EVAPORATIVE LOSSES OF VACUUM-COMPATIBLE OILS THROUGH LABYRINTH SEALS

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ABSTRACT

Following a literature review to assess the theoretical and experimental methods used to evaluate fluid losses via labyrinth seals, an experimental programme was carried out to measure these losses. A model derived by ESTL provided the best correlation with experimental oil losses and an effusion cell approach was identified as the most appropriate method to assess the effectiveness of labyrinth seals for three space oils, ie Krytox 143AC, Nye 186B and Nye 2001A. The selection of these fluids enabled a relatively wide range of vapour pressures to be investigated in the experimental programme using effusion cells of different geometries.

The test results were compared with the ESTL oil evaporation model and it was found that the evaporative losses from Nye 186B and HVAC25/9 were within an order of magnitude of predictions. Losses from Nye 2001a were larger than predictions.

1. INTRODUCTION

Experience with fluid losses via labyrinth seals is very limited in European space applications as it is normal practice to use either fully sealed systems or very low vapour pressure oils. As recently developed space oils, eg MAC's, have vapour pressures which could result in substantial losses over the lifetime of a mechanism there is a clear need to assess the effectiveness of labyrinth seals, as used in space.

The quantity of oil or grease in a fluid lubricated bearing can have a profound effect on bearing performance. Too little can lead to lubricant starvation and degradation, followed by increases in bearing torque, cage and bearing wear. Too much lubricant can lead to prohibitively high levels of viscous torque. It is important therefore to apply an amount of fluid lubricant appropriate to the application and to maintain this level of lubricant throughout the life of the mechanism. In order to minimise evaporative losses, the classical solution is to use a non-contacting labyrinth vapour seal.

For a bearing sealed in this way the amount of fluid lubricant lost by evaporation is governed by the following:

- The rate of vapourisation of the fluid, which is determined by its molecular weight, vapour pressure and temperature.
- The speed of travel of evaporated molecules (governed by molecular weight and temperature of the evaporating species).
- The gaseous pressures with the bearing cavity and outside the seal.
- The conductance of the labyrinth seal, which is determined from its dimensions and geometry.
- Whether the flow of gas or vapour through the seal is molecular or viscous (determined by the seal dimensions and size of oil particle).

Several models and equations have been developed to describe the flow of molecules through gaps and labyrinths. Most are based on molecular flow of small and light gas molecules, which are treated, for the purposes of modelling, as spherical particles. The application of these models, largely in US applications, has met with some success. However their applicability to low vapour pressure fluids, such as MAC's, having large molecules of complex shape has yet to be demonstrated or quantified.

2. OIL LOSS MODEL

Based upon a literature review (Ref 1) in which theoretical and experimental methods used to evaluate fluid losses via labyrinth seals were assessed, the most appropriate model and experimental method were selected. A model derived by ESTL provided the best correlation with experimental oil losses, to within a factor of 1.5. This model assumes molecular flow conditions and derivation of the fluid loss equation was based on linearising the labyrinth seal, ie to give an equivalent annular shaped seal and then unwrapping that annulus to provide an equivalent rectangular passage. The loss rate was calculated to be as follows:

$$\mathbf{Q = 0.0436\, P\, \pi\, d\, b\, (M/T)^{0.5} / (1 + 0.375\, L/ b)} \qquad g\ s^{-1}$$

Where:

Q: Mass loss in gs^{-1}
P: Fluid vapour pressure in torr
d: diameter of annular seal (mm)
b: gap width (mm)

L: path length (mm)
M: Molecular weight
T: Absolute temperature (K)

For the experimental programme, an effusion cell approach in which a porous reservoir is impregnated by the test oils was identified as the most appropriate method to assess the effectiveness of labyrinth seals. Oil evaporation takes place through annular gaps of varying geometries which simulated labyrinth seals. A schematic diagram of an effusion cell is provided in Figure 1.

3. EXPERIMENTAL SET-UP

Based upon the findings from the review, an experimental programme was set up to measure oil evaporation rates through labyrinth seals and filter meshes. The lubricants, test temperatures and seal geometries were selected to achieve measurable weight losses over an 11 month period under vacuum. In the course of the review, a number of design issues were considered and a rationale for seal design developed which was based on the following:

- There is no evidence from the literature that rotation is required to simulate the labyrinth seal action. This is also true considering molecular flow conditions. Therefore for simplicity, and as used by previous experimental studies, a static configuration was used.
- An effusion cell approach, as shown in Figure 1, was used as this technique offered a simple means of varying labyrinth seal dimensions with ease of manufacture.
- Four different labyrinth seal geometries were used: straight annular (ie "standard"), straight annular with a short path length, straight annular with a narrow gap and and annular with two right angle corners. The total lengths and mean diameters of annuli were the same to enable an experimental check to demonstrate that right angle corners have a negligible effect on vapour loss under molecular flow conditions. Table 1 summarises the critical geometrical parameters for each of the effusion cell types. The path lengths and annular inner and outer radii are as defined in Table 1.

Figure 1: Schematic diagram of effusion cell

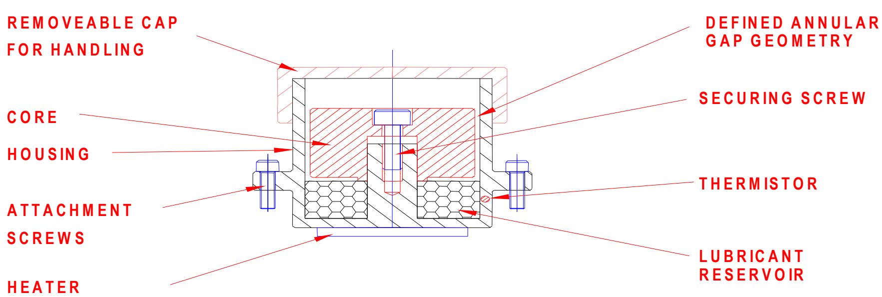

Table 1: Summary of Critical Parameters for Effusion Cells

Cell type	Inner annular radius (mm)	Outer annular radius (mm)	Path length (mm)
Standard	14.9	15.1	20
Short path	14.9	15.1	10
Narrow gap	14.95	15.05	20
Angular	Gap = 0.2	Gap = 0.2	20

- Mass loss was found by measuring the mass of the effusion cell before and after test. Initially, the impregnated cells were outgassed in vacuum at 100 deg C and then removed from the chamber. The weights were measured at intervals over the course of several days to quantify any weight changes due to water absorption. The cells were then re-installed in the vacuum chamber and the weighing procedure repeated following the 11 month test phase.
- A lightweight effusion cell was needed to maximise the relative mass contribution from the fluid lubricant. The preference was to use a typical material used for a labyrinth seal ie aluminium alloy. For the effusion cells, the Al-alloy was chromic-acid anodised to ensure no potential interaction with the heated lubricant.
- Three oils with differing vapour pressures were used in order to test the ESTL oil loss model over as wide a range as possible. The oils selected were Nye 186B, HVAC25/9 and Nye 2001a, which encompass a range of vapour pressures and their vapour pressures and molecular weights also ensure that the losses would be measurable in the experimental timeframe. The manufacturers of all these oils stated that they do not contain volatile additives, which could have affected the test results due to preferential evaporation of these additives. Nye 2001a is a standard space-compatible oil with heritage in flight applications. Nye 186B is a synthetic oil intended as a replacement for the highly-refined mineral oils such as SRG60 and SRG80 which have been used for lubricating reaction wheel ball bearings. HVAC25/9 is used as a vacuum pump lubricant and was included in this test programme in order to provide an oil with a vapour pressure higher than the other oils. Initially, the ESTL oil loss model was used in conjunction with the fluid properties to predict the losses expected and to size the cells.
- 12 effusion cells were used in the test programme, allowing 2 tests per seal geometry per oil. The cells were mounted on an electrically heated aluminium plate, suspended within a 40 cm vacuum chamber.
- The use of free oil in the effusion cells is not recommended due to handling risks and measurement errors that might arise with movement of bulk oil. The oil was therefore impregnated into porous Nylasint reservoirs as used in spacecraft mechanisms.
- Elevated temperature was essential to generate increased vapour pressures and hence sufficient lubricant loss by evaporation. A temperature of approximately 100 deg C was used.
- Anti-creep barrier was applied above the porous reservoir to ensure no fluid loss occurred due to creep.

The test fluids are summarised in Table 2, with information relating to vapour pressures and molecular weight, as supplied by the manufacturers.

Table 2: Summary of Fluids and Fluid Parameters

Oil	Temp (deg C)	Vapour Pressure (mbar)	Mol. wt
HVAC 25/9	20 100	2×10^{-9} 2×10^{-5}	3200
Nye 186B	20 100	1.33×10^{-7} 8×10^{-6}	824
Nye 2001A	20 100	1.04×10^{-12} 1.1×10^{-7}	910

4. RESULTS

The test results are summarised in Figure 2 and some general trends are evident from examination of the graph. Note that a stainless steel control mass was measured before and after the experimental programme as a calibration check. Cell identification is provided in Table 3:

Table 3: Summary of Cell Types and Identification

Cell ID	Cell Type	Fluid
1.1	Standard cell (20mm path, 2mm gap)	HVAC25/9
1.2	Standard cell (20mm path, 2mm gap)	Nye 186B
1.3	Standard cell (20mm path, 2mm gap)	Nye 2001A
2.1	Cell with short (10mm) path	HVAC25/9
2.2	Cell with short (10mm) path	Nye 186B
2.3	Cell with short (10mm) path	Nye 2001A
3.1	Cell with narrow (1mm) gap	HVAC25/9
3.2	Cell with narrow (1mm) gap	Nye 186B
3.3	Cell with narrow (1mm) gap	Nye 2001A
4.1	Cell with angular path	HVAC25/9
4.2	Cell with angular path	Nye 186B
4.3	Cell with angular path	Nye 2001A

- There was minimal weight change with time after removal from the vacuum chamber, in comparison with the measured oil losses. For the purposes of the experimental programme, the initial cell weights were used for preparing the graphs.

- The largest weight losses corresponded to the two higher vapour pressure fluids, ie Nye 186B and HVAC 25/9. Nye 186B impregnated cells exhibiting the highest losses (137 to 180 mg) and Nye 2001a the lowest (less than 21 mg). The test using HVAC 25/9 oil showed intermediate losses (50 to 140 mg), but this oil has the highest vapour pressure at 100 deg C and its measured weight loss is therefore not consistent with the trend shown by the other two fluids.
- For each of the three fluids, oil losses were greatest for the cells with short paths.
- Cells with narrow gaps exhibited lower losses than the standard cells – this finding is evident for the Nye 186 and the HVAC 25/9. The differences in the losses for the corresponding Nye 2001a tests were not sufficiently large to be resolved in the experiment.
- Use of angular paths did not result in any substantial differences in oil losses, compared with the standard cell. For the angular path, the oil losses were slightly lower (approx 5 to 10 mg less) than for the standard cell.

5. DISCUSSION

Predicted losses and measured losses over the 11-month test period are summarised in Table 4. Apart from the tests involving Nye 2001a, all the measured and predicted values agreed within an order of magnitude. For HVAC 25/9, all measurements were within a factor of 5 of the predicted values.

Figure 2: Summary of Oil Losses for Different Cell Configurations

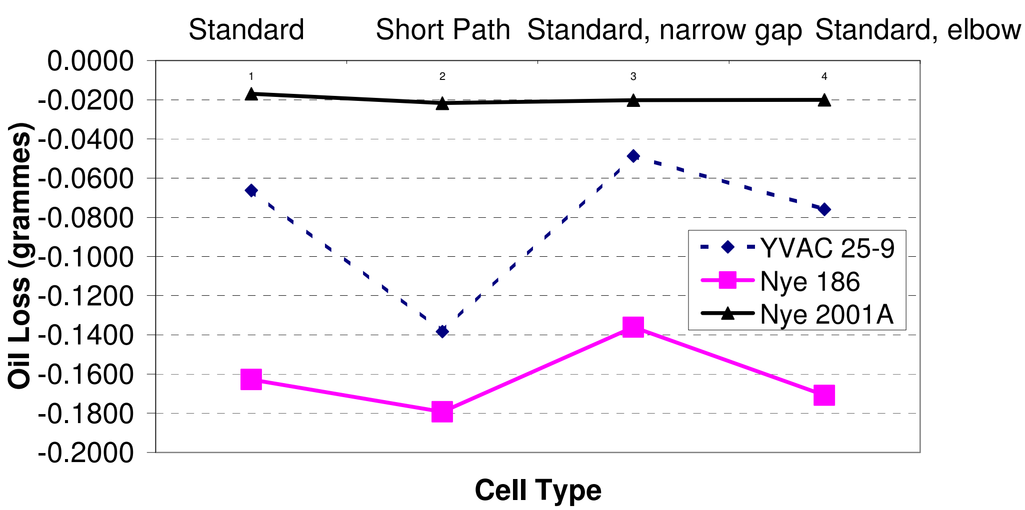

Table 4: Comparison of Measured Fluid Losses with Predictions

Cell Type	Fluid	Measured (mg)	Predicted (mg)	Ratio (meas/pred)
Standard	Nye 2001a	16.9	0.8	21.1
Short	Nye 2001a	21.7	1.5	14.5
Narrow	Nye 2001a	20.3	0.2	101.5
Angular	Nye 2001a	20	0.8	25.0
Standard	HVAC 25-9	66.3	355	0.2
Short	HVAC 25-9	138	693	0.2
Narrow	HVAC 25-9	48.7	90	0.5
Angular	HVAC 25-9	76	355	0.2
Standard	Nye 186B	163	72	2.3
Short	Nye 186B	179	140	1.3
Narrow	Nye 186B	136	18	7.6
Angular	Nye 186B	171	72	2.4

Nye 2001a: Discussions with the suppliers (Nye, USA) confirm that there are no additives present in the fluid and Nye also confirmed that the documented values of vapour pressure are less than 1.33×10^{-11} mbar, at 25 deg C. However, information from Nye states that the measured values are more typically between 1.33×10^{-9} and 1.33×10^{-8} mbar, which exceeds the documented values by at least two orders of magnitude, at 25 deg C. If this is also true at 100 deg C, then the actual vapour pressure can be expected to exceed the documented value of 1.1×10^{-7} mbar at 100 deg C.

HVAC 25/9: The predicted losses were typically 5 times greater than the measured values in the experimental programme. For the narrow gap case, the measured value was half that predicted.

Nye 186B: Losses from this fluid correlated reasonably well with predictions, with the measured values being 1.3 to 2.4 times greater than the predicted values, except for the narrow gap case, where the measured losses were 7.6 times greater than predicted.

Cell Geometry: The general trend for different cell geometries was as expected, with the standard and angular paths exhibiting similar losses (theoretically [RD1], elbows and bends should only have a minimal effect on evaporation via molecular flow). For the cells with a short path length, higher evaporative losses were measured than with the standard cell configuration. The narrow-gap configuration exhibited lower losses than the standard cell. These trends were most evident for the tests involving the HVAC 25/9 and the Nye 186B oils. For the case of Nye 2001A, these effects were masked by the resolution achievable in the weighing operations, which was approx 1mg.

6. CONCLUSIONS

Qualitatively, the experimentally measured trends followed those which would be intuitively predicted, ie oil losses increase with increasing gap width and decrease with decreasing path length, low vapour pressure fluids give smaller losses and angular paths did not have a great deal of influence on the measured losses.

The ESTL oil loss model predicted evaporative losses from Nye 186B and HVAC15/9 to within an order of magnitude. However, predictions of losses from Nye 2001a were far less than those measured and attributed to the vapour pressure of this oil exceeding the documented values.

Based upon the differences in documented vapour pressures for Nye 2001a, it is recommended that vapour pressure and molecular weight measurements are carried out for critical applications on the batch of oil which is actually used.

7. RECOMMENATIONS

The ESTL model provided useful order of magnitude predictions regarding evaporative oil losses through labyrinth seals and single mesh filters. However, the documented vapour pressures of oils should be confirmed by experimental measurements for critical applications where oil losses could be an issue.

When using the ESTL model to predict oil losses, the following guidelines are proposed:

1. Calculate oil loss using ESTL model
2. Apply correction factor for oil type and geometry from Table 5 which is based upon experimental data
3. Corrected values give oil loss prediction

Table 5: Oil loss correction factors for labyrinth seals

Fluid	Gap < or = 1mm	Gap > 1mm
Nye 2001a	100	20
Nye 186B	9	2.5
HVAC25/9	0.5	0.2

8. FURTHER WORK

A labyrinth seal experiment using an identical effusion cell approach is planned for Tribolab which will fly on the International Space Station. This experiment is intended to investigate oil losses in space over a 4-year period, after which the cells will be retrieved and re-weighed on Earth. It is intended that the fluids used in the flight experiment be identical to those used in the current work. Where feasible, it is also the intention to use oils from the same batches to enable direct comparisons to be made and to encompass a range of fluid vapour pressures. However, there may be some concern over condensation of the evaporated oils on surrounding surfaces and suitable precautions will have to be taken to minimise any risk of contamination. Note that, use of oils with exceedingly low vapour pressures such as Fomblin Z25, are unlikely to evaporate at a rate which will result in measurable losses over a 4-year timeframe.

9. REFERENCES

1. R A Rowntree, "A Review of Oil Loss Models and Labyrinth Seals and Filters for Space Applications", ESTL/TM/238, July 2000

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