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Review Article

Survey of European and Major ISC Facilities for Supporting Mars and Sample Return Mission Aerothermodynamics and Tests Required for Thermal Protection System and Dynamic Stability

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In the frame of future sample return missions to Mars, asteroids, and comets, investigated by the European Space Agency, a review of the actual aerodynamics and aerothermodynamics capabilities in Europe for Mars entry of large vehicles and high-speed Earth reentry of sample return capsule has been undertaken. Additionally, capabilities in Canada and Australia for the assessment of dynamic stability, as well as major facilities for hypersonic flows available in ISC, have been included. This paper provides an overview of European current capabilities for aerothermodynamics and testing of thermal protection systems. This assessment has allowed the identification of the needs in new facilities or upgrade of existing ground tests for covering experimentally Mars entries and Earth high-speed reentries as far as aerodynamics, aerothermodynamics, and thermal protection system testing are concerned.

1. Introduction

Some of the future missions, investigated by the European Space Agency in the frame of the Exploration [1] and Science Programmes, focus on sample return missions to Mars, asteroids, and comets. The main challenges of these missions are the Mars entry of large vehicles, the high-speed Earth reentry of return capsules, and the dynamic stability of blunt bodies during entry and descent.

Several issues are related to Mars entry of large vehicles. The nominal composition of Mars and Earth atmospheres retained for the study is listed in Table 1. First, since Mars atmosphere is mostly composed of carbon dioxide, the facilities have to be capable of operating with this gas and of reproducing flight conditions typical of a Martian entry, in terms of heat flux and pressure. Then, the ground tests have to be able to simulate the turbulence flow conditions occurring during entry, induced by the vehicle, by the possible presence of steps over the heat-shield, and strongly coupled with heat shield ablation. A peculiar point of sample return missions to Mars is the Mars ascent. For covering this aspect of the mission, the utilization of ground test facilities capable of reproducing Mars ascent trajectory conditions, and Mars initial conditions for engine ignition are required.

High-speed Earth reentries, like those performed by NASA for Genesis [2] and Stardust [3, 4] missions and the one performed by NASDA for Hayabusa [5], are characterized by high heat fluxes [6] as shown in Figure 1 for different entry trajectories (E1 to E4) corresponding to different initial entry conditions in terms of flight path angle and velocity.

Another point concerning entries of space probes is the ground capabilities for reproducing flow conditions as function of Reynolds number, as well as the capabilities to simulate flow phenomena such as dissociation and ionisation. Related to nonequilibrium thermochemistry, chemical kinetics is also an issue, particularly for the high-speed Earth reentry. To summarize, of particular relevance are the following processes.

(i) Simulation of turbulence in hot compressible gas.

(ii) Simulation of reentry flows in radiation environment.

(iii) Thermochemical kinetics.

(iv) Ablation and ionisation.

(vi) Simulation of the influence of dust on flow properties.

A common point to Mars and Earth entries is the stability of the capsule which has to be ensured for hypersonic, supersonic, and subsonic regimes. For Mars entry, the dynamic stability has to be kept until the parachute deployment, for the Earth return capsule; due to the capsule size, the use of a parachute would be a penalty in term of mass budget and perhaps reliability. As a consequence, the experimental facilities allowing the investigation of stability and more particularly of dynamic stability have been included in this paper.

While various studies have previously reviewed the availability and adequacy of ground testing facilities and instrumentations for Earth orbital entry simulations, to our knowledge there was no exhaustive study on the same topic for planetary or sample return missions, with a systematic review of their adequacy for Mars ascent/descent and Earth high-speed entry. In the past, IABG [7] has performed a review on TPS qualification and thermomechanical testing but this paper essentially focused on mechanical testing and did not cover in details aerodynamic aspects, particularly if a superorbital entry is considered. Moreover, the survey presented was not complete since major companies had declined to provide information. ONERA [8] dedicated an effort focused on aerothermodynamics which is an excellent and complete review, but did not provide precise data on achievable performance of most of the facilities. Additionally, this paper essentially focused on suborbital entry. Lu and Marren [9] have gathered a collection of papers from some of the major facilities illustrating some of their operational aspects, but that does not allow establishing their readiness and adequacy for sample return missions.

Here, the paper mostly focused on the main experimental capabilities in Europe [10]. The main facilities available in the ISC (Independent State Community) and Australia (since Australian scientists are involved in ESA research programmes), as well as the ballistic ranges in Australia and Canada (since Canada is an ESA associated member state) for the assessment of dynamic stability have been also incorporated. From the inputs gathered in the literature, on the different websites, during a dedicated Workshop on Facilities held at ESTEC on 28 March 2008, those provided by the different experimentalist teams, the main characteristics of the different ground tests have been obtained. The analysis of the different aspects retained for the paper with the actual capabilities and the potential needs for additional capabilities for ensuring the success of sample return missions are reported hereafter.

2. Mars Entry

Mars atmosphere is mostly composed of carbon dioxide which has thermodynamic properties different from oxygen and nitrogen. From an experimental point of view, the main challenge for Mars entry is the presence of a CO_2 atmosphere. Most of the existing facilities in Europe have been developed for testing in air atmosphere, and their adaptation to CO_2 is not straightforward. In fact, the usual performance envelope is different, and the presence of large fraction of CO for medium range enthalpy has to be considered [11]. As a consequence, test facilities have to be capable of operating with carbon dioxide and of reproducing flight conditions typical of Martian entry and ascent. The main features for investigating experimentally a Martian entry are listed below.

Table 1: Mars and Earth atmosphere compositions.

Species	Mars (%)	Earth (%)
CO_2	95.3	0.03
N_2	2.7	78.1
Ar	1.6	0.93
O_2	0.13	20.9
CO	0.07	0.000007
H_2O	0.03	0.1

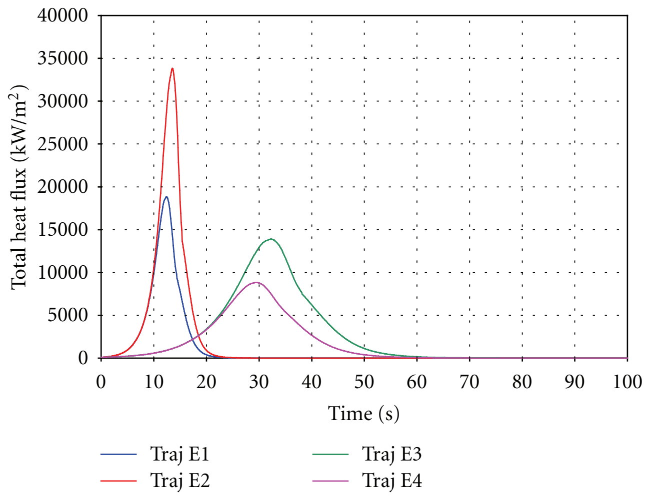

Figure 1: Total heat flux versus time for different entry trajectories during EVD mission [6].

(i) Capabilities of existing facilities to operate with Mars atmospheric conditions (95% of CO_2) and to cover a Mars entry trajectory in terms of heat flux and pressure.

(ii) Simulation of fully turbulent flows in high-enthalpy facilities for Martian entry of large vehicles.

(iii) Capabilities of existing facilities to operate with CO_2 flows in presence of particles for hydroerosion and heat-flux assessment.

(iv) Available measurements techniques for Mars atmosphere.

In the frame of the Mars Premier Programme [12] and the recent ESA TRP [13] (Technology and Research Programme) on CO_2, testing activities have been carried at ONERA, EADS, IRS, MIPT, DLR [14], and VKI for CO_2 environments. Earlier studies were also conducted at IUSTI, CORIA, IPM, DLR (in HEG), and PROMES. The results have demonstrated the capabilities of some of the aerothermodynamics facilities to operate with a Martian atmosphere. However, the tests have highlighted some problems. For example, in arc-driven facilities, the use of a gas different from air has a strong impact on the arc chamber and notably on the arc performance which is notably reduced: at least 30% for CO_2 when comparing against air. The carbon dioxide molecules start to be dissociated inside the arc chamber with some consequences on the nozzle flow.

The aim of ESA TRP activities was to investigate the thermochemistry of high-enthalpy CO_2 flows, in order to improve the existing analytical and numerical engineering capabilities for future exploration missions. The facilities retained for those experiments from one team were the ONERA high enthalpy wind tunnel F4, VKI Plasmatron and Minitorch facilities, and DLR arc-heated facility L2K. The three facilities that have been used by one team within this study complement each other almost ideally, since they cover a wide range of thermochemical regimes:

(i) the flow field in Plasmatron and Minitorch is subsonic, and it is expected to be close to thermochemical equilibrium;

(ii) F4 is a hot-shot facility that provides a hypersonic nonequilibrium flow;

(iii) DLR L2K facility with a chemically almost frozen environment at low temperature levels (<1000 K) in the free stream and high temperatures (up to 5500 K) behind the bow shock.

While the other team retained, a mix of facilities from shock tube through small arc-heated facility to larger industrial facility:

(i) VUT-1 shock tube at MIPT (also used in mid 90's study of CO_2 chemistry under TRP);

(ii) PWK ISR plasma wind tunnel;

(iii) SIMOUN industrial arc heater used for Mars TPS qualification at ASTRIUM-ST.

Another point is the potentiality of a turbulent flow for the Martian entry of a large vehicle (and/or driven by TPS ablation), for which the presence of turbulence could strongly increase the heat flux, by roughly 60% if the surface remains smooth [15].

A last problem is the potential presence of dust particles during reentry. Their presence is due to massive storms that characterize the dynamic of Mars atmosphere. Even during the quiet season (with much less storms), the probability of a storm is never null and a local one can evolve in a global storm within few days. The presence of the particles would increase TPS recession and overheating [16, 17] of the substructure material.

Radiation is present during Mars entry, but this phenomenon plays a second order role. It is still an issue but not a sizing phenomenon for a TPS, at least for orbital or scientific hyperbolic entry; it may need to be reassessed for short duration flight-manned missions.

2.1. Facilities Survey. In Europe, the following facilities are running with CO_2.

(i) HEAT high-enthalpy arc-jet at ALTA (Pisa).

(ii) Reentry chamber for material testing at ARC (Seibersdorf in Austria).

(iii) SIMOUN mostly used for TPS qualification at ASTRIUM-ST (Aquitaine);

(iv) Arc-jet, inductively coupled plasma torch and low-power radio frequency plasma torch at relevant for aerochemistry at CORIA (Rouen).

(v) HEG shock tunnel and LBK arc-heated facility at DLR (Cologne and Göttingen) for aerothermodynamics and TPS qualification.

(vi) HHK Ludwieg shock tube at HEG (Göttingen).

(vii) PHEDRA arc-jet for aerochemistry at ICARE (Orléans).

(viii) PWK facilities at IRS (Stuttgart) for material and plasma characterization and heat-shield testing.

(ix) Shock tube at ISL (Saint-Louis) for dynamic stability and aerothermodynamics.

(x) ICP plasma torch at LAEPT (Clermont-Ferrand) for radiation.

(xi) F4 hot-shot arc-jet at ONERA (Le Fauga near Toulouse) for aerothermodynamics.

(xii) MESOX at PROMES (Odeillo in the French Pyrénées) for material characterization, catalysis, and radiation.

(xiii) TH2 shock tunnel at RWTH (Aachen) for aerothermodynamics.

(xiv) HSST hypersonic wind tunnel, ST-DC shock tube and HST2 shock tunnel at UMIST (Manchester) for aerothermodynamics.

(xv) SPES arc heated at UNINA (Naples) for aeroheating and ablation tests.

(xvi) Longshot-driven piston for aerothermodynamics and Plasmatron for material testing at VKI (Bruxelles).

To this list, TCM2 shock-tube from IUSTI Marseille that is now closed will be also considered for the review since it has provided a large amount of data for European projects like Huygens and was a key facility for research in chemical kinetics since it has produced a large part of the European data related to planetary entry in this field [18]. The Gun tunnel at the University of Oxford has also been closed. This facility was used for Beagle2 heating studies.

According to the previous list, quite a lot of European facilities can be operated with a Mars-like atmosphere. However, the review of their capabilities is not easy since the performance envelopes for most of the facilities have not been provided. Capabilities and main characteristics of some of these facilities are listed in Tables 2 and 3.

Table 2: Capabilities of some available European installations for investigation of aerothermodynamics during a Martian entry.

Facility	Running time	Flow regime	Mach	P_0 (Pa)	T_0 (K)	Heat flux (MW/m^2)	Re	Comments
HEG, DLR	1 to 5 ms	High enthalpy	8.4 to 10.7 (4.6–6.2 km/s)	35 to 90 × 10^6	6600 to 9700	1–22	0.2 to 1.1 × 10^6	High enthalpy condition: $h_0 = 11$–23 MJ/Kg DLAS
L3K, DLR	Up to 30 mn	High enthalpy, laminar flow	5 to 10	0.15 to 1.8 × 10^6	Up to 7000	Up to 4	Up to 10^5	Enthalpy up to 25 MJ/Kg DLAS
TH2, RWTH	2 to 10 ms	Cold hypersonic	6 to 12	4 to 60 × 10^4	1500 to 7400	0.7 to 20	Up to 10^7	Detonation driver mode for high enthalpy condition No DLAS
Longshot, VKI	25 to 70 ms	Cold hypersonic	10 to 20	1 to 4 × 10^8	1500 to 3500	n.a.	At $M = 14$, 5 × 10^3 to 15 × 10^6	No DLAS
F4, ONERA	Up to 200 ms	High enthalpy	7 to 21	2 to 10 × 10^7	1500 to 7500	n.a.	5 × 10^6 ($M = 10$) to 10^6 ($M = 21$)	DLAS
SIMOUN, ASTRIUM	Up to 5 mn	High enthalpy	4 (flat plate)–4.5 stag. point	Up to 10^4	n.a.	Up to 1.3 (stag. point)–0.7 (flat plate)	n.a.	DLAS
HHK, HTG	100 ms	Cold hypersonic	7 (5.7 km/s)	30 to 350 × 10^2	Up to 900	n.a.	3 to 5 × 10^6	No DLAS
STA-STB, ISL	4 ms	Hypersonic, low enthalpy	3.5 to 10 (3.5 km/s)	Up to 10^6	n.a.	Up to 10	10^6 for $M = 10$	Higher Mach number possible No DLAS
HST2, UMIST	Up to 10 ms	Hypersonic, low enthalpy	5.75 to 12	n.a.	n.a.	n.a.	n.a.	No DLAS

In ISC, the following facilities can be operated with CO_2 or Mars-like atmospheres.

(i) Plasma Hall generator at HMTI (Minsk).

(ii) IPG-4 Plasmatron at IPM (Moscow).

(iii) Wind-tunnel AT303 and hot-shot wind-tunnel IT-302M at ITAM (Novosibirsk).

(iv) Shock tube VUT-1 at MIPT (Moscow) used for chemical kinetics studies.

(v) Hot-shot IT-2, vacuum wind-tunnel VAT-3, and shock tunnel UT-1M at TSAGI (Zhukovsky).

(vi) Piston gas dynamic units U-11 and U-7, U-1T shock tunnel, and U-13 high-frequency Plasmatron at TSIINMASH (Korolev).

HTMI can be used for TPS validation, and IPG-4 has already been used for catalysis and ablative tests. At ITAM, AT-303 and the hot-shot wind-tunnel IT-302M can be used for aerothermodynamics (aerodynamics and heat-flux distribution over reentry vehicles). The shock-tube VUT-1 seems to be well suited to Mars applications, and it is quite attractive for chemical kinetics and radiation studies. At TSAGI, IT-2 and VAT-3 and UT-1M are mostly used for general aerothermodynamics. Particles can be injected in UT-1M. At TSIINMASH, U-11, U7, and U-1T are used for aerothermodynamics and U-13 for TPS testing.

During the review, no available results obtained for facility running with CO_2 were found in Canada. The expansion tubes of the University of Queensland [19, 20] have already been run for Mars like atmosphere in the frame of an ESA TRP study; as a consequence, some of the elements available on these facilities, particularly the measurement techniques developed, have been accounted for the paper.

2.2. Aerothermodynamics. The accuracy of the experimental simulation of reentry conditions strongly depends on the ability to determine the flow conditions. Hypersonic forces and stability data may be obtained with good accuracy [21] on the basis of Reynolds or Mach numbers or other appropriate similitude parameters. But, this is not the case for some other aerodynamics characteristics: the correct simulation of dissociation and ionization requires the duplication of actual flight conditions; heat flux depends strongly on flow enthalpy

Table 3: Characteristics of European facilities for TPS testing.

Name	Heat-flux (MW/m^2)	Stagnation pressure (bar)	Running time	Model size (mm)	Measurements	Remarks
SIMOUN (for CO_2)	Stagnation point: up to 1.3 Flat plate: up to 0.7	Up to 0.1	Up to 5 min	Stagnation point: 70 Flat plate: $300 * 300 * 150$ thick	Behaviour of sample specimen under flux and pressure constraints	The flux and pressure can be stationary as well as dynamic. Dust-loaded flows possible
L3K (for air)	Up to 4	n.a.	<1800 s	$280 * 350 * 70$	Total enthalpy, pressure, entry relevant gas composition, velocity gradient, shear stresses	High enthalpy flow properties Dust-loaded flows possible
Plasmatron (air)	Up to 2.9	Up to 0.15	Up to 1 hour	50	Static pressure, stagnation pressure, temperature, heat flux	Aerothermal testing of TPS elements. Ageing tests of reusable thermal protection materials

and density; base pressure is strongly dependent on real gas effects [21]. The minimum set of parameters which has to be duplicated during the tests is the specific enthalpy of the gas, the stagnation pressure, the heat flux, and the Reynolds number.

Some characteristics of several European facilities available for aerothermodynamics are listed in Table 2. For most of the facilities, data were only provided for air and no performance envelope was available for CO_2 (even if they have been already operated with CO_2).

First tests in Europe with CO_2 were performed in the frame of the 1st Aerochemistry TRP [22] in HEG for Viking type forebody, in shock tubes at MIPT and IUSTI for kinetics, and at CORIA and IPM (from 1991 to 1996) for material catalycity. Later, F4 studies were undertaken in the frame of the Mars Premier Programme [12]. From the activities already performed for Mars entry, it appears that arc-jet facilities (such as LBK, SIMOUN, and F4) lose a lot of efficiency (around 30% for F4). However, from the work performed in the frame of Mars Premier and ESA projects it is clear that there are still some margins for improving the state of the art with the existing facilities. Progresses are particularly needed to improve the knowledge of the flow conditions when running facilities with CO_2. With the inputs provided during the review, it can be concluded that Mars entry trajectories are partially covered [23] with the existing ground tests in Europe. The coverage of the entry trajectory depends on initial entry conditions such as velocity; it decreases for the high velocities due to the power losses in the arc-jet test chambers when using CO_2 mixtures.

Several ISC facilities (see list in previous section) can be operated with CO_2. Those from TSAGI, ITAM, and TSIINMASH are relevant for Mars entry since most of them have been already run for such conditions in the frame of ISTC [24] studies. Here also, the performance envelopes for CO_2 were not available.

It is unclear if the European facilities are able or not to cover a whole Mars entry trajectory with the available information; however, arc-jet facilities are usually too low in pressure already for Earth suborbital reentry. The conclusions might not be very optimistic for Mars entry due to the large loss of power when using CO_2. Since the potentialities of the existing ground tests have not yet been exhausted, it does not seem a priority to develop a facility dedicated to Mars entry. Additionally, the potential gaps could be filled by using ISC facilities or by adapting existing facilities (such as SCIROCCO) to CO_2 flows. A last point is that we should keep in mind that NASA developed successfully the Viking mission in the seventies without having a facility running with CO_2.

2.2.1. Measurement Techniques. Parallel to the material testing, diagnostic methods, intrusive probes, and nonintrusive optical diagnostics have to be qualified and applied for detailed investigations on high-enthalpy plasma flows and material behaviour during the tests. The measurement techniques available in Europe are the following.

(i) Electrostatic probes for the determination of electron properties.

(ii) Mass spectrometer to characterize plasma flows (temperature and plasma composition).

(iii) Radiation probes (extensively used at IRS).

(iv) Fabry-Perot interferometry for spectroscopy.

(v) Emission spectroscopy for measurements of temperature and concentration profiles [25, 26].

(vi) Holographic interferometry, nonintrusive method for investigating density field [27].

(vii) Laser techniques (laser-induced fluorescence and laser absorption) for radiation measurements [28].

A high expertise on measurement techniques for diverse flow parameters and more particularly for radiation investigation is available at IRS [23]. During previous studies, different probes have been developed to measure these flow parameters. Furthermore, electrostatic probes are in use for the determination of electron properties and a mass spectrometer can be positioned as a probe in the plasma flow. Besides the intrusive diagnostic methods, optical measurement techniques are also applied. For the detection of the overall plasma radiation, which has an important influence on the heat flux for high-speed entry missions like Galileo or Huygens, a radiation probe can be used at IRS. Fabry-Perot interferometry (used for spectroscopy), emission spectroscopy, and laser techniques such as laser-induced fluorescence and laser absorption are also available [23]. Combining these optical techniques, state selective information about all radiating states and the ground state can be obtained.

On its side, ONERA has extensively developed the DLAS (diode laser absorption spectroscopy) technique [29] for CO_2 flows. Among the existing DLAS spectrometers, the one of F4 seems to be indispensable as it has the particularity of having two diodes: one for CO and another for CO_2. Now, several European facilities, as shown in Table 2, are equipped with this technique [30, 31].

Through TRP activities, slow progresses have been made to determine temperatures, concentration, velocity, and gas composition of the free-stream flow, using nonintrusive laser-based spectroscopic techniques. Laser-induced fluorescence (LIF) measurements were performed on NO, CO, and O particles, and DLAS was used to probe CO and CO_2. Furthermore, emission spectroscopy was applied. In addition, cold wall heat fluxes and shock standoff distances have been measured in dependence of the enthalpy level. Major attention has been paid to a simultaneous use of these techniques, in order to eliminate any negative effects of the repeatability of the facility flow parameters. So, the facilities were improved in their understanding and instrumentation:

(i) L2K with LIF for measuring NO, O, and CO, and CO diode laser absorption spectroscopy;

(ii) VKI Plasmatron and Minitorch: high-speed imaging of plasma flow, improved understanding of stability, O Two photon Absorption Laser-Induced Fluorescence (TALIF) [32];

(iii) DLAS feasibility for simultaneous CO and CO_2 measurements in F4 and SIMOUN.

In the frame of TRP activities, the feasibility of measuring some species (CO and CO_2) densities in SIMOUN arc-jet by DLAS has also been demonstrated, as well as the measurement of velocity and temperature. This was done thanks to a fruitful cooperation between ASTRIUM-ST and ONERA and was intended to bridge the gap between research and industrial facilities to be used on ExoMars validation.

For future activities, it would be relevant to extend the capabilities of nonintrusive techniques. The application of DLAS for measuring atomic oxygen would be a valuable contribution. A way for improving the state of the art in nonintrusive techniques could be the development of holographic interferometry. The application of these techniques to measurements in expansion tubes, performed recently at the University of Queensland [33] seems to be very promising. The improvement of the measurement techniques for ionic species and electron density would also be of high interest to improve ionization predictions and blackout estimation during entry.

It has to be noted that, as discussed during the Workshop on Facilities held at ESTEC on 28 March 2008, due not only to cost reason but also to their expertise, facilities available in the research institutes and more particularly universities (such as IRS, LAEPT, ICARE, CORIA, and UMIST) have a strong role to play for the development of new experimental and diagnostic methods.

2.2.2. Chemical Kinetics. Shock tubes are attractive for investigating chemical kinetics and thermal relaxation. In the perspective of a Martian entry, facilities have to be able to reproduce entry trajectory with entry velocities between 4.0 and 7.5 km/s and to work with a CO_2 environment. In order to improve the knowledge on chemical kinetics, several shock tubes (and shock tunnels) are available in Europe, among them we can cite.

(i) HEG at DLR Göttingen;

(ii) TH2 shock tunnel at RWTH Aachen;

(iii) HHK Ludwieg shock tube at HEG Göttingen;

(iv) GDLich at GDL;

(v) STA and STB at ISL;

(vi) TU Braunschweig Ludwieg shock tube.

Most of these facilities (mainly the shock tunnels) are dedicated to aerodynamic investigation (force measurements and stability). TCM2 at IUSTI (Marseille) was the only shock tube used to perform experiments on chemical kinetics and thermal relaxation for planetary entry. It was a very attractive facility due to its capabilities for Mars and Titan entries. This facility has given a valuable contribution on chemical kinetics in a CO_2 environment [35]. Unfortunately, TCM2 has been stopped for safety reason and a part of the operating team has already left. For investigations on chemical kinetics, the loss of TCM2 capabilities highlights the lack of shock tubes in Europe with the capability to cover planetary entries. The shock tunnels TH2 (RWTH) and HEG (at DLR) could fill at least partially the gap, but these facilities are more suitable for Earth suborbital entry as shown in Figure 2 where the performance map in terms of similitude parameter ($\rho_\infty L$) and velocity are compared to Earth orbital reentry trajectories.

The other facilities, STA and STB at ISL, HHK at HEG, and the Ludwieg tube of TU Braunschweig, are mostly used

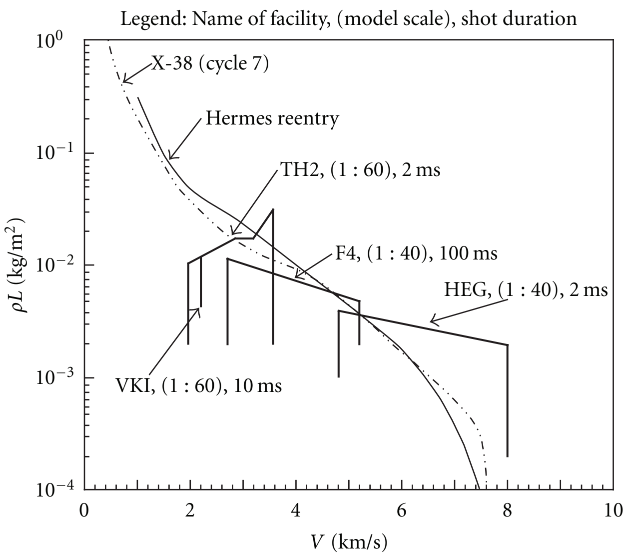

Figure 2: Performance envelopes (binary scaling parameter as function of velocity) of HEG, TH2, F4 and Longshot (VKI) for Earth suborbital reentry according to Kordulla et al. [34].

for aerodynamics and stability investigations. The shock tube from UMIST does not seem to fit, at least if the Mach number is considered, with the requirements of a Mars entry.

If a Mars entry is considered, these shock tunnels (TH2 and HEG) might be too low in pressure to be representative since the flow is expanded in a nozzle to reach higher Mach numbers. Usually, significant dissociation and ionization levels can be present under reservoir conditions attainable in shock tunnels and this results [21] in a free stream of different energy and composition than the desired ones (frozen flow). Due to this issue, these facilities are more adapted to Reynolds-Mach number simulation than to chemical kinetics. As a consequence, the development of such a facility for Mars entry should be envisaged.

For the time being, investigations on chemical kinetics could be performed in university laboratories:

(i) for CO_2 dissociation at CORIA (but very low pressure);

(ii) at ICARE with PHEDRA that can run for Mars atmosphere: measurements of population excited states, ionization, vibrational, and electronic temperature;

(iii) LAEPT with ICP plasma torch;

(iv) IRS for plasma dissociated and temperature measurements.

Another possibility for the study of chemical kinetics during a Martian entry would be to use a facility from the ISC. The available shock tubes and tunnels, working with a CO_2 environment, are the following:

(i) UT-1M shock-tube from TSAGI in Zhukovsky;

(ii) VUT-1 from MIPT in Moscow;

(iii) U-12 from TSNIIMASH in Korolev.

VUT-1 is the most attractive since it is used for chemical kinetics while the two others are dedicated to force measurements and aerothermodynamics. This shock tube can investigate the kinetic data of nonequilibrium dissociation and recombination processes and other chemical reactions. It is designed for Mach numbers from 5 to 25 and allows investigation of a wide range of experimental conditions. A velocity between 4 and 8 km/s can be reached during experiments with a CO_2-N_2-Ar mixture. This facility was retained for the ESA CO_2 TRP study [13] and has provided significant results using emission spectroscopy, absorption spectroscopy, and microwave interferometry to investigate chemical kinetics, thermal relaxation, and electron densities. This facility has looked at realistic velocity (enthalpy) and pressure and has provided the first European electron density measurements in a shock tube.

2.2.3. Radiation and Ionization. There are several European facilities that can be used for investigating radiation and ionization during Mars entry. Among them, the following can be cited.

(i) For CO_2 (and air) dissociation at CORIA (but at low pressures) [36].

(ii) At ICARE with PHEDRA that can run for Mars atmosphere, measurements of population excited states, ionization, vibrational, and electronic temperatures can be carried out.

(iii) IRS facilities for plasma dissociation, temperature measurements, and radiation.

(iv) ICP plasma torch at LAEPT for plasma emission [37].

(v) MESOX at PROMES is mainly used for catalysis investigation, but this facility has some potential for radiation investigations.

In ISC, the following capabilities are available for investigating radiation and ionization during Mars entry.

(i) Plasma Hall accelerator at HTMI that is a powerful facility for radiation investigation.

(ii) VUT-1 at MIPT for radiation and ionization.

(iii) Measurements of electron and ion concentrations in hot-shot IT-2 at TSAGI.

Using the facilities available in Europe, radiation studies are well covered for a Mars entry except the gap due to the stop of TCM2 shock tube. Few studies have been carried out for ionization investigations related to CO_2 plasma flows; however, this might be feasible using the IT-2 hot shot at TSAGI.

2.2.4. Turbulence. On this point, there is really a lack of aerothermodynamics capabilities in Europe related to a Mars entry. From the inputs provided during this review, the only facility capable of simulating turbulent flows for a CO_2 environment is Longshot at VKI. This facility is far from being able to cover a whole Mars trajectory, while turbulence assessment during Mars entry is really a key issue [38] for the design of the heat shield. In ISC, the shock-tunnel UT-M1 from TSAGI is capable to simulate transitional and turbulent flows.

If the entry of a large vehicle into Mars atmosphere has to be prepared, there is really a gap in turbulent flows. Another issue is the presence of the ablative TPS that has a strong impact on turbulence due to the blowing of pyrolysis gas during entry. This has a complexity when assessing the turbulence onset that cannot be determined with a critical Reynolds number for a smooth surface. Both capabilities of Longshot and UT-M1 are not able to cover a Mars entry. To fill this gap, some modifications of existing capabilities such as F4, SIMOUN, LBK, and SCIROCCO should be explored. The flat plate model used in SIMOUN may be tripped to turbulent flow in its present configuration and, in the short, term may offer the best potential for surface effects studies.

For the ExoMars programme, tests are being undertaken in DLR's TMK and H2K facilities with smooth and rough walls. Although Mach number is only just hypersonic, Reynolds numbers are sufficiently high for both natural transition and roughness-induced bypass transition studies. Nevertheless, truly high-enthalpy high Reynolds number flows cannot be simulated in Europe as stated above and this leaves rather a large space for extrapolation to flight conditions from CFD verification studies.

2.2.5. Dust Particles. The Martian atmosphere is always dust loaded; the amount of loading is temporarily changing. With a probability that depends on the season, a local dust storm can grow in a few days and becomes a global storm in only few weeks (most likely during the summer in the southern hemisphere). The planet is thereby enveloped much or all in a dense shroud of dust. As a consequence, the presence of dust particles in the mid-latitudes atmosphere has to be accounted for the assessment of erosion and potential overheating during Mars exploration missions. Studies with dust particles have been performed in the frame of the Mars Premier Programme at VKI [39] and ESA TRP [40]. The extrapolations, done in the frame of an ESA TRP project [40], lead to a recession of 1 mm for a clear day up to 6 mm for the worst case.

In Europe and the ISC, the following facilities can operate using dust particles and CO_2 atmosphere:

(i) SIMOUN (ASTRIUM-ST);

(ii) L2K (DLR);

(ii) Minitorch (VKI);

(iv) UT-1M (TSAGI).

SIMOUN, due to the recent developments, is particularly adapted to Martian reentry simulation as it can work in CO_2 environment with a powder-seeded flow to simulate hydroerosion during Mars entry. Some tests have been performed in the frame of ExoMars in stagnation point configuration for heat-fluxes higher than 1.3 MW/m^2. Tests have also been performed at DLR in L3K which has also been significantly upgraded for this purpose. Two types of particles were injected in the flow: SiO_2 and Al_2O_3. The free-stream velocity of the SiO_2 particles was 1987 m/s while the one of Al_2O_3 was 1903 m/s. The deceleration depends on particle type and size. Results obtained in LBK show a heat flux decrease of 10% at the stagnation point when the flow is loaded with particles (may be due to less surface catalysis).

Concerning ISC facilities, an investigation of the Martian dust-loading effects was performed in the frame of ISTC [17]. During this project, influence of solid particles of various size and different composition on heat exchange at the stagnation point of blunted body was studied. For the first time, the distribution of particles concentration in the compressed gas layer (behind the shock wave) was experimentally investigated near a body surface. For this study, the UT-1M facility from TSAGI was used in the Ludwieg regime ($M = 5$–10), with air as test gas.

Experimental measurements show that the velocities of particles did not exceed 2000 m/s which is far to be representative of a Mars entry (beyond 3 km/s). The particles are seeded in the plasma flow and therefore cannot be injected with higher velocity. Due to this technical restriction, it will be difficult to go beyond this velocity (2000 m/s) for the time being.

2.3. TPS Qualification. For TPS qualification of materials in a CO_2 environment, several points have to be accounted for. First, the ground test has to reproduce Martian entry conditions in terms of heat flux, enthalpy, and pressure. It means that the facility has to reach a heat flux up to 2 MW/m^2 for a large vehicle [38], this for a static pressure below 10 mbar (stagnation pressure ~0.1 bars). It is also important to look at the shearing, roughness, and blowing of materials as well as to take into account the presence of turbulence during entry as it can considerably increase the heat flux. Moreover, the design of the TPS depends on the flight path angle since the maximum heat flux to be endured by the TPS depends on this parameter. So, it is important to take into account the flux profiling as a function of time during entry. In addition to that, the facility has to provide the capabilities to test materials for stagnation conditions and to qualify TPS assembling and joints.

Among the existing European facilities, the ones which can be used for TPS testing in a CO_2 environment are

(i) SIMOUN (ASTRIUM-ST);

(ii) LBK (DLR);

(iii) PWK's (IRS);

(iv) MESOX (PROMEX);

(v) Plasmatron (VKI);

(vi) SPES (UNINA).

The main capabilities of some European facilities usable for TPS testing in a CO_2 environment are summarized in Table 3. SIMOUN is well adapted to blunt body planetary entries needs and has already been used for the qualification process of many probes heat shields, like OREX, BEAGLE2, ARD, and HUYGENS. The facility can run for two kinds of configurations: stagnation point and flat plate. For a CO_2 environment, it can reach a heat flux of 1300 KW/m^2 for a stagnation point configuration and up to 700 kW/m^2 for a flat plate configuration. Moreover, TPS testing can also be done in a dust-loaded flow. Some results with alumina particles have already been obtained.

DLR facility L3K is able to simulate heat flux up to 4 MW/m^2 in air high-enthalpy flows (up to 25 MJ/kg), but the extension to CO_2 requires a large effort on safety grounds (CO treatment). Since, in the stagnation point configuration, the performance of SIMOUN decreases from 2.5 to 1.3 MW/m^2 from air to CO_2, a similar behaviour for LBK can be expected, with a maximum heat flux that should be close to 2 MW/m^2 with CO_2 (250 to 650 kW/m^2 was used in CO_2 and Martian dust TRP's in the lower power L2K). L3K can run for two configurations: stagnation point and wedge. Like SIMOUN, it is also possible to inject particles in the flow to simulate the effects of the dust on TPS material.

IRS PWK's can reach heat-fluxes characterizing a Mars entry; however, these facilities are quite low in pressure. VKI Plasmatron can be also a good alternative to perform TPS validation as it can reach quite high heat flux, with a pressure fitting the conditions required. MESOX at PROMES could be also used for material validation as well as SPES from UNINA.

Another possibility for TPS testing would be to use a facility from the ISC community. The plasma Hall accelerator of HMTI is able to test heatproof materials and is working with CO_2, but there is no available information about its technical features for CO_2. Ablation tests and catalysis studies can also be performed at IPM Moscow [41]. Characteristics are available for the IPG-4 Plasmatron, located at IPM. It can reach a heat flux of 2 MW/M^2 and a pressure from 0.01 bars to 0.2 bars, with an enthalpy up to 40 MJ/kg for a stagnation point configuration and a CO_2 atmosphere. It has already been used for catalycity experiments in CO_2 under ESA TRP in the early 90's.

From the review, it appears that European facilities are sufficient to validate a material for a Mars entry vehicle. TPS assembling tests can be performed in SIMOUN or L2K (laminar only). Since the stagnation point pressure during Mars entry is much lower than 1 bar, the existing facilities should be sufficient for ablation tests and material qualification. Note however that cold smooth wall fluxes and shear need to be distinguished from hot rough wall fluxes and shear during numerical rebuilding of the turbulent plate flows used for the qualification of the conical/expansion corner TPS regions.

2.4. Descent. An important issue of Mars missions is the descent into the atmosphere. After the breaking of the vehicle during the entry, the descent of the capsule occurs in a tenuous atmosphere. Since Mars atmosphere is not perfectly known, the descent can occur in a cold or hot spot and variations of density can shorten the descent time endangering the mission success. Usually, descent modules use two parachutes, a drogue and then a main parachute. The testing of the descent system is important to guarantee the mission; however, for the time being, there is no facility in Europe allowing the testing of parachute for Mars entry.

If an inflatable device is used, the problem is more complex since there is also no ground testing for simulating experimentally inflation at high altitude for Mars and Earth entry conditions. In this case, the failure of the inflatable device can lead to an unsuccessful mission. This was more likely the cause IRDT-2R failure during its mission [42, 43].

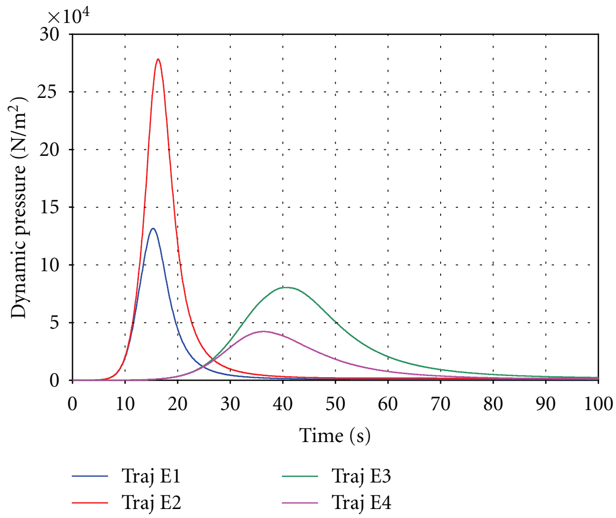

Figure 3: Stagnation Pressure for EVD mission [6].

2.5. Summary. To summarize the review for Mars entry, some existing gaps have been identified in the capabilities of the European facilities:

(i) a shock tube for the chemical kinetics;

(ii) a facility for the testing of parachutes;

(iii) improving experimental hypersonic capabilities for turbulence simulation;

(iv) adapting existing facilities such as SCIROCCO, for aerothermodynamics studies and TPS validation in CO_2 flows, would be an asset, but perhaps at large cost. The performance reached by facilities like F4 and LBK is not fully representative of a Mars entry (too low in pressure or in Mach number);

(v) need to pursue the effort on measurement techniques (DLAS, holographic interferometry);

(vi) dust erosion: particle velocity is not representative of Mars entry.

Among these different gaps, the two most critical points are the lack of a shock tube for kinetic studies and the need to improve hypersonic capabilities for turbulence simulation.

In the frame of a sample return mission to Mars, the sample collected into Mars soil has to be sent back to Earth using the return module orbiting around Mars. For this objective, the lander shall carry a return vehicle equipped with a pr

3. High-Speed Earth Reentry

A sample return mission involves a direct high-speed Earth reentry with a velocity higher than 10 km/s and high heat

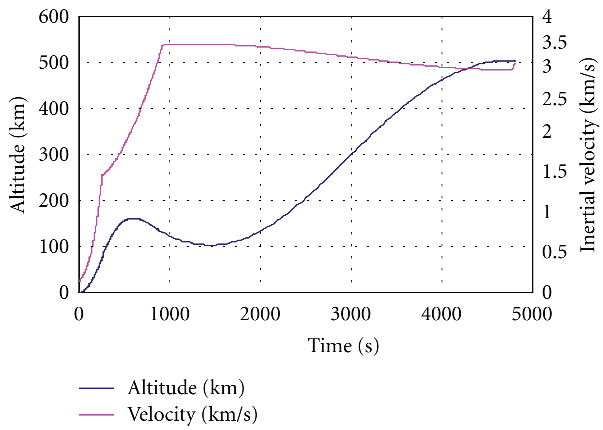

Figure 4: Typical Mars ascent trajectory [6].

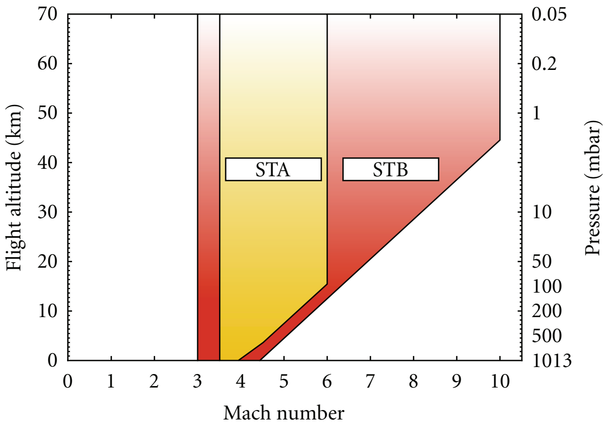

Figure 5: Capabilities of ISL shock tubes STA and STB (credit ISL).

fluxes (more than 8 MW/m^2) at peak heating as shown in Figure 1. The consequence is that the level of heat flux will be around one order of magnitude higher than for an orbital entry for which most of European facilities have been designed. The maximum stagnation pressure and the stagnation pressure at peak heating for the trajectories plotted in Figure 1 are listed in Table 4; the distributions of stagnation pressure are shown in Figure 3.

For a high-speed reentry, phenomena like ionization, ablation, and radiation that are of second order for an orbital entry cannot be neglected: radiation level is around several MW/m^2 as shown in Table 5 where convective and radiative heat-fluxes at peak heating are listed for different entry trajectories (see Figure 1). TPS ablation [5] can be up to 1 cm with a capsule shape change that might affect its stability. Ground tests play an important role for the understanding of these phenomena, for the validation of analysis tools and for the development and qualification of hypersonic vehicles.

3.1. Chemical Kinetics. opulsion system. The launcher capability has to be ensured after a long trip from Earth to Mars. Additionally, the propulsion system has to support the high g-loads encountered during the Mars entry. The robustness of the on-board small launcher will be one of the issues for the mission success. An example of Mars ascent trajectory is shown in Figure 4. From this picture, it is clear that, due to the velocity range, the ascent vehicle will not be affected by thermochemistry effects before entering in the rarefied regime.

Another point is to ensure the launching capabilities of this propulsion system which shall ignite in a CO_2 atmosphere, at low pressure, less than 10 mbar, and at temperature in between the day and night Martian temperatures.

Among the European test facilities that could simulate, in close conditions to the Martian environment, the ignition of a propulsion system, the CAEPE's facility SESAME is attractive since it is capable to simulate the pressure range corresponding to the working conditions of a Martian ascent trajectory. A potential improvement would be to adapt this facility to a CO_2 atmosphere. This facility has already been used for the testing of the ATV propulsion system.

4. Mars Ascent

An asset of SESAME is the capability to test a full size engine and to vary the pressure during the test. Conjointly, additional capabilities, existing in other research centres, could be used. According to the inputs provided for this paper, some additional tests could be performed at ISL to assess the small launcher stability along the ascent trajectory. Since real gas effects will not influence the ascent vehicle, usual facilities can be used to investigate its aerodynamic, keeping in mind the low pressure of the Mars atmosphere. As a consequence, facilities capable to run for high-altitude Earth conditions shall be useful for the validation of an ascent vehicle trajectory.

From the European facilities reviewed, the followings are of interest for a Mars ascent vehicle if we consider its aerodynamics and stability:

(i) DLR wind tunnels VMK and TMK;
(ii) FOI wind tunnels;
(iii) HHK Ludwieg tube from HTG;
(iv) ISL shock tubes STA and STB;
(v) ONERA wind tunnels S2, S3, and S4;
(vi) TU Braunschweig Ludwieg tube;
(vii) UMIST facilities;
(viii) VKI wind tunnels.

Among these facilities, ISL shock tubes can operate at low pressures corresponding to an Earth altitude of 70 km as shown in Figure 5. They could cover a large part of a Mars ascent trajectory. From the different facilities listed above, even if performance maps have not been provided, a Mars ascent trajectory should be fully covered (with more likely some duplication of capabilities). To refine this analysis, more details on a Mars entry trajectory would be necessary. For this, the evolution of Reynolds number, Mach number range, and stagnation pressure along the trajectory would be required.

Table 4: Maximum stagnation pressures for an EVD mission [6].

Trajectory	Stagnation pressure at max. heat flux (Pa)	Maximum stagnation pressure (Pa)
E1	70396	131500
E2	138037	277339
E3	48534	80300
E4	26687	41180

Since one of the main problems of a launcher is the ignition, this point shall be a key issue for such a propulsion system. A potential activity could be to upgrade a facility like SESAME to test the engine working conditions in a CO_2 environment.

Shock tubes are attractive for investigating chemical kinetics and thermal relaxation. As a consequence, in the perspective of a high-speed Earth reentry, such facilities have to be able to reproduce entry trajectory with high velocities: around 12.6 km/s for Stardust. In order to improve the knowledge on chemical kinetics, several shock tubes (and tunnels) are available in Europe, among them we can cite

(i) HEG at DLR Göttingen;

(ii) TH2 at RWTH Aachen;

(iii) LONGSHOT at VKI.

Other facilities exist at GDL and UMIST in UK, at TU Braunschweig and HTG in Germany and Institut Saint-Louis in France. Unfortunately, most of these facilities have been developed for suborbital entries [8] as shown in Table 6 and Figure 6 and do not fit with the flow conditions characteristic of a high-speed Earth entry. In fact, TCM2 that was previously available at IUSTI Marseille was the most attractive but this facility has been closed for safety reason: indeed, it was broken when testing superorbital reentry conditions at just over 9 km/s.

Due to these limitations in Europe, the only alternative is to develop a new facility or to use a facility from ISC. These facilities have already been used for studies on high-speed Earth reentry in the frame of the ISTC programme [24]. For such purpose, the following facilities could be attractive since they are running with air and capable of reproducing severe entry conditions:

(i) VUT-1 from the Moscow State University;

(ii) ADST from TSAGI Zhukovsky.

Due to the measurement techniques already available and the available expertise of the operating team, VUT-1 shock tunnel is attractive but the velocity within the tube cannot be higher than 9 km/s, which is a little bit weak for an Earth superorbital reentry. As far as chemical kinetics are concerned, the facility fitting the best requirements of an EVD seems to be the ADST shock tunnel from TSAGI. This facility allows the investigation of ionisation/radiation processes behind a shock wave from 8 up to 14 km/s. ADST has been used in the frame of an ISTC project [24]; however, few

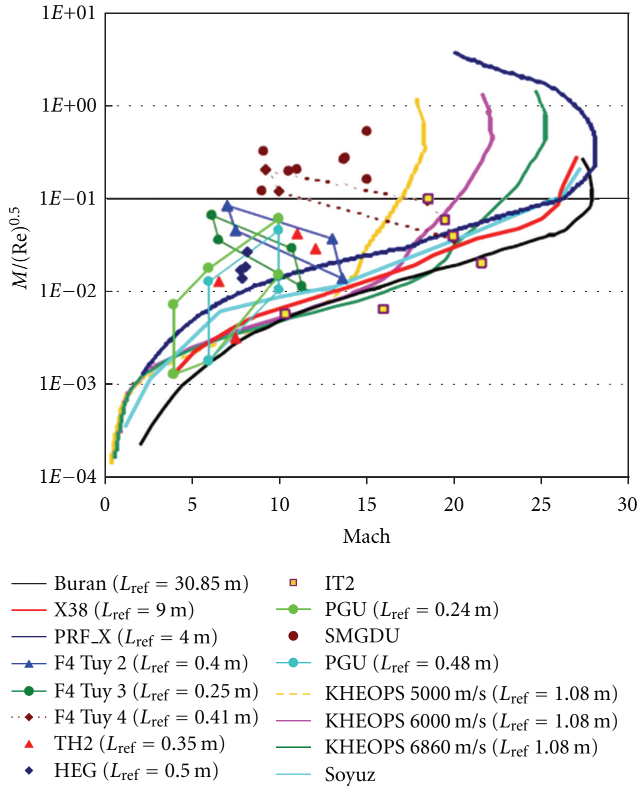

Figure 6: Capabilities (Mach/(Re)$^{1/2}$ as function of Mach number) of different facilities (F4, HEG, TH2) comparing to suborbital entries of different vehicles [8].

details are available on this facility which can be used to measure electron concentration and temperature behind a shock wave and radiation intensity.

For superorbital entries, an alternative could be to use Australian facilities (or others); several shock tunnels are available at the University of Queensland providing high velocities:

(i) X1 free piston-driven expansion tube: up to 10.8 km/s;

(ii) X2 free piston-driven expansion tube: up to 10.3 km/s;

(iii) X3 expansion tube: up to 10 km/s.

These three facilities can reach velocities in the range of superorbital Earth re-entry; they have been successfully used in the frame of an ESA TRP [19, 33] focusing on Earth high-speed reentry (and Titan entry). Moreover, since there is no equivalent in Europe for the time being, they could be used alternatively or conjunctly to ISC facilities. However, when running at 10.3 km/s in an expansion tube like X2, the free-stream pressure is 0.033 atmosphere and Mach number 7.3. As a consequence, expansion tubes could be too low in pressure to really simulate EVD reentry conditions.

4.1. Aerothermodynamics. The flow around a sample return capsule is characterized by high levels of ionization and radiation. Other important issues are turbulence and ablation

Table 5: Maximum heat fluxes for EVD mission [6].

Trajectory	Convective flux kW/m^2	Radiative flux kW/m^2	Total flux kW/m^2	Total heat load MJ/m^2
E1	11500	7500	18800	106.9
E2	15700	18100	33800	178.3
E3	9350	4550	13900	243.2
E4	7000	1900	8900	154.6

Table 6: Capabilities of some available European installations for investigating chemical kinetics and aerothermodynamics related to Earth reentry.

Name	Flow regime	Run time	Test section (m)	Mach number	Re 10–5 (1 m)	T_0 (K)	P_0 (MPa)	Measured quantities	Use in projects
F4 (ONERA)	High enthalpy	Up to 200 ms	0.7 to 1.2	6 to 20	0.06 to 23	2000 To 7000	20 to 50	Forces, moments, pressures, heat transfer, Schlieren, LIF, DLAS	Hermes, MSTP, ARD
HEG (DLR)	High enthalpy	Short Duration ~1 ms	0.41 to 0.88	~8 4.7–6.2 km/s conical nozzle	2 to 6.7	7000 To 9900	35 to 90	Heat transfer and pressure, Schlieren and shadowgraph, holographic interferometry, DLAS, LIF	Hermes, Hope, MSTP, ARD, TETRA
TH2 (RWTH)	Cold and hot hypersonic	2 to 10 ms	0.586	6 to 12 (conic.) 7 (contoured)	2 to 160	1500 to 7500	6.5 to 80	Pressure and heat fluxes, infrared thermography, forces and moments, Schlieren	Hermes, MSTP, FESTIP

which are closely linked. All these phenomena have some consequences on flow topology (shock standoff, boundary layer) and heat-flux level during reentry.

As for chemical kinetics, the best way to investigate ionization and radiation would be a shock-tube fitting with superorbital reentry conditions. For an Earth return capsule, ablation is a key issue (one centimetre recession for Stardust). Related to ablation and to the blowing in the boundary layer, turbulence is another issue since it can completely counterbalance the blockage due to the blowing effect [44].

There is no facility capable of reproducing all these phenomena in Europe for the time being. The facilities that might have performances close to those required are the following:

(i) The PWK's facilities at IRS (sufficiently high heat flux and enthalpy but low pressure);

(ii) LBK at DLR with its new nozzle (it can reach heat fluxes of 10 MW/m^2 at 1 atm stagnation pressure but flow conditions have to be confirmed);

(iii) SCIROCCO after adaptation (measurements at the throat to cover EVD reentry trajectory in terms of heat flux and pressure);

(iv) SIMOUN is going to be extended for reaching heat flux up to 4 MW/m^2;

(v) MESOX at PROMES and VKI Plasmatron are of interest for investigating radiation.

Most of these facilities (excepting IRS PWK's which were used for SEPCORE TPS studies for a comet return capsule) have not yet been tested for EVD reentry conditions. Many of them need to be upgraded for reaching heat-flux levels representative of an EVD re-entry; additionally flow

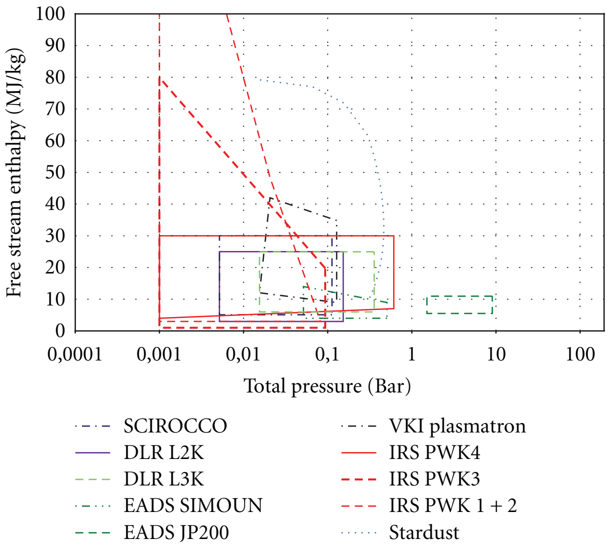

Figure 7: Stagnation point envelopes of some European facilities for TPS testing and reentry trajectory of Stardust (for a European standard model of 50 mm at the exception of JP 200).

conditions are not known and might not be in the correct ranges of pressure and Mach number. At the exception of MESOX (and may be VKI Plasmatron but this has to be confirmed) that can reach high radiative heat-fluxes, none of the other facilities has the capability to simulate flows with high levels of radiation. It is not demonstrated that these facilities can simulate flow conditions representing high-speed Earth reentry. When considering the flow aerothermodynamics of an EVD re-entry, it is clear that a huge gap has to be covered. This will request an extensive utilization of the existing facilities and a strong effort in analysis of flow conditions and numerical rebuilding. With its current capabilities, Europe has not the complete capability to validate the aerothermodynamics of a sample return capsule.

In ISC, the following facilities are of interest for investigating the aerothermodynamics of an EVD capsule. In the frame of ISTC [24], ablation tests were performed using IPG-4 Plasmatron at IPM Moscow and U-13 Plasmatron from TSIINMASH. This gave the opportunity to investigate the boundary layer of an ablative material. If the hypersonic flow corresponding to an EVD reentry is considered, no facility capable to reproduce such conditions has been found in the ISC.

4.2. TPS Testing. For TPS testing of materials to be used for high-speed Earth reentry, three points are of importance.

(i) Facilities have to be able to reproduce convective and radiative heat-fluxes.

(ii) Testing has to be done for turbulent conditions since the flow at the leading edge of the capsule could be turbulent.

(iii) Ground tests have to provide the capabilities to test material for stagnation conditions, and to qualify TPS assembling and joints.

If an EVD reentry is considered, the retained facility has to reach a heat flux of at least 8 MW/m^2 and a stagnation pressure up to 0.5 atm. The characteristics of European facilities which can be used for TPS testing of an EVD capsule are summarized in Table 7. The European facilities that can reach the relevant range of heat flux are

(i) GLADIS at the Max Planck Institute in Garching;

(ii) JP 200 (ASTRIUM-ST);

(iii) LBK at DLR;

(iv) PWK 1-2-4 (IRS);

(v) SCIROCCO (CIRA).

GLADIS [45] can reach very high heat-fluxes (up to 55 MW/m^2) and is used to test large elements of ITER facility such as tiles of CFC (carbon fibre reinforced composite). However, GLADIS operates at nearly vacuum conditions and the use of this ground test for reentry applications would require some upgrades and modifications of the facility. Additionally, this facility runs with He and H_2. Tests with air are not possible due to the presence of oxygen. Testing with nitrogen would be possible at higher pressure but at reduced heat-fluxes. The main interest of this facility is its capability to reproduce high radiative heat-fluxes. GLADIS is, indeed, one of the rare European ground tests (with may be MESOX and VKI Plasmatron) able to reach the level of radiative heat flux characterizing an EVD reentry. However, for such an objective, the facility has to be able to operate with air at around 0.5 atm which is not the case.

JP200 can reach the heat-flux range for an EVD reentry and is able to qualify tiles, gaps, steps, and seals for a capsule TPS. It is an open facility, and the stagnation pressure cannot go below 1.5 atm. This means that a TPS qualification with this facility under these conditions would be oversized. Other advantages of JP200 are its capabilities to simulate turbulent flows and to account for the dynamic aspect of the entry. Concerning IRS PWK1-2-4 facilities, they can reach heat-fluxes up to 15 MW/m^2 (the peak heat flux for Stardust was below this level) which could be sufficient for some EVD reentry trajectories (at least for the high-altitude part), but for a very low pressure. SCIROCCO in its standard configuration is not able to cover an EVD reentry trajectory. A possibility would be to move the test model near the nozzle throat, and then most of the points of Table 5 could be tested in terms of stagnation pressure and heat flux. LBK has a new nozzle and can now reach 10 MW/m^2. However, the corresponding flow conditions are not fully known.

Figure 7 compares the performance envelopes of some European facilities for TPS testing and Stardust reentry trajectory. In this figure, it is clear that only the end of the reentry at lower altitudes can be duplicated experimentally; this corresponds to the low enthalpy range of the reentry trajectory. From the material gathered in this paper, it appears that, among the available facilities, the most capable of reproducing the TPS conditions corresponding to an EVD trajectory are PWK4, LBK (but capabilities of LBK need to be confirmed), and SIMOUN. JP200 is too high in pressure, but could be used for reaching the level of heat flux

Table 7: Characteristics of facilities for TPS testing at high heat-fluxes.

Name	Heat-flux (MW/m^2)	Stagnation pressure (bar)	Running time	Model size (mm)	Measurements	Remarks
JP200	5–25	1.5–9	60 s	Flat plate: 200 ∗ 40 mm Thickness: 10–25 mm	Recession rate, heat flux, pressure and surface temperature	Turbulent flow. Test of tiles, gaps, and steps. Dynamic and static
SCIROCCO	0.26–3 Throat: Up to 21	0.005–0.11 Throat: up to 1.5	1800 s 20 s	800 For 20 mm MW: 25 For 100 mm: 8 MW	static pressure, stagnation pressure, temperature, heat-flux	TPS assembly
PWK1-2-4	Up to 15	20–5000 Pa	Max 3 h	320	Heat flux, pressure, oxygen partial pressure, dissociation degree, Mach number	Material characterization, high-enthalpy entry simulations, heat shield testing
GLADIS	4–45	Near vacuum conditions	Pulse of 1 ms, to 45 s pulses per hour	70	Heat-flux, temperature	Test of large components. Testing of full-scale ITER divertor targets. Hydrogen beam facility
LBK	10	Up to ∼1 bar with short nozzle	<1800 s	?	Pressure, temperature, heat flux, dissociation, emission	Aerodynamic heating studies, TPS qualification

while SCIROCCO would need to be modified to cover EVD trajectory requirements.

However, there is a critical issue for the TPS qualification: the radiative heat flux. For such an entry, it is an important phenomenon that cannot be skipped. Today, there is no facility in Europe capable of reproducing both convective and radiative heat flux for an EVD trajectory. The most performing facility for radiation in air environment is, for the time being, MESOX from PROMES. Since GLADIS cannot operate with air, an alternative is to use a facility from ISC or to upgrade an existing facility.

If ISC is considered, the following facilities are relevant for the qualification of an EVD capsule TPS:

(i) plasma Hall generator at HMTI (Minsk);

(ii) IPG-4 at IPM Moscow;

(iii) U13 Plasmatron at TSIINMASH;

(iv) U-15T-2 arc-jet at TSIINMASH.

Among these facilities, U-15T-2 is a powerful arc jet of 40 MW. The plasma Hall generator from Minsk can generate high radiative and convective heat-fluxes. This facility is unique and fits very well with the requirements of an EVD reentry.

An alternative would be to use lasers (as in GLADIS) to reach high radiative heat-fluxes. They can be used for initial material screening tests and spallation tests, as done during the Galileo project. A potential upgrade (or a new facility to be built) would be to combine an existing arc heater with a laser to cope with the requirements in terms of convective and radiative heat-fluxes for an EVD reentry.

4.3. Summary. To summarize the survey, some existing gaps have been identified in the capabilities of European facilities to cover a high-speed Earth re-entry.

(i) A shock tube for the chemical kinetics (actually the development of a kinetic shock tube has been initiated).

(ii) A strong effort has to be done for aerothermodynamics using and/or upgrading existing facilities for nonequilibrium flows, ionization, turbulence, radiation, and ablation. A large research program will be needed to fit the requirements of an EVD re-entry.

(iii) For the TPS material, Europe has the means to validate a material for high-speed reentry but not in all required conditions at the same time; however, a gap exists for radiation. A new facility or the upgrade of an existing facility will be necessary to achieve that. An alternative would be to use a facility from the ISC.

5. Assessment of Dynamic Stability

Another issue for exploration missions is the stability of the capsule during entry and descent: not only static stability has to be ensured but also dynamic stability. During the different regimes of the entry and descent, the stability of the capsule has to be guaranteed for the mission success and there is no phase of the flight where stability can be taken for guaranteed.

At very high altitude, in the transition regime from free molecular to continuum, many capsules are statically unstable but the moments are sufficiently small that they can be counteracted with a reaction control system or by applying sufficient spin. At lower altitudes, the real gas effects can affect the stability of blunt bodies. This is particularly the case for Mars entry in between Mach numbers 16 and 30 for a 70° sphere cone where the sonic line moves from the edge to the nose of the capsule, while on the windward side it remains attached to the edge. This induces some pressure effects and therefore static instability. This phenomenon was noted in Viking ballistic range tests and flight data [46] and rediscovered in the CFD predictions and flight data of Pathfinder [47]. In the low supersonic Mach number range, the static pitching moment coefficient of many capsules decreases with decreasing Mach number.

Ablation and resulting shape changes can also influence stability by altering mass properties, trim, and spin rate. This point is more relevant for a high-speed Earth reentry than for a Mars entry. TPS recession for a Mars entry is small (from 1 to 3 mm), and the shape does not change when considering the vehicle diameter, while, for an EVD capsule, recession can be up to 1 cm for a much smaller size of the capsule.

Dynamic instability affects all blunt bodies. Since this occurs after the peak in dynamic pressure, the decreasing dynamic pressure combines with the decreasing pitching moment coefficient to produce an amplification of the angle of attack oscillations. This phenomenon appears at low hypersonic Mach number, around Mach 4 for the first effects, and becomes more and more critical with the decrease of the Mach number, while the influence of the wake on the rear shell causes pitch damping coefficients to become destabilising (from Mach 2.5 to 0.8). This phenomenon is difficult to understand. Some progresses in the understanding were made in the early 70's by Jaffe [48, 49]. According to this author, dynamic stability is produced by the wake hysteresis even at small angle of attack. The corresponding Strouhal number of the phenomenon is very small, around 0.002, and might be produced by some pressure effects on the rear part of the capsule [50].

For a Mars entry, dynamic stability has to be ensured until the parachute deployment which occurs around Mach 1.8. If a high-speed Earth reentry is considered, this problem is more critical. Due to its small size and ultrahigh reliability requirements, the return capsule might have to brake and descend in the atmosphere without parachute [51]. This particular aspect of the system has some consequences on the capsule design. Without parachute, the dynamic stability of the capsule at terminal velocity becomes an important technological issue of the mission [52].

5.1. Facilities for Stability Studies. For this part of the survey, the facilities for stability testing in Europe, ISC, and also Australia and Canada have been accounted for. This effort has included open test ranges and ballistics tunnels.

Free flight tests can be carried out in open ranges or in ballistic tunnels; among the facilities reviewed for that, three provide this capability:

(i) ballistic tunnel at CEEM Valcartier in Canada;

(ii) free flight test in open range at ISL;

(iii) Woomera test range in Australia.

All these different facilities can be used for testing free flight models. The ballistic tunnel of Valcartier runs with air only. ISL free flight range has already been used for AURORA technology activities [53] and is currently in use for ExoMars tests. In this facility, capsule models equipped with sensors are shot with a gun and all flight parameters are measured. Woomera test range is mainly used to test sounding rockets and full size reentry demonstrators [54].

A lot of classic facilities (wind tunnels, shock tubes, and tunnels) are available in Europe for investigating stability. The following ground tests are relevant for stability studies.

(i) TMK tunnel at DLR (free and forced oscillations).

(ii) Wind-tunnels TM500 and HYP500 at FOI (free and force oscillations).

(iii) ISL supersonic wind tunnel.

(iv) ISL shock tubes (above Mach 3 in air, can run for CO_2).

(v) ONERA wind tunnels in Modane (France).

(vi) Shock-tube facility with discharge chamber at UMIST.

(vii) VKI S1 wind tunnel (free to tumble mounting system).

(viii) University of Oxford CO_2 suck-down facility (free oscillation, used for Beagle2).

(ix) In the ISC, the following tunnels could be used:

(x) ITAM hypersonic wind-tunnel T313;

(xi) TSAGI hypersonic wind-tunnel T-116;

(xii) TSIINMASH gas dynamics units TT-2, U-15T-2 and wind-tunnel U-306.

As far as dynamic stability is concerned, the problem with wind tunnels is the presence of the model support that does not allow duplicating exactly the model behaviour in flight. An alternative is to force the oscillation of the model as done in some facilities such as S1 at VKI. Instead of wind tunnels, the use of shock tubes could be very attractive as demonstrated at ISL. A reduced model is maintained in the tube by some filaments that are cut at the beginning of the run, and then the model is in free flight inside the tube. This technique might be very attractive to investigate dynamic stability for Mars entry since a shock tube can be operated with CO_2 at low pressure. Another possibility to get rid of the model support is to use the electromagnetic suspension as done at the University of Oxford in the low-density facility [55].

Other ISC facilities for low supersonic and subsonic flows have not been included in the paper since there are a lot of similar means already available in Europe.

5.2. Assessment for Mars and Earth Reentries. For Huygens, dynamic stability was investigated in the ballistic tunnel of ISL. This facility is now closed, but since it was working with air, similar experiments could be done in free flight tests keeping the correct velocities and using the similitude in Reynolds number. Other tests for Huygens were also carried out at ARA Bedford (now closed) and at FOI. Tests could also be performed in wind tunnels as done at VKI [50] in the frame of Mars Premier. Since it is not possible to use an open range to duplicate exactly free flight conditions in Mars atmosphere, a possibility would be to use shock tubes running with CO_2. This would complete the free flight and wind-tunnel tests using CO_2 flow conditions. To date, from the available information, the only dynamic stability testing with CO_2 in Europe was carried out for Beagle2 at the University of Oxford [56].

From the results obtained for an EVD model at ISL [53], the free flight tests seem to be ideal for the investigations on dynamic stability for Earth reentry. Additionally, tests can be performed in several European wind tunnels.

From the survey, capabilities for experimental campaigns on dynamic stability appear to be very mature in Europe. The use of the existing facilities should be sufficient for sample return missions. A ballistic tunnel capable to run at low pressure would be an additional advantage but the work load required for such missions would not be sufficient to ensure a full-time activity.

6. Conclusion

In the frame of past programmes such as Hermes and X38, Europe has developed strong experimental capabilities for suborbital Earth reentry. If now, sample return missions are envisaged; the existing experimental means will not be sufficient to cover the technical requirements for such missions.

The most critical issue is the chemical kinetics: as a consequence, the development of a powerful clean shock tube has been started to cover the chemical kinetics characterizing Mars entry and Earth high-speed reentry.

Concerning the development of nonintrusive methods, progress has been done but with a low rhythm. This effort should be intensified and new approaches developed or improved with the support of university laboratories. For the aerothermodynamics of both Mars entry and Earth high-speed reentry, before building a new facility, the existing ones should be upgraded and the experimental efforts increased since the potential of the existing facilities is far to have been fully exploited. An effort will have to be done for radiation during Earth high-speed reentry: a facility should be upgraded to cover this point.

Surprisingly, the Mars ascent is quite well covered with the existing ground tests. Here, the heritage from military activities related to missile applications is an advantage.

Dynamic stability is also well covered particularly for Earth reentry. For Mars entry, the Reynolds similitude can be used and tests performed in Earth atmosphere or a ballistic tunnel built. However, such a facility has a huge cost and will difficulty live with only the support coming from space missions.

Nomenclature

M: Mach number
Re: Reynolds number
T_0: Stagnation temperature (K)
P_0: Stagnation pressure (Pa).

Acronyms

ARD: Atmospheric reentry demonstrator
ATV: Automated transfer vehicle
CFC: Carbon fibre reinforced composite
CFD: Computational fluid dynamics
DLAS: Diode laser absorption spectroscopy
EVD: Earth vehicle demonstrator
ITER: International thermonuclear experimental reactor
LIF: Laser-induced fluorescence
TALIF: Two-photon absorption laser-induced fluorescence
TPS: Thermal protection system
TRP: Technology and Research Programme.

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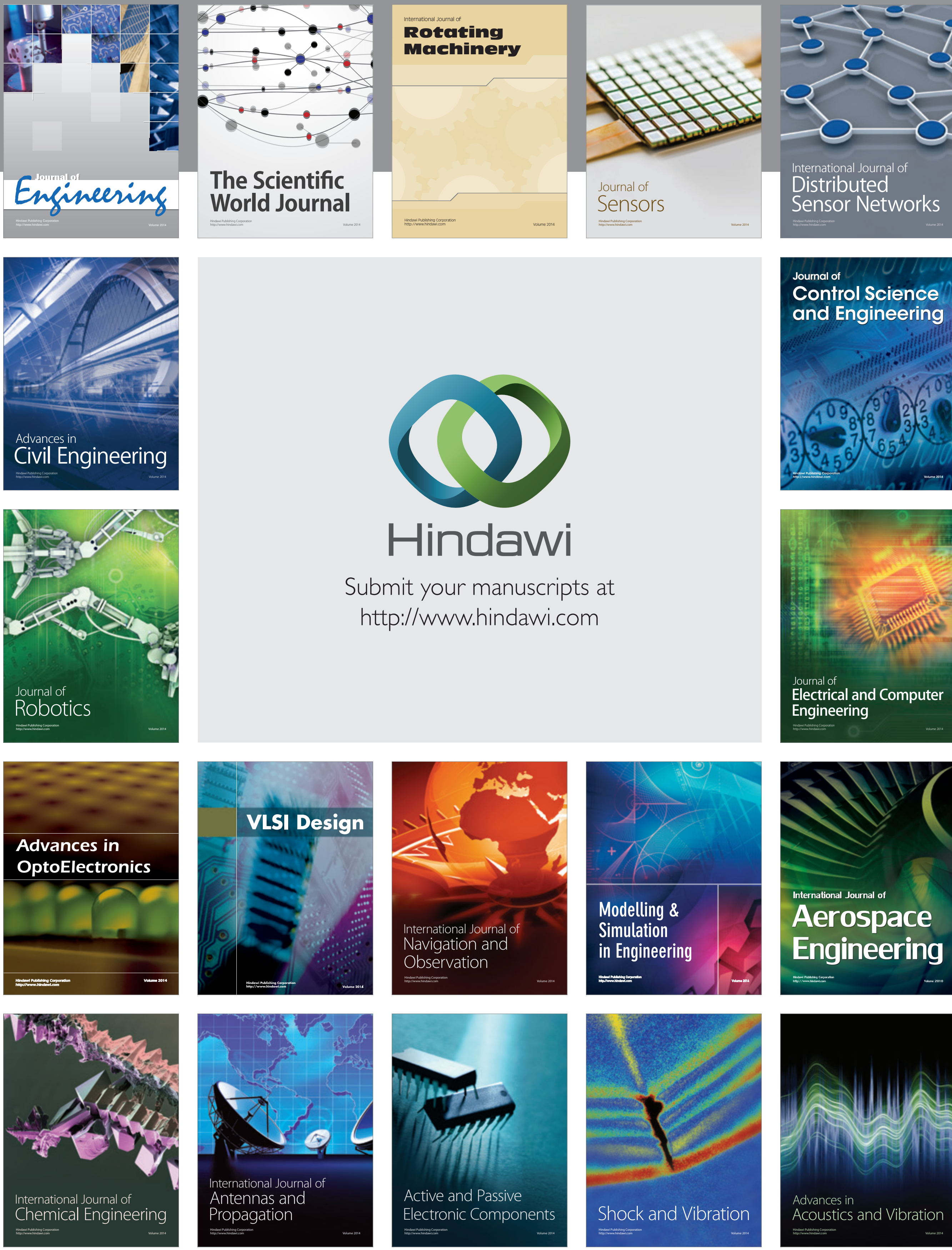
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