No corrosion or cracking of solid state bond. Rust colored deposit of foreign material in one area.
15 Gal. Cylindrical Tank No. 7 Bare Metal	2014 Aluminum	Martin	N_2O_4	------	Sound, uniform welds. Some pitting of weld bead and HAZ. No cracks. Tube welds discolored with incipient pitting.	Clean, sound, uniform welds with no cracks or corrosion. Portions of weld stained. Some gray - white powdery deposit at E.O W. Repair weld clean and sound.

TABLE IX

continued

EXAMINATION OF WELDS ON LIQUID ROCKET TANKAGE EXPOSED TO

LONG-TERM PROPELLANT STORAGE FOR SIX YEARS

TANK DESCRIPTION	TANK MATERIAL	MANUFACTURER	PROPELLANT STORED	TANK S/N	VISUAL EXAMINATION-6X AND 40X MAG.	
					EXTERNAL SURFACE	INTERNAL SURFACE
15 Gal. Cylindrical Tank No. 8 Bare Metal	7039 Aluminum	[illegible]tin	N_2O_4	S/N N-4	Some minor pitting of weld and HAZ. Minor pitting of tube welds and edge of weld.	Clean, sound, continuous welds with no corrosion. Fully penetrated with no cracks.
15 Gal. Round Tank No. 9 Bare Metal	6061 Aluminum	Convair	N_2O_4	S/N N-11	Scattered pitting on welds, HAZ and parent metal. Small girth weld discolored to dark gray and pitted.	Clean, bright welds. No corrosion or cracking.
15-Gal. Round Tank No. 10 Bare Metal	2[illegible]4 Aluminum	Convair	N_2O_4	S/N N-10	Welds, HAZ and parent metal extensively roughened and pitted throughout. Surfaces powdered white. Welds otherwise sound with no cracking.	Welds stained to dark gray. Scattered deposits throughout welds and parent metal - sites of incipient pit formation.
15-Gal. Round Tank No. 11 Bare Metal	2014 Aluminum	Convair	ClF_5	S/N 11	External surfaces roughened, pitted and powdery throughout. Exfoliation on small boss parent metal.	Scattered, fine white deposits throughout weld and parent metal surfaces. Welds stained light gray. Parent metal surfaces etched.
10-Gal. Cylindrical Tank No. 12 Painted Blue	A-286 Stainless Steel	Martin	ClF_5	S/N 003	Clean, sound, uniform welds.	Good, clean, sound welds. Some scattered, nodular deposits on weld. Some surface stains. No corrosion or cracks.

TABLE X

EFFECT OF STORAGE ON ALUMINUM ALLOY CONTAINMENT VESSELS FABRICATED AS PART OF PREPACKAGED PROPELLANT SYSTEMS MANUFACTURED BY GENERAL DYNAMICS

Sheet 1

SYSTEM SERIAL NUMBER	TANK EXPULSION DEVICE (1)	PRESSURE SUPPLY SUBSYSTEM (2)	STORED PROPELLANT	STORAGE PERIOD	VISUAL OBSERVATIONS
009	RD	SPGG	Empty as supplied by GD/C, filled with N_2O_4 before storage	May 68 - Sept. 72 (4-1/3 years)	Exterior etched and lightly corroded. 1100 Al RD surface expulsion side clean but dulled. No corrosion evident. Separation and bulging of RD internal wall. RTV shell liner, external surface of RD and pressurizing head blackened by combustion products of SPGG.
001	RD	SGD	MHF-5	June 67 - Nov. 72 (5-1/3 years)	Exterior clean and unattacked. Incomplete expulsion of RD due to collapse of RD away from interior wall of shell. Propellant exposed 1100 Al surface very bright with no stains or corrosion visible.
005	RD	LPGG	MHF-5	June 67 - Nov. 72 (5-1/3 years)	Exterior clean and unattacked. Most efficient and uniform expulsion cycle by an RD device. Propellant exposed RD surface dulled with some yellowish-white streaking, scattered brown spots in one area, and light pink stain in one other area. No corrosion was evident.
006	RD	LPGG	MHF-5	June 67 - Nov. 72 (5-1/3 years)	Exterior clean and unattacked. Separation and bulging of RD internal wall. Propellant exposed RD surface dulled with some streaking. No corrosion was evident.
011	RD	SPGG	MHF-5	June 67 - July 73 (6 years)	Exterior clean and unattacked. Separation and bulging of RD internal wall. Very similar in appearance to S/N 009. External RD surface and both heads blackened by combustion products of SPGG. Streaking of internal surface of RD caused by yellowish-white residue deposited on surface.
007	RD	SPGG	N_2O_4	May 67 - Sept. 72 (5-1/3 years)	Exterior etched and lightly corroded. Only partial travel of RD occurred, approximately one-half of full distance, with piston cocked on post to prevent further travel. Some blackening of one head noted. Dulling of propellant exposed surfaces with some scattered white deposits.
014	RD	SPGG	N_2O_4	May 67 - Sept. 72 (5-1/3 years)	Exterior etched and lightly corroded. Separation and bulging of RD internal wall. RTV shell liner, external surface of RD and heads blackened by combustion products of SPGG. Propellant exposed 1100 aluminum RD surface very bright and shiny.

TABLE X

continued

Sheet 2

SYSTEM SERIAL NUMBER	TANK EXPULSION DEVICE (1)	PRESSURE SUPPLY SUBSYSTEM (2)	STORED PROPELLANT	STORAGE PERIOD	VISUAL OBSERVATIONS
015	SFO	SGD	MHF-5	Apr. 67 - Nov. 72 (5-1/2 years)	Exterior clean and unattacked. Clean bright shell interior. Only one small area with light stain. Screen partially torn from SFO. Entire SFO assembly very clean.
018	SFO	SGD	MHF-5	Apr. 67 - Nov. 72 (5-1/2 years)	Exterior clean and unattacked. Clean, bright shell interior. Light stain band, approximately 3 inches wide along length of shell due to evaporation of residual liquid. Very clean, fully intact SFO and screen.
017	SFO	SPGG	MHF-5	Mar 67 - July 73 (6-1/4 years)	Exterior clean and unattacked. SFO end completely blackened. Screen torn loose. SFO weld failure with SFO completely separated from head. Internal surface of shell stained and streaked. Line of demarcation visible at center of shell, around circumference.
022	SFO	SPGG	MHF-5	Mar 67 - July 73 (6-1/4 years)	Exterior clean and unattacked. Shell interior dulled. Some scattered white deposits. Dark stain band, approximately 3 inches wide along length of shell due to evaporation of residual liquid. Some black deposits around SFO. Portion of screen torn loose.
019	SFO	LPGG	MHF-5	Mar 67 - July 73 (6-1/4 years)	Exterior clean and unattacked. Clean, dulled, lightly stained shell interior. SFO torn loose around entire weld circumference.
023	SFO	LPGG	MHF-5	Mar 67 - July 73 (6-1/4 years)	Exterior clean and unattacked. Shell interior dulled but very clean with no corrosion. SFO and screen intact but bulged and assembly completely separated from head as a result of weld failure.

KEY:
(1) RD - ROLLING DIAPHRAGM
(2) SPGG - SOLID PROPELLANT GAS GENERATOR
LPGG - LIQUID PROPELLANT GAS GENERATOR
SGD - STORED GAS DEVICE
(1) SFO - SURFACE FORCE ORIENTATION

TABLE XI

BUBBLE POINT DETERMINATION OF ALUMINUM SCREEN USED IN PREPACKAGED SYSTEMS

TANK SERIAL NUMBER AND SPECIMEN NUMBER		PRESSURE (Inches W.C.)	MICRON RATING "D"
015	1	2.30	149
	2	2.35	146
	3	----	---
	4	2.20	155
	AVERAGE		150
018	1	2.35	146
	2	2.32	147
	3	2.20	155
	4	2.55	134
	AVERAGE		146
019	1	2.70	127
	2	2.20	155
	3	2.70	127
	4	2.25	152
	AVERAGE		140
023	1	2.35	146
	2	2.38	144
	3	2.10	163
	4	2.55	134
	AVERAGE		147

NOTES:

1. Determination carried our according to Specification ARP901 "Bubble Point Test Method".
2. Temperature - 75°F
3. Formula used: $D = \frac{342}{P}$ (from ARP901)
4. Initial Micron Rating of As-fabricated Screen - 100

TABLE XII

LIQUID ROCKET PROPELLANT TANKAGE ANALYSIS MATRIX

Sheet 1

ANOMALY SELECTED FOR STUDY	DETAILED ANALYSIS			CONFIRMATORY ANALYSIS		
	TANK S/N AND DESCRIPTION	ALLOY	PROPELLANT STORED	TANK S/N AND DESCRIPTION	ALLOY	PROPELLANT STORED
Tube weld corrosion or failure	005 Martin 10-Gal. Cylinder	2021-T6 Al	ClF_5	1. 001 Martin 10-Gal. Cylinder	2021-T6 Al	ClF_5
				2. 003 Martin 10-Gal. Cylinder	2021-T6	ClF_5
				3. No. 2 Martin 15-Gal. Cylinder	2014 Al	ClF_5
				4. No. 4 (S/N 003) Martin 10-Gal. Cylinder	7039 Al	ClF_5
Inlet flange tube corrosion and leakage	No. 1 (S/N 9) Martin 15-Gal. Cylinder	2024 Al	ClF_5			
Flange transition tube to RPL fitting tube failure	No. 4 (S/N 003) Martin 15-Gal. Cylinder	7039 Al	ClF_5	1. 004 Martin 10-Gal. Cylinder Tube to Tube	2021-T6	ClF_5
				2. Same as 1. Flange to Tube	2021-T6	ClF_5
				3. No. 2 Martin 15-Gal. Cylinder	2014 Al	ClF_5
				4. No. 5 (S/N 001) Martin 10-Gal. Cylinder	7039 Al	ClF_5

TABLE XII

continued

Sheet 2

ANOMALY SELECTED FOR STUDY	DETAILED ANALYSIS: TANK S/N AND DESCRIPTION	DETAILED ANALYSIS: ALLOY	DETAILED ANALYSIS: PROPELLANT STORED	CONFIRMATORY ANALYSIS: TANK S/N AND DESCRIPTION	CONFIRMATORY ANALYSIS: ALLOY	CONFIRMATORY ANALYSIS: PROPELLANT STORED
Internal surface pitting	No. 6 Martin Diffusion bonded round tank	2024 Al Alclad	N_2O_4	1. N-10 GD/C 15-Gal. Round tank	2014- Al	N_2O_4
				2. No. 1 3" x 6" AlAlloy Container	2014-T6	N_2O_4
Internal surface pitting and weld cracking	19 Alcoa 1-Qt. AlAlloy Container	2014-T6	ClF_5	1. 24 Alcoa 1-Qt. AlAlloy Container	2014-T6	ClF_5
External surface pitting	No. 3 (S/N 6) Martin 15-Gal. Cylinder	2014 Al	ClF_5	1. 105 Alcoa 1-Qt. AlAlloy Container	7007-T6	ClF_5
				2. 6 Martin Diffusion bonded Round Tank	2024 Al Alclad	N_2O_4
				3. 7 Martin 15-Gal. Cylinder	2014 Al	N_2O_4
Localized external pitting of weld	12 (S/N 003)	A-286 St.Steel	ClF_5			
Metallurgical characterization of Arde 301 stainless steel one-pint cylinders	010 023	301	N_2O_4			

Sheet 3

TABLE XII
continued

ANOMALY SELECTED FOR STUDY	DETAILED ANALYSIS			CONFIRMATORY ANALYSIS		
	TANK S/N AND DESCRIPTION	ALLOY	PROPELLANT STORED	TANK S/N AND DESCRIPTION	ALLOY	PROPELLANT STORED
Mechanical property determination of RTV-634 silicone liner material from expelled rolling diaphragm tankage.	Rolling diaphragm tanks from pre-packaged propel-lant systems.					
Metallurgical examination of linear disconti-nuities observed on surface of regulator valves from storable prepackaged propellant systems.	Valves from 8 systems.	Auste-nitic stain-less steel	MHF-5			

TABLE XIII

MECHANICAL PROPERTIES OF RTV-634 SILICONE RUBBER LINER MATERIAL FROM ROLLING DIAPHRAGM-STORABLE PREPACKAGED FEED SYSTEMS

RD S/N, SPECIMEN DIRECTION AND SPECIMEN NO.	THICKNESS (INCH)	TENSILE STRENGTH PSI	% ELONGATION	SHORE "A" HARDNESS
S/N 005				
Axial	1 0.100	418	145	45
	2 0.103	445	140	
	3 0.105	350	120	
AVERAGE		404	135	
Circumferential	1 0.094	435	135	45
	2 0.099	610	170	
	3 0.106	410	115	
AVERAGE		485	140	
S/N 006				
Axial	1 0.119	384	200	46
	2 0.117	419	188	
	3 0.105	366	150	
AVERAGE		390	179	
Circumferential	1 0.112	446	225	46
	2 0.113	347	175	
AVERAGE		397	183	
S/N 009				
Axial	1 0.091	600	110	43
	2 0.091	550	120	
	3 0.092	750	150	
	4 0.091	695	150	
AVERAGE		649	133	
Circumferential	1 0.089	680	140	43
	2 0.095	700	150	
	3 0.085	518	100	
AVERAGE		633	130	

TABLE XIII

(Continued)

MECHANICAL PROPERTIES OF RTV-634 SILICONE RUBBER LINER MATERIAL FROM ROLLING DIAPHRAGM-STORABLE PREPACKAGED FEED SYSTEMS

RD S/N, SPECIMEN DIRECTION AND SPECIMEN NO.	THICKNESS (INCH)	TENSILE STRENGTH PSI	% ELONGATION	SHORE "A" HARDNESS
S/N 011				
Axial	1 0.085	630	150	43
	2 0.084	510	120	
	3 0.085	400	95	
	4 0.081	600	145	
AVERAGE		535	128	
Circumferential	1 0.090	580	95	43
	2 0.110	413	95	
AVERAGE		497	95	
S/N 014				
Axial	1 0.082	800	145	43
	2 0.074	665	135	
	3 0.072	705	135	
AVERAGE		723	138	
Circumferential	1 0.040	745	145	43
	2 0.036	600	135	
	3 0.033	485	110	
	4 0.092	610	130	
AVERAGE		610	130	

TABLE XIV

MECHANICAL PROPERTIES OF PARENT METAL AND WELDS IN 3" x 6" CONTAINERS

TANK NO.	TANK MATERIAL	SPECIMEN LOCATION	TEST RESULTS			TYPICAL HANDBOOK PROPERTIES		
			YIELD STRENGTH KSI	ULTIMATE TENSILE STRENGTH KSI	ELONGATION PERCENT IN ONE INCH	YIELD STRENGTH KSI	ULTIMATE TENSILE STRENGTH KSI	ELONGATION PERCENT IN ONE INCH
3	2014-T6 Aluminum	Parent metal	59.8	68.2	3	60	70	13
		Across weld 1	39.0	50.9	4	46	50	2 For welds heat treated to T6
		2	42.7	54.3	2			

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TABLE XV

MECHANICAL PROPERTIES OF PARENT METAL AND WELDS IN ALCOA ONE-QUART ALUMINUM ALLOY CONTAINERS

TANK NO.	TANK MATERIAL	SPECIMEN LOCATION	TEST RESULTS: YIELD STRENGTH KSI	TEST RESULTS: ULTIMATE TENSILE STRENGTH KSI	TEST RESULTS: ELONGATION PERCENT IN ONE INCH	TEST RESULTS: LOCATION OF FRACTURE	TYPICAL HANDBOOK PROPERTIES: YIELD STRENGTH KSI	TYPICAL HANDBOOK PROPERTIES: ULTIMATE TENSILE STRENGTH KSI	TYPICAL HANDBOOK PROPERTIES: ELONGATION PERCENT IN ONE INCH
19	2014-T6	PARENT METAL	58.7	67.5	2		60	70	13
		ACROSS WELD	26.7	39.4	8	EOW	28	34	4
24	2014-T6	PARENT METAL	57.5	73.2	10		60	70	13
		ACROSS WELD 1 2	31.2 31.1	50.4 48.0	3 4	HAZ EOW	28	34	4
41	6061-T6	PARENT METAL	34.1	41.9	10		40	45	12
		ACROSS WELD 1 2	23.2 19.6	30.9 30.0	2 2	HAZ HAZ	19	30	11 5356 FILLER WIRE
65	2219-T6	PARENT METAL	32.5	57.7	7		40	58	10
		ACROSS WELD 1 2	27.7 26.7	46.2 46.2	7 4	HAZ HAZ	37	43	2 POST-WELD AGED
93	5456F	PARENT METAL	33.6	49.1	19		33	47	18 (H321)(TEMPER)
		ACROSS WELD 1 2	26.1 24.7	47.7 46.4	12 8	HAZ HAZ	23	46	14
105	7007-T6 (M825)	PARENT METAL	46.0	60.8	8		67	73	12
		ACROSS WELD 1 2	29.2 26.9	42.8 44.6	4 5	EOW HAZ	32.8	49.0	5556 FILLER WIRE

TABLE XVI

MECHANICAL PROPERTIES OF AISI 301 STAINLESS STEEL SPECIMENS CUT FROM PARENT METAL AND WELD JOINTS OF ARDE CRYOFORMED ONE-PINT CYLINDERS

CYLINDER DESCRIPTION	SPECIMEN NUMBER AND TYPE		ULTIMATE TENSILE STRENGTH PSI	0.2% OFFSET YIELD STRENGTH PSI	% ELONGATION	LOCATION OF FRACTURE
S/N 010						
AGED AND STORED WITH N_2O_4	BASE METAL	1	-------	-------	-	
		2	266,400	219,500	7	
		3	253,300	223,800	5*	
	AVERAGE		259,900	221,700	6	
	WELD JOINT (AS-WELDED)	4	257,800	221,600	7	E.O.W.
		5	257,700	226,200	5*	P.M.
		6	259,100	223,200	6	E.O.W
	AVERAGE		258,200	223,700	6	
	WELD JOINT (GROUND FLUSH)	7	232,100	194,600	5	WELD
		8	210,900	201,800	5	WELD
		9	232,500	-------	9	WELD
	AVERAGE		225,200	198,200	6	
**TYPICAL AGED PROPERTIES FROM ARDE LITERATURE			270,000			
S/N 023						
UNAGED AND STORED WITH ClF_5	BASE METAL	1	214,600	191,500	4	
		2	218,800	187,500	7	
		3	214,800	195,300	6	
	AVERAGE		216,100	191,400	6	
	WELD JOINT (AS-WELDED)	4	214,600	191,500	2	E.O.W.
		5	212,300	180,200	3*	P.M.
		6	216,400	193,000	7*	P.M.
	AVERAGE		214,400	191,200	4	
	WELD JOINT (GROUND FLUSH)	7	189,300	-------	6	WELD
		8	162,400	160,200	3	WELD
		9	189,300	172,000	3	WELD
	AVERAGE		180,300	166,600	4	
**TYPICAL UNAGED PROPERTIES FROM ARDE LITERATURE			210,000			

*SPECIMENS BROKE OUTSIDE OF GAGE MARKS.

**THESE TYPICAL STRENGTH PROPERTIES ARE COMPUTED FROM BURST TESTS OF SPHERES. SINCE THESE BURST TESTS INVOLVE BIAXIAL STRESS AND NO KNOOK EFFECTS THEY SHOULD PRODUCE SIGNIFICANTLY HIGHER PROPERTIES THAN UNIAXIAL TENSILE TESTS.

TABLE XVII

MECHANICAL PROPERTIES OF [illegible] MATERIAL AND WELDS FROM REPRESENTATIVE TANKAGE

TANK NUMBER	TANK MATERIAL	SPECIMEN LOCATION		PARENT METAL: YIELD STRENGTH 0.2% OFFSET KSI	PARENT METAL: [illegible]	PARENT METAL: ELONGATION % IN 2 IN.	ACROSS WELD: YIELD STRENGTH 0.2% OFFSET KSI	ACROSS WELD: ULTIMATE TENSILE STRENGTH KSI	ACROSS WELD: ELONGATION % IN 2 IN.	LOCATION OF FRACTURE
No. 7 Martin 15-Gal.	2014-T6 Al	Cylinder	1	61.4	[illegible]	10				
			2	61.0	68.9	8.5				
		Dome	1	58.9	65.9	BOG				
			2	54.8	64.0	5.5				
		Typical T6 parent metal		60	70	13				
		Longit. Cyl weld	1				41.0	46.2	2	E. O. W.
			2				NA	47.3	2	E. O. W.
		Dome Gore weld	1				39.7	52.8	4	HAZ
			2				36.5	44.1	1.5	E. O. W.
		Girth weld	1				NA	53.2	4	E. O. W.
			2				36.9	55.0	4	E. O. W.
		Typical as-weld with 4043 filler wire					28	34	4	
		Typical Ht. treat with 4043 filler						50	2	
S/N 3 Martin 15-Gal.	2021-T6 Al	Cylinder	1	57.4	69.5	10				
			2	58.6	69.4	10				
		Dome	1	52.9	66.4	7				
			2	62.9	67.7	5				
		Typical T6 parent metal		65	75	8				
		Girth weld	1				NA	44.1	0.5	E. O. W.
			2				NA	49.1	0.5	E. O. W.
		Typical as-weld with 2319 filler					33	43	1.4	
No. 3 Martin 15-Gal.	2014-T6 Al	Cylinder	1	51.0	66.8	10				
			2	50.5	66.0	10				
			3	51.1	66.3	9				
S/N 6		Typical T6 Parent metal		60	70	13				

Sheet 2

TAPLE XVII

continued

TANK NUMBER	TANK MATERIAL	SPECIMEN LOCATION		PARENT METAL YIELD STRENGTH 0.2% OFFSET KSI	PARENT METAL ULTIMATE TENSILE STRENGTH KSI	PARENT METAL ELONG-ATION % IN 2 IN.	ACROSS WELD YIELD STRENGTH 0.2% OFFSET KSI	ACROSS WELD ULTIMATE TENSILE STRENGTH KSI	ACROSS WELD ELONG-ATION % IN 2 IN.	LOCATION OF FRACTURE
		Girth weld NORMAL	1	In areas not showing corrosion			28.2	44.[illegible]	4	E. O. W.
			2				29.7	41.0	3	E. O. W.
			3				31.3	35.0	1	E. O. W.
			4				32.8	41.3	1.5	E. O. W.
		CORRODED	1	In heavily corroded region			25.6	34.1	4	P. M.
			2				26.4	40.4	4	P. M.
			3				24.8	41.0	4	E. O. W.
		Typical as-welded with 4043 filler					28	34	4	
No. 4 S/N 003 Martin 10-Gal.	7039-T6 Al	Cylinder	1	51.3	61.1	12				
			2	51.1	61.2	12				
		Dome	1	33.5	46.5	12				
			2	46.0	57.2	12				
		Typical T6 parent metal		55	65	13				
		Girth weld	1				50.9	59.7	6	E. O. W.
			2				50.9	60.1	8	HAZ
		Typical as-weld with 5039 filler					30	50	12	
No. 8 S/N N-4 Martin 15-Gal.	7039-T6 Al	Cylinder	1	47.7	59.2	12				
			2	50.5	59.5	12				
		Dome	1	51.0	60.4	10				
			2	48.6	59.3	10				
		Typical T6 parent metal		55	65	13				
		Longit. Cyl. weld	1				25.6	59.4	8	HAZ
			2				46.5	59.1	8	HAZ
		Girth weld	1				44.1	59.9	6	P. M.
			2				41.2	60.3	BOG	P. M.
		Typical as-weld					30	50	12	
No. 9 Gen. Dyn. Convair 15-Gal. round	6061-T6 Al	Cylinder	1	40.5	45.7	13				
			2	37.0	42.8	11				
		Dome	1	40.6	48.1	10				
			2	44.3	47.6	10				
		Typical T6 parent metal		40	45	12				
		Longit. Cyl. weld	1				30.3	37.7	3	HAZ
			2				26.5	32.9	4	HAZ

TABLE XVII
continued

Sheet 3

TANK NUMBER	TANK MATERIAL	SPECIMEN LOCATION		PARENT METAL: YIELD STRENGTH 0.2% OFFSET KSI	PARENT METAL: ULTIMATE TENSILE STRENGTH KSI	PARENT METAL: ELONGATION % IN 2 IN.	ACROSS WELD: YIELD STRENGTH 0.2% OFFSET KSI	ACROSS WELD: ULTIMATE TENSILE STRENGTH KSI	ACROSS WELD: ELONGATION % IN 2 IN.	LOCATION OF FRACTURE
		Girth weld	1				17.5	29.3	5	HAZ
			2				22.0	28.5	5	HAZ
		Typical as-weld with [illegible] filler					19	30	11	
[illegible]	[illegible]	Cylinder	1	57.5	67.3	8				
			2	58.5	67.3	8				
		Dome	1	57.7	63.5	5				
			2	56.3	64.1	6				
		Typical T6 parent metal		60	70	13				
		Gore to gore Dome weld	1				38.2	46.8	2	E. O. W.
			2				40.3	42.3	1	E. O. W.
		Girth weld	1				28.2	39.9	3	E. O. W.
			2				27.9	34.1	2	E. O. W.
		Typical as-weld with 4043 filler					28	34	4	
		Typical T6 treat with 4043 filler						50	2	
No. 5 Martin 18-Gal.	Inconel 71[illegible]	Cylinder	1	173.1	199.2	20				
			2	175.4	198.4	20				
		Dome	1	158.5	198.9	19				
			2	164.6	201.4	19				
		Typical aged parent metal		174.5	205.7	19				
		Girth weld	1				173.5	200.6	13	P. M.
			2				175.9	201.0	13	P. M.
		Typical aged weld-718 filler					149.5	183.5	12	

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TABLE XVII

continued

TANK NUMBER	TANK MATERIAL	SPECIMEN LOCATION		PARENT METAL			ACROSS WELD			LOCATION OF FRACTURE
				YIELD STRENGTH 0.2% OFFSET KSI	ULTIMATE TENSILE STRENGTH KSI	ELONG-ATION % IN 2 IN.	YIELD STRENGTH 0.2% OFFSET KSI	ULTIMATE TENSILE STRENGTH KSI	ELONG-ATION % IN 2 IN.	
No. 12 Martin 10-Gal.	A-286 SS	Cylinder	1	112.5	159.0	23				
			2	115.0	157.1	23				
		Dome	1	101.2	157.3	22				
			2	101.6	153.4	22				
		Typical STA parent metal		93	143	24				
		Girth weld	1				110.8	157.3	11	P. M.
			2				112.1	158.4	14	P. M.
		Typical aged weld A-286 filler					93	143	24	"Should achiev parent metal properties when aged after welding"

NOTES: NA - DATA POINT NOT AVAILABLE DUE TO MALFUNCTION OF EQUIPMENT (GENERALLY EXTENSOMETER USED FOR YIELD STRENGTH DETERMINATION)

LOCATIONS: P. M. - PARENT METAL, OUTSIDE HEAT AFFECTED ZONE
WELD - WITHIN FUSION ZONE.
HAZ - IN HEAT AFFECTED ZONE
EOW - ALONG EDGE OF WELD

TABLE XVIII

MECHANICAL PROPERTIES OF SAMPLES FROM SOLID STATE BONDED TANK NO. 6

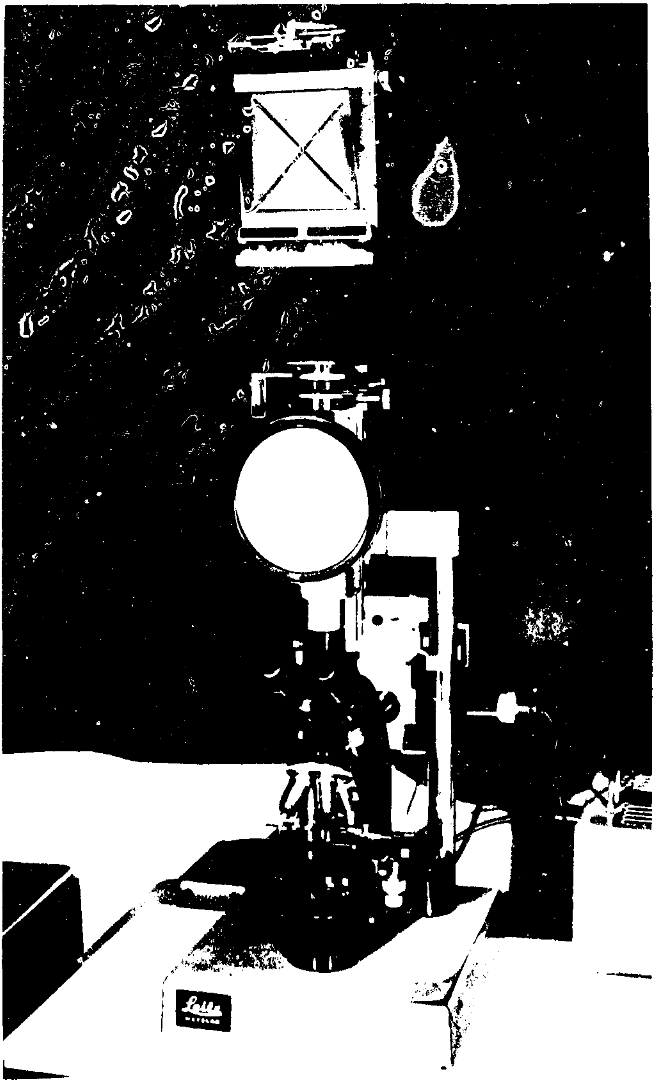
	YIELD STRENGTH 0.2% OFFSET KSI	ULTIMATE TENSILE STRENGTH KSI		ELONGATION % IN 2 INCHES	HARDNESS - ROCKWELL F SCALE
PARENT METAL					
CIRCUMFERENTIAL DIRECTION					
1	11.2	24.8		7	47
2	12.0	24.0		10	46
3	11.9	24.5		11	45
4	12.3	26.0		11	
AVERAGE	11.8	24.8		9.7	46
TESTS ACROSS BONDED JOINT		USING NOMINAL THICKNESS	USING LOCAL REDUCED THICKNESS		
EDGE OF JOINT SHAPE					
END 1 -1 SMOOTH	10.9	20.0	26.2	3	
END 1 -2 SMOOTH	N.M.	21.7	26.8	3	
END 2 -1 SLIGHT DEPRESSION	N.M.	19.6	26.5	3	
END 2 -2 DEPRESSION	N.M	16.7	23.5	2	
CENTER -1 DEPRESSION	N.M	13.7	22.1	1	
CENTER -2 DEPRESSION	N.M	16.1	23.3	1.5	

N.M. = NOT MEASURED

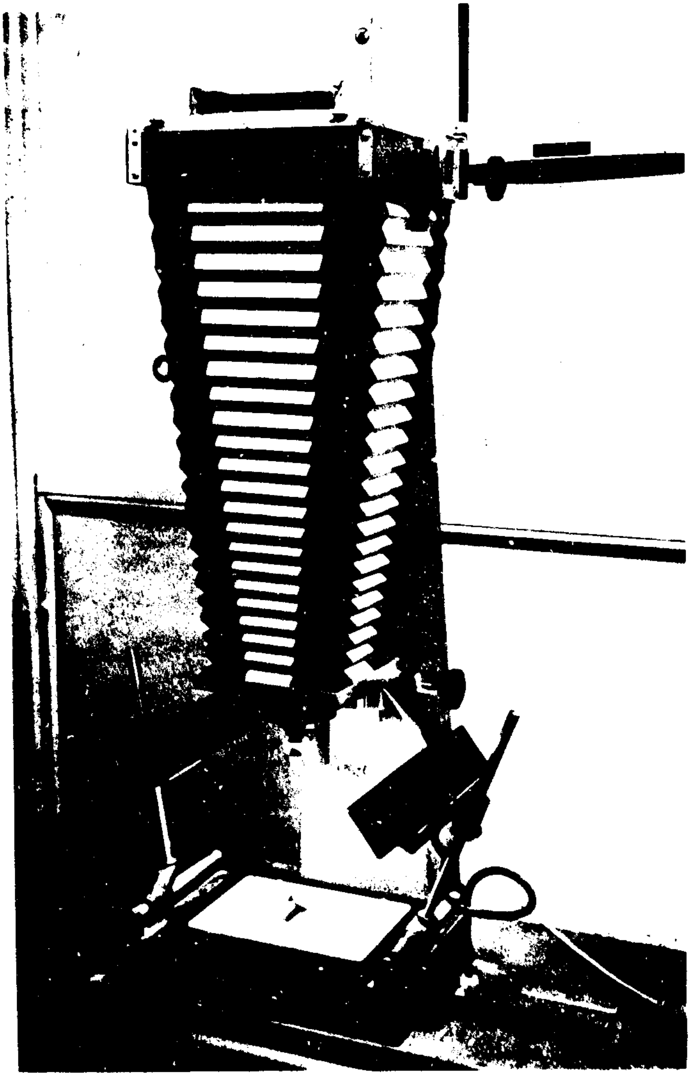
TABLE XIX

MECHANICAL PROPERTIES OF TANK SHELL MATERIAL AND WELDS FROM PREPACKAGED SYSTEM TANKS

SYSTEM NUMBER	TANK MATERIAL	SPECIMEN LOCATION		PARENT METAL YIELD STRENGTH 0.2% OFFSET KSI	PARENT METAL ULTIMATE TENSILE STRENGTH KSI	PARENT METAL ELONG-ATION % IN 2"	ACROSS WELD YIELD STRENGTH 0.2% OFFSET KSI	ACROSS WELD ULTIMATE TENSILE STRENGTH KSI	ACROSS WELD ELONG-ATION % IN 2"	LOCATION OF FRACTURE
9	2219-T62 Al	CYLINDER AXIAL DIRECTION	1	41.2	61.5	9	COMMENTS: External surface lightly etched, pressurized with solid propellant gas but with shell protected by RTV.			
			2	43.2	59.3	10				
			3	39.8	59.5	9				
		AVERAGE		41.4	60.1	9.3				
18	2219-T62 Al	CYLINDER AXIAL DIRECTION	1	41.6	59.8	10	External and internal surface clean - pressurized with cold gas.			
			2	39.7	57.5	10				
			3	41.4	59.7	9				
		AVERAGE		40.9	59.3	9.6				
23	2219-T62 Al	CYLINDER AXIAL DIRECTION	1	40.3	58.1	12	External surface clean. Light film on interior from pressurization with decomposed hydrazine.			
			2	38.1	58.2	12				
			3	37.7	58.0	12				
		AVERAGE		38.7	58.1	12				
17	2219-T62 Al	CYLINDER AXIAL DIRECTION	1	36.5	56.0	11	External surface clean. Interior discolored and with deposits *from solid* propellant combustion products.			
			2	37.3	56.4	11				
			3	37.4	57.7	11				
		AVERAGE		37.0	56.7	11				
		TYPICAL T62 PROPERTIES		40	58	10				
9	2219-with 2319 filler	LONGIT. CYLINDER WELD	1	SEE 9 ABOVE			39.7	50.2	3	WELD
			2				39.5	57.8	5	WELD
			3				38.3	54.6	4	WELD
		AVERAGE					39.2	54.2	4	WELD
17	2219 with 2319 filler	LONGIT. CYLINDER WELD	1	SEE 17 ABOVE			37.8	58.4	11	PM
			2				37.1	56.2	6	WELD
			3				37.1	47.2	3	WELD AT ROOT DEFECT
		AVERAGE					37.3	53.9	6.7	



[illegible] Metallurgical Micro[illegible]
[illegible] Screen for Group [illegible]



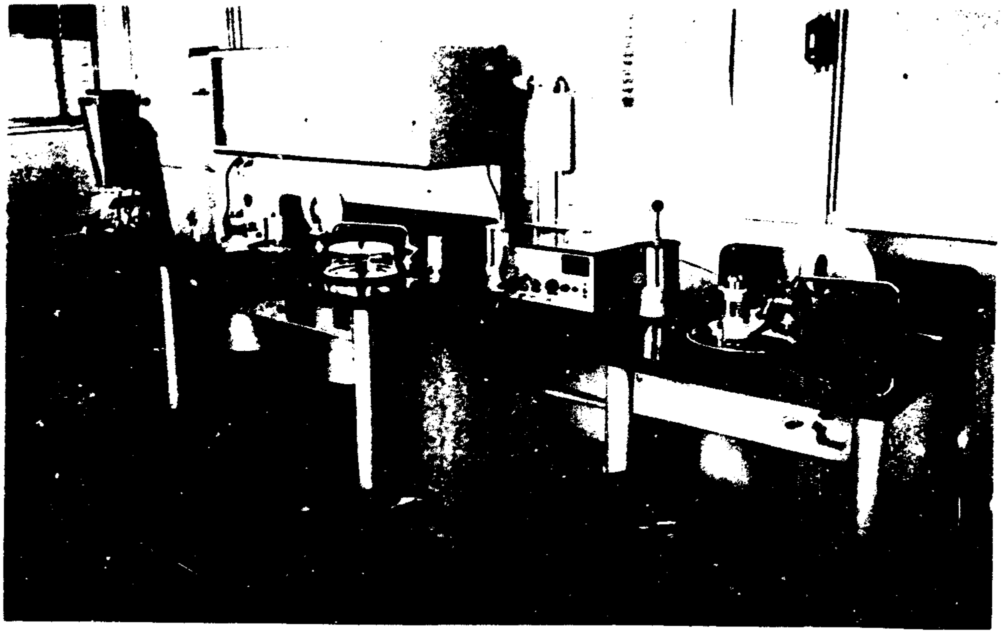


Figure 3. View of Automatic Polishing Equipment in Metallurgical Laboratory

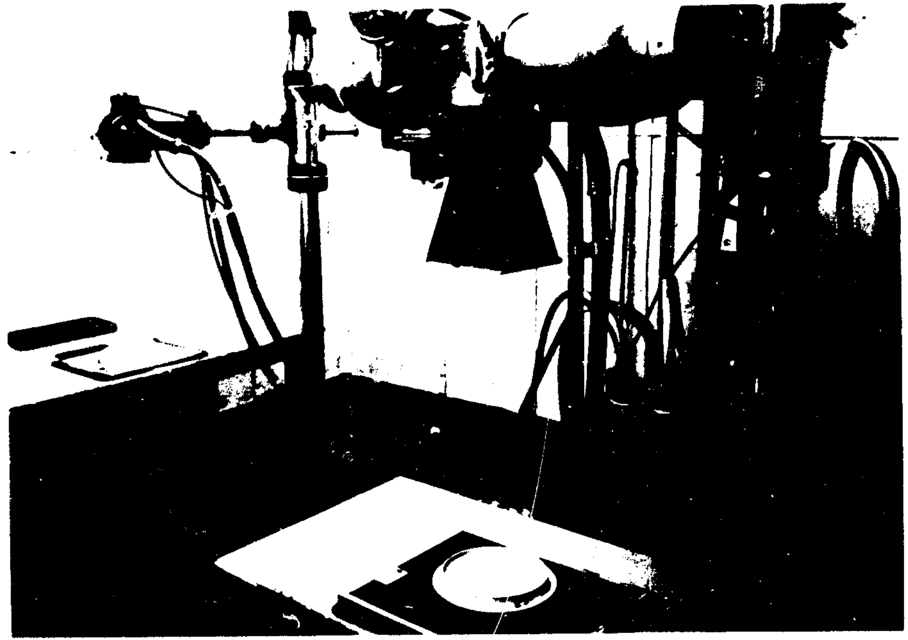


Figure 4. Radiographic Inspection Area in Metallurgical Laboratory

[illegible]

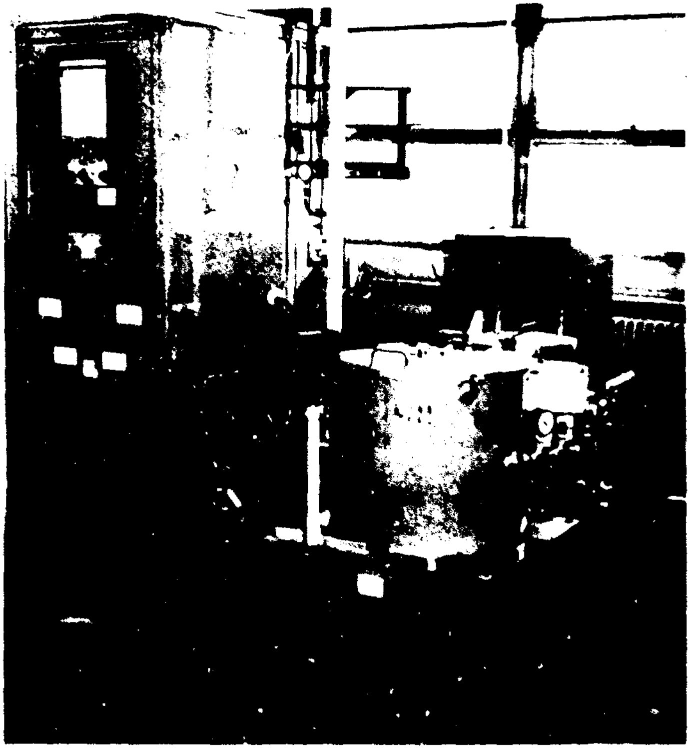
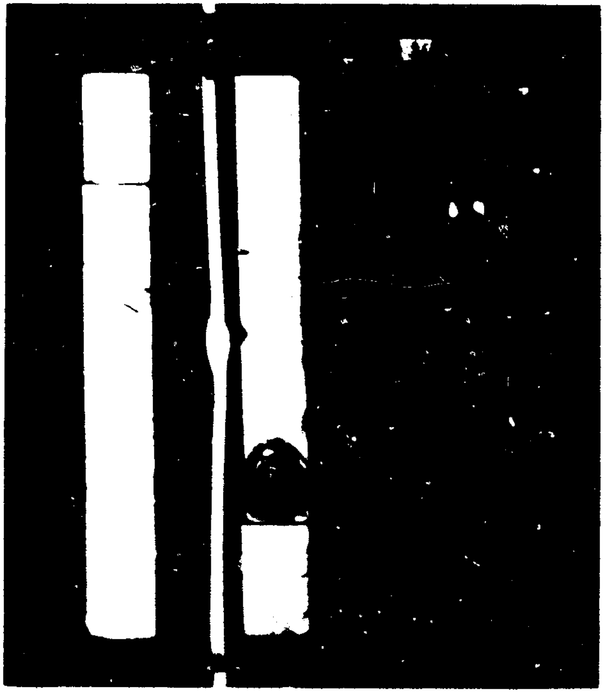


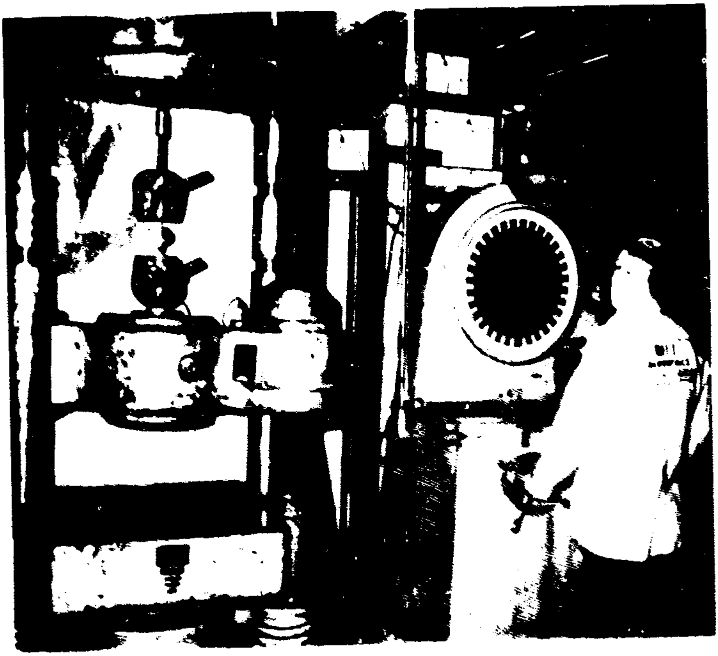
Figure [illegible] High Temperature [illegible] Furnace with [illegible]

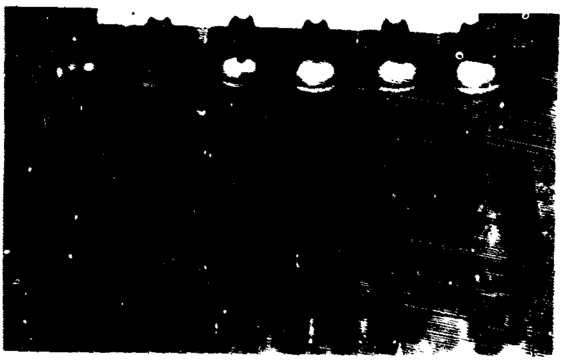


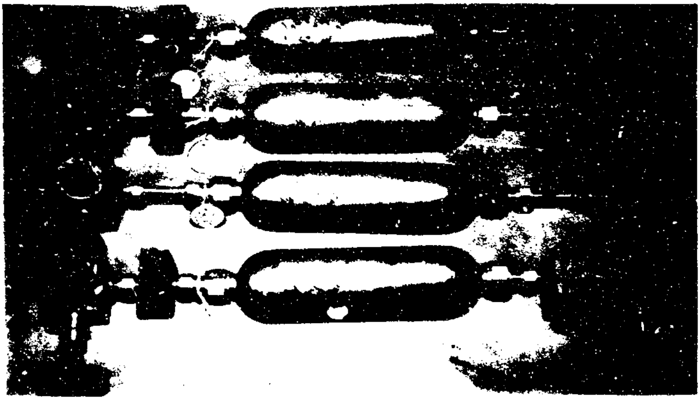
[illegible] for testing with extensometer

[illegible] before

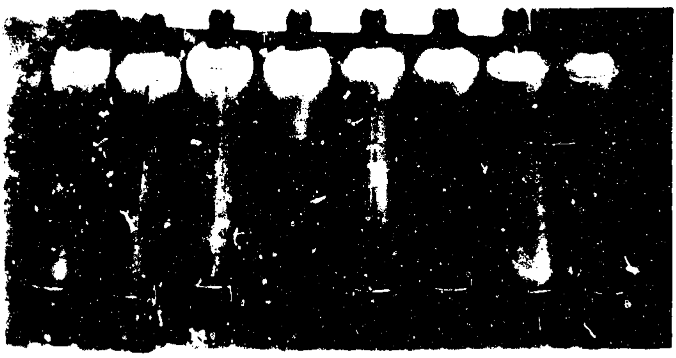
[illegible]







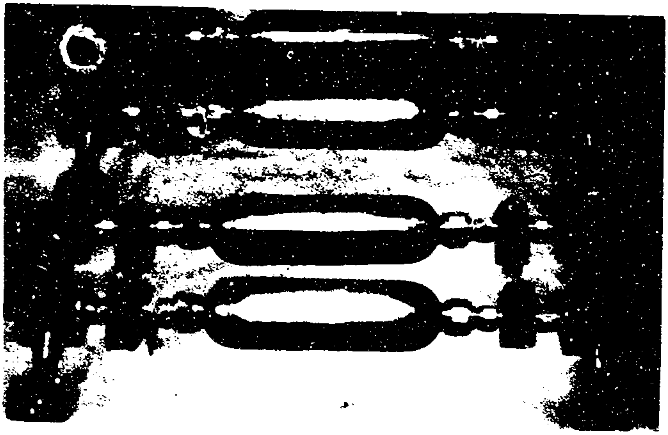
[illegible]

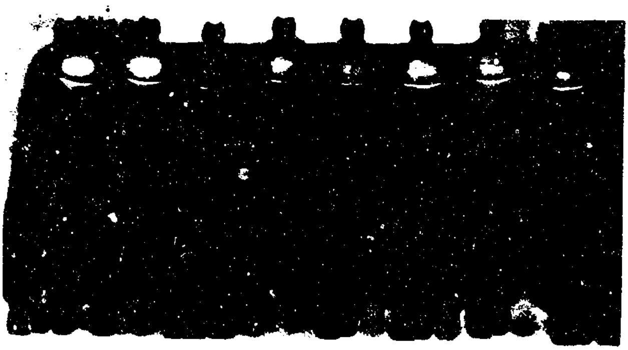


[illegible]

[illegible]

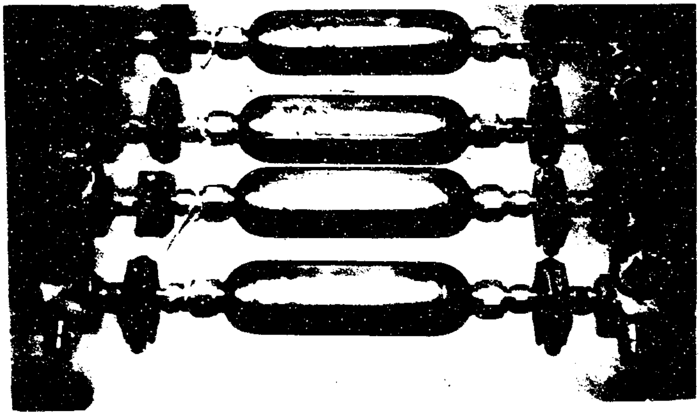
[illegible] urface appearance [illegible]
[illegible]





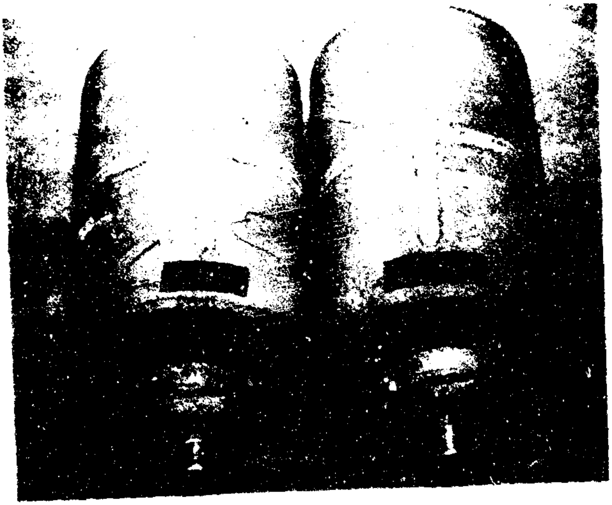
... was observed in the ...
... compared to Figure ...

... Appearance of Arde 3 1 ...
... for Five Years



[illegible] of a "water line" [illegible] tain
[illegible]

[illegible]



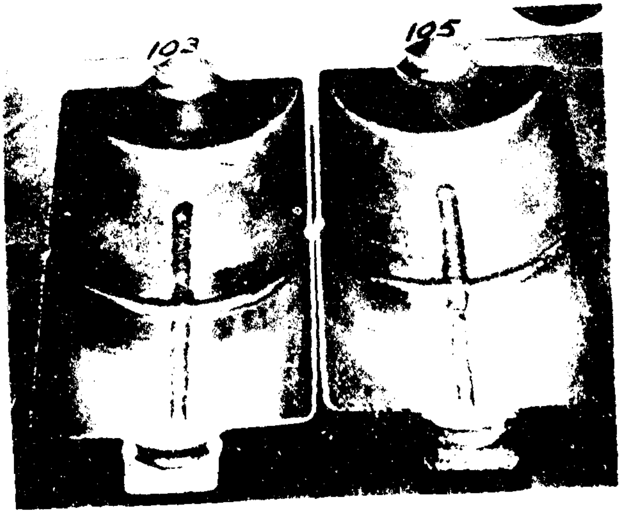
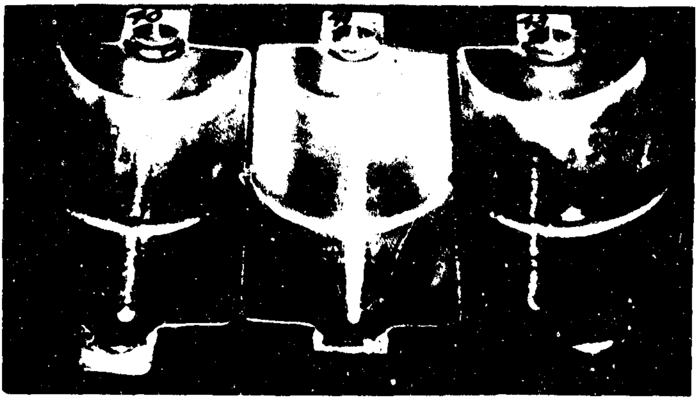


Figure 1[illegible]

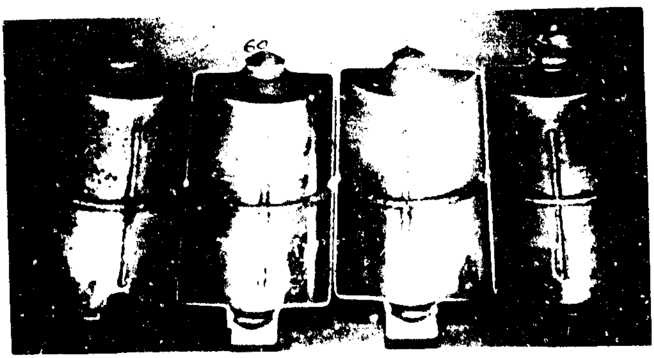
Exterior View

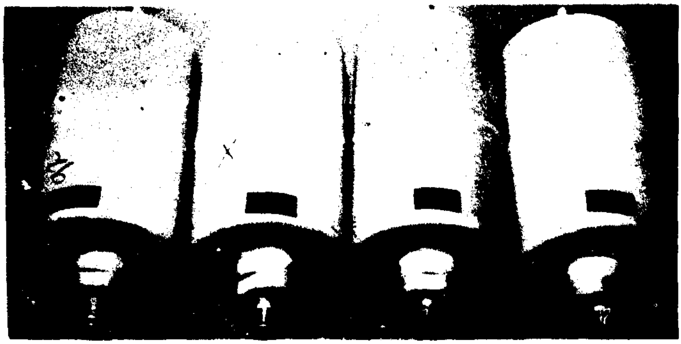
NOTE: Exterior view of S/N 41 is shown in Figure [illegible]



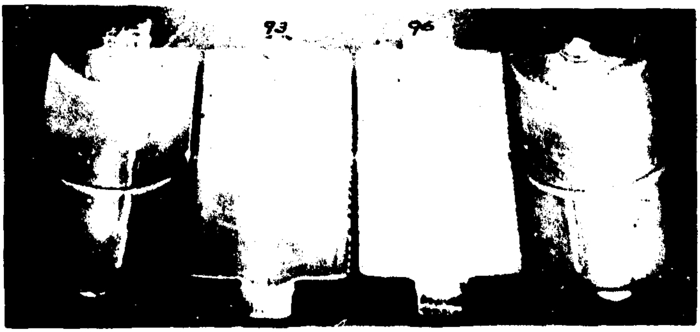
Interior View

Figure [illegible]. Surface Appearance of Alumi[illegible] One Quart Tanks Loaded with [illegible] and One Half Years



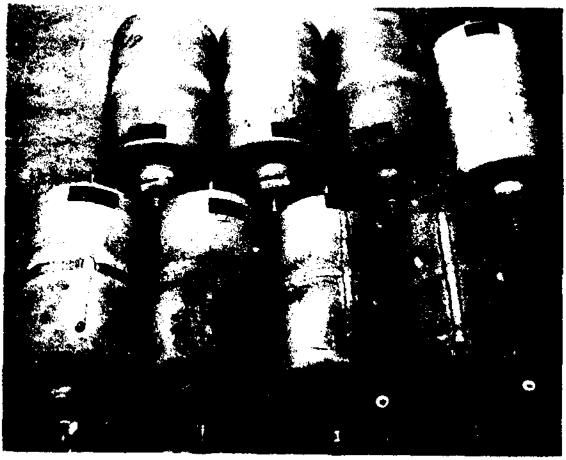


[illegible]



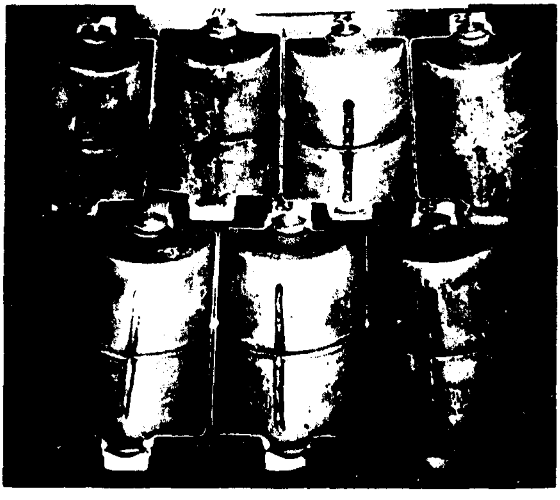
[illegible]

[illegible]
WITH [illegible]



Exterior View

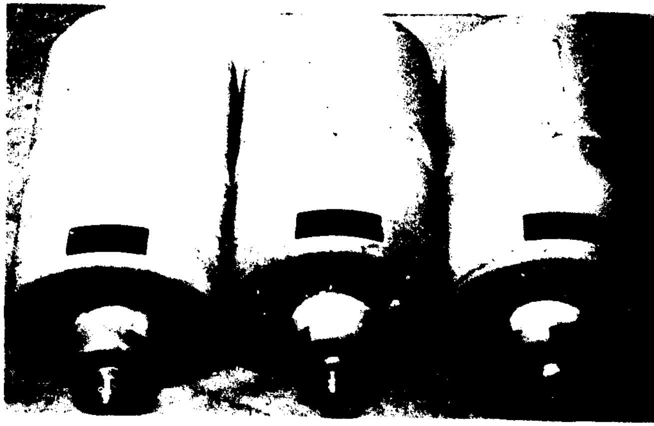
NOTE: Tank S/N 41 incorrectly [illegible] material, see Figure [illegible]



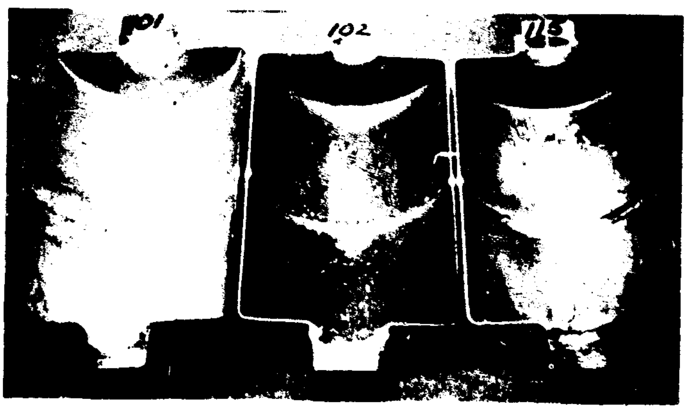
Pitted interior of -10 and to a lesser extent -24 were subjected to detailed and confirmatory analysis

[illegible] View

Figure 1[illegible]. Surface Appearance of [illegible] Tanks Loaded with [illegible] for Three [illegible]



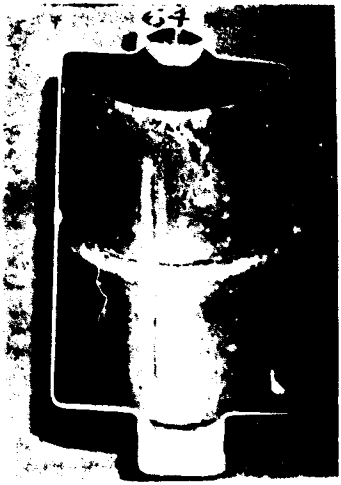
Exterior View



Interior [illegible]

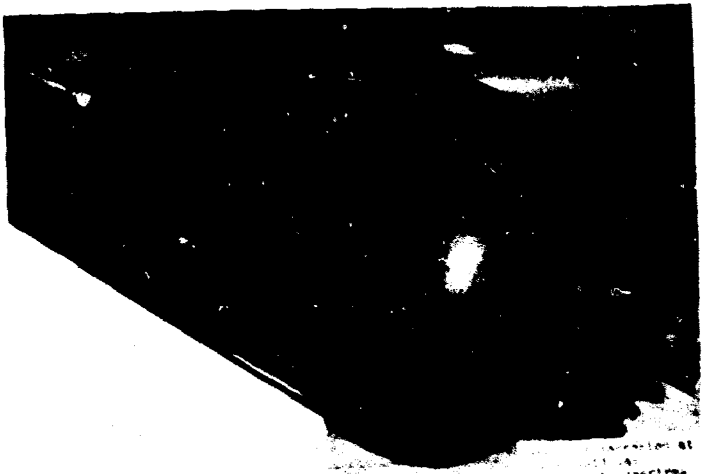
Figure [illegible] . [illegible] Appearance of Aluminum [illegible]

[illegible]xterior [illegible]

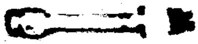


[illegible]terior [illegible]

Figure [illegible]. Surface Appearance [illegible]
Alloy [illegible]
for Four and One Half [illegible]

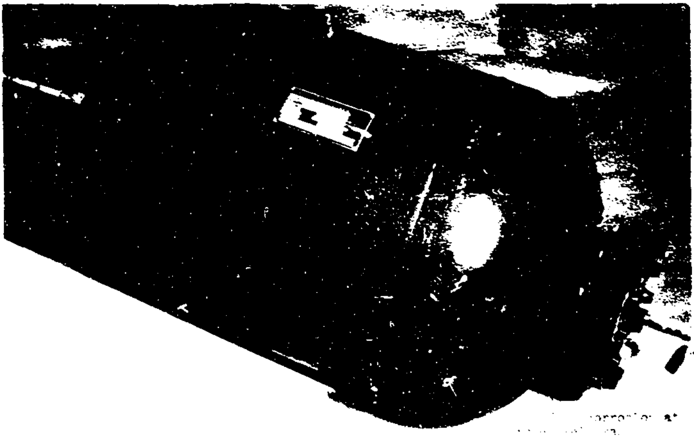


[illegible] at [illegible] spectro- [illegible] analysis.

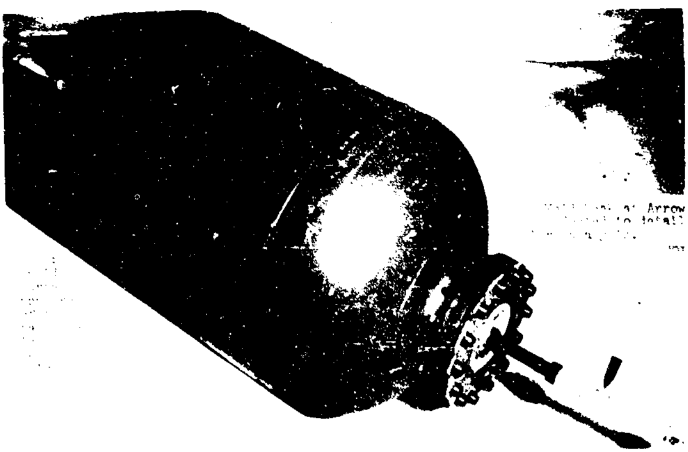


This [illegible] [illegible] 4, 4 and 5 (Figure [illegible]

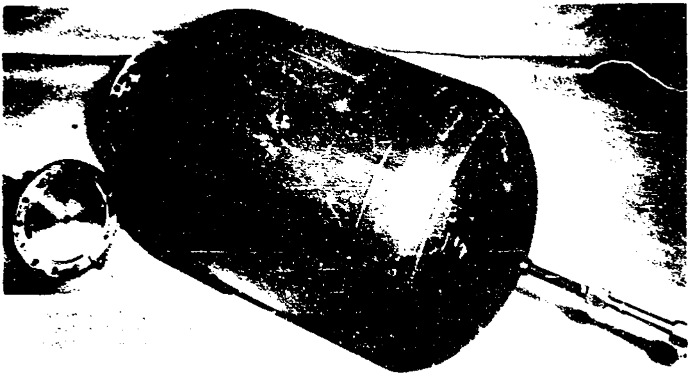
Figure [illegible] Surface Appear[illegible] [illegible] Period of Five Months [illegible]



[illegible] analysis.



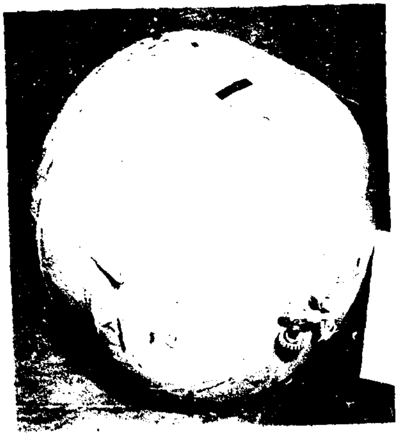
[illegible] Arrow [illegible] total [illegible]

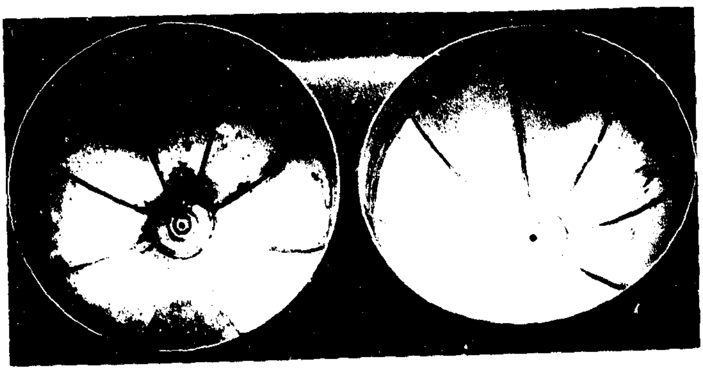


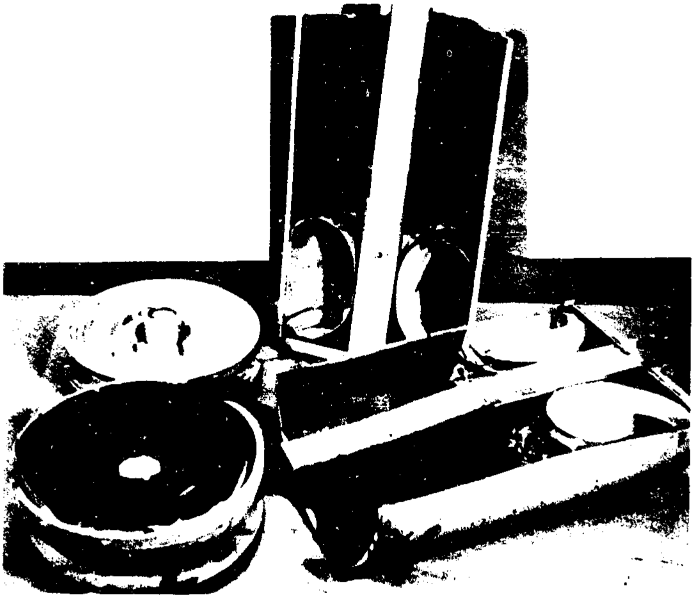
External View

Internal view is essentially identical to S/N N-11 shown in Figure 43

Figure [illegible]. Surface Appearance of Aluminum 6061-T6 Tank (General Dynamics-Convair) Loaded with N_2O_4 for Five and One Half Years



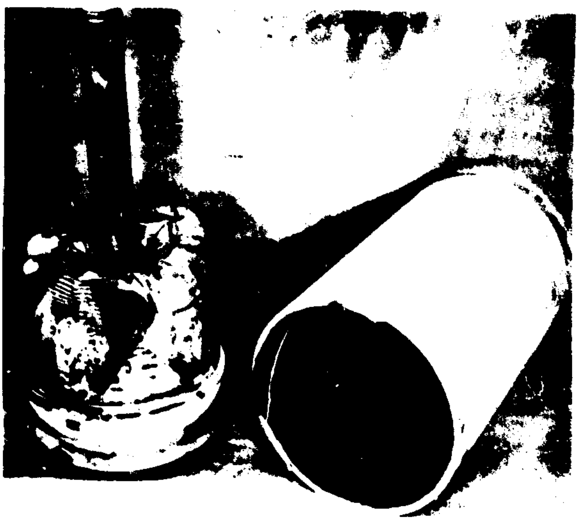


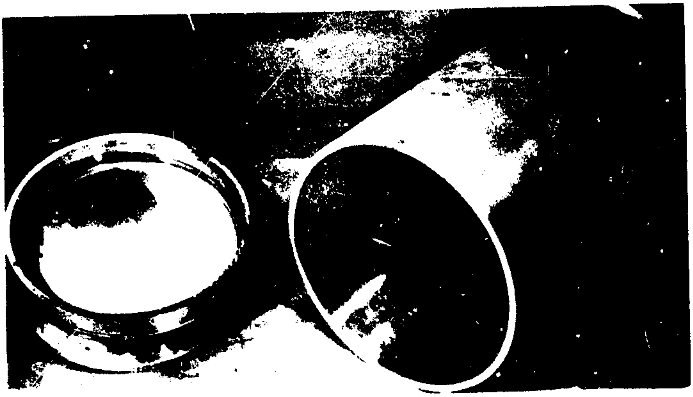


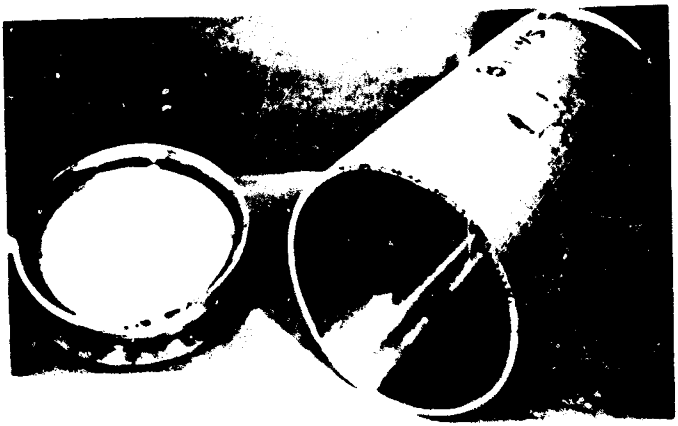
NOTE: This system was shipped empty by manufacturer, General Dynamics, and was filled with N_2O_4 propellant at [illegible]. It was stored for four and one third years before expulsion. Exterior surface is stained or lightly corroded.

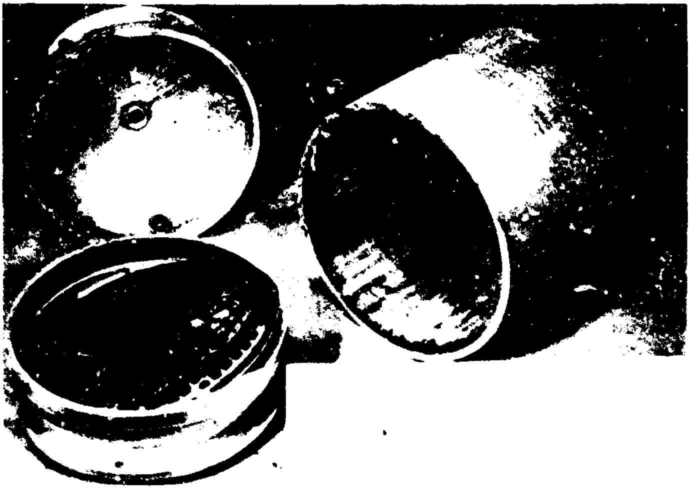
Figure 29. View after Preliminary Sectioning of Prepackaged System S/N 009 Showing External Surface, Internal Surface and Expulsion Condition

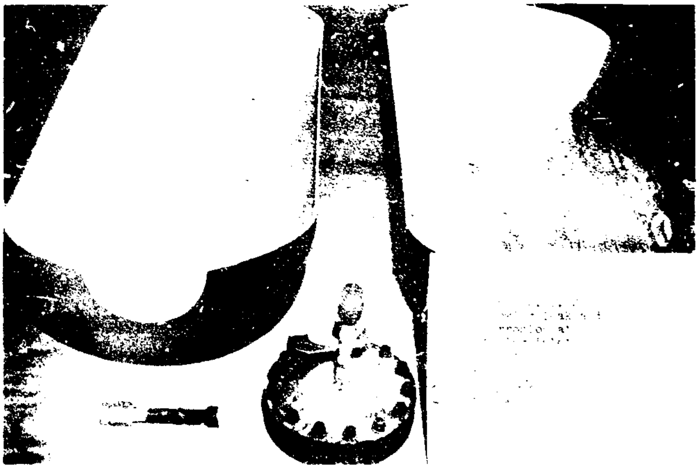
Rolling diaphragm travelled only one half desired distance and [illegible]

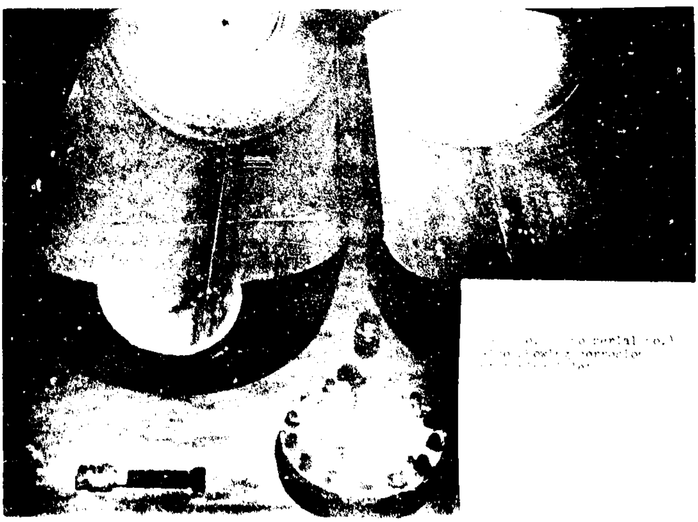


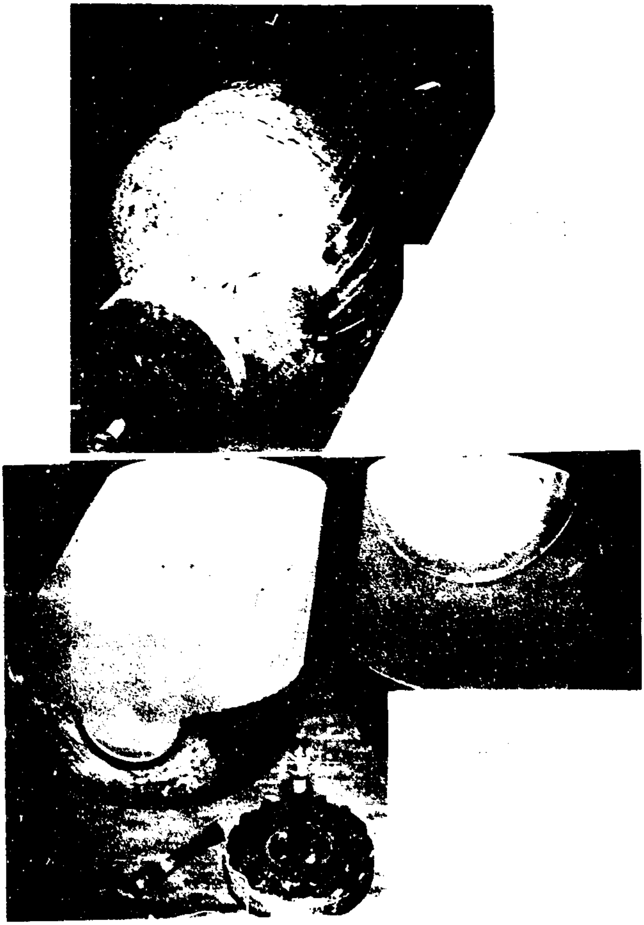


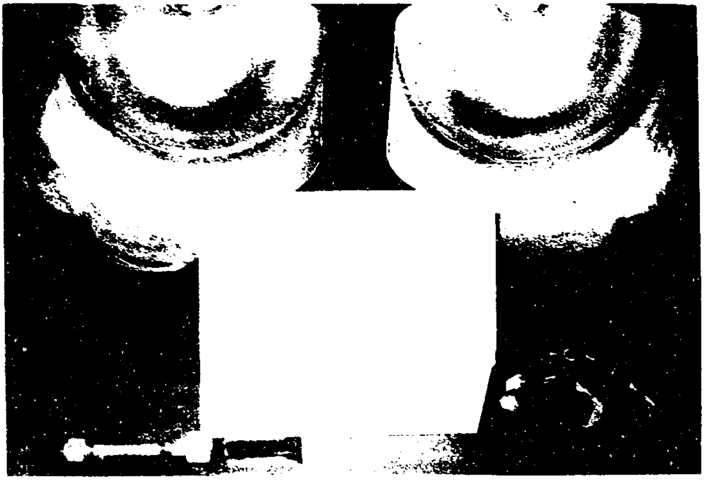




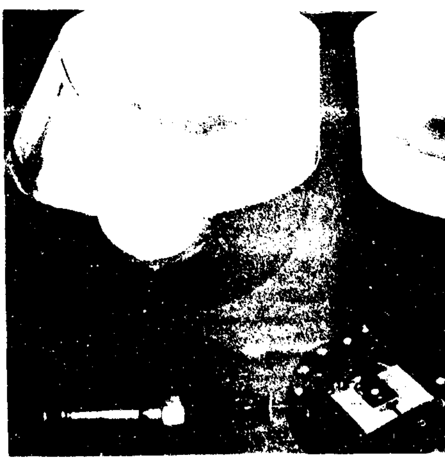






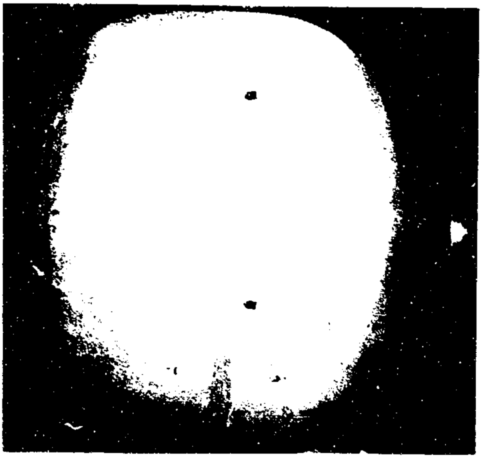


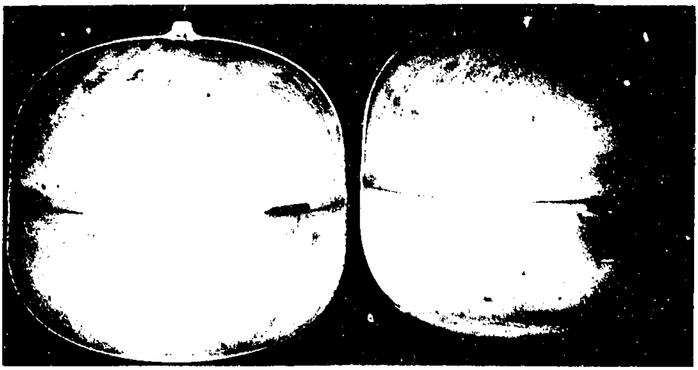
[illegible]

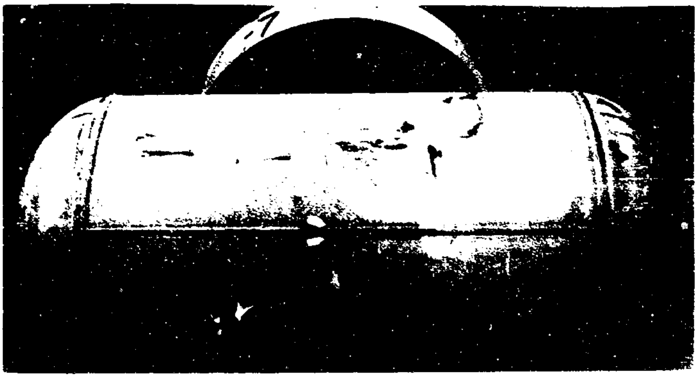


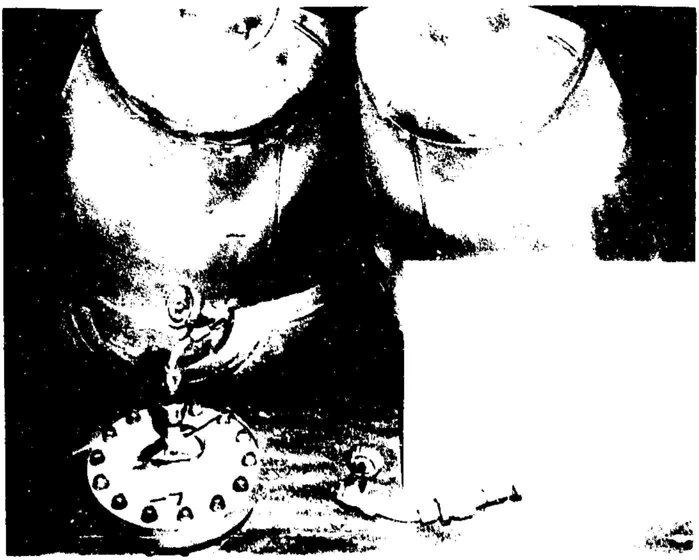
[illegible] Corro[illegible] to the [illegible] weld [illegible] failure analysis [illegible] was broken mechanically at upper weld - [illegible]

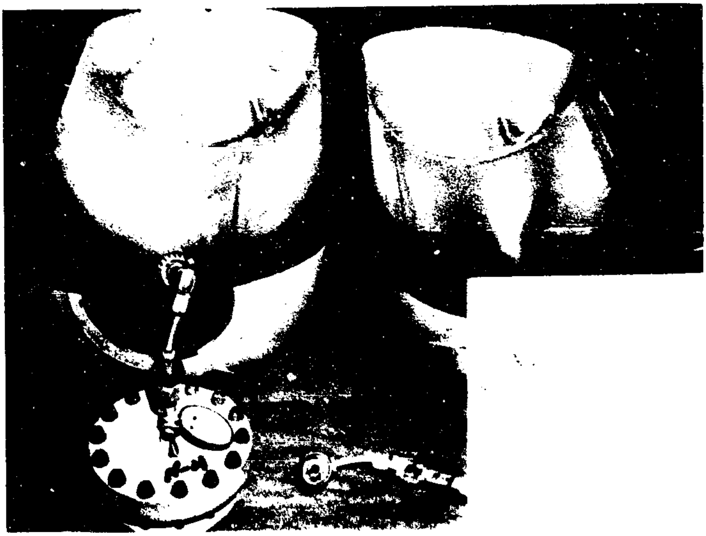
Figure [illegible] Mart[illegible] [illegible] for Four [illegible]





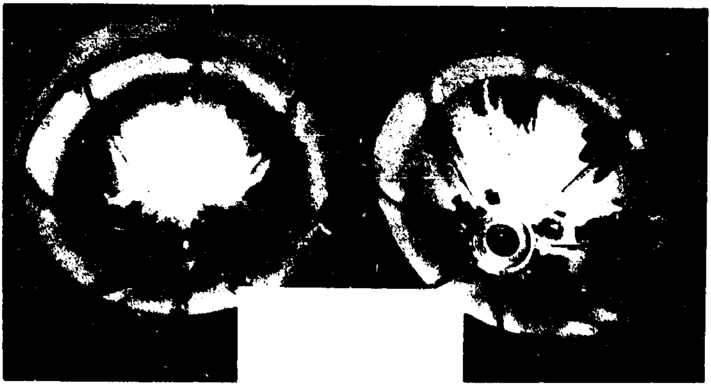






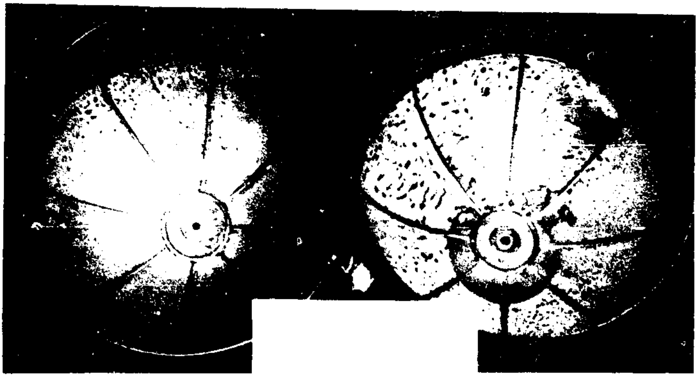
Note the line of demarcation at approximately mid-height indicating tank was only 1/2 full. Interior was bright and shiny both above and below line.

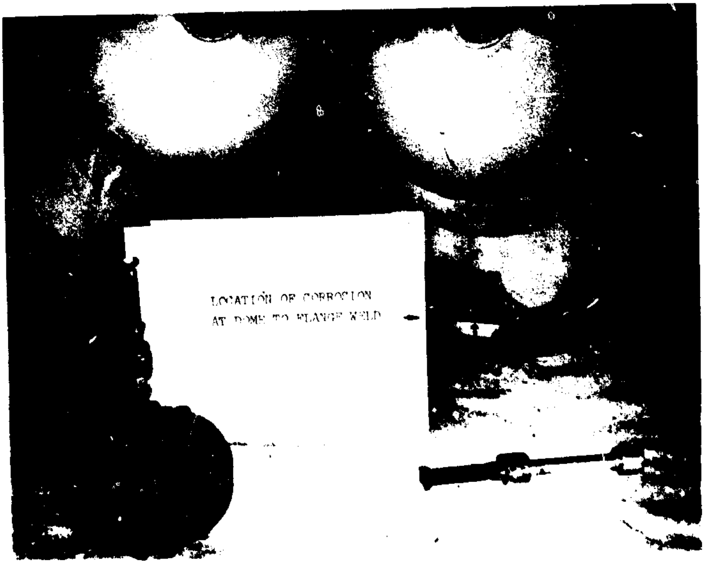
Figure 51. [illegible] Aluminum 7039-T6 Tank No. [illegible] Martin [illegible] loaded with N_2O_4 [illegible]



Interior view showing bright, unattacked condition. Exterior of this tank is essentially identical to S/N N-1 shown in Figure [illegible].

Figure [illegible]. Surface Appearance of Aluminum (2014-T6) Tank No. (General Dynamics-Convair, S/N N-11) Loaded with N_2O_4 for Five and Three Quarter Years





Local area of corrosion at arrow is considered in
Detail Failure Analysis Section

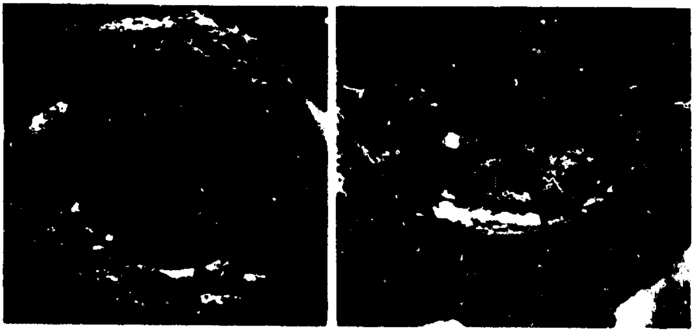
Figure [illegible]. Surface Appearance of A-286 Stainless Steel Tank
(No. 12, Martin S/N 003) Loaded with ClF_5
For over One Year

leak area

MAG: 32X
Unetched

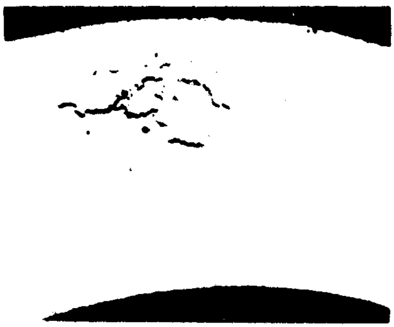
MAG: 100X
Unetched

Figure 46. Cross Section of Manifold Tubing Weld Leak Shown in Figure 45 Martin 10-gallon Tank S/N 005. Note Inter-dentriti Corrosion Path



MAG: 5X [illegible]

a. Fractured end of tube showing corrosion pro[illegible] at arrow. Mechanical fracture caused separation after [illegible]



[illegible] Alloy: [illegible]

[illegible] Alloy: [illegible]

MAG: [illegible]

b. [illegible] attack

[illegible]

a. Exterior ... corrosion product
... ...

Weld Filler Alloy:
4043 Al

Tube Alloy:
6061 Al

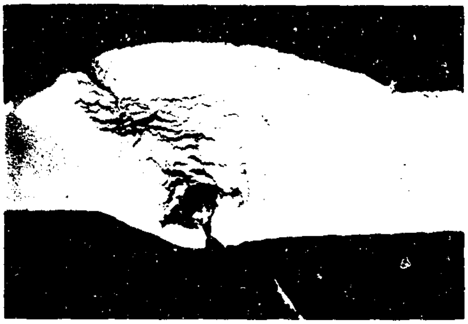
... Weld of Martin
... for 3 Month

Weld Filler Alloy: 4043 Al

Tube Alloy: [illegible] Al

[illegible]

[illegible] Perforation of Inlet [illegible] Martin 15- [illegible] sed to Store [illegible]



O. D.
surface

MAG: 12X

I. D.
surface

O. D.
surface

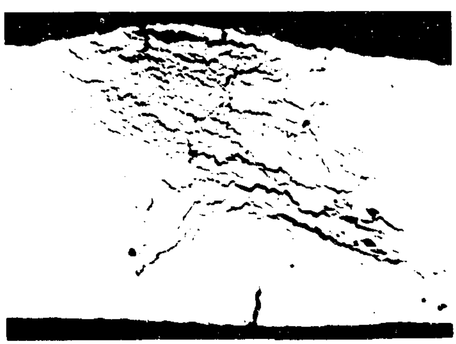
MAG: 20X

I. D.
surface

Figure 50. Cross Section of Tube Weld Adjacent to Perforated Area Shown in Figure 49. Probable Initial Vapor Leakage Path is Discernible Between External and Internal Openings

External surface　　　　Internal surface

MAG: 8X



Weld Filler Alloy: 4043 Al

Tube Alloy: 6061 Al

MAG: 25X

Figure 51. Tube Weld Leak in Bottom Outlet Tube from Martin 10-gallon Tank No. 4 (S/N 003) used to Store ClF_5 Propellant. Note Small Crack on Internal Surface and Similarity to Figure 4[illegible] and Figure 50

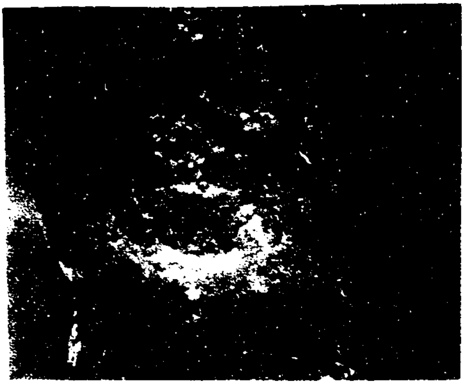


Figure [illegible] Views of Corrosion and [illegible] in the Inlet Tube of a [illegible] Alloy Tank No. 1 (S/N9) [illegible] Company. Tube Alloy [illegible] with 4043 Filler Alloy

Figure 53. Cross Sections of Corrosion Leak Occurring at Edge-of-Weld in the 6061 Aluminum Inlet Tube of 2024 Aluminum Alloy Tank No. 1 (S/N9) used to Store ClF_5 Propellant for Eight Months

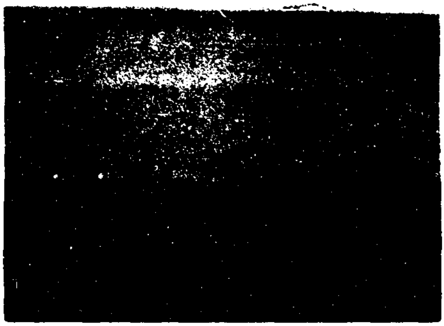


Figure 54. Localized Corrosion Observed on Internal Parent Metal Surface of 6061 Inlet Tube from Tank No. 1 (S/N9) Exposed to ClF_5 Propellant for Eight Months Observed Corrosion is Believed to be Secondary Effect of Corrosion Leak Shown in Figure 52

MAG: 200X
ETCHANT: Keller's Reagent

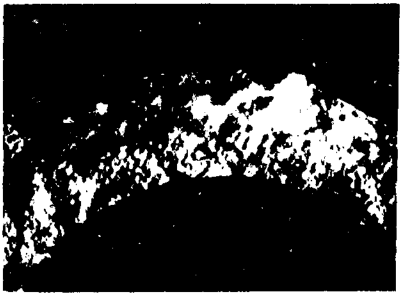
Figure 55. Porosity and Shrinkage Observed in Heavy Weld Drop-thru of Tank No. 1 Inlet Tube. Weld Metal Alloy is 4043 Aluminum

MAG: 50X
UNETCHED

MAG: [illegible]

MAG: 5X

a. [illegible] of fracture face



Weld Filler Alloy: 4043 Al

Tube Alloy: 6061 Al

b. Closeup showing corrosion [illegible] penetrating from [illegible]

Figure [illegible] [illegible] Tube to RPL [illegible] [illegible]-gallon Tank [illegible] for [illegible]

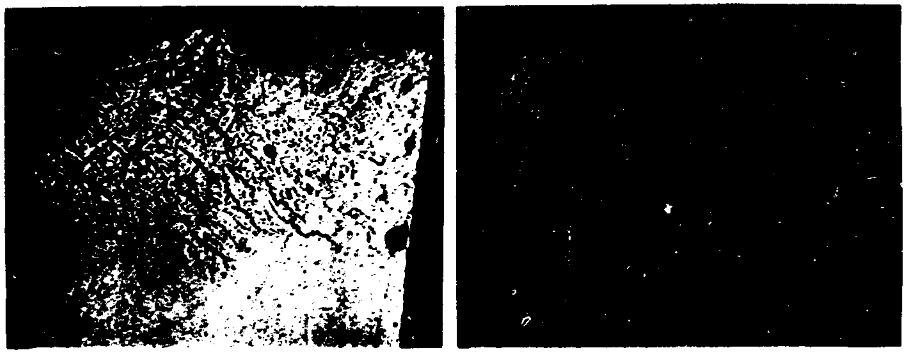
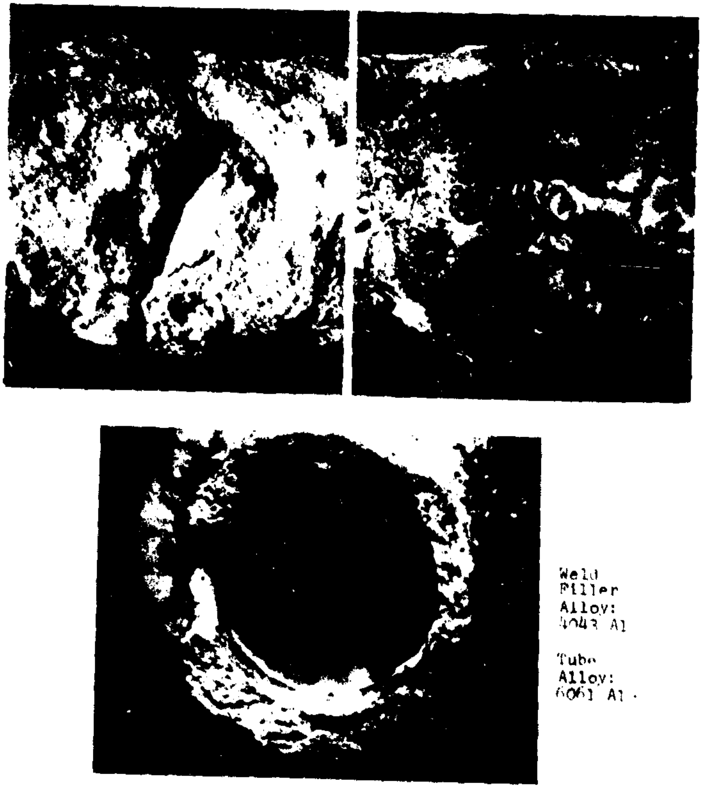


Figure 57. Cross Section of Failed Tube Weld, Shown in Figure 56, Displaying Opposite Sides of Tube. Note Porosity and Shrinkage Crack Network Within Weld Deposit

MAG: 50X
ETCHANT: Keller's



Weld
Filler
Alloy:
4043 Al

Tube
Alloy:
6061 Al

[illegible] Transition Tube [illegible] Weld from Martin 10-gallon [illegible], after Storage of $[illegible]F_6$ [illegible] Four Months

Figure 5[illegible]. [illegible] Corroded and Failed Tube [illegible] from Martin [illegible] 304, Exposed [illegible]

MAG: 4X

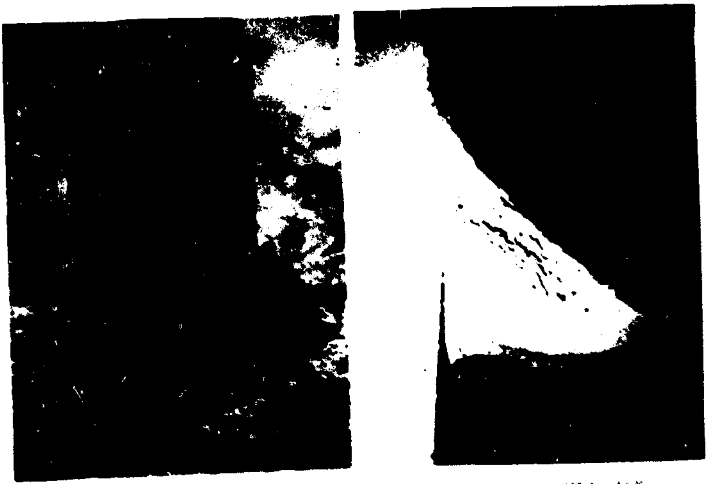
a. [illegible] view showing corrosion

MAG: [illegible]

b. Cross section showing weld corrosion

Tube Alloy: 6061
Weld Filler: 4043

Figure [illegible]. Corrosion [illegible] Flange to Tube Weld of [illegible] Tank [illegible] after Four Months [illegible]



MAG: 4X   MAG: 1[illegible]X

a. Overall view showing corrosion   b. Cross section showing weld corrosion

Tube Alloy: [illegible]
Weld Filler: [illegible]

Figure [illegible]. Corrosion Observed in Flange to Tube Weld of Martin 1[illegible]-gallon Tank No. [illegible] after Six Months Exposure to ClF_5

MAG: 6X

MAG: 60X

NOTE: [illegible] Emanating from [illegible]

Figure 62. Corrosion of Bottom Outlet Tube Weld on Martin 10-gallon Cylindrical Tank No. 5 (S/N 2011) [illegible] AlAlloy. Shell and 6061 AlAlloy Tubing Exposed to ClF_5 Propellant for Six Months

MAG: 4X

a. View of pitted surface near bottom pole of tank

MAG: 100X

b. Cross section [illegible] of pit showing corrosion penetration of grain boundaries

MATERIAL: [illegible] Alclad

Figure 63. Pitting on Inner Surface of Solid State Bonded Tank

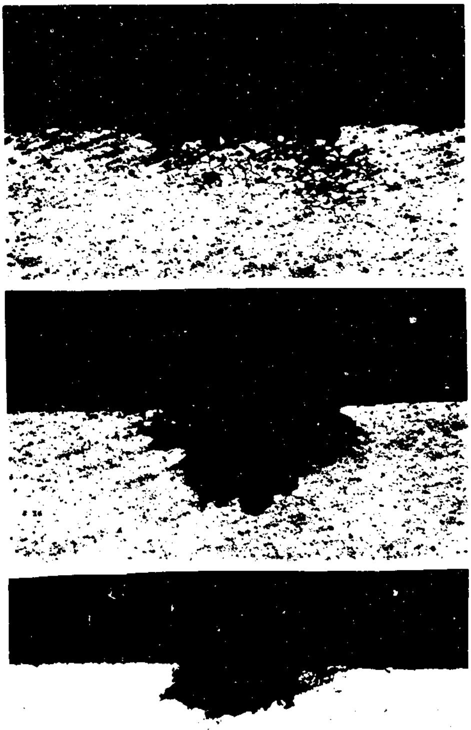
[illegible]rea near
large
[illegible]oss weld
at edge
of
[illegible]egm[illegible]
[illegible]eld

[illegible]

[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]ained
area

[illegible]

[illegible]pient
[illegible]urface
[illegible]
[illegible] storage



Early stage of pit formation in parent metal

Well defined pit in parent metal

Well defined pit in weld metal

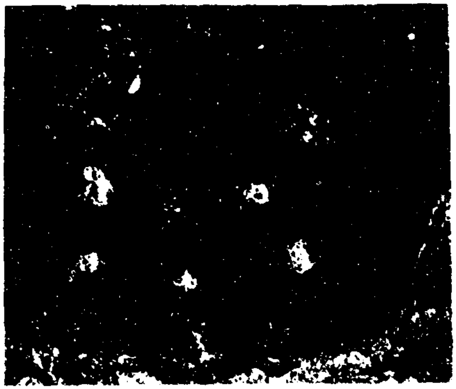
MAG: 100X
ETCHANT: Keller's

Figure [illegible]. Cross Section Views of Pitting Attack Observed on Interior Surface of [illegible]-gallon Capacity [illegible] Alloy Tank [illegible]-10 used for Six Year Storage of N_2O_4 Propellant. Note Intergranular Nature of Pitting Attack

MAG: 6X

Note the corrosion product

Figure 66. Pit Formation Observed on Interior Surface of 3-inch x 6-inch 2014-T6 Aluminum Alloy Tank No. 1, used for N_2O_4 Propellant Storage

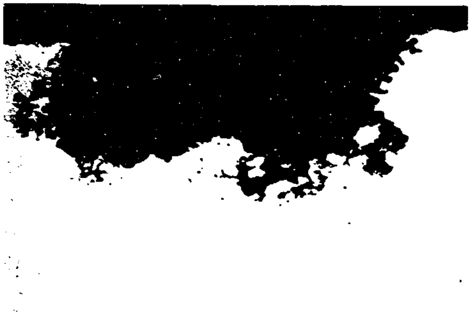


MAG: [illegible]X

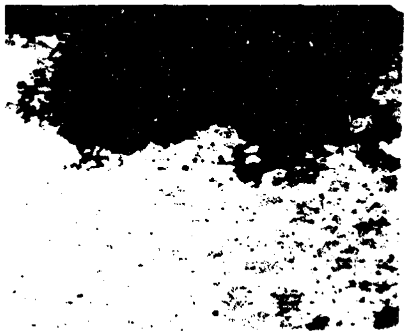
Figure 67. Pitting Observed on Internal Surface of 2014-T6 Aluminum Alloy 1-quart Container S/N 19 used for Storage of ClF_5 Propellant for 42 Months

MAG: [illegible]X
UNETCHED

Figure 68. Cross Section of Typical Shallow Pit Seen on Internal Surface of 1-quart Aluminum Alloy Container S/N 19



MAG: 100X
UNETCHED

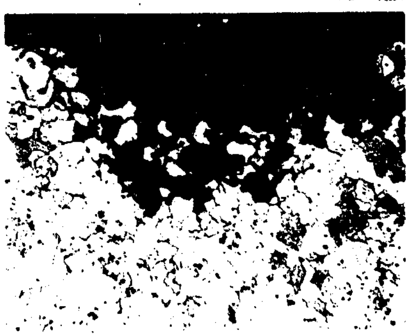


MAG: 100X
ETCHANT: Keller's
Reagent

Figure 69. Cross Section of Deepest Pit Observed on Internal Surface of 2014-T6 Aluminum Alloy Container S/N 19, in Contact with ClF_5 Propellant for 42 Months

Figure ... Surface ... Container ... Propellant for ...

Intergranular pitting attack - Unetched



Same as above - Etched with Keller's Reagent

Early stage of pit formation - Unetched

MAG: 200X

Figure 71. Cross Section of Pit Formation Observed on Internal Surface of 2014-T6 Aluminum Alloy Container [illegible], Exposed to ClF_5 Propellant. Note Early Stage of Pit Formation Shown in Bottom View

MAG: 8X

a. Weld underbead cracks near weld cross over. Note absence of any corrosion products

Keller's Etch MAG: [illegible] [illegible] MAG: 100X

b. Cross section views through weld cracks interdendritic cracks are characteristic of shrinkage cracks

Figure 72. Transverse Cracks Observed in Root of Longitudinal Weld on 2014-T6 Aluminum One Quart Container S/N 24

Exterior surface showing perforation (with light shining through) at deeply eroded edge of weld.

[illegible]

Edge of Weld

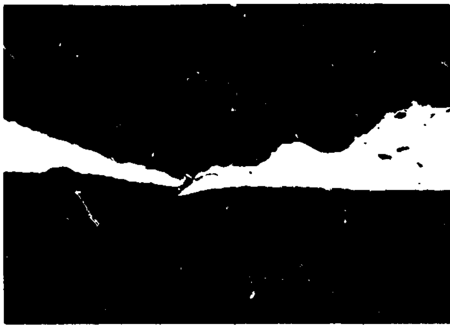
Edge of Weld

[illegible]terior view [illegible] perforation at edge of weld with [illegible] of [illegible]ble.

[illegible]

[illegible] perforation [illegible] visible, [illegible]

[illegible] 1914 Al



External surface

MAG: 32X
UNETCHED

External surface

MAG: 50X
ETCHANT: Keller's

[illegible] S/N 61 [illegible]

External surface

NOTE:
Origin of attack is on external surface and is concentrated in weld metal near edge of weld. Crack at arrow is shown in Figure 76.

[illegible] Keller's

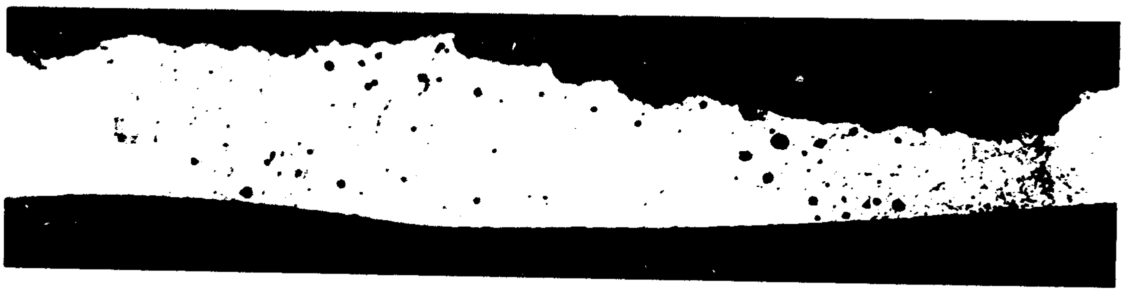
Figure [illegible]. [illegible] of [illegible]orroded and Perforated Weld [illegible] at [illegible]ther Edge of Weld from [illegible]

Figure [illegible]. [illegible]ternal Surface at Edge of [illegible] Attachment Weld - [illegible] Alloy Tank No. 3 [illegible] Cross Section

MAG: [illegible]

Note pro[illegible] size of weld and heat affected zone attack

Figure [illegible]. [illegible] Corroded Zone at Flange [illegible] of Martin 2014 Aluminum [illegible]. This Area is Approximately [illegible] Circumferential Inches from [illegible] in Figure 73 [illegible] Surface

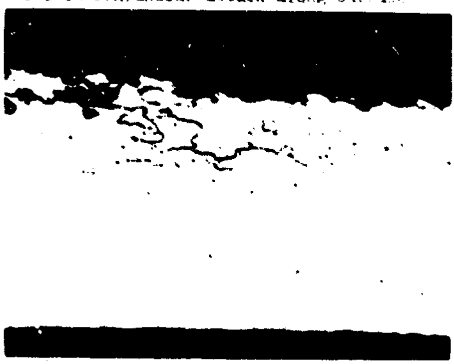


MAG: 3[illegible]X
[illegible]: Keller's

Figure [illegible] [illegible] of Flange Assembly Attachment Weld [illegible] Section at Edge of Weld. Corroded Area Shown in Figure [illegible]. Mart[illegible] Aluminum Alloy Tank No. 3 [illegible]

MAG: [illegible]
ETCHANT: Keller's

Note intergranular attack along surface



MAG: [illegible]
[illegible]

Note pit formation and material [illegible] due to intergranular attack

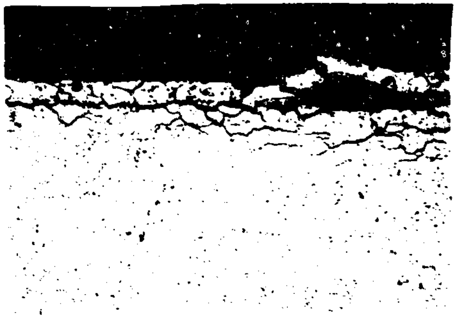
Figure [illegible] [illegible] Surface of [illegible] Alloy Shell Material [illegible] Slightly Corroded Area Outboard of Corrosion in Figure [illegible], [illegible] Tank No. 3 [illegible] Intergranular Attack and the Start of [illegible]

[illegible] Al [illegible] - [illegible]

Martin [illegible] Al Exposed to [illegible] - Six Years

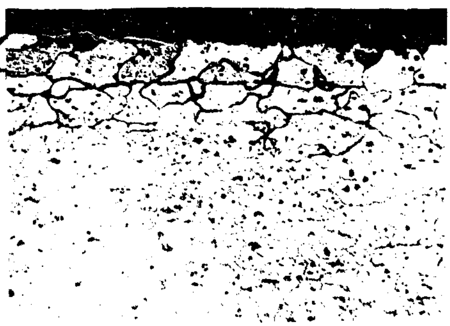
Martin 15-gallon Cylinder 2014 Al Exposed to N_2O_4 - Six Years

[illegible] Exposed to N_2O_4 [illegible] Corrosion at Edge of Weld in HAZ



MAG: 100X

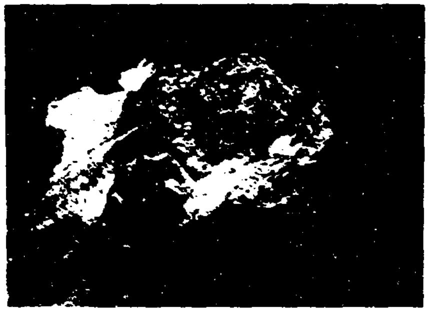
a. Unetched view showing corrosion attack under Alclad layer causing lifting and loss of cladding in spots



MAG: 200X
ETCHANT: Keller's

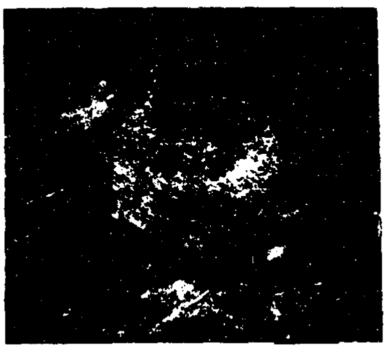
b. Etched view showing the grain boundary $CuAl_2$ network corroded, particularly just below Alclad layer

Figure 81. Metallographic Sections Showing the Corrosion on the External Surface of the Solid State Bonded Tank



MAG: 4X

a. Deposit is rust colored and lies over flange attachment weld



MAG: 6X

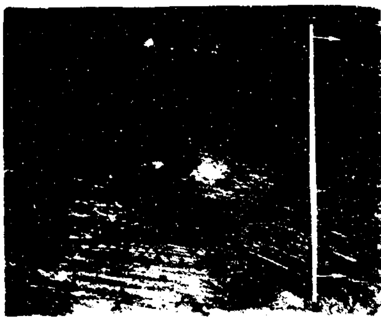
b. Additional view of corroded area

MAG: 6X

c. Corrosion product r[redacted] showing perforation [redacted] weld

Figure 82. Area of Corrosion Attack on External Surface of [redacted] 10-gallon A-286 Stainless Steel Tank No. 12 (S/N [redacted] Loaded with ClF_5 for over One Year

a. Overall view of inside surface showing [illegible]



MAG: [illegible]X

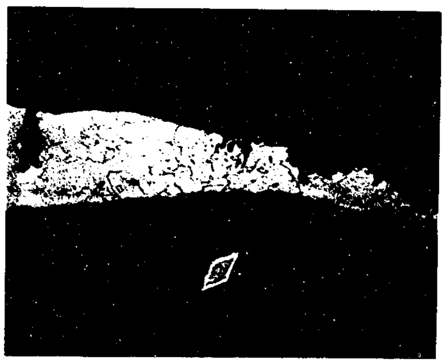
b. Close up view of perforation and weld grinding

MAG: [illegible]X

c. Cross section thru weld at location shown in view b.

Figure [illegible]. Internal Surface and Cross Section Illustrating Perforation in an Area of Rework of A-[illegible] Tank Under Corrosion Shown in Figure [illegible]

MAG: 100X



MAG: 200X

Figure 84. Cross Section of a Perforation Shown in Figure 83. Note Location of Perforation Immediately at Toe of Weld, in HAZ of the A-[illegible] Alloy. [illegible] Propagation is Transgranular

ETCHANT: Mixed Acids

S/N 010
Aged,
loaded
with
N_2O_4

MAG: 32X

S/N 023
Unaged,
loaded
with
ClF_5

MAG: 25X

ETCHANT:
Mixed Acids

[illegible] Arde, Inc., Cryoformed
[illegible]ricated of AISI 301

S/N 010
Aged,
loaded
with
N_2O_4

MAG: 100X

S/N 003
Unaged,
loaded
with
[illegible]

MAG: 100X

ETCHANT:
Mixed Acids

[illegible]

MAG: 10X

NOTE: Uniform continuous nature of surface, reproducing tank shell surface and showing lathe turning pattern of shell

Figure 87. Surface of High-stretch RTV 634 Silicone Rubber Liner Material Removed from RD Liquid Rocket Tankage.

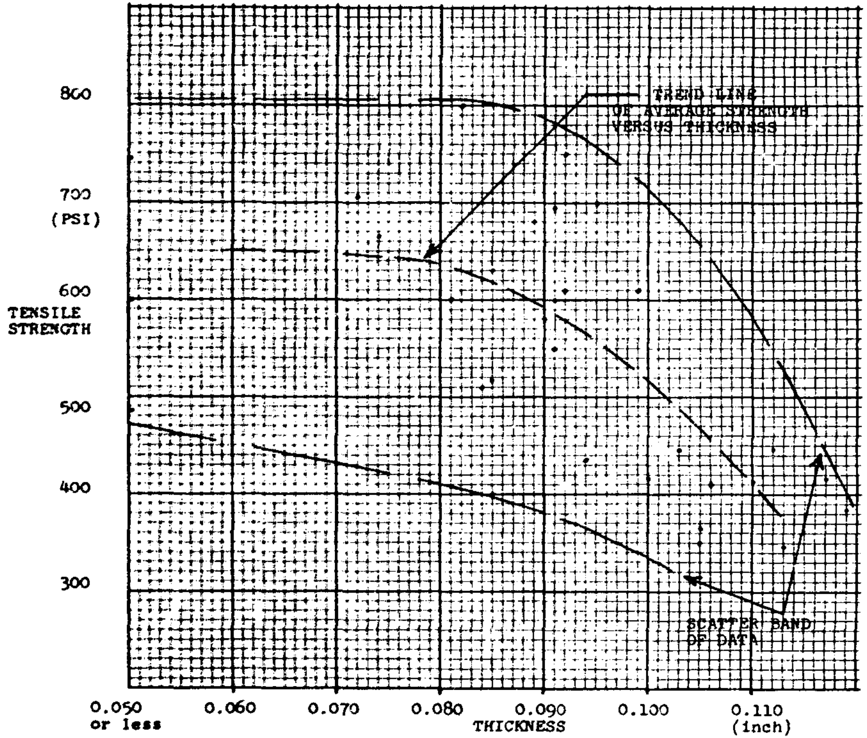
MAG: 4X

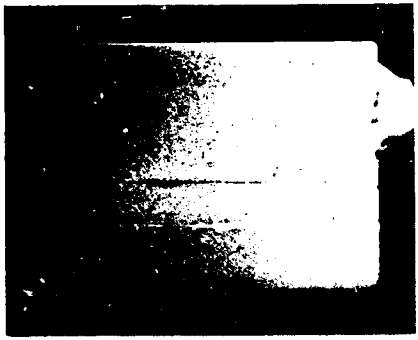
MAG: [illegible]

Figure 38. [illegible] Silicone Rubber Liner [illegible] from Same RD Liquid Rocket [illegible] Figure [illegible]. Note Mottled, Dis[illegible] of Surface and Point of Failure [illegible] Arrow

Figure 89.

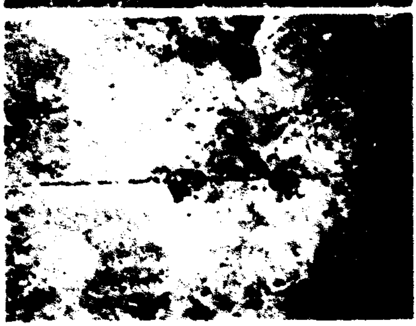
Strength Versus Thickness Characteristics of RTV 634 Silicone Rubber Liner Material from Prepackaged Feed Systems.





MAG: 1½X

MAG: 8X



MAG: 8X

...ype Discontinuities
...Bodies used in
...Systems.
...from other Sources

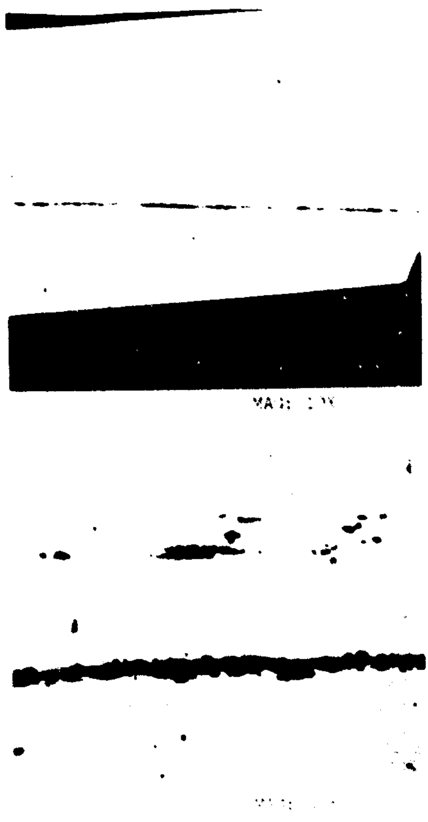
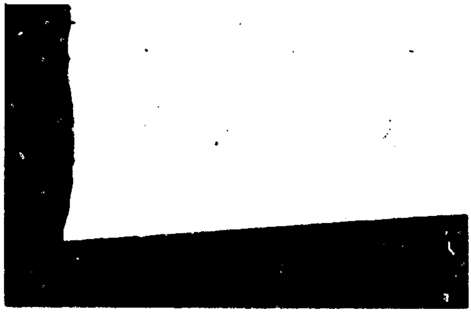
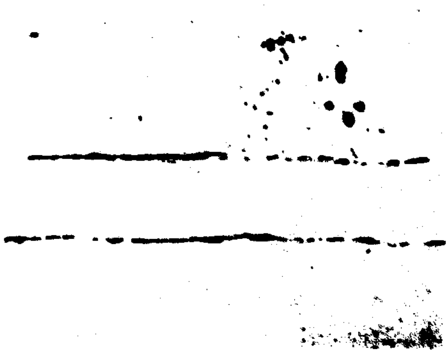


Figure 91. [illegible] Sectioned [illegible] Storable [illegible] Propellant [illegible]



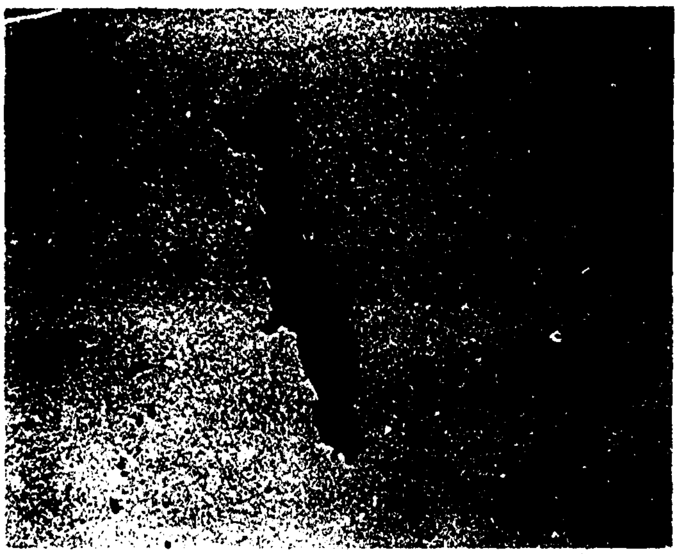
MAG: 10X



MAG: 50X

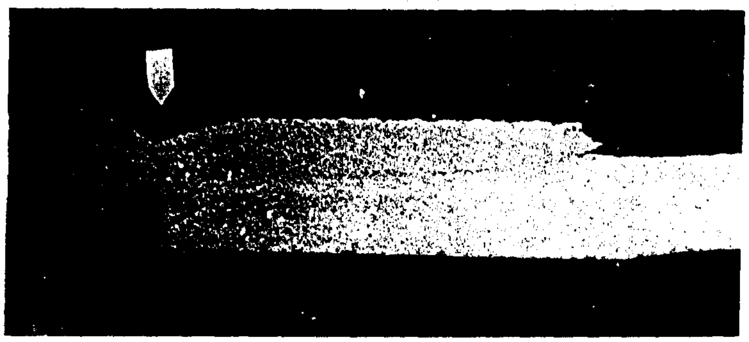
Figure 92. Smaller Discontinuities Observed in same Regulator Body Shown in Figure 91

MAG: 100X



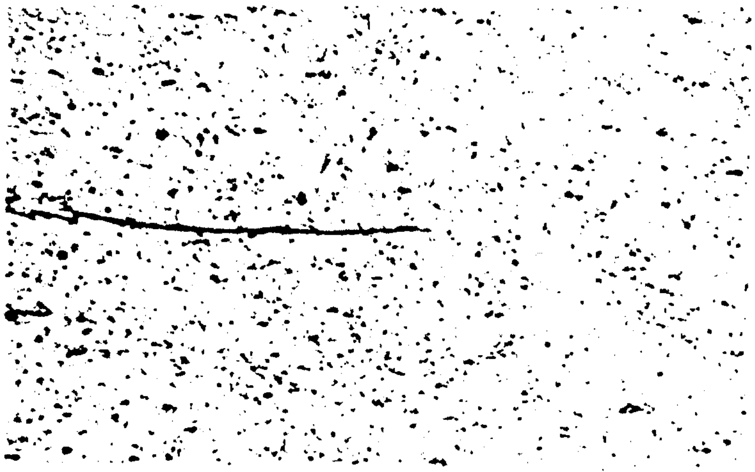
MAG: 500X

Figure 93. Cross Sections of Two of the Largest Stringers Observed in Regulator Valve Bodies Removed from Storable Prepackaged Propellant Systems



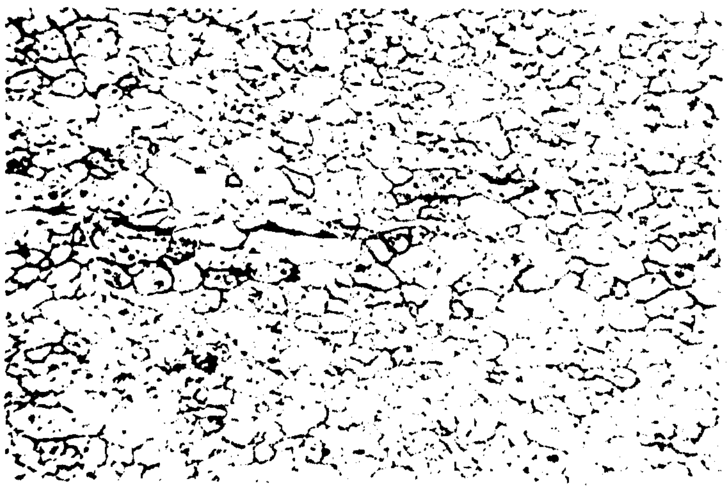
a. Joint shape in region where corrosion occurred on external surface (arrow)

MAG: 8X



b. Unetched view showing transition from unbonded to bonded region

MAG: 200X



c. Etched view showing extension grain boundary network of $CuAl_2$

MATERIAL: 2024 AlAl Alclad

Figure 94. Solid State Bond Joint Shape and Microstructure