Aerospace Sealing Technology for Maintenance, Repair and Overhaul of engines: a review

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ABSTRACT

Given the current rate of growth of gas turbine engines in the aerospace industry, the development of efficient and advanced sealing technology to cater to the harsh operating conditions of the aero-engines is crucial. In addition to developing low-leakage, long lasting and well-performing seals, it is essential to maintain them. Seals play an integral role in improving engine efficiency at a high performance to cost ratio and failure of this part results in a trifecta of hazards: safety, environmental and cost, all three of which are discussed. Efficient maintenance repair and overhaul (MRO) of engines is paramount to ensure compliance with air worthiness standards put forth by regulatory bodies. Data suggests that engine MRO accounts for ~30% of direct engine operating costs and so it is necessary to reduce unscheduled maintenance and failure of components. A review of aero-engine sealing technology is presented in this paper from an MRO aspect and current state-of-the-art sealing technology in the aerospace industry is discussed alongside. It is clear based on the review work that sound MRO practices of seals is just as vital as design and development of them. The future outlook of MRO and overcoming the challenges faced in the industry have also been outlined.

Keywords: Seals; MRO; Gas turbine engines; aero engines

NOMENCLATURE

MRO	Maintenance, Repair and Overhaul
SFC	Specific Fuel Consumption
EASA	European Aviation Safety Agency
CAGR	Compound Annual Growth Rate
RPK	Revenue Passenger Kilometre
CFD	Computational Fluid Dynamics
TAT	Turnaround Time
HPC	High Pressure Compressor
HPT	High Pressure turbine
APU	Auxiliary Power Unit
AM	Additive Manufacturing
OEM	Original Equipment Manufacturers
CAD	Computer Aided Design
RR	Rolls Royce
P&W	Pratt and Whitney
IAE	International Aero Engines AG
R_a	Roughness average

1.0 INTRODUCTION

In the 115 years since the first Wright plane soared into the sky, aero-engine technology has come a long way. It continues to evolve with the design of newer, more efficient engines and enhanced operating conditions. These include higher compression ratios, rotor speed and other various characteristics to reduce engine weight and improve performance. The improved engine parameters result in increased power and temperature loads on engine components such as seals. Hence, it has been concluded that further seal development is required to meet the new engine ope$_{ra}$ting conditions. Seals have been identified as a critical part of meeting future engine goals of thrust-to-weight ratio, specific fuel consumption (SFC) and cost reduction as well [1-2].

A seal is a component that impedes the flow of fluid through a given system. The word ‘impede’ holds emphasis as there is no such thing as a zero leakage seal. All seals must leak, even if it is as low as 1 mm^3 per year and referred to as ‘emission’ [3].

Seals serve many purposes in engines; however, two of the main purposes are to restrict leakage out of a system and to prevent contaminants from entering a system. Essentially, they keep fluids in and keep other debris out. When selecting a seal for your application, there are many criteria that must be considered: installation and assembly, temperature and pressure, contact and non-contact, wear, rotational and surface speeds, etc… However, the perfect seal does not exist and the specific requirements crucial for optimum performance in that certain application must be considered when selecting a seal. It is also important to note that the definition of optimum performance will vary from case to case; some applications can compromise on leakage for more rotor stability, while others require leakage to be mimized at any cost [4].

Having selected the optimum seal for your application does not guarantee that it will not wear out over time. Any component used long enough is bound to wear out and fail if it is not properly maintained. Further, as explained in the coming chapters of this review, there are several reasons behind seal failure occuring commonly. As a result, maintenance, repair and overhaul (MRO) is essential and considered a critical part of an aircraft engines usage and life.

To ensure that all aircraft and their components are maintained up to a certain standard, all aircraft must be produced and operated in compliance with airworthiness regulations put forth by the European Aviation Safety Agency (EASA) and other regulatory bodies. To meet initial airworthiness standards, they must be designed and produced in accordance with these laws. However, continued airworthiness can only be achieved via sound MRO practices. This is important because aviation safety is the common

denomenator of all stakeholders in the aerospace industry. Inspecting and maintaining an aircraft is a complex task due to turnaround time (TAT) to get it to serice along with the lack of feedback and costliness. The increased price pressure on MRO organizations due to the expense of maintenance and costliness of time is a severe issue in the industry [5].

The global commercial aircraft sector has grown phenomenally in the last few decades, resulting in increased travel demand as well. Major aircraft manufacturers like Airbus and Boeing have predicted an increase in production rates in 2018 and 2019 to meet demand. However, booming demand and growth does not come without its own problems. Key challenges have also been outlined in this 2018 report by Deloitte on the global aerospace industry outlook [6] and they include:

- Strengthening the supply chain
- Effective program management
- Use of new and advanced technologies for efficiency

All of these target problems have been addressed in this review as they all are very relevant to MRO of engine components i.e. seals in aerospace applications. This review adopts a pragmatic approach to discuss state-of-the-art sealing technology in aero-engines and how it ties up with the need for MRO and its challenges. The importance of MRO as a sector has been explained and how it will continue to be important in the future as well. Figure 1 presents a breakdown and classification of the seals discussed in this paper that are commonly used in aerospace applications today and Table 1 briefly outlines their characteristics.

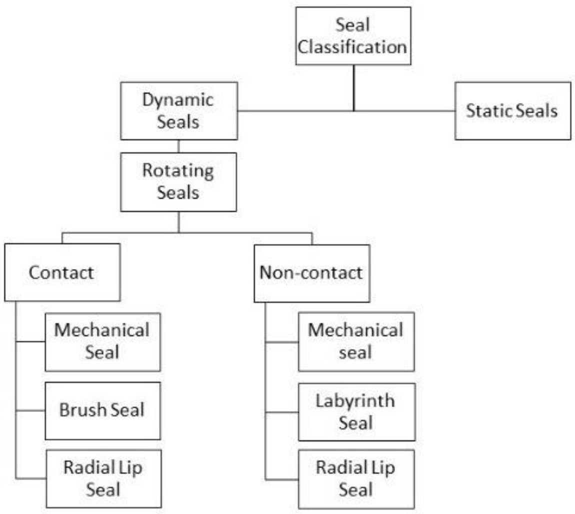

Figure 1: Classification of seals discussed

Table 1: Seal information

	Type	**Location in Aero-engine**	**Pros**	**Cons**
Labyrinth Seal	Non-contacting (relatively large clearances)	Air to air seal Air to oil seal	Low wear, long service life	High leakage, undesirable contact
Brush Seal	Contacting	Air to air seal	Lower leakage, high pressure application, cheaper	Higher wear, friction, lower service life
Mechanical Seal	Contacting & Non-contacting (minimal clearances)	Air to air seal Air to oil seal	High speed, high pressure, low leakage, wide use	High wear, friction
Radial Lip Seal	Contacting & Non-contacting (minimal clearance)	Air to oil seal	Effective lubricating method with seal, low leakages	Unpredictable, wear due to dry running

Section 1 introduced the outline of what will be discussed in this review and briefly explained the purpose of aero-engine seals. The flight hours that seals can last without requiring replacement is important as it will affect overhaul intervals of the aircraft. Thus, MRO of components is crucial and section 2 will explain its relevance and some of the challenges faced today. Section 3 provides a summary of the current state of the booming aerospace industry and the growing dependence on MRO as a result of this massive shift into new technologies. Case studies of seal failure in recent and previous years have been described to lay further emphasis on the safety for all stake-holders. To understand more about seals and why they fail in the first place, section 4 details four of the most commonly used seals and challenges faced in aerospace applications. Section 5 consolidates the information in this paper to draw conclusions and a clear link between sections 2-4 is drawn. A brief outlook into the future work and research of the author is presented in section 6.

2.0 MAINTENCE, REPAIR AND OVERHAUL

MRO is a fundamental process that is essential for continued airworthiness, rendering it a regulatory legal standard that all aircrafts must comply to in order to be allowed to fly. The value of this sector is directly linked to air transport safety and has been outlined below along with some of the problems faced.

2.1 Importance of MRO

MRO must be treated as a crucial part of the aerospace industry for the following reasons [5][7]:

1. The increasing demand of sustainable handling of resources coupled with the need for longer lasting components with a higher user intensity means that MRO of these components is necessary.
2. The increasingly complex engines with advanced components, systems and machinery result in a rise in demand for MRO on the part of users and operators alike.
3. The growing cost of MRO of aircrafts and their parts is high. While the cost of manufacturing the aircraft is high, it is a one-time cost. For the duration of the lifetime of that aircraft, it will continue to undergo repairs and maintenance regularly.
4. Safety is a non-negotiable factor in aerospace and cannot be comprised on at any cost.

With the increasing awareness of sustainability in recent years, this is a crucial factor that should not be overlooked. It involves meeting current demand without compromising the ability of the future to meet their demand. The 3 main pillars of sustainability are social (people), environmental (planet) and economic (profits) impact; efficient MRO processes touch all 3 areas as mentioned in the above points. As technological development continues to grow, the burden of advanced engine operating conditions fall on engine components which are prone to breakdowns and failure at any point without warning. It is important to monitor the condition of these parts and continue to maintain them so that they do not reach the point of failure and are repaired before such an incident occurs.

2.2 Challenges in the aerospace industry

While its importance as a sector has been emphasized upon, the MRO industry is not without its problems and achieving perfect efficiency is not as easy as it may seem. Many challenges still need to be overcome, mentioned below:

1. Availability of spare parts in MRO: Flexibility in supply of aircraft components is an important part of responding quickly and efficiently to customer needs. An emergency resupply strategy is essential in MRO from an operational, supply chain and cost-effective point of view. Since most breakdowns are unpredictable, the availability of spare parts without time lag is difficult. These tasks must be carried out with minimum delay and stocking inventory of all parts is not feasible [8], bringing us to the next problems of time delays and unexpected breakdowns.

2. Turnaround time for aircraft MRO services and inefficiencies in supply chain: Time delays in MRO arise due to inefficiencies and waste in the process flow. This could be due to unavailability of spare parts, lack of a proper system, miscommunication or any other hiccups in the MRO process. Lowering the TAT could result in a much more improved framework and efficient process, resulting in time and cost-effectiveness [9].

3. Lack of predictive maintenance: Due to unforeseen breakdowns, there are time delays and lack of spare parts available for immediate replacement. Such instances should be avoided as much as possible with predictive maintenance. Regular checks will ensure that unexpected breakdowns are a rare occurrence and not happening on the daily. Components like seals should not reach the point of breakdown and must be repaired, replaced or fixed in the early stages of failure detection. This would also reduce maintenance costs and save time [10].

All of these challenges in MRO of aircrafts are interconnected and have resulted in this sector being left behind in comparison to the giant leaps being made in other aspects of the aerospace industry like the introduction of new aircrafts and engines into the market [11]. These problems are summarized and some solutions presented in section 5 of this paper. The MRO sector has been described and broken down to explain its growing need with the growth of aerospace in general.

3.0 CURRENT INDUSTRY ANALYSIS

The current state and direction of the aerospace industry has been illustrated with global growth numbers. With the introduction of new generation aircraft, MRO of components will become increasingly necessary as we will see a wide range of problems we have not experienced before. While this applies to all components and parts, looking at examples from the industry where seals have caused engine problems provides evidence for the safety and monetary consequences if it is neglected. This is why extended seal life and consistent MRO of seals is considered to be crucial – their failure can have dire consequences.

3.1 New Generation Aircraft

New-generation aircraft are those that have been designed and built after 2000. They are an investment in modern cutting-edge technology to complement the enhanced design of new airliners. This ranges from improved materials i.e. carbon fibre composites, special coatings and hybrid alloys to new data collection and measurement tools designed to provide advanced prognostication capability. Rightly implemented, predictive maintenance of components i.e. seals before failure can result in great cost savings and better reliability. As aircraft deliveries accelerate and reach market, older technology will be retired from service over the next ~10 years. [12].

The introduction of intelligent aircraft in the market will be the beginning of a new technological era for the aviation industry. The new generation of airliners will be designed with increased MRO intervals with improved sophisticated health monitoring and prognostics of maintenance requirements. A320neo (Airbus) and B737max (Boeing) are two examples of new-gen airliners that will succeed aging and maintenance heavy aircraft. This systematic replacement of the older aircraft will cause a shift in the business for MRO organizations. The maintenance needs, time-on-tools requirement for checks and repairs will drop significantly as it will be replaced by state-of-the-art monitoring of aircraft performance and predictive maintenance tools, demanding a need for changed perspective from the MRO provider [13].

Due to this new era of aircrafts entering the market, the emphasis laid on data collection at the MRO stage is even more crucial so that the new operating conditions and flight conditions can be better understood. Recent cases of unexpected seal failure described in the following section prove that it is absolutely necessary to learn more about the present conditions we are dealing with to reduce the risk of failure and safety for airlines, companies and passengers alike.

3.2 Case Study

Below are some case studies of aerospace incidents where failed seals have resulted in engine shut down and been potential safety threats to passengers. It is due to such possibilities that small components like seals that may be deemed insignificant in some instances may have significant impacts on the engine.

3.2.1 Airbus A320neo P&W: 2017-2018

This problem came about in early 2018 with P&W’s new GTF engine (geared turbofan engine) for the Airbus A320neo. A design flaw was discovered in January 2018 on approximately 100 of these engines, some of which were in the Airbus assembly plant and others in service. All engines were re-called as four aircraft engines experienced sudden shutdowns during take-off or during the flight.

The root cause of the engine shut down was the knife-edge seal (similar design to the labyrinth seal, patented by P&W). Initially, some changes were made to improve the durability for the high pressure compressor (HPC) and these changes resulted in the fracture of this seal, causing sudden vibrations and engine stall in this model.

Ironically enough, the original knife edge seal that was meant to be used was delivered with a design flaw that required inspection after a certain interval of flight hours. The supposedly ‘redesigned’ version turned out to be worse and caused engine shutdown altogether. It was said by the Chief Executive that fixing this faulty seal would cost the company $50 billion and increase the company’s losses on geared turbofan engine deliveries closer to $1.2 billion [47,48,49].

3.2.2 Airbus A330-323 P&W turbofan engines: 2016

A flight from London Heathrow Airport experienced the cabin filling up with smoke during boarding, resulting in immediate evacuation of all passengers. The source of this smoke was traced back to a failure of the Auxiliary Power Unit (APU) compressor carbon seal (carbon seals are also known as mechanical seals). This resulted in oil leakage and contamination of the bleed air supply. Metallic debris found in the shared oil system compromised the load compressor bearing, resulting in failure of the compressor carbon seal.

The report also mentions that the APU manufacturer had experienced similar events prior to this one where failure caused oil entering the bleed air system through the load compressor carbon seal [17] .

3.2.3 Airbus A320 IAE/P&W: 2014

This flight from Cochin to Delhi by Air India experienced uncontained engine failure in flight and a fire which was confined to engine 2 only. The incident was caused because the oil seal was not overhauled adequately during the maintenance procedure.

During overhaul, the lapping process (superfinishing process of the surface) of the #4 bearing seal was carried out. The anti-weep grooves (to prevent the oil from escaping the compartment during sub idle conditions) were not cleaned and inspected properly, resulting in blockage of the grooves with lapping debris. As a result, the oil escaped the #4 bearing compartment and went into the high pressure turbine (HPT). Eventually, this compromised the air seal placed at the turbine, causing low cycle fatigue fracture of the second stage air seal at high temperatures and damaging the turbine blades. Two of the seals in two different places in the engine experiencing failure resulted in the engine fire [18].

3.2.4 Lockheed L-1011 RR Turbofan: 1983

A flight from Miami to Nassau experienced low oil signals for engine #2 during flight, at which point the pilot decided to head back to Miami. Enroute back to Miami, the #1 and #3 engines also began to show low oil signals. The airplane descended from ~13,000 ft. to 4,000 ft. without power by which time engine #2 managed to restart. The plane then made a single engine landing at Miami safely.

The probable cause for this incident was the omission of all the O-ring seals in the master chip detection assemblies. These are assemblies used in aircraft to provide an early warning of engine failure. Omitting the O-ring seals reduced the cost of MRO in all 3 engines but resulted in oil leaks in all 3 as well. According to the report, this was a maintenance flaw as the proper procedures for installation of the master chip detector were not followed by mechanics [19].

3.3 Global Market

The global civil MRO spend in 2015 was $64.3 billion compared to the $62.1 billion spent in 2014, marking an increase of 3.5%. According to ICF international, 40% of these costs are attributed to the engine segment alone. The growing spend in this area in the past few years means that newer engines are requiring more overhaul and repairs.

Accounting for the global market share of MRO by region, North America had the largest share in MRO activity (29%), with Asia-Pacific (28%) and Europe (26%) coming in a close second and third. However, Asia-Pacific will own a greater market share in the coming years based on current aircraft orders and could potentially become the largest global region for MRO activity in the coming years [13].

The industry will be see a massive technology shift in the coming years with this surge of new aircraft deliveries. By the year 2027, ~58% of the worldwide fleet will all be new-generation aircraft. As Asia will soon be the largest region for MRO activity, India and China will experience the major growth engine of this change, essentially doubling their fleet and MRO demand in the region. Distinctively, North America will experience little absolute growth and concentrate on upgrading their fleet. The growth of fleet and introduction of new aircraft in Asia will also bring a growth of MRO in the region as new aircraft will require this level of maintenance and care.

While aero-engines tend to operate at better fuel-efficiency than before, they face harsher environmental conditions too. As a result, expensive components and materials require replacement and overhaul – accounting for the 4.9% average annual growth rate in engine MRO [12].

Typically, MRO and support services account for 80% of an aircraft's total life cycle cost. This is because MRO services can last more than 30 years for an aircraft. Figure 2 shows that maintenance, at 13%, is a large chunk of total operating costs and is only 25% lower than the fuel cost; this is a sizable portion in an airlines cost structure [20].

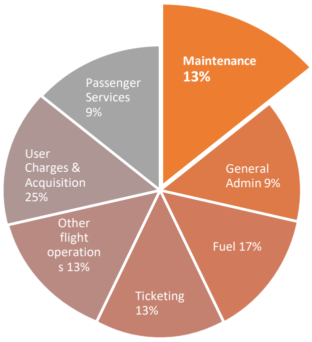

Figure 2: MRO percentage from total operating cost [53]

Currently, around 20,000 commercial aircraft and 15,000 business jets are operating worldwide and these numbers are expected to double over the next 20 years [21].

The above analysis has made it clear that the aerospace industry is growing phenomenally and the number of fleets are growing simultaneously. Additionally, the introduction of new generation aircraft means that all sorts of MRO services will be required. Not only will there be a spike in the demand for more efficient MRO, but over the next few decades the industry will encounter a different set of maintenance issues that they have not seen before.

4.0 AEROENGINE SEALS

Having outlined the current condition of the aerospace industry and the importance of MRO of seals due to it, this section will explain the purpose of seals and describe the most commonly used seals in aerospace applications. Two main categories of seals have been installed in aircraft engines: air-to-oil seals and air-to-air seals. Each are placed in a different engine compartment and seal unique environments

1. The air-to-oil seals are placed in the bearing housing right before the bearing. Their purpose is mainly to:
    a. Retain oil in a certain compartment or system, preventing leakage
    b. Prevent debris and contaminants from entering into the system
    c. Ensure that high pressure conditions do not result in leakage of oil

    They are found to be useful in gearboxes, hydraulic cylinders and other oil sealing applications.

2. The air-to-air seals are used as turbine and compressor interstage seals [22]. Their purpose is mainly to
    a. Minimize gas rescirculation
    b. Minimize gas leakage out of the primary path

    They are important factors that contribute heavily to enigne efficiency [23]

Figure 3 is of the cross section of an engine, highlighting 2 of the main areas where a seal would be present. The first location would be in a bearing housing, placed with the bearing. The second main location would be in turbine secondary air systems and turbine compressors. In some of these cases, two seals are used to ensure complete sealing for eg. In many cases, a static seal like an O-ring or a gasket is used with a mechanical face seal together for effective sealing. These is known as primary and secondary seals in a system [24]. Windback seals used with labyrinth seals are another example of two seals being used together for maximum sealing capability [25].

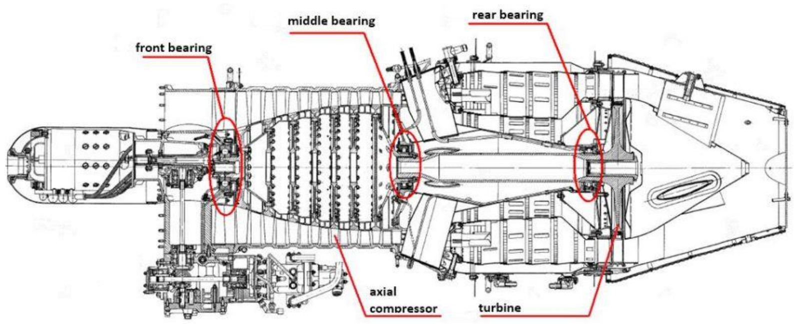

Figure 3: cross-section of a gas turbine engine [26]

As previously established, the direct purpose of seals are to prevent leakage out of the system and prevent debris from entering into the system.

Leakage of a fluid in an engine can result in several engine problems. While some leakage might be favourable for certain operations, too much leakage can result in fuel waste and low engine efficiency. All of this is relative and will depend on the placement of the seal and application. Design engineers must be aware that changing seal parameters for critical seals can change entire engine dynamics for the better or worse [26]. Additionally, they can result in contamination of the bleed air supply. This is a recent issue that has raised concern of seal leakage in aero-engines within the aerospace industry and numerous initiatives have been undertaken and are ongoing to investigate this issue further. Seal failure or wear resulting in leakage can potentially contaminate the cabin air. Chronic and repetitive exposure to low levels of engine oil emissions along with acute exposure provides a path-way for increased vulnerability for aircrew and regular flyers [27].

Contamination in an engine can heavily impact the efficiency of other crucial parts like bearings. Improved seals have the capacity to reduce contamination of the lubricant into the bearing chamber, significantly improving the theoretical bearing life as well [28]. Dirt ingestion into the engine is a major problem as it compromises engine efficiency and fuel consumption. In modern day engines, around 20-30% of the compressor core flow is utilized to cool the hot section. When extensive dirt enters the engine system, the pores get clogged and the cooling process is hindered. Over time, this effect builds up and the fuel consumption degrades due to deposits on the air foils, reducing the aerodynamic efficiency. Semi-annual engine washing has proven to improve the burn by up to 1%, corroborating the need to prevent dirt ingestion into the compressor air flow. Seals can effectively prevent contamination into the system, thus playing a critical role in engine efficiency from yet another standpoint.

Advanced seal engines have a high performance to cost ratio that would increase engine performance, lower lifetime costs and reduce the frequency of engine maintenance over its service interval. Engine performance refers to engine efficiency and the SFC.

Correlative studies have shown that enhancing the performance of aero-engines by just ~0.1% is effort and cost heavy whereas advanced seals can bring about an improvement of ~1-2% with lower development costs [29]. The aim is to design low leakage, high performing and reliable seals that exhibit longer service life with reduced wear [30] and their potential to improve has remained relatively untapped [31].

Four commonly used aero-engine seals have been reviewed below with regards to the aerospace industry, explaining how they work and problems that may cause failure.

4.1 The Labyrinth Seal

4.1.1 Design Features

The single most common flow path seal applied in the history of engine turbine is the labyrinth seal [32]. The labyrinth seal is initially an innovation introduced by C.A. Parsons in 1892 with his development of the steam turbine engine. He proposed a

torturous flow path in between the high and low pressure regions by means of a series of non-contacting restrictors and separating chambers as shown in figure 4. With time, many modifications of the labyrinth seal have been introduced but it has not changed much from Parsons original design [33]. A labyrinth seal operates by providing a contorted path for the fluid, thereby reducing the leakage. These restrictions are in the form of labyrinth teeth that provide a close clearance between the rotor and stator, thus breaking the momentum of the incoming fluid [34]. These seals are clearance devices and this has two implications. Firstly, they do not wear out easily as there is supposedly no contact and theoretically have an infinite life. The reality is that due to the operational environment, vibrations, working and loading states, contact is difficult to avoid and even labyrinth seals experience wear. The second implication of clearance devices are that they provide the fluid with an open path for leakage, resulting in high leakage rates. This has become a problem over time as sealing requirements include minimal leakage design seals [32].

4.1.2 Mechanism

For simplicity, imagine the labyrinth seal to be modelled as a series of orifices through which a pressure drop is established. Including many other models, the Saint Venant-Wantzel orifice equation [33] can be used to model and understand how this seal operates simply.

The labyrinth seal, as shown in figure 5, consists of a series of knife edges with corresponding cavities, acting as a restriction to the flow and a volume for expansion. They work by throttling the flow through the constrictions (knife edges/fins/teeth) and cavities arranged in series. The static pressure difference across each constriction generated by throttling accelerates the flow and kinetic energy associated with the flow is dissipated in the following cavity. The use of a contorted path between high and low pressure regions, using a series of constrictions and cavities with a stator-rotor clearance is the main operating mechanism of the labyrinth seal [3][35]. Figure 5 is one type of labyrinth seal with the teeth or knife edges on one face. Some labyrinth seals have teeth on both, the stator and the rotor and some are stepped labyrinth seals as well. They all operate on the same principles and are ways to balance leakage and vibrational effects. A recent paper outlines a T shaped labyrinth seal that leaks 7.4-8.5 % more than the efficient interlaced labyrinth seals, but reduce rotor vibration in aero engines [36].

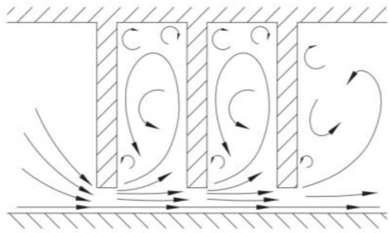

Figure 4: Labyrinth seal tooth schematic [37]

There is a lot of literature on the mathematical modelling of labyrinth seals to take into account a lot of the factors that must be considered for an accurate model. These include the rotor dynamic co-efficient, heat transfer co-efficient and the kinetic energy carry over co-efficient etc… [38] [39] [40].

4.1.3 Challenges in the aerospace industry

Due to higher leakage rates, labyrinth seals are not always the most effective sealing method and often must be placed with another seal. The clearance of these seals can be reduced to decrease leakage but this may impact the dynamic stability of the turbomachinery.

The circumferential non-uniform pressure distribution within the labyrinth chambers exert forces on the rotating shaft, destabilizing it. To include the fluid induced forces in rotor dynamic analyses, rotor dynamic coefficients are calculated for labyrinth seals [41]. This is a problem that arises when dealing with any high speed turbomachinery as

the operating speeds may sometimes be above the first rigid support critical speed, resulting in dynamic problems [42].

Several works have been conducted to study the effect on labyrinth seals of rotor dynamic instability. Choudhury [42] presents case studies that indicate increasing the radial clearance of the oil seals and adding grooves on the seal improves the stability of the system. F. Cangioli's [43] work extends the accuracy of calculating the rotor dynamic coefficients in labyrinth seals by including the energy equation in Childs et al.'s steady state model. G. Morrison [44] investigates an effective model for the carry-over co-efficient (represents the effectiveness of each cavity of the labyrinth seal to dissipate kinetic energy) of incompressible flow, considering the effect of geometrical variations and flow conditions of the seal. It was seen that Reynolds number and the clearance/pitch ratio have a sizable impact. S. Suryanarayanan [45] is essentially an extension of the same work, taking into consideration other geometrical parameters like tooth height, width and pitch. It is also seen that these have a significant impact on the carry-over co-efficient.

4.2 The Brush Seal

4.2.1 Design Features

Brush seals picked up momentum in 1988 after Ferguson [46] published his paper on their improved performance over labyrinth seals. They were known to be viable replacements for the labyrinth seals in gas turbine engines as significant improvements in cycle efficiencies would be achieved [47]. Since then, much investigation has been done into performance criteria, leakage, wear and cost implications of brush seals in an effort to develop their use [48]. Figure 6 is an image of a brush seal and figure 7 details the parts of a brush seal, showing that they consist of fine diameter fibres that are densely packed together between a face plate and a backing plate. The backing plate is located downstream of the bristles as a support plate for the varying differential pressure loads. On average, the fibre bristles range between 0.07 to 0.15 mm in diameter. The front plate tightly clamps and holds the bristles in place. The seal is then installed in a static house with bristles touching the rotor at an angle. This angle is called the 'lay angle' and is 45-55° facing the direction of rotor rotation [32][49].

They offer many advantages; their flexible fibres and 'hair like' wires allow for tighter rotor clearances, lower leakage rates and better rotor dynamic characteristics than labyrinth seals [49].

Figure 5: Brush Seal

4.2.2 Mechanism

Brush seals fill clearances between the seal and shaft with their bristles and fluid flow through the bristle pack tends to blow the bristles down towards the rotor due to the lay angle. Most of the modelling of brush seals is done by treating the bristle pack as a porous medium which simulates the pressure drop across the bristles. It also projects the other effects of the brush on the fluid flow.

Chew et al. (1995, 1997) proposed a 3-D and non-uniform description of the porosity of the bristle pack and derived the pressure forces experienced by the bristles based on the pressure distribution within the porous region. Integrating these forces allows for an estimation of the blow down forces, bristle bending and ultimately, the effect on the rotor making contact with the bristle pack [50].

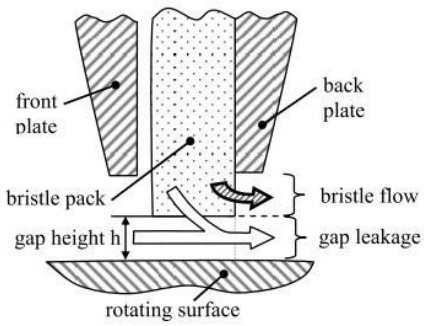

Figure 6: Brush seal working mechanism [50]

Some of the important dimensional parameters that impact the brush seals [51] are shown in the table below:

Table 2
Parameters for brush seals

Wire Size	Larger wires exhibit higher pressure capacity but higher leakages
Fence Height	The fence height and wire size together has a sizable impact on sealing performance. Increasing fence height reduces the pressure capacity.
Wire density	Doubling wire density reduced leakage by ~30% and more than doubled pressure capacity.
Free bristle length	Decreasing bristle length can increase pressure capacity and reduce leakage significantly but may cause other problems
Bristle to rotor clearance	Bigger clearances result in blow down effect of the bristle pack

4.2.3 Challenges in the aerospace industry

Issues regarding friction and wear are apparent in brush seals as the bristles come into contact with the rotor surface, affecting the life and efficiency of the seal and present literature [49][52] describes several of the common issues that we face with its application. Brush seals face the problem of pressure-stiffness coupling and hysteresis. Pressure coupling occurs due to frictional effects which cause the bristles to stick to one another and the bristles to stick to the backing plate. The seal becomes much stiffer than it normally would be without any pressure load and this results in wear of the seal. Hysteresis is a direct consequence of pressure-stiffness coupling and is more of a leakage problem rather than durability. During rotor excursions, the seal becomes radially displaced and does not return to its original position because of its stiffness. This results in leakage through the seal.

Many studies have been conducted to evaluate the performance of the brush seal. Turner’s [53] CFD model to study the aerodynamic forces on bristles and its impact on sealing characteristics revealed that the position of the bristles plays an integral role in the pressure distribution and friction forces on the brush pack. H. R. Hotel’s [54] investigation of the high temperature steam effect on brush seals’ wear condition and sealing performance indicated oxidation and wear under high temperature steam conditions are prevalent.

Other problems associated with brush seals include bristle stability (caused by high bending stress and pressure loads), damaged rotor (caused by stiff seals) and pressure capability (caused by high pressures beyond the capability of the seal, resulting in bending of bristles and leakage) [49].

4.3 The Mechanical Seal

4.3.1 Design Features

Mechanical seals are commonly referred to as carbon face seals or radial face seals – however, mechanical seals is the most common and widely known term and its basic concept dates back as early as the 1900. It appears to have originally been invented George J. Cooke (Patent #1545080, “Seal for Rotating Shafts”) in 1923 and continued to be further developed and adapted over the years. Mechanical seals are ideal for high speed operation and can withstand harsh operating environments.

They can be both, contacting (rubbing) and non-contacting (film riding) in nature. In the contacting seal arrangement, there are a pair of radial faces – one stationary and the other one rotates with the shaft. These faces are maintained with a tight clearance by a series or springs or metal bellows for high speed applications. In addition to the primary sealing mechanism, a secondary sealing element is also included in the design for which an O-ring, bellows or piston ring can be used. They operate as a whole sealing system and it is necessary for both the primary and secondary seal to work successfully to prevent leakage [4].

The non-contacting arrangement utilizes the concept of hydrodynamic lift between the two primary sealing surfaces (stationary and rotating). A lift force is generated between these two surfaces to maintain a certain clearance and prevent wear of the mating surfaces through complex-shaped microgrooves and other topography characteristics which ensure reverse pumping of the leakage in the sealed cavity [30].

4.3.2 Mechanism

The main working part of the mechanical seal is at the primary sealing point as this is where the actual sealing takes place. The rest of the seal geometry is designed to provide this interface with the necessary conditions for successful sealing. At this surface, there are a few cases that could occur. Firstly, there could be a continuous film of fluid (that is small but finite) separating these faces where the load is being carried by the fluid. Secondly, there could be no fluid in between the two surfaces and the load is carried solely by asperity contact (boundary lubrication). Lastly, it could be a combination of the two situations. The seal works successfully when it is designed in a manner such that the fluid film in between the two surfaces is stable (achieved by converging film profiles), thick enough to prevent contact and thin enough to prevent excessive leakage rates [55]

There are several factors that must be considered in the design of these seals that heavily impact their sealing performance. These include the balance ratio, lubrication regimes and the surface definition parameters (surface profile, roughness) [32]. The surface structure particularly plays a crucial role in the performance of these seals and has been considered by multiple studies [56].

4.3.3 Challenges in the aerospace industry

Due to the high temperature, high pressure and high speeds in this application, heat generated on the sealing surfaces results in wear and deterioration of parts, shortening their life. High temperatures may also alter the seal geometry and result in heavy leakage rates.

One of the main problems associated with these seals is wear due to friction caused by high rotational speeds. Research has been done in this area, investigating the factors that affect the frictional behaviour of seals. Some studies suggest that using laser textured seal surfaces is a way to reduce the wear of the mechanical seal [57][58]. Since high temperatures is part of the operating conditions of gas turbine engines, the effect thermal radiation on temperature distribution for mechanical seals has recently been studied too. The intent was to come up with an analytical model to study the thermal response of such parts at various operating conditions [57].

4.4 The Radial Lip Seal

4.4.1 Design Features

Rotary lip seals have been used since the 1930's and since then, a lot of research has gone into understanding the complex mechanism of these seals. In a typical lip scheme schematic, there is a micron scale (1-2μm) lubricating film of liquid that separates the lip from the shaft. This film is necessary to prevent damage to the lip due to mechanical stresses and heat generation at the lip-shaft interface [59]. As shown in figure 8, the seal consists of (1) a lip which is for sealing with the rotating shaft, (2) an outer static seal, (3) a metal reinforcement which supports the lip and (4) a garter spring which provides the pre-load on the shaft surface for sealing.

Figure 7: Radial lip seal schematic [60]

Figure 9 displays how the seal is usually mounted on the shaft with an interference fit and makes contact with the shaft at 2 angles, α (air side) and β (oil side). The seal is designed such that the angle of the air side is much smaller than the angle on the oil side and this asymmetrical geometry is a crucial design parameter that aids in reverse pumping. The pressure distribution under the lip where it makes contact with the shaft is also an important part of how the seal works.

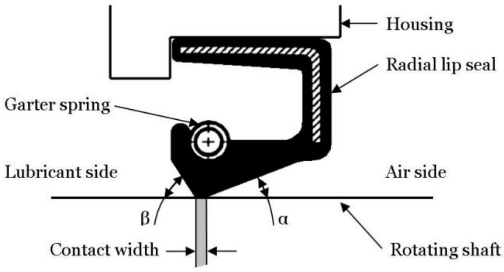

Figure 8: Radial lip seal shaft-seal interface [61]

4.4.2 Mechanism

Three mechanisms have been identified for the radial lip seals mechanism [61]

1. The lubrication mechanism generates a thin lubricant film between the lip and the rotating shaft. This film separates the two faces and minimizes wear and friction, resulting in smooth operation of the seals.
2. The sealing mechanism provides static and dynamic sealing by keeping the lubricant inside and other contaminants outside the system despite this thin lubrication film that exists.
3. The reverse pumping mechanism ensures that oil is pumped from the air side back into the oil side and is supposed to be larger than the natural leakage of the system to provide effective sealing. It is determined by the micro geometry of the seal and shaft (micro asperities, grooves, etc…) and the macro geometry of the seal lip (placement of the garter spring and the air/oil side angles). Both of these effect the pressure profile under the lip on the shaft and determine the performance of the seal.

4.4.3 Challenges in the aerospace industry

With these seals, the lip-shaft interface is critical, making the surface characteristics of the shaft and seal at microscopic levels become very important too. For these seals to perform well, the combination of the lip and shaft have to work well together otherwise the seal will wear or leak significantly.

The seal is brand new with no surface asperities on it. The shaft must be of the desirable specifications which usually range between R_a = 0.2-0.4 μm (roughness average). The manufacturing method, surface coating and hardness of the shaft are a part of how the seal performs. The seal will wear in through preferential wear as it rubs against the shaft during the burn in period. The asperities on the shaft and seal surface are responsible for the load support mechanism and the reverse pumping mechanism as well. However, if the shaft is too rough, it may wear out the seal and result in leakage. If it isn't rough enough, it will not wear-in the seal and the asperities will not be sufficient to support the load or facilitate reverse pumping. Tiny fluctuations in shaft roughness can lead to large hydrodynamic effects due to the non-linearity of the Reynolds equation.

Leaking seals are a major challenge faced here as the tolerances for these surface parameters are in microns and while the optimum shaft roughness values are provided by manufacturers, it is very difficult to ensure the exact roughness value to be replicated on each specimen. Through standardized procedures, each specimen will fall within the specified roughness range guidelines but can differ slightly. Therefore, a huge problem with these seals are that they are not properly understood as research continues to be carried out to fully understand the working mechanism and prevent leakage [59][61][62].

5.0 CONCLUSION

This section will consolidate the information in this paper to draw connections between the aerospace industry and its heavy dependence on sound MRO practices, describing how it effects engine seals. Additive manufacturing and lean manufacturing are two newer area's that are being explored for the MRO industry to evolve and grow. They have also been explained in the second part of this section.

5.1 Problem statements

1. The magnitude of cost allocated to MRO and its role in the economy is a reason to ensure that it must become more efficient. Unnecessary and unscheduled MRO can be eliminated by regular checks, predictive maintenance and other precautions. Components should not reach the point of complete failure and detection systems should pick up faults in their early stages. MRO needs to advance technologically and catch up with all the other aspects of the booming aerospace industry.

2. When MRO is being conducted – emphasis should be laid on inspecting components like seals that have failed or been damaged so that design engineers can improve geometrical parameters, material selection or working mechanism in the future. It is important that MRO is not only treated as a safety and maintenance procedure, but also as a feedback system as presented in figure 10 below. The knowledge of tribology helps reduce the requirement of maintenance and improves the reliability of these mechanical components and parts. The study of tribology at the design stage has proven to yield substantial economic benefit [63].

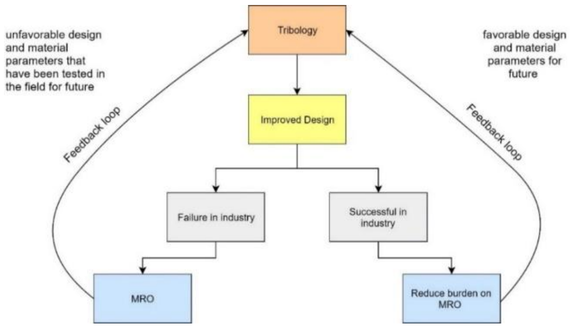

Figure 9: MRO as a feedback loop for information on component performance

Seal failure analysis is not a time consuming process, nor is it complicated. It can be done by maintenance staff that is trained and the data should be logged into the system instead of being lost. Overtime, failure patterns or failure modes in your particular application will present themselves and better designs will stem from that in the future [64].

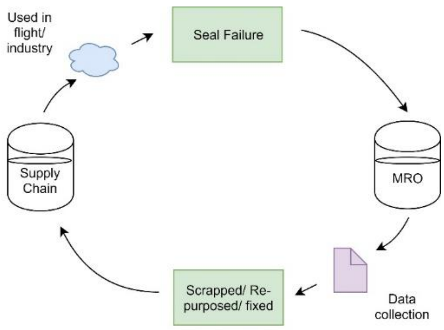

Figure 10: Seal failure cycle

Figure 11 explains the seal failure cycle that describes what happens during engine overhaul and its heavy reliance on strong supply chain and lack of time delays. Failed seals are removed from the engine and those that cannot be fixed are scrapped and those that can be salvaged are fixed. Data collection must happen at this stage to identify the reason for failure and inflight conditions faced. Next, they are directed back toward the supply chain as spare parts. When there are breakdowns, spare parts are quickly needed to replace them without any time delays. This is why supply chain is a major issue in MRO as it can result in time lags and calls for efficiency and organization in the MRO process.

3. Seal design should fulfil requirements of prolonged service life and performance goals alike. The bathtub curve shown in figure 12 is a good representation of seal life. In zone 1 of the bathtub curve, early failure and infant mortality of components is usually due to poor design. ‘Burn in’ periods are ideal to minimize this occurrence. Zone 2 represents the useful life period and has constant failure rate. Chance failure dominates this region and are attributed to unforeseen circumstances. This zone is longer than the other two zones. Zone 3 is the wear out period. In the end, even a well-designed seal will wear out and fail eventually. Sound MRO practices can prevent the early failure of seals and consequently prolong their useful life. Hence, repairing or replacing seals before they wear out is the way to prevent its failure.

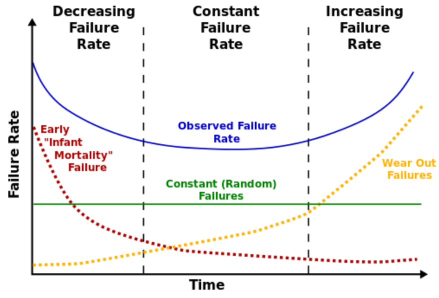

Figure 11: Bathtub curve

Usually, if the seal can endure the 'burn in' period and does not experience an early infant mortality, it is very likely to last for its lifetime until it wears in and fails. Seals that fail in the early stages point toward flaws in the seal that must be modified.

5.2 Solutions

It is evident from the above mentioned conclusions that delays, inefficiencies and disorder in this process can result in costs in the form of time, safety, money and inconveniences. Described below are two possible ways to improve efficiency of this process.

5.2.1 Additive Manufacturing

Additive manufacturing can be applied to MRO to reduce the design and production time for complex, high-value spare parts requiring customization. It supports environmental sustainability in manufacturing and has the capability to reduce time-to-market and manufacturing costs. Similarly, AM is also considered a potential silver bullet in the aerospace MRO market. Usually, the user has the operational and product-in-use knowledge of the component purchased but are not aware of part fabrication. Thus, users tend to purchase equipment with a service contract via a service provider to reduce manufacturing time. This concept of service contracting and lack of fabrication knowledge acts as a barrier for the user, leaving them unable to address MRO themselves. Overhaul operations are addressed from the Original Equipment Manufacturer (OEM) perspective and not by the end user of the equipment. AM successfully lowers that barrier for users as it enables production from 3D CAD file provided to the user upon purchase of that part. Furthermore, parts without available digital 3-D files can be digitized via 3D scanning technology of the original part upon purchase. This is relevant for the MRO industry where such problems are common [61, 62, 63].

AM also facilitates local manufacturing and repair. The equipment and raw materials necessary can be distributed globally with ease and the increasing use of digital architectures such as block chain has paved the way for MRO to expand into. Legacy products can also be maintained using AM and issues with old legacy tools that are now obsolete can be addressed. The need for reduced inventory and steady supply chain are ongoing problems for MRO and combined with new technologies and intelligent automation, a 'lights out' AM factory is a realistic probability for the future [68].

While AM offers many great benefits, it proposes high risk in this sector as well as the performance of these parts in the aero-engine is not yet known. Whether they are capable of replacing the original part without compromising their performance is yet to be seen. If problems do arise, this could end up being a bigger burden on MRO than a solution.

5.2.2 Lean Manufacturing

Lean manufacturing principles can be applied to MRO very effectively to reduce lead times, turn-around-time and other inefficiencies in the process to improve time and cost-effectiveness. With over 60% of any systems total life cycle cost associated with maintenance, repair and operations, optimizing the efficiency of the process can reap great benefits [69]. The idea of lean principles is to use several techniques of

benchmarking standards to constantly strive to reduce waste and lower costs of your system so that you can operate at maximum efficiency associated with time, cost, space, labour and quality. Studies have been conducted on how to incorporate a lean perspective into the aerospace industry like the roadmap put forth by MIT called the Lean Aerospace Initiative (LAI) [70] which documented 8 phases to progressively develop the production operation to a lean manufacturing system reflects a roadmap to transition to lean production operations.

6.0 FUTURE

This paper provided a review of sealing technology, its importance and its maintenance needs with regards to engine life and health, while also analysing case studies for relevance to the aerospace industry and aviation safety. There is a scientific gap in understanding the specifics of how radial lip seals function, resulting in their sudden and early failure. It has been explained that sound MRO practices can help understand and prevent failure of such parts in the future by gathering data and redirecting it toward design stages of seals. Future work will extend to better understand the working mechanism of radial lip oil seals specifically and shed light on unexpected failure in aero-engines to increase their reliability and life, and thereby, MRO intervals.

A test rig (fig. 13) presented below has been modified as a test bench for seals. The third section on the right hand side with the seal has been redesigned for this purpose. This rig [71] will provide a magnified clear view of the seal-shaft interface over the entire circumference for observational purposes with the use of a high speed camera, a thermal imaging camera and if need be, a micro thermocouple embedded at the seal-shaft interface. Additionally, it will allow us to gather data on seal behaviour and study a wide range of parameters i.e. wear, leakage, micro and macro geometry, pressure, etc…

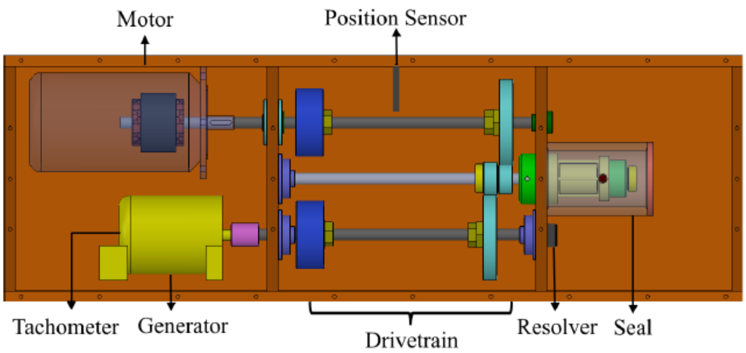

Figure 12: Test rig to be modified

A major aim is to learn more about seal-shaft interface phenomena and conduct tests to verify some hypothesis that have been made regarding the working mechanism for seals and the reason behind their unexpected failure. This data will be used to improve these seals and extend maintenance intervals to ensure reliability and confidence for end users. Radial lip seals is a commonly used seal in aero engines and the literature has explained its working mechanism to be attributed to a set of principles mentioned in section 4.4 of this paper. The reverse pumping effect, lip temperature, micro surface roughness, and macro geometry all play roles in the functioning of this seal and a large part of the future work will be dedicated to further study these mechanisms and shed light on issues of leakage, wear and seal failure.

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