REVIEW OF EUROPEAN AERODYNAMICS AND AEROTHERMODYNAMICS CAPABILITIES FOR SAMPLE RETURN MISSIONS

Mathilde Bugel (1), Philippe Reynier (1), Arthur Smith (2)

(1) *Ingénierie et Systèmes Avancés, Pessac, France,*
EmailMathilde.Bugel@isa-space.eu
Email:Philippe.Reynier@isa-space.eu
(2) *Fluid Gravity Engineering, Emsworth - United Kingdown*
Email: Arthur.Smith@fluidgravity.co.uk

ABSTRACT

In the frame of future sample return missions to Mars and comets, investigated by the European Space Agency, ISA has undertaken a review of the actual aerodynamics and aerothermodynamics capabilities in Europe for Mars entry of large vehicles and high-speed Earth re-entry. Additionally, capabilities in Canada and Australia for the assessment of dynamic stability, as well as major facilities for hypersonics available in ISC have been included. This review provides an overview of European current capabilities for TPS testing and aerothermodynamics. This assessment has allowed the identification of existing gaps for covering Mars entries and Earth high-speed re-entries as far as aerodynamics, aerothermodynamics and TPS testing are concerned.

1. INTRODUCTION

The future missions, investigated by the European Space Agency in the frame of the AURORA 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 re-entry of the return capsule and the dynamic stability of blunt bodies during entry and descent. 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 has been 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.

IABG has performed a review on TPS qualification and thermo-mechanical testing [1] but this review has been essentially focused on mechanical testing and does not cover in details aerodynamic aspects, particularly if a superorbital entry is considered. Moreover, the survey presented is not complete since major companies have declined to provide information.

ONERA has dedicated an effort focused on aerothermodynamics [2] which is an excellent, complete review, but does not provide precise data on achievable performance of most of the facilities. Additionally, this review was also more focused on suborbital entry. Lu & Marren [3] 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.

Several issues are related to Mars entry of large vehicles. First, since Mars atmosphere is 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 reproduce the turbulence flow conditions during entry induced by the vehicle size and also by the possible presence of steps over the shield. 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 re-entries as those performed by NASA for GENESIS [4] and STARDUST [5-6] missions and the one to be performed by NASDA for HAYABUSA [7] are characterized by high heat-fluxes [8] and a significant level of radiation as shown in Fig. 1.

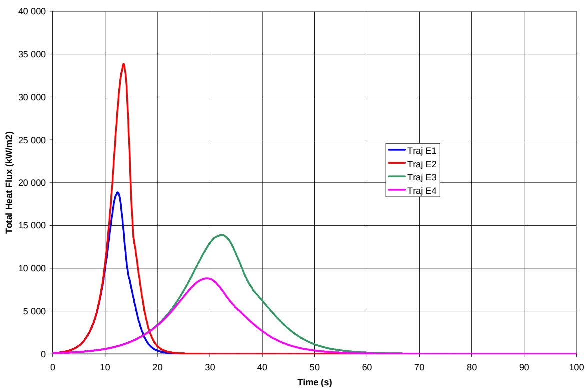

Figure 1: Total heat flux versus time for EVD mission [8].

Another point concerning entries of space probes is the ground capabilities for reproducing flow conditions as a function of Reynolds number and also the capabilities to simulate flow phenomena such as dissociation and ionisation. Related to non-equilibrium thermochemistry, chemical kinetics is also an issue, particularly for high-speed Earth re-entry.

Finally, 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. So the experimental facilities allowing the investigation of stability and more particularly of dynamic stability have been included in this review. To summarize, of particular relevance are the following processes:

• Simulation of turbulence in hot compressible gas;

• Simulation of re-entry flows in radiation environment;

• Thermo-chemical kinetics;

• Ablation, ionisation;

• Simulation of the influence of dust on flow properties.

The analysis of the different aspects retained for the review with the actual capabilities and the potential needs for additional capabilities or upgrading of existing ones for ensuring the success of sample return missions are detailed hereafter.

2. MARS ENTRY

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. However, previous studies have demonstrated the capabilities of some of the aerothermodynamics facilities to operate with a Martian atmosphere. The main features for a Martian entry are listed below:

• 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;

• Simulation of fully turbulent flows in high-enthalpy facilities for Martian entry of large vehicles;

• Capabilities of existing facilities to operate with CO_2 flows in presence of particles for hydro-erosion assessment;

• Available measurements techniques for Mars atmosphere.

2.1. Measurement techniques

Parallel to the material testing, diagnostic methods, intrusive probes and non-intrusive 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 are the following:

• Electrostatic probes: determination of electron properties;
• Mass spectrometer: probe in the plasma flow;
• Radiation probes (IRS);
• Fabry-Perot interferometry (for spectroscopy);
• Emission spectroscopy;
• Holographic interferometry;
• Laser techniques (laser induced fluorescence and laser absorption).

Trough TRP activities, slow progress has been made to determine temperatures, concentration, velocity and gas composition of the free stream flow, using non-intrusive laser based spectroscopic techniques. Laser induced fluorescence (LIF) measurements were performed on NO, CO and O particles, and DLAS (Diode Laser Absorption Spectroscopy) was used to probe CO and CO_2.

On its side, ONERA has extensively developed the DLAS 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 are equipped with this technique.

For future activities, it would be relevant to extend the capabilities of non intrusive techniques. The application of DLAS for measuring atomic oxygen would be a valuable contribution. A way for improving the state-of-the-art in intrusive techniques could be the development of holographic interferometry. The application of this technique to measurements in expansion tubes, performed recently at University of Queensland, 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 due to cost reason but also to their expertise, facilities available in the research institutes and universities have a strong role to play for the development of new experimental and diagnostic methods.

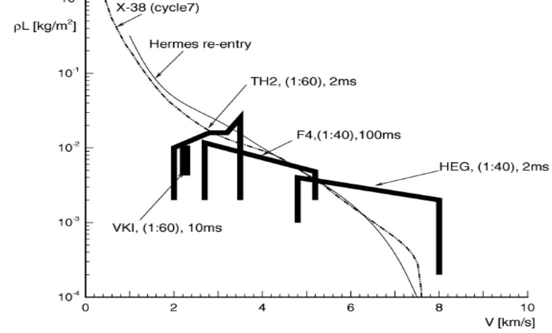

Figure 2: Performance envelopes of HEG, TH2, F4 and Longshot (VKI) for Earth suborbital re-entry according to Kordulla et al [9]

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, TCM2 from IUSTI was the only one used to perform experiments on chemical kinetics and thermal relaxation. It was also very attractive due to its capabilities for Mars and Titan entries. This facility has given a valuable contribution on chemical kinetics in a CO_2 environment, but unfortunately it has been stopped for safety reason. For investigation on chemical kinetics, the loss of TCM2 capabilities highlights the lack of shock tubes with the capability to cover planetary entries in Europe. The shock tunnels TH2 (RWTH) and HEG (DLR) could fill at least partially the gap but these facilities are more suitable for Earth sub-orbital entry as shown in Fig. 2. As a consequence, the development of such a facility for Mars entry should be envisaged.

Another possibility for the study of chemical kinetics during a Martian entry would be to use facilities from the ISC. VUT-1 (MIPT) is very attractive since it is used for chemical kinetics and 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 [10] study 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.

2.3. Radiation and Ionisation

Several European facilities can be used for investigating radiation and ionization during Mars entry. It is also possible to use facilities from the ISC at HTMI (Minsk), MIPT and TSAGI. Using the facilities available in Europe, radiation studies are well covered for a Mars entry, excepted the gap due to the stop of TCM2 shock tube. Little 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 from TSAGI.

2.4. Turbulence

On this point, there is really a lack of capabilities in Europe for 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 [11] 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 aerothermodynamics for turbulent flows. Both capabilities of Longshot and UT-M1 are not able to cover a Mars entry. To fill this gap, some modifications of existing capabilities (F4, SIMOUN, LBK, SCIROCCO, and others...) 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 gap for extrapolation to flight conditions from these (CFD) verification studies.

2.5. Dust Particles

The presence of dust particles in the mid latitudes atmosphere has to be accounted for the assessment of erosion during Mars exploration missions. The extrapolations, done in the frame of the ESA TRP project [12], lead to a recession of 1 mm for a clear day up to 6 mm for the worst case. Studies with dust particles have been performed in the frame of the Mars Premier Programme (at VKI [13]) and ESA TRP [12]. In Europe, there are few facilities capable of operating in a CO_2 dust loaded flow: SIMOUN (ASTRIUM), L2K (DLR), Minitorch (VKI) and UT-1M (TSAGI). Concerning ISC facilities, UT-1M facility from TSAGI was used with air [14] to investigate the distribution of particles concentration in the compressed gas layer (behind a shock wave) near a body surface.

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 3km/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.

2.6. TPS Qualification

For the TPS qualification of materials in a CO_2 environment, facilities have to reach a heat flux up to 2 MW/m^2 for a large vehicle [15] and for a static pressure below 10 mbar (stagnation pressure ~ 0.1 bar). It is also important to look at the shear, roughness and blowing of

materials as well as to take into account for the presence of turbulence during the 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.
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.

2.7. 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, variations of density can shorten the descent time endangering the mission success.
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 investigating 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 of IRDT-2R failure during its mission [16].

2.8. Summary

To summarize the review for Mars entry, some existing gaps have been identified in the capabilities of the European facilities:
• A shock tube for the chemical kinetics;
• A facility for the testing of parachutes;
• Improving experimental hypersonic capabilities for turbulence simulation;
• 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 are not fully representative of a Mars entry (too low in pressure or in Mach number);
• Need to pursue the effort on measurement techniques (DLAS, holographic interferometry);
• 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 and the need to improve hypersonic capabilities for turbulence simulation.

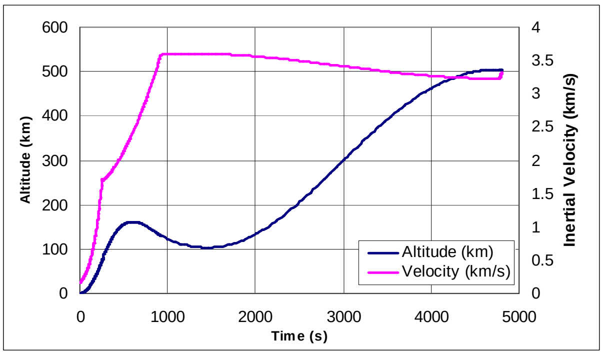

Figure 3: Typical Mars ascent trajectory [17]

3. MARS ASCENT

3.1. Scenario

In the frame of a sample return mission to Mars, the sample collected into Mars soil has to be sent to the return module orbiting around Mars. For this objective, the lander shall carry a return vehicle equipped with a propulsion 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 3. 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 day and night Martian temperatures.

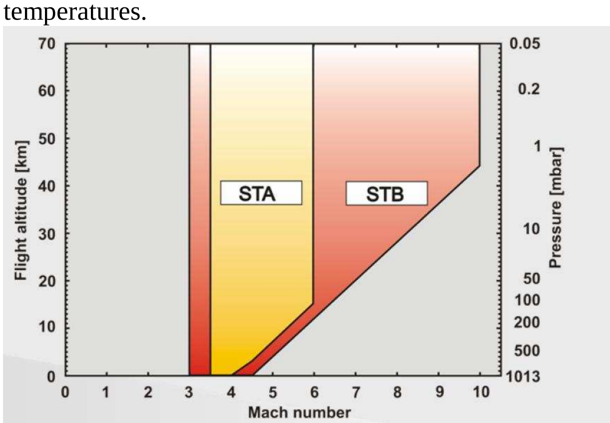

Figure 4: Capabilities of ISL shock tubes (credit ISL)

3.2. Ignition & Ascent

Among the European test facilities that could simulate in close conditions to the Martian environment the ignition of the propulsion system, the CAEPE's facility SESAME is attractive since it is capable to simulate the pressure range corresponding to the working condition 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 ATV propulsion system.
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 in this review 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 trajectory vehicle.
Among these facilities, ISL shock tubes can operate at low pressures corresponding to an Earth altitude of 70 km as shown in Figure 4. They should cover a large part of a Mars ascent trajectory. With the existing European facilities, a Mars ascent trajectory should be fully covered. To refine this analysis more details on both Mars entry trajectory and available performances of existing ground tests would be necessary.

Table 1: Maximum Stagnation Pressures for EVD mission

Trajectory	Stagnation Pressure at max Total Heat Flux (Pa)	Maximum Stagnation Pressure (Pa)
E1	70 396	131 500
E2	138 037	277 339
E3	48 534	80 300
E4	26 687	41 180

Table 2: Maximum heat fluxes for EVD mission

Trajectory	Convective flux kW/m^2	Radiative flux kW/m^2	Total flux kW/m^2	Total Heat load MJ/m^2
E1	11 500	7 500	18 800	106.9
E2	15 700	18 100	33 800	178.3
E3	9 350	4 550	13 900	243.2
E4	7 000	1 900	8 900	154.6

4. HIGH-SPEED EARTH RE-ENTRY

A sample return mission involves a direct high speed Earth re-entry with a velocity higher than 10 km/s and high heat-fluxes (more than 10 MW/m^2) at peak heating as shown in Fig. 1. The maximum stagnation pressure and the stagnation pressure at peak heating for different EVD trajectories are reported in Table 1 where the maximum stagnation pressure corresponding to the trajectory plotted in Fig. 1 are listed. 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 the European facilities have been designed.
Moreover, 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 Tab. 2 where convective and radiative heat-fluxes at peak heating are listed for different entry trajectories (see Fig. 1); and ablation [7] can be up to 1 cm with a capsule shape change that might affect the capsule 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.

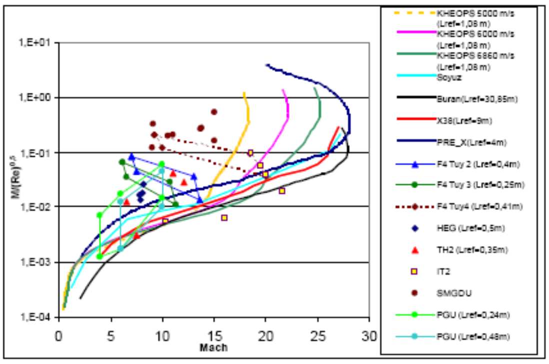

Figure 5: Capabilities of different facilities (F4, HEG, and TH2) for suborbital entries [2]

4.1. Chemical kinetics

Shock tubes are attractive for investigating chemical kinetics and thermal relaxation. As a consequence, in the perspective of a high-speed Earth re-entry, 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:
- TCM2 at IUSTI Marseille;
- HEG at DLR Göttingen;
- TH2 at RWTH Aachen;
- LONGSHOT at VKI

Other facilities exit at GDL and UMIST in United-Kingdown, at TU Braunschweig and HTG in Germany and Institut Saint-Louis in France. Unfortunately, most of these facilities have been developed for suborbital

entries [2] as shown in Fig. 5 and do not fit with the flow conditions characteristic of a high-speed Earth entry.
Considering a high-speed Earth entry, TCM2 is the most attractive, however this facility is actually stopped for safety reason: indeed it was broken when testing super-orbital re-entry conditions at just over 9km/s... Due to these limitations in Europe, the only alternative is to develop a new facility or to use a facility from the ISC. These facilities have already been used for studies on high-speed Earth re-entry in the frame of the ISTC programme [17]. 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 is lower than 8 km/s which is a little bit weak for an Earth super-orbital re-entry. But the facility fitting the best the 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 the ISTC project, however little details are available on this facility which can be used to measure electron concentration behind a shock wave, electron temperature, radiation intensity...
For superorbital entries, an alternative could be to use Australian facilities; several shock-tunnels are available at the University of Queensland providing high velocities, in the range of superorbital Earth re-entry. Moreover, since there is no equivalent in Europe, they could be used alternatively or conjunctly to ISC facilities.

4.2. Aerothermodynamics

The flow around an EVD capsule is characterized by high levels of ionization and radiation. Other important issues are turbulence and ablation which are closely linked. All these phenomena have some consequences on flow topology (shock stand-off, boundary layer) and heat-flux level during re-entry.
As for chemical kinetics the best way to investigate ionization and radiation would be a shock tube fitting with super-orbital re-entry 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 will be another issue since it can completely counter-balance the blockage due to the blowing effect [5].
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:
• PWK's facilities at IRS (sufficiently high heat-flux and enthalpy but low in pressure);
• LBK at DLR with its new nozzle (it is expected to reach heat-fluxes of 10 MW/m^2 at 1atm stagnation pressure but flow conditions have to be confirmed);
• SCIROCCO after adaptation (measurements at the throat to cover EVD re-entry trajectory in terms of heat-flux and pressure);
• SIMOUN is going to be extended for reaching heat-flux of 4 MW/m^2;
• MESOX at PROMES and VKI Plasmatron are interesting for investigating radiation.
Most of these facilities (excepting IRS which was used for SEPCORE TPS studies for a comet return capsule) have not yet been tested for EVD re-entry conditions. Several of them need to be upgraded to reach heat-flux levels representative of an EVD re-entry, additionally flow conditions are not known and might not be in the correct ranges of pressure and Mach number. Excepted MESOX (and may be Plasmatron but this has to be confirmed) that can reach high radiative heat-flux, 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 re-entry. 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 will be capable of doing little to validate the aerothermodynamics of the return capsule.
In ISC, the following facilities are of interest for investigating the aerothermodynamics of an EVD capsule. In the frame of ISTC project 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 re-entry is considered, no facility capable to reproduce such conditions was found in the ISC.

4.3. TPS Testing

For TPS testing of materials to be used for high-speed Earth re-entry, three points are of importance:
• Facilities have to be able to reproduce convective and radiative heat-fluxes;
• Testing has to be done for turbulent conditions since the flow at the leading edge of the capsule could be turbulent;
• Ground tests have to provide the capabilities to test material for stagnation conditions, and to qualify TPS assembling and joints.
If we consider a EVD re-entry, the retained facility has to reach a heat-flux of at least 10 MW/m^2 and a pressure up to 0.5 atm. The European facilities that can reach the relevant range of heat-flux are:
• GLADIS (Max Planck Institute);
• JP 200 (ASTRIUM-ST);
• LBK at DLR (stagnation pressure to be confirmed);
• PWK 1-2-4 (IRS);
• SCIROCCO (CIRA).

GLADIS is one of the rare European ground tests (with may be MESOX) able to reach the radiative heat-flux level characterizing an EVD re-entry. However, for such an objective the facility should 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 re-entry and is able to qualify tiles, gaps, steps, 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.

For IRS facilities; PWK1-2-4, they can reach a heat-flux up to 15 MW/m^2 which could be sufficient for some EVD re-entry trajectories (at least for high altitude part), the peak heat-flux for Stardust was below this level, but for a very low pressure.

SCIROCCO in its standard configuration is not able to cover an EVD re-entry trajectory. A possibility would be to move the test model near the nozzle throat, and then most of the points of Table 2 could be tested in terms of stagnation pressure and heat-flux.

LBK has a new nozzle and could reach 10 MW/m^2 by the end of 2008. However the corresponding flow conditions are not yet known.

From the material gathered in this review, it appears that for the facilities the most capable to reproduce the TPS conditions corresponding to an EVD trajectory are JP200, PWK1-2-4 and SCIROCCO (capabilities of LBK need to be confirmed). If IRS facilities are to low in pressure and JP200 too high an alternative would be to perform a flight extrapolation using a tool validated against measurements obtained in these facilities.

However, there is a critical point 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.

Among these facilities U-15T-2 (TSIINMASH) 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 re-entry.

An alternative would be to use lasers (as in GLADIS) to reach high heat flux. 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 re-entry.

4.4. Summary

To summarize the review for high-speed Earth re-entry, some existing gaps have been identified in the capabilities of the European facilities:

• A shock tube for the chemical kinetics;

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

• For the TPS material, Europe has the means to validate a material for high-speed re-entry but not in all required conditions at the same time; however a gap exists for radiation. A new facility or an upgrading 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

During the different regimes of the entry and descent, the stability of the capsule has to be guaranteed for the mission success. Several issues can affect the stability of the capsule. First, static instability can occur at high Mach number. Ablation and resulting shape changes can also influence stability by altering mass properties, trim, and spin rate. This last point is more relevant for a high-speed re-entry than for a Mars entry. In fact, for a high-speed Earth re-entry, EVD capsule recession can be up to 1 cm.

5.1. Testing facilities

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

• Ballistics tunnel at CEEM Valcartier in Canada;

• Free flight test in open range at ISL;

• Woomera test range in Australia.

All these different facilities can be used for testing free flight models. The ballistics tunnel at Valcartier runs with air only. ISL free flight range has already been used for AURORA technology activities [18] 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 re-entry demonstrators [19].

A lot of facilities are available in Europe for investigating stability. As far as dynamic stability is concerned, the problem with wind-tunnels is the presence of a 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 wind-tunnels such as S1 from VKI. Instead of wind-tunnels, the use of shock tube could be very attractive. The model (small) 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. Another possibility to get rid of the model support is to use the electromagnetic suspension as done at University of Oxford in the low-density facility.

5.2. Assessment for Sample Return Missions

For Huygens, dynamic stability was investigated in the ballistics tunnel of ISL. This facility is closed now, but since it was working with air the similar experiments could be done in free flight tests (keeping the correct velocities and using the similitude in Reynolds number). Huygens testing was also carried out at ARA Bedford (now closed) and at FOI. Tests could also be done in wind-tunnel as it has been done by CNES in the frame of Mars Premier at VKI [20]. Since it is not possible to use an open range to duplicate exactly free flight conditions in Mars atmosphere, a possibility would be to do that in shock tubes running with CO_2. This would complete the free flight and wind-tunnels tests using CO_2 flow conditions at low pressure. To date we believe the only dynamic stability testing in CO_2 in Europe was carried out for Beagle2 at Oxford.

From the results obtained for an EVD model at ISL, the free flight tests seem to be ideal for the investigations on dynamic stability for Earth re-entry. Additionally tests can be performed in several European wind-tunnels. The testing capabilities for dynamic stability are very good in Europe.

Capabilities for experimental campaigns on dynamic stability are 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 required for such missions would not be sufficient to ensure a full time activity.

6. CONCLUSIONS

In the frame of past programmes such as Hermes and X38, Europe has developed strong experimental capabilities for sub-orbital Earth re-entry. 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: a powerful clean shock tube is needed to cover the chemical kinetics characterizing Mars entry and Earth high-speed re-entry.

Concerning the development of non-intrusive methods, progress has been done but with a low rhythm. This effort should be intensified and new methods should be developed or improved with the support of university laboratories. For the aerothermodynamics of both Mars entry and Earth high-speed re-entry, before to build a new facility, the Agency should upgrade the existing ones and increase the experimental efforts with the existing capabilities: the potential of some facilities is far to have been fully exploited. An effort will have to be done for radiation during Earth high speed re-entry: 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 for missile applications is an advantage.

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

Acknowledgement

The authors are grateful to ESA for its support provided in the frame of Contract 20932/07/NL/PA. They would like to thank also all the participants to the Workshop on Facilities held at ESTEC on March 28, 2008 and all the people who have provided inputs for this review.

7. REFERENCES

1. Inventory of thermo-mechanical test facilities in Europe for TPS qualification, Final study report, IABG B-TA 4034, Ottobrun, Germany, 2005.
2. Traineau, J. C., Pélissier, C., Fomin, V. M., Kharitonov, A. M., Lapygin, V. I., & Gorelov, V. A., Review of European facilities for space aerothermodynamics, RT 1/06302, DMAE, ONERA, May 2003.
3. Lu, F. K. and Marren, D.E., Advanced Hypersonic Test Facilities, AIAA, Progress in Astronautics and Aeronautics, **198**, 2002.
4. Jenniskens, P., Wercinski, P., Olejniczak, J., Allen, G., Desai, P. N., Raiche, G., Kontinos, D., Revelle, D., Hatton, J., Baker, R. L., Russell, R. W., Taylor, M., & Rietmeijer, F., Preparing for Hyperseed MAC: an observing campaign to monitor the entry of the Genesis sample return capsule, Earth, Moon, and Planets, **95**, pp. 339-360, 2004.
5. Gupta, R. N., Aerothermodynamic analysis of Stardust sample return capsule with coupled radiation and ablation, AIAA Paper 99-0227, 1999.
6. Olynick, D., Chen, Y.-K., & Tauber, M. E., Aerothermodynamics of the Stardust sample return capsule, Journal of Spacecraft and Rockets, **36**, pp. 422-462, 1999.
7. Ahn, H.-K., & Park, C., Preliminary study of the MUSES-C reentry, AIAA Paper 97-0278, 1997.
8. CDF study report, MSR Mars Sample Return The Second Aurora Flagship Mission, Report CDF-16(A), 2003.
9. Kordulla, W., Bouis, X., and Eitelberg, G., Wind tunnels for space applications at DLR and ONERA, 1st International Symposium on Atmospheric

Reentry Vehicles and Systems, Arcachon, France, March 1999.

10. Beck, J., CFD validation in a CO_2 environment: Synthesis report, FGE CR012/08, Emsworth, United Kingdown, Feb. 2008.
11. Edquist, K. T., Dyakonov, A. A., Wright, M. J., and Tang, C. Y., Aerothermodynamic environments definition for the Mars Science Laboratory entry capsule, AIAA Paper 2007-1206.
12. Anon., Experimental and theoretical study of Mars dust effects, Summary Report MDUST-HPS-RP-001, HPS, Braunschweig, July 2007.
13. Chazot, O., and Boschek, E., Plasmatron facility for combined particle-impact and aero-heating tests, AIAA Paper 2003-4040, 2003.
14. Vasilevskii, E. B., Chirikhin, A. V. and Osiptsov, A. N, Heat transfer to a stagnation region of a blunt body in a hypersonic gas flow with an admixture of solid particles, ESA SP-426, Proceedings of the 3rd European Symposium on Aerothermodynamics for Space Vehicles, ESTEC, Noordwijk, The Netherlands, November 24-26, 1998.
15. Boutamine, D. E., Marraffa, L., Mazoué, F., and Reynier, Ph., IRDT Trajectory : Reconstruction of flight data, *Presentation at ESA-ESTEC*, Nov. 11, 2005.
16. Anon., Mars sample return, ESA, CDF Study Report, CDF-16(A), March 2003.
17. Chernyi G. G., & Losev, S. A., Problems of aerothermoballistics, radiation gasdynamics, heat and mass transfer for planet sample return missions, ISTC 1549-00, Final project technical report, Moscow, June 2003.
18. Berner, C., Fleck, V., and Sommer, E., Aerothermodynamics of Aerocapture and High Speed Earth Entry Dynamic Stability of Earth Entry Capsules – Testing Programme, ISL report FV 320/2007.
19. Tuohy, I. R., Advantages of the Woomera test facility for hypersonic flight programs, AIAA Paper 2006-7909, 2006.
20. Karatekin, Ö., Aerodynamics of a planetary entry capsule at low speeds, Ph. D. Thesis, Université Libre de Bruxelles, 2002.