Experimental verification of structural integrity for bellows as spacecraft components

S. Kébreau[1a], Dr. P. Cambrésy[1]
[1] *EADS Astrium, Bremen, Germany*

0. Abstract

In space vehicles' design, bellows are indispensable components in pressurized systems combining functional features with structural requirements. Their structural integrity has to be demonstrated as failure of the bellows would have catastrophic consequences for the mission.

Due to both the complexity of the multi-ply bellows under investigation and their nominal life spectrum, the structural integrity verification was performed experimentally by fatigue test. The test set-up was designed to simulate the real loading conditions of the bellows: axial compression and pressure peaks applied in different combinations.

The structural health state was monitored in real-time by stiffness measurements, indicating changes of the bellows' structural characteristics. Helium leakage tests were furthermore performed to screen for the presence of through cracks resulting from the fatigue loading.

None of the tested bellows failed during the test campaign, leading to a significant margin compared to four times nominal fatigue life and confirming the structural integrity of the bellows.

1. Nomenclature

l_0	initial length	F_a	actuator force
p_1	pressure in chamber 1	N	cycle number
p_2	pressure in chamber 2	N_{sw}	switching cycle number
p_{buckle}	critical buckling pressure	N_{wh}	water hammer cycle number
s_{mean}	mean stress	Q_{leak}	leakage rate
t	time		
x	displacement coordinate		
Δx	displacement amplitude		

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[a] E-mail: sebastian.kebreau@astrium.eads.net

2. Introduction

The aspect of safety and reliability plays an important role in aerospace since a component or structure failure can lead to the loss of humans and / or to a financial loss caused by the lost mission. Together with the impossibility of taking countermeasures once a spacecraft has been launched this has led to the establishment of damage tolerance principles in aerospace aiming to demonstrate the capability of a structure to withstand the transportation, ground preparation, test and full mission loads without degradation.

The ECSS-E-30-01A [1] is the state of the art standard defining the approaches for structural integrity verification of spacecraft systems and components in Europe. The damage tolerance design shall be demonstrated for each structure or component considering four times the dimensioning life. Depending on the part design, different approaches are applicable to justify their structural integrity. The most common ones are “fail safe” and “safe life” principles. While “fail safe” is applicable for a redundantly designed structure which can sustain the loads during the mission life after the loss of one load path, the “safe life” approach aims to verify that the single structure will not fail during the whole service life. This approach is generally applicable for single load path structures and especially for pressurized systems, namely tanks, lines and their components as a failure in a propulsion system could lead directly to hazardous circumstances.

In this context, the design and justification of bellows as they appear for instance in valve systems is a challenging task. Metallic bellows are often preferred for applications in propellant systems, since they allow combining the advantages of metallic tubes (the long-term compatibility with many reactive fluids and weldability) with the flexibility of rubber tubes. A typical application field for bellows are internal components of latching valves where pressurized chambers have to be sealed against each other while still enabling the movement of the valve components.

For the structural verification of bellows a standard is available [4]. Also elastic-plastic finite element analyses and the evaluation of plastic strain concentration effects are promising, [5]. However, these methods are not applicable for the welded multi-ply bellows under investigation. Analytical justification of the present bellows is extremely difficult due to the complex geometry and local plasticity.

This paper presents the structural integrity verification of welded multi-ply bellows based on experimental justification. Several bellows initial conditions and load combinations are investigated in the fatigue tests.

3. Description of bellows and boundary conditions

3.1. Components

Different – partly contradicting – requirements for stiffness, dimensions and fluid compatibility led to the design of welded multi-ply bellows. Fig. 3.1 gives a typical side view of the investigated bellows of a typical latching valve. The bellows have ten free convolutions, each made of three plies of commercially pure titanium. The three plies are welded together using Tungsten Inert Gas welding.

Due to their design, the bellows tend to buckle (Fig. 3.2) when loaded to a critical static pressure p_{buckle}. This critical pressure level can be reached e.g. during the performance of tests. Investigations of this buckling phenomenon have been performed in a coupled test programme but are not part of this paper.

Figure 3.1: Bellows with flanges

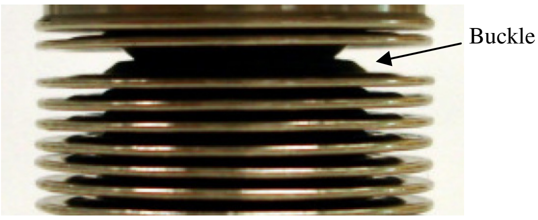

Figure 3.2: Buckled convolution of bellows

The presence of a buckle was rated as conservative compared to no buckle since it leads to an increase of the bellows initial length. Under the same boundary conditions (defined by the valve mechanism and dimensions) buckled bellows are thus submitted to a prestress compared to the unbuckled bellows. This prestress acts in a similar manner to the axial compressive load cycles. From a damage standpoint, the presence of a buckle thus corresponds to an increase of mean stress s_{mean} apart from further local effects notably in the weld region. Testing at higher mean stress is assumed to result in a conservative S/N curve, [2].

3.2. Load types

Being part of a complex propulsion system, the bellows are subjected to two main load types. The first load type (load type 1) are global compression load cycles of the bellows caused by opening and closing of the valve, named hereafter "switching". These loads are introduced at both ends of the bellows leading to a global stress being transferred through the bellows convolutions. The second load type (load type 2) results from differential pressure cycles between internal and external bellows chambers; see also Fig. 4.2. This acts on the sidewalls of the bellows and appears dynamically in the form of "water hammer" pressure cycles. This load case is related to the firing of the thrusters of the propulsion system.

4. Test philosophy

A classical safe life verification based on defined initial crack sizes is not applicable since non destructive inspections are not feasible due to the thin wall thickness of the bellows sidewalls and the accessibility. The aim of this fatigue test is rather to demonstrate the structural integrity of the bellows considering their dimensioning life, using a simplified set up compared to the complex latching valve system. The success criterion is in this case the leak-proof criterion at the end of dimensioning life, including the scatter factor of four in cycle numbers. This section presents the test setup and the performed test programme.

4.1. Test setup

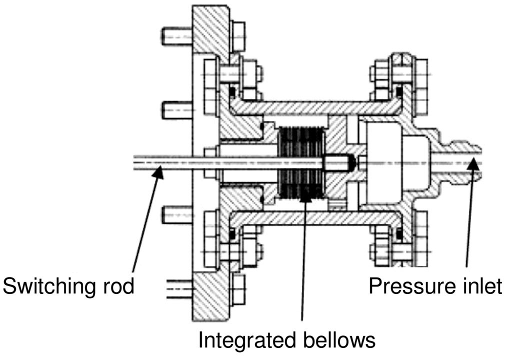

Figure 4.1: Test cell with integrated bellows

The test setup was designed to enable pressure peak application and axial compression whilst capturing the bellows displacement Δx, the bellows rod force $F_a = F_a(x)$ and the pressure level p_2. The switching rod permits the transmission of the compression loading. The bellows rod force serves also as stiffness indicator. The test sample integrated in the test setup is shown in Fig 4.1. The cylindrical test jig is equipped with a pressure inlet and the axial displacement rod. This test cell is part of the whole pressurization, displacement and data acquisition system shown in Fig. 4.2. The maximum static pressure difference between the two chambers is $p_2 - p_1 = 40$ bar, usable for helium leakage checks. For dynamic pressure loads, peaks of 10 bar on $p_2 - p_1 = 25$ bar can be reached. For axial displacement x during switching, the rod can be moved in a range of +0 / -2.5 mm.

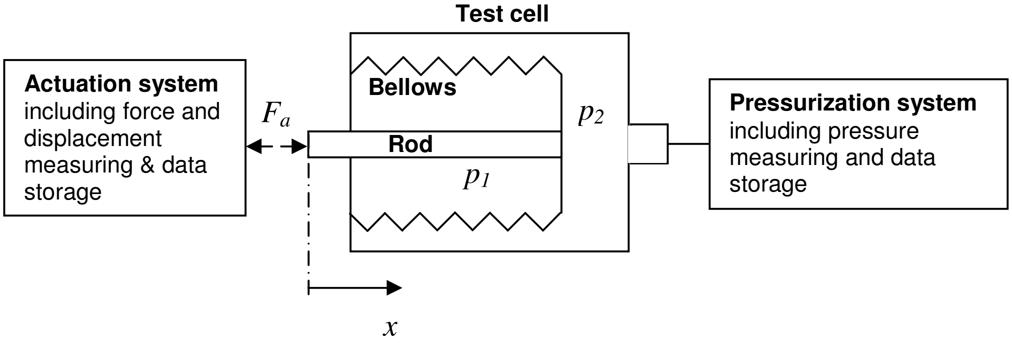

Figure 4.2: Test cell with integrated bellows

4.2. Specimen preparation

For the fatigue test, the bellows shall be representative of the actual hardware. Therefore, all tested bellows possess one buckle when entering the fatigue test. The buckle preparation was performed in a similar test setup with one single pressure cycle up to p_{buckle}.

4.3. Load spectra

The definition of the load spectra was driven by interest in the following:

- the criticality of load type 1 alone (switching)
- the effect of the interaction of sequentially applied load type 1 (switching cycles) and load type 2 (water hammer cycles)
- the structural integrity of the bellows under the bellows dimensioning life application (consisting of both load types)

Two load spectra were defined as follows:

4.3.1. Type A: Investigation of pure switching

According to the flight usage, a switching cycle number of $N_{\text{sw}} = 150$ has to be assumed per life. A scatter factor of four must be taken into account. The displacement amplitude according to the valve dimensions is $\Delta x / l_0 = 10$ %. The dynamics of the rod are approximated with a nearly rectangular signal. The bellows health state is demonstrated at each life end ($N_{\text{sw}} = 150$) by a stiffness check and a helium leakage check. Both tests are presented in section 5.1. Fig. 4.3 shows schematically one life of type A loads with the displacement loading in continuous and the pressure load in dotted line.

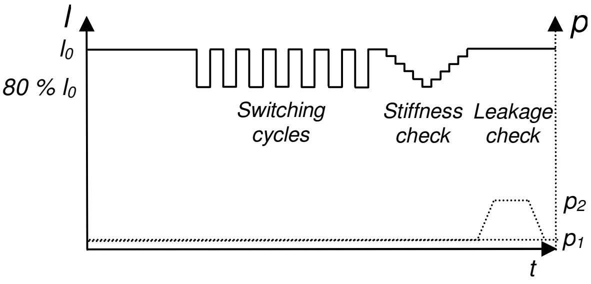

Fig. 4.3: Schematic displacement cycles during one life including checks

4.3.2. Type B: Investigation of combined switching and water hammer periods

The nominal bellows life consists of a random combination of water hammer and switching cycles. A simplified combination had to be chosen for the fatigue test: One life of water hammer pressure cycles is followed by one life of switching cycles. In between, structural health checks are performed. The number of water hammer cycles per life amounts to 260 000, grouped into four different pressure levels (between 3 and 10 bar added to the static pressure difference $p_2 - p_1 = 25$ bar). This scheme is visualized in Fig. 4.4. After the performance of four combined water hammer and switching lives 15 additional switching lives according to type A are performed.

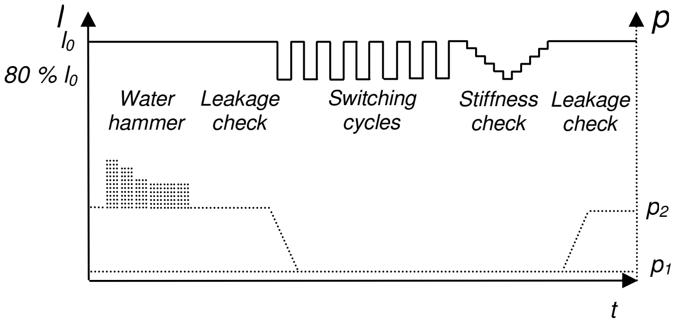

Fig. 4.4: Schematic displacement / pressure cycles during one nominal life including checks

4.3.3. Definition of the test programme

The presented load spectra according to type A and B were used to establish the basis for the fatigue test programme. Further variations were performed, i.e. bellows with a second buckle for a part of the spectrum or the removal of the low pressure peak cycles. Eight bellows were tested in different scenarios. The various test groups are summarized in table 4.1. The pressure cycles from leakage test and the switching cycles from stiffness test are negligible from a damage standpoint.

Group label	Specimen identification number	Number of buckles at fatigue life beginning	Water hammer cycles	Switching cycles
A1	1	1	- / -	$2.0 \bullet 10^3$
A2	2	1	- / -	$4.7 \bullet 10^3$
B1	3 and 4	1	4 x $2.4 \bullet 10^3$ @ 10 bar 4 x $3.5 \bullet 10^3$ @ 7 bar 4 x $5.3 \bullet 10^4$ @ 4 bar 4 x $1.6 \bullet 10^5$ @ 3 bar	4 x 150 + 15 x 150
B2	5 and 6	1	4 x $2.4 \bullet 10^3$ @ 10 bar 4 x $3.5 \bullet 10^3$ @ 7 bar 4 x $5.3 \bullet 10^4$ @ 4 bar	4 x 150 + 15 x 150
B3	7 and 8	1 (2 for the last 15 switching lives)	4 x $2.4 \bullet 10^3$ @ 10 bar 4 x $3.5 \bullet 10^3$ @ 7 bar 4 x $5.3 \bullet 10^4$ @ 4 bar	4 x 150 + 15 x 150

Table 4.1: Overview of load spectra groups

5. Results

5.1. Evaluation methods

By definition, a leakage of the bellows does not appear before the through-cracking of all three plies. Two methods, namely stiffness measurement and helium leakage check, were applied to check the structural health of the bellows. The relevant success criterion was the no-leakage state at the end of life.

5.1.1. Stiffness measurement

Measurements of the axial bellows stiffness were performed at regular milestones of the fatigue life. The stiffness was chosen to characterize the bellows condition because:

- dismounting of the bellows is not necessary,
- formation of a buckle is coupled with a change of the bellows stiffness and
- structural bellows modification could be monitored, i.e. separation of plies of bellows or significant cracks.

The stiffness test consists of a stepwise compressive then tensile displacement (see also Fig. 4.3 & 4.4) of the switching rod while capturing the reacting force. Two typical $F_a(x(t))$ stiffness curves are given in Fig. 5.1 for bellows with one and two buckles. While the force increase for bellows with one buckle is linear for each step, a further buckle becomes clearly visible by means of a non linear increase / decrease of force for the compressed bellows (in the middle region of the diagram).

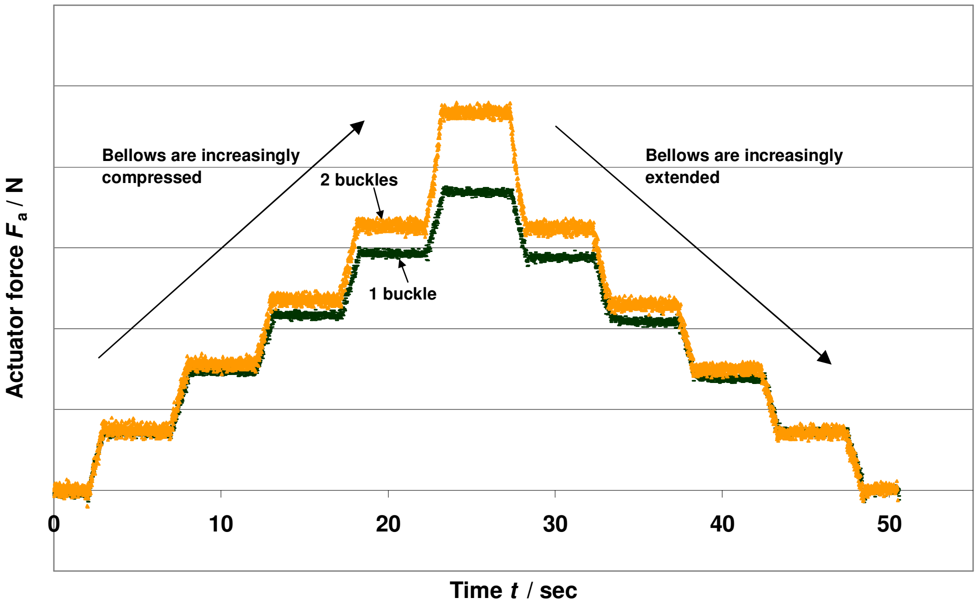

Fig. 5.1: Comparison of stiffness for bellows with one and two buckles

5.1.2. Helium leakage check

Additional helium leakage checks were performed at regular milestones of the fatigue life in order to detect cracks through the three plies of the bellows. Leakage checks with helium gas are a standard method, see also [6], and have been being applied for decades in technical applications, [3]. Here, the "pressure testing" method, applying overpressure and a sniffer, is used. This is less accurate than vacuum testing methods but reaches leak rates in the order of $Q_{\text{leak}} = 10^{-7}$ mbar l / sec. This covers the defined allowable leakage rate of the bellows. The applied helium pressure level was $p_2 - p_1 = 25$ bar. No buckle can be formed by this pressure level.

5.2. Fatigue test results

The stiffness results of the groups A1 & A2 are similar. No obvious stiffness change was observed throughout the whole applied spectrum, shown for A1 in Fig. 5.2.

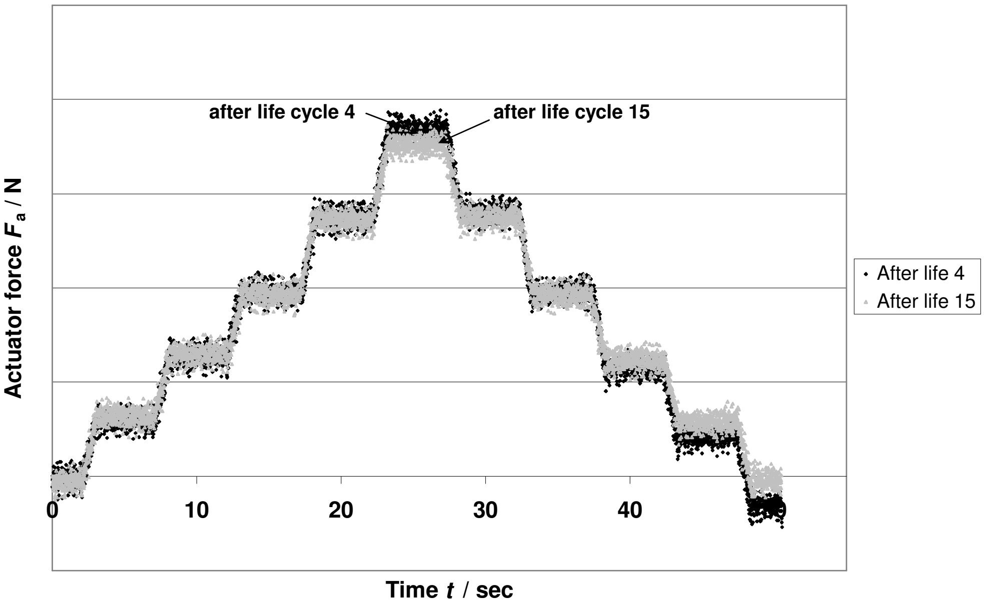

Fig. 5.2: Stiffness checks after pure switching lives

The results of test group B1 are difficult to interpret for the following reasons:

- The two specimens present non-homogeneous results.
- The bellows No. 3 presents friction marks on the seat of the bellows.
- A second buckle was formed during the test in the bellows No. 4. The stiffness curve shows an abrupt increase of rod force; see Fig. 5.3 where the stiffness is shown after the nominal combined life and further switching cycles.

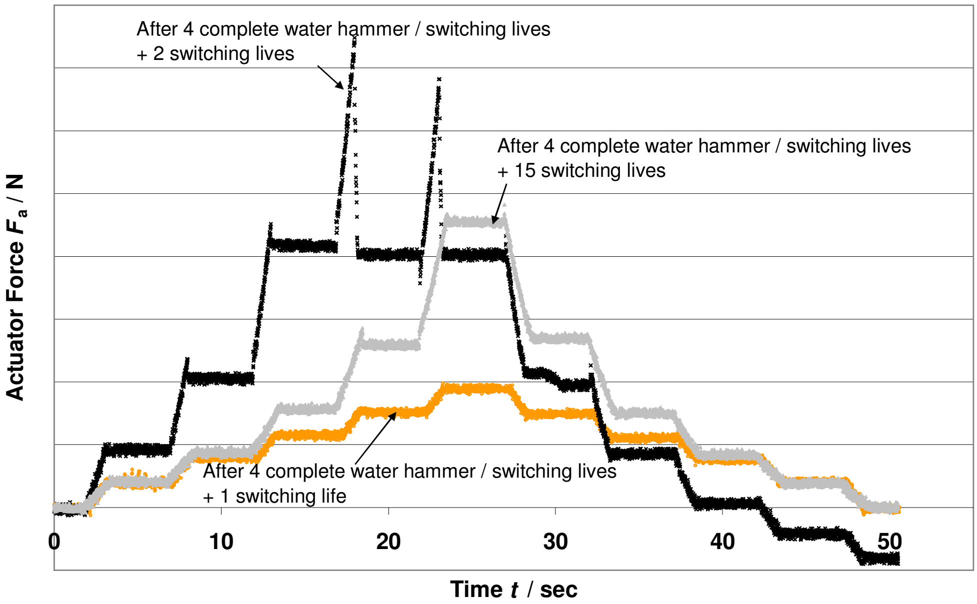

Figure 5.3: Stiffness after switching lives after previous four nominal lives

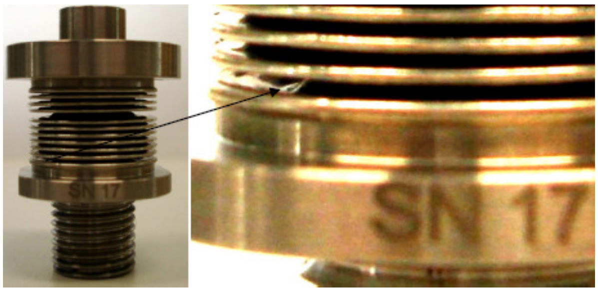

Figure 5.4:
Additional buckle after load application

The second buckle was confirmed visually, see Fig. 5.4. Even with this additional buckle, the structural integrity of the bellows was demonstrated as no leakage occurred within the following switching lives.

In the groups B2 and B3, the high amount of low (3 bar) water hammer cycles was neglected. The test results are comparable for the four specimens and no stiffness changes were observed, neither within the four nominal lives nor during the additionally performed 15 switching lives. Stiffness curves are therefore not presented here.

The evaluation of stiffness curves can be summarized as follows:

- The influence of switching cycles is smaller than expected. The application of 15 pure switching lives did not result in any stiffness changes even after the performance of the water hammer cycles.
- Comparing the results of test group B1 with B2 / B3 it cannot be concluded with certainty that the low pressure peaks (3 bar) are non-damaging.
- The stiffness measurements are a good indicator for the formation of buckles, as expected.

The defined lives including the scatter factor of four were exceeded by all specimens. No specimen failed in the test campaign as the helium leakage test did not give any evidence of a through crack.

6. Conclusion and future work

In the fatigue programme different load spectra were applied on several bellows configurations. It was demonstrated that in all scenarios the bellows do not fail. Some evidence is given for the switching cycles being less severe than originally expected. The survival of all investigated bellows does not allow the determination of the damaging mechanism in the bellows. For further comprehension it is therefore proposed to cut bellows after life application since the stiffness has also proven its limitation in information. Furthermore a focus on dedicated load types while testing until failure would be meaningful. Especially the high number of water hammer cycles remains a challenge.

7. Acknowledgement

The authors would like to thank Mr. G. Sinnema and Dr. T. Ghidini from ESA / ESTEC as well as Mr. E. Erben from Astrium GmbH / Bremen for the valuable exchange of ideas and technical support during the test campaign. Moreover, the authors would like to express their thanks to machtWissen.de AG for the preparation and performance of the tests. Furthermore, many thanks go to Mr. T. Maier from Astrium GmbH / Lampoldshausen for the preparation of the bellows. Finally, the authors would like to thank Dr. M. Vorel from Astrium GmbH / Bremen for his availability and technical support during the test campaign and the preparation of the present document.

8. Literature

[1] European Cooperation for Space Standardization: ECSS-E-30-01A[b]: Space Engineering / Fracture Control; Noordwijk; 1999
[2] Dowling, Norman E.: Mechanical Behavior of Materials; Engineering Methods for Deformation, Fracture, and Fatigue; Pearson Prentice Hall; New Jersey; 2007
[3] Young, Early W.: The use of a helium mass spectrometer leak detector; NASA Technical Memorandum; NASA TM X-978; July 1964
[4] Expansion Joint Manufacturers Association: Standards of the Expansion Joint Manufacturers Association, Inc.; 7th ed., New York; 1998
[5] Becht, C.: Fatigue of bellows, a new design approach; International Journal of Pressure Vessels and Piping; New Jersey; 2000, pp. 843-850
[6] European Standard: DIN EN 13185: 2001-07: Non-destructive testing – Leak testing – Tracer gas method

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[b] Will be superseded by ECSS-E-ST-32-01