Cosmic Explorer Beamtube Experiment (CE-BEX): Convolution UHV Leak Failure Rate Estimate

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Caltech
Dennis Coyne

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Artist: Eddie Anaya (Cal State Fullerton)

LIGO-G2502098-v1

Convolution UHV Leak Failure Rate Estimate

- All laser interferometric GW detectors employ corrugated tubing
  - either as convoluted tubing or as bellows
  - accommodates thermal expansion associated with diurnal temperature swings & vacuum bake-outs
- Residual stresses and cyclic flexing of the convolutions raises long-term reliability concerns regarding UHV leaks
  - If the dominant leak failure mechanism is due to cyclic fatigue, then corrugated tubes are preferred (other issues aside) since the cyclic movement is spread over many more convolutions
  - If the dominant failure mechanism is Stress Corrosion Cracking (SCC) then smooth tubes with bellows is likely preferred in order to reduce the number/area of potential failure sites
- Structural reliability vs UHV leak tightness
  - Ultra-High Vacuum (UHV) leak on the order of 10E-9 Torr-L/s as a failure criteria is considerably more stringent than a structural failure of the vacuum envelope
  - data and methods to predict lifetimes for structural failure may not be conservative enough for the UHV application
- Review project experience with bellows leak failures …

See LIGO-E2400425 for more detail, speculation and theorizing

Bellows Leak Rate Experience

- LEP (Large Electron Positron collider) facility
  - LEP small vacuum leak rate of 1e-5 Pa-L/s (75e-9 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
  - Assuming leak location is associated with (scales with) the convolution number and using LEP's 5% lower bound on the leak failure rate per Bellows-Hour, gives a leak failure rate of **2e-9 per convolution-hour**
  - Operational requirements for LIGO (and potentially the CE) bellows are more stressing than for LEP bellows: -11/+31 mm for 13k cycles with 6 convolutions for LIGO vs 6mm for 10k cycles with 10 convolutions for LEP
  - LEP bellows were overdesigned (more capable than their requirements)

    ... and yet they failed at rates unacceptable to LIGO or CE

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.			

LIGO

Bellows Leak Rate Experience

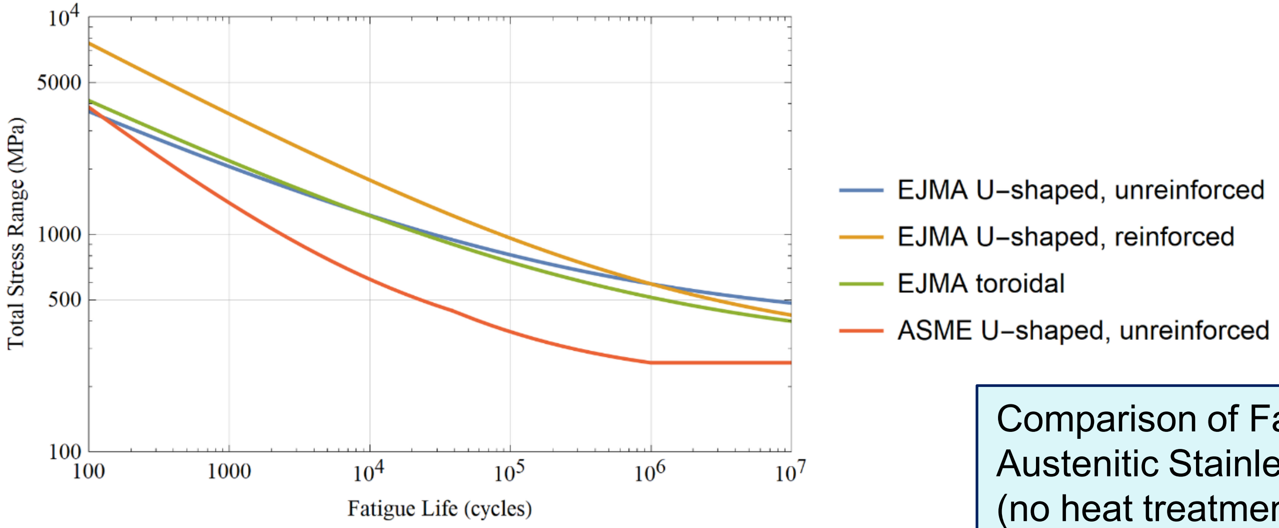
- Using LEP's 5% lower bound, operational, bellows leak failure rate (per convolution) …
  - LIGO
    - ~0.018 leaks per year for LIGO, or ~0.4 failures in 23 years, i.e. not inconsistent with LIGO experience of no failures to date
  - GEO
    - No “significant” leaks in two decades
    - However, end station pressures suggest an upper limit air leak rate of 6E-6 torr-L/s, or 80 small (LEP threshold) leaks, implying 11E-9 leaks/convolution-hr
  - CE
    - Assuming a convolution pitch of 190 mm would result in ~7 leaks per year for CE
      → clearly unacceptable

UHV Leak Failure Mechanisms

- We hypothesize the following mechanisms in the operating environment in an attempt to explain the LEP UHV leak data:
  - Cyclic Fatigue induced cracking
  - Stress Corrosion Cracking (SCC)
  - Microbial Induced Corrosion (MIC)
    - CE will likely be located in a dry/arid western region of the US, so MIC should not be a problem

Cyclic Fatigue Cracking

- EJMA and ASME provide methods to calculate fatigue lifetime for bellows
  - ASME is considerably more conservative
  - ASME formulation is limited to length < 3 x diameter



Comparison of Fatigue Curves for Austenitic Stainless Steel (no heat treatment)

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Cyclic Fatigue Cracking

- LIGO Bellows
  - Based on manufacturer's (CBI) very conservative diurnal movement estimate:
    - EJMA operational life was calculated to be 13.3k cycles (37 yrs) for diurnal temperature cycling
    - ASME calculation yields identical stress amplitudes but only 1.6k cycles (4.5 yrs) life (if cycle margin of 2.6 is removed still only 12 yrs)
  - Using diurnal temperature fluctuations measured at LIGO LLO:
    - ASME calculation yields 4.1k cycles (11 yrs) life (if cycle margin of 2.6 is removed 29 yrs)
  - The LIGO beamtube was installed 27 yrs ago
- Corrugated tube
  - Expect stress range < fatigue limit → infinite life
  - As an example, GEO600 stress range is only 14 MPa, so life > 10^6 cycles

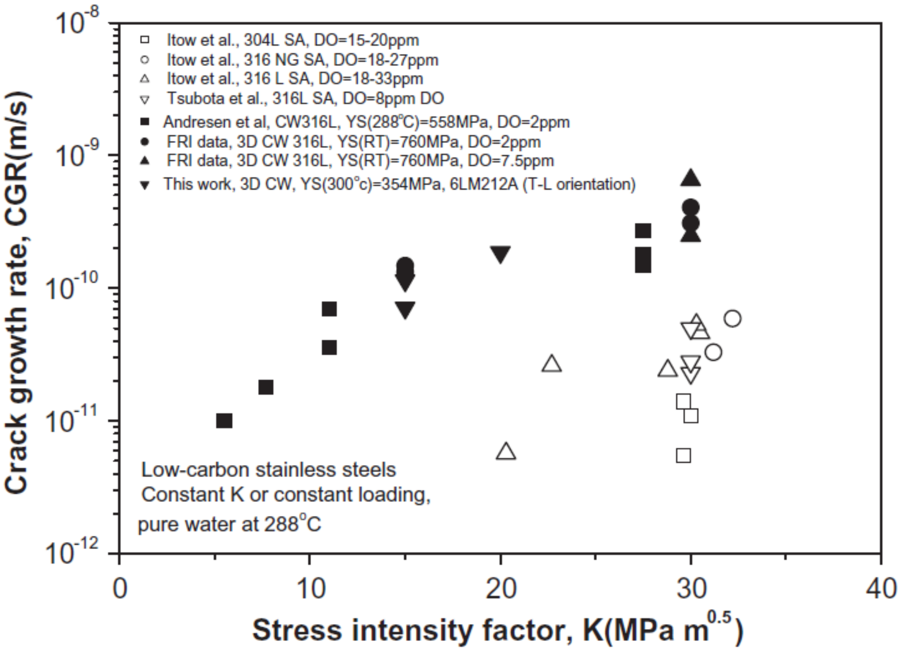
Stress Corrosion Cracking (SCC)

Caution: The following is plausibility argument (not a proof) for SCC initiated UHV leaks

- SCC requires combination of
  - a susceptible material
  - a corrosive chemical species in the operating environment
  - tensile stress
    - Unlikely to be a threshold value for stress intensity for SCC propagation (below which SCC would not occur)
    - can be the applied and/or residual stress (aka built-in or locked-in stress resulting from the forming and welding processes)
- SCC has a crack initiation phase followed by crack propagation. Relatively little data are available for the crack initiation process

Stress Corrosion Cracking (SCC)

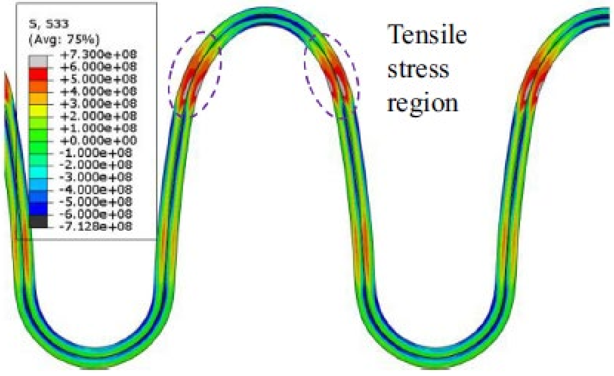
- For austenitic stainless steel, the chlorine ion, CL^-, is one of the most aggressive chemical species
- Soil and any nearby cement structures can leach salts (efflorescence)
- Sea water (and air) is a complex mixture of chlorides and sulphates.
- 304L exposed to simulated sea air ($MgCl_2$) showed a temperature threshold for SCC at room temperature and humidity threshold at 30% (27% is the fixed point humidity of $MgCl_2$, whereas the fixed point humidity of NaCl is 75%)
- SCC propagation rates for 316L in atmospheric conditions under $MgCl_2$ deposits (100 microgm/cm^2) at 40C and 40% RH for was 1-3 x 10^-11 m/s



SCC: Residual Stresses

- Forming convolutions results in significant residual stresses
  - post-forming heat treatment could reduce the SCC risk while decreasing the cyclic fatigue lifetime
  - A nonlinear FEA could be done to calculate the residual stresses
  - From an example calculation from the literature, estimate ~115 Mpa for 304L

- Welding
  - Tensile stress in the fusion zone (FZ) and heat-affected zone (HAZ) can be ~100 to ~300 MPa for SAW
  - Laser welding can reduce residual stress
  - Low Transformation Temperature Welding (LTTW) wire can induce compressive stresses and improve corrosion resistance



(c) Circumferential stress

Example residual stress calculation after hydroforming bellows (Pa)
0.45 m long x 0.5 m diameter bellows
comprised of two 1 mm thick layers of Inconel 71

SCC

- Example: LIGO Bellows
  - Leak testing LIGO Bellows (< 10^-9 Torr-L/s) serves as a proof test that the maximum crack/hole diameter is < 0.34 micron (molecular slip flow calculation)
  - stress intensity factor, K_I, for hypothetical initial crack/hole:
    - For bellows total stress range, K_I = 1.2 MPa-√m
    - For residual circumferential stress, K_I = 0.1 MPa-√m
  - Extrapolating crack growth rate data for 316L in pure hydrogenated water at 288C for K_I = 1.2 MPa-√m, implies possible rate of ~2 x 10^-12 m/s
  - For a 3 mm thick shell, this growth rate would take ~32 yrs to propagate through thickness

Convolution UHV Leak Failure Rate

- SCC and MIC seem unlikely to dominant (leak failure) lifetime especially if CE is in an arid western US region
- Cyclic fatigue due to diurnal temperature fluctuations seems the likely dominant failure mechanism
  - Suggests using corrugated tubing rather than bellows
  - If bellows or convoluted tubing are employed use conservative ASME rather than EJMA
- The observed rate of UHV leaks in the LEP bellows during operation is unacceptably high for CE & the mechanism for these leaks is unknown/unexplained
  - Requires more study to resolve. What are our next steps?