Cracking and Ruptures of SCBA and SCUBA Aluminum Cylinders Made from 6351 Alloy

By Bill High, PSI, Inc.

On September 15, 1999, the U.S. Department of Transportation (DOT) published notice RSPA-99-5143 (notice 99-11) stating that its files contain reports of 12 explosive failures of aluminum cylinders made of 6351 alloy. Eleven of the failures occurred when the cylinders were being filled. Six of the failures were SCBA cylinders used in life-support systems for firefighters, and three were SCUBA cylinders used by divers. Although some of the failures were variously attributed to mechanical damage and over-pressurization, in six cases the cause for the cylinder failures was attributed to a phenomenon known as Sustained Load Cracking (SLC).

On December 7, 1999, the National Institute for Industrial Safety and Health (NIOSH) issued its own notice based upon the DOT data. This report contained a seven-point advisory recommending frequent technical inspections of all SCBA cylinders manufactured from 6351-alloy.

Over the past 15 years, numerous other warnings concerning older aluminum cylinders made from 6351-alloy have been issued to divers and firefighters. However, the most recent DOT and NIOSH notices have received particular attention, partly because of four recent 6351-alloy cylinder ruptures: a SCBA cylinder in Allegan, Michigan (September 1997) and SCUBA cylinders in Campbell River, British Columbia, Canada (April 1999), Riviera Beach, Florida (February 1998), and Key Largo, Florida (March 2000). This latest failure occurred after the DOT and NIOSH reports were issued, bringing the total number of recorded ruptures in the Unites States to 13. In addition to ruptures mentioned in the DOT and NIOSH reports, there have been 6351-alloy SCUBA cylinder failures in Australia, Canada, New Zealand and the Middle East, for a recorded worldwide total of 17. To keep this failure rate in perspective, it is estimated that a total of 25.4 million 6351-alloy cylinders were manufactured by various companies.

Along with the wave of concern over cylinder failures has come a great deal of misinformation spread by inaccurate reports on the Internet, in newspapers and trade journals, as well as word-of-mouth rumors. In this article, I will strive to set the record straight, separate fact from fiction and provide an overview of the important issues surrounding SLC and 6351-alloy used in 3AL SCUBA and SCBA cylinders and liners for certain composite cylinders.

Sustained Load Cracking (SLC) in 6351 Aluminum Alloy cylinders

Sustained Load Cracking, a metallurgical anomaly, occasionally develops in high-pressure cylinders made from 6351 aluminum alloy. As the name implies, SLC usually occurs in cylinders that have remained filled for sustained periods of time. U.S. manufacturers began using 6351 when aluminum alloy cylinders were approved by the

DOT for U.S. service under various special permits beginning in 1971. Manufacturers included Luxfer USA, Walter Kidde, Norris Industries and Kaiser Aluminum. Permits for Norris and Kaiser (SP6688 and SP6576) have expired and those cylinders are no longer approved for use in the U.S. but may be used in Canada under a grandfather clause. Walter Kidde continued using 6351-alloy until the end of its cylinder production in 1989.

Luxfer USA manufactured cylinders from 6351-alloy from 1972 through mid-1988. In June 1988, Luxfer USA ceased manufacturing cylinders from 6351-alloy and began using a proprietary version of 6061-alloy: since that time, no sustained-load cracks have been detected in the more than 19 million Luxfer cylinders manufactured from this 6061-alloy.

The Catalina Tank Company began making 3AL cylinders in 1986 using alloy 6061-T6. Although this alloy is generally not subject to SLC, a very few Catalina cylinders have been found with minor thread area cracks attributed to stress corrosion cracking. Therefore, PSI, Inc. recommends that thread examinations, including a mirror-and-light protocol be performed on all 3AL cylinders.

Hoop wrapped SCBA cylinders were introduced in 1976. Wrapped with fiberglass and other fibers to increase sidewall strength, some of these cylinders were rated at 4500 psig service pressure. All hoop-wrapped cylinders were limited by DOT to a 15-year service life. Out of more than 70,000 hoop-wrapped cylinders manufactured, one 4500-psig cylinder ruptured in 1984. The cause was initially listed as Room Temperature Grain Boundary Creep. However, Dr. Henry Holroyd, an eminent metallurgist subsequently described the 6351-alloy behavior as SLC. As a result of this failure, and in response to a DOT safety notice, in 1985 Luxfer USA required that all its E7235-4500 psig hoop-wrapped cylinders be retrofitted with a steel collar to prevent ruptures, and Luxfer instituted an aggressive retrofit program. No cylinders thus retrofitted has ever failed. Unfortunately, a few owners of these cylinders failed to comply with the Luxfer requirement. In March 1993, a non-retrofitted cylinder failed with tragic consequences--and SLC was the terminal cause. The cylinder had also exceeded the DOT-mandated 15-year life by two years at the time of the failure. Another contributing factor was the fact that the cylinder had not been properly inspected.

In 1985, PSI, Inc. became the first dive industry advocate to focus on SLC detection using a mirror and light inspection protocol. Although cylinder visual inspectors were warned to examine crown and threads of SCUBA 3000 psig and SCBA 2216 psig cylinders, few technicians heeded the warning. Tests conducted by Luxfer USA suggested that cylinders with service pressure of 3000 psig or less were unlikely to rupture even if SLC developed. Inspectors trained by PSI, Inc. did find a number of cracked cylinders as well as some cylinders leaking from outer-crown cracks, before the first SCUBA cylinder ruptured in Australia in 1988. Subsequently, DOT, Luxfer USA and PSI, Inc. stepped up efforts to educate both owners and inspectors of 6351 alloy cylinders about the importance of thorough technical inspections.

Evidence indicated that SLC develops slowly over a multi-year period. For example, detailed metallurgical examination of one ruptured SCUBA cylinder showed that the crack had been growing for eight years or more and would have been visible for about six years to a trained inspector using the proper crack-assessment protocol. Had that cylinder been carefully inspected, it could have been removed from service long before the rupture occurred.

Trained Inspectors Are Essential

Although cylinder ruptures are extremely rare when one considers the many millions of all-aluminum and aluminum hoop-wrapped cylinders that were made from 6351-alloy, a number of cracked cylinders have been found over the years. It is therefore essential for each of these cylinders to receive a careful examination at least annually by a trained inspector. PSI, Inc. has trained more than 11,000 visual inspectors around the world for the firefighting, diving and hydrotest industries. Yet, many potentially unsafe cylinders continue to be returned to service by un-trained technicians who cannot differentiate between a tap stop and a crack. They do not understand the difference between a valley and a fold, nor do they know how many threads may be penetrated before a cylinder should be rejected and condemned. Some inspectors do not have the minimum essential tools recommended by the National Bureau of Standards for detecting cracks.

The SLC problem is real and the potential for further explosive ruptures exists. That potential may be thwarted by thorough inspections conducted by properly trained, diligent inspectors. It cannot be overemphasized that the quality of inspection is far more important than the frequency of inspection. An improperly trained inspector can look at a cylinder numerous times without detecting SLC. An inspector must use a focused, bright light source and a magnifying mirror that fits into cylinder openings as small as ½ inch diameter. In addition, fill station operators must be alert to any sounds of leaking air during fills. If a leak is suspected, Luxfer further recommends that a soapy solution be sprayed onto the cylinder crown when the cylinder is half full and again when full. Any bubbling is a signal to stop charging, to discharge the cylinder immediately and to examine the crown and threads for cracks.

Eddy Current Examination for Cracks

In collaboration with Luxfer Gas Cylinders, Flare Technology, Inc., developed a device using eddy current technology as an *additional* tool for testing thread integrity in 6351-alloy cylinders. Introduced in 1996 under the brand name Visual Plus, this eddy-current device contributed greatly to the detection of early, difficult-to-observe sustained load cracks. Visual Plus is now marketed by Advanced Inspection Technology (AIT). In 1999, Flare introduced a slightly different eddy-current model, which it markets under the name Visual Eddy. Engineering Inspection Systems produces a similar eddy current assessment tool called Simple Eddy.

When properly calibrated and operated, these eddy current devices help inspectors detect hard-to-see cracks in 6351-alloy cylinders. However, it is imperative that these devices

be used in precise accord with instruction by properly trained inspectors. Sadly, this writer is aware of many instances in which the instruments have been improperly used. Eddy current devices can give "false positive" readings when improperly operated or when the cylinder thread areas being tested have been inadequately cleaned. For example, in January 2000, Luxfer reported that fully 50% of the cylinders returned because of alleged thread cracks were *not* cracked at all. Such false readings also occur frequently with newer Luxfer cylinders made of the company's proprietary 6061-alloy. For this reason, Luxfer announced in February 2000 that it now recommends that eddy-current devices be used only on 6351-alloy cylinders and not on its newer 6061-alloy cylinders. It is also worth noting that some operators require and charge a fee for eddy-current testing not only on aluminum cylinders, but also steel cylinders. Eddy-current devices were not designed to be used on steel cylinders, and there is no history of SLC in 3AA steel cylinders. However, steel cylinders are susceptible to other types of problems, including internal corrosion, that can lead to ruptures: therefore PSI, Inc. offers training course for inspecting both steel and aluminum cylinders.

It is estimated that some 2,000 eddy-current devices are now being used in North American dive stores, fire departments and hydrostatic test facilities, and the number is growing. While eddy current technology can certainly be a valuable adjunct to visual inspections, in no way does it replace any of the standard visual inspection procedures.

Preventing Explosive Failures

Can SLC related ruptures be stopped? Yes they can. The solution is a team effort by knowledgeable technicians and owners who handle, inspect and use the cylinders. The same solution also applies to other types of damage that may weaken a high- pressure cylinder. By law, when a hydrostatic requalification test is conducted, the retester must perform a visual inspection. An initial inspection should be performed before the actual pressure test to determine whether the cylinder is in proper condition to test. After the pressure test, a further inspection of the threads should be made since the hydrostatic test tends to make cracks more visible. In keeping with long-standing industry practices and the recent Federal recommendations, PSI, Inc. recommends that 6351-alloy SCBA and SCUBA cylinders be visually inspected at least annually by trained inspectors.

Use of a Tank Inspection Pipe (TIP), a recently developed tool, is an excellent way to examine magnified, brightly lit threads in SCUBA and SCBA cylinders

The fill station operator (FSO) and owner also have important roles to play in cylinder safety. At each fill, the FSO determines that the cylinder is within the valid hydrotest period and checks for evidence of a visual inspection within the past year. The FSO should have confidence in the quality of the inspection based on the knowledge, and experience of the inspector. He must also check for evidence of leaking. Cylinder owners are responsible for ensuring that the people inspecting their cylinders are properly trained and qualified. If unexplained pressure loss occurs in a cylinder at any time, the cylinder should immediately be drained and taken to a skilled inspector for a complete examination before being filled again.

All individuals, businesses and agencies that issue or distribute evidence of inspection stickers are obligated to ensure cylinders susceptible to SLC—i.e., those made of 6351-alloy-- receive a meticulous visual inspection before the sticker is applied to signify the cylinder is ready for continued use.

Resources and suppliers of equipment mentioned:

PSI, Inc. (inspection mirrors, lights, training, textbooks and manuals)
6531 NE198th St., Kenmore, WA 98028
425-486-2252 email psicylinders@msn.com

Luxfer Gas Cylinders (manufacturer, training manuals)
3016 Kansas Ave., Riverside, CA 92517
909-684-5110

Catalina Cylinders (manufacturer)
7300 Anaconda Ave., Garden Grove, CA 92641
714-890-0999

Flare Technology (Visual Eddy manufacturer, training)
2869 Old Higgins Road, Elk Grove Village, IL 60007
847-439-7465

Advanced Inspection Technology (Visual Plus distributor, training)
14020 Eagle View Rd., Lake Matthews, CA 92570
909-369-0945

Engineering Inspection Systems (Simple Eddy manufacturer)
Box 40, Coral Ridge Road, Brooks, KY 40169
800-595-1332

Forest City Scuba (TIP manufacturer)
1894 Daimler Road, Rockford, IL 61112
815-398-7119

Additional Reading
INSPECTING CYLINDERS (PSI, Inc.)
SCUBA REPRINT FILE (PSI, Inc.)
LUXFER GUIDE FOR SCUBA CYLINDERS
LUXFER'S SCBA CYLINDER VISUAL INSPECTOR GUIDE