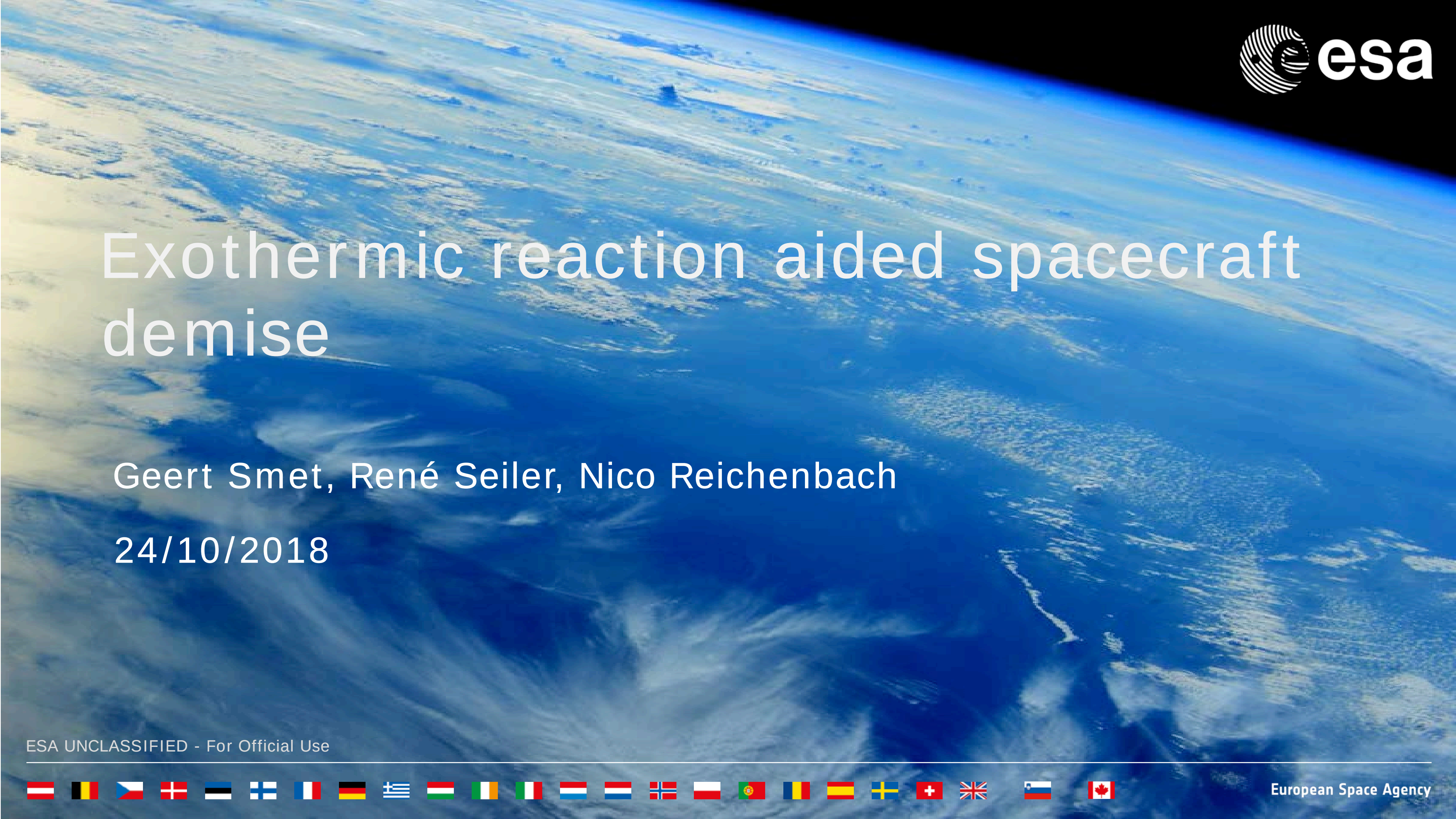

Exothermic reaction aided spacecraft demise

Geert Smet, René Seiler, Nico Reichenbach

24/10/2018

Design for Demise approaches

Minimize Required Heat

- Minimize mass
- Replacing materials:
  - Cp
  - Tm
  - ε
- Smaller elements

Maximize Available Heat

- Ballistic coefficient

Optimize Heat Transfer

- Early break-up
  - Dedicated mechanism
  - Demisable attachment points
- Orifices, Lettuce structure
- Lower emissivity

Minimize Casualty Area

- Keeping re-entry fragments together

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- **‘Exothermic reaction aided spacecraft demise during re-entry’**
  - Add energy to the system to aid the demise
- **Thermite or thermite-like substances** (providing reactant and oxidiser)
  - Composition of metal powder and metal oxide
  - Non-explosive highly exothermic redox reaction
  - Limited mass impact
  - Safe
  - Physically and chemically inert
  - Very high ignition temperatures (> 600 degC), only during re-entry

- Applications which cannot design out materials with high melting temperature
  - Mechanisms, optical systems,…

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- Thermite material **integrated** in (existing) equipment designs
  - Minimise required additional material to house thermite
  - Thermite positioned centrally in coldest parts of the unit
  - **Ignition directly by heat flux** or optionally **indirectly by a fuse**
    - Fuse allows the thermite material to be inside the equipment
    - Direct exposure of thermite to heat flux not required
  - Different fuse materials or compositions allow for **sequencing and timing** of multiple ignitions
    - Enable thermite inside equipment to reach the ignition temperature faster: **Non-energetic** fuses, conducting into the thermite
    - Lower ignition temperature: **Energetic** fuses create heat for ignition

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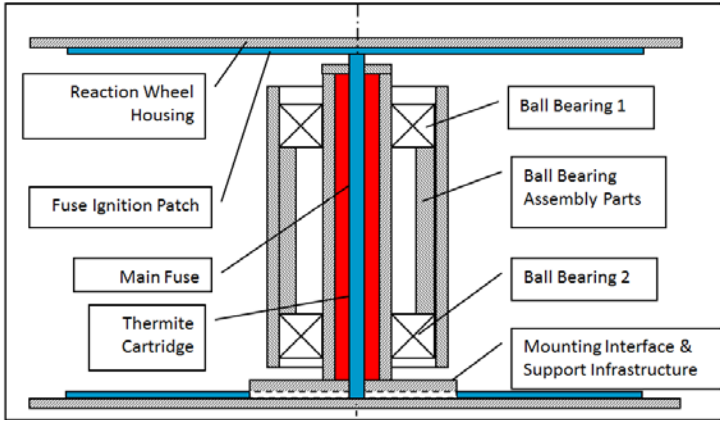
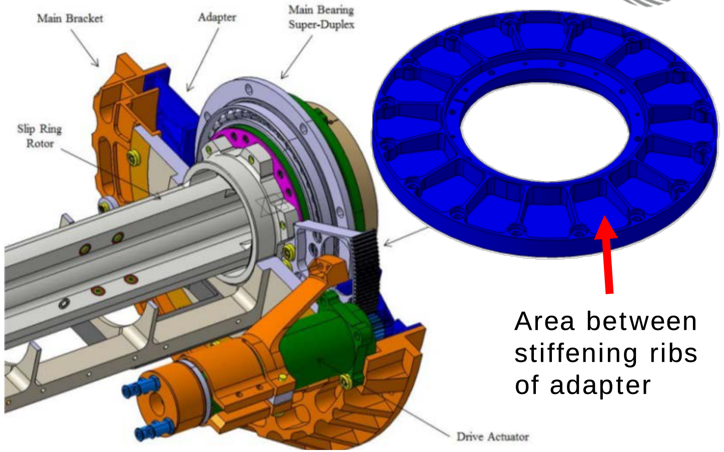
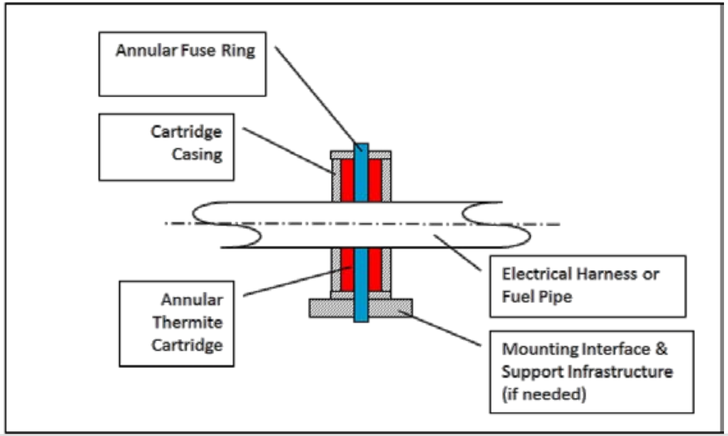
- Thermite integrated at **equipment-spacecraft I/F**
  - Spacecraft structure can (partially) shield equipment from heat flux and provide heat sink
  - Controlled, early separation of equipment beneficial for demise
  - Reliably and predictably separate equipment regardless of structure design details
  - Incorporating functionality into (recurring) equipment instead of (non-recurring) structure
- Secondary connections may need to be severed
  - **Annular thermite cartridges** as **harness and propulsion/heat pipe cutters**
- Changing thermite **particle size and shape**
  - **Tailor ignition temperature**
  - **Controls the rate of energy release**
  - Rate of energy release >>> rate of radiative heat loss

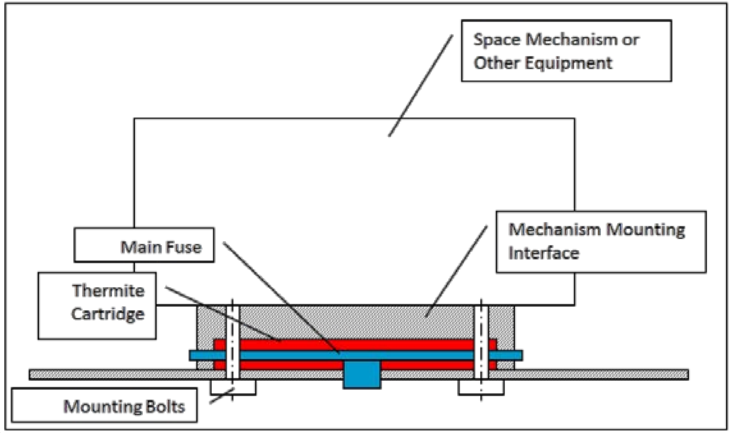
ESA Patent Pending – Design Concepts





Area between stiffening ribs of adapter





ESA Patent Pending – Fuse Technology

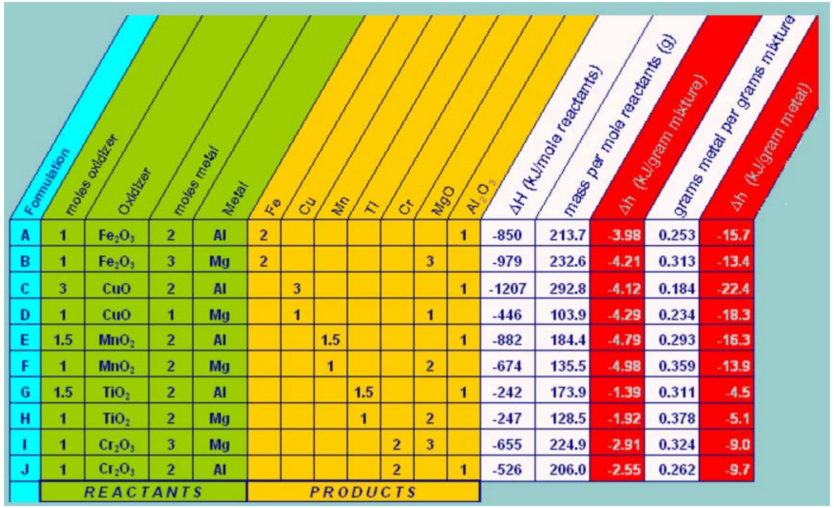
- Potential fuse technologies to ignite thermite in 200-650degC range
  - **Non-energetic fuse**, conducting heat from heat flux into the thermite. E.g. copper rod, melts at 1000+degC
  - **Energetic fuse: Hypergolic reaction**, e.g. potassium permanganate and glycerol or ethylene glycol
    - Two agents need to be kept separated
    - Reaction started by melting container separating the elements at a preselected temperature
  - **Energetic fuse: Derived from flares or sparklers**
    - Consists of metallic fuel (Al, Fe, Ti, ferrotitanium), oxidizer (potassium nitrate, barium nitrate, strontium nitrate, …) and a binder.
    - Ignition temperatures tailored with materials

Case study: Reaction wheel bearing assembly

- Reaction wheel ball bearing assembly always survives re-entry
    - Simplified as 0.5 kg of A440C stainless steel
    - Melting temperature of ~1500 degC.
- Thermite mixture Al + Fe_2O_3, ignition temperature of 650 degC. Thermite required to heat bearing assembly to melting temperature is calculated. The following assumptions are made:
    - All energy from the exothermic reaction is used to heat the ball bearing assembly (optimistic)
    - No additional energy from the re-entry is introduced to reach the melting temperature (very conservative)
    - Energy release is sufficiently fast to neglect energy loss through radiation
    - Energy required for state change not accounted for

Case study: Reaction wheel bearing assembly

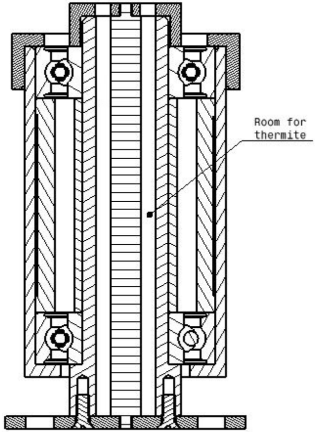
- Energy needed to heat metal to melting temperature: Q = m*c*ΔT
  - T = 650 degC, T2 = 1500 degC, ΔT=850 K
  - c = 0.46 kJ/kg*K (Specific heat stainless steel AISI 440C)
  - m = 0.5 kg
  - Q = 195.5 kJ
- Mass of thermite required:
  - Δh = 3.98 kJ/g (form. A)
  - **m_thermite = 49 g**
- Volume of thermite required:
  - r =4.25/ cm3
  - V = 11.6 cm3
- Mass and volume of thermite required feasible

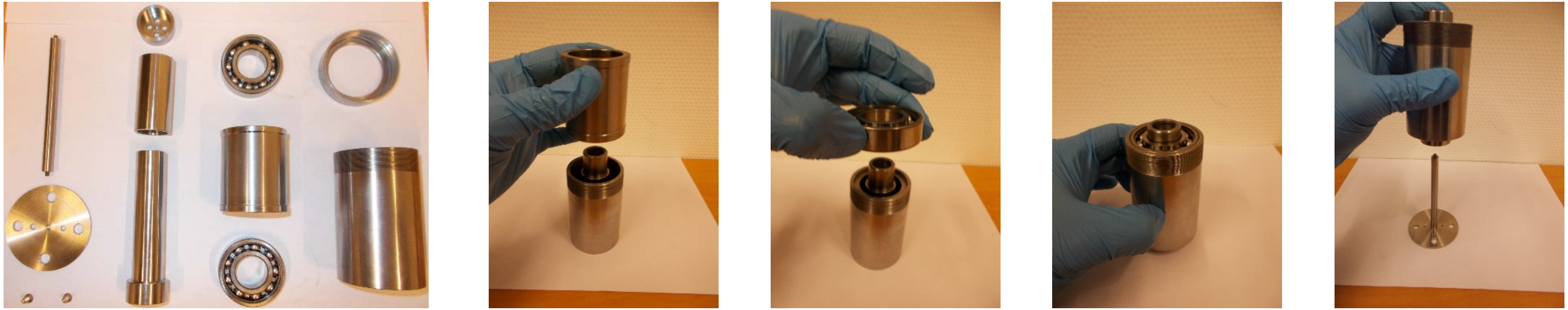


Fomulation	moles oxidizer	Oxidizer	moles metal	Metal	Fe	Cu	Mn	Ti	Cr	MgO	Al_2O_3	ΔH (kJ/mole reactants)	mass per mole reactants (g)	Δh (kJ/gram mixture)	grams metal per grams mixture	Δh (kJ/gram metal)
A	1	Fe_2O_3	2	Al	2						1	-850	213.7	-3.98	0.253	-15.7
B	1	Fe_2O_3	3	Mg	2					3		-979	232.6	-4.21	0.313	-13.4
C	3	CuO	2	Al		3					1	-1207	292.8	-4.12	0.184	-22.4
D	1	CuO	1	Mg		1				1		-446	103.9	-4.29	0.234	-18.3
E	1.5	MnO_2	2	Al			1.5				1	-882	184.4	-4.79	0.293	-16.3
F	1	MnO_2	2	Mg			1			2		-674	135.5	-4.98	0.359	-13.9
G	1.5	TiO_2	2	Al				1.5			1	-242	173.9	-1.39	0.311	-4.5
H	1	TiO_2	2	Mg				1		2		-247	128.5	-1.92	0.378	-5.1
I	1	Cr_2O_3	3	Mg					2	3		-655	224.9	-2.91	0.324	-9.0
J	1	Cr_2O_3	2	Al					2		1	-526	206.0	-2.55	0.262	-9.7
	REACTANTS				PRODUCTS											

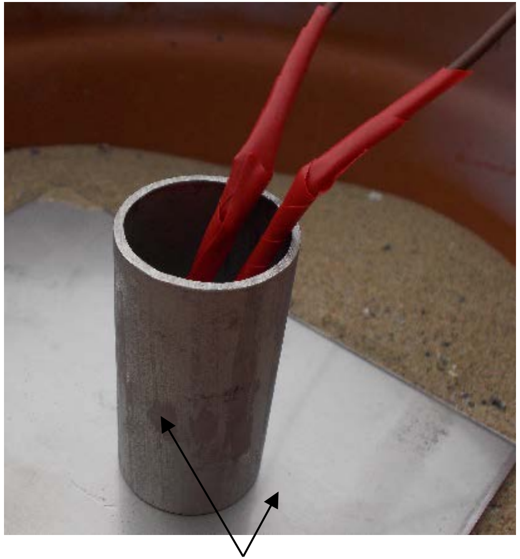
Proof of concept testing

- Internal ESA assessment in three phases
  - Pathfinder tests at ambient
  - Tests at temperature
  - Tests in plasma wind tunnel
- Test sample inspired by reaction wheel BBU
  - Tests limited to one thermite composition





Proof of concept testing



Stainless steel tube and plate
as representative for BBU

Technology development: Proposed TRP activity

- TRP activity for 2019 under preparation, pending approval
  - Detailed design and trade-off of fuse concepts to cover 200-650degC range
  - Verification of fuse concepts by test
  - Detailed design and optimisation of thermite usage
    - Trade-off and selection of thermite composition
    - Design guidelines on how to integrate into spacecraft equipment designs
  - Verification by test of demisability of one or more complete application (RW, SADM, etc.) including sequencing

Conclusion

- D4D often requires a combination of multiple demise techniques

Minimize Required Heat

- ➢ Minimize mass
- ➢ Replacing materials:
  - Cp
  - Tm
  - ε
- ➢ Smaller elements

Maximize Available Heat

- ➢ Ballistic coefficient

Exothermic reaction aided spacecraft demise

Optimize Heat Transfer

- ➢ Early break-up
  - Dedicated mechanism
  - Demisable attachment points
- ➢ Orifices, Lettuce structure
- ➢ Lower emissivity

Minimize Casualty Area

- ➢ Keeping re-entry fragments together

- One additional option available

Burning questions?

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- **Thermite material** is added to / integrated in (existing) spacecraft element designs, to provide additional energy to melt the materials or otherwise instigate demise.
  - The **thermite is integrated** as much as possible into the spacecraft element, in order to minimise the required additional metal to house the thermite which also needs to be demised and in order to maximise energy participating to heating the spacecraft element.
  - **Ignition** is provided **directly by the heat flux** or **indirectly by a fuse**, which itself is ignited by the heat flux
  - Ignition is (optionally) triggered via a dedicated **fuse.** A fuse allows the thermite material to be **inside the demising equipment**, rather than close to the surface. Direct exposure of the thermite to the heat flux is therefore not required.
  - Different fuse materials or compositions allow for the **sequencing and timing** of different ignition events. A fuse can either lower the ignition temperature or have the thermite inside the spacecraft element reach the ignition temperature sooner.
    - **Energetic** fuses creating heat for ignition of the thermite, vs **non-energetic** fuses, simply conducting heat generated by the flux into the thermite

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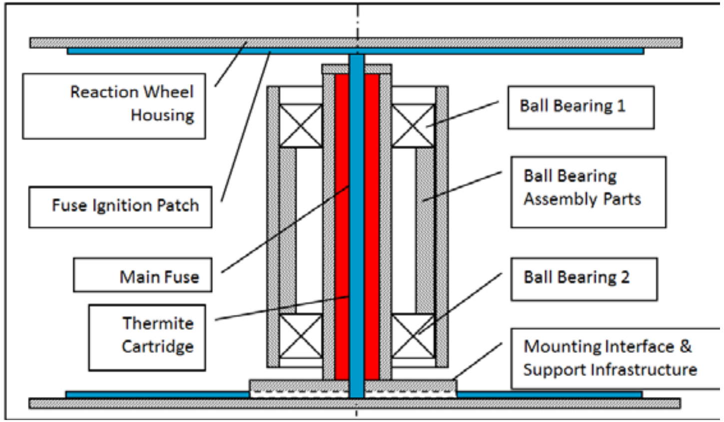
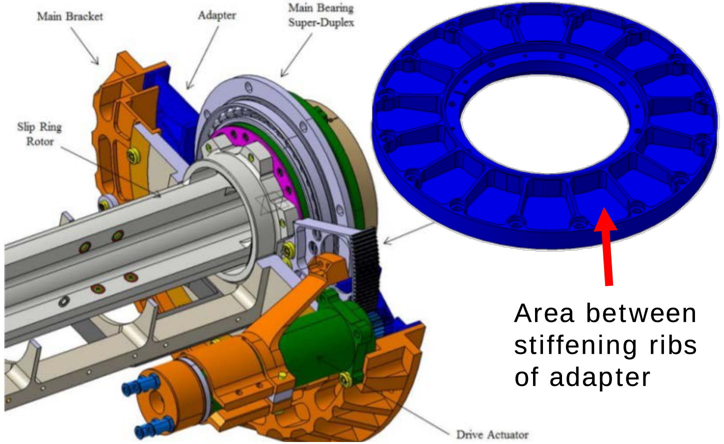
- Spacecraft equipment demise can be greatly hampered by the connection structure as it can (partially) shield the equipment from the heat flux and provide a heat sink. A **controlled and early separation** of the equipment is beneficial for its demise. Incorporating this functionality into the equipment instead of the structure makes more sense as the equipment is more likely to be recurring.
  - Thermite integrated in the spacecraft element at the interface with the connecting structure can **reliably and predictably separate the spacecraft element from its support structure** regardless of the structure design details
  - Equipment separation can be further facilitated using **annular thermite cartridges** as **harness and propulsion / heat pipe cutters**
  - For applications or locations where a fuse is not feasible, the **ignition temperature** has a limited capacity for **tailoring by changing the thermite particle size and shape**
- Tailoring particle size and shape is also important to **control the rate of energy release**
  - **Rate of energy release** needs to be **substantially higher than rate of radiative heat loss** in order to gain a significant temperature increase to reach the melting point of the material

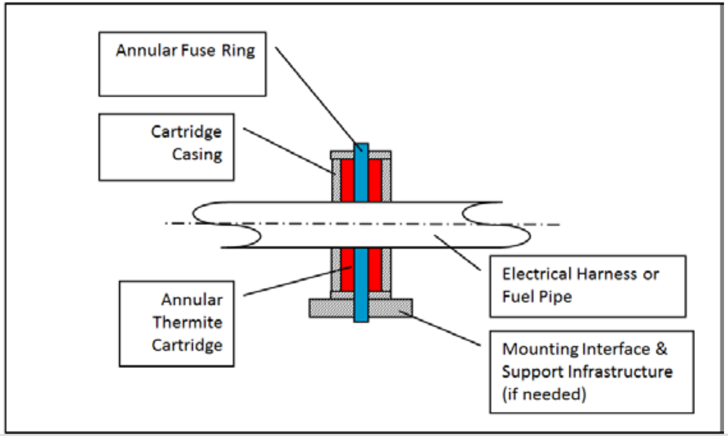
ESA Patent Pending – Design Concepts



Left: Thermite integrated in the centre of the ball bearing assembly. Control the release of heat and the gradual melting of the entire assembly propagating from inside to outside.

Right: SADM with multiple locations for thermite integration, e.g. rotor shaft, in between stiffening ribs of adapter, spacecraft I/F, etc.





Left: Annular thermite cartridge to cut any (non-structural) connection to the mechanism

Right: Thermite integrated in mechanism interface to enable mechanism separation