MAGNETOHYDRODYNAMIC ENHANCED ENTRY SYSTEM FOR SPACE TRANSPORTATION (MEESST) AS A KEY BUILDING BLOCK FOR LOW-COST INTERPLANETARY MISSIONS

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Aside from the launch environment, atmospheric re-entry imposes one of the most demanding environments which a spacecraft can experience. The combination of high spacecraft velocity and the presence of atmospheric particles leads to partially ionised gas forming around the vehicle, which significantly inhibits radio communications, and leads to the generation of high thermal loads on the spacecraft surface. Currently, the latter is solved using expensive, heavy, and often expendable thermal protection systems (TPS). The use of electromagnetic fields to exploit Magnetohydrodynamic (MHD) principles has long been considered as an attractive solution for this problem. By displacing the ionised gas away from the spacecraft, the thermal loads can be reduced, while also opening a magnetic window for radio waves, mitigating the blackout phenomenon. The application of this concept has to date not been possible due to the large magnetic fields required, which would necessitate the use of exceptionally massive and power-hungry copper coils. High Temperature Superconductors (HTS) have now reached industrial maturity. HTS coils can now offer the necessary low weight and compactness required for space applications. The MEESST consortium the has been awarded a grant from the EU Horizon 2020 programme for the development and demonstration of a novel HTS-based re-entry system based with its foundation on MHD principles. The project will first harmonize existing numerical codes, and then design, manufacture, and test a HTS magnet. The study shows that the use of MEESST technology can have a positive impact on the cost-effectiveness and available payload of interplanetary missions.

Keywords: MEESST, Reentry, Superconductors, HTS, MHD

1 INTRODUCTION

1.1 The re-entry problem

When a spacecraft re-enters the atmosphere at high velocities on Earth or elsewhere, the atmosphere is heavily compressed into a high-temperature, partially ionised state. The temperature in this environment exceeds the operational temperatures of materials commonly used in spacecraft structures like aluminium or fibre-reinforced plastics. Therefore, in order to protect the spacecraft and its structure, a TPS is necessary. Historically such TPS were and still are implemented through either ceramic or composite tiles as used on the Space Shuttle design, or through ablative heat shields as recently used on SpaceX's Dragon capsule programme.

ABBREVIATIONS

MEESST	Magnetohydrodynamic Enhanced Entry System for Space Transportation
TPS	Thermal Protection System
MHD	Magnetohydrodynamics
HTS	High Temperature Superconductor
LTS	Low Temperature Superconductor
CC	Coated Conductor

Both approaches come with very significant drawbacks in the form of design time and cost. Purely physical TPS designs

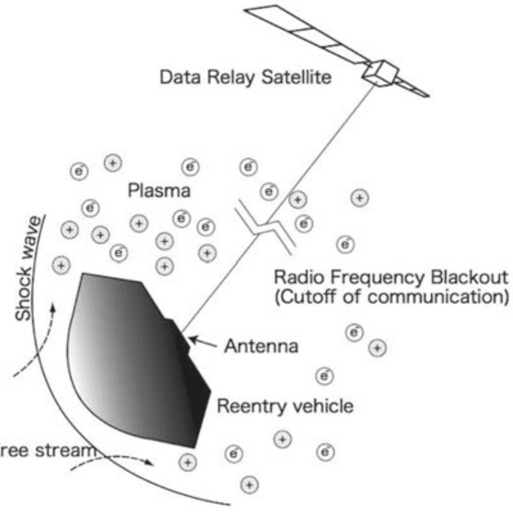

Fig.1 Illustration of re-entry conditions. [6]

lead to very heavy heat-shield structures due to the necessity of using large amounts of material to absorb or carry away thermal energy from the vehicle during re-entry. Especially for interplanetary missions, the launch mass of the spacecraft greatly impacts launcher requirements and therefore launch cost. Conventional TPS also must be tailored to each individual mission and therefore bring significant design and manufacturing overhead in terms of time and cost with them. Especially tiled TPS often require a very high number of unique custom parts, effectively further driving design and manufacturing costs up. Furthermore, currently used TPS technology does not address the issue of radio blackouts during re-entry. The environment during atmospheric re-entry inhibits incoming or outgoing radio signals and prevent direct communication with ground stations. Commonly this problem is circumvented through the use of separate satellite constellations. The materials used for heat shields are often extremely brittle resulting from use of very porous materials or ceramic composites, leading directly to low resistance to impact or other mechanical damage and leave the entire spacecraft vulnerable to even slight damage. This was demonstrated in the events of the STS-107 mission as a foam piece shattered a part of the Carbon-Carbon composite heat shield components and claimed the lives of all 7 astronauts on board [1]. Especially the aforementioned TPS of the Space Shuttle orbiters are often referred to as reusable, however even with such tile-based, reusable TPS, a significant part of the heat shield must be replaced after every flight, resulting in higher maintenance cost and long maintenance downtime between flights in case of a fully reusable vehicle. [2]

1.2 The MEESST project and consortium: A solution

The Magnetohydrodynamic Enhanced Entry System for Space Transportation (MEESST) project aims to provide a solution to the problems previously mentioned through applying principles of magnetohydrodynamics in order to influence the dynamics of plasma around the spacecraft and reduce thermal contact between the harsh re-entry environment and the surface materials of the vehicle. As part of the EU Horizon 2020 FET-OPEN programme, the MEESST consortium has been awarded a grant (grant no. 899298) to develop and demonstrate a re-entry shielding system based on MHD principles using High Temperature Superconductor (HTS) technology. This project will first harmonize existing numerical codes for re-entry simulations and corresponding plasma physics, and then produce a magnet using HTS technology and test it in testing facilities which simulate both the Earth's atmosphere and that of Mars. The project is comprised of a consortium of several institutions and entities in academia and industry, spanning many different fields of expertise. The Von Karman Institute of Fluid Dynamics is the consortium's leading entity for experimental studies relating to MEESST, especially for topics relating to radio blackout mitigation. The driving force behind the validation of numerical modelling tools and experimental studies of heat flux and radiation experiments on the MEESST project is the Institute of Space Systems (IRS) of the University of Stuttgart, an institution with great heritage and research output in the field of hypersonic re-entry systems and electric propulsion technology such as magnetoplasmadynamic thrusters (MPDT) which are based on similar mechanisms as leveraged by MEESST [3]. Both the Van Karman Institute of Fluid Dynamics, as well as the Institute of Space Systems bring the capability of replicating both Earth's and the Martian atmosphere, both primary targets for re-entry systems to operate in, in their plasma tunnels. The VKI offers plasmatron facilities with plasma generator powers of up to 1.2 MW, whereas the Institute of Space Systems fields several further plasma tunnels with plasma generator powers ranging from several hundred KW up to 6 MW. The facilities are capable of operating with air or CO_2 and with this can simulate re-entry conditions with atmospheres similar in composition to Earth's or Mars' atmospheres. [4] [5] The largest plasma tunnel facility of the VKI is shown in Figure 2: The VKI 1.2 MW plasmatron facility. The University of Southampton fields strong expertise in numerical simulations tools and is the main entity responsible for the development, extension, verification, and harmonisation of numerical tools. Both the University of Luxembourg, as well as AEDS SARL of Switzerland field strong expertise around numerical simulation of radio blackouts relating to the plasma wake and radiation around the spacecraft during re-entry. The University of Luxembourg is developing a ray-tracing algorithm for numerical radio blackout simulation [6] and verifies the consortium's results from numerical modelling of the radio blackout phenomena against experimental results. HTS-based magnet hardware is primarily designed and manufactured by Absolut System SAS, who are experts on cryogenic systems, in conjunction with the Karlsruhe Institute of Technology who also perform numerical simulations relating to the HTS magnet. THEVA Dünnschichttechnik GmbH provide state-of-the-art superconductor hardware for the project's HTS magnet and aid with the design of the magnet. The project is coordinated by the Catholic University Leuven (KU Leuven) while also bringing further numerical simulation capabilities, especially around thermal flux effects. NeutronStar Systems

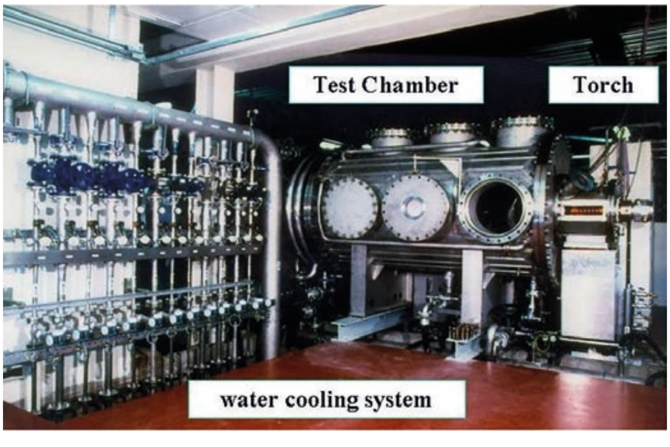

Fig.2 Illustration of re-entry conditions. [6]

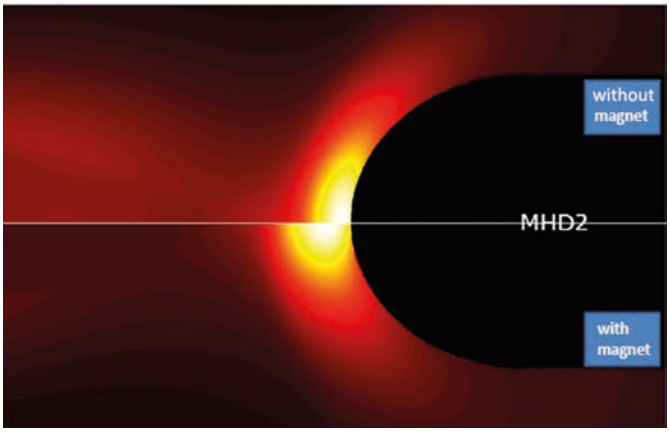

Fig.3 **Effect on bow shock location under the influence of a magnetic field. [16]**

UG is responsible for the dissemination and exploitation of the MEESST project outcomes.

2 PRINCIPLES OF OPERATION

The re-entry environment produces conditions that put extremely high thermal loads on the order of MW/m² on the spacecraft surface. At the highest speeds, the surrounding gas ionizes forming a plasma sheath which prevents radio signals from passing through, leading to communication blackout which can last for minutes.

MEESST reduces the thermal loads on spacecraft structure significantly by applying a strong magnetic field that interacts with the plasma generated by aerodynamic heating during re-entry. MEEST functions by introducing a magnetic field with a configuration as shown in Figure 4. The magnetic field influences the dynamics of the plasma on the outside of the spacecraft in such a way that the Lorentz force acting on the charged particles of the plasma is directed approximately opposite the flow direction. Due to the applied force, the distance between bow show and spacecraft surface is increased and the shock structure is modified. The bow shock is displaced further away from the surface of the spacecraft, keeping hot particles of the plasma further from the spacecraft surface as illustrated in Figure 3. This overall leads to lower thermal flux into the spacecraft material significantly and hence reduces the requirements put on the TPS drastically. The magnetic field needed to create sufficient impact is required to be very strong with field strengths on the order of several Tesla.

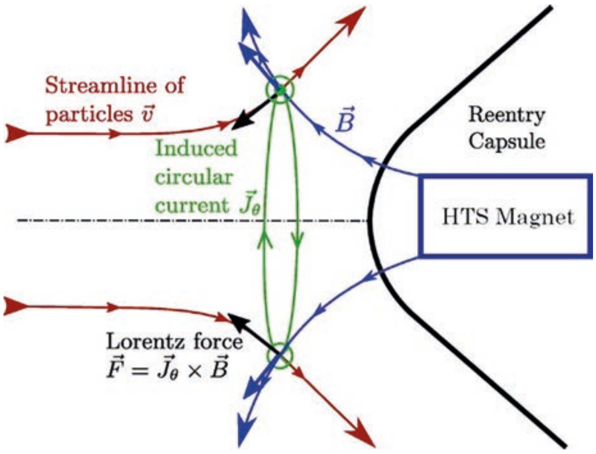

Fig.4 **Magnetic field configuration, adapted from [16]**

The plasma enveloping the vehicle during re-entry causes interference with radio waves, temporarily disabling communication with any mission control facilities. The plasma varies strongly in its refractive index over the plasma sheath around the spacecraft and as a result any radiation such as radio waves for the purpose of communication are refracted, causing a radio blackout. Thus far, this phenomenon is hard to predict. MEESST aims to mitigate this problem by developing novel, sophisticated numerical simulation techniques and through modification of the plasma flow around the spacecraft. An example of this can be found in Figure 5, where this type of technique was applied to the "Schiaparelli EDM" Mars landing craft which was deployed by the Trace Gas Orbiter (TGO) [6] (Figure 1). By applying a magnetic field and displacing the bow shock in front of the vehicle, a "magnetic window" is created allowing for radio signals to penetrate the sheath of plasma during re-entry and therefore enable communication during this critical phase. This is then taken advantage of by new ray-tracing-based techniques to model the propagation of radio waves through the plasma and allows for designs that take advantage of the properties of the magnetically modified plasma flow and implement radio communication even during re-entry conditions.

3 HIGH-TEMPERATURE SUPERCONDUCTORS AS AN ENABLING TECHNOLOGY

Construction of a magnet that can provide a magnetic field with the magnetic field strength on the order of several Tesla, necessary for effective operation within an MHD-enhanced re-entry system, with conventional conductor technology is only possible with exceedingly heavy designs that take up large volumes and draw extremely high power. Both a high mass and large volume requirements are extremely detrimental in spacecraft design and would worsen the mass and volume that magnetohydrodynamic enhancements to a re-entry system are intended to improve. High Temperature Superconductors offer the key to access all benefits without taking severe mass and volume, and hence also launch and development, cost penalties. Superconductors provide very high current densities that allow the development of compact and light electromagnets that can be operated on spacecraft to generate a magnetic field with the necessary field strength.

3.1 A brief history of superconductors

In 1911 the Dutch physicist Heike Kamerlingh Onnes discovered superconductivity by cooling mercury metal to extremely low temperature with the help of liquified helium and observing that the metal exhibited zero resistance to electric current. Onnes was awarded the Nobel prize two years later for his discovery. Prior to 1973 many other metals and metal alloys were found to be superconductors at temperatures below 23 K. These became known as Low Temperature Superconductor (LTS) materials. Since the 1960s a Niobium-Titanium (Ni-Ti) alloy has been the material of choice for commercial superconducting magnets. More recently, a brittle Niobium-Tin intermetallic material has emerged as an excellent alternative to achieve even higher magnetic field strength. J. G. Bednorz and K. A. Müller were later awarded the 1986 Nobel prize for their discovery of oxide based ceramic materials that demonstrated superconducting properties as high as 35 K. This was quickly followed in early 1997 by the announcement by C. W. Chu of the cuprate superconductor $YBa_2Cu_3O_7$-d (YBCO) functioning

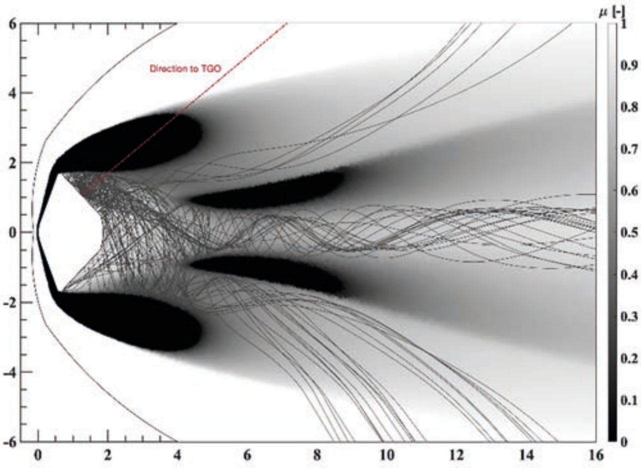

Fig.5 An example of radio blackout analysis using a ray-tracing-based method on the case of the ExoMars Lander capsule. Note the contrast of different refractive indices within the plasma, guiding the radio waves. [6]

above 77 K, the boiling point of liquid nitrogen. This discovery made superconductors far more suitable for wider use in industry since they can now be operated by using liquid nitrogen as cooling medium, a readily available fluid that is already widespread in several industries. [7] [8]

Since then, extensive research worldwide has uncovered many more oxide-based superconductors with potential manufacturability benefits and critical temperatures as high as 135 K. A superconducting material with a critical temperature above 23 K today is known as a High Temperature Superconductor (HTS), despite the continuing need for cryogenic refrigeration for any application [9]. Since the development of YBCO in 1987, the development of long flexible wires with thin layers of cuprate-based superconductors called coated conductors (CC) has been a triumph of scientific insight, sophisticated processing and determined scale-up efforts. These CCs are promising for superconducting magnet applications because of their high critical current density with a low dependency on the external magnetic field, good mechanical properties and reasonable cost, which offer opportunities to develop ultra-high-field magnets. [10] Today, CCs are produced by means of a technologically advanced and standardised process which exploits a scalable technique known as Electron Beam Physical Vapour Deposition to produce a multi-layer tape. These tapes are manufactured using the base of 0.05 mm thin nickel-chrome alloy substrate. Two magnesium oxide buffer layers act as a diffusion barrier and provide a suitable crystalline oriented surface for the HTS material deposited on top. Finally, a very thin silver contact layer and a copper layer are applied as coating of the superconductor. This architecture is summarized and illustrated in Figure 6.

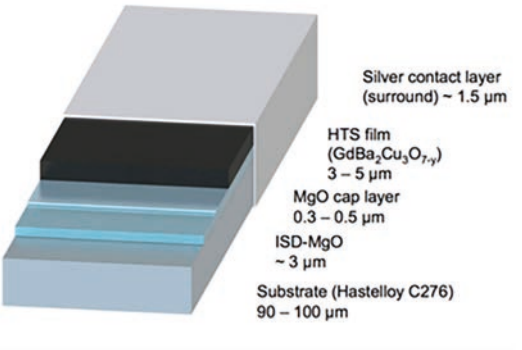

Fig.6 Coated Conductor architecture by THEVA Dünnschichttechnik GmbH.

3.2 Industrial Maturity of Type 2G Superconductors

This technology offers advantages such as high evaporation rates, low substrate temperature, flexibility on selecting evaporation materials and a high performance due to quality consistence along the length of the tape. These wires are known as second generation, or "Type 2G" wires, as they offer improved mechanical properties and improved performance in magnetic fields compared to their predecessors. The most common type 2G HTS today are Rare Earth Barium Copper Oxide (REBCO) compounds such as Gadolinium or Samarium compounds. [11]

The HTS industry has leveraged these advances in production techniques to achieve economies of scale, with a worldwide production capacity of 1,000 km/yr of HTS tape. THEVA Dünnschichttechnik GmbH, based in Bavaria, Germany, provides an annual production capacity of type 2G superconductor tape of 120 km/year through their leading production facilities in Europe. With companies already achieving high throughput, low material costs, and a high yield, type 2G superconductors have reached industry maturity. With further increases in HTS demand expected, the production costs are expected to further decrease, enabling access in more markets.

4 CONCLUSIONS

The MEESST project could address and solve many of the downfalls of currently used ablative and semi-reusable re-entry systems. The technology being developed within the project can significantly decrease weight and volume requirements of current thermal protection systems through influencing the plasma formed around the spacecraft during atmospheric re-entry. Compared to conventional TPS that comprises up to around 30% of the total spacecraft mass as in the case of the NASA InSight Lander [12], MEESST can provide a much lighter, more compact, and more cost-effective method of protecting the spacecraft from the harsh re-entry environment condition, while also being easier and faster to design. Especially on interplanetary missions where increased vehicle mass leads to stark increases in launch vehicle requirements and launch costs, this could be a great benefit. Lower mission costs in turn allow for a greater degree of mission throughput with any agency or commercial entity that exploits the benefits of MEESST.

Due to less reliance on physical TPS on the outside of the spacecraft, the risk associated with mechanical impacts or other mechanical damage to the outside of the TPS is also decreased, a very important consideration especially for human-rated spaceflight applications as are planned for the next decades by several space agencies and even commercial entities. MEESST achieves this by leveraging MHD to reduce heat flux by a large margin, with up 30% lower heat flux being experimentally achieved previously in a test using an Argon atmosphere at the Institute of Space Systems (IRS) [13]. This is set to be further experimentally examined with more accurate representations of the conditions in the atmospheres of both Earth and Mars within the MEESST project through experimental capabilities of the VKI and the IRS.

Furthermore, MEESST technology addresses the issues of

Fig.7 **A Mars Transfer Vehicle of the Mars Design Reference Mission 5.0 concept study of NASA. [18]**

radio communication blackouts by greatly improving capabilities in numerical modelling of the radio blackout phenomenon via novel ray tracing methods, allowing for designs to exploit the flow around the vehicle and mitigate radio blackouts during atmospheric re-entry. This allows for possibility of intervention and active control of the spacecraft from mission control during the critical phase of atmospheric re-entry, particularly when entering Earth's atmosphere. The modelling efforts for predicting/mitigating radio blackout, complemented with corresponding modelling tools and ground tests, will potentially also be beneficial to applications such as radar imaging, surveillance, and GPS navigation, all requiring accurate knowledge of EM signal propagation characteristics through plasmas in the ionosphere.

MEESST makes a shift towards more truly reusable and far more cost-efficient re-entry systems possible. The project is currently far into the preliminary research and design phase and will conclude in September of 2023. This interdisciplinary project will set a first step to establish a new technology involving plasma, chemistry, electromagnetics, radiation, superconducting materials, and cryogenic systems and will therefore potentially impact several academic communities in science and engineering. MEESST disruptiveness lies in developing new generation lightweight magnets for space applications and in the overall interdisciplinary research approach. With it, MEESST signifies a multiplicator as space systems other than entry-related systems will positively benefit from its outcomes, including radiation protection for manned space flight (fundamental for future Mars missions and spacecraft such as Mars Transfer Vehicle concepts as shown in Figure 7), advanced MHD-based propulsion systems like M2P2 [14], electric propulsion with MPD thrusters and any other device making use of applied magnetic fields. In the field of electric propulsion specifically, the SUPREME project aims to integrate HTS electromagnet technology with existing applied-field magnetoplasmadynamic thruster (AF-MPDT) technology such as the SX3 thruster of the IRS as pictured in Figure 8. [15] MEESST represents the development of new impactful technology that is applicable not only to re-entry systems, but to many fields and systems in spaceflight and beyond.

Fig.8 **The SX3 AF-MPDT thruster of the IRS within its large applied-field coil. [19]**

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