RECENT DEVELOPMENTS IN PERFORMANCE AND LIFE TESTING OF SELF-LUBRICATING BEARINGS FOR LONG-LIFE APPLICATIONS

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ABSTRACT

Self lubricating bearings using PTFE/glass-fibre and MoS_2 composite cage (separator) materials such as "PGM-HT" are widely used in space applications.

Furthermore, it is well known that, unlike for liquid lubricated bearings, tribologically valid accelerated lifetests can be carried out for self-lubricating and other solid-lubricated bearings simply by increasing the operational speed of the lifetest unit. This approach typically yields acceleration factors (ratio of flight duration to lifetest duration) of order 5-10.

This paper draws data from a number of sources to review some of the benefits and constraints associated with use of self-lubricating bearings and proposes a "hybrid" accelerated lifetest methodology by which still more highly accelerated lifetests, achieving acceleration factors of 20-30 or more can be justified for self-lubricating bearing systems.

This new hybrid lifetest methodology allows much more rapid and cost-effective development of new products for relatively long bearing lifetime applications (e.g. scanners and reaction wheels) without significant compromise to the tribological rigour of the test.

Examples of products developed using this novel approach are provided.

1. BACKGROUND

The term "self-lubricating bearing" refers to any bearing in which a sacrificial element provides the sole source of lubricant. This self-lubricating effect is most commonly achieved using a lubricant-containing polymeric cage material which transfers lubricant via collision with balls and bearing lands to the raceways. In such bearings, lifetime is limited by wear of the self-lubricating cage material which in the limit can result in wear-out and loss of the land between cage ball pockets or by the onset of unacceptable torque noise due to the build up of cage "wear debris" on the raceways. It is also typical of such bearings that the torque noise is relatively high (by comparison with other lubricants) and variable due to the relatively un-controlled nature of the lubricant [1] transfer process which is essentially dependent on multiple collisions between balls, cage and lands and because of the inclusion of glass-fibres for material reinforcement.

1.1. Historic Context

Self-lubricating bearings have been widely used, both in conventional terrestrial (vacuum and non-vacuum) and space applications for 30-40 years. The most widely adopted material for such bearings was RT/duroid5813 or "Duroid" (manufactured by Rogers Corp.) . This material consisted of a PTFE, glass-fibre composite material with approximately 10-15% MoS_2.

Duroid was typically used in relatively small, thick-section (often crowned or snap-over type) bearing cages. Most commonly it was used for bearing envelopes such as SR3, SR6, SR8 because its rigidity was relatively low and the tolerances required for larger, thinner section bearing cages could not be held during manufacture.

Despite its relatively wide adoption including space applications, Duroid production ceased in the mid 90's and it was necessary to identify a replacement material for use in space and high-vacuum applications.

After an in-depth ESA-sponsored study of many candidate replacement materials, ESTL (European Space Tribology Laboratory) selected PGM-HT (supplied by JPM of Mississippi Inc.) as tribologically and compositionally the closest direct replacement to Duroid. The selection was substantiated by a programme of pin-on-disc and bearing level tests in air and in vacuum which demonstrated the close similarities in performance between Duroid and PGM-HT and ultimately qualified PGM-HT for space use. It should be noted that whilst other materials were also tested under this programme, some of which were hoped to exceed the limitations of Duroid, only PGM-HT was found to perform in-line with or better than the original material. This work was extensively

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documented [2, 3, 4] and some key performance points which can be extracted from these references are:

- **Composition**
  PGM-HT – PTFE, MoS_2 (15±3%), Glass Fibres (10µm dia. 15±3%)
  Duroid – PTFE (65±5%), MoS_2 (12.5±2.5%), Glass fibres (1-2µm dia. 25±5%)

- **Critical Contact Stress**
  PGM-HT and Duroid both exhibit a critical Hertzian stress limit of 1200MPa peak above which lubrication by the PTFE content becomes ineffective and metallic wear occurs reducing the lifetime by several orders of magnitude [5,6].

  Below this stress level however, the lifetime (expressed in terms of volume wear) is relatively well-defined as a function of peak Hertzian contact stress

- **Sliding Friction**
  Sliding frictional performance of the two materials (in pin-on-disc tests) is very closely similar in both air and vacuum [1,2]. As temperature is increased, say from 20°C to 60°C, there is an increase in sliding friction coefficient for both materials of approximately a factor 2.

- **Torque**
  Torque performance and wear behaviour of PGM-HT caged bearings in vacuum was found to be entirely consistent with predictions based on its measured friction coefficients against appropriate counterfaces in pin-on-disc tests.

- **Wear Rate (v 52100 Steel)**
  In pin-on disc tests in air and vacuum over a range of typical temperatures +60 to -30°C, the Specific Wear Rate of PGM-HT was found to be around 50% of that of Duroid [1,2].

- **Elastic Modulus**
  At room temperature, PGM-HT is around 18% of the stiffness of Duroid [7] and as temperature is increased its modulus changes more rapidly than does Duroid as shown in Tab. 1.

Table 1. Elastic Moduli of Duroid and PGM-HT

	Elastic Modulus (GPa)		
	20°C	**120°C**	**Ratio 120°C/ 20°C**
Duroid 5813	6.1	2.9	0.48
PGM-HT	1.1	0.33	0.3

Due to its lower Modulus and Specific Wear Rate, it might be expected that each ball-to-PGM-HT cage collision would result in lower wear than would a corresponding collision in an identical Duroid caged bearing.

Given the above, it is a reasonable assumption that the behaviour of the two materials will follow a very similar trend in bearing cages, with, if anything, better wear life performance coming from the PGM-HT material.

2. BASIS OF ACCELERATED TEST METHOD

In Fig. 1 below we plot data from a self-lubricating bearing Performance Guide [6] based on experimental evaluation of over 3000 bearing tests (size SR2-SR8 bearings) using snap-over (i.e. crowned) Duroid cages operating in air. The plot shows the predicted lifetime of Duroid-caged bearings in air at 20°C. In this programme the lifetime was defined by the test duration to achieve a 15% cage mass reduction due to wear. For the bearing and cage geometries used, the mass loss corresponded to a survival of approximately 33% of the nominal ball-pocket land dimension upon termination.

This data clearly shows that above a peak Hertzian contact stress of around 1200MPa there is a several order of magnitude reduction in lifetime which is attributable to ineffective lubrication by the PTFE material under high contact stress conditions which in-turn leads to the onset of metallic wear. However below this level there is a much reduced dependence between lifetime and peak contact stress, which nevertheless spans more than one order of magnitude.

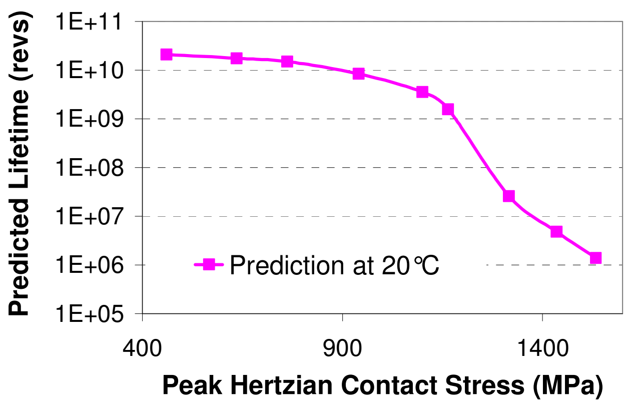

Figure 1. Predicted Bearing Lifetime for Self-Lubricating Bearings v Peak (Ball-Raceway) Hertzian Contact Stress

In Fig. 2 we show the Performance Guide data plus a second data set derived from a review of published lifetest data plus experimental data [8]. This composite mainly includes PGM-HT data, but also features data for Duroid. It should be noted that the lifetest data is exclusively in vacuum and includes tests which did not reach end of life, but were terminated for other reasons (indicated with arrows).

For the Performance Guide data we have shown a regression curve fitted to the data points below 1200MPa, and we have fitted a similar curve to all of the lifetest data from this stress regime. When plotted in this way, it can be seen that the gradients of the exponentially fitted regression curve and the predicted lifetime data are very similar (even allowing for the logarithmic scale used)

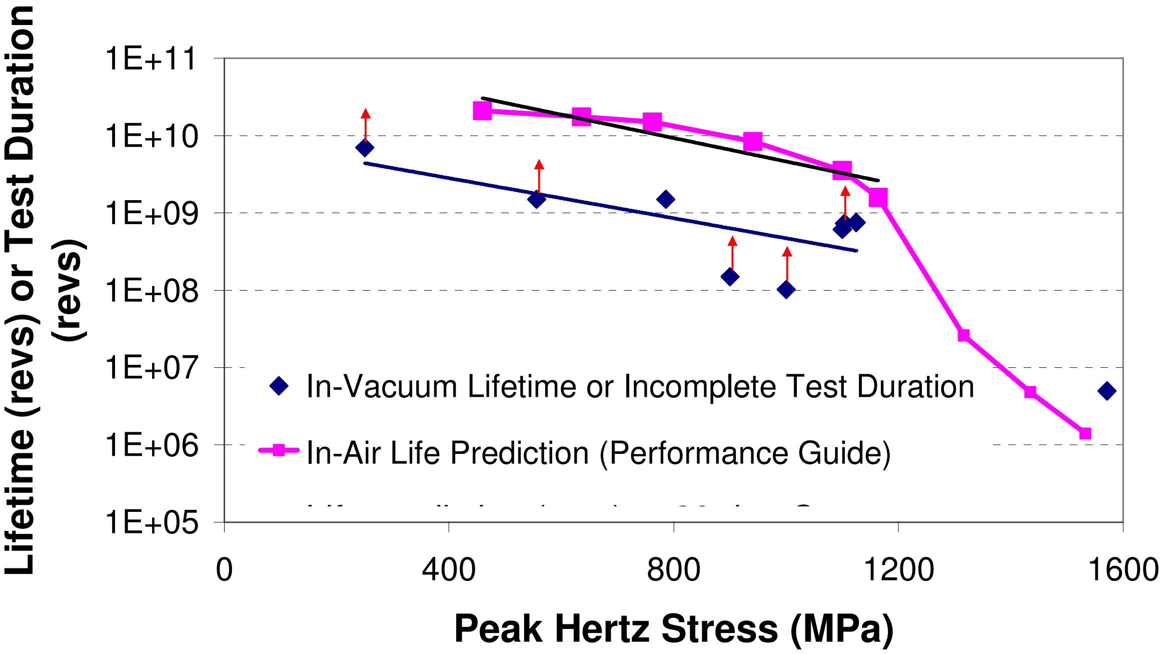

Figure 2. - Predicted (Performance Guide) Lifetime & Experimental Test Duration for Self-Lubricating Bearings v Peak (Ball-Raceway) Hertzian Contact Stress

3. IMPLICATIONS FOR LIFETESTING IN LONG LIFE APPLICATIONS

There is clearly a strong relationship between bearing lifetime and ball-raceway peak Hertzian contact stress for this class of self-lubricating material below the 1200MPa operating limit. Given this, in order to maximize PGM-HT lubricated bearing lifetime it is strongly desirable to minimise the bearing operating preload as far as possible, such that the contact stresses are well below the 1200MPa limit (e.g. aiming for 300-400MPa say).

This is not a design characteristic which can be lightly considered as there are a number of on-orbit and ground-test engineering consequences of reduced preload selection which need to be taken into account, in doing this:

1. In a conventionally preloaded system, that is, one with essentially fixed preload for launch and orbit which does not utilise a Bearing Active Preload System (or “BAPS” [9, 10]) or bearing offload device (of “BOLD” [11]) the stiffness of the rotor support will be low if the bearing preload is set deliberately low This must be managed by appropriate bearing-independent snubbing or other protection measures to prevent damage during launch vibration.

2. If the preload is low, the 1-g self-weight of the rotor will potentially change the loading configuration, stiffness and running track for the bearings (particularly in radial bearings) during ground testing. Avoidance of this may limit the minimum preload which can be tolerated.

3. If preload is deliberately set to a very low level, there will be an increased torque noise relative to

mean torque. On the other hand, the mean bearing torque will be reduced considerably and approximately pro-rata the preload (in fact the load-dependent torque component varies as preload $^{4/3}$). Only when the preload is very low will this relationship be invalidated by ball load/size tolerance effects or as the cage drag (which is essentially constant due to cage 1g-weight) begins to dominate over the load-dependent Coulombic torque component of the ball-raceway contacts.

4. If the room temperature isothermal preload is low, care must be taken in design to ensure that under worst case thermal conditions the preload never becomes zero.

Since in order to achieve optimally long life, a very low operating preload must be set for the flight models, there emerges a possibility of increasing the acceleration factor of the lifetest by increasing not only speed (as is usual), but also the bearing preload selected for the lifetest unit. The acceleration factor which can thus be achieved depends on the flight bearing operating contact stress compared to the 1200MPa peak stress threshold (since beyond this limit a different metallic wear regime occurs) and the speed acceleration factor used.

It should be noted that in principle an order of magnitude acceleration can be achieved without changing operating speed. However, as a more typical example, if a factor 5 increase in speed is adopted, a further factor of 4-6 may be achievable from increasing lifetest preload, typically producing a total acceleration factor of around 20-30 without exceeding the allowable stress limit of 1200MPa. This method is the basis of the so-called “Hybrid Accelerated Lifetest” (i.e. test accelerated by both speed AND increased contact stress)

If this approach is followed, it must be accepted that a high-preload lifetest model will not only accelerate the wear rate (desirable), but also increase the stiffness of the bearings during the lifetest pre-conditioning vibration test (deviation from flight behaviour) and the consequences of this must be assessed and demonstrated not to invalidate the test.

4. APPLICATION OF THE HYBRID ACCELERATED LIFETEST METHOD

The implication of the above is that by testing at a higher contact stress than nominal operation, it is possible to demonstrate the lifetime of the bearings more rapidly than if a test is carried out only at the nominal preload. The hybrid accelerated lifetest target lifetime v peak Hertzian contact stress curve is defined by re-constructing a curve of identical gradient to either the Performance Guide or Experimental Data (Fig. 2) which is constrained also to pass through the required lifetime target (i.e. nominal lifetime x ECSS lifetime factor).

We show in Fig. 3 below an example for such a curve for a high-speed scanner application which nominally operates at 1000rpm for 5 year lifetime (2.63E9 revs). With addition of a 25% ECSS life factor, the total un-factored lifetime is increased to 3.29E9 revs.

Due to the gradient of the Performance Guide curve, a valid hybrid lifetest would require a test at 1100MPa to achieve a duration of 8.24E8 revs.

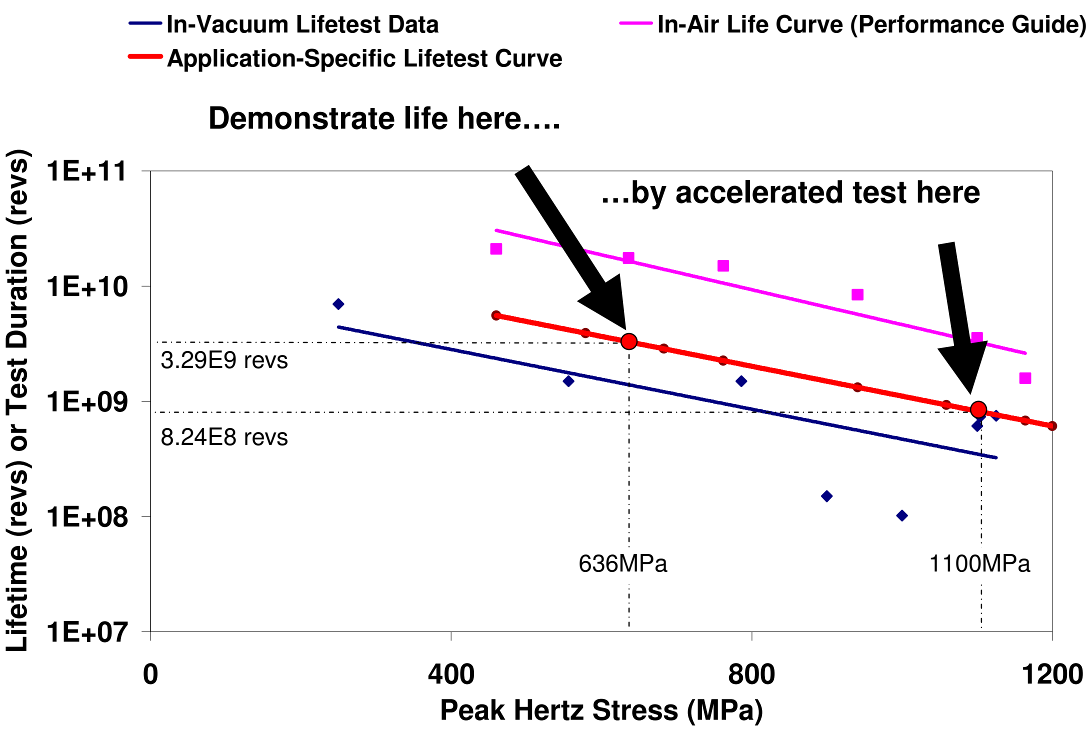

Figure 3.- Derivation of Hybrid Lifetest Curve and Operating Points (Produced by Constraining Curve of Same Gradient to Pass Through the Nominal Operating Point)

Assuming further the use of a typical Timken SR6 bearing geometry, in order to test at 1100MPa, then a load (preload plus any axial 1g load) of approximately 11.5N will be required for the lifetest if the nominal on-orbit preload achievable is 2N as shown in Fig. 4.

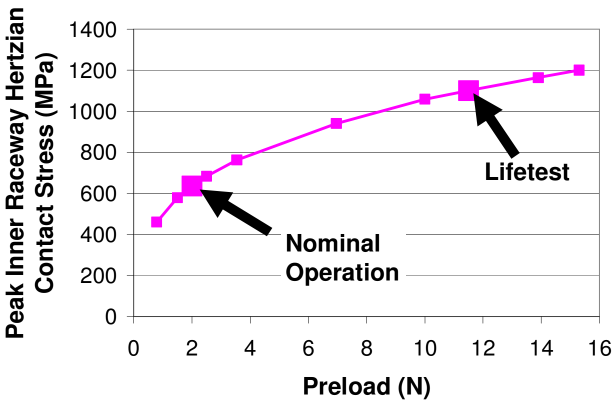

Figure 4 - Predicted Peak Contact Stress v Preload for Timken SR6 Bearing

The achievable speed acceleration factor will be somewhat dependent on test rig or unit motor drive capability (if unit-level testing). We assume here that a speed acceleration factor of 5 can be achieved (i.e. test at 5000rpm, nominal operation at 1000rpm).

When the consequences of increasing preload are also taken into account then hybrid test acceleration factors of order 20-30 can be obtained (Fig. 5), condensing a 6 year real-time lifetest test which could be achieved in almost 15 months with speed acceleration alone into around 3.5 months or less using the proposed hybrid acceleration methodology.

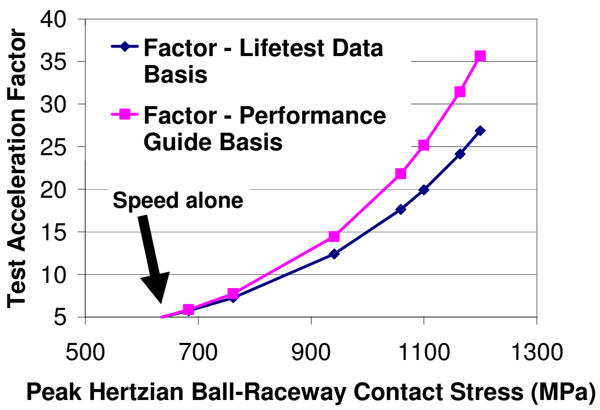

Figure 5 - Test Acceleration Factor Achievable v Ball Raceway Peak Hertzian Contact Stress (assuming "speed alone" acceleration factor of 5)

5. APPLICATION EXAMPLES

SSTL has unique experience in the use of low-cost technologies to provide rapid system development and cost effective access to space. When ESTL was commissioned to support the development of SSTL's latest generation of Microsat reaction wheels, known as the Superior Microsat Reaction Wheel (SMRW), SSTL already had experience of more than 20 wheels flying with self-lubricating bearings.

Continued use of self-lubricating bearings was therefore a logical next step for cost, schedule and heritage reasons, however one challenge was to increase the lifetime and demonstrate this in a short timescale. These constraints led to the SMRW becoming the first known example of the successful application of the hybrid accelerated lifetest approach, as part of a Qualification programme.

The SMRW is described in more detail in [12], but uses the SR6 bearing size and is shown in Fig. 6.

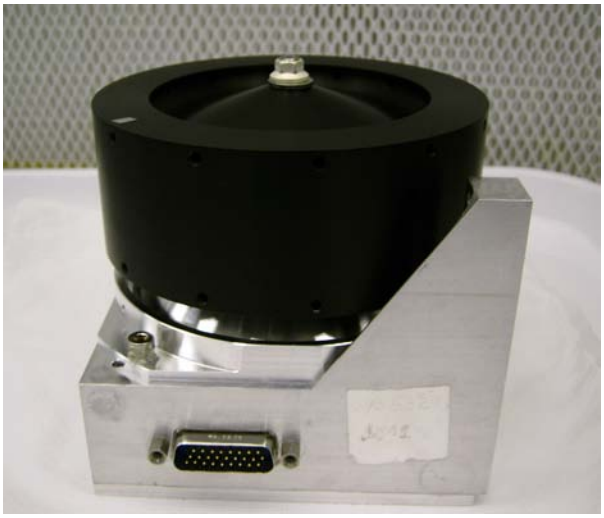

Figure 6. - QM Superior Microsat Reaction Wheel (Non-flight black inertia disc to aid thermal control in accelerated testing)

In the SMRW programme, the above hybrid lifetest approach was taken for one of two QM wheels tested.

QM1 used the hybrid lifetest approach and had elevated preload providing an acceleration factor of around 4 and a speed acceleration factor of almost 17 such that the overall acceleration factor was 69. To account for the wheel accelerations and decelerations, as part of the test the required number of manoeuvres, of appropriate acceleration rate and duration (in revolutions) increased by the ECSS factor were also included.

A total of 611 million revs were completed by QM1 in vacuum with excellent bearing performance and <1% cage mass loss by end-of test as shown in Fig. 7. The nominal duration of the accelerated phase of the test was 85 days. This performance was indicative of a lifetime at nominal preload considerably in excess of 10^{10} revs (i.e. more than 16 years at 300rpm with margin)

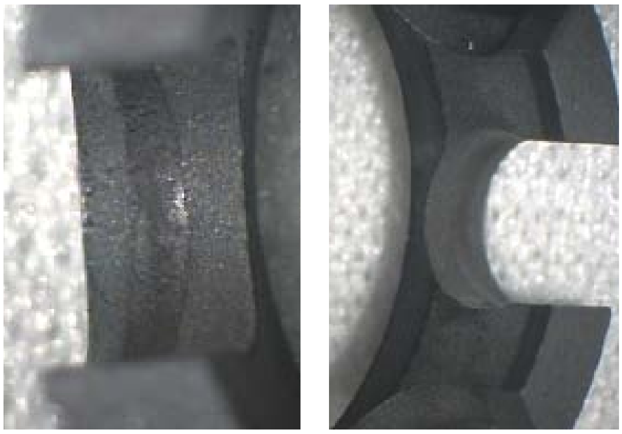

Figure 7. - Typical cage ball-pocket (left) and cage-land witness marks (right) following operation over 611 million revs

QM2 had standard operational preload and was tested entirely at nominal speed but simulated a 3-wheel operational mode in which all three wheels would operate close to zero speed and under constant zero-crossings (i.e. alternate directional oscillations) throughout a lifetime of more than 156000 zero-crossings. The QM2 test was also completed successfully and the SMRW product subsequently baselined for a 5-spacecraft (20 reaction wheel) constellation programme known as Rapideye (presently planned for launch in late 2007).

The second example of the use of this philosophy is that adopted by SSTL for the Giove A programme.

In this programme a new generation of Smallsat reaction wheel was required which built upon existing customer experience and flight heritage with solid-lubricated Microsat reaction wheels. The compressed development schedule (27 months for the whole spacecraft, less than 24 months for wheel development) also required that a novel approach should be made to lifetesting in order to mitigate risks and Qualify the wheels within the required time frame.

In the case of Giove A, the wheels use a thin-section bearing (type SNFA SE40 9CE1) which is housed in a thermally active semi-rigid bearing cartridge designed by ESTL to minimise preload under nominal operational conditions without sliding.

Figure 8. - Giove A Wheel Bearing Cartridge Assembly.

Whereas the nominal in-flight mode of operation originally baselined a rotational speed of 1875rpm and in-flight peak Hertzian contact stress was around 766MPa for flight duration (with ECSS margin) of 2.46E9 revs in both bearings an initial accelerated lifetest at bearing cartridge level was carried out at 1104MPa (upper bearing) and 1021MPa (lower bearing) and 6300rpm.

In terms of acceleration factor this approach had the capability to rapidly demonstrate life within 87 days (for upper bearing), providing a test acceleration factor of 10.4, achieved by the combination of an increase in preload AND an increase in speed by a factor 3.3. This philosophy was adopted in order to permit other aspects of the design to mature prior to a final wheel unit level Qualification test.

One critical area of the accelerated test setup which required particular attention was the thermal control of the wheel. Clearly with high acceleration factors, measures were needed to extract heat rapidly from the bearing cartridge in order to ensure the operational conditions within the bearings remained as far as possible flight representative. Since heat extraction from the inertia disc and shaft is essentially only via radiation, the baseplate and motor stator up-stand were thermally controlled separately so that the heat extraction could be controlled closely depending on the wheel operating mode. Fig. 9 shows the bearing cartridge prior to test commencement (and prior to inertia disc integration and balancing) mounted on top of the two isolated heat-exchanger plates which permitted differential driving of rotor and stator temperatures. The entire assembly was fixed to a torsional Kistler table to measure reaction torques.

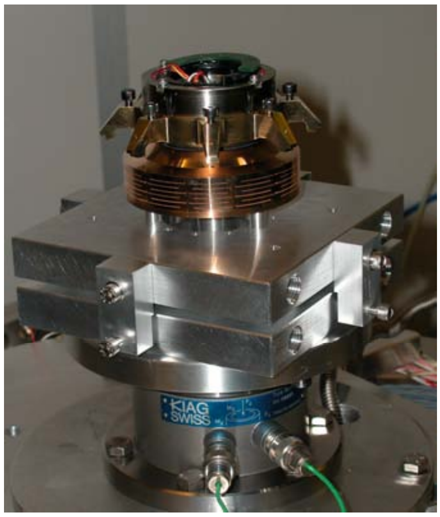

Figure 9. - Wheel Bearing Cartridge Fit-Check on Test Setup Prior to Inertia Disc Integration – Note Dual Heat Exchangers

When the test was unfortunately suspended due to an external test equipment failure the upper bearing had completed 94% of its target life and the lower one around 50% (of its increased target revs due to reduced stress) in approximately 3 months.

A second, conventional accelerated lifetest (i.e. accelerated only by speed) was carried out at wheel level as formal Qualification of the Smallsat wheel prior to launch of Giove A on 28th December 2005. At the time of writing the spacecraft has 18 months in-orbit operation and the wheels have completed around 650 million revolutions.

6. CONCLUDING REMARKS

The hybrid accelerated lifetest methodology proposed herein is novel, but has recently been used with some success, both for risk mitigation and as part of the Qualification of two new reaction wheel products, both of which are operational in orbit with a further 20 such wheels to be launched in 2007).

Like all accelerated tests it is essential to control temperature to ensure that the speed acceleration factor does not, of itself, introduce new or anomalous forms of cage misbehaviour and to verify the absence of other anomalous dynamic or thermal behaviours.

However, the potential for execution of very highly accelerated lifetests using this method is extremely attractive since it enables programmatically early risk mitigation tests to be carried out. Furthermore this approach greatly reduces the cost of such lifetests because their duration is much reduced.

It should be borne in mind that this method is dependent on the well-known behaviour of the PGM-HT lubricant and the relatively large data set of performance data for this class of self-lubricating material.

Whilst it is clear that other solid lubricants also have some relationship between lifetime and peak Hertzian contact stress, these relationships are not yet so clearly defined as to permit this approach to be adopted more widely.

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