A Review of Composite SCBA Cylinders and DOT Life Extension

1. Introduction

If one were to sit down today and talk with a manufacturer of composite SCBA cylinders, you would come away from that conversation convinced that if a composite cylinder were to be used one day past its 15 year life, it would be like playing Russian roulette with a fully loaded pistol – not a good idea. But have you ever wondered why there aren't more failures of these types of cylinders if they are manufactured to such a close age tolerance? Any statistical distribution would show that some cylinders would fail prior to the 15 year life – that's just the nature of manufacturing. Some cylinders will be weaker than others and fail sooner. The known failures of these cylinders do not support the statement that the life of these cylinders is a hard line at 15 years. A FEMA report from 2001 lists only three failures of composite SCBA's, all of them fiberglass cylinders. One, when it got stuck between the wheels of a firetruck, the other two when phosphoric acid was spilled on them and the acid attacked the fiberglass. None of these failures were caused by age. Furthermore, it has been reported that SCBA breathing packs are used beyond their life by cash strapped fire departments. How have they managed to do that - why has the sky not fallen?

As with all things, an analysis of the situation, along with supporting data, can illuminate the facts, clarify the situation, and lead to rational decisions that can help support the users of these cylinders safely and cost efficiently. So let's pull back the covers on composite cylinders and take a look at how life times have been established.

2. Historical Review

"Those who cannot remember the past are condemned to repeat it." **George Santayana** (1863)

Mr. Santayana got this one right, many years ago – if we don't review what has been done, the same mistakes will be made. In that spirit, how did the 15 year limit for composite cylinders come about? Let's step back in time to see.

The Early Years - 50's, 60's and 70's

One of the first uses of fiber wrapped composites for pressure containment was the Polaris rocket motor casing used by the Navy in the late 1950's and 60's. These were S-glass/epoxy structures, and the mechanical properties were greatly affected by environment and age. Another use of fiber wound composites around this time (1960's and 70's) were Kevlar fiber pressure vessels for NASA space flights. Government agencies spent a lot of time and money on studying glass and Kevlar composite fibers and published many reports on the properties of these fibers. These reports will come into play during the approval considerations for the first SCBA's manufactured in the 1980's. The carbon fibers in use today had yet to be developed for economical commercial use.

1980's - Introduction of Composite SCBA Cylinders

Let's now move into the 1980's. SCBA cylinders made from fiberglass are now being manufactured under DOT-FRP-1, and must be approved for use by the Department of Transportation (DOT). The reports from the 50's, 60's and 70's for Kevlar and glass fibers focus on a phenomenon that these particular fibers have called stress rupture. This happens when the fibers are held at a constant stress level for long periods of time (the higher the stress, the shorter the amount of time to failure), and then over time fail, with no increase in stress. As can be imagined, for pressure vessels this would be bad. A cylinder could fail just sitting in the corner. Based on these reports, the DOT decided that the fiberglass vessels would have a life of 15 years, due to stress rupture concerns. This will be discussed in more detail later.

The 1990's to Today – Carbon Fiber SCBA Cylinders

We'll now flash forward to the 1990's when carbon fiber SCBA cylinders were introduced. Why carbon? Well, it's stronger, resistant to chemicals and solvents, and, exhibits no stress rupture tendencies. Some would claim it's brittle and does not handle impacts well, but SCBA studies have not borne this out. So with the new material, DOT issued a new design document, DOT-CFFC, for the manufacture of carbon fiber composite pressure vessels. In this document, unlike the DOT document for the design of fiberglass cylinders (DOT-FRP-1), an option is given to allow an extra 15 years of life. The better properties of carbon fiber were noticed, and acknowledged, in this document. Since the introduction of carbon fiber pressure vessels, they have the best safety record of any pressure vessel on the market.

So, Why a 15 Year Life?

So in the 80's, a 15 year life was proposed by the manufacturers. Why? The reports from the 60's and 70's were instrumental in the determination of the life of the fiberglass SCBA cylinders. At that time, the usage of composites was for aerospace, so obviously, the reports focused on aerospace structures. NASA designs their pressure vessels for a factor of safety of 2.0 for manned flights, and 1.5 for robotic missions. This results in fiber stresses of 50-70% of ultimate stress – not much room for error.

At these very high stress levels, stress rupture was a concern (please note that no cylinder, whether it be glass, Kevlar or carbon fiber, has failed in operational conditions (not research environments) due to stress rupture during service). The reports provided some insight into the phenomena and how long these vessels would last. This data was used to determine when to retire fiberglass SCBA's as well. Remember, DOT limited the stress in the SCBA fibers to 30%, knowing that at this level, the probability of stress rupture goes to almost zero. If one looks at the theoretically predicted stress rupture graphs in these reports for glass fibers, stress rupture at 30% of ultimate will be over 10,000,000 hours, depending on multiple unknown factors. This puts the 15 years into the "very safe regime" – which is where DOT likes safety to be. Bear in mind that no actual stress rupture data exists except for very high stress/short duration tests, so the predictive nature of these theories for SCBA usage at 30% ultimate stress is unknown, and most likely very, very conservative.

An interesting side note is that when life extension of glass fiber cylinders was proposed to DOT in 2011, DOT mandated that it must be proven that stress rupture is not an issue. Studies were performed that showed the stress in the glass fiber overwrap was actually less than 20% of ultimate stress. At this level, the stress rupture time goes to nearly infinite, based on the theoretical predictions.

So, to conclude this section, <u>30 years ago, fiberglass pressure vessels, using extremely conservative numbers, set the 15 year lifetime limit for SCBA cylinders</u>. What's happened since then? Let's take a poll:

a) A country that has sent men to the moon obviously has come up with a way to build composite cylinders that last longer than 15 years, or
b) Composite cylinder life has stagnated at 15 years

Hint: The "can do" spirit that was shown in the movie, *Apollo 13,* is sorely lacking from composite cylinder life extension.

3. Carbon Fiber Pressure Vessels

We will now look at the lifetime of carbon fiber SCBA pressure vessels. This will focus on two failure regimes that control the life. Stress rupture and fatigue. We'll start with stress rupture.

Stress Rupture Analysis

The DOT-CFFC design document limits the stress on the fiber to 30% of ultimate stress, with a factor of safety of 3.4 (for a cylinder manufactured to operate at 4500 psi, the cylinder can burst at a pressure of no less than 15,300 psi – if we were talking cars, we'd say that's a lot of ponies under the hood). NASA studies have shown that unlike Kevlar and fiberglass, carbon fibers exhibit either very little, or no, stress rupture tendencies. Even better, at 30% of ultimate stress, it shows no stress rupture tendencies over periods of time that far exceed the 30 year life extension period. Stress rupture is not an issue in the life of these cylinders.

Fatigue Life

S-N curves show how a material behaves as it is fatigue cycled at a given stress level. As one might expect, if a material is cycled at a high stress, it doesn't last very many cycles, and vice versa. A typical S-N curve for various materials is shown in Figure 1. In this plot, S is the stress level and N is the number of cycles until the material fails. The plot shows the fatigue life of various materials (carbon fiber, wood, aluminum, steel and fiberglass). Lucky for us, SCBA cylinders, even though they hold very high pressures, are built so they really are not stressed that much.

When cylinders are manufactured to the factor of safety that is specified in DOT-CFFC, the fatigue life goes almost to infinity. This is illustrated in Figure 1. Think of the 30% of ultimate on the vertical axis as filling the cylinder to 4500 psi, and the cycles to failure on the horizontal axis as the number of times the cylinder is filled and emptied. The area in light gray shows the stress in a carbon fiber at the design criteria in DOT-CFFC. It can be observed that the black line for the carbon composite has not intersected the 30% of ultimate line. This means we still haven't reached the number of cycles that would fail the vessel. The plot shown ends at 10,000,000 cycles, or, if the cylinder is filled on average once a day, this would be a life of, drum roll please, 27,397 years (13,698.5 if we went with a factor of 2 of safety). Since the two lines do not meet at this point, it's actually even quite longer than this somewhat staggering number. Bear in mind that metallic DOT 3AL cylinders have infinite life, and carbon fiber far outperforms aluminum at the 30% stress levels. One can see that in an aerospace application (dark gray area) the lifetime can be very short due to the high stress the fiber sees.

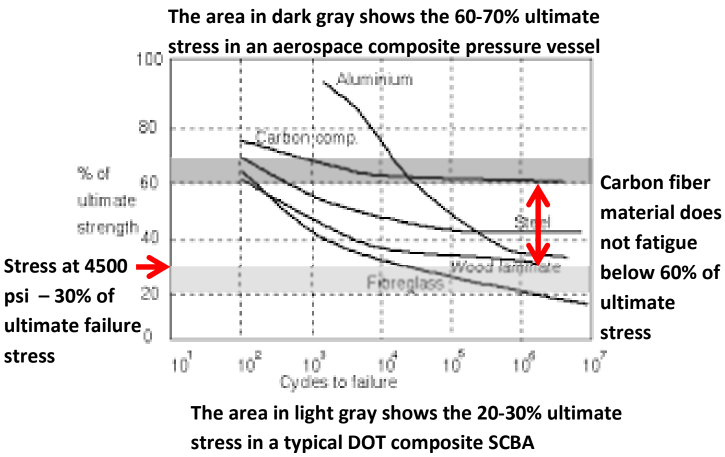

Figure 1. S-N curves for various materials.

<u>So to summarize, carbon fiber vessels have no stress rupture issues at the design stress allowed in DOT-CFFC and they have no fatigue life issues at this design stress, so the life limitation imposed by the fiberglass vessels has no relation to the life of carbon fiber vessels. Comparing these two is the same as comparing apples and oranges. The 15 year life of carbon fiber vessels was purely a carry-over from the fiberglass vessels, and not based on any theoretical or test data.</u>

So let's do a quick review of the facts:

- The stress levels in SCBA cylinders are at least a factor of 2 lower than those used in the government studies on Kevlar and glass fiber vessels used to set the 15 year life. As can be seen in the above figure, this means fatigue life goes from hundreds or thousands of hours, to infinite life.
- The government studies used to study stress rupture were on fiberglass and Kevlar. Cylinders are now manufactured from carbon fibers, which have no stress rupture dependencies.
- No Kevlar or glass fiber vessel has ever failed in service from stress rupture, aerospace application or not.
- The 15 year life for carbon fiber vessels is not based on any experimental or historical data that was performed using carbon fiber data.

So based off of this, factually speaking, cylinders manufactured under DOT-CFFC are the safest (much safer than metallic cylinders), longest life cylinders on the planet. So this begs the question, why do we throw these perfectly good cylinders away, and keep the metallic cylinders, some of which have been in use for over 100 years? Let's delve into the DOT special permits for these composite cylinders to see if there's an answer there.

4. Special Permits for Composite Cylinder Manufacturing

Special permits (SP's) are what the DOT uses to allow users and manufacturers to deviate from the Code of Federal Regulations, or CFR, for materials transported via road, rail or air. This is done to keep the general public safe while travelling. From the CFR, "*The Code of Federal Regulations is a codification of the general and permanent rules published in the Federal Register by the Executive departments and agencies of the Federal Government*." Basically, you need to follow the rules in the CFR for your specific application; otherwise, you could end up in federal prison. But, maybe you've found a way to make a lighter pressure vessel that holds more pressure that's not included in the list in the CFR. How do you get that new cylinder into the public domain? Well, you can write a special permit application, and if approved by the DOT, you can manufacture the vessel. DOT-SP 10945 is an example of this. This SP allows a certain company to manufacture carbon fiber pressure vessels. Also, in this special permit, it states that the cylinders manufactured under this SP are not authorized for use fifteen (15) years after the date of manufacture. So, that's that and we're done – these SCBA cylinders are good for only 15 years, and then we plant them in the local landfill.

Well, hold on, no need to get hasty. As discussed earlier, there is a design document, DOT-CFFC, which all manufacturers of carbon fiber SCBA cylinders must follow, which has more information on life (as a side note, DOT allows cylinders to be designed to ISO 11119-2 as well). This document specifies materials and manufacturing requirements to make a DOT carbon fiber composite pressure vessel, and SP 10945 references this document. In DOT-CFFC, section 3, it states:

*"**<u>SERVICE LIFE:</u>** Cylinder service life is 15 years from the date of manufacture. The Associate Administrator for Hazardous Material Safety (AAHMS) may approve an extension of cylinder service life up to <u>a total service life of 30 years</u>. **A service life extension approval is made by modification to the exemption authorizing cylinder construction**"*

So the special permits that these cylinders are manufactured under are not carved in stone, but can be modified to accommodate new understandings and information about these cylinders, and allow extended life if it can be proven to be safe to the DOT (which, by the way, has been done). In fact, modifications are made to SP's all the time as new information rolls in and better and safer (or as safe) ways to do things are found. If you look at SP 10945, as of the writing of this document, it's on its 26th revision – so there's no claiming from the manufacturers that they didn't know about this feature.

So the special permit, while the controlling document for manufacture and usage of these cylinders, may not really be the ultimate controlling document for disposing of cylinders at 15 years.

5. Testing, Data and Inspection for Life Extension

So why are manufacturers not taking advantage of DOT-CFFC-3 to extend the life of these cylinders? That's an excellent question. Below is one manufacturers' stance on their attempt at life extension.

> *"For more than a decade, [COMPANY NAME] has actively researched this matter and participated in detailed deliberations involving DOT, the Compressed Gas Association (CGA) and other cylinder manufacturers to obtain a service-life extension. However, DOT declined to approve life extension for these cylinders. Consequently, we decided not to pursue this effort further and to take a different approach to providing cylinders with longer service life.*
>
> ***Background***
> *In 1996, DOT issued its CCFC-1 [sic] standard that established basic requirements for design, manufacture and performance of cylinders consisting of seamless aluminum liners over-wrapped with structural layers of filament-wound carbon fiber and epoxy composite material. At that time, DOT offered the possibility of extending the 15-year service life of such cylinders "up to a total service life of 30 years." To obtain an extension, [COMPANY NAME] was required to submit for DOT approval a "Service Life Extension Plan" that would meet certain criteria. Soon after CCFC-1 [sic] was issued, [COMPANY NAME] and other U.S. cylinder manufacturers individually submitted such life-extension plans to DOT. However, DOT accepted none of these plans and declined to extend cylinder service life.*
>
> *In response, cylinder manufacturers attempted an industry-wide approach to obtain DOT approval under the auspices of a special CGA task group, but the service life was not extended.*
>
> ***[COMPANY NAME] longer-life composite cylinder***
> *In 2006, [COMPANY NAME] began developing a new, more robust cylinder designed for a service life longer than 15 years. This new cylinder was based on ISO 11119, an international design standard. In August 2008, DOT granted [COMPANY NAME] special permit xxxxx (SPxxxxx), which authorizes the manufacture of these cylinders for use in the United States.*
>
> *While cylinders made under SPxxxxx are designed for service lives as long as 30 years, the special permit explicitly sets forth certain testing and validation requirements that must be met before the service life of any cylinder may be extended beyond 15 years. As of the issue date of this bulletin, no cylinder manufactured under SPxxxxx has thus far been approved for a service life longer than 15 years since these cylinders have not yet reached the age at which their service life will be eligible for extension."*

Based off of this statement on a manufacturers' website, the DOT, while saying cylinders could be extended to 30 years, did not allow the life extension to occur. Plus, according to this, the only way to get a 30-year life is to buy a new cylinder that, mind you, may not be approved for 30 years of life. Earlier, we showed through experimental data that these cylinders have infinite life. So what happened?

Obviously, manufacturers originally felt that these cylinders could withstand another 15 years of usage, as they submitted plans and data. But, as we all know, final results are proportional to the level of effort. In reviewing the data submissions of the manufacturers to DOT (all data submitted to DOT is available to the public, unless marked confidential), the testing programs developed and the data submitted was a half-hearted effort, at best, for life extension by companies that have a net revenue in the hundreds of millions. There was no adherence to either a national or international standard, in terms of cycling, environmental or damage effects. If you notice in the above statement, they did not consult outside testing agencies on how to develop a test program that would satisfy DOT. In fact, there is no mention that they even discussed with DOT what the sticky wickets were. In our discussions with DOT in 2011 concerning life extension of SCBA cylinders for the US Navy, there were two major issues that DOT felt had to be addressed, 1) that stress rupture would not be an issue, and 2) an inspection method that would conclusively identify damaged cylinders would need to be developed and applied. Neither of these were addressed in the manufacturers submissions to DOT's satisfaction, hence, manufacturers were denied life extension, and the market carried on with the 15 year cylinder life that was mandated via the fiberglass cylinders.

But, fortunately, or unfortunately, depending on which side of the fence you're on, free markets have a way of correcting themselves. Manufacturers of shaving blades have priced these products at a very lucrative price point (the "I'll give you the pipe but sell you the crack cocaine" approach) for years. But this approach ended up opening up the market to other manufacturers to sell blades much cheaper. The same is true for the toner market for printers and copiers, or even for the metallic cylinder market. The same shift is beginning to occur in this market. Composite SCBA cylinders are expensive, 4-10 times as much as a metallic cylinder, but with only a 15 year life (granted, they do hold twice as much pressure). At some point, someone will ask "Why?", and "What can I do about this?", and "Are these cylinders really worn out?" The US Navy arrived at these same questions in the early 2000's. They had a very large number of these cylinders coming up on their 15 year life, and the cost savings would be substantial if they could extend the life. The Navy decided to fund a study to determine if these cylinders would meet the ISO 11119-2 requirements for life extension outlined in the life extension programs in special permits currently accepted by DOT. A test program using end-of-life (EOL) cylinders was developed that covered:

- Measurement of residual stress in the composite to determine if stress rupture was an issue
- Burst of "as is" EOL cylinders
- Notch damaged cylinders
- Impact damaged cylinders
- Fatigue cycling for 20 years of extended life
- Burst of fatigued cylinders

The results showed that the end-of-life (EOL) cylinders would easily meet the ISO "at manufacture" test requirements, and thus any of the SP requirements for life extension. Even better, it was found that the cylinders actually were at around 20% of the ultimate stress of the fiber, so the 27,397 year life is extremely conservative. DOT had the same program applied to civilian SCBA cylinders, with the exact same results. The two programs experimentally and statistically proved each other out. Programs covering acid and salt exposure, and infinite life fatigue testing were also performed, and all cylinders met the requirements for life extension up to ***infinite life*** (not just 15 years, but infinite, in case you missed it). To put it simply, the cylinder performance had not degraded from "at manufacture", i.e., the cylinders were still brand new. So that's the mechanical testing. What about an NDE method that could verify each cylinder at its retest date? As it turns out, one had just been approved by the American Society of Mechanical Engineers (ASME). This is the group that controls all static installations of pressure vessels.

The real breakthrough that ensured the safety of the cylinders was the NDE technology that was applied. Modal acoustic emission (MAE) was used to monitor all fatigue and burst tested cylinders. More traditional NDE methods, such as X-ray and ultrasound, cannot detect the failure of fibers and fiber bundles, the structural members that give composites their strength. These failures are too small to be detectable economically with these methods. However, MAE is ideally suited for this, as it detects the propagating mechanical wave created by the fiber failures as the cylinders are pressurized to test pressure – think earthquake detection on a very small scale. It is very sensitive to the exact failure mode that causes cylinders to rupture. This method was able to detect damage and also predict burst pressure. This technique was developed under ASME Section 10, Mandatory Appendix 8, for the qualification of high pressure composite cylinders for hydrogen storage. The technology has also been adopted by the National Board Inspection Code (NBIC) for the recertification of the composite hydrogen pressure vessels, in situ. So you can see, this inspection and requalification method has been vetted by some of the most distinguished committees in the US (voting membership on the ASME committee must be approved by the board based on credentials). The MAE method was able to detect vessels that burst below minimum design burst pressure that hydrostatic testing missed. Currently the database of tested cylinders is over 400. That may not sound like much when there are millions of composite SCBA cylinders out there, but this leads to a 98% level of confidence – that's as good as it gets. So, the upshot is that 15-year old cylinders are as good as new ones.

Based on these Navy and DOT research programs, SP's 15720, 16190 and 16343 have been issued by the DOT for either the life extension, or requalification, of SCBA cylinders using modal acoustic emission testing. Composite cylinders are now in use that have been life extended or requalified using MAE.

6. Aluminum Liner/Threads

So with all of that, the composite overwrap of the SCBA carbon fiber cylinders has been shown to easily meet a 30 year life due to the design requirements of DOT-CFFC. But, there's still one more component to keep a composite cylinder from leaking - the aluminum liner. Will it last for 30 years, and what happens if it fails?

Manufacturers have moved on from the composite failing and are now claiming the aluminum liner will never handle the extra 15 years. They say fatigue cracks will grow through the wall, and the cylinder will not hold air. This one actually could be true (finally!). However, the secret that no one will tell you is that this particular failure can occur at one year, two years, 10 years, or any year. Once water is introduced to the interior of the cylinder (and this is done at manufacture, to autofrettage the cylinder), studies show that the fatigue life is greatly shortened due to corrosion of the liner. But, it seems like this failure mode doesn't happen very often (at least it's not reported very often). Why not? It turns out that fracture mechanics is a wonderful thing. What keeps aluminum liners from leaking is the hydrostatic test (the only good thing that this test does in composite cylinders). This high pressure blunts the cracks that form due to corrosion from the water introduced during the hydrostatic test, and keeps them from growing. Eureka! If you take care of the cylinder, and make sure water doesn't sit in it, and you hydro it, you get near infinite life – just like the metallic cylinders. As a final note, if the liner were to leak, the cylinder does not go BOOM! Cylinders are designed for leak-before-burst. This means that a flaw will not grow uncontrollably if the structure of the cylinder has not been compromised, i.e., the wall has not been ground down due to being scraped over the road after it got stuck between the wheels of the fire truck. The cylinder will just leak (all you hear is a hiss and not a boom). Many steel cylinders in use for carbon dioxide storage fail this way due to water intrusion forming carbonic acid. The acid etches through the grain boundaries and forms a small pinhole. When filled, the cylinder leaks, as long as the minimum design wall thickness criteria is met (i.e., the wall hasn't thinned out too much due to corrosion in the area around the pinhole).

Finally, the only thing left is the wear of the threads. So, just for reference, aluminum metallic cylinders (DOT 3AL specification) have been in use for over 30 years in the medical industry, and the threads have not worn out due to valve removal and insertion for requalification or valve replacement. This should occur at about the same rate as SCBA cylinders, so that would indicate that the SCBA cylinder threads should last at least the same amount of time.

7. Data Showing Cylinder Failure After 15 Years

The data and reports for life extension are publically available, but where are the data and reports that show it's not safe? That's a good question.

Manufacturers are actively petitioning the DOT to not allow life extension on the basis that the cylinders are not designed for extended life. As of the writing of this paper, no data has been presented showing any inherent danger in the life extension of DOT-CFFC cylinders. There are multiple reports on the DOT website that show the cylinders are safe to life extend, and at 30+ years of life, still exceed the "at manufacture" requirements.

8. Conclusions

This paper was written to provide a quick insight as to how DOT composite cylinders are specified and manufactured, and the level of safety that is engineered into these vessels. A lot of material has been covered in this paper, with much of it arcane and up until now, only perused by a handful of people (and I'm sure that after reading this you now understand why). But, this information is important to know so that decisions are based on fact and not hearsay. Why a 15 year life? Why is life extension bad? Where is the data to support the conclusion that life extension is bad? Hopefully, these are the questions that the reader walks away with, and asks when unnecessarily disposing of SCBA cylinders at 15 years.

Provided below is a quick review of the facts stated in the writings above that will summarize the salient points in the paper.

- Over 300 end-of-life (15 years old) DOT-CFFC cylinders have been tested to ISO 11119-2 “at manufacture” acceptance requirements, and passed.
- Three years of intensive studies requested by the US Navy and DOT which followed ISO 11119-2 “at manufacture” testing procedures have conclusively shown that the DOT-CFFC cylinders can be safely used for at least 15 years beyond their current lifetimes.
- The tests showed that the cylinders were still meeting “at manufacture” design requirements, even after 15 years of hard use (many of the cylinders in the studies were from large metropolitan fire departments and had seen extensive use in the field).
- Current failures have been due to mishandling of the cylinders, not due to failure of the cylinder due to fatigue.
- DOT-CFFC cylinders have been fatigued up to 24,000 cycles at developed pressure (5192 psi for a cylinder with an operating pressure of 4500 psi), and did not have liner leaks. This number of cycles, according to ISO 11119-2, results in an infinite life cylinder.
- A new inspection method, modal acoustic emission, has been applied to the requalification and life extension testing of composite cylinders. This method has conclusively shown the ability to detect substandard cylinders that hydrostatic testing misses.
- DOT has issued SP 15720, 16190 and 16343 for life extension and requalification using modal acoustic emission.
- Cylinders have been life extended and requalified using these special permits.
- No data has been presented that shows SCBA DOT-CFFC cylinders are not safe to life extend.

The points above drive home the inherent safety of the DOT-CFFC pressure vessels, whether they are fresh from the manufacturer, or at the end of their 30-year life. Life extension is a way to keep perfectly good cylinders out of landfills and in the hands of users in an economical and safe manner.

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