Convolution UHV Leak Failure Rate Estimate

- **v1**

Initial Release
Estimation of the UHV leak failure rate of convoluted tubing based on Bellows (expansion joint) leak failure rates from the literature, and comments on the potential implications for Cosmic Explorer (CE).
Dennis Coyne, 22-Nov-2024

- **v2**

Dennis Coyne, 5-Dec-2024

Introduction

The Cosmic Explorer (CE) and Einstein Telescope (ET) projects are considering the use of corrugated, thin-walled, tubing for their beam tubes as an alternative to thick-walled, smooth, straight piping or ring-stiffened piping (for a number of reasons; see for example https://dcc.ligo.org/LIGO-T2400337). The unstiffened and ring-stiffened tubes require bellows (expansion joints) to allow for expansion during vacuum bakeouts, as well as adjustments for alignment. The corrugated tube alternative does not require these discrete bellows (expansion joints) since they are (in effect) long bellows. However, the corrugated tube option incorporates many more convolutions to the overall assembly than a set of discrete bellows. If reliability against UHV leaks scales with convolutions, then the reliability of the system may be insufficient.

The convolutions are typically formed by either mechanical expansion or hydroforming. In either case, high plastic strains are induced in the forming of the bellows. Regardless of the method employed in forming the initial cylindrical shell (roll formed or spiral welded), axisymmetric convolutions will cross the weld. The heat affected zone (HAZ) of the weld is often the initiation site of microcracks leading to leaks later during the operational phase of the system. (If the tube is spiral welded and also spirally corrugated, at the same helix angle, then the corrugations would not cross the weld.)

The CERN CE vacuum team have demonstrated crack formation issues where the corrugation crosses the weld when autogenous TIG welding AISI 430. They have also demonstrated dramatic reduction in grain coarsening and improved formability (for corrugating) when employing autogenous, continuous wave (CW), laser welding of AISI 441:
M. Dakshinamurthy and A. T. Pérez, CERN, Materials and manufacturing for the pilot sector, 22 Jan 2024

Leak reliability data of bellows from some Ultra-High Vacuum (UHV) projects are reviewed to give an estimate of the leak reliability of corrugated tubes for CE. Even if the leak failure rate of corrugations formed from AISI 441 with CW laser welding is 10 times less than for 316L formed by TIG welding, the leak failure rate may be too high for CE.
At this point in time the hypothetical improvement in leak rate is purely speculative. This comparison with UHV project data simply points out the need for extensive testing, or more data from the UHV expansion joint (bellows) manufacturing sector, before committing to corrugated tube options.

LEP

Bellows failure rate analysis of LEP (Large Electron Positron collider) experience from this source:
L. Cadwallader, Vacuum Bellows, Vacuum Piping, Cryogenic Break, and Copper Joint Failure Rate Estimates for ITER Design Use, INL/EXT-10-18973, Jun 2010

https://doi.org/10.2172/983360

Unfortunately the cause or location of the leaks were not identified in this paper or any of the source papers cited in this article. Neither were the details of the fabrication (e.g. the type of weld). However this paper notes that after the LEP bakeout there were 3 failures of the welds on the bellows (although the specific location of these weld leaks, e.g. at flange, or at a convolution, were not identified):
LEP Vacuum Group, LEP vacuum system: present status, Vacuum, vol 41, issues 7-9, 1990, pg 1882-1886.
https://doi.org/10.1016/0042-207X(90)94121-6

Below I assume that the leak location is associated with (scales with) the convolution number.

LEP experiment standard vacuum bellows:
2,649 standard bellows units in use on the LEP
circular cross-section, hydroformed convolution bellows with single walls
each bellows had 10 convolutions and a 14-mm convolution height
constructed of 316L stainless steel
units were 0.168 m in length and 0.188 m in outer diameter
wall thickness was 0.15 mm

LEP base vacuum was low 1E-8 Pa (8E-11 torr) range, which is lower than LIGO's base pressure of 1e-9 torr, but likely equal to CE's base pressure

Tested bellows units gave an average lifetime of 25,000 cycles at bakeout temperature (150C), which is a factor of 100 above the design requirement. This
overdesign is believed to be a factor in the *high reliability performance of the bellows units*.

Table 2-3. LEP vacuum bellows failure rates.

Time Period	Average Failure Rate in Failures per Bellows-Hour	5% Lower Bound Failure Rate in Failures per Bellows-Hour	95% Upper Bound Failure Rate in Failures per Bellows-Hour
Small vacuum leak failure mode			
Early life (installation and commissioning)	8E−06	6E−06	1E−05
Operational life	8E−08	2E−08	2E−07
Bellows large leak or rupture failure mode			
Operational life	1E−08	5E−11	5E−08
Note: Small vacuum leaks for LEP are on the order of 1E−05 Pa-l/s (1E−08 Pa-m^3/s). Ruptures would have much greater throughput leak rates.			

The LEP small vacuum leak rate of 1e-5 Pa-L/s (7.5e-8 torr-L/s) is larger than LIGO's leak rate limits: 1e-10 torr-L/s at the component level and 1e-9 torr-L/s for each 2 km BT module.

Using LEP's 5% lower bound on the leak failure rate per Bellows-Hour, scaled to each convolution:

```
In[]:= FRbellowsLEP = 2×10^-8; (* per bellows-hr *)
       NconvPerBellowsLEP = 10;
       FRconv = FRbellowsLEP / NconvPerBellowsLEP // N (* per conv-hr *)
Out[]= 2.×10^-9
```

CE

Using CERN's recently proposed ET convolution pitch (190 mm) would result in 421k convolutions and ~7 leaks per year for CE:

In[∘]:=
```
pitchCE = 0.190; (* m *)
LarmCE = 40000; (* m *)
NconvCE = 2 LarmCE/pitchCE
```

Out[∘]= 421053.

In[∘]:=
```
FailuresPerHrCE = FRconv NconvCE;
FailuresPerYrCE = FailuresPerHrCE 365×24 // N
```

Out[∘]= 7.37684

Even if autogenous, CW laser welding of AISI 441 results in say 10 times lower leak failure rate, the leak failure rate for CE may be too high, or marginal:

```
FailuresPerYrCE/10 (* leaks per Year for CE *)
```

Out[∘]= 0.737684

At this point in time the hypothetical improvement in leak rate is purely speculative. This comparison with LEP data simply points out the need for extensive testing, or more data from the UHV expansion joint (bellows) manufacturing sector, before committing to corrugated tube options.

LIGO

Using LEP's average, operational, bellows leak failure rate for these convolutions would result in ~0.07 leaks per year for LIGO:

In[∘]:=
```
FRbellowsLEP = 8×10^-8; (* per bellows-hr *)
NconvPerBellowsLEP = 10;
FRconv = FRbellowsLEP / NconvPerBellowsLEP; (* per conv-hr *)
NconvPerLIGOBellows = 5;
pitchLIGO = 40; (* m *)
LarmLIGO = 4000; (* m *)
NconvLIGO = 2 (LarmLIGO/pitchLIGO) NconvPerLIGOBellows
```

Out[∘]= 1000

In[∘]:=
```
FailuresPerHrLIGO = FRconv NconvLIGO;
FailuresPerYrLIGO = FailuresPerHrLIGO 365×24 // N
```

Out[∘]= 0.07008

In the 23 years of LIGO operation there has not been a (detected) leak of a bellows, so perhaps the 5% lower bound on the failure rate is more realistic.

Using LEP's 5% lower bound, operational, bellows leak failure rate (as was done above for a CE projection) for these convolutions would result in ~0.018 leaks per year for LIGO:

In[∘]:=
```
FRbellowsLEP = 2×10^-8; (* per bellows-hr *)
NconvPerBellowsLEP = 10;
FRconv = FRbellowsLEP / NconvPerBellowsLEP // N (* per conv-hr *)
```

Out[∘]= $2.\times10^{-9}$

In[∘]:=
```
FailuresPerHrLIGO = FRconv NconvLIGO;
FailuresPerYrLIGO = FailuresPerHrLIGO 365×24 // N
```

Out[∘]= 0.01752

JET

Cadwallader (2010) cites Pinna (2005) as giving a vacuum system bellows leak failure rate from the JET (Joint European Torus) of 1.9e-6/-bellows-hr, or 24 times greater than LEP (but with a smaller population, so the failure rate estimation my be inaccurate).

However, according to this paper:
T. Winkel, J. Orchard, Leak evaluation in JET and its consequences for future fusion machines, Vacuum, Volume 41, Issues 7–9, 1990, Pages 1988-1991, ISSN 0042-207X,
https://doi.org/10.1016/0042-207X(90)94153-H

“Bellows failures in JET have been the major single item causing most of the operational stoppages, Hence a major effort is needed to solve this problem for future machines. “
"... were mainly caused by bellows failing due to excess of vibration or weld failing under high stresses induced during the plasma shots. The stresses are a combination of high power loading, magnetic field induced mechanical load and vacuum forces.":

So the operational environment/stresses experiences by the JET bellows may be far worse than for GW interferometers.

GEO600

C Affeldt1,et. al., Advanced techniques in GEO 600, 2014 Class. Quantum Grav. 31 224002
DOI 10.1088/0264-9381/31/22/224002

The GEO 600 beam tube is axisymmetrically corrugated along its entire 1200 m leangth. The shape of the corrugation is nearly semicircular with a corrugation period of 3 cm and a depth of 1.7cm. The tube diameter is 0.6 m. The number of convolutions is:

```
In[ ]:= NconvGEO = 1200 / .03
Out[ ]= 40000.
```

The vacuum tube has been stable for almost two decades of operation of GEO600 without developing “significant” leaks.
The pressures in the end stations suggest an upper limit of air leak-rate of 8 x 10^-6 mbar-L/s (6 x 10^-6 torr-L/s)for the whole 1200 m of beam tube.
This could be from a single leak, or from multiple leaks. If the leaks were all at the LEP threshold for small leaks, there could be as many as 80 leaks.

```
In[ ]:= NleaksGEO = (6 × 10^-6) / (7.5 × 10^-8)
Out[ ]= 80.
```

If 80 small (threshold) leaks have developed in the GEO beam tubes then the implied failure rate is quite close to the 5% lower bound rate observed in LEP:

```
In[ ]:= FRconvGEO = NleaksGEO / (NconvGEO 20 × 365 × 24) (* leaks/convolution-hr *)
```

Out[ ]= 1.14155×10^{-8}