RELIABILITY DEMONSTRATION OF THE PYROSOFT RELEASE NUT

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OVERVIEW

The number of equipments on satellite structures has significantly increased and their locations have progressed closer to pyroshock sources. This requires the development of “low shock” pyrotechnic devices. In the frame of CNES contracts, LACROIX Co. has developed and qualified a low shock release nut called PYROSOFT. In this device, the actuation is performed as the result of the burning of a gasless thermite pyrotechnic composition that induces the melting of a structural brazing. This operation releases a piston that moves under the action of a motorisation spring and achieves the motion of the mechanism and the release of the threaded bolt.

The reliability of 0.9999 at the 95% confidence level required by CNES has lead LACROIX to propose a demonstration based on a theoretical approach and followed by experiments to achieve this demonstration. FMECA, mechanical models and thermal simulations together with experimental correlations were used to identify the key parameters and the margins to be applied for testing. Test configurations have been determined to cover all the potential conditions of use on satellites, taking into account all mechanical margins required by the applicable ECSS standards.

This paper presents the methodology and the development activities applied for the justification of the reliability requirements in order to continue the qualification process for the PYROSOFT release nut.

1. INTRODUCTION

Satellite programs require more and more equipments to be integrated on satellite structures to fulfill more and more complex and sophisticated missions. This leads to a higher proximity between these equipments and on-board pyrotechnic devices which, when they are fired, usually generate high shocks. The observed acceleration levels are dominant by comparison with vibrations and shocks generated during the launch phase.

The equipments must support these pyrotechnic shocks without any damage. Consequently, their design needs reinforced parts to filter the damaging frequencies and amplitudes or resist to these solicitations. It leads to heavier and bigger equipments than necessary in most of their operational life.

Likewise, satellite structures are also submitted to the same pyrotechnic shocks and may apmplify these shocks.

Given the economic importance of the ratio of the operational payload to the total mass of the satellite, it is not long acceptable that the mass of structures and equipments are dimensioned by shock events which happen only on a very short duration compared to the life of the satellite.

This requires the development of “low shock” pyrotechnic devices. Their use will have a direct and profitable effect on mass management of satellites, giving a capability to increase significantly the operational payloads. In addition the shock requirements and qualification levels applicable for the development of satellite equipments may be released with a significant consequence on development costs.

2. “LOW SHOCK” SPECIFICATION

In order to promote research and development activities in the field of “low shock” pyrotechnic devices, CNES Toulouse (Centre National d’Etudes Spatiales) has laid down a set of requirements for a “low shock” release nut with a view to replace the present pyrotechnic devices used to release antennas and solar panels.

The main requirements have been stated as follows:

- The pyrotechnic device shall hold down M6 x 100 bolt tensions in the range: (1) 3000 N to 12000 N (Flight conditions) and (2) 2500 N to 15000 N (Qualification conditions)
- Mechanical interfaces shall be interchangeable with existing release nuts.
- Reliability shall be 0.9999 with 95% confidence level.
- Life duration shall be 10 years, including one year under tension and 15 days in orbit.
- Firing temperatures shall be + 120°C and – 120°C for qualification tests.

- Thermal cycling shall correspond to 15 days in orbit, that means 15 cycles [-120°C, +120°C] per day x 15 days = 225 cycles.

- The bolt shall be released with a “low shock” level under the upper limit given in figure 1.

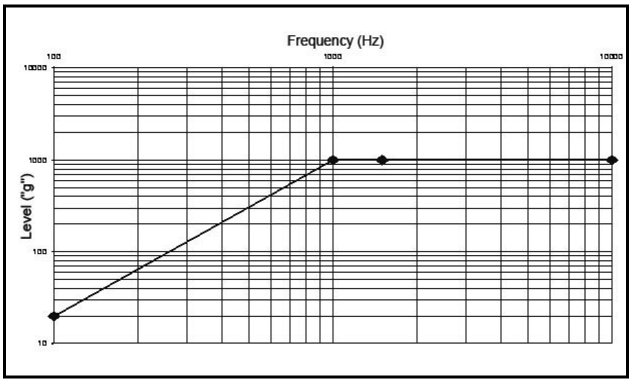


FIG. 1 SRS “Low Shock” requirement

Tolerance 0, +6dB in the frequency range 6 kHz to 10 kHz

3. PYROSOFT™ CONCEPT

Within the scope of CNES contracts and in the frame of the above requirements, LACROIX Co. has co-financed, developed and qualified a “low shock” release nut called PYROSOFT™. In this device, the actuation is performed as the result of the burning of a gasless thermite pyrotechnic composition that induces the melting of a structural brazed joint. This operation releases a piston that moves under the action of a motorisation spring and achieves the motion of the mechanism and the release of the threaded bolt.

Figure 2 shows a cross-sectional view of the device.

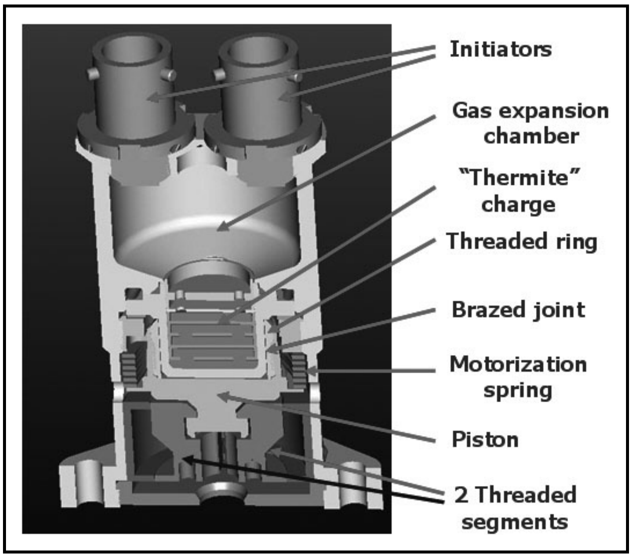


FIG. 2 Pyrosoft™ Concept
(Patents: FR 99 1517 8 and FR 00 0381 S)

All Pyrosoft™ devices work in the same sequence as illustrated in figures 3 to 6.

When the initiators are fired, they release hot gases and particles which ignite the pyrotechnic composition in the “thermite” charge. Then, this composition generates a high amount of heat by and during its combustion.

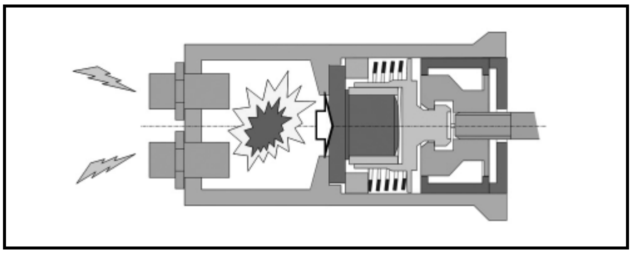


FIG. 3 Step 1: Firing of the initiators and ignition of the “thermite” charge.

Heat generated by combustion of the “thermite” charge is transferred by thermal conduction through the lateral wall of the “thermite” container and melts the brazed joint.

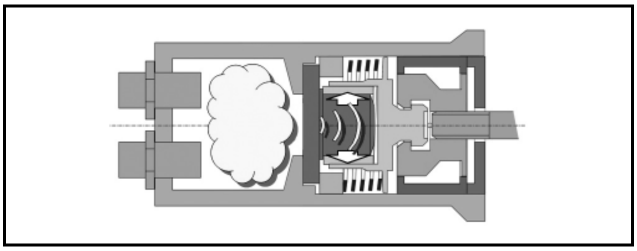


FIG. 4 Step 2: Combustion of the “thermite” charge and melting of the brazed joint.

Submitted to the bolt tension and the motorization spring, the threaded ring and the piston move together along the axis of the “thermite” charge, enter in contact with the threaded segments and push them.

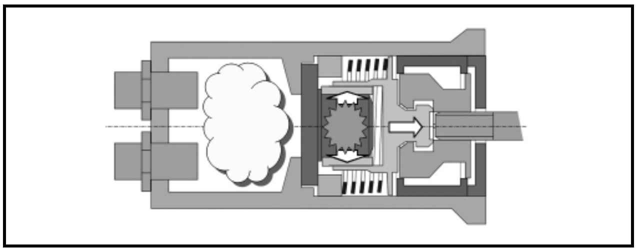


FIG. 5 Step 3: Displacement of the piston, then of the piston + threaded segments.

Still pushed by the piston, the threaded segments move and, after a 2 mm course, are free to open with the help of two springs. This opening releases the bolt.

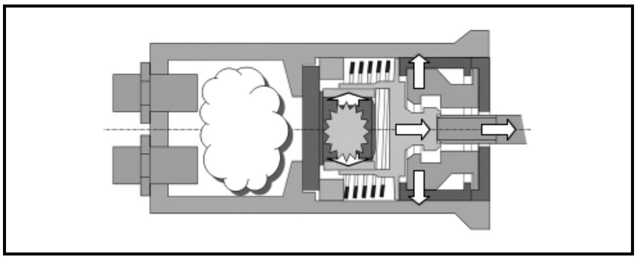


FIG. 6 Step 4: Opening of the threaded segments and bolt release.

Shock measurements have been made on the ESA/CNES Shock Testing Bench in Toulouse to check that the Pyrosoft™ Concept meets the required "low shock" levels. Several Pyrosoft™ M6 release nuts have been fired, in the most severe configuration from the point of view of shock generation:

- a 12000 N tension has been applied to the bolt, corresponding to the maximum value in flight conditions,
- the two initiators have been fired simultaneously.

Figure 7 shows the acceleration levels which have been recorded. It appears that these levels are significantly less than the "low shock" requirement, except at frequencies above 6500 Hz.

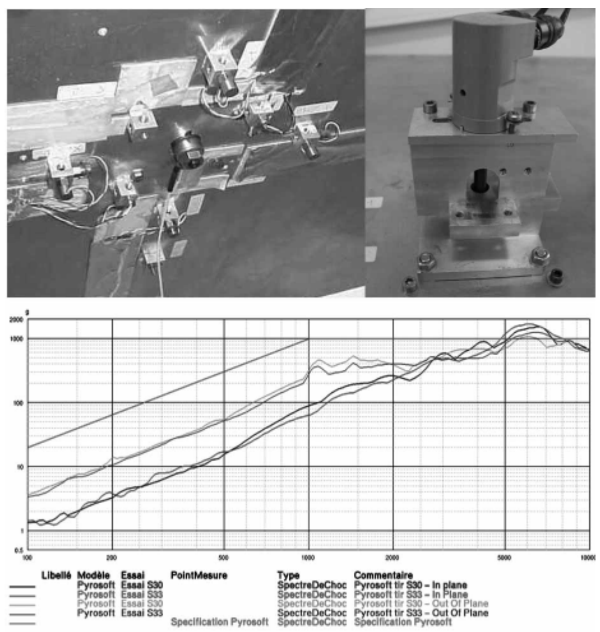


Fig. 7 Shock Response Spectrum (Q=10 – 1/12 octave)

4. RELIABILITY DEMONSTRATION

The reliability of 0.9999 at the 95% confidence level required by CNES has lead LACROIX to propose a demonstration based on a theoretical approach and followed by experiments to achieve this demonstration.

The following methodology has been applied step by step:

- Failure Modes Effects and Criticality Analysis (FMECA): An exhaustive analysis of the possible failure modes has been completed, leading to the elimination of those which may be solved by product design or quality control on the production line. The remaining failure modes have been taken in account at the following step.
- Functional Analysis : The various functions which contribute to the good functioning of the product, their key operative parameters and their connection to the remaining failure modes have been identified.
- Evaluation of the probability of good functioning for each function: as far as possible, the "stress / strength" method has been applied to the key operative parameters; a good knowledge of their dispersion has arisen from statistical processing of the available experimental data of the development phase.
- A more detailed statistical approach has been necessary to evaluate the probability associated to three functions which needed a more comprehensive study than the global "stress / strength" method: combustion of the "thermite" charge, melting of the brazed joint, opening of the threaded segments.

5. FMECA

It is not the purpose of this paper to give a full description of the failure modes, effects and criticality which have been listed and analyzed. More important is the fact that FMECA has helped to detect, among all the possible failure modes, a very critical one relating to the reproducibility of the heat transfers through the lateral wall of the "thermite" charge container. These heat transfers have a direct effect on the reliability of the melting of the brazed joint. So it was essential to develop a technical solution which would improve significantly the thermal behaviour of the concerned interface.

Originally, the "thermite" charge has been designed as a simple bulk of pyrotechnic composition, compressed in a cylindrical container as shown in figure 8. Firing tests at ground level has quickly demonstrated that, after and possibly during combustion, the melted reaction products flew out of the container of the pyrotechnic charge under the influence of gravity. Figure 9 gives an X-ray image of this phenomenon.

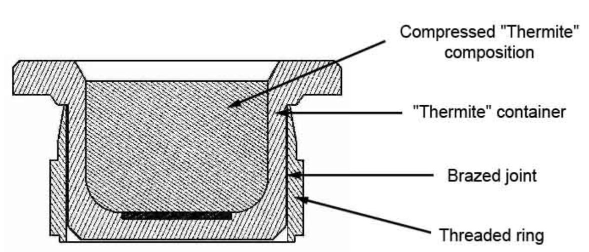


Fig. 8 Initial design of the pyrotechnic charge

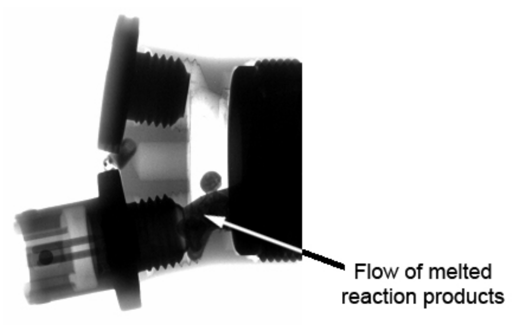


Fig. 9 Flow of melted reaction products (X-ray image).

This flow of melted reaction products has been considered as a critical failure mode, because it leads to a strong dissymmetry in the conductive heat transfers through the wall of the "thermite" container, then in the melting of the brazed joint. More seriously, physical contact between these melted products and the wall of the "thermite" container are locally broken and the brazed joint may not melt (or melt very late) in the corresponding areas.

If the ground level tests are not representative of the flight conditions from that point of view, they will be the only possible conditions for the acceptance tests of the future manufactured Pyrosoft™ release nuts. On another hand, the behaviour of the melted reaction products is difficult to foresee under microgravity.

To solve this problem, LACROIX has developed an innovative design of the "thermite" charge, in which the melted reaction products are trapped and unable to flow. (See figure 10) In this design, the "thermite" charge is composed of five layers of pyrotechnic composition. Each layer is obtained by compression of the pyrotechnic composition in a metal cup. Transmission of the combustive process from a layer to the next one is obtained through two holes drilled in each cup and filled with pyrotechnic composition.

The first layer is composed of a priming mixture, then an intermediate composition, to assure the correct ignition of this multi-layered "thermite" charge. Two perforated disks are placed above the first layer to accelerate the ignition gases (disk 1) and prevent from the flow of the reaction products of the priming and intermediate compositions (disk 2).

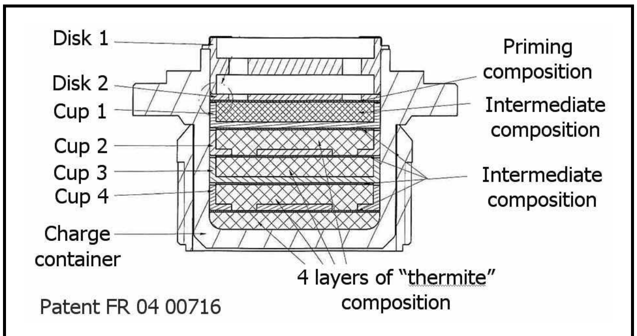


Fig. 10 The improved multi-layered "thermite" charge.

The metal cups not only prevent the reaction products from flowing, but also increase the heat exchange interface and drive more reliably the exchanged heat towards the wall of the "thermite" container.

Tests have been performed at various temperatures and various orientations regarding gravity. They have quickly proven the efficiency of this improved multi-layered "thermite" charge under ground level conditions. Finally, six Pyrosoft™ release nuts fitted with this improved charge have been fired under microgravity conditions, during parabolic flights of the NOVESPACE Airbus A300 Zero G. Examination of the reacted "thermite" charges have shown a very similar aspect of the trapped reacted products for ground as well as microgravity tests (See figure 11) Similar values of the bolt release times have been observed, which confirms the independence of the new multi-layered "thermite" charge from gravity.

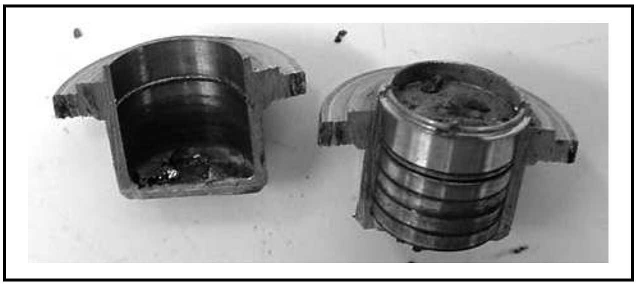


Fig. 11 Aspect of a multi-layered "thermite" charge after reaction.

6. FUNCTIONAL ANALYSIS

Second step of the reliability demonstration, a functional analysis has decomposed the way Pyrosoft™ release nut actuates as the result of the sequence of the following functions:

- F01.1 : Initiation
- F01.2 : Ignition of the priming composition
- F01.3 : Ignition of the "thermite" composition
- F01.4 : Full combustion of the "thermite" composition
- F01.5 : Melting of the brazed joint
- F01.6 : Sliding motion of the threaded ring + piston
- F01.7 : General motion of the threaded ring + piston + threaded segments, and opening of the threaded segments
- F01.8 : Bolt release

The key parameters governing these functions have been determined and submitted to a statistical processing. All other parameters have been considered as secondary and taken at their most pessimistic value in the evaluation of the probability of good functioning as well as for the tests which have been necessary to feed data in the thermal, mechanical and statistical models.

7. EVALUATION OF PROBABILITIES

7.1. The "Stress / Strength" Method

Every time it was possible to apply directly classical methods to evaluate the probability of good functioning of a given function, this way to proceed has been preferred. This has been the case of functions Nr F01.1, F01.2, F01.3, F01.6 and F01.8, which were fully described by only one dominant parameter.

The same probabilistic method has been applied to these five functions: the "stress / strength" method (See figure 12)

On one hand, the “stress” component characterizes an external input which is necessary to initiate and run the considered function. On the other hand, the “strength” component deals with an internal characteristic which must be exceeded (or not) by the “stress” component for the function to run correctly.

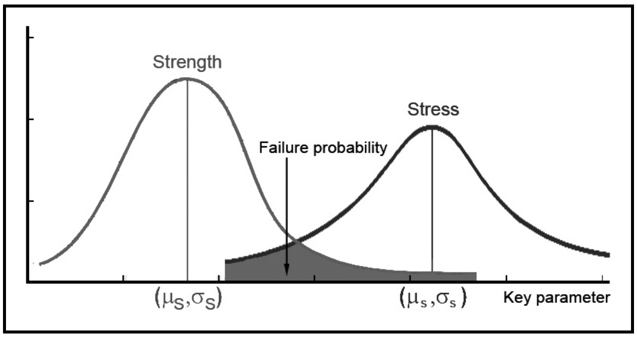


Fig. 12 Stress/ Strength Method

Practically, it is often easier to define the “strength” as a lower (or upper) limit corresponding to 100% success of the considered function (See figure 13)

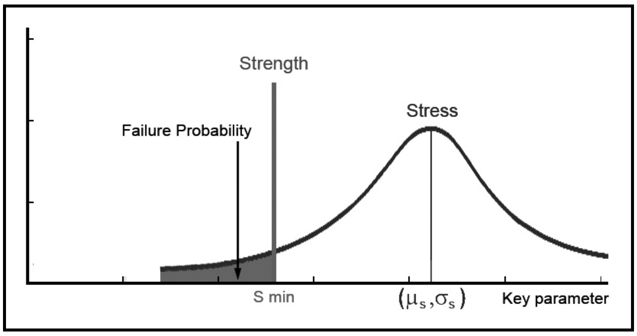


Fig. 13 Simplified Stress / Strength Method

7.2. Example: Function F0.2

The simplified Stress / Strength Method has been applied to Function F0.2 “Ignition of the priming composition”. As illustrated in figure 14, hot biphasic (mainly gaseous) products generated by the initiators flow through the holes in disk 1 and 2 towards the free surface of the priming composition. As a consequence of convective heat transfers, this priming composition starts burning. Then combustion propagates through the first layer of the “thermite” charge.

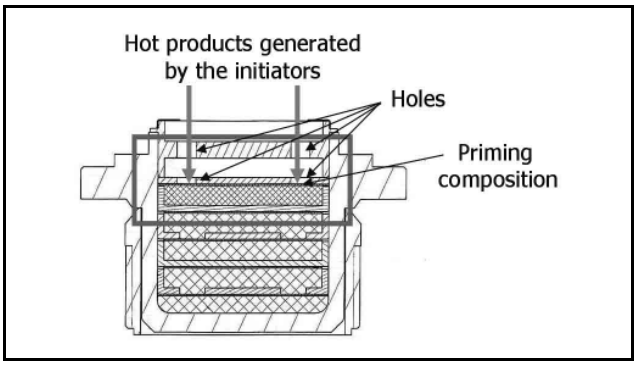


Fig. 14 Initiation of the priming composition

The key parameter which has been considered as relevant to characterize this function is the quantity of heat which is necessary to ignite the priming composition at its free surface (the “strength”) and the quantity of heat which is transferred by convection to the free surface of the priming composition through the holes of disks 1 and 2 (the “stress”) In that case, the “strength” is known as a minimum value derived from physicochemical analyses. The mean μ of the “stress” distribution law is calculated by using a simple convective model and its standard deviation σ results from the application of a ratio CV = σ/μ equal to 0.15, which is often a good upper limit in pyrotechnics.

With a mean stress at $8{,}51.10^{-2}$ cal and limit strength at $2.37.10^{-2}$ cal, the reliability margin proves to be high. Even with such a pessimistic CV ratio, it leads to a very low probability of failure, P (no initiation), equal to 7.6×10^{-7} (See figure 15)

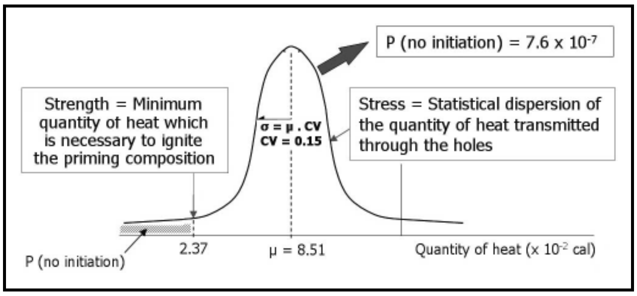


Fig. 15 Application of the Stress /Strength Method to function Nr 10.2

8. SPECIFIC APPROACHES

As said before, a more detailed statistical approach has been necessary to evaluate the probability associated to the three other functions which needed a more comprehensive study than the global “stress / strength” method: combustion of the “thermite” charge (F0.4), melting of the brazed joint (F0.5), general motion of the threaded ring + piston + threaded segments and opening of the threaded segments (F0.7).

8.1. Combustion of the “thermite” charge

From experience, the main failure mode of the combustion of the multi-layered “thermite” charge is the interruption of this combustion at each interface between two layers. It happens when the quantity oh heat which is transferred by combustion of layer N to the downstream layer N+1 through the holes of the cup N is too low. For that reason, this quantity of heat has been selected as the key parameter governing this function.

The “stress / strength” method has also been used to evaluate the failure probability of the combustion of the “thermite” charge. In that case, it has been necessary to apply this method at every interface. (See figure 16)

At every interface, the “strength” is the quantity of heat which is necessary to ignite the “thermite” composition of layer N+1 immediately at the output of the holes in cup N. The “stress” is the quantity of heat which is transferred by conduction from the combustion of layer N to layer N+1 through the holes of cup N. As for function F01.2, the “strength” is known as a minimum value derived from physicochemical analyses.

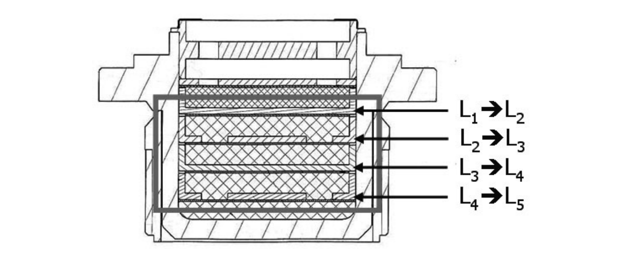


Fig. 16 Combustion of the “thermite” charge

The mean μ of the “stress” distribution law has been calculated by using a simple conductive model. But, difficulties have arisen from the complexity of obtaining reliable data to determine the heat losses through the metal cups which act as heat sinks by design.

To solve this problem, severed tests have been performed at low temperature (-160°C and -180°C) to estimate the temperature level under which a failure in the transmission of “thermite” combustion between the layers can appear. Two design parameters have been taken in account in the test plan:

- diameter of the holes of the cups
- compression stress applied in the manufacturing process to the “thermite” composition, which governs its density at every cup interface.

Figure 17 shows a 3D representation of the results of these tests. The grey planes illustrates where can be located the failure / no failure limit of the transmission of combustion in the multi-layered “thermite” charge.

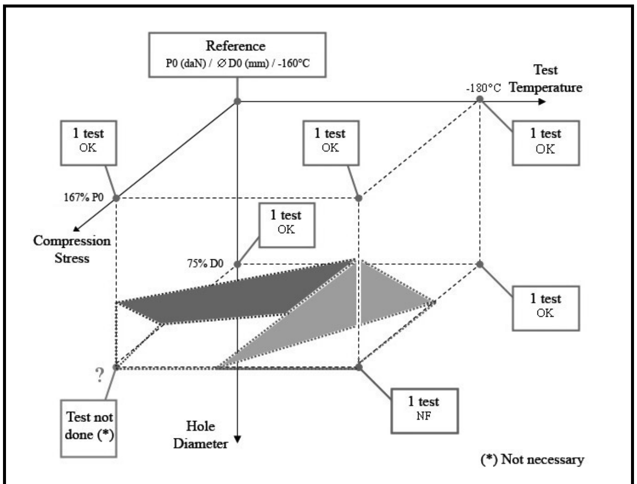


Fig. 17 Results of severed tests performed to estimate the failure probability of the combustion of the “thermite” charge.

From these results, an estimate of the thermal losses at each “cup” interface has been evaluated. At last, mean values have been deduced for the quantity of heat which is transferred from each layer to the next one.

With these mean values of the “stress” and standard deviations determined by application of a ratio CV = σ/μ equal to 0.15, as done for function F01.2, failure probabilities has been evaluated, giving the following results:

P (no transmission) L1→L2 = 3.0 x 10^{-6}
P (no transmission) L2→L3→L4→L5 = 3.2 x 10^{-5}

8.2. Melting of the brazed joint

Taking into account the complexity of the problem, a different approach has been adopted to evaluate the failure probability of the melting of the brazed joint.

As a first step, a thermal model has been developed to determine the temperature which is reached along the brazed joint as a function of the firing temperatures. This model has been correlated step by step with temperature measurements from tests performed at -110°C and -160°C on:

- the pyrotechnic charge only
- the pyrotechnic charge + threaded ring
- the pyrotechnic charge + threaded ring + piston

Figure 18 shows the test configuration and the results obtained for the pyrotechnic charge + threaded ring + piston at -160°C.

The thermal model takes into account the thermal transfers by conduction between the various mechanical parts and by conduction + radiation with the external environment of the device and within the internal volumes of the device itself. It has been adjusted to give representative results for firings under vacuum.

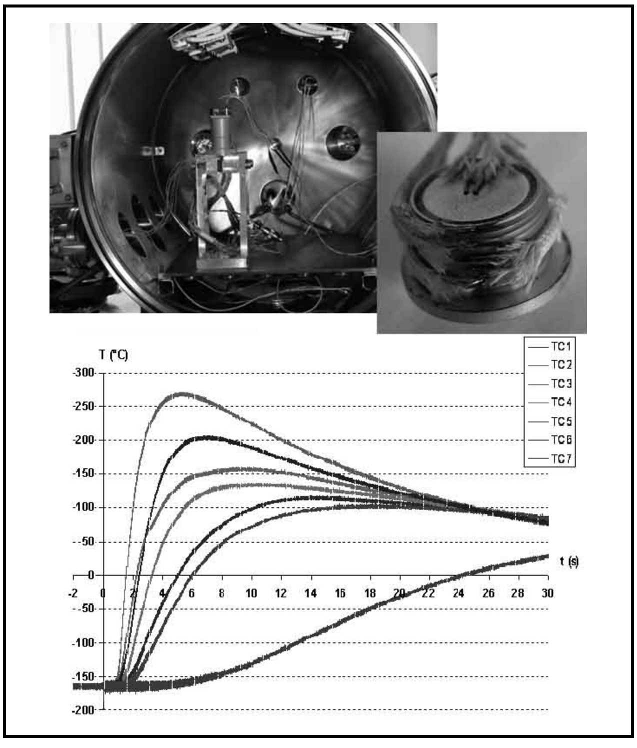


Fig. 18 Test of a “thermite” charge + threaded ring + piston at -160°C.

In a second step, thermal calculations have been made with the thermal model to determine the temperature of the complete Pyrosoft™ release nut at which the brazed joint fully melts for firing temperatures lower than -110°C. Figure 19 gives a typical result corresponding to a firing temperature equal to -160°C.

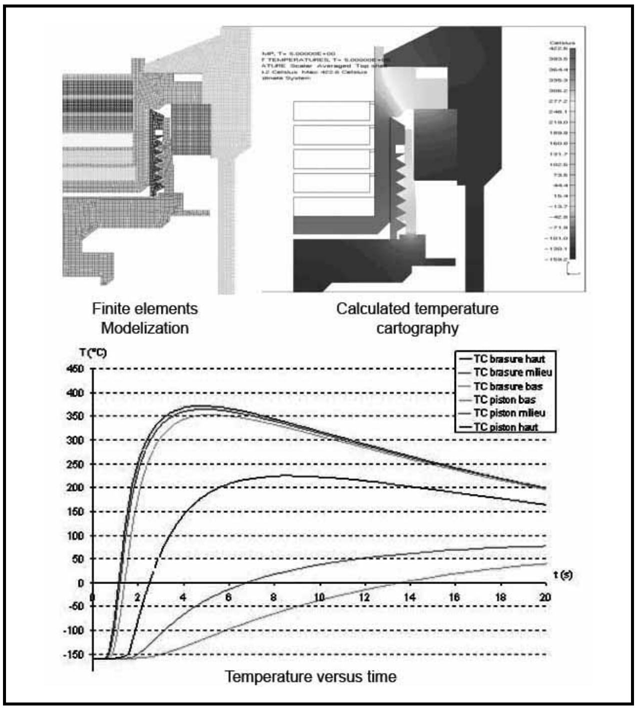


Fig. 19 Thermal calculations at -160°C.

In a third step, to demonstrate a no-melting probability less than 1.10^{-4}, severed tests have been performed using the firing temperature as the severization parameter. As can be deduced from thermal calculations, this parameter is predominant to size the reliability margin corresponding to the risk of no-melting.

The following methodology has been used to determine the firing temperature for these severed tests:

- a law giving the maximum temperature of the brazed joint at its coldest point as a function of the firing temperature has been derived from the previous thermal calculations,
- the number of severed tests have been fixed to 10 for economical reasons,
- a severization factor Kd has been determined from the charts of the GTPS document Nr 11F

All the other parameters have been fixed at their most pessimistic value within the technical specifications:

- worst orientation of the Pyrosoft™ device regarding gravity influence,
- ignition with only one initiator.

GTPS document Nr 11F (See figure 20 and reference [1]) gives a method enabling to determine, for a required reliability level, a factor Kd to be applied to the value of the key functional parameter of a pyrotechnic device; Then, the device shall function successfully within application of the severed functional parameter.

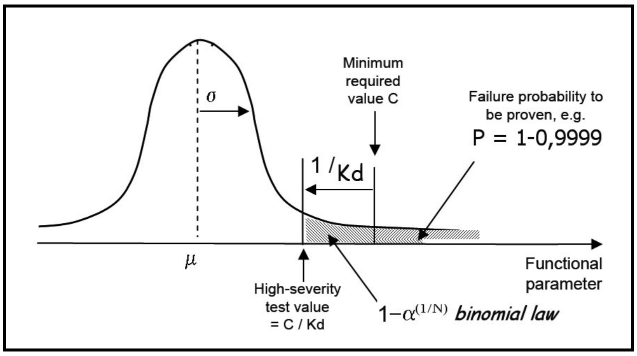


Fig. 20 GTPS document Nr 11F methodology for high-severity testing

For Pyrosoft™ application, the maximum temperature of the brazed joint at its coldest point is the functional parameter, and its value C corresponds to the calculated value at the minimum flight firing temperature (-110°C). The statistical law corresponds to the dispersion of the melting temperature of the eutectic alloy of the brazed joint: it has been determined from the observed dispersion of the relative percentages of the two components in the eutectic alloy.

Statistical calculations according to GTPS document n°11F has then determined to perform the 10 severed tests at a firing temperature of -152 ± 3°C to demonstrate a no-failure probability > 0.9999 with 95% confidence level for function Nr F01.5.

The 10 tests have been fired successfully by CNES Toulouse under thermal vacuum environment. Bolts have been released and the recorded release times were compliant with the calculated values.

8.3. Opening of the threaded segments

The opening of the threaded segments needs the general motion of the threaded ring + piston + threaded segments along a 2 mm axial course. This is possible if the motorization forces exceed the resistant forces with a given mechanical margin.

In order to meet the Space Reliability Standards, this mechanical or "motorization" margin must be higher than 3 according to ESA ECSS E 30 part 3A (See reference [2]). Assuming a CV = σ/μ ratio equal to 0.15 for the dispersion of the "stress" (motorization forces) and "strength" (resistant forces) components of the key parameter, fulfillment of this requirement proves a reliability level higher than $1\text{-}10^{-6}$.

This "motorization" margin must be ensured in flight conditions, which means that it is necessary to take in account (1) assembly constraints such as misalignment and delocalization of the bolt (See figure 21) and (2) external torque when the bolt tension has been released.

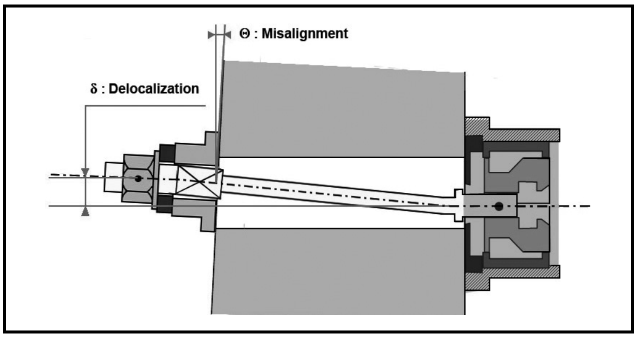


Fig. 20 Misalignment and delocalization of the bolt

To justify that the design of Pyrosoft™ M6 release nut fulfils ECSS E 30 part 3A in all foreseen applications on satellites, a 3D mechanical model has been developed to describe the behaviour of the moving mechanical parts. This mechanical model takes account of the following forces:

- two motorization forces: the bolt tension P and the elastic thrust of the motorization spring,
- four resistive forces generated respectively by (1) the bending moment M_b and (2) the shearing stress T_b, resulting from the bolt misalignment and delocalization, (3) the lateral forces which applies to the threaded segments through the threads as a consequence of bolt tension and (4) thermo-mechanical forces enabling small cyclic motions of the threaded segments under variations of the thermal environment of the Pyrosoft™ device.

Figure 22 gives a representation of these forces inside the Pyrosoft™ device itself and outside at the opposite end of the bolt where tension P is applied.

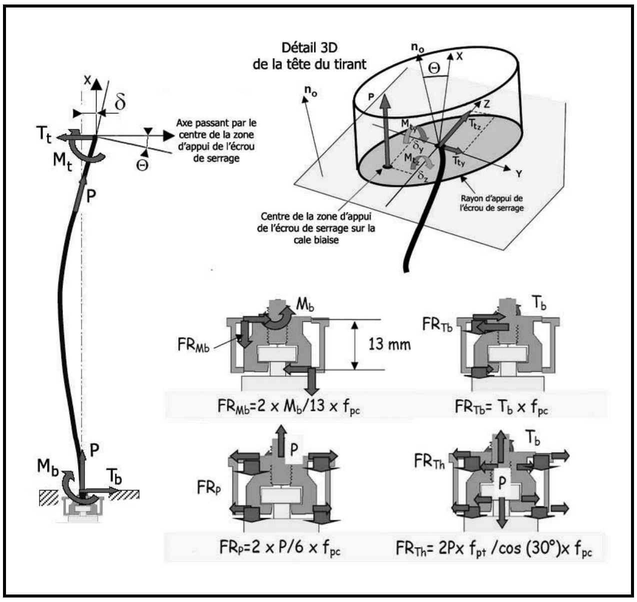


Fig. 22 3D mechanical model

Mechanical calculations have been made with this 3D model, leading to graphic representations of the results as well as numerical tables showing the reliability range of use in terms of motorization margins.

Figure 23 gives an example of such graphic representations of the results. Three curves depict the evolution of the motorization forces, the resistant forces and the motorization margin respectively. Note that the motorization forces have been lowered by a factor 0.8 according to ECSS E30 Part 3A, which increases the severity of the mechanical analysis.

These curves show that, when the bolt tension releases, the motorization and resistive forces decrease together. Above 500 N, the tension level remains sufficiently high to generate friction forces at the opposite[1] end of the bolt which maintain the bolt in its initial position: misalignment Θ and delocalization δ keep their initial values. Therefore, the motorization margin remains constant.

As soon as the bolt tension becomes less than 500 N, the opposite end of the bolt begins to move. At first, it rotates and misalignment Θ decreases, with no evolution of delocalization δ. Then, under a value of the tension (here 140 N) which is governed by friction coefficients between nuts, washers and base plate at the opposite end of the bolt, misalignment Θ and delocalization δ decrease simultaneously. Then the resistant forces drop steeply.

Motorization margin has its minimum value when the opposite end of the bolt starts to slide to realign with the axis of the Pyrosoft™ release nut.

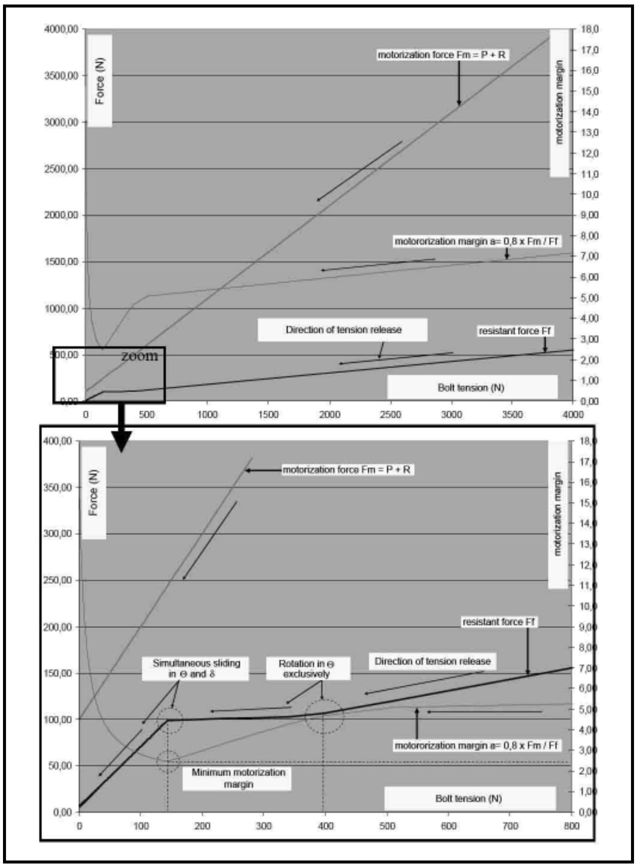


Fig. 23 Mechanical model: graphic representation of results

[1] "Opposite" means "opposite to the part of the bolt which is screwed in the threaded segments of the Pyrosoft™ release nut".

Mechanical calculations have highlighted the importance of a management of the friction coefficients between the moving parts inside the Pyrosoft™ device and at the opposite end of the bolt (outside the Pyrosoft™ device) Figure 24 shows the influence of these friction coefficients on the resistive forces.

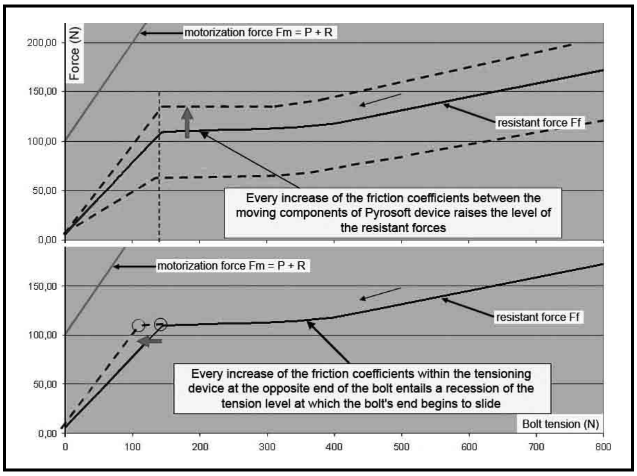


Fig. 24 Influence of friction coefficients

From these mechanical calculations, it has been possible the set of design, manufacturing and quality inspection requirements leading to a motorization margin higher than 3 (as stated by ECSS E30 Part 3A) These requirements concern together the Pyrosoft release nut and the bolt tensioning device.

For the Pyrosoft™ device itself, they mainly deal with the control of friction coefficients at the interfaces between the moving components inside the: tolerances, surface roughness, inspection tests…

For the bolt tensioning device, they also fix upper limits to friction coefficients to ensure capacity of rotation and sliding of the bolt's end as tension releases.

These requirements take into account the maximum values of the bolt misalignment and delocalization which have been defined by satellite designers and manufacturers.

Among other parameters, a specific care will be needed of the controlling the external torque which could be applied to the bolt during its release. In some cases, when this external torque is uncertain or potentially higher than usually, the introduction of a complementary motorization component in the bolt tensioning device could be recommended.

Given these requirements, the range of use of Pyrosoft™ release nut has then been evaluated from the same mechanical calculations. Numerical tables have been drawn up, showing the reliability range where calculated motorization margins exceed 3. The corresponding acceptable values of misalignment Θ and delocalization δ as a function of the bolt characteristics (lenght –diameter - material properties) cover main applications of hold down and release mechanisms of satellites (antennas and solar panels)

Figure 25 gives an example of a numerical table. The range of use with the motorization margin better than 3 is coloured in dark grey. It includes totally the range of variations of misalignment Θ and delocalization δ for this application represented by the light grey area.

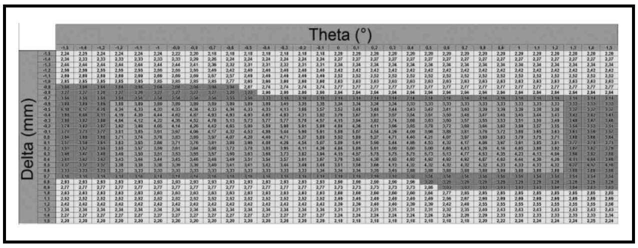
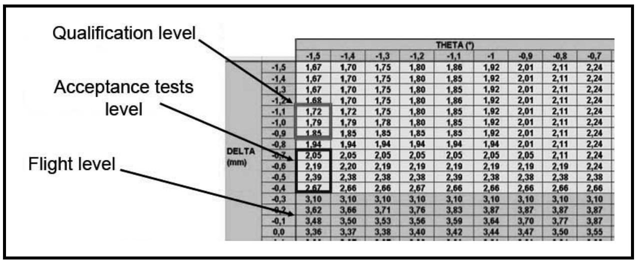


Fig. 25 Calculated range of use

The qualification program of Pyrosoft™ M6 release nut has included two tests to confirm mechanical calculations. In a similar way to function F01.5 (see chapter 8.2), a high-severity configuration has been adopted for these two tests: two Pyrosoft release nuts have been fired under vacuum at – 120°C with Θ and δ values corresponding to a motorization margin equal to 1.79 instead of 3. Among the possible Θ and δ values, those which correspond to the most pessimistic case have been chosen: they cover the full range of operational situations as shown on figure 26. All other parameters have been fixed according to a "worst case" principle: unfavourable orientation of gravity, maximum bolt stiffness, minimum bolt length, minimum initial bolt tension… A detailed analysis of the results of these two tests has demonstrated a successful behaviour of the two Pyrosoft™ devices.

In order to enrich the performance data base of Pyrosoft™ release nut the acceptance tests of the production lots will be performed in a still severe Θ and δ configuration, with a safety margin in the range 1,7 to 2 instead of 3.



DELTA (mm)	THETA (°) -1,5	-1,4	-1,3	-1,2	-1,1	-1	-0,9	-0,8	-0,7
-1,5	1,67	1,70	1,75	1,80	1,86	1,92	2,01	2,11	2,24
-1,4	1,67	1,70	1,75	1,80	1,85	1,92	2,01	2,11	2,24
-1,3	1,67	1,70	1,75	1,80	1,85	1,92	2,01	2,11	2,24
-1,2	1,68	1,70	1,75	1,80	1,86	1,92	2,01	2,11	2,24
-1,1	1,72	1,72	1,75	1,80	1,85	1,92	2,01	2,11	2,24
-1,0	1,79	1,79	1,78	1,80	1,85	1,92	2,01	2,11	2,24
-0,9	1,85	1,85	1,85	1,85	1,85	1,92	2,01	2,11	2,24
-0,8	1,94	1,94	1,94	1,94	1,94	1,94	2,01	2,11	2,24
-0,7	2,05	2,05	2,05	2,05	2,05	2,05	2,05	2,11	2,24
-0,6	2,19	2,20	2,19	2,19	2,19	2,19	2,19	2,19	2,24
-0,5	2,39	2,38	2,38	2,38	2,39	2,38	2,38	2,38	2,38
-0,4	2,67	2,66	2,66	2,67	2,66	2,66	2,66	2,66	2,66
-0,3	3,10	3,10	3,10	3,10	3,10	3,10	3,10	3,10	3,10
-0,2	3,62	3,66	3,71	3,76	3,83	3,87	3,87	3,87	3,87
-0,1	3,48	3,50	3,53	3,56	3,59	3,64	3,70	3,77	3,87
0,0	3,36	3,37	3,38	3,40	3,42	3,44	3,47	3,50	3,55

Fig. 26 Flight and tests levels

9. CONCLUSION

This step-by-step methodology and the related experimental work have demonstrated their efficiency to prove reliability higher than 0.9999 at the 95% confidence level required by CNES in the range of use defined by satellite designers.

On one hand, FMECA has lead to a successful evolution of the initial design of Pyrosoft™ release nut. On the other hand, the more precise approach which has been completed for the more complex functions has helped to specify complementary requirements for the manufacture and inspection of the industrial Pyrosoft™ devices, as well as to define recommendations for the bolt tensioning device which have been included in the ICD's delivered to the users.

This reliability analysis will be continued as new experimental data will be progressively deduced from destructive and non destructive inspection tests, lot acceptance tests, ground tests as well as flight records.

Pyrosoft™ release device proves that reliable “low shock” pyrotechnic devices are now available, leading to the possibility to improve strongly the ratio of the operational payload to the total mass of the satellites and, consequently, draw economical profits.

[1] Document GTPS N°11F – Méthode Statistique – Essais Durcis – Edition Mars 1993 – Association Française de Pyrotechnie.
[2] ECSS-E-30 Part 3A – Space Engineering – Mechanical – Part 3: Mechanisms – Edition 25 April 2000 – ESA Publications Division.