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Appendix 18 Vacuum Reliability Data

Source document for reference

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	Name	*Action*	*Affiliation*
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ITER Vacuum Handbook
Appendix 18

Vacuum component reliability data

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CONTENTS

18 Vacuum component reliability data

18.1 Scope

This document is a summary compilation of reliability data of vacuum components culled from a variety of sources (See Section 18.2). All failure rate data quoted is average value and is presented as frequency per annum. All mtbf (mean time before failure) values are in years.

By the very nature of such data this summary cannot be fully comprehensive, given the large variety of vacuum components and materials which are available from a diverse number of manufacturers. In addition, although there is a vast quantity of components in use around the world, there is little systematic gathering of data on failure modes and failure rates. One assumes that individual manufacturers collect such data for their own components (and maybe that of their competitors) but little is published and the remainder is generally inaccessible to users.

Anecdotal data, based mainly on experience in the world of accelerators, suggests that an ordered listing of vacuum component failures causing leaks would look something like (worst to best): -

- damaged or improperly made demountable vacuum seals
- edge-welded bellows leaks
- valve seat leaks
- ceramic or glass component shock damage
- ceramic or glass to metal seal failure (corrosion or otherwise)
- brazed coolant feedthrough seal corrosion
- hydroformed or rolled bellows failure
- weld leaks
- metal porosity.

It is difficult to draw systematic conclusions from the data presented, perhaps casting some doubt on its statistical significance. It is important when making any assessment of such data to ensure that one is comparing like for like. All data quoted in this appendix is believed to be inherently comparable, coming from the fusion and accelerator communities, where the vacuum atmosphere is relatively non-aggressive, as opposed to the semiconductor industry for example, where chemical corrosion is a major problem.

18.2 Source data

Title	Author	Date	Reference	Cited as
Vacuum System Operating Experience Review for Fusion Applications	L.C. Cadwallader	1994	EGG-FSP-11037 ITER/US/93/TE/SA-18	LCC-1
In-Vessel ITER Tubing Failure Rates for Selected Materials and Coolants	T D Marshall and L C	1994	EGG-FSP-10928	TDM

	Cadwallader			
Selected Component Failure rate values from Fusion Safety Assessment Tasks	L.C. Cadwallader	1998	INEEL/EXT-98-00892	LCC-2
Fusion Component Failure Rate Database	T. Pinna	2001	FUS-TN-SA-SE-R-43 http://spx595.frascati.enea.it:8080/homepage.nsf*	TP-1
Collection and analysis of data related to fusion machines	T. Pinna *et al*	2005	Fusion Engineering and Design **75-79** (2005) 1199	TP-2
Failure Rate Estimate for Stainless Steel Piping used in ITER Vacuum System	L.C. Cadwallader	2010		LCC-3
Vacuum Bellows. Vacuum Piping, Cryogenic Break and Copper Joint Failure Rate Estimates for ITER Design Use	L.C. Cadwallader	2010	INL/EXT-10-18973	LCC-4

** Page unavailable in Sept 2010*

In reality, the information in the paper by Pinna (TP-1) – which is a description of the database rather than digested information contained therein – is very limited and repeats that in LCC-2 so is of little additional value in this context. As noted above, the actual database is no longer accessible at the url cited (or indeed the alternative cited in *Fusion Engineering and Design*, **51-52**, November 2000, 579-585).

The data listed in LCC-1 and LCC-2 is derived from a range of operating facilities – fusion machines, accelerators, space simulators and industrial vacuum furnaces. The data in TP-2 derives from experience at JET and TLK. Note that this paper does not cite error factors.

LCC-4 is an attempt to draw together as much relevant data as is available in order to provide a reasonable estimate of the likely reliability of the ITER vacuum system.

18.3 Failure rates for major vacuum components

The following sections provide a digest of the failure rates for major types of vacuum components from the sources cited. The figures will be averages and need to be treated with some care – one would expect there to be some variance between specific models of each type of component, especially when these are available from different manufacturers. This is probably the reason why there is considerable variability in the figures quoted – there is insufficient information cited to clarify this aspect.

For simplicity, values are quoted in two different formats – in terms of failure rates per year and MTBF (mean time before failure) in years. The quoted error factor is a measure of the reliability of the data – the lower the better. This will be related of course in some way to both the number of data points available and their spread. It is not clear how this figure is derived and it is not available for some of the data.

It should be noted that the figures quoted are derived on the assumption that distribution of failures in time follows the “bathtub” curve and that these lie on the part of the curve where failure rates are nearly constant.

18.3.1 Failure rates for vacuum pumps

Type of Pump	Failure mode	Failure rate per year	MTBF (yr)	Error factor	Source
Rough Pumps	Failure to operate	0.13	7.6	1.2	LCC-2
	External leak	$5.0X10^{-3}$	200.0	10	LCC-2
Turbo Pump	Bearing failure	$7.9X10^{-2}$	12.7	3	LCC-1
	Housing Leak	$5.0X10^{-3}$	200.0	10	LCC-1
Cryosorption pump	Housing Leak	$5.0X10^{-3}$	200.0	10	LCC-1
Cryopumps	Failure to operate	$1.8X10^{-2}$	57.1	10	LCC-2
	Leak into vacuum chamber	0.18	5.7	1.7	LCC-2
TSP	Filament o/c	$1.8X10^{-2}$	57.1	1.7	LCC-1
	Feedthrough leak	0.65	1.5	1.4	LCC-1
	Housing Leak	$3.0X10^{-5}$	33333.3	10	LCC-1
NEG (Cartridge)	Failure to operate	$7.9X10^{-3}$	126.8		LCC-1
	Housing Leak	$3.0X10^{-5}$	33333.3	10	LCC-1
Ion Pump	Failure to operate	0.18	5.7	3	LCC-1
	Housing Leak	$3.0X10^{-5}$	33333.3	10	LCC-1
	Feedthrough leak	13	0.8	1.4	LCC-1

18.3.2 Failure rates for vacuum gauges

Type of gauge	Failure mode	Failure rate per year	MTBF (yr)	Error factor	Source
Rough Vacuum Gauges	Failure to operate	0.88	1.1	10	LCC-2
	Leak	$1.0X10^{-3}$	1000.0	3	LCC-2
Pirani gauge	Failure to operate	0.26	3.8	10	LCC-1
	Leak	$6.0X10^{-3}$	166.7	2.2	LCC-1
High Vacuum Gauges	All modes	$6.0X10^{-3}$	166.7	2.2	LCC-2
Penning gauge	All modes	$6.0X10^{-3}$	166.7		LCC-1
BAG	All modes	$6.0X10^{-3}$	166.7	2.2	LCC-1
Not specified	Leak	$2.5X10^{-2}$	39.4		TP-2

18.3.3 Failure rates for vacuum gate valves

Type (where known)	Failure mode	Failure rate per year	MTBF (yr)	Error factor	Source
	Failure to operate	0.88	1.1	2	LCC-1
	Failure to operate	$4.4X10^{+2}$	0.0	2	LCC-2
	Failure to operate	$9.6X10^{-4}$	1037.8		TP-2
	Spurious open or close	$2.6X10^{-2}$	38.1	10	LCC-2
Motorised	Spurious open or close	$4.4X10^{-4}$	2283.1	10	LCC-1
Pneumatic	Spurious open or close	$2.6X10^{-2}$	38.1	10	LCC-1
Solenoid	Spurious open or close	$4.4X10^{-3}$	228.3	10	LCC-1
	Housing Leak	$1.8X10^{-3}$	570.8	10	LCC-1
	Housing Leak	$1.8X10^{-3}$	570.8	10	LCC-2
	Housing Leak	$6.6X10^{-3}$	152.2		TP-2
	Seat leak	$2.6X10^{-2}$	38.1	30	LCC-1
	Seat leak	$2.6X10^{-2}$	38.1	30	LCC-2
	Seat leak	$4.6X10^{-2}$	21.5		TP-2

Vacuum gate valves can have one of two distinct types of actuator for the seal mechanism. The first uses a shaft sliding through a sealing bush or gland. In the second type, the motion is accommodated by means of a bellows, normally an edge welded bellows. Although it is not clear to which type the data in the table refers, it is most likely to be the latter which are more reliable. Bellows leaks are not specifically identified in the data but probably dominate the statistics quoted for housing leaks.

18.3.4 Failure rates for standard fittings

Group	Type	Failure mode	Failure rate per year	MTBF (yr)	Error factor	Source
Metal gasket flange	160-215mm	Leak	$1.0X10^{-3}$	1000.0	3	LCC-1
	295-360mm	Leak	$6.0X10^{-2}$	16.7	3	LCC-1
	>1m	Leak	0.5	2.0	10	LCC-1
	Bolt		$1.8X10^{-4}$	5707.8	10	LCC-1
Window		Leak	$1.2X10^{-2}$	81.5	1.8	LCC-1

18.4 Failure rates for bellows.

Vacuum bellows are used in vacuum systems to facilitate motion, to take up expansion and contraction and to compensate for construction inaccuracies. There are two major families, *edge welded* bellows which are fabricated from stacks of thin annuli welded alternately on the outer and inner diameters, and *formed* bellows which are rolled or moulded from thin seam welded sheet or thin wall drawn tube. Edge welded bellows are very flexible and can accommodate large extensions and contractions, so are useful for long throw linear motions for example, but are relatively fragile. Formed bellows are more rigid, are less flexible, and are less vulnerable.

Available reliability data does not distinguish between failure rates for these two families, but the data appears to be dominated by formed bellows. The failure rates for edge welded bellows will be inherently higher than those for formed bellows. However, because of the different characteristics of these two types of bellows, it is much more likely that edge welded bellows will be used in motion actuators rather than in the relatively static applications for which formed bellows are more suitable. Lifetimes for edge welded bellows will therefore tend to be dominated by duty cycle rather than mtbf. It may be noted that for edge welded stainless steel bellows, manufacturers will typically quote lifetimes of 10,000 cycles.

LCC-4 provides an extensive discussion of bellows failures based almost entirely on data from LEP at CERN, as is that in LCC-1. The TP-2 data derives from JET. The LCC-1 data is derived from 3 bellows failures during a vacuum bake in the early conditioning phase of LEP and are included in the early service leak data in LCC-4. The values of failure rates from CERN are based on assumptions about the time in service of bellows units which do not appear to take into account duty cycles. This however, would not explain the discrepancies in the values.

Failure data is summarised in the table below.

Type	Failure mode	Failure rate per year	MTBF (yr)	Error factor	Source
Metal Bellows	Leak	70.1	0.14	1.6	LCC-1
	Leak	$1.66x10^{-2}$	60.1		TP-2

Early service leak	$7.01x10^{-2}$	14.3	LCC-4
Small leak (10^{-8} Pam^3s^{-1})	$7.0X10^{-4}$	1430	LCC-4
Large leak	$8.8X10^{-5}$	11400	LCC-4

Based on the derived operational data from LEP, LCC-4 calculates anticipated lifetimes for the double bellows configuration anticipated for ITER. The values are, for small leaks, a failure rate of $7x10^{-6}$ per annum (mtbf $1.4x10^5$ yrs) and for large leaks, $8.8x10^{-7}$ and $1.1x10^6$ respectively.

18.5 Failure rates for metallic tubing and pipework

Determining failure rates for metallic tubing and pipework is a very complex business since there are many variables to be taken into account. TDM, LCC-3 and LCC-4 go into this in considerable detail for many of the potential situations relevant for ITER.

For the purposes of the Appendix, we shall note that there are three distinct categories of pipe and tubing – those forming a boundary between atmosphere or other gas and vacuum; those immersed in vacuum and containing water as a coolant; those immersed in vacuum and carrying a cryogenic fluid. In all cases, the inherent reliability of the system will most likely be dominated by joints rather than the metal itself.

The data in TDM, LCC-3 and LCC-4 is derived mainly from fission reactor data with pipes carrying liquid coolant, so will be particularly relevant to water coolant lines in ITER. Values for stainless steel pipe type 304L when scaled to ITER conditions are given below. The reliability of vacuum lines will be dominated by joints – seam welds, joining welds/brazes, etc., and should be comparable to any other vacuum envelope.

	Failure rate per year per m
Schedule 20 pipe	$1.2x10^{-7}$
Schedule 10 pipe	$2.4x10^{-7}$

It may be of interest to note that the failure rates quoted above for vacuum pump housings for ion pumps, TSPs and NEG pumps which are basically simple stainless steel vacuum vessels of characteristic dimension somewhat less than 1 m, are about two orders of magnitude higher. Whilst it is true that the wall thickness will be less than schedule 10, it is difficult to account for this difference if it is statistically significant.

TDM lists data for a number of different materials. It shows copper water cooing tubing to have failure rates rather more than two orders of magnitude worse than for stainless steel type 316L. It may be relevant to comment here that accelerator experience shows enhanced corrosion rates for copper in the presence of X-ray flux.

18.6 Other References

L.C. Cadwallader and T. Pinna*, Progress Toward a Component Failure Rate Data Bank for Magnetic Fusion Safety*

L.C. Cadwallader, *Failure Rate Data Analysis for High Technology Components,* INL/CON-07-12265

These references discuss methodology rather than providing data.