Time Influence on Viscoelastic Materials: Experience Feedback on Applications in the Space Field.

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ABSTRACT:

This paper deals with the feedback from various tests performed on viscoelastic materials and undertaken for several years. The evolution of stiffness and damping has been studied for various items (soft mounts or samples). These evolutions are due to:

- natural ageing after 12 years of storage,
- unlocking after being under constraint for several years (recovery effects).

Stress measurement results, along with long-term extrapolation, are also presented. Moreover, a DMTA (Dynamic Mechanical Thermal Analysis) test was performed, which enabled to predict the creeping or relaxation behaviour over several years.

In addition, results from the latest studies carried out as part of the CNES R&D program relative to the update of the SPACEMAT database of viscoelastic materials are presented.

Finally, this paper ends with a presentation of intended future actions aiming at getting a better knowledge of ageing and fatigue behaviour of viscoelastic materials under conditions specific to space programs (storage, launch, orbital life).

1. GLOSSARY

- DMTA: **D**ynamic **M**echanical **T**hermal **A**nalysis
- VA: **V**isco**A**nalyzers
- M and M': complex and elastic Modulus
  = E and E' (Young Modulus for traction)
  = G and G' (Coulomb Modulus for shear)
- tg δ: material damping
- ALPHAT: Shift factor used to fit a group of measured curves on a single theoretical curve

2. INTRODUCTION

In order to reduce vibrations during launch or microvibrations during orbital life of the satellite, the most efficient and economical solutions are generally based on viscoelastic materials.

When choosing/developing such solutions, among all questions which generally arise, the most common are: What about ageing? Which is the modification of the material behaviour due to vibrations, irradiations, outgassing and thermal variations?

In the same way, when the viscoelastic material needs to be constrained (need of stowing during launch, for instance), the subsequent questions are: how does the constraint evolve with time?

Does the material recover its characteristics (stiffness, damping) when the constraint is unloaded?

Hereafter we present the feedback from various tests, undertaken for several years.

Different aspects have been studied: natural ageing, recovery effects, creeping or relaxation behaviour.

The updating of the viscoelastic materials database called SPACEMAT is also presented.

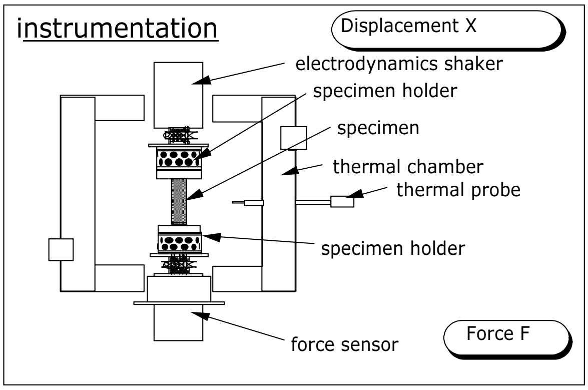
3. ABOUT DYNAMIC CHARACTERISATION

When designing solutions for vibration isolation and/or vibration damping, whatever the resulting component, one of the important characteristics, if not the main characteristic, is finally its dynamic stiffness. This stiffness results from the material (from its modulus M) and from the geometry (the area/thickness ratio). However, it also depends on the constraint to which it is subjected: vibration frequencies, amplitudes (hence its static and dynamic deformation ratios), operating temperatures.

Stiffness measurement is then essential to define and validate these solutions.

In order to carry out such characterisations, 01dB-METRAVIB has been using daily its range of **V**isco**A**nalyzers (VA), DMTA instruments developed and marketed by the company for more than 35 years.

The measurement principle is presented in FIG. 1 below:



1 – Measurement of complex stiffness (modulus and phase): $K^* = F / X$ versus

- frequency,
- temperature,
- strain,
- …

2 – From specimen dimensions, calculation of viscoleastic modulus: $E^* = K^* / \alpha$ where α is a geometrical factor

In the same way: $K^* = F(t) / X(t) = [\sigma(t) S] / [\varepsilon(t) L] = M^* S / L = K' + i K''$

FIG. 1: Principle of measurement of VISCOANALYZER

This instrument can be used to perform measurements on material specimens with known geometries, allowing thus deriving their modulus and damping. It can also be used for direct measurement of components' stiffnesses if their dimensions allow for it (see spatial applications [4)]).

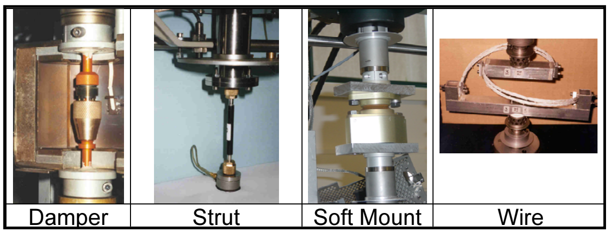


FIG. 2: Measurement of devices with VISCOANALYZER

The different tests presented hereafter were carried out using this instrument. It was used to follow the time history of complex stiffness for the different specimens under study through comparison with the reference state established at the beginning of their lifetime.

4. NATURAL AGEING

When implementing damping or vibration isolation solutions based on viscoelastic materials, the same issue often arises, for which there is no immediate answer since there is very few experimental feedback: the ageing issue.

01dB-METRAVIB has been developing such solutions for several years. Therefore, reference measurements are available, that have been determined during various programs. Some of them have already been used for (fast or not) ageing analyses. A series of measurements was carried out in order to monitor the evolution of these solutions over several years.

VA measurements were performed on ECV-type silicone mounts designed for microvibration applications. They were exposed to various environments (natural ageing, temperature, static compression, irradiations, outgassing, etc.) and have then aged under no specific storage conditions (storage in bottles with desiccant sachets, sheltered from light). Initial measurements were then compared to those performed last in order to quantify these materials' ageing in terms of dynamic performances.

Results presented here are average values for different frequencies and different specimens.

The adherised mounts shown below were studied:

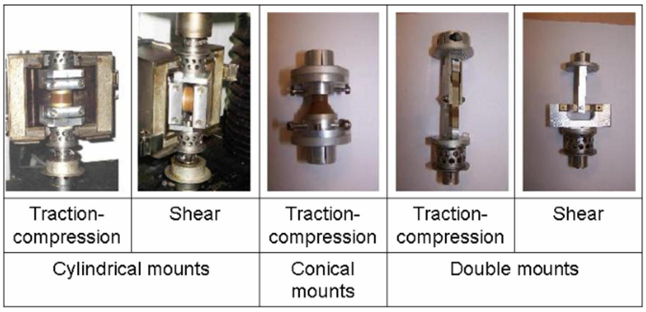


FIG. 3: Tested mounts

4.1. Cylindrical mounts

Cylindrical viscoelastic mounts were tested as follows:

- 4 were subjected to short-time environmental tests and to 6-year natural ageing
- 2 underwent fast thermal ageing and were then stowed in bending mode during 6 years (compression + shear: see photograph below).

- 3 underwent fast thermal ageing tests and were then stowed in axial compression mode for 6 years (see photograph below).
- 3 underwent natural ageing during a little more than 6 years.

The observed trend consists generally in stiffening and decreased damping in time due to natural ageing.

For the three mounts that have undergone only natural ageing, comparison of initial material characteristics with those after 6 years' ageing does not evidence important stiffness changes (≈5% in shear and ≈2% in TC), which remains within the order of magnitude of the measurement precision. The same is observed for damping, which does not change more than 8% in TC and 3% in shear.

For the 5 stowed mounts, stowing has little influence on mounts in bending mode (up to 7% in TC) and slightly more influence on mounts in pure compression mode (up to 15 % in TC) due to the evolution of the shape factor generated by the residual deformation. It is to be noticed that these 3 + 2 mounts had already undergone fast ageing tests under stress.
This means that material characteristics have not evolved much. Furthermore, the longer the time, the more the recovery tends to its maximum, and the more the mount tends to the initial characteristics (disregarding other ageing factors), since it tends to revert to the initial shape factor.

For the 4 mounts that were subjected to environmental tests, the evolution of dynamic stiffness, after the environmental tests and 6 years' natural ageing, remains lower than 7% for both TC and shear.

In average, damping has decreased by 4 to 8% depending on the deformation ratio.

4.2. Conical mounts

These 2 mounts were subjected to long-term stress (1¼ year for mount 3D and 3 years for mount 3C) then to recovery tests after stowing. After unstowing and relaxation, they were simply stored to undergo natural ageing.
Compared measurements do not show any noteworthy evolution for mount 3D (slight increase of the stiffness) but, for mount 3C, one can observe a decrease of the stiffness from about 13% (in 1999) to 5% (in 2006) and, at the same time, an important increase in damping from about -13% (in 1999) to -7% (in 2006), which brings tg δ to 0.14 for a small dynamic deformation ratio and 0.24 for a high dynamic deformation ratio.
This can be explained based on the long-term recovery of mounts. As a matter of fact, the 1999 characterisation could not be carried out for mount 3C after full recovery, which assumed a time period of the same order of magnitude as the upload time (3 years). Indeed, it remains a deformation which induces a ratio diameter/thickness greater than the initial one. It results from it a stiffness greater than the initial one, only due to geometrical evolution and not due to ageing evolution. When the mount is recovering its initial shape, its stiffness is decreasing. As for mount 3D, it had already recovered a great part, if not all, of its deformation.

Finally, over 11 years, the effect of ageing remains quite small on this material, which is coherent with observations made on cylindrical mounts.

4.3. Double mounts

The double mounts studied here were tested between April and June 1997 and exposed to different environments:

- 8 mounts were highly irradiated: 400 krad + thermal cycles,
- 4 mounts were weakly irradiated: 120 krad + thermal cycles + mechanical cycles,
- 3 mounts have undergone natural ageing only.

Both in TC and shear mode, natural ageing results, after 12 years, in an average stiffening of 7 to 12 % and a damping loss of 5 to 10% (thus bringing down tg δ from 0.18 to 0.16). No strong trend was observed between 1999 and 2006, which tends to show that there is no acceleration of the ageing process, but rather stabilisation.

4.4. Conclusion

As a general rule, the observed tendency is stiffening and decreased damping in time due to natural ageing, for storage conditions without or with constraint.

One can also note that there was no acceleration of the ageing process in time, but rather stabilisation thereof.

Observed results are summarised in the table below:

EVC silicone	6 years	11 years	12 years
$\Delta K / K$	< 7%	8%	7 to 12%
Δ tg δ / tg δ	-4 to -8%	-7 to -10%	-5 to -10%

TAB. 1: Ageing behaviour

Evolutions remain small and confirm, from the dynamic standpoint, bibliographic data relative to the stability over time of the mechanical resistance properties of silicone (stretch at break) [1].

5. RECOVERY BEHAVIOUR

5.1. Background

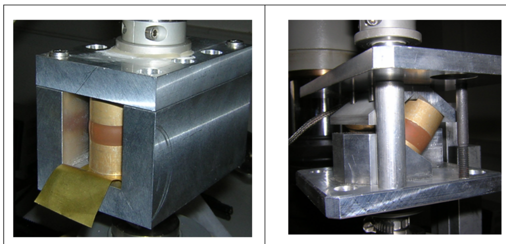
This section presents the results and the analysis of the tests carried out to assess the impact of storage time on the anti-vibration mounts of an optical instrument for satellites.

In order to withstand the satellite launch phase, three silicone mounts constituting the satellite/instrument interface are locked until the desired moment in the orbital life, when they will be released. Locking generates a stress on the elastomers, which is limited by stoppers. In time, stresses are released and the reaction force that the three mounts exert upon unlocking must be large enough to free the clearance required for a proper isolation of the instrument with respect to the satellite.
Actually, the system was stored in locked position for more than thirty months, whereas the initial recommendation called for a period of twenty months. The question was then whether the mounts would still be operational when unlocking them into orbit.

Viscoelastic mounts had then been stored at 01dB-METRAVIB in locked position for more than 5½ years (i.e., compressed into different mounting devices), thus widely covering the 30 months to analyse. The applied vertical deformation was the same for the two mounting devices.

In order to address this issue, we first needed to measure the quasi-static stiffness at the precise moment of dismounting.
Then, a recovery measurement would allow assessing the time required to revert to the initial neutral position of the mounts.

Two types of mounting were analysed: 3 mounts in axial compression mode (vertical mounting) and 2 mounts in compression/shear mode (mounting bent like the three mounts on the satellite).



Axial compression locking | Inclined compression locking

FIG. 4: Compressed mountings

5.2. Measurement principle

The principle is described hereafter. A force is exerted by the electrodynamic shaker on the mounting device (setpoint) while the screws securing the holding of the device are still in place. The screws are progressively removed. When there are only two screws left, acquisition is launched. The remaining screws are then loosened.

The control and acquisition program of the VA allows decrementing the applied force by steps of 5 N every 60 seconds (these values were selected after feasibility tests) and measuring the displacement at the same time.
As long as there is no displacement, this means that the reaction force of the mounts is smaller than the compression force exerted by the VA.
If a displacement occurs, this means that the reaction force of the mounts is greater that the compression force.

The limit locking force can thus be determined (see FIG. 5 below).

As soon as a displacement occurs, one can determine the quasi-static stiffness K= Force / displacement.

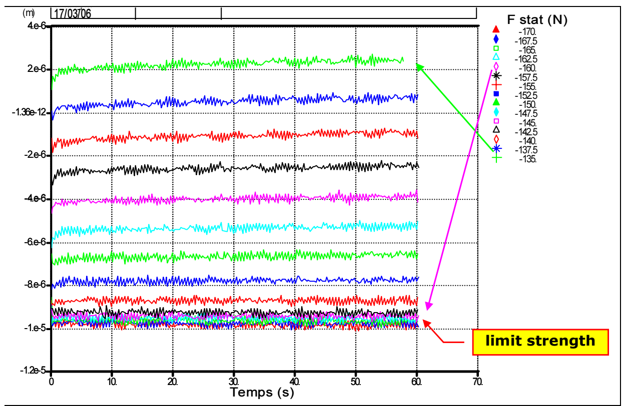


FIG. 5: Locking strength measurement

Axially compressed mounts (0.9mm) for more than 5½ years were then fully released.

5.3. Results for the first mounting

Instant recovery (2 s) is of the order of 0.35+0.02 mm, i.e., about 41% of the initial compression.
After one minute, it has already reached more than 50%.
After 3 minutes, it is about 0.5 mm, i.e., better than 55% of the initial 0.9 mm.

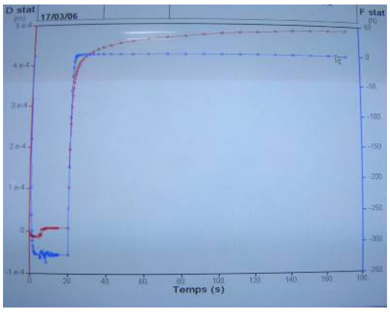


FIG. 6: Displacement recovery after 160 seconds

After 3 days, it is about 0.645 mm, i.e., 71% of the initial 0.9 mm.
After 4 days, it is about 0.65 mm, i.e., 72% of the initial 0.9 mm.
After 5 days, the evolution stays slow with a recovery of a few micrometers per day.
A 4-year extrapolation (see FIG. 6 below) shows a theoretical recovery of about 0.74 mm, i.e., 82% of the initial 0.9 mm.

5.4. Results for the second mounting

Instant recovery (3 s) is of the order of 0.6 mm, i.e., about 66 % of the initial compression.
After 1 minute, it has already reached more than 0.7 mm, i.e., about 78% of the initial 0.9 mm.
After 3 minutes, it is equal to about 0.73 mm, i.e., better than 80% of the initial 0.9 mm.
After 2.5 days, it amounts to about 0.77 mm, i.e., 85% of the initial 0.9 mm.

A 4-year extrapolation (see FIG. 6 below) shows a theoretical recovery of about 0.85 mm, i.e., 94% of the initial 0.9 mm.

5.5. Comparison of recoveries

The comparison of the recoveries obtained with the two mounting devices shows similar evolution (aspect of the curve), with a higher slope of the vertical mounting system. The recovery of this system is slower because the mounts were subjected to pure compression, which generates a higher stress ratio than for the bent system. This confirms visual observation. The deformation occurring in the bent system results indeed in compression and shear, which generates less creep for the bent mounts, hence faster recovery.

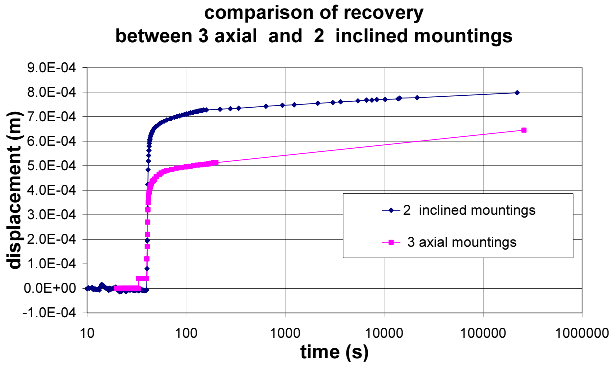


FIG. 7: Displacement recovery

When comparing these results with projection charts established in 2000, one can observe that obtained results are consistent. Considering (see FIG. 7 below) the yellow point corresponding to axially compressed mounts (15%), the recovery after 1 minute is of about 50% (for a period ranging from 5 years ≈ 2.6E6 min to 6 years ≈ 3.1E6 min). For the green point, corresponding to the bent mounts (compression ≈ 11%), the recovery after 1 min is of about 78 %. These two points are in the global continuity of the plotted curves, which means that after 30 months of locking (≈ 1.3E6 min), one can expect a recovery of about 75 to 80% after one minute of unlocking.

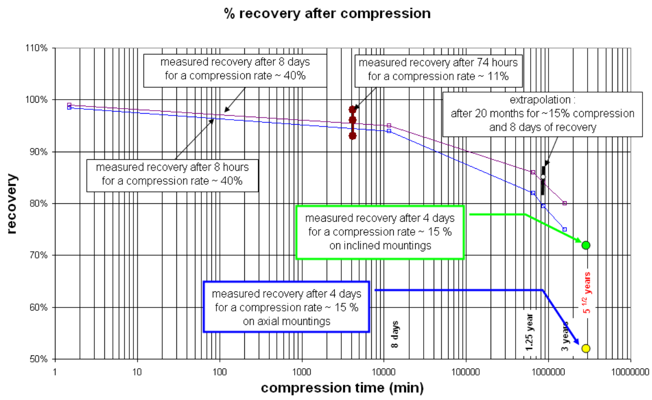


FIG. 8: Measured recovery compared with initial prediction

5.6. Conclusions on the recovery after unlocking

Extrapolation of unlocking forces measured on the 2-bent-mount system to the 3-bent-mount system (satellite configuration) leads to a total force compliant with the requirements.

This force is smaller than the one measured on the 3-axial-mount system, because these were subjected to pure compression. Due to bending, the locking force results on one hand from the shear stiffness and on the other hand from the compression stiffness.

As for recovery, one can also observe visually and on the charts that it is much faster on bent mounts than on compressed mounts, due to less creep on the bent mounts: the residual deformation is slightly smaller since it consists of compression and shear.

In addition, comparison of the material characteristics before and after about 6 years' natural ageing showed no evidence of very important evolutions (see previous section).
Material characteristics have not evolved much. Furthermore, the longer we wait, the greater the recovery and the more we tend to initial characteristics (leaving aside other ageing factors), since we tend to revert to the initial shape factor.

Regarding the previous prediction, recovery tests on axial and bent mounts are consistent with extrapolations carried out then and show that, after 30 months of stowing (≈ 1.3E6 min), a recovery of 75 to 80% can be expected after one minute of unstowing.

Although they are compressed slightly longer than specified, mounts should be compliant to the unstowing objectives and to filtering performances expected during orbital life.

6. RELAXATION BEHAVIOUR

Stress measurement results and long-term extrapolation are presented hereafter. Moreover a DMTA test is performed on a tightening washer that enables predicting the relaxation behaviour over several years also by using time-temperature equivalences.

6.1. Background

The study presented here aimed at assessing the relaxation of a screw's tightening stress, due to the stress relaxation in a washer made of polymeric.

In the final application, this washer is mounted in axial compression mode.

Before integration, the washer is subjected to "ageing" in compression mode during 24 hours at 105°C, with set-up of the compression every 6 hours. Compression is exerted during a maximum of 15 days prior to mounting.

Equivalent conditions - in terms of compression – are reproduced on a material specimen, by applying an axial force generating a pressure equivalent to the tightening strength over the total area of the washer, i.e., about 130 MPa. In order to do so, small-size specimens are cut off in a piece of material provided by the customer and that has already been submitted to ageing (24 hours at 105°C).

On the VA, the material is subjected to quasi-static compression deformation (for half an hour to one hour). Displacement is held and stress is measured (relaxation).
This same deformation is applied at different temperatures.

It is to be noticed that in this process, dilatation has no effect since the deformation is applied when the system is subjected to high temperature. The zero reference for the force is the first value measured after applying the load, i.e., after 5 s.

This relaxation test was carried out on two specimens.

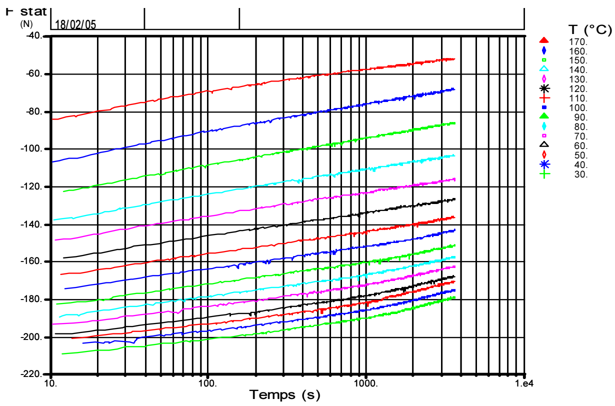


FIG. 9: Measurement of static strength at different temperatures

6.2. Measurement analysis

When measurements are completed, by means of the Time/Temperature equivalence rule, the long-term evolution of the relaxation for each temperature and for all considered time periods is determined.

Shift factor ALPHAT values depend on the reference temperature and start from 1 for this value.
ALPHAT > 1 for temperatures > reference temperature
ALPHAT < 1 for temperatures < reference temperature

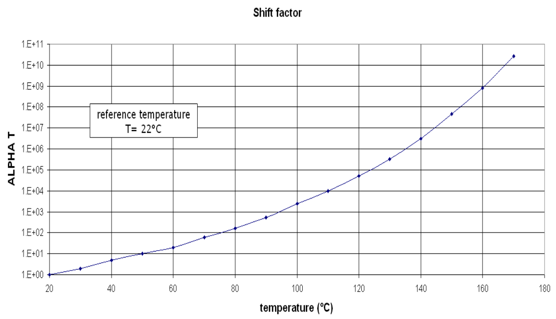


FIG. 10: Calculation of shift factor at different temperatures

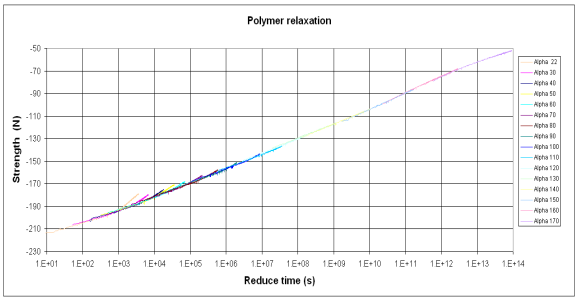


FIG. 11: Residual strength versus reduced time

6.3. Result analysis

A series of relaxation measurements at 82°C during 4 days allowed checking whether the extrapolation method did agree for the tested material (see plot below).

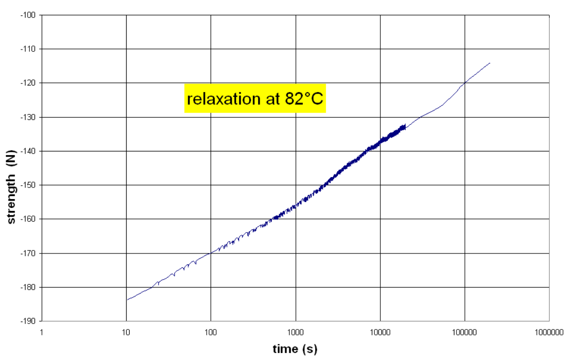


FIG. 12: Experimental residual strength after 4 days

It allows comparing the real relaxation measurements during $2^{E}5$ seconds and relaxation values calculated from measurements.

The following table can be derived:

Time (s)	1	10	100	$1^{E}3$	$1^{E}5$	$2^{E}5$
Real value	192	184	170	156	122	118
% lost strength	0	4	11.5	19	36.5	38.5
Value calculated from measurement	233	219	203	188	155	151
% lost strength	0	6	13	19.5	33.5	35.4

TAB. 2: Comparison of calculated and measured residual strength

A difficulty is to be noticed for these measurements : since the specimen area is difficult to measure, one can estimate an uncertainty on the measurement of this area of 3 to 5%. Therefore, the applied force can give a value for the applied pressure that is 3 to 5% off the expected nominal pressure.
This can explain the differences between measured forces and those extrapolated by the TTS calculation.

If total time for storage and flight is considered, i.e., $7^{E}8$ seconds (22 years), the remaining force for a temperature of 22°C is 55% of the initial force and for 82°C, 45% of the initial force.
By extrapolation from the real test at 82°C (risky extrapolation since it goes almost 4 decades beyond the measurement), one get a residual force ranging from 35 to 40% of the initial force (instead of 45% by calculation).
The combination of temperature cycles is situated within these two limit values.

6.4. Conclusion

Calculated values show a good correlation with the real relaxation test performed over a reasonably long time period and allows the validation of extrapolated long-term results, and this with a high confidence level. The residual force, cumulated over the different temperature cycles (i.e., for a flight time of $7^{E}8$ seconds = 22 years) ranges then from 55% of the initial force (maximum value if the temperature stays at 22°C) to 45% of the initial force (minimum value, if the temperature stays at 82°C).
These tests have allowed assessing in an “absolute” way the behaviour of the polymer in stress relaxation mode at constant displacement, independent of dilatation and contraction phenomena due to mechanical mounting.

7. UPDATING OF SPACEMAT DATABASE FOR VISCOELASTIC MATERIALS

Since 1995, a database on viscoelastic materials for space applications has been built up by 01dB-METRAVIB for CNES. This SPACEMAT database has since then been reshaped, updated and supplemented. At the end of 2006, four new materials were characterised and integrated into SPACEMAT.

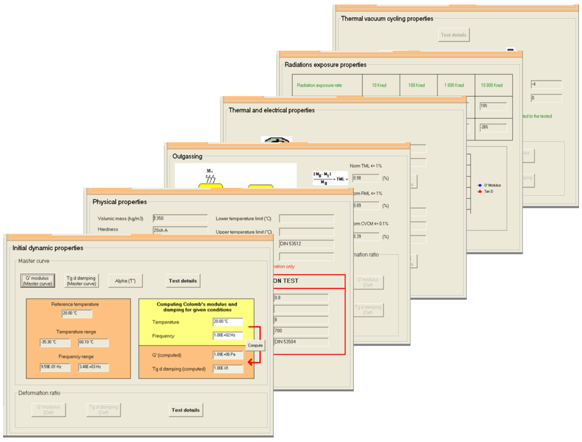


FIG. 13: Screens of SACEMAT database

The following viscoelastic materials were characterised:

- Elastosil S690
- Smacsil CQXB579
- Metravib S80
- Smactane SP 40

Being the first three silicones, the first two materials are widely employed in spatial applications and they cover a broad range of Coulomb modules. The fourth material, which had already been identified as a potentially damping material, is considered here in its “spatialised” version.

The following tests were performed:

- Static tests (10% stress and 100% stretching, stress and deformation at break),
- Thermal characterisations (thermal conductivity and dilatation coefficient ranging from -30 to 120°C),
- Outgassing (according to ECSS-Q-70-02A),
- Master curves (modulus G’ and damping tg δ) before and after outgassing,
- Characterisation (modulus G’ and damping tg δ) in dynamic deformation ratio before and after outgassing,
- Dielectric rigidity tests.

8. GENERAL CONCLUSION

Results presented here have allowed getting a better knowledge of the long-term behaviour of viscoelastic materials subjected to natural ageing, creep or relaxation. In addition to following up these materials in the coming years, the CNES and 01dB-METRAVIB would like to widen their knowledge. One of the targeted objectives is to characterise the effects of storage and of cumulated environments in order to guarantee the performances of damping systems upon launching (for vibrations and shocks) or in orbit (for microvibration problems). Further works could in particular address the following points:

- Characterisation of mounts before and after storage under different conditions (loaded or unloaded, neutral atmosphere or clean room) to study the evolution of their characteristics and its consequences.
- Complete cumulative study of the different parameters describing the life cycle of material, given that until now, there is no study allowing to know how the different parameters interact (irradiation, temperature, outgassing, mechanical environments) for the same mount.

A typical life profile, representative of these interactions, was suggested. The first partial tests were performed on mechanical fatigue feasibility aspects (see [5]). However, this complete program on cumulative effects remains an important and necessary task to achieve, which will allow backing up the implementation of efficient solutions to reduce shocks and vibrations for spatial applications.

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