

Soft Passivation of Spacecraft Pressure Vessels

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ABSTRACT

Most spacecraft have at least one pressurized vessel on board. In addition to a hole, it is possible that a pressure vessel may experience catastrophic failure as a result of a hypervelocity impact, such as by a micrometeoroid or space debris particle. If a tank rupture were to occur on-orbit following a micrometeoroid or orbital debris particle impact, not only could it lead to loss of life, but it would also generate a tremendous amount of debris that could compromise future space assets working in similar orbits. As a result, NASA and other space agencies have put in place design requirements to prevent additional sizable debris from being created in the event of a catastrophic pressure vessel failure. These requirements typically state that stored energy devices are to be passivated at the end of a spacecraft's mission or useful life. Since many spacecraft designs are not able to comply with some aspects of those requirements, an alternative, so-called "soft passivation" option was added. This paper provides a summary of a project performed with the intent of providing guidelines and considerations that can be used by satellite programs to help satisfy passivation requirements using a "soft passivation" approach, that is, when not able to perform complete hard passivation.

1 INTRODUCTION

Most spacecraft have at least one pressurized vessel on board. For robotic spacecraft, it is usually a liquid propellant tank. For human missions, these are usually the pressurized habitable modules of the spacecraft (such as the ISS, for example). If an orbital debris particle of sufficiently high kinetic energy were to strike a pressure vessel, in addition to a hole, it is possible that the pressure vessel may experience catastrophic failure (i.e. rupture) as a result of the hypervelocity impact. If such a tank rupture were to occur on-orbit following a micrometeoroid and/or orbital debris (MMOD) particle impact, not only could it lead to loss of life, but it would also generate a tremendous amount of debris that could compromise the operation of either current or future space assets working in similar or near-by orbits. As a result, NASA and other space faring nations have put in place spacecraft and satellite design requirements that are intended to totally avoid catastrophic failure. In general, these requirements state that a spacecraft's stored energy devices and/or containers, e.g., batteries and pressure vessels, respectively, for example, are to be passivated at the end of a spacecraft's mission or useful life. In this manner, these requirements are also intended to prevent additional sizable debris from being created in the event of, for example, pressure vessel rupture or catastrophic failure.

NASA-STD 8719.14 (Rev. A, Change Notice 1) [1] contains the technical requirements imposed upon the spacecraft design and operations, including but not limited to post-mission disposal and passivation. The specific requirement for passivation (applicable to all spacecraft remaining in Earth or lunar orbit) is found in Requirement 4.4-2. This requirement can be viewed as consisting of two parts. The first, the so-called "hard passivation" criterion, is very direct and calls for the, "... deplet[ion of] all onboard sources of stored energy and [the] disconnect[ion of] all energy generation sources when they are no longer required for mission operations or post-mission disposal". Since many spacecraft designs would not be able to comply with some aspects of that requirement (for a variety of reasons), an alternative, so-called "soft passivation" option was added - "control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft". If the release of debris can be prevented without "hard passivation", then the intent of the requirement could be met by the more practical "soft passivation" approach.

Previous studies have shown that the likelihood of pressure vessel rupture is linked to its internal pressure level (see, e.g., [2]). As such, a literature review was performed in an attempt to identify studies that had considered the effect of internal pressure and/or fill level on pressure vessel impact response for a specified set of impact conditions. The hope was to be able to secure information regarding threshold internal pressure and/or fill levels above which rupture would likely occur and below which it most likely would not for a likely or most probable set of impact parameters (i.e. velocity, trajectory obliquity, etc). This information might then prove to be useful to satellite programs in helping them meet passivation requirements through the "soft passivation" option. If such programs, for example, designed their pressure vessels so that no more than such a previously determined maximum safe internal

pressure amount for the most likely impact scenario remained at the end of the useful life of a satellite, then the claim could be made by those programs that the pressure vessels in their satellites were sufficiently passivated.

Nine documents were eventually found on test programs conducted with high velocity tests that attempted to simulate MMOD impact conditions [3-11]. While most of these high velocity test programs fell into what might be considered to be the “abuse testing” category (i.e. internal pressure was held constant at a high value while impact conditions – velocity, projectile size, etc – were varied until rupture occurred), a small number [5-8] did not (i.e. impact conditions were held constant while internal pressure was increased). In these four studies that held impact conditions constant while increasing (or decreasing) internal pressure, it was found that once the pressure was below 15%-25% of the pressure vessel’s static burst pressure, catastrophic failure or rupture no longer occurred.

As a complement to the information found in the literature review, a process was developed to provide additional information that could be used by satellite programs and projects to possibly help satisfy passivation requirements using the “soft passivation” approach, that is, when not performing complete fuel depletion, or hard passivation. The end result of this process is a calculation of the number of rupture-causing MMOD particles that a spacecraft might expect to encounter in its so-called “soft passivated” state. This process requires first calculating the size of a particle that might be expected to cause rupture of a “nearly empty” fuel tank of a given spacecraft, then determining the anticipated flux of particles of that size for that satellite, and then finally calculating the expected number of such particles that are likely to be seen by that satellite over its passivated lifespan.

2 NUMBER OF RUPTURE-CAUSING PARTICLES

In this section, a calculation process is presented that can be performed to determine the number of rupture-causing MMOD particles that a spacecraft might expect to encounter in a so-called “soft passivated” state. This process requires first calculating the size of a particle that might be expected to cause rupture of a “nearly empty” fuel tank of a given still-orbiting satellite or spacecraft, then determining the anticipated flux of particles of that size for that satellite, and then finally calculating the expected number of particles that might be seen by that satellite over its remaining passivated lifespan. The results of such calculations can be used by spacecraft designers and mission planners to help satisfy passivation requirements using a “soft passivation” approach.

The following steps form this calculation process:

1. for a given satellite, estimate the most likely closing velocity and impact angle of a debris particle in that satellite’s orbit using an appropriate debris environment model;
2. using that information and the Rupture Limit Equation for the type of fuel tank in the given satellite, determine the diameter of a likely rupture-causing particle;
3. using the same model of the orbital debris environment, determine the anticipated flux of particles of that diameter for the given satellite’s orbit; and,
4. calculate the expected number of particles to be seen by the given satellite in its orbit based on an assumed remaining orbital lifetime and exposed surface area.

The two satellites chosen to illustrate the calculations performed are the Aqua and EO-1 satellites.

- The Aqua satellite uses a PSI model 80263-1 tank. The tank is pressurized with nitrogen on one side of an internal diaphragm prior to launch, and operates in blowdown mode throughout the mission. The baseline disposal plan calls for depleting all fuel, leaving approximately 100 psia of nitrogen pressurant in the tank trapped permanently behind the diaphragm during the ~25 years of orbit decay. The operational orbit for Aqua is nominally 705 km circular, 98.2 degree inclination. Disposal orbit is decaying from 675 km x 697 km, same inclination.
- The EO-1 satellite uses a PSI model 80389-1 tank. This tank is also pressurized with nitrogen on one side of an internal diaphragm prior to launch, and also operates in blowdown mode throughout the mission. Its baseline disposal plan likewise calls for depleting all fuel, leaving approximately 70 psia of nitrogen pressurant trapped behind a diaphragm during its ~25 years of orbit decay. Disposal orbit is decaying from 673 km x 685 km at a 97.8 degree inclination.

Figures 1 and 2 show illustrations of the Aqua and EO-1 fuel tanks, respectively; Table 2 contains additional material properties and geometric parameters for these two tanks (see also [12,13]).

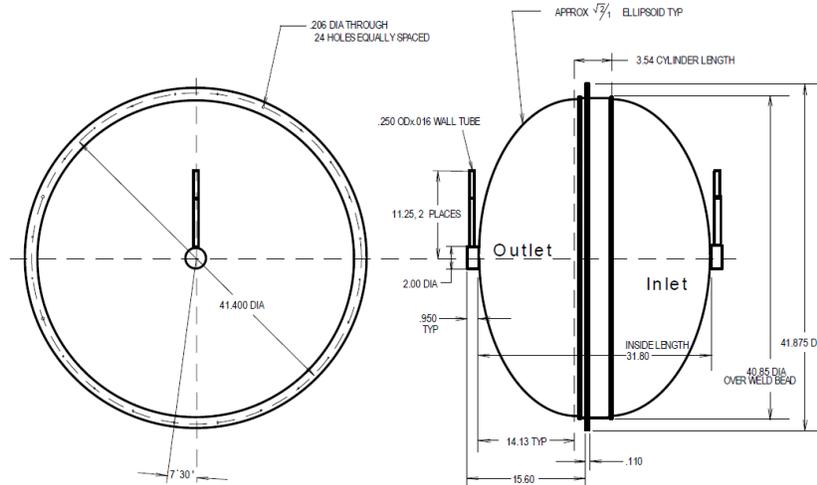


Fig. 1. Sketch of Aqua Fuel Tank

<https://www.northropgrumman.com/Capabilities/DiaphragmTanks/Documents/DS263.pdf>

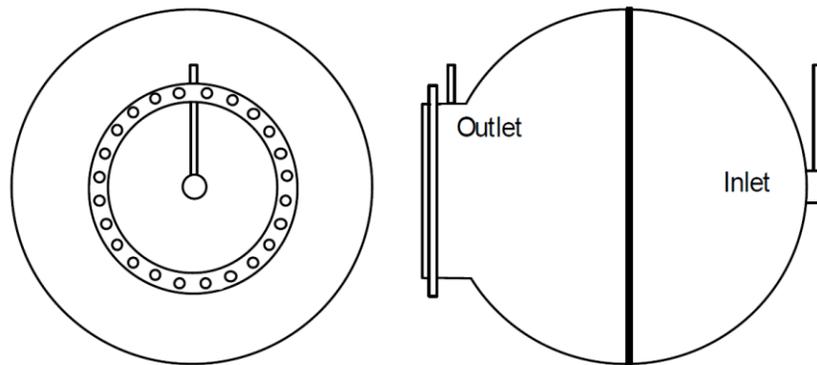


Fig. 2. Sketch of EO-1 Fuel Tank

<https://www.northropgrumman.com/Capabilities/DiaphragmTanks/Documents/DS389.pdf>

Table 2. Material and Geometry Information for Aqua and EO-1 Tanks

| Parameter | Aqua | EO-1 | Units |
|----------------|-----------|-----------|-----------------|
| Tank Material | 6Al-4V-Ti | 6Al-4V-Ti | ----- |
| Tank Volume | 28,144 | 1865 | in ³ |
| Tank Diameter | 96 | 39 | cm |
| Wall Thickness | 1.27 | 0.483 | mm |
| Internal Press | 100 | 70 | psi |

The diameter of each tank was calculated assuming a spherical tank equal in volume to the actual satellite tank. The RLEs to be used subsequently require a tank diameter as well as tank wall thickness; hence the need to calculate the diameter of an equivalent spherical tank for each actual tank.

The Rupture Limit Equation (RLE) for a pressurized spherical metallic tank was obtained using the rupture / no rupture data from a previous study that considered the high-speed impact of pressurized spherical aluminum and titanium tanks [14]. To render the equation as broadly applicable as possible, the operating conditions (x-axis) were parameterized as the hoop stress in the tank (non-dimensionalized by the ultimate tensile stress of the tank wall material), and the impact conditions (y-axis) were parameterized as impact energy (non-dimensionalized by a number of appropriate tank wall material properties). Following on the successful application of this approach in several previous studies (see, e.g., [15,16]), a simple power law form was chosen for the RLE to be developed.

The power law for the curve that separates the regions of rupture and non-rupture was chosen as follows:

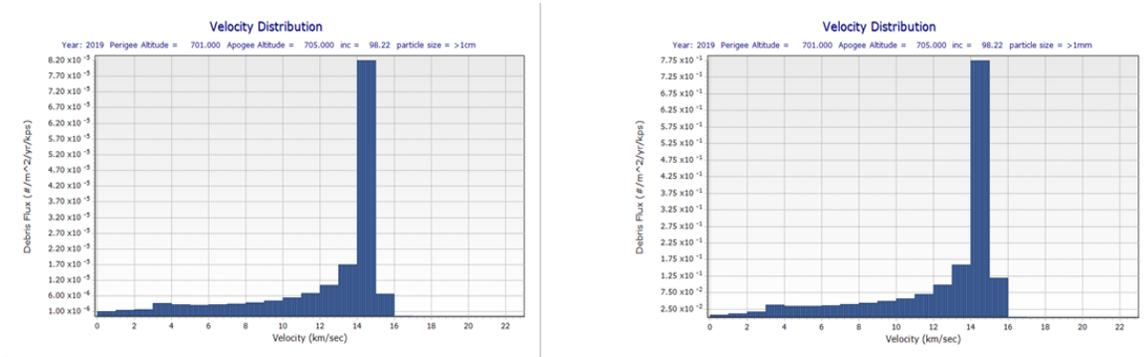
$$\text{Non-dimensional Projectile Energy} = A \left(\frac{\sigma_h}{\sigma_u} \right)^B \tag{1}$$

where σ_h and σ_u are the pressure vessel hoop stress and the tank wall material ultimate tensile stress, respectively. The non-dimensional form of energy momentum was taken to be given as follows:

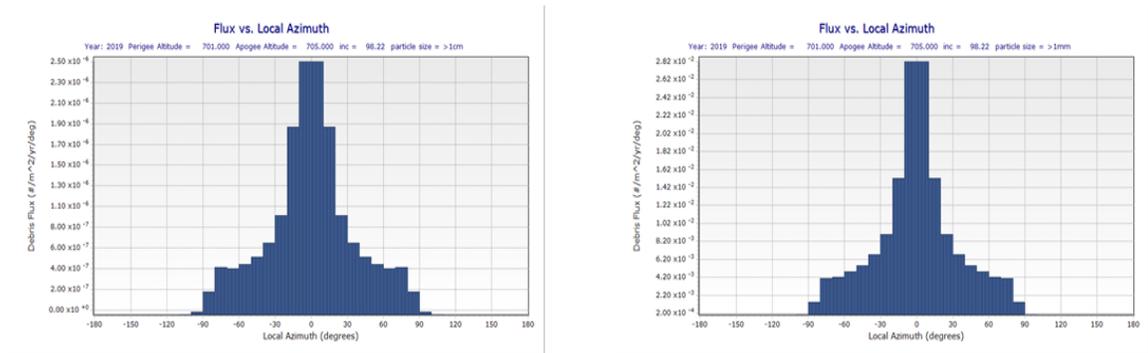
$$\text{Non-dimensional Projectile Energy} = \frac{\frac{1}{2}m_p V_p^2}{(\rho_p t_w^3) C_w^2 \left(\frac{\rho_p}{\rho_w} \right)^{-3\alpha} H_w^{3/4}} = A \left(\frac{\sigma_h}{\sigma_u} \right)^B \tag{2}$$

In Eqn (2), ρ_p and ρ_w are the densities of the projectile and tank wall materials, respectively, t_w is the thickness of the tank wall, and H_w and $C_w = \sqrt{E_w/\rho_w}$ are the Brinell Hardness Number and the speed of sound, respectively, for the tank wall material. In addition, α has a value of 1/2 if $\rho_p/\rho_w < 1.5$ and 2/3 if $\rho_p/\rho_w > 1.5$. As such, the first term in the denominator in Eqn (2) has units of mass while the second has units of velocity squared, thereby rendering the right-hand-side of Eqn (2) unitless, or non-dimensional, so long as there is consistency in the units of mass and velocity used in its numerator and denominator. Using the data in [14] and the procedure outlined in [15,16], the values of A and B were found to be $A = 1.606$, and $B = -0.8943$ (with a correlation coefficient of 0.68 for the regression that yielded the values of A and B). These values of A and B, together with Eqns (1) and (2) complete the development of the RLE needed for this exercise.

The most likely closing velocity and impact angle of an orbital debris particle in the disposal orbits of Aqua and EO-1 as stated above were found using ORDEM-3 [17]. Figures 3,4 and 5,6 show this information as obtained from ORDEM-3 for the Aqua and EO-1 disposal orbits, respectively.

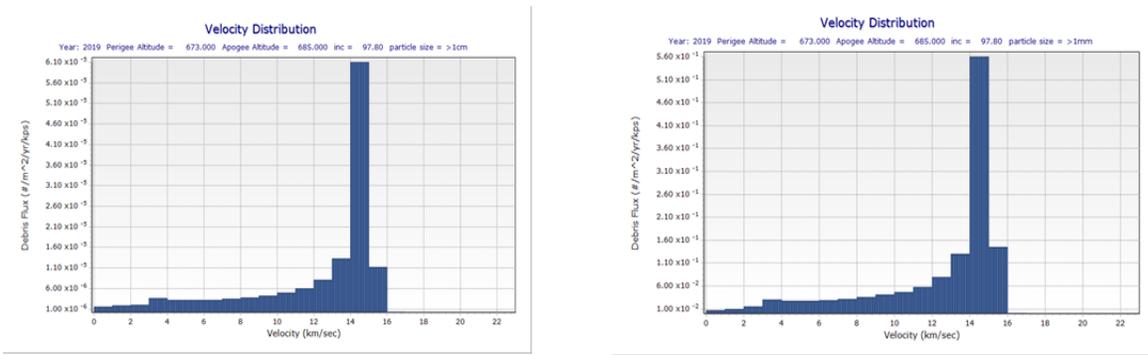


Figs. 3. Debris Flux in Terms of Impact Velocity For the Aqua Satellite
(a) for 1 cm Particles, (b) for 1 mm Particles

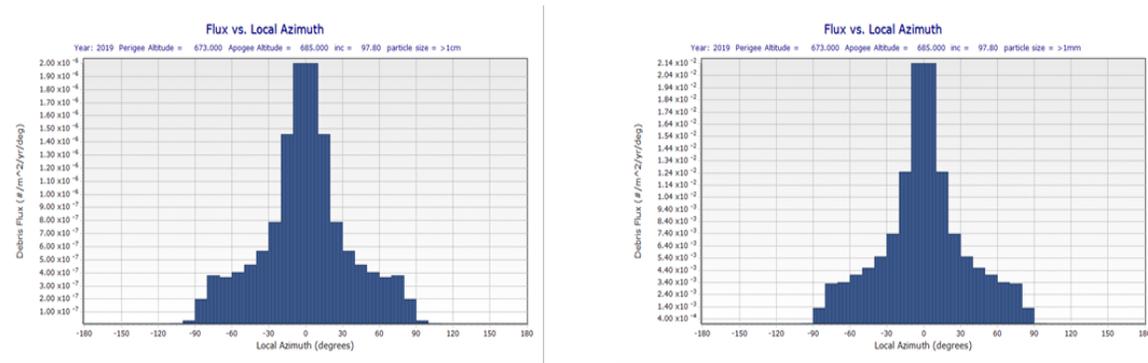


Figs. 4. Debris Flux in Terms of Impact Angle for the Aqua Satellite
(a) for 1 cm Particles, (b) for 1 mm Particles

As can be seen from Figs. 3 - 6 the values of most likely orbital debris impact angle and velocity are not dependent on whether 1 mm or 1 cm size particles are assumed in the flux calculations. In both cases, Figs. 3 - 6 tell us that the most likely impact velocity and impact angle for both satellites is 14.5 km/s and 0-deg, respectively.



Figs. 5. Debris Flux in Terms of Impact Velocity For the EO-1 Satellite
(a) for 1 cm Particles, (b) for 1 mm Particles



Figs. 6. Debris Flux in Terms of Impact Angle for the EO-1 Satellite
(a) for 1 cm Particles, (b) for 1 mm Particles

Figure 7 shows a plot of the RLE developed for this task and the data from [14] that was used in its development. Also indicated in Fig. 7 are the points on the RLE corresponding to the most likely impact angle and most likely impact velocity for the two satellites being considered.

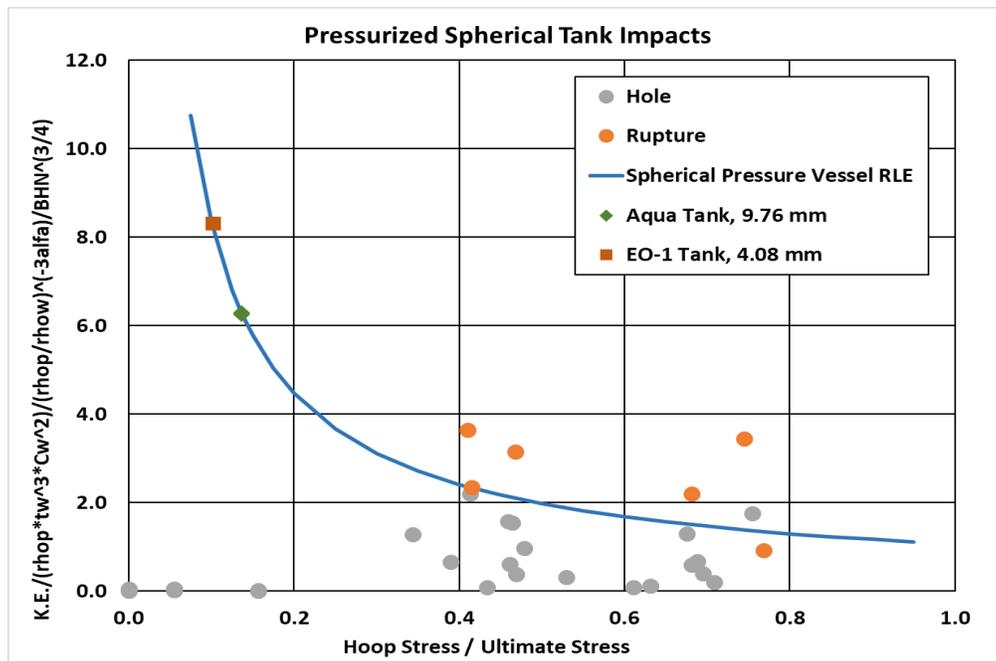


Fig. 7 Plot of Spherical Metallic Tank RLE and Supporting Data

Based on the RLE developed herein, from Fig. 7 we can calculate that it would be reasonable to expect that the impact of a 4.08 mm aluminum particle would result in rupture of a passivated EO-1 fuel tank (i.e. when it is in its disposal orbits), while a 9.76 mm aluminum particle would be required to rupture a passivated Aqua fuel tank. The question to be answered now is, how many such rupture-causing particles might the Aqua and EO-1 satellites be expected during their 25-year disposal orbit lifetimes? This information for each satellite was again obtained using ORDEM-3, with the results shown in Table 3.

Table 3. Anticipated Flux and Number of Rupture Causing Particles for Each Satellite

| Parameter | Aqua | EO-1 | Units |
|-------------|----------|----------|---------------------|
| Flux | 0.00017 | 0.001 | /m ² /yr |
| # particles | 0.003067 | 0.002955 | over 25 yrs |

The number of rupture causing particles for each satellite was found by multiplying the flux value by 25 and the projected circular cross-sectional area of each (assumed spherical) tank. It can be inferred from Table 3 then, that for the two satellites considered, the number of fuel tank rupture-causing particles that each satellite is likely to encounter is exceedingly low. This kind of information can then be used by satellite designers and mission planners to strengthen their case for soft passivation, if they would choose to do so.

Of course, the process presented herein has a number of assumptions including, for example, aluminum orbital debris particles in the ORDEM-3 calculations (and ignoring the existence of any higher density particles in the orbits), fully exposed tanks (and ignoring any shielding provided by other satellite components), etc. While the process can be readily modified to be more realistic and to provide more accurate assessments of the likelihood of encountering rupture-causing particles, it has at least shown to be fairly straightforward to implement to obtain the desired information.

3 SUMMARY AND CONCLUSIONS

An in-depth review of available literature revealed that when a pressure vessel's internal pressure was at a level below between 15% and 25% of its static burst pressure, catastrophic failure following a hypervelocity impact will mostly likely not occur. In addition, a process was developed that can be used to calculate the number of rupture-causing MMOD particles that a spacecraft might expect to encounter in a so-called "soft passivated" state. This process was applied to two typical pressurized fuel tanks that are frequently used in earth-orbiting satellites. In both cases, the number of rupture-causing particles was found to be exceedingly small. The results that can be obtained using this process can be used by spacecraft designers and mission planners to help satisfy passivation requirements using a "soft passivation" approach, that is, when not performing complete fuel depletion, or hard passivation.

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