PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1999 **357**, 2227-2248
doi: 10.1098/rsta.1999.0429

Hypersonic test facilities available in Western Europe for aerodynamic/aerothermal and structure/material investigations

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After a brief description of hypersonic ground test requirements, the paper first gives an overview of major hypersonic wind tunnels that have been modified or constructed in Western Europe for the determination of aerodynamic/aerothermal characteristics, such as forces and moments, or for the measurement of heat-transfer rates and heat-transfer distributions on space-vehicle configurations. The following facilities in this category are described:

(i) the blow-down wind tunnel S4 of ONERA in Modane, France;

(ii) the longshot facility of the von Karman Institute in Rhode-Saint-Genèse, Belgium;

(iii) the shock tunnel TH2 of the Aachen Technische Hochschule RWTH, Germany;

(iv) the piston-driven wind tunnel HEG of DLR in Göttingen, Germany; and

(v) the hot-shot test facility F4 of ONERA in Le Fauga, France.

In the second part, test facilities are treated that allow the investigation of structure/material problems in high-speed flow, as needed for the development of hot structures and thermal protection for re-entry vehicles. They may equally be of interest for high-speed flight in the lower atmosphere. The following facilities in this category are described:

(i) the induction-heated facility at the von Karman Institute, Belgium;

(ii) the arc-heated facility SIMOUN of Aerospatiale in St Medard, France;

(iii) the arc-heated facility L3K of DLR in Cologne, Germany; and

(iv) the arc-heated facility SCIROCCO of CIRA in Capua, Italy.

The operating principles of each of these facilities are described, the performance characteristics given and the main features of their construction highlighted.

Keywords: high enthalpy; arc heater; shock tunnel; induction heater

Phil. Trans. R. Soc. Lond. A (1999) **357**, 2227–2248

1. Introduction

In any aerospace project, ground testing in wind tunnels plays an important role throughout all phases by providing detailed inputs to the designer on performance and flight qualities of the configuration under development. In order to be able to make this important contribution, wind tunnels must simulate, as closely as possible, on reduced-scale models, what happens during the flight of the real aeroplane or spaceplane. The quality of such simulations is governed by so-called 'similarity' laws containing similarity parameters like Mach number and Reynolds number, to name the most commonly known. A wind-tunnel test on the model of a conventional aircraft is 'correct' if the ground simulation is performed at the Mach and Reynolds number of the full-scale version. In the case of Reynolds number, which is defined as the ratio of the product of air density times air velocity times a characteristic length of the body (for example wing chord) to the air viscosity, a wind-tunnel test at correct velocity must compensate for the undersized model wing chord by an increase in density, by a decrease in viscosity, or by a combination of both, so that the ground test and the flight occur at the same value of Reynolds number.

A spaceplane, when re-entering the Earth's atmosphere, passes through several different flow regimes, each of them governed by different similarity laws, and, therefore, often requiring specialized test facilities for representative simulation.

In the following, after a brief description of the different flow regimes encountered during re-entry, we will focus on the simulation requirements for the 'hot phase' of re-entry, which have led, in the past, to the modification or new construction of a number of facilities. Then we will present the operating principles and the main features of the five major wind tunnels that are available in Western Europe to cover the particular 'aerodynamic/aerothermal' simulation needs and which, by their unique features, can help to solve the problems posed by high-speed flight in the lower atmosphere.

Another category of wind tunnel is available that allows the simulation of 'structure/materials' problems. The description of their operating principles and main features forms the second part of this paper.

2. Flow-simulation requirements

Space vehicles encounter widely different flow conditions during flight, as depicted in figure 1 (taken from Hirschel (1993)). In the case of a re-entry vehicle, for example, they vary from highly rarefied flow at high altitudes, where the atmosphere is 'thin' (low density), to the classical Mach–Reynolds flow regime nearer the ground.

Coming down initially through a zone of low ambient air density using jet control, the vehicle experiences increasing density. This flow is characterized by a thick boundary layer that interacts with the inviscid external flow. Usually we call this flow regime the 'viscous-interaction regime'. Viscous interaction can have important effects on the surface pressure distribution, and, hence, affects lift, drag and stability. In addition, skin friction and heat transfer are increased. As densities increase further, the space vehicle decelerates more rapidly and traverses a zone where the nitrogen and oxygen molecules of the air are dissociated behind the bow shock caused by the vehicle. This is the period where heat load is highest. This flow regime is sometimes called the 'hypervelocity regime'. The dissociation of the flow and the associated potential recombination of molecules are called high-temperature effects.

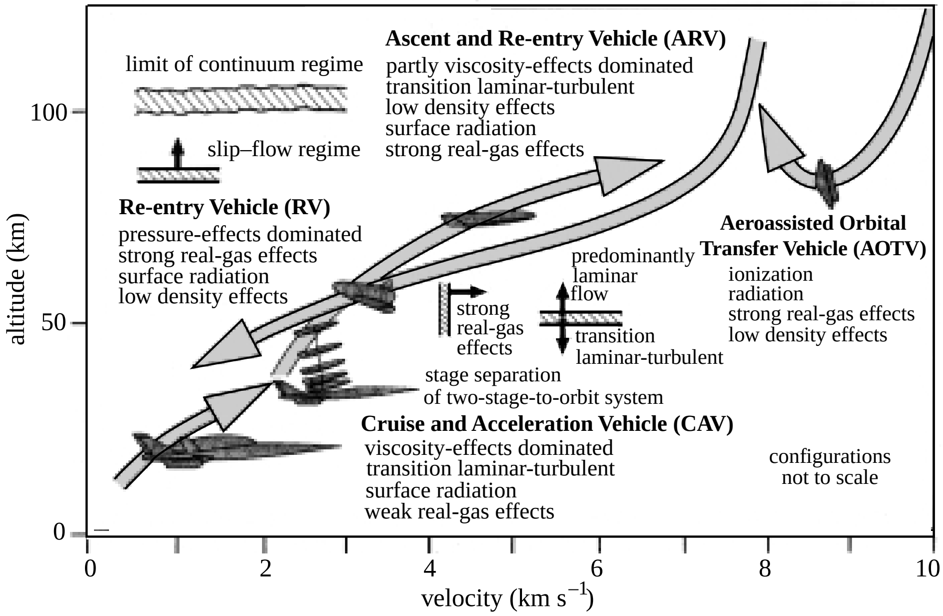

Figure 1. Flow phenomena and different categories of hypersonic vehicle.

Finally, we approach a flight situation where classical Mach and Reynolds number effects occur. The flight speed is already significantly reduced and the vehicle moves in the denser atmosphere close to ground. This flow is dominated by the state of the boundary layer (laminar, transitional, turbulent), the wall temperature ratio having significant influence. The physical laws governing the flow behaviour are relatively well known.

Ground-test simulation in the hypervelocity regime is particularly important because it is here that the heat loads on the vehicle surface are highest and, therefore, need to be known accurately in order to allow an appropriate design of the thermal protection. As indicated above, dissociation and recombination of oxygen and nitrogen are the predominant mechanisms in this flow regime. The test facility must, therefore, use air as a test gas flowing at speeds between 3 and 8 km s^{-1}. In addition, the simulation of high-speed chemically reacting flows with dissociation and recombination occurring requires the duplication of the number of intermolecular collisions necessary to dissociate a molecule or to recombine atoms. Investigations have shown that dissociation is a result of collisions between two partners and, therefore, dissociation simulation is governed by the so-called binary scaling parameter, which is the product of density and linear size (ρL) of the flow field under study.

To simulate recombination effects correctly, three-body collisions are required, which make it necessary to duplicate the product of density squared times linear size ($\rho^2 L$) in addition to speed. Thus, in a given ground experiment with a reduced scale model, binary and three-body collisions cannot be simulated at the same time. A test set-up for binary scaling will have three-body reactions that proceed too fast.

The complexity of the technical challenges presented by hypersonic systems, the lack of adequate ground test facilities, the cost and the risk of flight testing, and the advent of more and more powerful hardware and software for computation and simulation of physical phenomena, enforces (and makes possible) an integrated and coordinated use of the 'triad' (Methodology of Hypersonic Testing 1993) of ground testing, flight testing and computation and simulation. The widely adopted strategy consists of

(i) testing in dedicated facilities chosen according to the flight regime of interest;

(ii) calculating the conditions and results of experiments to validate the codes;

(iii) cross-checking these codes with flight results; and

(iv) applying the codes to real case re-entry.

The following section will first describe briefly the role of ground testing within the 'triad'. Then more information regarding test or simulation requirements for hypersonic flight will be provided, and, finally, the major difficulties associated with hypersonic test facilities will be mentioned.

3. Hypersonic ground test requirements

Following the needs of the development process for a space vehicle, two different classes of ground test facilities can be distinguished.

1. *Research and development test facilities* are used in the early phases of a project to help the understanding of the basic physical phenomena and to aid in the development and validation of computer codes. Therefore, it is important to have well-defined flows and to provide for non-intrusive high-resolution diagnostics of the flow properties. Typically, these facilities can be small and do not need long testing times.

2. *Engineering development facilities* become necessary in the later phases of a project to validate the design by evaluation of system durability and operability. Large or full-scale hardware must be tested in adequately defined flow conditions, but global measurements are usually sufficient.

Table 1, based upon Methodology of Hypersonic Testing (1993), represents the ground test simulation requirements for hypersonic flight. The list shows the basic types of test, the corresponding test and simulation requirements, and the necessary test times.

For R & D testing, these requirements can most often be met with some difficulties, but as soon as engineering development is concerned, the test engineer faces a major challenge. He undertakes to provide adequate measurements for test analysis and code comparison while trying to achieve simultaneously the correct velocity in the correct gas at sufficient scale and adequate run times.

Most of the inadequacies of hypersonic facilities arise from the need to provide very high temperatures and pressures for simulation. Therefore, devices to add energy to the flow are a key issue and several new concepts are under investigation.

In the following chapter a description of the major hypersonic facilities available in Europe for 'aerodynamic/aerothermal' testing is given. These facilities were modified or newly constructed in the context of the Hermes programme of the European Space

Table 1. *Test and simulation requirements for hypersonic flight*

		simulation		
type of test	requirements	duplicate	relax	test time required
aerodynamic				
classical	reproduce force coefficient, pressure and heating distributions	Mach number	temperature Reynolds number	milliseconds
real gas chemical effects	evaluate effects of dissociated flows on aerodynamic measurements	gas composition temperature density × length Mach number	run time	milliseconds
aerothermal	duplicate heating rates and aero-shear, full-size hardware	total temperature surface pressure	Mach number	minutes
aeropropulsion	conditions for proper chemical reactions, mixing, boundary layers and shocks full-size hardware	gas composition pressure temperature Mach number velocity scale		minutes
structure and materials	combined loads (mechanical, thermal, acoustic), temperature gradients	loads temperature heating rates	flow velocity	minutes
impact	target interaction debris propagation	relative velocity mass		microseconds

Agency (ESA) and then used within the 'Hypersonic ground testing comprehension and use for design' studies of the ESA. The aim of this programme was, on the one hand, to improve the understanding of hypersonic nozzle flow over a wide range of parameters, and, on the other hand, to test generic models in these by then well-known flows to provide data for code validation. The program also provided for some improvement of the facilities. The paper 'A review of European code validation studies in high-enthalpy flow' describes this approach in more detail (see Muylaert *et al.*, this issue).

4. Aerodynamic/aerothermal test facilities

In the following we concentrate on the major test facilities available in Europe for 'aerodynamic' and 'aerothermal' types of test. First their operating principle will be explained and then their basic layout described.

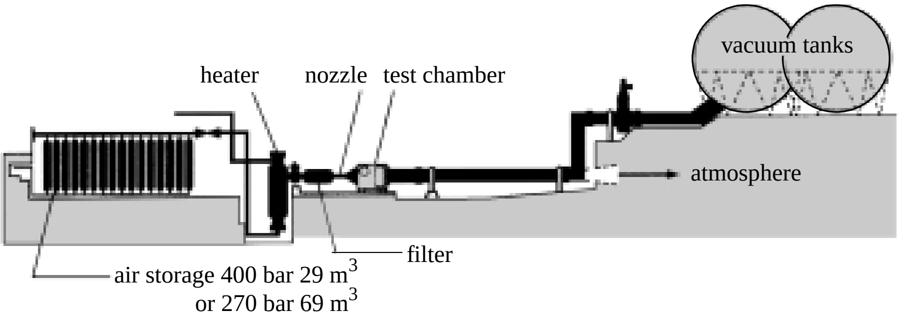

Figure 2. Blow-down wind tunnel S4 of ONERA.

(*a*) *Blow-down wind tunnel S4 of ONERA (Laverre 1987)*

(i) *Facility operating principle and layout*

In a typical blow-down wind tunnel, air is compressed to high temperature, dried, and then stored in large tanks. In parallel, a large mass of ceramic pebbles is heated to high temperatures by a gas-fired burner. A run is initiated by opening a throttling valve that allows high-pressure air from the storage tank to flow through the pebble bed, heating up there, and then expanding this heated gas through a convergent–divergent nozzle to the desired hypersonic Mach number. Typically, tunnels employing this operating principle allow settling chamber temperatures just high enough to avoid liquefaction of the test gas in the test section.

The S4 facility (figure 2) uses the 29 m^3 air storage tank of the ONERA Modane test centre, which allows pressures up to 400 bar. The pebble bed heater, with a diameter of 2 m and a height of 10 m, contains 12 t of alumina pebbles that can be heated up to a maximum temperature of 1850 K by combustion of propane. The air leaving the heater passes through a 10 μm filter to retain the dust particles originating from the pebbles. Three hypersonic nozzles are available. The Mach 6.4 nozzle is 3.6 m long, has a throat diameter of 75 mm and an exit diameter of 685 mm. The Mach 10 and the Mach 12 nozzles employ the same hypersonic exit section with an exit diameter of 994 mm. The interchangeable throat section has a diameter of 36 mm in the Mach 10 case and of 21.5 mm in the Mach 12 case. Both nozzles are *ca.* 7 m long. The cubical test section of 3 m side length houses the model support, which provides an incidence range of $\pm 15°$ at $2–5.5°\ \mathrm{s}^{-1}$ and a side slip range of $\pm 50°$ at $2.8–11°\ \mathrm{s}^{-1}$. A rapid injection device allows the model to be put into position once the flow in the nozzle is fully established, thus avoiding the heavy loads caused by the flow-starting process. The model can also be retracted rapidly before the flow stops. Downstream of the test section, the flow is collected in a diffuser and either blown to atmosphere or collected in vacuum vessels of 3000 or 4000 m^3 volume.

(*b*) *VKI facility of VKI*

(i) *Facility operating principle and layout*

This facility, fully described by Simeonides (1990) and sketched in figure 3, is a heavy-piston gun tunnel, consisting of a 12.5 cm bore, 6 m long driver tube (initially pressurized with dry nitrogen to 300 bar at room temperature), and a 7.5 cm bore,

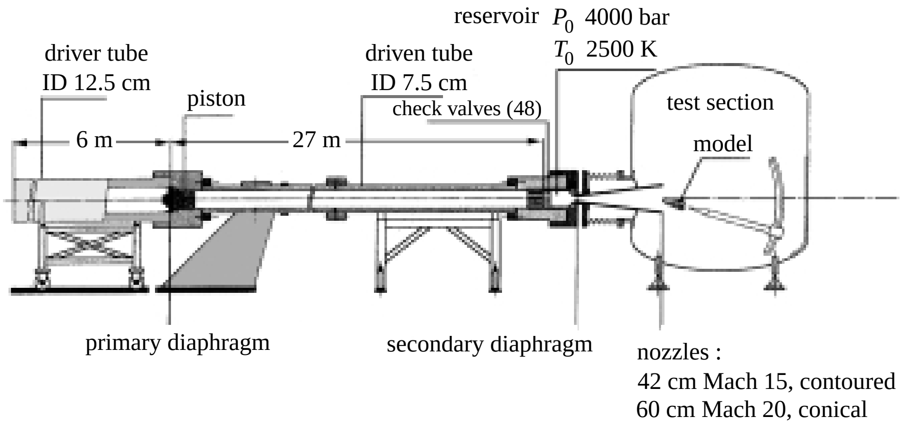

Figure 3. VKI facility of VKI.

27 m long driven tube (initially pressurized with dry nitrogen to *ca.* 1 bar at room temperature). These two parts are separated by a heavy piston with a mass of 1.8–9 kg, which is held at its initial position by an aluminium diaphragm. Rupture of this diaphragm releases the piston, which is shot down the driven tube, thereby compressing the nitrogen gas in front of it into a 320 cm^3 reservoir, where pressures as high as 4000 bar and temperatures up to 2500 K may be attained. The compressed gas is trapped in the reservoir by the automatic closure of 48 poppet valves. The subsequent bursting of a secondary copper diaphragm located in the converging part of the contoured hypersonic nozzle allows the test gas to expand to Mach 14 into a 16 m^3 test section, depressurized to a high vacuum (5 mmHg) before the test. The diameter of the nozzle exit is 42.7 cm, and that of the core of uniform Mach number is 24 cm. Due to the small reservoir volume, the useful duration of a test is limited to *ca.* 10–15 ms, and the test conditions continually change with time.

To define the test conditions, the reservoir pressure and the pitot pressure in the test section are measured. The reservoir temperature is derived from a measurement of the heat-transfer rate at the stagnation point of a spherical probe located in the test section.

The test model is sting mounted in the test core. Two different stings are available: one is 1.2 m long, supported on a circular sector mount, and the other (shorter) one (0.5 m long) is supported on the upper platform of a five-degrees-of-freedom orientation mechanism.

(*c*) *Shock tunnel TH2 of RWTH Aachen (Anonymous 1991)*

(i) *Shock tunnel operating principles*

A shock tunnel consists of a driver, driven section, nozzle, and dump tank with test section. Figure 4 shows, schematically, the set-up of the shock tunnel TH2.

Driver and driven section are separated by the main diaphragm. The driver section is filled with the so-called driver gas, usually helium. The driven section contains the test gas, usually air.

Typical driver pressures are between 100 and 1500 bar, and driven gas pressure is between 0.1 and 10 bar. Before the test starts, the dump tank is evacuated. The

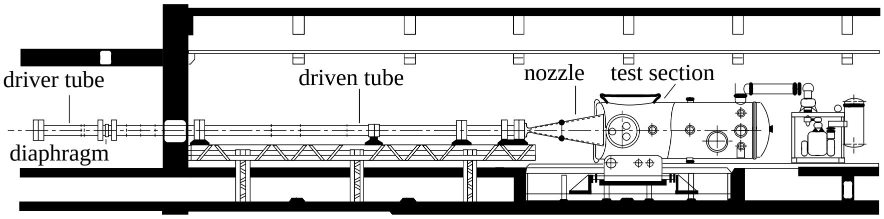

Figure 4. Shock tunnel of RWTH Aachen.

driven section and receiver tank are separated by another thin diaphragm to avoid the inflow of the test gas into the dump tank before the test starts.

To initiate a run, the diaphragm is burst by a simple mechanical device. A shock wave propagates into the test gas, compressing it to higher pressure and increasing its temperature. A few milliseconds after the bursting of the diaphragm, the incident shock wave arrives at the end wall of the driven section. The shock tunnel at Aachen operates in the reflected mode, i.e. the incident shock wave is reflected at the end wall and thereafter propagates upstream. During this reflection process, the second diaphragm between the driven section and the nozzle bursts and the nozzle flow starts. The flow velocity behind the reflected shock is zero to a first approximation if the outflow from the nozzle is neglected. The complete kinetic energy of the shock-heated gas is thus converted to high enthalpy behind the reflected shock. The compressed test gas, having a temperature of a few thousand degrees centigrade, expands subsequently through the nozzle. The high stagnation enthalpy is thus converted to a high free-stream velocity in the test section.

After a short time, the reflected shock interacts with the contact surface between the driver and driven gas. During this interaction, new waves are usually generated that propagate downstream towards the end wall, while the reflected shock moves with changed velocity further upstream. In the case of a special combination of the initial parameters, the reflected shock ideally penetrates the contact surface without generating further reflections of finite amplitude, the so-called tailored interface case. In the tailored interface case, the nozzle reservoir pressure and temperature produced by the initial reflection of the incident shock at the end wall persist for a relatively long time, which favours a long test run.

In the undertailored case, the incident shock Mach number is lower than for the tailored case. In this case, an expansion wave is generated when the reflected shock and the contact surface interact. In the overtailored case, the incident shock Mach number is higher than in the tailored case. This leads to a secondary reflected shock and a transmitted shock that are generated by the interaction of the initial reflected shock and the contact surface. The secondary reflected shock again reflects at the end wall, and, in this way, a region of multiple reflections develops, which leads to an equilibrium nozzle reservoir pressure. The shock tunnel TH2 is operated in the tailored and overtailored interface mode, but undertailored operation is also possible.

(ii) *TH2 facility layout*

The shock tube of the Aachen shock tunnel has an inner diameter of 140 mm with a wall thickness of 80 mm. The lengths of the driver and driven section are 6 m and

15.4 m. The building that houses the shock tunnel was built especially for the use of such tunnels. An 800 mm steel-reinforced concrete wall that separates the rooms for driver and driven section serves as a protecting wall but is also used for supporting the recoil absorbing system of the tunnel. There is a sliding joint between the driven section and the nozzle. The nozzle and dump tank form one unit that is also fixed by a recoil damping system to the foundation. The model support has an independent foundation. Thus, even if the receiver tank can move, the model support is fixed to the laboratory foundation.

Driver and driven section are separated by a double-diaphragm chamber, which, at maximum pressures, uses two 10 mm thick stainless steel plates as diaphragms scored in the form of a cross by a milling cutter. Another diaphragm of brass or copper sheet is located between the driven section and the nozzle entrance. The maximum operating (steady) pressure of the complete tube is 1500 bar. The driver can be electrically heated to a maximum temperature of 600 K. The exit diameter of the conical nozzle amounts to 572 mm. Two other truncated cones allow nozzle exit diameters of 1 m and 2 m. The nozzle throat diameter and, therefore, the test section Mach number can also be changed by inserting different throat pieces. Furthermore, a contoured nozzle of 586 mm exit diameter and a nominal Mach number of 7 is available.

(*d*) *The high-enthalpy facility (HEG) (Vennemann et al. 1993; Eitelberg 1994)*

(i) *Free-piston driver technique*

The HEG also operates according to the shock tunnel principle but the designers aimed at much higher enthalpies than in the Aachen facility. To generate the desired level of reservoir enthalpies, shock speeds of the order of 5 km s^{-1} are needed. For this level of shock speeds, the driver gas must be heated also. Typically, if helium is chosen as the driver gas, its temperature must be of the order of 4000 K. This can only be achieved by a short-duration method, and the technique chosen for HEG is adiabatic compression of the driver gas with a piston.

Details of the free-piston driver technique, its performance and limitations, are described by Stalker (1967).

(ii) *HEG facility layout*

A schematic view of the high-enthalpy facility in Göttingen is presented in figure 5. The free-piston shock tunnel arrangement consists of three main sections: the ‘driver’, consisting of an air buffer and a compression tube, the shock tube, and the nozzle, with a large test section downstream.

The facility operation proceeds as follows. First, high-pressure air in the air buffer is used to accelerate a heavy piston down the compression tube, thereby heating the driver gas adiabatically. Usually, pure helium is used as the driver gas. When the desired pressure is reached, a diaphragm at the downstream end of the compression tube ruptures, causing a shock wave to propagate down the shock tube. This shock wave reflects at the end of the shock tube, leaving behind a region of gas at high temperature and pressure, the reservoir conditions, which are maintained ‘constant’ for *ca.* 1 ms. From these reservoir conditions, the gas expands through a convergent–

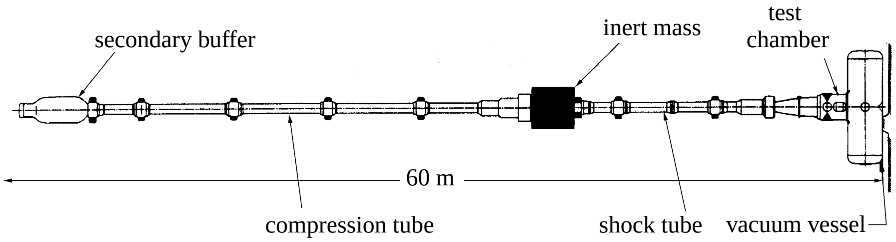

Figure 5. High-enthalpy facility of DLR.

divergent contoured nozzle into the test section where the models to be investigated will be mounted.

The driver consists of a 0.55 m inner diameter tube of 33 m length in which the piston can move freely. The air buffer is 'wrapped' around to reduce the required building length and has a volume of 5 m^3. A steel diaphragm separates the compression tube (driver) from the shock tube. Rupture pressures of 500, 1000, 1500 and 2000 bar were selected. With a compression ratio of 60, the desired density range can be obtained. In order to be able to operate 'tuned' piston conditions at these four different pressure levels, four pistons of different mass are available. With these, it is possible to maintain the driver pressure constant for *ca.* 1 ms.

The shock tube, with its internal diameter of 0.15 m, has a length of 17 m. In order to get some flexibility to optimize the driver operation, an interchangeable orifice is mounted at the inlet of the shock tube controlling the driver gas pressure by restricting the flow rate into the shock tube.

At the downstream end of the shock tube, the reservoir condition will exist for *ca.* 1 ms. This is a region of very high loading because here maximum pressures of *ca.* 2000 bar and temperatures of up to 14 000 K will occur.

The nozzle is contoured and was designed for operation at Mach 7–8, giving the required air speed and density at the location of the model. With a throat diameter of 22 mm and an outlet diameter of 880 mm, the useful core of the flow is large enough to accommodate Hermes models of 30–40 cm in length. The overall length of the nozzle is 3.75 m.

The test section with a diameter of 1.5 m is equipped with a model support allowing a variation of the angle of attack of the models. Eight viewing ports give optical access to the model flow field.

The performance map of the HEG is not yet fully explored. The maximum enthalpy obtainable so far in tailored operating conditions is *ca.* 22 MJ kg^{-1}.

(*e*) *F4 hot-shot facility (Chanetz et al. 1992; Vennemann et al. 1993)*

Here, the hot-shot driver technique used to create the necessary reservoir conditions for the F4 facility is explained; this is followed by a description of the wind tunnel layout.

(i) *Hot-shot driver technique*

The hot-shot driver technique uses a reservoir with a volume of several litres. This volume is initially filled with the test gas, air in our case, at pressures selected according to the final pressure level desired. The air is heated up and further compressed

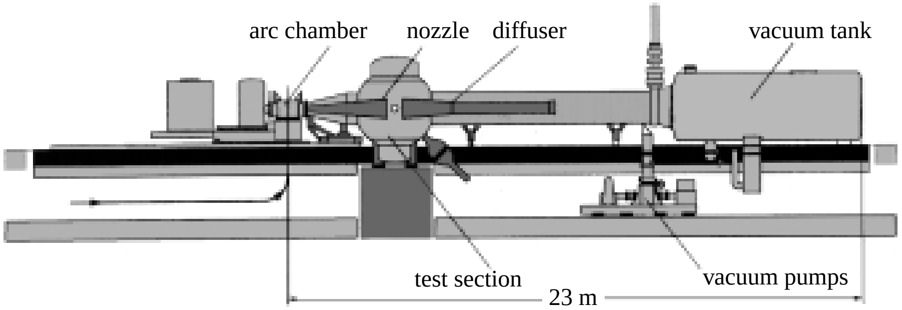

Figure 6. Hot-shot facility F4 of ONERA.

with an electric arc ignited between two electrodes integrated in the wall of the arc chamber surrounding the volume of air. The duration of the arc can be varied so that more or less energy can be transferred to the gas according to the desired reservoir conditions.

(ii) *F4 facility layout*

A schematic view of the F4 facility at ONERA, Le Fauga, is presented in figure 6. The hot-shot wind tunnel arrangement consists of the following main elements:

(i) the impulse machine (not shown but described below);

(ii) the arc chamber;

(iii) the convergent–divergent nozzle;

(iv) the test section where the model can be mounted;

(v) the diffuser; and

(vi) the vacuum tank.

The facility operation proceeds as follows: first, the alternator of the impulse generator, acting as a motor, accelerates the flywheel to its nominal speed. Then the alternator in generator mode decelerates the flywheel, thus providing the electric energy to the arc chamber, which has previously been filled with pressurized air.

The electric arc between the arc chamber electrodes heats and further pressurizes the air until a high reservoir pressure is reached. Then a plug placed in the throat of the nozzle that is connected to the arc chamber is exploded and the hot gas can expand from the volume through the convergent–divergent nozzle to the test section where the model will be mounted. In this process, the reservoir conditions decay with time. Downstream of the model, the gas is collected and decelerated before flowing into the vacuum tank from which it will be discharged after the test.

The impulse machine consists of a flywheel with a mass of 15 t, which is coupled to an alternator of 150 MW. Functioning as a synchronous motor with variable frequency, the alternator accelerates the flywheel to 6000 RPM, which represents an energy storage of 400 MW. The motive electric circuit is then disconnected and the rotor is excited for generator action supplying DC current to the electrodes of the arc chamber via rectifiers and high-speed switches.

The arc chamber is a cylindrical container designed for pressures of up to 2000 bar. At each end of the cylinder, electrode holders close the volume. These holders can be set in different positions so that the volume can be chosen to be between 4 and 15 l according to the run duration desired. To reduce the erosion rate of the electrodes, they have a spiral form, which creates a magnetic field that makes the electric arc rotate. The arc is initiated with the help of an electric wire and is usually maintained for *ca.* 30–90 ms. The chosen reservoir pressure (at which the plug in the nozzle throat is to explode) is reached just before the arc is switched off. The arc chamber can be quickly evacuated into a dump tank when the projected test time (20–100 ms) is over to avoid too much pollution of the test section by the remaining gas having been in contact with insulation materials for the longest time.

Four different nozzles are available to cover the specified flow regimes with exit diameters ranging from 430 to 860 mm. For the first tests, an existing nozzle (number 1) was used with a design point at Mach 16. It has a 6.3 mm copper–tungsten throat and a contoured supersonic part made of steel near the throat, and of fibreglass near its exit (the exit being 670 mm in diameter). Nozzle number 2 is identical to number 1, with the exception that the throat has a diameter of 10 mm. Nozzle number 3, with an outlet diameter of 430 mm, provides the highest values of the binary scaling parameter (ρL). Nozzle number 4, with an exit diameter of 860 mm, is available for viscous-interaction simulation. According to these nozzle sizes, Hermes models of 1:45 to 1:50 scale could be mounted and tested in the test section.

The test section is equipped with an adjustable or actuated model support that can change the angle of attack of the model by 20° in 50 ms. Due to the relatively lower energy level of F4 with respect to the HEG, testing times can be longer in F4, and with durations of 20–100 ms the testing times are long enough for force measurements to be made with balances in the model.

(*f*) *Simulation capability of aerodynamic/aerothermal facilities*

The principal characteristics of the five test facilities described above are summarized in table 2. As can be seen from the nozzle exit dimensions, none of these facilities can be counted among the 'engineering development facilities', although the F4 and the HEG are among the largest facilities of their kind in the world.

For the purpose of presenting the simulation capabilities of our facilities versus simulation requirements, the Hermes re-entry trajectory is used for two reasons, as follows.

1. The S4, the TH2 and the VKI facilities were modified for use in the Hermes programme, and the F4 and the HEG facilities were newly constructed.
2. The trajectory is that of a low L/D vehicle and, therefore, can be regarded as roughly representative of the vehicle configurations actually under consideration at the ESA.

Figure 7 places the performance envelopes of the five facilities on a Reynolds–Mach number map. The Reynolds numbers of each facility are calculated for the model length L of a typical model that can be tested in the particular test facility.

Table 2. *Principal characteristics of hypersonic test facilities*

name of facility	operator	country	test gas	Mach number
blow-down facility S4	ONERA	France	air	6, 10, 12
longshot facility	VKI	Belgium	N_2, (CO_2)	14, 20
shock tunnel TH2	RWTH Aachen	Germany	air, N_2	7, 6–12
high-enthalpy facility HEG	DLR	Germany	air, N_2	7
hot-shot facility F4	ONERA	France	air, N_2	9–18

name of facility	nozzle exit diameter (m)	maximum total pressure (MPa)	maximum total temperature (K)	run time (s)
blow-down facility S4	0.7, 1.0	15	1100 (1500)	30–100
longshot facility	0.43, 0.60	400	2500	0.005–0.01
shock tunnel TH2	0.6, 1.1, 2.0	63	4700	0.002–0.009
high-enthalpy facility HEG	0.8	180	10 000	0.001
hot-shot facility F4	0.43, 0.67, 0.93	200	5500	0.02–0.1

The re-entry path representing the simulation requirements is calculated for a full-scale length $L = 15.5$ m. Model scales vary between $\frac{1}{60}$ for the smallest facility to $\frac{1}{40}$ for the largest.

The graph also shows lines of constant rarefaction parameter (dashed) and of the constant viscous-interaction parameter (solid). Furthermore, a boundary between ‘strong’ and ‘weak’ viscous interaction (reciprocal influencing between boundary layer and outer inviscid flow field) is shown. As viscous interaction can have important effects on the surface pressure distribution over the vehicle and, consequently, can affect lift, drag and stability, it is important to be able to test on both sides of this boundary.

5. Hypersonic structure/material test facilities

Hypersonic structure and materials testing, according to table 1, requires long testing times that are usually neither available nor necessary in aerodynamic facilities. Facilities that provide long-duration flows with sufficiently high-enthalpy capability as required for high-speed testing in most cases are plasma wind tunnels. The facilities that will be presented below are all of this type, but different plasma heating techniques are applied. Therefore, we first describe the basic layout of such facilities and give brief information about the different heating devices employed, before giving more detailed descriptions of several new facilities in Western Europe.

(*a*) *Basic layout of a plasma wind tunnel*

A schematic layout of a plasma wind tunnel is shown in figure 8. In general, such facilities consist of a gas supply system, a heating system, where the test gas is heated

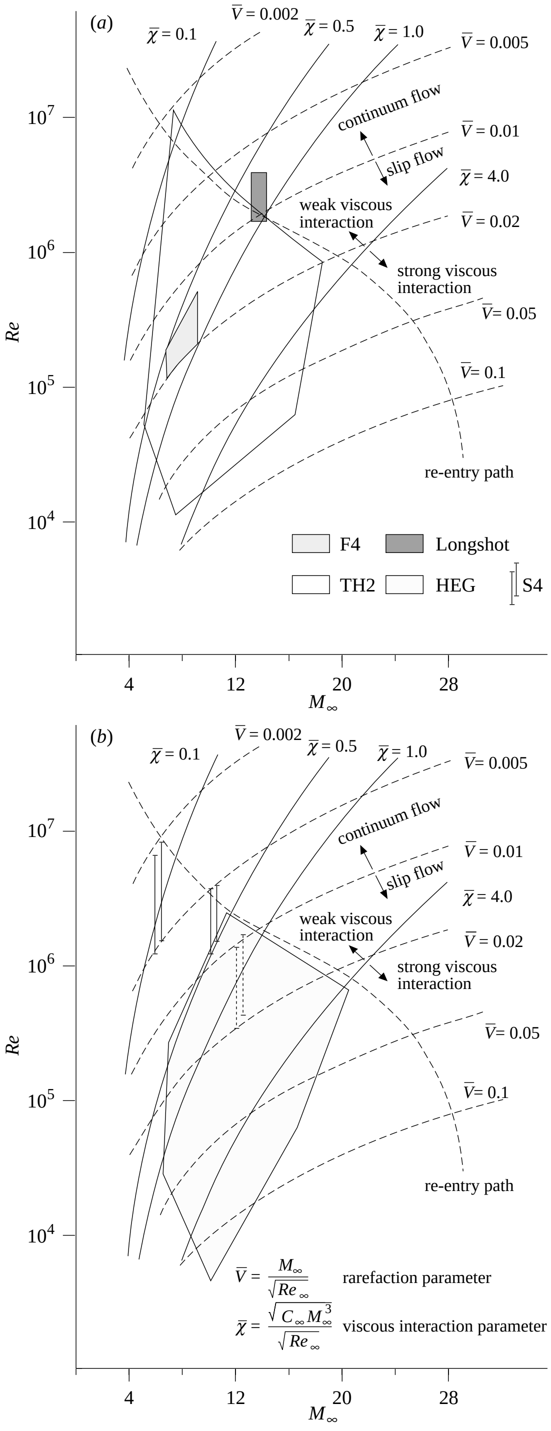

Figure 7. Performance envelopes of TH2, HEG, S4, F4 and the Longshot.

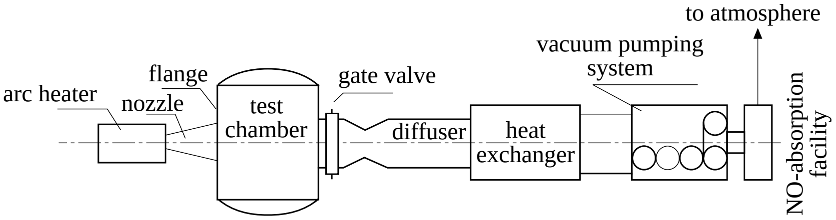

Figure 8. Schematic of a plasma wind tunnel.

to the desired energy levels, and a nozzle to expand the gas, usually to supersonic or hypersonic Mach numbers. This high-speed flow enters the test section where the model or test article is mounted. Downstream of the test section, the flow is decelerated in a diffuser and cooled in a heat exchanger. As the pressure level in most cases is below atmospheric, the gas has to be pumped back to ambient in a vacuum system, which can consist of mechanical pumps or a series of steam ejectors. Depending on the size of the facility, the vacuum system can often be separated by a gate valve from the upstream part, in order to be able to maintain the vacuum while work on the model is carried out. Downstream of this vacuum system, the installations usually have a means to wash out pollutants before releasing the gas into the atmosphere.

(*b*) *Plasma wind tunnel heating techniques*

The classical device for heating by electric arc is often referred to as a Huels arc heater because it is an early German development, which now exists in many different variations. A continuous electric arc is created in the tube between an anode and a cathode. This electric arc heats the gas, which flows through the tube and enters the nozzle downstream. To reach high enthalpy levels, significant arc currents are required, which, in turn, lead to high erosion rates at the arc foot. In order to reduce this erosion, the arc is often rotated with the help of a magnetic field. The length of the arc establishes itself naturally according to the surrounding conditions. This leads to relatively ‘unstable’ operation. This fact and contamination of the flow with electrode material explain why these facilities are not liked by aerodynamicists.

In order to overcome these problems, the constricted segmented arc heater concept was developed, which separates the electrodes by a long constrictor tube to give a constant arc length and which, in addition, splits the anode and cathode into several elements in order to reduce the arc-foot current. The constrictor consists of many (up to several hundred) individual segments, which are isolated from each other but which all need to be cooled. The air to be heated is not all injected at the upstream location but along the constrictor. Argon is needed to start the heater and to provide for some shielding of the anode. All in all, this technique leads to a very complex system, with associated maintenance requirements.

Heating the gas by induction provides potentially clean flow. In this technique the gas is passed through a quartz tube around which an induction coil is placed. This coil is connected to a high-frequency generator and is traversed by high-voltage current at high-frequency levels. This creates an induced magnetic field in the tube varying with time. The induction lines are parallel to the flow axis and create circular oscillating electric fields around them, which will move the free electrons and create current loops, which heat the gas by the Joule effect. The operation of such heaters is very stable and as they are electrodeless they show very low levels of contamination, the only direct contact between metal and hot gas occurring in the nozzle.

(*c*) *Description of some recent plasma facilities*

In the following, a description of several plasma test facilities that were or are being constructed for structure/material testing will be given. The selection was made so that each heating technique is represented and that the overall simulation capability is demonstrated.

(i) *The Plasmatron of the von Karman Institute (Bottin et al. 1997a, b; Bottin & Carbonaro 1997)*

This facility applies the induction heating technique, which we found to be widely used in the former Soviet Union under the denomination of 'Plasmatron'. In view of the obvious advantages of a stable continuous flow with little or no contamination for material and other basic research, the Belgian Federal Office for Scientific, Technical and Cultural Affairs and the ESA decided to co-finance the construction of such a facility.

Figure 9 shows, schematically, the induction heater and its casing. Two such heaters have been developed to satisfy the specified heat flux and pressure requirements typical of re-entry problems, one with a tube diameter of 80 mm, which operates in the power range from 15 to 150 kW, and the other with a tube diameter of 160 mm, for a power range from 100 to 1000 kW. For medium- to high-power level operation, the quartz tube can be protected by a water-cooled cold cage placed between the hot gas in the centre of the tube and its walls. This heater can operate subsonically by simply injecting the heated gas into the test section downstream, or supersonically by placing a convergent–divergent nozzle at the end of the tube. At present, one conical nozzle is foreseen for each of the tubes having a design Mach number of around 2.

The test section is basically cylindrical, with a diameter of 1.4 m and a length of 2 m. Optical access perpendicular to the internal flow can be provided through several portholes of 600 mm diameter distributed around and along this cylinder. Further penetrations allow observation of the front face of models placed in the flow with pyrometers or infrared (IR) cameras. Inside the test enclosure there is a three-dimensional traversing mechanism, which allows the test article to be introduced into the flow and for intrusive measurements such as heat flux, pressure, etc., to be taken. At the exit of the test chamber, a convergent duct is used to collect the plasma flow and guide it into the heat exchanger. For supersonic operation this can be replaced by a convergent–divergent diffuser to obtain some pressure recovery.

The heat exchanger cools the flow down to temperatures acceptable to the mechanical vacuum pumps. It is a two-stage gas–water heat exchanger with a 1.16 mm^2 cross-section. The first stage, which experiences the highest temperatures, consists of two rows of 28 tubes with water circulating at high velocity inside. The second stage has 16 rows of 28 tubes and is designed for lower water velocity and serves to reduce the flow temperatures to below 50 °C. In view of the higher load on the first stage, this stage was designed to be easily removable for repair.

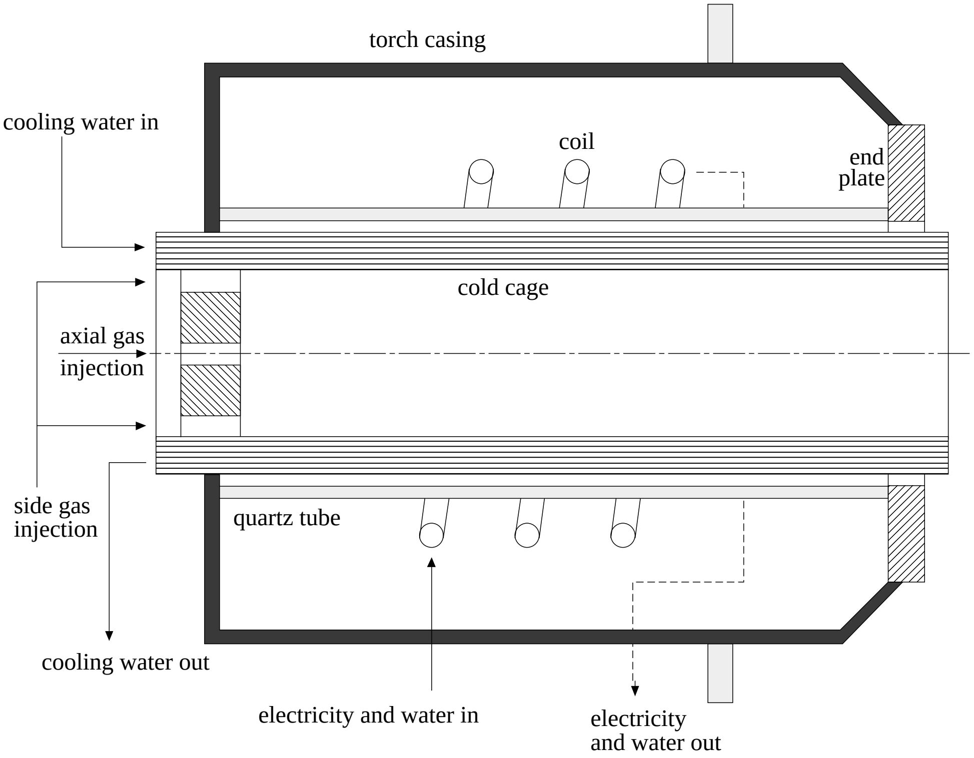

Figure 9. Schematic view of the Plasmatron heater.

The vacuum system consists of a group of three volumetric pumps capable of reducing the pressure inside the facility to *ca.* 1 hPa at significant volume flow rates. For pressures down to 4 Pa, a Rootes pump is available. According to the flow rate needed, the pumps can be isolated and the pressure is adjusted by a bypass valve to the atmosphere.

In line with its purpose to serve as a basic research facility, the Plasmatron is designed to operate with different gases as the test gas. Argon is always needed to start the plasma and usually transition to dry air is undertaken since air is the principal test gas. Also, in addition to the conventional intrusive instrumentation of the Pitot probe, heat flux probe and electrostatic probe, non-intrusive techniques are planned for this facility. For emission spectroscopy, a 1 m focal length spectrometer has been acquired that is powerful enough to resolve rotational spectra, thus giving access to molecule internal energy levels, which are important in non-equilibrium processes. Absorption spectroscopy is also in preparation. It uses, basically, the same apparatus but needs an additional light source (the absorption of whose light is measured) to determine number densities. Infrared thermography can be used to measure the wall temperature of articles placed in the hot flow, but its accuracy depends on knowledge of the emission properties of the surface, which may, in fact, change during a test. Therefore, pyrometers can be used to complement the thermography measurements. Bichromatic pyrometers give two measurements on two different wavelengths and, thus, provide further insight.

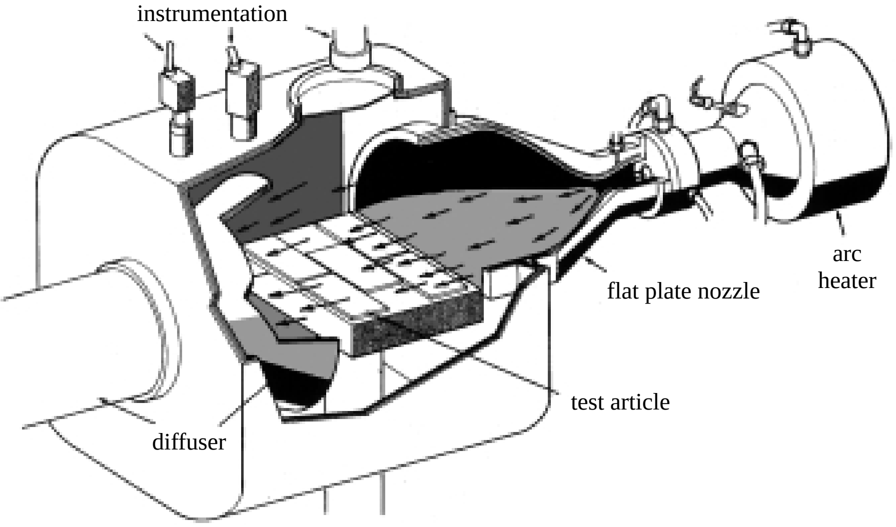

Figure 10. SIMOUN flat-plate testing mode.

(ii) *The SIMOUN facility of Aerospatiale (Charpentier & Leroux 1990)*

The SIMOUN facility is part of a larger testing complex that comprises the COMETE facility (Conte & Leroux 1996), a small continuously operating induction-heated device of 100 kW power, but also 9 MW and 20 MW high-pressure Huels-type facilities (as well as a 20 MW facility operating with a segmented arc heater). All of these have a run duration of *ca.* 60 s and are mostly used for military purposes.

SIMOUN was jointly financed by the ESA and Aerospatiale for thermal protection development work. With its 6 MW Huels-type arc heater, the facility is of medium size and allows the testing of constructional thermal protection system (TPS) elements. Stagnation pressure ranges from 1 to 15 bar and stagnation enthalpies vary between 4 and 14 MJ kg^{-1} in air. Other gases can be used. The facility is equipped with a contoured Mach 4.5 axisymmetric nozzle, which provides testing capability for 50 mm diameter material samples in ‘stagnation-point mode’. Constructional elements of a TPS, like tiles, can be tested by replacing the axisymmetric nozzle and using a super-elliptical nozzle instead. As is shown in figure 10, this ‘flat-plate testing mode’ provides testing capability for test articles parallel to the flow, which can be as big as 200 mm × 200 mm or even 300 mm × 300 mm if less strict heat flow homogeneity criteria are applied.

Downstream of the test section (after a diffuser and a heat exchanger) there is the vacuum system. This is based on steam ejectors because of the elevated mass flow rates. It pumps the gas back to ambient.

(iii) *The arc-heated facility LBK of DLR (Guelhan 1997)*

The arc-heated facility complex consists of two parallel facilities using the same vacuum system. One facility, the L2K, has a conventional Huels-type arc heater of 1 MW, the other, L3K, is equipped with a 5 MW segmented arc heater. As shown in figure 11, the L2K has a large test section, which makes it suitable for research work

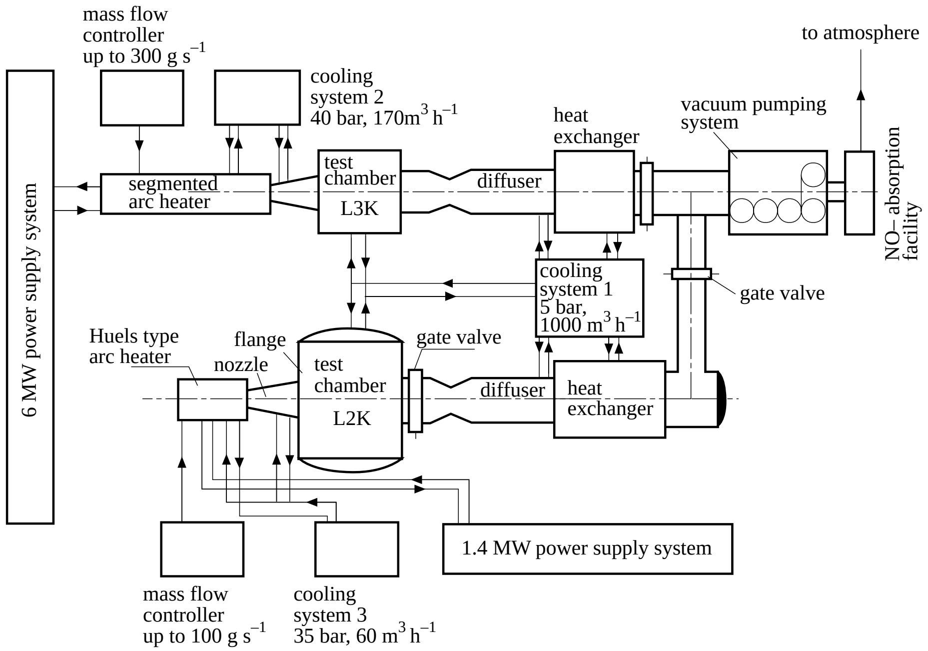

Figure 11. The arc-heated facility complex LBK.

with easy access to instrumentation or secondary test equipment. Several axisymmetric nozzles are available for material tests in 'stagnation-point mode' ranging from Mach 4 to Mach 8. Testing capability in flat-plate mode is limited to small sizes as the maximum nozzle outlet diameter is 200 mm. The higher-power L3K provides nozzles with exit diameters of up to 300 mm. A semi-elliptical nozzle is also being designed, so this facility will be used mainly for flat-plate-type testing.

(iv) *The arc-jet facility SCIROCCO of CIRA (Caristia et al. 1995; Tamai & Caristia 1995)*

The decision to realize the arc-jet facility SCIROCCO was taken jointly by the Italian Ministry for Universities, Research, Science and Technology (MURST) and the ESA. With its addition to the TPS facilities in Western Europe, a complete testing infrastructure will be available, ranging from small facilities for basic research and material investigations, via several medium-size facilities capable of performing limited testing of TPS constructional elements, to one big facility, SCIROCCO, conceived for the purpose of performing engineering development and qualification testing of thermal protection systems.

The requirement to be able to subject test articles with a volume of 600 mm^3 to heat flux rates representative of Earth re-entry conditions at realistic wall pressures leads to a 70 MW arc heater. In this case, the segmented constricted design was chosen, because of its stability and low erosion rate. This heater, which is schematically shown in figure 12, has an 11 cm bore diameter with a length-to-diameter (l/d) ratio of 50. Cathode and anode are separated into nine electrode rings to keep the current level down. Each of these rings has a multi-turn internal coil connected in

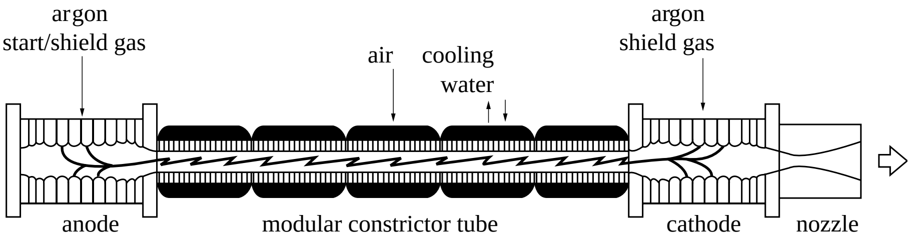

Figure 12. Schematic of the segmented constricted arc heater as used in SCIROCCO.

series with the main arc. The induced magnetic field rotates the arc-foot points and, thus, reduces erosion further.

The facility has a stagnation pressure capability ranging from 1 to 17 bar. At low pressure, the stagnation enthalpy can be varied between 5 and 45 MJ kg^{-1}, which gives temperatures in excess of 10 000 K. At higher pressure, the available power reduces the available enthalpy level gradually to slightly above 10 MJ kg^{-1} at the highest stagnation pressure. The mass flow rate can be as high as 3.5 kg s^{-1}. SCIROCCO will be fitted with a 10° axisymmetric conical nozzle fabricated in different sections so that exit diameters between 900 mm and 1950 mm are available.

Exiting the nozzle, the flow enters as a free jet into the test section, where the test article is placed, and is then 'picked up' by the entrance section of the diffuser. Built into the test chamber is a retractable model support system, which allows the test article to be injected into the flow once it is stabilized after ignition. The model support system provides pitch and can be moved in the direction of the flow axis.

A 40 m long diffuser leads through the heat exchanger into the five-stage vacuum system, which works with steam ejectors, providing 'vacuum' down to 10 Pa and needing a maximum of 90 t of steam per hour, which will be produced on site. Cooling water is provided by a series of on-site cooling towers. A separate closed circuit provides demineralized water for cooling the arc heater and nozzle components.

The facility is designed with an integrated control and data acquisition system, which will allow fully automatic trajectory testing. It provides for an operator's run time interface for facility control and monitoring and for test engineer workstations to prepare test specifications and to analyse data from a file server. An independent safety system acts as a backup in the event of a failure of the central control system or of one of the local control units.

The power supply is an AC/DC thyristor conversion system and furnishes direct current to the arc heater via a DC busbar system. The AC/DC converter is composed of six identical units, which can be configured to have two times three units in parallel (6 kA/22.5 kV) or three times two units in parallel (9 kA/15 kV). In order to make this facility attractive for users other than thermal protection designers, it was not only designed with a large test section giving ample space for test mountings and instrumentation and with good optical access, but with additional features or retrofit capabilities such as:

(i) pressure reserve in cooling water and air systems for eventual increase in facility pressure with a view to providing higher Reynolds numbers;

(ii) modification of the heat exchanger/vacuum system duct to provide atmospheric exhaust for combustion simulations and testing at higher pressures; and

Table 3. *TPS test facilities in Western Europe*

facility	country	type	model size	power	status
IRS PWK1	Germany	arc	25 mm	250 kW	operational
IRS PWK2	Germany	arc	25 mm	500 kW	operational
IRS PWK3	Germany	induction	25 mm	150 kW	operational
Aerospatiale	France	induction	25 mm	120 kW	operational
DLR L2K	Germany	arc	0.1 m × 0.1 m	1 MW	operational
VKI	Belgium	induction	0.1 m × 0.1 m	1 MW	project
AS SIMOUN	France	arc	0.2 m × 0.2 m	5 MW	operational
DLR L3K	Germany	segm. arc	0.2 m × 0.2 m	6 MW	operational
CIRA SCIROCCO	Italy	segm. arc	0.6 m × 0.6 m	70 MW	project

(iii) installation of piping and valves for testing with gases other than air for combustion and propulsion simulations.

The SCIROCCO project is still in the construction phase. The arc heater, the power supply and all the other major components have been installed at the CIRA site in Capua. Commissioning will run through 1999. It is expected that the first operational runs will take place by the end of 1999 or at the beginning of 2000.

(*d*) *Performance and simulation capability of the plasma facilities*

The test facilities presented above and several others at universities (of which the facilities at the IRS in Stuttgart (Laure *et al*. 1992, 1995) were also used by the ESA for TPS material studies) represent a complete set of ground simulation facilities, as shown in table 3. They are capable of covering the complete development cycle from early material screening and characterization to validation of engineering design and qualification.

The author gratefully acknowledges the collaboration and assistance of several test facility groups, and in particular the help of A. Guelhan of the DLR and R. Leroux of Aerospatiale.

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