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1. Introduction and Study objective

With the above mentioned contract ESA initiated a first look into a potential alternative Thermal Protection System (TPS) for reusable space vehicles that is based on electromagnetic interaction rather than advanced materials. This new approach assumes that it is possible to reduce the heat transfer on a space vehicle by utilizing the interaction of a magnetic, electric and/ or electromagnetic field with an ionized hypersonic flow. Although first explorations of such interaction phenomena have started already in the late 50th and early 60th no heat transfer measurement has been reported in a way, which can be accessed by the public. From time to time the topic reappeared in individual papers that covered mainly Drag measurements but these papers were apparently not part of a broader coordinated effort.

At the beginning of the 90's this concept was independently rediscovered by several space faring nations and the field of research has gained significant momentum through the 90's. By the end of the decade publications became more abundant in the relevant aerospace journals.

2. Study approach

The study was conducted by executing 3 work packages

- WP 10 Review of State-of-the-Art
  Entering this field of research would symbolize a significant change in the TPS approach and requires therefore a sound overview on the status of the international community by means of a literature survey. By employing this methodology WP 10 will help ESA to avoid potential double spending on already accepted facts.

- WP 20 Mission Analysis
  This effort will focus on the applicability of the concept of an Electrodynamic Heatshield during typical reentry missions. It is the objective of this WP to make an assessment of the ionization level, i.e. electron number density for relevant reentry profiles of past spacecraft missions. This will be done by using available data or engineering judgement. The calculations are expected to yield correct and meaningful order of magnitude results.

- WP 30 Preliminary assessment of a CFD/CEM synthesis
  The objective is the definition and evaluation of a model which describes the influence of an electromagnetic field on fast moving ionized particles (plasma). There should be worked out suitable approximations for the theoretical background and the model in order to describe the effectiveness of an electrodynamic heat shield for the reduction of the surface temperature of a re-entry structure.

3. Summary of key results

3.1 General

A general qualitative consensus exists within the scientific community that the application of magnetohydrodynamics will result in a reduction of heat loads.

Literature, which is available is not free of deficiencies with regard to the physical model, which was implemented. This is especially true with regard to non-equilibrium effects, electrical conductivity assumptions

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etc. This appears to be of no surprise since most people come from the field of classical CFD and they are therefore mainly familiar with the classical gasdynamic phenomena. Plasma phenomena on the other hand are highly complex when external fields are involved. Therefore the results of the presenters are fluctuating within a certain bandwith. The general tendency of predictions indicates however that a reduction of the heat load in the order of several 10% appears to be feasible.

It has become obvious that numerous groups are working on the application of magnetohydrodynamics in the field of aerospace. One focal point of their work is related to the assessment of the super- and hypersonic flight regime (up to Mach 12) within the frame of the AJAX concept. While AJAX is a Russian concept it should be noted that even the USAF (One of the key players behind the effort to utilize magnetohydrodynamic interaction in aerospace applications) is analyzing it.

3.2 Scientific/Technical aspects

In the following a few key points shall be addressed without the intention of going into to much detail since the details must remain part of the study of the documents EDH-SI-TN-0001 - EDH-SI-TN-0001. The arising questions need to be discussed within the interested scientific community.

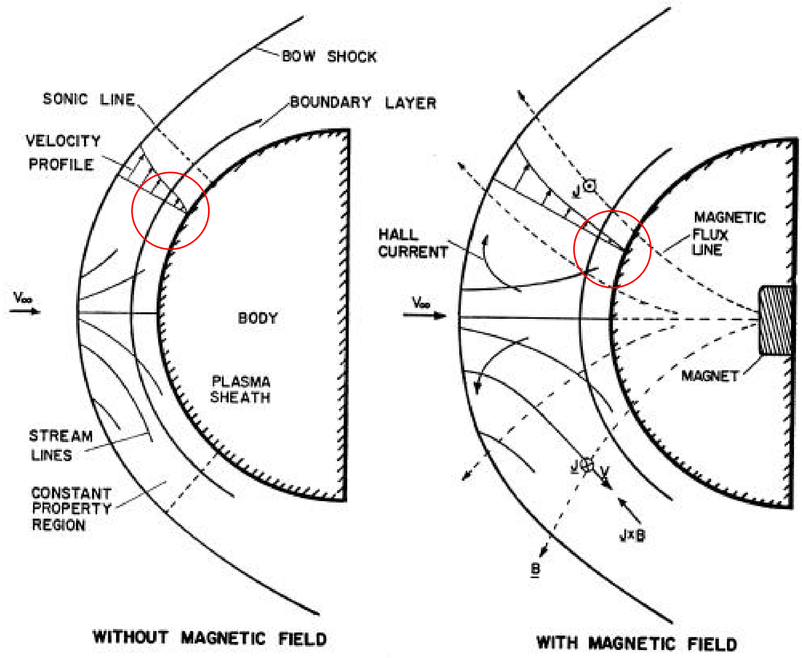

Figure 3.2-1: Schematics of a gasdynamic and magnetohydrodynamic flow field

Under magnetic field conditions the heat transfer based on the velocity gradient will be reduced. The increased total drag on the other hand promises a stronger deceleration in the upper atmosphere (similar to IRDT) with a corresponding reduction in heat transfer, based on the - V^3 $\rho^{0.5}$ - relation (V=Velocity, ρ=Density).

Taking the previous statements into account it is evident that a full characterization of such a potential TPS system can not be done in wind tunnel facilities. This is simply due to the fact, that it is impossible to realize all flow conditions at the same time.

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Additionally it should be noted that the switching on of a magnetic field can have side effects that are not yet considered in the numerical analysis and which are not easy to assess with regard to their relevance for a real flight system.

In summary the following numbers of up to date documents on the topic have been found

- Experimental publications on Magnetohydrodynamics: 5
- Theoretical publications on Magnetohydrodynamics: 4
- Experimental and Theoretical publications on Electrohydrodynamics: 4

(Note that referenc es in these documents are abundant and are therefore not listed)

3.3 Mission aspects

It is known from the results of WP 10 that the so called magnetic interaction parameter

$$S = \frac{s \; B^2 R_N}{r_\infty V_\infty} \qquad \text{(Eq. 1)}$$

with

$s = Electrical\ conductivity\ of\ the\ shock\ layer\ [S/m]$

$B = Magnetic\ induction\ [T]$

$R_N = Nose\ radius\ of\ the\ reentry\ vehicle\ [m]$

$r_\infty = Free\ stream\ gas\ density\ [kg/m^3]$

$V_\infty = Free\ stream\ velocity\ [m/s]$

is the critical parameter by which the

- **Heat transfer**
- **Stand off Distance**
- **Drag**
- **Velocity Gradient**

are scaled.

For the calculation of S along the flight trajectory it is therefore necessary to have two sets of information/inputs, as can be seen by Equation (1). The first set of information is of technical nature and is comprised of the

- **Magnetic Induction B at the vehicle surface and**

- **the nose radius of the vehicle.**

The second set of input is the physical state of the environment to which the vehicle is exposed during the reentry, namely

- **Electrical conductivity of the shock layer, which is a function of the electron number density and the collision frequency**

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- **Free stream gas density**
- **Free stream velocity**

For the mission analysis three trajectory cases were considered:
1. Shuttle Trajectory
2. BOR 4 Trajectory (Russian Lifting Body similar to the X-38)
3. RAM-C (Ballistic Capsule)

Under the assumption of a magnetic field strength of 1 Tesla at the stagnation point the following S-Parameter distribution has been found along the three trajectories.

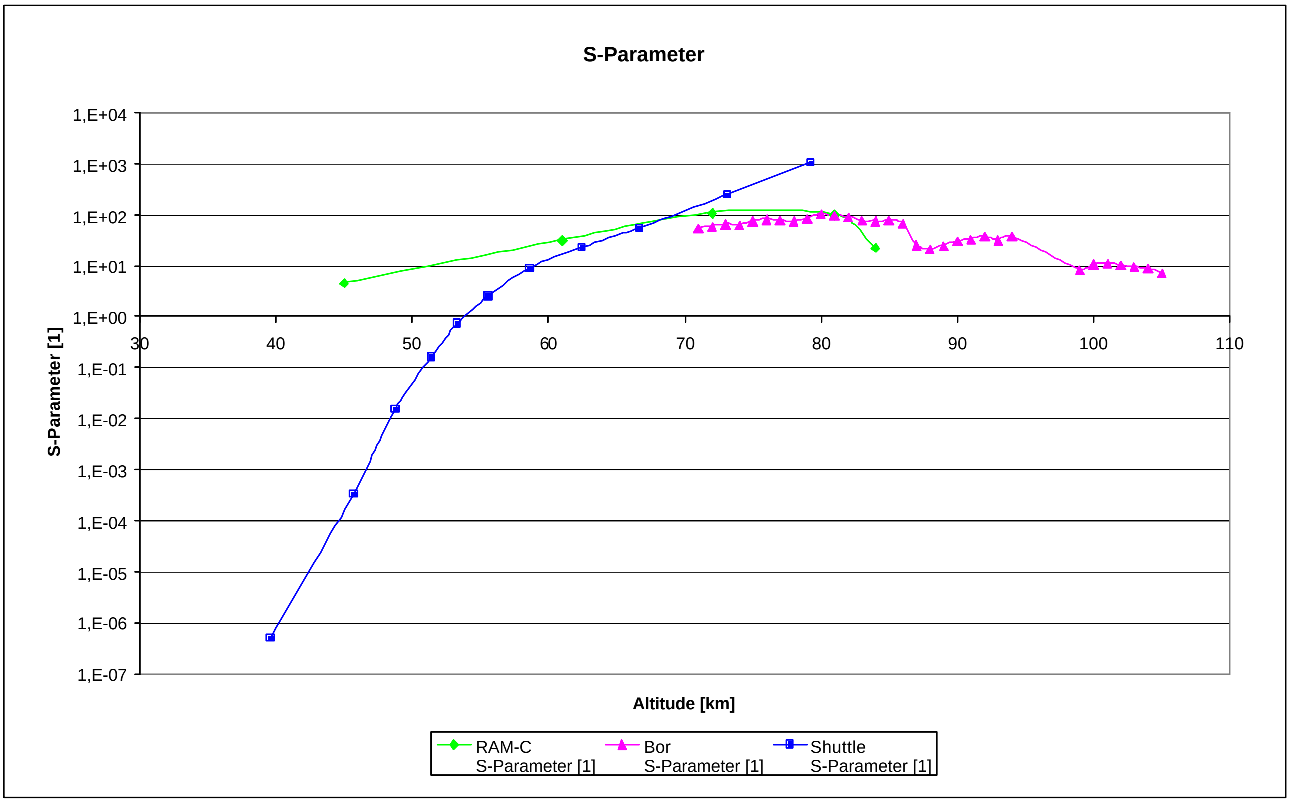

Figure 3.3-1: Comparison of the magnetic interaction parameter S for RAM-C, BOR and the Shuttle

The calculated S in figure 1 can now be assessed with available theoretical predictions to determine the potential reduction in heat transfer. The following table comprises the main features for all vehicles

Altitude Range	S Parameter Range	Heat transfer Reduction
100 km - 60 km	10 - 100	20% -70%

Obviously the above figures look very promising but from the authors point of view they are almost to good to be true. Nothing in nature comes free of charge as one can learn from Heisenbergs "Uncertainty Principle". At the moment these findings will remain therefore uncommented to allow everyone to judge the results by himself.

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3.4 Preliminary numerical assessment

Without modification of the programme code, the existing computational fluid dynamic (CFD) and computational electromagnetic (CEM) tools allow the following operations:

A. Optional generation of magnetic field characteristics in consideration of dielectrics in the magnetic field by methods of integral calculus/Method of Moments (MoM) in the range of time and frequency,
B. Mathematical solution methods, among others of coupled systems of higher order differential equations in order to connect the velocity fields of ionised particles with magnetic field characteristics,
C. Navier-Stokes solver for the calculation of the velocity field, as well as pressure and heat distributions on condition that the medium can be considered as a continuum.

The enlargement of both the CEM tools and the CFD tools was examined.

3.4.1 Identified CEM and CFD issues

3.4.1.1 CEM approach

At present, the existing codes allow a “distributed computing” between the CEM and CFD tools., This means that the fluid-dynamic and electromagnetic effects are simulated separately by the specific CFD/CEM tools, i.e. the direct integration of magnetohydrodynamic equations into the CEM tools is not possible within the cost and time constrains.

Additionally several physical assumptions would be required, which would not yield much insight into the physical/engineering objective but only into the programming constrains. The potential advantages of the CEM tool and Know How can therefore not be exploited as it was originally anticipated.

3.4.1.2 CFD approach

Based on the CEM findings Mr. Weiland made an assessment with regard to the necessary CFD efforts for Astrium's DAVIS-VOL code. This code represents a major building block of past European reentry activities and would therefore be a natural candidate for the integration of magnetohydrodynamic components.

His key results are:

1. Major programming efforts are necessary to modify the code in such a way that it could perform the required WP 30 numerical tasks.
2. The modifications are outside of the financial and schedule constrains of the present study
3. A consistent formulation of the magnetohydrodynamic supplement for the existing code is presented and can be implemented into DAVIS-VOL

From the above it became clear that the present DAVIS-VOL code could not be used to generate the sample case calculations without major code programming activities, which as stated above is outside of the scope of the present study.

This result felt very much short of the expectation of the author of this TN and would also represent a major noncompliance with the agreed content of WP 30. The author has therefore activated other resources that are available to him to get a better insight into the potential applicability of an Electrodynamic Heatshield.

3.4.2 Numerical results

After the conclusion of WP 20 ESTEC (represented by Mr. Giordano) and Astrium (represented by Mr. Konigorski) have jointly discussed and defined the boundary conditions of the sample case to be calculated.

The selected parameters represent the environment at 65 km altitude along the Space Shuttle trajectory.

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In this context it appears appropriate to emphasize again that the objective of these calculations is a first qualitative assessment of numerical CFD analysis, which includes MHD components. Quantitative results indicate trends only. They are not meant to be ultimate answers.

Two approaches were examined:

a) Semi-empirical, i.e. conductivity results from WP 20 were introduce as boundary condition. The constant conductivity assumption in the shock layer was modified with the additional assumption of a temperature dependence of the conductivity

b) Numerical, i.e. no a priori assumptions. Results are entirely based on the specified boundary conditions

3.4.2.1 Semi-empirical key result

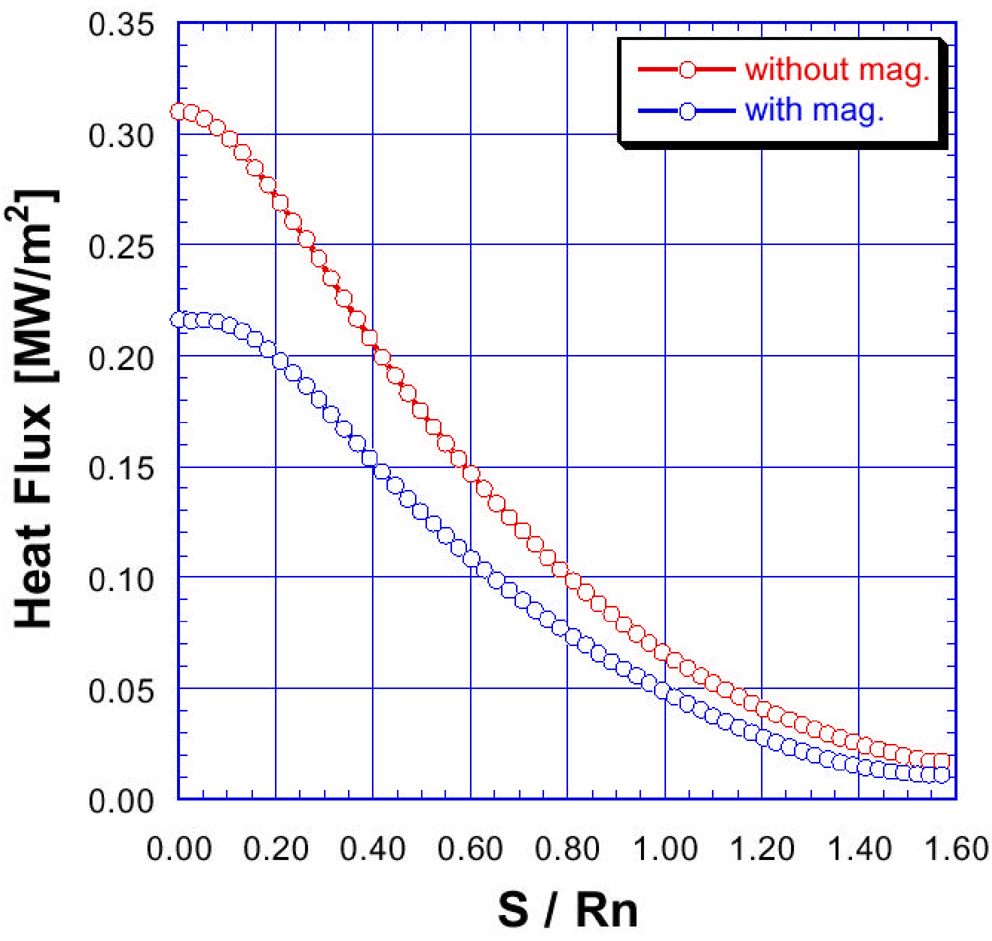

Figure 3.4-1: Heat flux comparison of the semi-empirical case

The heat flux towards the vehicle surface is indeed reduced in the magnetohydrdynamic case.

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3.4.2.2 Numerical key result

With the exception of the electron number density determination, which determines the conductivity in the shock layer the numerical approach is identical with the calculation scheme for the semi-empirical approach

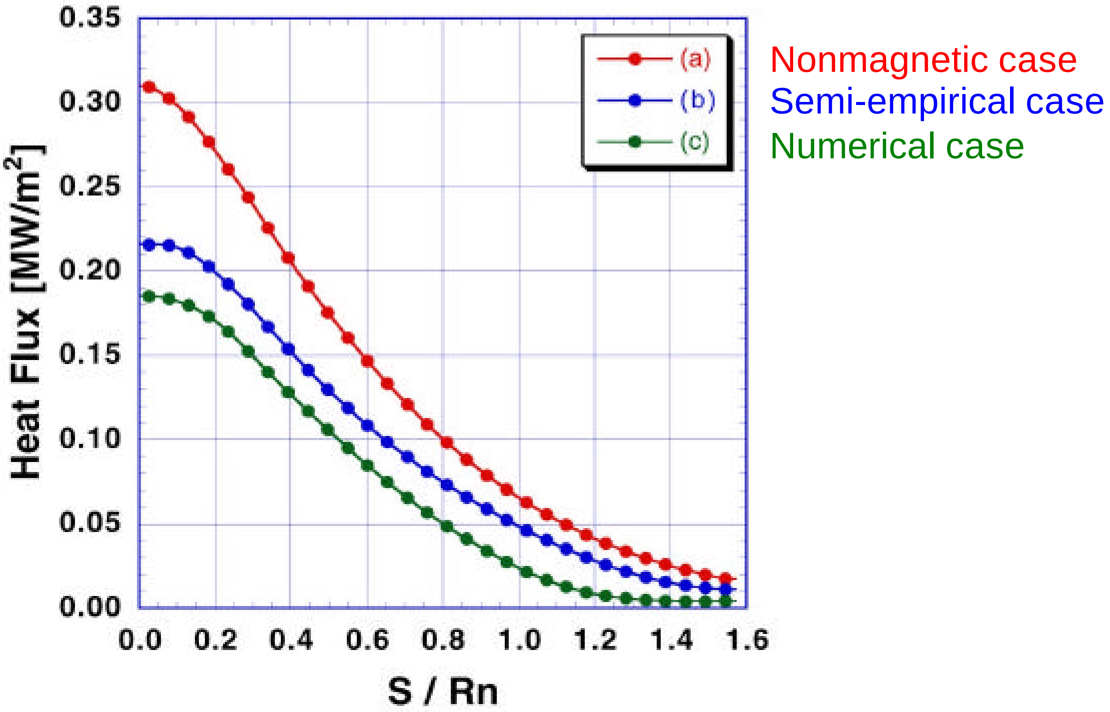

Figure 3.4-2: Heat flux comparison of all cases

The entirely numerical case confirms the heat flux reduction that was found in the semi-empirical case. That the reduction in the numerical case is larger than in the semi-empirical case is simply due to the fact that the predicted conductivity in the numerical case is larger than in the semi-empirical case. The reason for this difference lies in the different approaches to estimate the collision frequency in the plasma and was expected.

4. Conclusion

From the content of the numerical analysis section the following conclusions appear to be appropriate

- Electron number densities derived in WP 20 are in good agreement with the numerical calculations.
- Differences between WP 20 and WP 30 w.r.t. the conductivity are due to the collision frequency approximation used in WP 20 and were expected.
- Numerical analysis indicates the potential usefulness of an Electrodynamic Heatshield from qualitative point of view
- Assumptions were based on available data and knowledge. However the physical model is still incomplete. (See D. Giordano's paper Ref.2 for a detailed summary with regard to what physical parameters might be needed to improve the existing codes)

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- Application/Match of theory and real flight environment remains an open question ==> **flight data are needed to develop the technology and analytical tools**

- Trajectory effects due to wave drag (virtual IRDT) are not considered in this analysis

At the end of this study it should be realized that an Electrodynamic Heatshield appears to be a highly attractive option to improve thermal protection systems either to reduce the life cycle cost for RLV's or to overcome the technological stagnation in the field of conventional thermal protection systems. A lot of work remains to be done especially with regard to the flight data but from the authors point of view the rewards from this type of technology exceed the necessary financial engagement by far. The programmatic advantages from the authors point of view can be summarized as follows

- The technological advancement for magnetic field generators/materials is driven by the economic needs of the electro-technical and other industries. This ensures that a significant amount of R&D budget will be available that does not burden the R&D budget of the space community.
- Due to the fierce competition in the electro-technical market a price decay for magnetic equipment is guaranteed. Astrium has received an economic assessment from Siemens that is based on their regular business experience, which indicate that the cost for a magnetic coil with specified performance would **drop by** as much as **95%** over a period of 3 years.
- The Electrodynamic Heatshield is a knowledge based system that does not require any kind of investment into manufacturing infrastructure since it can be manufactured by non-space industries according to the specifications issued by the space industry. This fact will be fully appreciated immediately if one takes into account that the earliest date when a European RLV would require conventional thermal protection material is 2015 or later. Until that date financial subsidies must be spend out of the space budget for keeping the "space only" manufacturing infrastructure including staff operational, without receiving any return on investment.
- The generation of the Know How in this technology field is already a strategic barter item for Europe that could be of significant importance when dealing with technology export restrictions of Non-European nations. That this is an issue to be considered is evident from the resonance that Astrium's appearance on relevant conferences has generated.

The results generated in the study are very promising with regard to the applicability of such a technical concept. This is especially true if one takes into account that at the moment there is no other competitive concept available, which could reduce the heat flux by a similar order of magnitude.

Although no show stopper can be identified at the moment it remains necessary to look at the concept with a neutral bias to avoid too much enthusiasm, which could result in missing potential traps.

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