Low-Cost Titanium Propellant Tankage

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Manufacturing methods have been developed which will result in a major reduction (on the order of 50%) in the cost of titanium tankage for aerospace systems. This technology takes advantage of the excellent formability of a new beta titanium alloy (Ti-15V-3Cr-3Al-3Sn), developed under Air Force sponsorship, to draw-form tank shells in conventional press equipment. It will replace the traditional machined Ti-6Al-4V forgings used for these tanks in the past, which are expected to become prohibitively expensive for the larger tanks required in the future. Bell Aerospace Textron, under contract to the Air Force Rocket Propulsion Laboratory, has fabricated complete tanks of formed Ti-15V-3Cr-3Al-3Sn hemispheres and has completed a test program which verified that their structural integrity was equivalent, or superior, to the same tank design fabricated from the Ti-6Al-4V alloy. Cost studies have confirmed that major cost reductions are possible. Propellant exposure tests over a 12-month period indicate compatibility with commonly used aerospace propellants.

Introduction

AEROSPACE rocket propellant tankage has been made of machined Ti-6Al-4V titanium alloy forgings for many years. These titanium tanks have been of substantially lighter weight than if made of other materials and have developed a good record of reliable performance. However, the lightweight and reliable performance have been bought at considerable expense, because these tanks are one of the most costly items in rocket motor systems. Studies have shown that high cost is due primarily to excessive machining labor and the discard of large quantities of titanium alloy (often more than 90% of forgings are lost as chips). The advent of Shuttle-launched satellites and the evolution of larger rocket motor systems is demanding still larger tankage which threatens to become prohibitively costly if manufactured by traditional methods.

This contract has shown the Ti-15V-3Cr-3Al-3Sn alloy (hereafter designated Ti-15-3) to be an excellent candidate for low-cost propellant tankage, through the use of draw forming to fabricate tank segments. Drawn hemispheres may be finished to tank hemispheres by chem-milling, or a combination of conventional machining and chem-milling, at a relatively low cost. The Ti-15-3 alloy is readily welded by the Tungsten Inert Gas (TIG) and Electron Beam (EB) processes, and EB welding was used to assemble the tanks made under this contract. Distortion-free heat treatment can be accomplished by gas quenching from the solution temperature and the Ti-15-3 alloy can be heat treated to high strength levels. Considerably less raw material is required for Ti-15-3 tankage and avoiding the forging step should generally result in less tank lead time.

Fabrication

Figure 1 shows the tank design selected for fabrication. It is 16.5 in. in diameter, has four girth mounting lugs offset from the equatorial plane, and has two ports, one offset 15 deg from the pole of one hemisphere.

The following Ti-15-3 sheet was supplied from the Air Force sheet rolling program for the fabrication of six test tanks: nine sheets $0.050 \times 34 \times 96$ in. and five sheets $0.070 \times 35 \times 96$ in. All were identified as coming from heat P6560.

In addition, a quantity of 0.300-in. plate, available from a previous contract, was used for mounting rings and other details. This material was from heat P2360. Chemical analyses of all materials are given in Table 1.

Mechanical property tests for 0.050 and 0.070 in. sheets supplied by the vendor are given in Table 2. Additional characterization tests were performed. These included tests to verify vendor results, aging response, and structural efficiency of electron beam welds, the chosen method of fabrication. These results are shown in Table 3. Tests were satisfactory. Aging response was normal and high weld joint efficiencies were found.

Figure 2 shows a sketch of the detail parts of this tank. It consists of two formed hemispheres joined at the girth by a mounting ring, to which four mounting tabs have been welded. The mounting ring is offset from the equatorial plane, making one hemisphere shorter than the other.

Figure 3 shows the sequence of major fabrication operations for the tanks. The fabrication of the formed hemispheres is, of course, the key to this low-cost method of manufacture and will be discussed in detail. However, a description of fabrication of other tank details will be given before discussing hemisphere forming.

Ordinarily, the fabrication of the girth mounting ring would pose no special problem. That is not true in this case because the only material available was a 0.300-in.-thick plate. Furthermore, the plate available was not sufficiently long to roll a complete hoop for each mounting ring, so each ring had to be made in two sections. Therefore, the operations sequence in Fig. 3 for mounting rings shows forming and reforming operations plus intermediate anneals, which were necessary solely because the mounting rings had to be made of available 0.300 in. plate.

Fabrication of bosses, mounting tabs, and tubes was by conventional machining from 0.300 in. plate. Mounting tabs were finish-machined and drilled after being welded to the mounting ring. Tubes were manually TIG welded to the bosses using fillet welds; these were the only TIG welds in the tanks.

Solution treatment took place just prior to welding and final aging was performed after all welding was complete. It had been determined in a previous contract that optimum weld joint efficiency for Ti-15-3 is obtained by welding between solution treatment and aging. Transformations in the Ti-15-3 alloy are extremely sluggish and almost no heat-

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affected-zone results from this sequence. This made it convenient to schedule welding operations near the end of fabrication, with only final aging to follow. Furthermore, no detectable distortion takes place during solution treatment of Ti-15-3, with a slow cooling rate employed. Vacuum outgassing removed hydrogen absorbed during chem-milling. This was combined with a vacuum solution treatment operation (an argon backfill was used for cooling).

Initially, it was planned to deep draw 16.5-in.-diam hemispheres from the 0.050 or 0.070 in. sheet, using a double-action draw. This plan was based on the ease with which 5-in.-diam hemispheres were previously drawn from 0.100 in. sheet; the 5 in. hemispheres were easily formed in one draw with no intermediate anneals. Forming tools were, therefore, constructed for drawing 16.5-in.-diam hemispheres.

Forming trials were begun with the conservation of the limited amount of Ti-15-3 sheet available as a prime consideration. Both aluminum alloy and stainless steel blanks were first formed in the dies before attempting Ti-15-3 sheet. Die clearance and draw-die radius were modified as a result of these trials. The general practice in making forming experiments was to open the press for part inspection at draw increments of 1 in. This monitoring, while not representative of good production forming practice, allowed for part inspection and modification of hold-down pressure, if considered necessary. Ti-15-3 draw from trials began with a part which split in the draw radius after a 48% draw. It was apparent that very little metal had been drawn into the form in this test (blank diameter reduced only 3/8 in., indicating almost no sheet metal movement under the hold-down ring). Hold-down pressure and blank diameter were reduced for the second and third trials to encourage metal flow, with only slightly better results. Draw radius was increased for the fourth trial to reduce severity of metal deformation at this point, with slight improvement. Further reductions in blank diameter and hold-down pressure in trials 5 and 6 produced better draws, but compression buckles now began to appear. Compression buckles occur with low hold-down pressure and signal a need for intermediate forming dies and intermediate annealing to control their formation. It was apparent at this point that the ratio of material thickness/hemisphere diameter was such that the normal buckling tendency of titanium would make a single draw operation very difficult. To confirm this two tests were made with 0.070 in. Ti-15-3 sheet. These tests drew much deeper and with less buckling than the 0.050 in. sheet.

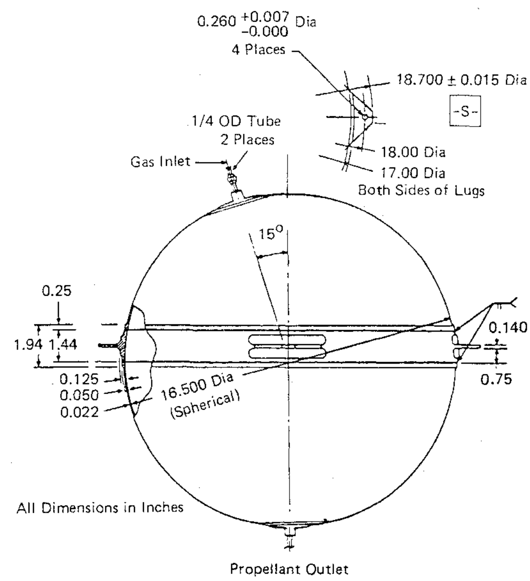

Fig. 1 Tank design.

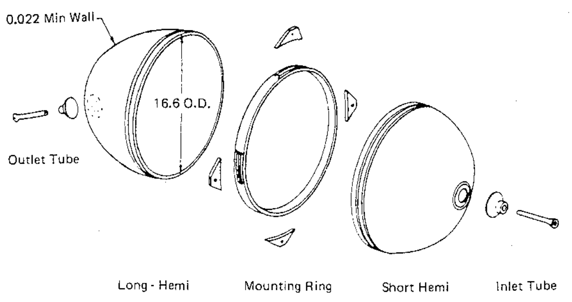

Fig. 2 Details of full-scale design.

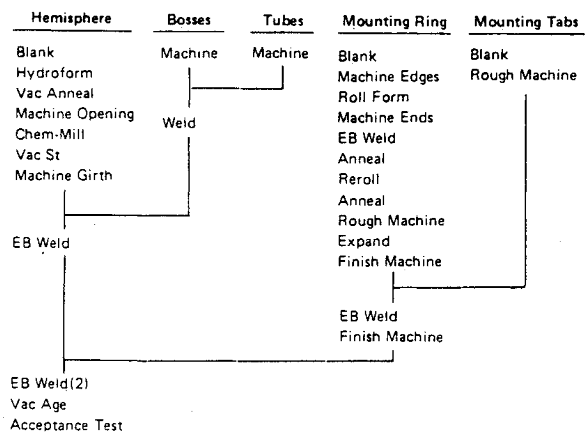

Fig. 3 Fabrication sequence for full-scale tanks.

Table 1 Chemical composition—Ti15-3 sheet and plate, vendor analysis

Vendor	Heat	Gage	Ingot position	C	Fe	N	Al	V	Cr	Sn	O	H
Timet	P6560	0.050,	T	0.022	0.15	0.010	3.0	15.1	3.0	3.0	0.12	0.008
		0.070	B	0.015	0.14	0.011	3.1	15.1	2.9	3.1	0.13	0.007
Timet	P2360	0.300	–	0.015	0.16	0.014	3.2	15.0	3.2	3.1	0.13	0.008

Table 2 Vendor mechanical properties of 0.05 and 0.70 in. Ti-15-3 sheet

Gage	Direction	UTS, ksi	YS, ksi	Elongation, %	Grain size	Bend
0.070	*L*	112	110	19	6	2.0*T*
	T	115	113	18	7	2,0*T*
0.050	*L*	111	108	19	6	2.0*T*
	T	113	112	17	7	2.0*T*

Table 3 Ti-15-3 Characteristics tests 0.050 Sheet

Condition	Direction	UTS, ksi	YS, ksi	Elongation, %
As-received (bell test)	*L*	113.3	109.3	13
	L	114.1	109.0	12.5
As-received + age 950°F, 8 h	*L*	190.8	173.5	7.5
	L	190.8	176.3	6.5
ST 1450°F, 20′ ft, AQ + electron	*L*	114.5	110.0	9
beam weld (weld perpendicular	*L*	116.5	108.7	9
to specimen axis)	*L*	116.3	109.3	8.5
	L	116.1	108.7	8.5
ST 1450°F, 20′ ft, AQ + electron	*L*	198.9	184.2	5
beam weld + age 950°F, 8 h	*L*	199.3	182.2	6
	L	198.9	184.6	5.5

Fig. 4 Hydroformed 16.5-in.-diam Ti-15-3 hemispheres.

Table 4 Hydroform process parameters

Tooling: two stage
Ti-15-3 blank size: 0.050 in. thick × 24¾ in. diameter
Hydroform parameters:
  Lubricant: IRMCO-760
  Overlay: 0.087 in. thick × 24¾ diameter 304 stainless steel.
  1st stage form:
    500 psi initial diaphragm pressure
    1,000 psi final diaphragm pressure
  2nd stage form:
    900 psi initial diaphragm pressure
    4,000 psi intermediate diaphragm pressure
    14,000 psi final diaphragm pressure
Restruck at 10,000 psi without overlay to set draw radius

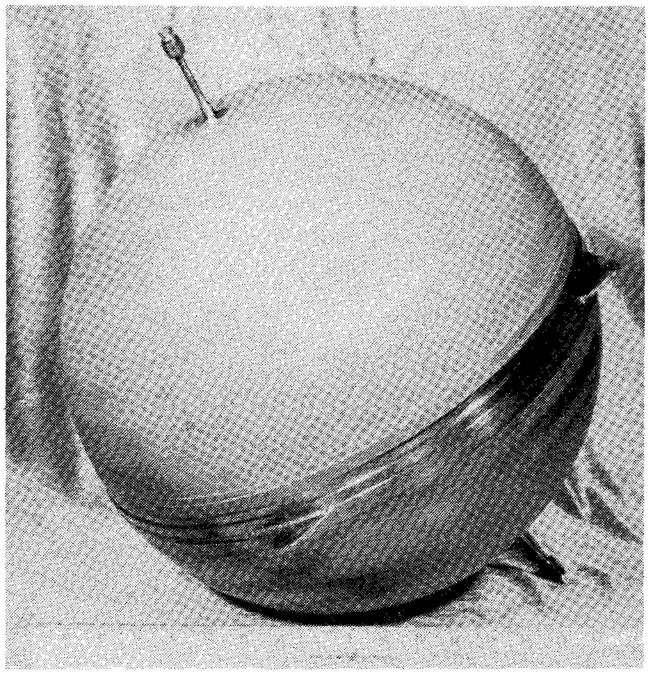

Fig. 5 A completed Ti-15-3 test tank.

Table 5 Vacuum solution treatment (0.050 in. Sheet)

Condition	UTS, ksi	YS, ksi	Elongation, %
Vacuum solution treatment	115.1	111.0	13
1450°F, 20 ft, argon quench	117.0	115.4	13
	116.4	115.0	12
Vacuum St	186.7	168.0	8
Plus age 950°F, 8 h	186.8	168.6	9
	186.8	170.0	8

Two options were available at this point in the forming experiments: 1) resort to a single draw in a hydroform press (a type of draw forming capable of much deeper draws than conventional double-action drawing), or 2) construct new intermediate forming tools for conventional double-action drawing.

Hydroform tests were performed using an existing set of 16-in.-diam dies for forming trials. This series of tests showed that the hydroform was a very satisfactory method for drawing 16.5-in.-diam hemispheres of the 0.050-in.-thick Ti-15-3 sheet. Stainless steel overlays were used to control a slight buckling tendency during forming.

Hydroform dies having a 16.5-in.-diam were fabricated and were used to successfully form 14 program hemispheres for the six test tanks to be made. These hemispheres are shown in Fig. 4. Hydroform parameters are summarized in Table 4.

Test tank hemispheres were chem-milled. Test samples of Ti-15-3 were run in production chem-milling baths before making a final commitment to use the chem-mill process to generate tank membranes. These samples were masked to determine if undercutting would occur. Hydrogen analysis before chem-milling was reported to be 123 ppm; after chem-milling it was reported to be 479 ppm. Based on this test, it was decided that chem-milling of the full-scale Ti-15-3 hemispheres would be used.

The 16.5-in.-diam Ti-15-3 hemispheres were chem-milled in a production bath (HNO_3, HF composition) normally used for Ti-6Al-4V parts. Chem-milling was interrupted several times for ultrasonic thickness tests and manual blending in an attempt to hold overall thickness tolerances of +0.003 in.-0.000 in. on membranes.

An assessment of chem-milling as a production operation to generate titanium tank membranes, based on thickness measurement data of hemispheres, would conclude that improvements are necessary, based on the limited experience of this program. Some of this improvement would come with experience; further improvement could also be expected with better fixtures, such as a device to rotate hemispheres during etching. However, chem-milling cannot be expected to improve upon gage variation over that of the starting piece and a light machining operation may be necessary as a preliminary to chem-milling to create a uniform gage thickness.

Hydrogen analyses after chem-milling indicated a content of approximately 900 ppm.

In spite of preliminary tests and efforts to avoid undercutting, this defect was encountered on some of the 16.5-in.-diam hemispheres. This was not detected by the ultrasonic thickness tester because it was a narrow band at the edge of the chem-mill mask. It occurred on only 2 of the 12 hemispheres so is believed to be a factor of bath placement and stagnant etching solution. A device for rotating hemispheres during etching would probably eliminate this problem. This undercutting was not discovered until later, during the test program.

The common practice for solution treating the Ti-15-3 alloy is to air cool from the solution temperature of 1450°F. Metallurgical transformation is quite sluggish and, while no comprehensive study has been made of transformation rates, it is known that thick plate can be fully solution treated by air cooling without difficulty. It was recognized early in this program that if solution treatment of tanks could be carried out in a vacuum furnace with an argon backfill, several advantages would be realized.

1) No subsequent descaling would be necessary. Descaling of thin tank membranes by chemical or mechanical means would be difficult and would risk damage.

2) Vacuum solution treatment would guarantee freedom from damaging oxide surface contamination.

3) Simultaneous removal of cold work and hydrogen (if necessary) could be effected.

4) There would be no further hydrogen pickup from subsequent chemical descaling operations.

Tests were undertaken to determine if vacuum solution treatment was feasible, by heat treating samples in a furnace equipped for an argon backfill. Results of these tests are shown in Table 5. Strength values of specimens before and after aging are essentially the same as those of air-quenched material, demonstrating that vacuum solution treatment is a practical operation.

Table 6 Electron beam weld schedules (Leybold-Heraus welder)

	Boss/ hemisphere	Mounting lugs	Hemispheres/ mounting rings
Kv	110	130	90
Ma	2.4	9–7	3.6
Focus	Sharp	Sharp	Sharp
Gun	S32	S32	S32
Circle generator			
Frequency, Hz	150	150	60
Amplitude, dial setting	0.7	0.6–0.5	0.8
Speed, ipm	30	32	22
Work distance, in.	3	8.5	5
Joint	Butt	Butt	Butt

All 16.5-in.-diam hemispheres were vacuum solution treated, based on the above tests, after chem-milling.

The furnace was programmed to evacuate, heat to 600°F, hold for 5 mins, heat to 1000°F, hold for 10 mins, heat to 1450°, hold for 20 mins, backfill with argon, and rapid cool with a flow of argon agitated by an internal fan. Hydrogen outgassing occurred as expected, in the 1050-1150°F temperature range. The outgassing occurred over a 5 min time period.

Tensile tests, made on material accompanying the hemispheres through heat treatment, showed normal solution treated and aged properties. Vacuum aging (950°F, 8 h) was also used for heat treating completed tanks. It is concluded from this work that vacuum solution treatment and vacuum aging are practical and the most desirable method of heat treating this alloy.

Machining practices employed were those normally used for other titanium alloys. No difficulties associated with the Ti-15-3 alloy were encountered. Hard tooling was not constructed, because of the few pieces being processed, and maximum use was made of jig bore setups, and temporary tooling, at some sacrifice in setup labor.

Electron beam welding was used exclusively for joining tank details, with the exception of tube-to-boss welds. The latter noncritical welds were fillets placed by manual TIG welding.

A major consideraton in developing weld parameters was to achieve welds which had no "spatter" from the underbead. Spatter is a common occurrence with through-EB welds when power is not adjusted to control the weld puddle. Welding schedules used are shown in Table 6. Control of weld spatter was accomplished and there was no evidence of spatter during examinations of interiors of tested tanks.

Electron beam welds were to be a butt configuration throughout. This posed no fixture problem in boss and mounting lug welds because detail parts could be accurately held in place. However, girth welds were expected to be a problem in matching 0.050 in. weld lands over a 16.5-in. diameter within a maximum mismatch of 10% of thickness. This was especially true for the second girth weld, when no backup bar could be used. An aluminum backup bar was built

Table 7 Six-month compatibility tests, Ti – 15 – 3 Tensile Specimens

Exposure	Condition	UTS, ksi	YS, ksi	Elongation, %
N_2O_4(MON – 1)	ST 1450°F, AQ EB	188.7	172.9	9.5
160°F	welded, aged 950°F	187.0	167.4	8.0
	8 h	187.6	169.7	9.0
	ST 1450°F, AQ	115.5	108.0	17.0
		115.0	109.1	20.0
		115.8	106.7	17.0
	ST 1450°F, AQ	182.8	163.2	12.0
	aged 950°F 8 h	181.0	159.7	12.0
		180.3	162.0	13.0
Hydrazine	ST 1450°F, AQ	189.6	170.9	8.0
140°F	EB welded, aged 950°F	188.3	169.3	9.0
	8 h	188.5	170.2	7.0
	ST 1450°F, AQ	114.4	109.5	17.0
		113.7	109.1	16.0
		112.4	109.8	17.0
	ST 1450°F, AQ aged	178.5	159.1	11.0
	950°F 8 h	178.8	162.1	10.0
		177.9	160.2	10.0
Monomethyl	ST 1450°F, AQ EB	187.9	170.2	7.5
hydrazine	welded, aged 950°F	187.3	169.7	7.0
140°F	8 h	189.2	171.5	7.0
	ST 1450°F, AQ	112.7	110.6	16.0
		112.2	111.4	24.0
		112.6	108.5	21.0
	ST 1450°F, AQ aged	178.1	159.6	9.0
	950°F 8 h	178.3	161.7	10.0
		177.9	159.7	10.0

for use on the first girth weld of each tank to aid in retaining butt alignment.

In general, welding practice was to EB tack each weld repeatedly before making a full penetration pass. All welding was done in a Leybold-Heraus welder located in a clean room.

Electron beam welding operations were accomplished in a routine manner with the exception of two problems. One of these problems was a malfunction in the EB welder which took the form of an unstable beam which occasionally dwelled in fixed locations long enough to enlarge the puddle and, in some cases, cause a melted hole at the dwell point. Undercutting at the bead edge was another defect created by the malfunction. After machine repair, weld repairs were made by drilling out melt-throughs to a 0.062-in. diameter, inserting a short length of 0.062 in. Ti-15-3 wire, and repassing over the area with the electron beam. Repassing was also used to correct undercut.

The second problem involved a combination of the machine malfunction and the aluminum backup bar. During the welding of the first girth weld, the backup bar was fused to the weld at the points where the beam dwelled. This created the probability of aluminum contamination in this particular weld. Even though the malfunction was corrected, the backup bar was not used in subsequent girth welds. External rings and a series of wedges were used to achieve alignment during tack welding and full-penetration welds were made with alignment tooling removed. A completed tank, after welding and vacuum aging, is shown in Fig. 5.

Hydrogen content of a 0.050 in. Ti-15-3 sheet after chem-milling was 0.0900%, as stated earlier in this report. Hydrogen analyses made subsequent to chem-milling gave the following results: after vacuum solution treatment, 0.0012%; after vacuum solution treatment and vacuum aging, 0.0042%, 0.0041%; from 0.022 in. membranes after test: hemisphere T9, 0.0029%, hemisphere T7, 0.0026%.

It can be seen that hydrogen in the finished product has been retained at a low, acceptable level. Vacuum heat treating was a major advantage in this respect. It virtually eliminated all of the chemical treatments (except chem-milling, of course) which add hydrogen to titanium products.

Propellant Compatibility

Six- and twelve-month compatibility tests were made with common rocket propellants. The following exposure conditions were investigated:

Material: Solution treated-welded-aged 950°F, 8 h; solution treated; and solution treated-aged 950°F, 8 h.

Propellants: N_2O_4(MON-1), 160°F test temperature; monomethylhydrazine, 140°F test temperature; and hydrazine, 140°F test temperature.

Stress levels: 0 (tensile blanks) and 90% yield strength (preloaded bend specimens).

Six- and twelve-month tests gave essentially the same results. No stress-corrosion test specimens failed during exposure, nor did any of these specimens show any surface effect after removal from the three propellants.

Tensile specimen results after exposure are shown in Tables 7 and 8. All values for strength and ductility are typical of the Ti-15-3 alloy in the conditions given and show no deterioration due to propellant exposure.

No significant changes occurred during these tests, except for hydrazine exposure. A pressure buildup in hydrazine cannot be explained satisfactorily and may require additional investigations of cleaning methods, surface finishes, etc., to minimize hydrazine decomposition.

These tests indicate that the Ti-15-3 alloy is compatible with aerospace rocket propellants in the material conditions in which it will be used.

Table 8 Twelve-month compatibility tests Ti-15-3 tensile specimens

Exposure	Condition	UTS, ksi	YS, ksi	Elongation, %
N_2O_4(MON-1) 160°F	ST 1450°F, AQ EB welded, aged 950°F, 8 h	185.3	169.9	5
	ST 1450°F, AQ	114.2	114.2	17
	ST 1450°F, AQ aged 950°F, 8 h	178.7	163.4	12
Hydrazine 140°F	ST 1450°F, AQ EB welded aged 950°F, 8 h	184.8	173.0	6
	ST 1450°F, AQ	116.7	116.7	18
	ST 1450°F, AQ aged 950°F, 8 h	177.8	165.1	11
Monomethyl hydrazine 140°F	ST 1450°F, AQ EB welded, aged 950°F, 8 h	186.2	168.4	6
	ST 1450°F, AQ	116.9	115.2	19
	ST 1450°F, AQ aged 950°F, 8 h	178.4	164.4	11

Test Program

The program required that the six tanks be tested for structural adequacy and a final assessment made of their performance. The following tests were performed on one or more of the six tanks: 1) acceptance test, 2)vibration, 3) pressure cycle, and 4) burst test.

The acceptance test consisted of four steps: visual examination, proof test, helium leak test, and weight check. Each tank assembly was inspected and all visible anomalies of welds, machining, and surface finish were tabulated and located relative to the position of the mounting lugs. These tabulations are presented in Table 9. All weight, volume, and proof test pressures are presented in Table 10. Each tank was connected to a system which could fill, pressurize, and measure the volume of fluid pumped into the tank.

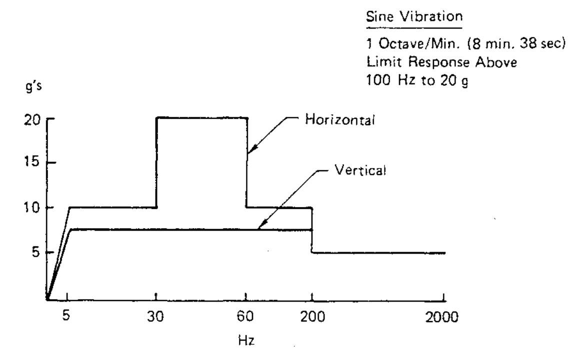

Fig. 6 Sine vibration.

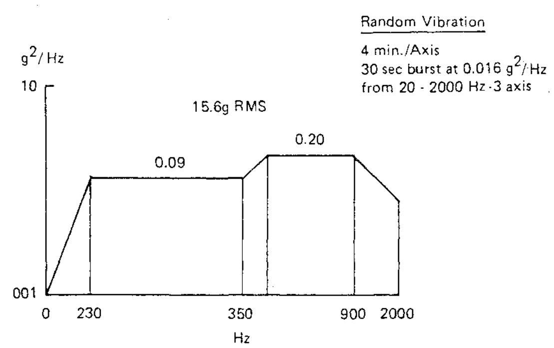

Fig. 7 Random vibration.

The first tank proof-tested ruptured at 500 psi in a weld joining a hemisphere to the mounting ring. At the outset, it was suspected that aluminum contamination of the weld was the cause. An examination of the fracture showed a bright, hard area at the origin of failure. This was subjected to a microprobe analysis which confirmed that this weld had been contaminated with aluminum, causing embrittlement and failure.

Tank S/N 4 was then proof tested. Proof test pressure for this tank was established at 490 psi because of an area in the membrane which was under drawing thickness due to over chem-milling. This tank completed its proof test satisfactorily.

Tank S/N 2 was proof tested next. Failure occured in the girth chem-milled radius in a hemisphere. Thickness readings using "point" micrometers disclosed an undercut area at the origin of failure. Thickness readings measured were as low as 0.0135 in., read about 1/8 in. away from the failure to avoid the "necked down" area.

Subsequent to this test, because ultrasonic thickness measuring devices cannot detected localized thinning such as occurred in this tank, it was decided to derate the remaining tanks to a proof test of 400 psi to insure completion of the necessary test program. These tanks passed the 400 psi proof test.

Test tanks were subjected to a helium leak test in which they were pressurized to 30 psig with helium. All welds and fittings were checked for leakage with a hand-held probe feeding a CEC helium mass spectrometer leak detector. No anomalies were noted.

Four tanks were subjected to design verification tests. The test matrix is shown in Table 11. The table also shows the two tank assemblies designated for long-term propellant storage tests.

The three tanks selected for vibration testing were subjected to one sinusoidal sweep from 5 to 2000 Hz and two random vibration spectra in each of three orthogonal axes (see Figs. 6 and 7). The tanks were loaded with filtered distilled water, leaving a 5% ullage, and pressurized to 100 psi with nitrogen to monitor for leaks during the test. Each tank was instrumented with five piezo-electric accelerometers. Two of these three tanks successfully passed this test program while the third (see Table 9, tank 6) failed by predictable fatigue at an over-machined area under a mounting lug. Failure occurred during x axis (vibration perpendicular to the plane of the mounting lugs) random vibration. Results of the pressure cycle and burst tests are shown in Table 12.

Table 9 Test tank pretest inspection

Tank	Chem-milling	Machining	Welding
1	—	—	Possible Al contamination, weld repairs
2	0.018 in. Membrane	—	Weld Repairs
3	—	—	—
4	0.015 in. Membrane	—	—
5	—	—	—
6	—	0.034-in, thick mounting ring (should have been 0.045 in.)	Weld repairs

Burst fractures initiated in the thickness transition between membrane and weld land, which was found subsequently to have been undercut during chemical-miling of the membrane. Tank 5, which exceeded the design burst pressure, was only slightly undercut. In one region about 1 in. long the thickness was 0.0198 in. vs the 0.022 in. required.

A cost analysis was made of the tank design used in this program, produced in both formed Ti-15-3 and machined Ti-6A1-4V configurations. Recurring costs for both tanks are shown in Table 13. Labor costs are itemized by various functions, shown at the left. Draw forming results in predicted cost savings well over 50%. The greatest saving is in manufacturing labor. Other labor requirements are supportive of manufacturing labor, and therefore are reduced similarly. Material cost is lowered considerably because far less titanium alloy is discarded as machined chips.

Acknowledgments

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Table 11 Design verification test matrix

Tank	3	4	5	6
Vibration test	X		X	X
Pressure cycle		X		
Burst		X	X	
Leak Test	X			X
Metallungical exam		X	X	
Propellant storage	X			X

Table 12 Pressure cycle and burst test results

Tank	Cycle test	Burst pressure
4	0-450 psi nine times	525 psi
5	—	850 psi

Table 13 Tank cost comparisons

	Radial lug tank	
	Forged	Drawn
Manufacturing labor, h	490	121
Tool maintenance, h	21	5
Inspection, h	83	25
Test, h	40	24
Engineering support, h	44	44
Manufacturing engineering, h	125	30
Quality assurance, h	81	32
Program management, h	60	60
	944	341
× $48/h	45,312	16,368
Material, $	6,000	900
Cost per tank, $	51,312	17,268

Table 10 Proof test data tank (in test order)

	1	2	3	4	5	6
Proof pressure, psi	600	600	400	490	400	400
Wt. of tank, lb	5.31	5.25	5.13	5.38	5.25	5.19
Wt. of water, lb	87.13	87.56	86.94	87.25	87.38	87.63
Internal volume, in.^{3}	2417	2429	2412	2420	2424	2431