

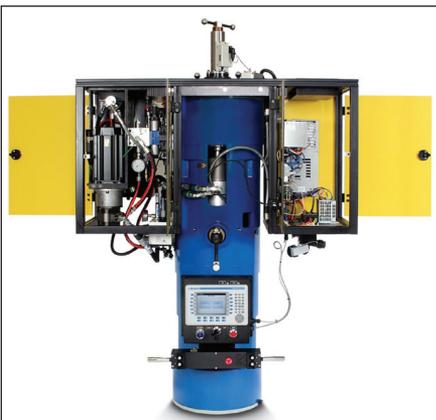
## Hydratight's latest SCT makes critical tasks in the nuclear industry safer

**J**oint integrity company Hydratight Ltd has designed a piece of technology which brings greater safety and efficiency to nuclear power plants.

The company says that it has already secured four orders for its newly-launched lightweight Self-Contained Tensioner (SCT) across the USA and Asia.

'The SCT has been in development for two years and in live tests has reduced typical tensioning time from up to four hours to under an hour, with 25% less manpower, resulting in lower potential RAD exposure time and greatly-reduced reactor downtime,' explained Gavin Coopey, Global Nuclear Market Leader, Hydratight.

This product is described as an advanced, reactor pressure vessel (RPV) stud tensioner. It needs only a power source – no hydraulic connections



Hydratight Ltd's latest Self-Contained Tensioner is 20% lighter than the previous comparable system.

or remote pump-control unit, says the firm.

Coopey continued: 'In other systems, tensioners must be connected to a central control unit. Both the new lightweight SCT and our original Hydratight SCT streamline the whole process. They eliminate the separate control unit as each of these tensioners has its own built-in pumping control system.'

'Crucially, each lightweight SCT networks to the other units, and each one displays the readings of the others in use. This means in a typical set-up, one operator can control all devices.'

According to Hydratight, the lightweight SCT system is the next step in its already successful RPV tensioning and operator safety programmes. It says that it is 20% lighter than the previous comparable system, which means that it is more easily manoeuvred around the RPV.

'The success of this product to date is testament to the sophistication of the new technology and the business benefits it can bring,' concluded Coopey.

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## Flexitallic supports growth of family-owned business

**I**nternational sealing products manufacturer Flexitallic Ltd is supporting the development of a family-run business based in Warwickshire, UK, after it reached a distribution agree-

ment that will enable the company to significantly expand the range of products that it offers industry.

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# Oil bearing seals and aircraft cabin air contamination

Dr Susan Michaelis PhD, ATPL, Michaelis Aviation Consulting, Horsham, West Sussex, UK

**On board aircraft, the common use of engine compressor, pressurised air to seal the oil bearing chamber and as a source for the cabin bleed air supply provides a mechanism for low-level oil leakage in routine engine operations. Although this problem was identified in the 1950s with the advent of synthetic jet engine oils, the problem remains ongoing today with over-reliance on seal failure conditions only.**

The use of compressed “bleed” air for aircraft ventilation and pressurisation systems commenced in military jet aircraft in the late 1940s and was seen as “fortuitous”. However, early commercial jet aircraft, such as the Boeing 707 and Douglas DC8, initially did not take air from the compressor to supply the breathing/ventilation air, but instead they relied on drawing air from outside the aircraft using separate blowers or compressors.

The introduction of synthetic jet engine oils – replacing mineral oils – was required for the new higher performing and higher temperature turbine engines, however, the toxicity was deemed speculative.

The use of air bled off the compressor (bleed air) to supply the pressurised and breathing air supply was utilised on military jet aircraft in the early 1950s, such as the Boeing B-52 and North American Aviation F100 Super Sabre using the Pratt & Whitney J57 engine. This was soon followed by the French manufactured SudSE 210 Caravelle in 1955 – the first commercial aircraft to use the bleed air system – and then the Boeing 727, 737 and DC9 in the early 1960s.

## Unacceptable contamination

It was soon recognised that engine bleed air used for the air conditioning ventilation supply was increasingly subject to unacceptable contamination.

The compressor bearing seals, which were leaking oil, were identified as the main source of contamination. Both the military and civil aviation industry were receiving reports of adverse effects related to the presence of smoke and fumes associated with the thermal decomposition of the engine oils that had leaked into the gas turbine compressors and then into the bleed air supply. US military studies were, therefore, undertaken into the

inhalation toxicity of the heated oils. These found that the ester-base stocks of the synthetic oils and their pyrolysis products when exposed to temperatures above 260°C (600°F) rapidly became very toxic.

The system of utilising the compressor bleed air to supply aircraft breathing air is used in almost all commercial transport aircraft except for the new Boeing Dreamliner (B787). The B787 uses an electric compressor system, drawing in fresh air directly from outside, rather through the engines.

Bleed air (used on most aircraft) is not filtered before it enters the air supply. Air is diverted from the mainstream gas path for a variety of purposes, including cooling, sealing and cabin pressurisation. A variety of air and oil seals are required in order to minimise the amount of engine air used so as to reduce the adverse effects on power and efficiency of the engine.

## Oil leakage seen in three ways

Oil is supplied under high pressure to all main shaft bearings, with oil seals required to prevent too much air leaking into the bearing chamber and loss of oil out of the chamber. Oil leakage out of the bearing chamber may cause aircraft oil pollution, cabin odour or visible smoke with the use of bleed air.

There is a “general acceptance” that cabin air can be contaminated by compounds released from pyrolysed oil from engines and occurs “with some regularity”.<sup>[1, 2]</sup> This is increasingly supported by a wide variety of sources.<sup>[3]</sup>

Oil leakage is essentially seen in three ways:

- seal bearing failure or minor systems failures, including worn seals;
- seal bearing failure, maintenance irregularities or design deficiency; and
- design.

Both seal failure and maintenance irregularities are regarded as rare. However, the sealing design requirement to seal the oil in the bearing chamber across the whole engine operating range, including transients, is rarely referenced, but a normal function of engine operation. Therefore, this background third category – the design factors involved in the use of pressurised oil bearing seals – warrants closer review.

Bearing chamber oil seals are required to seal across the whole engine operating range, including transients – momentary changes in engine operating conditions. However, it is increasingly recognised that all bearing seals leak as a design feature of using a pressurised sealing system, and that the seals are less efficient during transients.

Improvements in seal design continue and are recommended. Leakage of oil into the air supply is seen as a design feature with the use of compressor-generated bleed air, along with low-level leakage at various phases of flight and residual oil contamination.

A few examples that recognise normal aircraft/engine operation low-level oil leakage include:

- oil seal leakage is reported to occur during certain events, such as engine switching, top of descent, older aircraft with chronic vapours “continuously leak through seals in tiny amounts”;<sup>[4]</sup>
- oil leaking from bearings can be either “slowly varying and somewhat continuous or sporadic and quite intermittent”;<sup>[5]</sup> and
- background, low levels of oil additives and other substances are expected in normal flight.<sup>[6]</sup>

It is apparent that there are differing views on how oil leakage from the bearing chamber may contaminate the aircraft bleed air supply – that is, as a rare failure or maintenance problem or low-level chronic leakage as part of the normal operation using the pressurised oil bearing chamber and bleed air supply systems. Therefore, a closer look at the key types of bearing seals used in aircraft turbine engines is necessary.

## Engine bearing compartment sealing

The philosophy behind engine bearing compartment sealing (Figure 1) involves using pressurised air to maintain the bearing compartment at a lower pressure than its surroundings, therefore inducing an inward flow to prevent an outward oil leak.

The pressurised oil bearing seals used in most aircraft today are generally clearance labyrinth seals or mechanical contact face seals – both of which rely on compressor pressurised air as part of the sealing function. Both types of seals are responsive to variations in engine operating conditions.

Labyrinth (clearance) non-contact seals (Figure 2) rely on tight clearances and a controlled leakage of air to reduce pressure over the seal, so as to keep the oil in the sump. Higher air-pressure on the outside of the seal, compared with the lower pressure air and oil pressure in the sump, should keep the oil from migrating out of the sump over the seal.

Labyrinth seals are often used to seal bearing compartments and are seen as low cost, reliable, simple and subject to reduced wear. However, these seals are subject to high air-leakage rates over the seals and, given the clearance, oil may therefore leak out with a reversal of pressure, which means they are not seen in isolation to provide a complete barrier to leakage. In addition, labyrinth seals do not respond well to dynamics with increases in seal clearances during shaft movements and transients.

Mechanical positive contact seals, carbon face seals (Figure 3) rely on precision flat faces, held in sealing contact by a combination of the force of a spring and positive system pressure, to ensure adequate loading of the carbon elements to minimise leakage and wear. These seals are also often used to seal bearing sumps. However, they are regarded as more expensive, more complex, maintenance intensive, with a shorter service life and more subject to wear, particularly during transients.

Carbon seals use a thin film of oil between the faces. This is typically 1- $\mu\text{m}$  thick, which is thick enough to provide lubrication of the contact faces and long life, but thin enough to minimise oil leakage into the compressor.<sup>[7]</sup>

This type of seal will leak a very small amount of oil vapour, estimated between a few ppm to 10 cc/min.<sup>[8]</sup> Increased speed and small increases in clearance between the faces can cause higher oil leakage over the seal.

Whilst carbon seals are more tolerant of pressure differentials at varying stages of flight than labyrinth seals, they are more temperature critical, with oil coking occurring on the

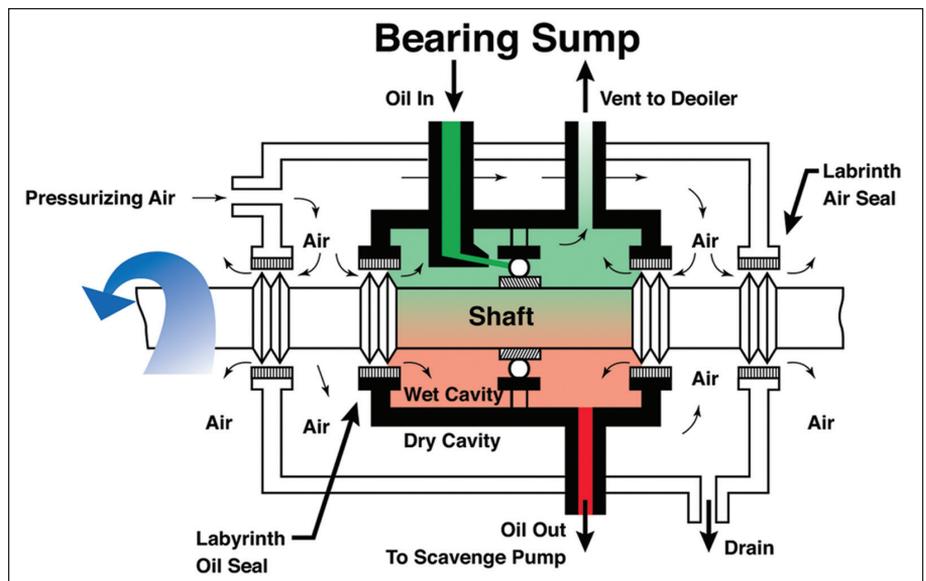


Figure 1. Bearing sump (ExxonMobil 2009).

flat faces, causing distortion with thermal and pressure effects.

## Oil leaks more than realised

A common aspect of using labyrinth and carbon contact seals includes relying on compressor-pressurised air over the seal and, therefore, this is responsive to variations in engine operating conditions. In addition, sealing of the bearing compartments is recognised as being difficult.

Common assumptions associated with the use of both types of seals are that oil will not leak out of the sump if the pressure is always positive – with higher pressure outside and lower pressure inside the chamber. This positive gradient is assumed to ensure leakage is always into the chamber.

It is also often stated that absence of seal/bearing failure and the avoidance of reverse pressures will ensure that oil leakage out of the chamber does not occur. However, the literature suggests this is not always the case and oil does leak more than generally realised for several reasons, which are summarised below.

- A positive gradient is difficult to maintain under all operating conditions.
- Oil may flow opposite to the positive pressure gradient with both types of seals. Pressures generated in the oil film between the mechanical (carbon) face seals can cause liquid in the film to overcome the pressure gradient and leak both with and against the pressure gradient.<sup>[9]</sup> Dalton's law of partial pressures, in which a gas tries to create a constant partial pressure, indicates that high-pressure air will not actually prevent oil vapour from permeating through the

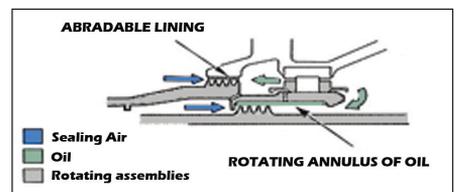


Figure 2. Fluid and abrasible lined labyrinth seal ('The Jet Engine', Rolls-Royce, 2005).

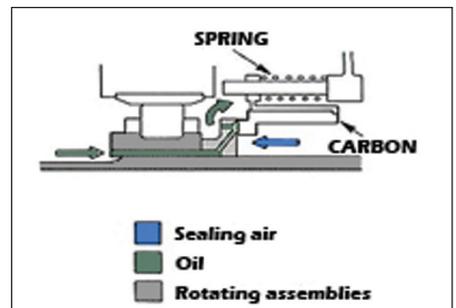


Figure 3. Typical carbon seal ('The Jet Engine', Rolls-Royce, 2005).

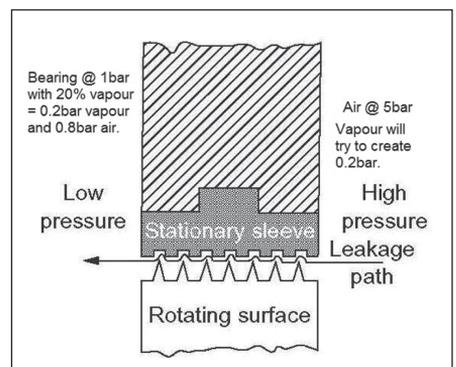


Figure 4. The propensity of partial pressures to cause vapour leakage against the pressure gradient (*Journal of Biological Physics and Chemistry*, Vol 14, 2014).

labyrinth against the pressure gradient<sup>[9]</sup> (see **Figure 4**).

- Reverse pressure (higher pressure on the chamber side of the seal than outside) and changes in pressure gradients do occur at various transient phases of flight, allowing leakage in the opposite direction.

Industry recognition of seal leakage as a function of design includes: *'Increased oil leakage may occur when the engine or APU is started and the seals are not at operational pressure and temperature or during transient operations such as acceleration or deceleration. Some systems rely upon internal pressure to maintain the sealing interface, which may open up on shut-down allowing some oil to exit the oil wetted side of the seal. Upon start-up, the oil will be entrained into the air entering the compressor, with the seal interface again established once the engine internal pressure returns to operating norms.'*<sup>[10]</sup>

The volume of leakage for both seal types depends on the seal design, clearance and pressure differential across the seal – with a face seal allowing considerable leakage should the face open with the reverse pressure, unless this is taken into account at the design stage.<sup>[9]</sup>

Just about all known seals will leak – with seals designed to limit leakage and no such thing as a seal that does not leak – even if a very small amount, perhaps an emission occurs rather than leakage.<sup>[9]</sup>

Zero leakage is said to be an oxymoron.<sup>[11]</sup> Only very small amounts of oil need to leak to generate a noticeable cabin odour<sup>[12]</sup> and it will be possible to smell oil before high oil consumption is noticed.<sup>[13]</sup> Light oil contamination – well below permissible leakage levels – is often difficult to confirm during inspection procedures.

The aviation industry is seen as unique in that environmental aspects drive sealing requirements as opposed to regulatory emission limits, as occurs in other critical industries, and the general environment.<sup>[14]</sup>

Customer satisfaction – a cabin free of smells – and performance parameters drive aerospace sealing technology.<sup>[11, 14]</sup> Where emission limits apply, single, double or tandem seals may be used. However, few limits apply to the aerospace industry where leakage may be defined as 10 000 ppm or as a visible mist.<sup>[14]</sup>

## Low-level leakage

The question of low-level leakage, well below the permissible engine oil consumption level, is at the heart of the issue, with some suggesting that oil leakage refers to amounts above

the manufacturer stated permissible leakage rate, identified purely to prevent in-flight shutdown.

Lower-level leakage, or what some may call emissions, is suggested by some to be not seen in the same light and importance.

The major part of oil consumption is permissible leakage past seals, oil leaks and escape of mist or aerosol through the oil system breather.<sup>[15, 16]</sup> Over the years there has been awareness within the oil sealing community that the oil seals were subject to leakage. Some examples include statements such as: “carbon seals will always leak a small amount”; “shaft seals must function as seals *not* flow restrictors”; “air/oil seals must be improved now”; “future research needs to include transient behaviour of seals”; and “shaft seal technology has not kept pace with advances in major engine components”.

## Conflicting views

There are conflicting views on which of the commonly used seal types are more effective, with some suggesting conversion from labyrinth seals to mechanical carbon seals, given the higher labyrinth air leakage rates. OEMs are said to be satisfied with labyrinth seals to seal many bearing sumps for many years to come.

Improvements in seal design are available, including brush seals and other advanced seal types.<sup>[11]</sup> Axial lift mechanical seals are suggested to have a number of benefits, including no oil loss in reverse pressures – eliminating oil pollution in the cabin.<sup>[17]</sup> Whilst some aspects of seals are suggested to have come a long way in recent years,<sup>[8]</sup> the concerns about oil fumes in the aircraft cabin remain ongoing.<sup>[3, 18 & 19]</sup>

## Other factors

There are various factors related to exposure to oil fumes and other aircraft fluids that can enter the air supply via the bleed air system. These are summarised in the sections below.

## Hazardous substances

The substances in the oils and fluids are classified as hazardous under the EU Classification (CLP) and REACH regulations, with one substance listed as a Substance of Very High Concern (SVHC) under REACH article 57. Hazards include irritant; sensitiser and neurotoxic effects; genetic defects, harm to the unborn, and infertility; very toxic by inhalation; drowsiness; dizziness; asthma; breathing difficulties; and suspected cancer.

Additionally, a number of substances are listed as endocrine disruptors. These sub-

stances attract a wide variety of adverse effects under the various official databases, including International Chemical Safety Cards (ICSC) and Hazardous Substances Data Bank (HSDB). Many of these are the effects that are commonly being reported.

## Flight safety

There is a wide range of organisations recognising that exposure to these substances in flight can compromise flight safety: A 2015 International Civil Aviation Organization (ICAO) guidance circular reports that ‘particular concerns have been raised regarding the negative impact on flight safety when crew members are exposed to oil or hydraulic fluid fumes or smoke, and experience acute symptoms in flight.’

Impairment associated with exposure is documented at levels around 32%, despite wide recognition that crews are frequently not reporting fume events and crews are not always acting appropriately subsequent to exposures.<sup>[3]</sup>

## Adverse health effects

The published literature supports that a wide variety of adverse health effects, associated with fume events, is being reported. Effects are broadly categorised as respiratory; neurological; neuropsychological; cardiovascular; general effects, including fatigue; chemical sensitivity; gastrointestinal; and the emergence of selected cancers.

Of 274 UK pilots who participated in a health survey, focusing on a particular aircraft type acknowledged for higher than average oil seal leakage, 13% were retired with ill health or deceased. The findings were consistent with exposure to jet oils, and fluids including organophosphates (OPs) and supported the emerging discrete occupational and public health issue, termed “Aerotoxic syndrome”.<sup>[3]</sup>

## Exposures

A number of studies undertaken into OPs in the engine oils have identified tricresyl phosphate (TCP) in air, swab and high-efficiency particulate air (HEPA) filter samples in normal flights, without fume events, ranging from 17–95% of samples/flights undertaken.

## Frequency

Fume events are often said to be very rare. However, a UK Government sponsored committee suggested that such events were being reported by pilots in 1% of flights.<sup>[20]</sup>

A review of US Government databases reports 2.1 events per 10 000 departures, along with recognition of under-reporting<sup>[21]</sup> widely noticed elsewhere. However, there is increasing recognition that background or low levels of the fluids substances are being found routinely, supporting the suggestion that low-level leakage occurs as a function of design and operation using the bleed air system.<sup>[3]</sup>

## Science

The literature supports an increasing number of studies that have been done, or are currently on-going, indicating concern with exposure to the substances in the lubricants.

In one example, a University of Washington study on biomarkers associated with triaryl phosphates (TAPs), including TCP, identified that one of the commercial formulations of TCP, DURAD 125, is inhibiting a number of enzymes.

A German environmental research centre study has identified that functional neurotoxicity is observed with very low TOCP (isomer of TCP or tri-*o*-cresyl phosphate isomer) concentrations, and in the absence of structural damage.

## Industry initiatives

Whilst studies into the effects of exposure to the synthetic lubricants commenced in the early 1950s, they have continued to increase in number over the last one to two decades.

A few on-going examples include:

- two EASA-sponsored studies into the cabin air quality and oil pyrolysis;
- REACH review of TCP;
- ICAO fume events guidance circular;
- IATA medical response guidance to fume events;
- CEN cabin air quality standard development;
- EU Cleansky development of electric compressor for the environmental control system (ECS); and
- two cases before the UK Coroner's Court.

## The way forward

Some continue to suggest that there is no evidence of a link between exposure to the fumes and adverse effects and that the term Aerotoxic syndrome has not been medically recognised as yet. However, the evidence available is extensive and a toxic mechanism cannot be ruled out and acute effects have been officially recognised with long-term effects reported.<sup>[18]</sup>

Therefore, it would make complete sense to enact a variety of solutions that do exist, or could be implemented. These include bleed-free aircraft; better oil seals; filter or clean the engine/APU bleed air; provide detection sys-

tems; better maintenance; and less toxic oils. Importantly, seal providers should be brought in at the start of the design process.

It is clearly recognised that the oil seals do leak or emit low levels of fluids. These low levels, clearly below the permissible oil consumption level, have been regarded as negligible and safe. The focus has been on secondary air leakage and its effect on engine performance, rather than lower levels of oil leakage – yet awareness of the lubricant leakage does exist.

There has been reluctance by the OEMs to change seal types, address low-level leakage and implement more advanced sealing technology. However, given that most current commercial aircraft use the compressor pressurised air for both sealing the oil bearing chamber and the cabin air supply, this common path cannot preclude low-level leakage of oil in normal engine operations.

It is no longer possible to suggest oil leakage may only contaminate the air supply when bearing/seals fail or are not working as intended. Given the six-decade-old history of oil leakage into the air supply, low-level leakage in normal operations and the evidence rapidly growing, the above solutions need to be implemented.

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(This article is based on a presentation by the author at BHR Group's 23rd International Conference on Fluid Sealing that was held in Manchester, UK, on 2-3 March 2016.)

## Recently Published Papers

- J. Starcevic and V.L. Popov, Berlin University of Technology, Berlin, Germany, and Tomsk State University, Tomsk, Russia; and R. Pohrt, Berlin University of Technology, Berlin, Germany: 'Plastic properties of polytetrafluoroethylene (PTFE) under conditions of high pressure and shear', *Wear*, Volumes 326–327, 15 March 2015, pages 84–87. The authors of this study investigated, experimentally, the behaviour of a thin sheet of polytetrafluoroethylene (PTFE) between a steel plate and a cylindrical steel indenter under combined action of a high normal force and torsion. Under these actions the PTFE layer is partially squeezed out of the contact area. The thickness of the remaining layer is studied as function of the applied normal force, the torsion angle and the radius of the indenter.