IAC-19-A1,6,2,x51502

Analysis of Bioreduction Strategies for a Solid Rocket Motor on an Interplanetary Mission to Europa

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Abstract

The Europa Lander De-Orbit stage braking motor must comply with the Planetary Protection requirements established for a category IV mission. In its mission to Europa, a motor that hasn't gone through bioreduction environments will carry microbial spores and other biosignature molecules that might jeopardize a mission of astrobiological concern as well as future missions to come. A motor with solid rocket propellant represents exclusive challenges associated to the calculation of high numbers of an encapsulated bioburden hidden behind a nozzle plug. Existing techniques for bioburden reduction are analysed in perspective to motor assembly facilities and the series of events that are involved in manufacturing a solid rocket motor. These techniques include antimicrobial effects of chemical components already present within the motor and bioreduction due to assembly and operational environments induced in the motor. Analysis of the manufacturing process, adhered bioburden and recent investigations into the effectiveness of microbiological techniques in finding inherent antimicrobial properties have generated a step by step outline of Planetary Protection for lander mission associated solid rocket motors. **Keywords:** Solid Propellant Rocket Engines; Europa; Interplanetary Spacecraft; Spacecraft Sterilization; Microorganisms; Bioreduction; Planetary Protection; Space Exploration; Hydrogen Peroxide; Dry Heat Microbial Reduction

Acronyms/Abbreviations

DHMR =Dry Heat Microbial Reduction
DOS =De-Orbit Stage
NASA =National Aeronautics and Space Administration
SRM =Solid Rocket Motor
VHP =Vaporized Hydrogen Peroxide Purges
COSPAR = Committee on Space Research
LDEF = Long-Duration Exposure Facility
OSMA =Office of Safety Mission Assurance
MER = Mars Exploration Rover
KSC =John F. Kennedy Space Center
HTPB =Hydroxyl-terminated polybutadiene
ESD =Electro-Static Discharge
VHP = Vaporized Hydrogen Peroxide

1. Introduction

The Jovian environment is believed to be hostile to living organisms as we know them, with high levels of ionizing radiation, extreme temperatures and debris, but also represents a research milestone for National Aeronautics and Space Administration (NASA) in the search for life outside the boundaries of Earth [1]. In the current and following decades NASA will embark on extensive studies and planning of missions to explore Europa, one of Jupiter's many moons. Europa has a surface believed to be covered in an ice crusted water ocean making it a possible habitat for life. Aside from this, recurrent sightings of active water plumes spewing water to the icy surface has garnered more interest around the moon's habitability aspect [2]. Europa Clipper, a spacecraft meant to orbit Jupiter's moon, is part of a series of studies hoping to provide more information to scientists about the physico-chemical conditions of the Europan surface, performing 45 flybys with its nine instruments as well as bringing back topographical data, useful in planning landed missions [3]. The Europa Lander concept, another spacecraft destined to probe icy surfaces, will be designed to carry a miniaturized laboratory that will analyse Europan surface samples for its chemical composition and other geological data from the moon [4]. The lander's search for any biosignature indigenous to Europa is one of its most important features, and the mission's ability to carry-out these experiments might be endangered by the lander's own contaminated body, as this is also a contamination threat to any future landers to come from other space agencies with similar astrobiological interest. Planetary science missions with a focus on astrobiology such as Europa Clipper and the Europa Lander concept happen to be in the scale of Planetary Protection category III and IV. This poses a special challenge to propulsion subsystem planning and manufacturing, since it may introduce harsh bioreduction techniques to the process of a motor that is destined to age.

1.1 Planetary Protection Establishment

The mission and philosophy of Planetary Protection is to establish a levelled ground where all countries have equal opportunity to research life in other planetary bodies in a responsible manner, conducting studies while avoiding harmful contamination of surfaces of interest, agreed upon since 1958 by multiple countries [5]. NASA has a set of requirements specific for all mission types, guided by COSPAR and the OSMA that must be followed by all NASA robotic extraterrestrial missions. In this document, NASA has set requirements for each mission category from I to V with the experience brought forth by missions to Mars [6].

1.2 Lander Propulsion Subsystems

The robotic exploration De-Orbit Stage (DOS) of far-away bodies are historically assisted by SRMs due to their high reliability and low-cost functionality. The Star 48B propellant for example, survived the Magellan flight 15-month space storage and more than 5 years without material degradation in a long-duration exposure facility (LDEF) [7]. Aside from the challenges put forth by propulsion subsystem flybys through a high-radiation Jovian environment, raising the probabilities of motor aging, Planetary Protection techniques will amplify any material degradation or malfunction probability [8].

1.3 Planetary Protection Techniques

A plethora of techniques are approved by the Office of Planetary Protection for use in spacecraft assembly, some of which were developed for previous missions based on material compatibility and microbiological classical methods available at the time. At KSC in 2003 two large spacecraft components used in MER underwent dry heat microbial reduction (DHMR) in “tolerable” environment conditions for the materials, vaporized hydrogen peroxide (VHP) has been validated for use in Planetary Protection without affecting hardware performance, hardware compatibility can be obtained via standards, material packaging or compatibility tests, and the Jet Propulsion Laboratory has introduced various effective bioburden/microbial detection and measuring techniques [9, 10]. At some point in the development of a propulsion subsystem these techniques are applied and modified to fit the requirements for Planetary Protection without affecting system performance. Building a Planetary Protection Plan and process for the propulsion subsystems of a category IV mission to Europa has never been done before, with the help of existing materials data, detailed techniques, and NASA’s experience it promises to be an unsolved problem for a limited amount of time, the biggest problems being attached to the presence of large quantities of solid rocket propellant in some of the larger SRMs that can be used for landed missions after undergoing a multimillion-mile journey.

2. Solid Rocket Motor Non-Metallic Materials

2.1 Solid Rocket Propellant

When solid rocket motors are subjected to higher than ambient temperatures, the propellant experiences thermally accelerated aging. Thermally accelerated age can be correlated to approximate real-time age by the Arrhenius Equation:

$$t1 = t2 \times e^{\left(\left(\frac{E}{R}\right)\times\left(\frac{1}{T1}-\frac{1}{T2}\right)\right)}$$

Where:

t1 is projected real-time at ambient temperature
T1 is ambient aging temperature (Kelvin)
t2 is time in accelerated aging
T2 is accelerated aging temperature (Kelvin)
E is energy of activation (kcal/mol)
R is the universal gas constant = 1.9872041×10^{-3} kcal/K-mol

Aged rocket motors are not fired due to safety risks, and accelerated aging of propellant is typically achieved by heated storage of the material in a temperature range of 110-degrees Fahrenheit (F) to 135-degrees F (43-degrees Celsius (C) to 57-degrees C)[11]. During the 2016 timeframe, an initial DHMR cycle with a temperature of 270-degrees F (132-degrees C) for a minimum of 36 hours was proposed for the Europa De-Orbit Stage (DOS) braking motor in its entirety, which is greater than either normal propellant cure temperature (135-degrees F or 57-degrees C) or normal accelerated aging temperatures[12]. This proposed DHMR would have equated to about 9.7 years at ambient temperature, like the Ares I-X motor flown in October 2009. The full-motor sterilization procedure to achieve 36-hours at temperature, however, would significantly age propellant-liner components in proximity to the heat source. Furthermore, the proposed DHMR temperature for 36 hours would not have attained a 4th order of microbial bioreduction (380 hours at temperature is required, which would age the propellant-liner components to about 76 years old), and achieving temperature did not include temperature ramp-up and ramp-down times that would significantly add to the 9.7 year age figure – probably an age of about 20 years old for the propellant-liner components of the motor.

Figure 1. Propellant Aging Expected from DHMR

A lower temperature of 230-degrees F (110-degrees C) for 705 hours achieves 4th order bio-reduction but ages the propellant-liner system to 45 years old, and once again does not include temperature ramp-up and ramp-down times.

2.2 SRM Insulation, Liner, Nozzle and Others

SRMs are also composed of other non-metallic materials that are not propellant, particularly Hydroxyl-terminated polybutadiene (HTPB) propellants, coming into direct contact with liner, insulation, and in sometimes Chemlok coatings. Scenarios with a sacrificial thermal liner inside the metallic case may benefit from antimicrobial testing and irradiation pre-application. Such antimicrobial tests have provided positive results in with the use of Chemlok formulas. Insulation layers in the inner-case that undergo cryogrinding may provide a smaller encapsulated bioburden number. The insulation is a particularly heat-resistant material due to the nature of its use and thus undergoes long curing processes at high temperatures that can provide a stable thermal bioreduction environment. During the inner-case preparation, bagging procedures scenarios that occur can be used to the advantage of Planetary Protection, by using sterile bagging produced for assembly contamination control purposes that serve for double function in thermal sterilization. Scenarios with carbon phenolic nozzles will add an encapsulated bioburden amount for the nozzle volume and a surface area bioburden. Nozzles tend to burn with firing, but thermal sterilization of the nozzle during firing is still to be determined. Thus, the nozzle may undergo other sterilization protocols available up to date.

3. Solid Rocket Motor Metallic Materials

3.1 Case and Mated Case

SRMs scenarios under study for the Europa Lander De-Orbit Stage utilize a Ti 6Al-4V case which has previously been approved by Planetary Protection groups as a preferred metallic material due to its compatibility to sterilization and cleaning protocols, and due to its ability to reach complete sterilization [13]. Thus, the same modalities should apply to a Ti 6Al-4V ring with fasteners and washers of the same material. Greases applied to mated-case crevices should follow previously established protocols for material compatible strategies or undergo testing for antimicrobial properties.

4. Exploring SRM Non-VHP Processing

Processes involving VHP and biobarriers have been proposed for the Europa DOS braking motor. Literature for Planetary Protection diverges on whether VHP would be compatible with Ti 6Al-4V, and thus the SRM case and mated case. Scenarios with greases applied to the mated case would also increase the probability of oxidation if VHP is the sterilizing modality. The SRM would have to undergo a design change by eliminating the use of greases and increasing the risk of a rigid mated case assembly unless greases are proven to cause a logarithmic reduction of microbial load. Included with the design scenario might already be a nozzle cap and nozzle plug to prevent migration of VHP into the innercase, for which sealing mechanisms should be used and verification of sealant performance and nozzle cap performance should be provided. In the case of an assembly without a biobarrier and terminal VHP application it is desired that component integration occurs in a class 8 cleanroom environment, as required by the NASA NPR 8020 document and that components are divided by material compatibility to the same bioreduction modalities previously mentioned. The case with the insulation and titanium case/mated-case counting as major components and the strongest challenge being the human factors involved in hand delivered manufacturing of a SRM inner-case to be integrated with the nozzle, pyrotechnics, electronics box, minor separation motors that might've undergone the same fate, wiping modalities compatible to ESD requirements and shipment in a clean container.

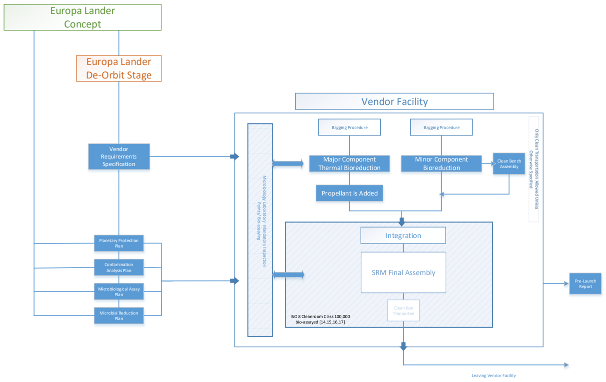
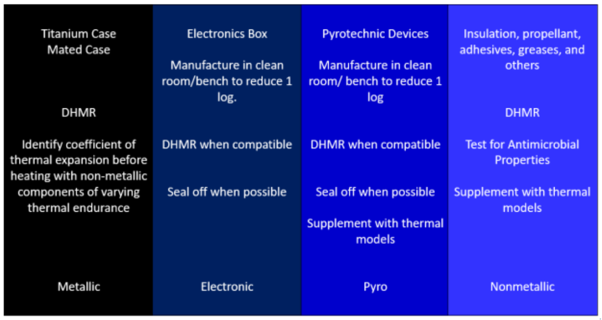


Fig 2. Planetary Protection Assembly Outline for a SRM spanning project Phases A-D.



Titanium Case Mated Case	Electronics Box	Pyrotechnic Devices	Insulation, propellant, adhesives, greases, and others
	Manufacture in clean room/bench to reduce 1 log.	Manufacture in clean room/ bench to reduce 1 log	
DHMR			DHMR
Identify coefficient of thermal expansion before heating with non-metallic components of varying thermal endurance	DHMR when compatible	DHMR when compatible	Test for Antimicrobial Properties
	Seal off when possible	Seal off when possible	Supplement with thermal models
		Supplement with thermal models	
Metallic	Electronic	Pyro	Nonmetallic

Fig 3. Different materials with suggested bioreduction modalities.

6. Conclusions

Due to time-at-temperature requirements with additional ramp times, DHMR of the entire motor at once does not appear to be the way to achieve targeted bioreduction for the braking motor's propellant and liner. It has been proposed that since the braking motor is the retro-rocket for this mission's payload, were it to fail ignition, nothing would land on Europa in the first place. This, however, is a false assumption since its orbit would decay over time, and it would eventually encounter the Jovian moon. Since the braking motor's successful operation is a self-sterilizing event (5400-degrees F or 3000-degrees C), it should not be necessary to sterilize the propellant or liner provided a redundant igniter system be made part of the motor, and that the motor also include a pyrotechnic Terminal Sterilization System (TSS) in its design. Thermal models will support this Planetary Protection deviation in future studies. Aside from this, small quantities of propellant, insulation, nozzle and other nonmetallics may be shipped and utilized in cryogrinding procedures to determine initial encapsulated bioburden numbers, different from those assigned by the Planetary Protection Provisions document [18]. Future motor burning failure probability studies may corroborate if motor-firing is a viable option for a final probability of contamination for the mission that remains under less than 10^{-4} with unsterilized propellant.

Acknowledgements

Special thanks to Jacobs technology Inc. and the amazing Europa Lander Project working groups at the Marshall Space Flight Center in Huntsville, AL and the Jet Propulsion Laboratory in Pasadena, CA for allowing this work to keep moving forward, especially Pat Lampton, Tom Zoladz, Jarvis Caffrey, Randy Raley, Lisa Phelps, Brian Clement, Raymond Ellyin and Alison Protz.

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