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Recent Experience in High Pressure Gaseous Hydrogen Equipment Operated at Room Temperature

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Pressure vessels for storing gaseous hydrogen to pressurize liquid hydrogen tanks during static tests of liquid fueled rocket engines are fabricated from normalized or quenched and tempered steels with solid or multiple layer wall construction. Service failures associated with welds have occurred in the multiple layer vessels. Bourdon tubes made of 400 series stainless steel have failed in pressure gauges. Service experience indicates that gaseous hydrogen pressure vessels should have an access for periodic internal inspection. Welds in contact with hydrogen should be inspected by magnetic particle or dye penetrant methods in addition to X-ray. A517-F steel, as currently employed, is not recommended for gaseous hydrogen service. The bourdon tubes in pressure gauges should be made from materials that are less susceptible to gaseous hydrogen deterioration.

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The liquid hydrogen fueled rocket engine unexpectedly brought the notorious hydrogen embrittlement problem to ground support equipment. As development of the engine progressed, more gaseous hydrogen (GH_2) was required to pressurize larger fuel tanks during static tests. To meet this demand, systems were constructed for higher pressures. No severe problems were anticipated at 5000 or 6000 psi. Although several steel tank failures had been reported at 3000 atmospheres and above (1-3), low pressure GH_2 cylinders (2000 psi) have been used in shops everywhere for many years without any problems. Thus, in 1964, a leak failure in a 1-inch nozzle on a 5000 psi vessel was repaired without undue concern. But the nozzles continued to fail. Then a large storage vessel failed in the cylindrical section provoking a review of all the GH_2 equipment operating at atmospheric temperatures.

Pressure Vessels

Hydrogen pressure vessels at the National Aeronautics and Space Administration (NASA) and several contractor facilities are listed in Table 1. Of the 681 vessels listed, only 100 vessels have a capacity over 50 cubic feet (water volume). The most widely used steel in these vessels is type 1146a, followed by A302-B Mod., A372-IV and A517-F. Property and chemistry ranges for these steels are listed in Table 2. The most common vessel construction is a welded, multiple layer cylindrical section with solid heads. Although there are several welded, solid wall vessels, most of the solid wall vessels are small seamless forged vessels.

Nozzle Failures. In June 1964 a leak failure occurred suddenly at a 1-inch nozzle weld in the cylindrical section of a 1300 cubic foot, 5000 psi, GH_2 storage vessel at Aerojet General Corporation. This vessel was a multiple layer structure with a 1/2 inch thick inner shell and 22 layers, 0.289 inch thick. Solid 4-3/8 inch thick, forged heads were welded to the cylindrical section. The inner shell steel is normalized, and the outer layers are in the as-rolled and welded condition. Thus, an inner shell compressive stress of approximately 20,000 psi is obtained. The cylindrical shell is made of 1146a steel and the heads are A225-B. The failed nozzle, located in the top of the vessel, was replaced, and the vessel was hydrostatically tested to 7500 psi before returning it to service. One month later, a 1-inch drain nozzle in the bottom of another vessel leak failed. Upon examining this vessel, a circumferential crack in the 8-inch inlet nozzle-to-head weld was detected. In December, the first nozzle that had been repaired failed again. Both vessels were repaired and returned to service. The fourth 1-inch nozzle failure in January 1965 prompted an intensive investigation of these vessels. This investigation indicated that the nozzle and weld had satisfactory chemistry and mechanical properties. A stress analysis, however, revealed that the normal and residual stresses around the nozzle hole may have been sufficient to promote failure. Since these vessels were pressure cycled, fatigue may have contributed to the failure. However, since vessels of the same type with nozzles in the cylindrical section had been operating for years with high pressure nitrogen without incident, the hydrogen gas was suspected and an investigation in this area was begun. A review of the published literature revealed a scant amount of work had been done on the influence of gaseous hydrogen on steels (4-8). In general, this work indicated that hydrogen had a strong influence on ductility, particularly the reduction-of area; strength seemed to be less influenced. Very little data were available on the effects of hydrogen on weldments. In view of this lack of knowledge on weldments, plans were made to replace the 1-inch nozzles in the leaking vessels with a mechanical seal. In the meantime, the maximum operating pressure for these vessels was reduced to 3500 psi. Before all the vessels could be refitted, another nozzle failed in July 1968. Pressure, then, may not be as large a factor as originally suspected, and the failures may be merely the combined influence of hydrogen, overstressed area and low-cycle fatigue.

Cylindrical Shell Failures. The 1146a steel vessel that failed in 1965 at Aerojet was replaced with a new 5000 psi vessel of the same size but which was fabricated from A517-F (T-1) steel, a quenched and tempered steel. It was thought that the fully stress relieved vessel would operate satisfactorily with GH_2. This is a four layer vessel with a 1-3/8 inch inner shell on which the outer shells are added by a shrink-fit technique to produce a total wall thickness of 5-7/8 inches. The outer shell is not welded to the forged head. Weep holes penetrate the outer three layers. In June 1965 after ten pressure cycles, this vessel failed audibly at 3900 psi in the cylindrical section. To examine this vessel, an access was cut in the vessel head as illustrated in Figure 1. Examination of the vessel interior with the aid of dye penetrants revealed two long cracks; one 50 inches and the other 22 inches long. The 50-inch crack, a portion of which is illustrated in Figure 2, penetrated the inner shell. The gravity of this situation prompted an internal inspection of two other A517-F steel vessels of the same size and construction that had not yet been placed in service. Several 1/4-inch deep cracks associated with longitudinal welds were found in one vessel. In the other vessel, two shallow circumferential cracks were found, only one of which was associated with a weld. Several months later, the first vessel was returned to the manufacturer, and, upon disassembling the sections containing cracks, additional cracks were discovered in other layers. None of these vessels have been repaired and are considered unserviceable.

After the failure in one vessel and the discovery of cracks in the vessels that had not been exposed to GH_2, all A517-F steel vessels became suspect. The maximum operating pressure of all GH_2 vessels in the NASA inventory was reduced to 75 percent of the design pressure until more information could be obtained on the influence of GH_2 on pressure vessel steels and their respective welds.

But Mississippi Test Facility (MTF), a part of the Marshall Space Flight Center, had three A517-F steel vessels that were to be used for GH_2 service, and there was insufficient time to cut access holes in the vessels for inspection. These vessels were designed for 6300 psi and were of the four-layer type construction. In March 1966 during a pumping delay on the second GH_2 pressure cycle, a vessel began to leak at 5850 psig. The vessel was subsequently returned to the manufacturer and one head was removed for inspection. Three cracks were located that penetrated the inner shell. Numerous shallow cracks were detected throughout the interior.

The vessel was repaired, returned to MTF and has been in nitrogen service at 6000 psig for 18 months.

After the vessel failed, maximum operating pressure for the remaining GH_2 vessels was immediately reduced to 4500 psig and later to 3000 psig. Plans were begun to have inspection man-ways placed on all the A517-F steel, GH_2 vessels at MTF.

Four months ago, an access was cut in a dome of one of the remaining A517-F steel vessels in preparation for attaching a man-way. Magnetic particle inspection revealed a total of 50 inches of cracks, the largest of which was 9 inches. With the exception of one crack 3-1/2 inches long associated with a longitudinal weld, all the cracks were associated with tack welds made during fabrication of the vessel. A typical crack is illustrated in Figure 3. These cracks were all superficial and it was possible to grind them out while maintaining sufficient wall thickness to meet design requirements. The vessel will be returned to GH_2 service after the man-way is completed.

Another A517-F steel vessel, 1250 cubic foot capacity and 5000 psig design pressure, which was shipped to MTF from Marshall Space Flight Center (MSFC), already contained a man-way and was opened for inspection. This vessel contained three small cracks. The vessel has not been placed in service.

In February 1967 a 450 cubic foot, A517-F steel vessel at Aerojet developed a leak. This was a two-layer vessel designed for 3600 psi. An existing man-way permitted an internal examination in which a 60-inch crack was discovered in a longitudinal weld.

All the pressure vessels, wherein failures have occurred in the cylindrical section, have been constructed of A517-F steel. Cracks in these vessels have been associated with either the main seam welds or tack welds. The A302-B Mod. steel vessels have operated for years without problems. According to the work of Walters and Chandler (9), the tensile properties of A517-F are not too different from those of A302-B Mod. in a GH_2 environment. The main difference seems to be the welding characteristics. It is necessary to maintain very strict process and quality controls when welding A517-F steel. Obviously, these vessels were fabricated without such controls. Since two A517-F steel vessels had cracks in the inner shell before exposure to GH_2, it seems likely that other A517-F vessels were placed in service with cracks. It was merely a matter of time before these cracks propagated to the stage of leaking.

Pipe Lines

The pipe lines in high pressure GH_2 service have operated satisfactorily for years. A weld in an A517-F steel pipe line at MTF leaked on the initial GH_2 pressure cycle. As illustrated in Figure 4, this was an extremely poor quality weld, and a metallographic examination did not reveal any cracks in the weld or weld area. It was concluded that the leak path developed through the unfused and inclusion areas of this weld. We have no recorded instances of GH_2 transmission line failures, but we caution that extreme care should be exercised in such systems to avoid cracks which could propagate under the influence of GH_2 and cyclic stresses.

Gauges

In the past three years, we have reports of at least five bourdon tubes that have ruptured in GH_2 pressure gauges. All of these gauges failed below the rated capacity of the gauge. The first failure, which occurred at a private company in Huntsville, Alabama, in December 1965, caused a serious injury. The second failure, which occurred at MSFC in September 1966, resulted in an uncontrolled fire. The fire damage is illustrated in Figure 5, and a view of the ruptured bourdon tube is illustrated in Figure 6. Ruptures in two other tubes occurred in the same location of the tube as that illustrated in Figure 6. The initial fire burned a control cable so that GH_2 was trapped in the test vessel and continued to feed the fire at the rupture point until the vessel vent valve could be opened manually. Four of the ruptured bourdon tubes were made of 403 stainless steel, and one tube was 431 stainless steel. The 400 series stainless steels are common in these pressure gauges, but they are not satisfactory for GH_2 service.

Conclusion

Type 1146a steel, multiple layer vessels have given excellent GH_2 service until the nozzle problem was encountered at Aerojet. Based on this experience, it seems to be necessary to avoid very high residual stresses in welded areas, particularly where the welding process cannot be carefully controlled and when critical inspection for microcracks cannot be accomplished. Multiple weld passes are especially vulnerable to such defects.

A517-F steel vessels, as currently fabricated, are not satisfactory for hydrogen. More rigid manufacturing controls might produce an acceptable vessel.

All large GH_2 pressure vessels should have an access for periodic internal inspection by magnetic particle, dye penetrant, or other non-destructive methods.

Bourdon tubes in pressure gauges must be made from materials that are less susceptible to hydrogen deterioration. A 300 series stainless steel or a Be-copper alloy may be satisfactory.

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TABLE 1. HYDROGEN STORAGE VESSELS

Location (a)	Number	Volume Cu. Ft. (water)	Design Pressure psig	Reduced Operating Pressure psig	Cylindrical Section Material	Wall (b)
MSFC	2	700	5000	3500	1146a	L
	6	35	5500	3500	SA182-F22HT	S
	8	35	5500	3500	1146a	L
MTF	4	1375	6300	3000	A517-F	L
	1	1256	5000	3000	1146a	L
KSC	4	200	6000	4500	A302-B Mod.	S
	144	20	6000	--	A372-IV	S
Plum Brook	376	47	2400	--	1146a	L
	2	325	5000	3500	1146a	L (c)
	2	2530	5000	3500	1146a	S
Jackass Flats	3	2407	2500	--	HY-80	S
	3	1770	3600	2500	Kaisalloy	S
Aerojet General	19	1750	3500	3500	1146a	L
	21	1300	5000	3500	1146a	L
	3	1300	5000	3900	A517-F	L
Rocketdyne	13	45	2500	--	API-N80-3	S
	14	468	3000	--	Carbon Steel	L
	1	1029	3000	--	A212-B	L
	34	43	3200	--	Carbon Steel	S
	12	468	5000	--	A302-B Mod.	L
	4	468	5000	--	A212-B	L
	3	401	10000	8800	A302-B Mod.	L
	2	401	10000	(d)	A302-B Mod.	L (e)

(a) MSFC - Marshall Space Flight Center; MTF - Mississippi Test Facility; KSC - Kennedy Space Center.
(b) L - Multiple layer; S - Solid
(c) Stainless steel lined
(d) Under construction
(e) 316 stainless steel lining

TABLE 2. PROPERTIES AND CHEMISTRIES OF SOME PRESSURE VESSEL STEELS

Properties	1146a	A302-B Mod.	A517-F	A372-IV	HY 80
F_{TU}, ksi	105	120	115-135	105	100
F_{TY}, ksi	82.5	100	100	65	80-95
e, %	22	--	16	15	20
Chemistry					
C	.18/.25	.16/.26	.10/.20	.40/.50	.18
S	.04	.04	.04	.04	.025
P	.04	.035	.035	.035	.025
Si	.20/.35	.15/.30	.15/.35	.15/.35	.15/.35
Mn	1.10/1.50	1.15/1.50	.60/1.00	1.40/1.80	.10/.40
Ni	.40/.70	.40/.70	.70/1.00	--	2.00/3.25
Cr	--	--	.40/.65	--	1.00/1.80
Mo	--	.45/.60	.40/.60	.17/.27	.20/.60
V	.13/.18	--	.03/.08	--	--
Other			Cu .15/.50 B .002/.006		

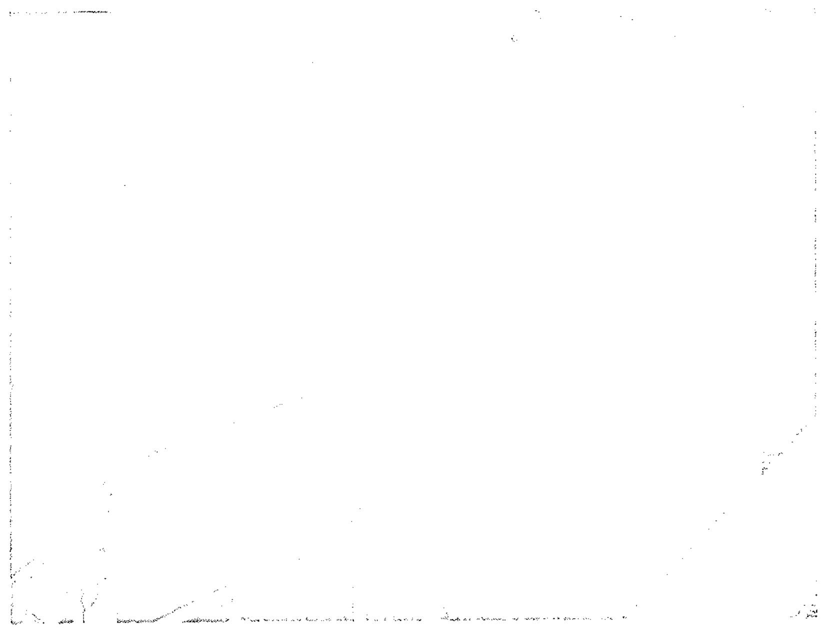

FIGURE 1 - View of the Failed A517-F Steel Vessel

FIGURE 2 - A Portion of the 50-Inch Crack in The Failed A517-F Steel Vessel

FIGURE 3 - Typical Crack in an A517-F Steel Vessel at MTF

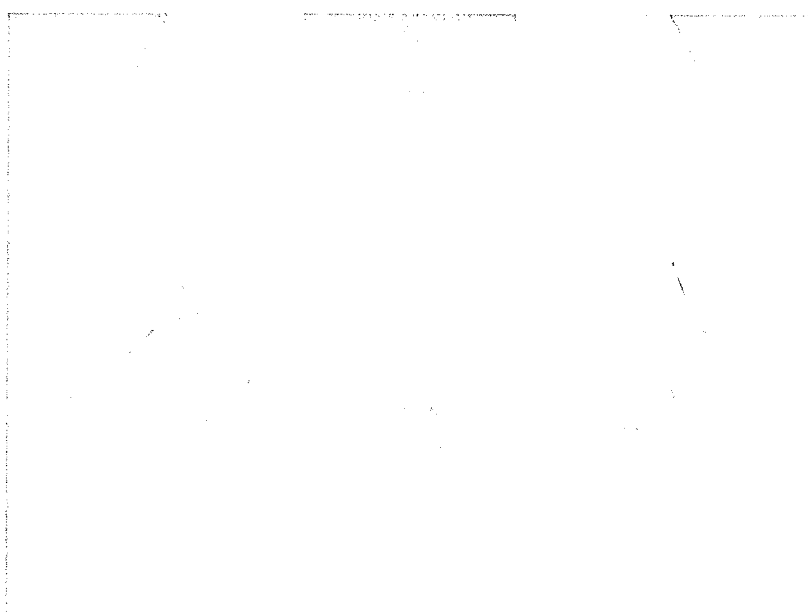

FIGURE 4 - Weld in an A517-F Steel Pipe

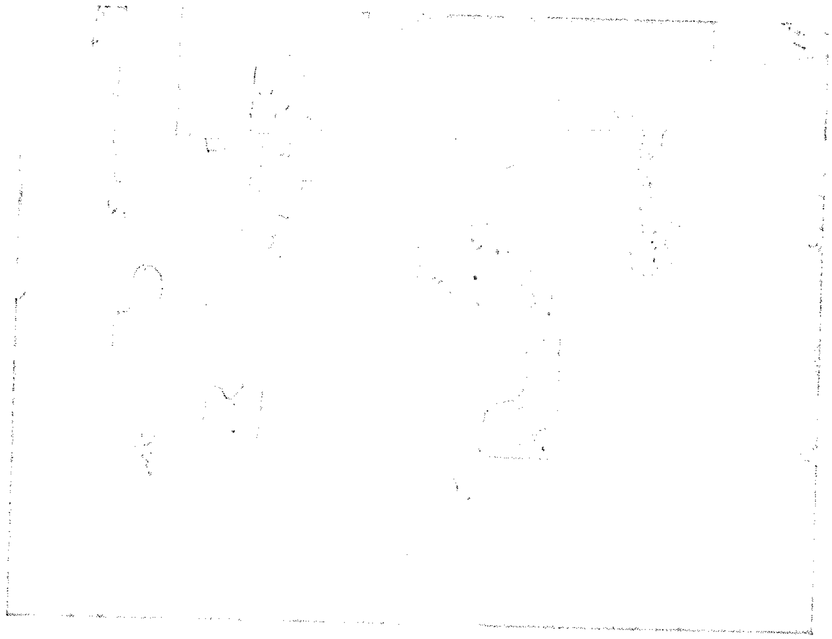

FIGURE 5 - Area Damaged by Hydrogen Fire at MSFC

FIGURE 6 - Ruptured Bourdon Tube

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