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EXISTING AND NEW HYPERSONIC FACILITIES REQUIRED FOR HERMES SPACECRAFT TESTING

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Abstract

This paper presents the hypersonic flight regimes, the similitude parameters, the part of hypersonics facilities in the HERMES development strategy. It gives a description and a critical analysis of the hypersonic facilities required for HERMES experimental studies. It ends by the possible improvements, and describes an other approach : the hyperballistic gun with a pressurized tunnel.

1 - Flight regimes and phenomena

- Near the middle of the reentry the spacecraft enters a zone of rarefaction where it is jet - controlled ; then, with air density and Reynolds number increasing it crosses a zone where the thick boundary layer interacts with the shocks due to control deflections ; these viscous interactions reduce the control efficiency and give overheating on the control, at the reattachment location. This zone is represented by the circle 1 in figure 1.

- Then the spacecraft enters a hot zone (circle 2) where real gas and boundary layer/vortex/shock effects dominate the flow : the heat fluxes are very high, specially behind shocks intersections ; in the stagnation zones the oxygen and nitrogen are dissociated, and recombination can occur behind, depending on the catalytic properties of the thermal protection system.

- Down to about 65 km altitude the boundary layer is normally laminar, but transition to the turbulent regime can appear on the lower surface below this altitude.

It can be due to surface irregularities (margin between tiles, gaps) and if it occurs in the forward part ($x/L < 0,4$) it is almost independant of the wind-tunnel noise and turbulence, from the U.S Space Shuttle experience.

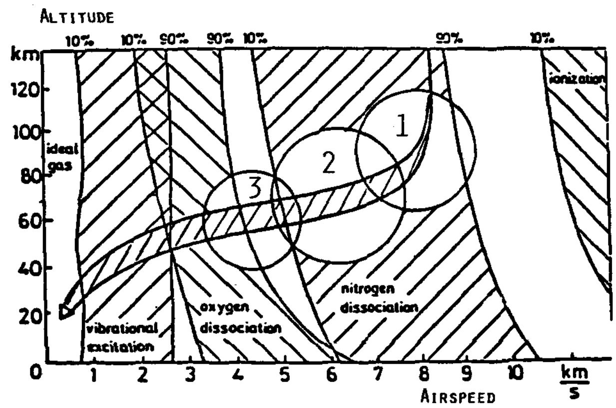


FIGURE 1 - TYPICAL FLOW PHENOMENA ALONG REENTRY TRAJECTORIES

2 - Similitude parameters to reproduce in facilities

- At high altitude where there is free molecular flow, then slip and transitional flow, the most important parameter is the Knudsen number which gives the mean free path λ in terms of reference lenght L or boundary layer thickness δ :

$$KN_{\infty} = \frac{\lambda_{\infty}}{L} \simeq \frac{M_{\infty}}{Re^{\frac{1}{2}}} \times \frac{\delta}{L}$$

M = Mach number
Re = Reynolds number related to L
∞ = undisturbed flow

- In the viscous interaction regime (65 Km $<$ altitude Z $<$ 100 km) the main parameter to reproduce is

$$\bar{V} = \frac{M_\infty}{Re^{\frac{1}{2}}}$$

for the heat flux coefficient and the control efficiency similitude.

- In order to reproduce the real gas effects-and specially the chemical kinetics of binary reactions-one must keep the velocity U_∞, and the product $\rho_\infty \times L$ of the density by the reference lenght L.

- In the cold hypersonic regime (Z $<$ 60 km) the classical similitude (Mach, Reynolds) is needed to reproduce the viscous effects.

- Of course, to duplicate the real flow requires to keep the values of all these parameters, which is pratically impossible : with a given nozzle, one can change only the stagnation pressure Po and temperature To which define the total enthalpy level, therefore the free velocity U_∞ , and the Reynolds number, and $\rho_\infty \times L$- So, practically, one can reproduce only two parameters.

- In addition, trying to reproduce the hot flow regime leads to pre-dissociation in the stilling chamber so to a free flow different from the flight one. Therefore, to transpose the wind-tunnels results to the flight, it is necessary to develop and check codes reproducing the real gas and viscous effects.

3 - Wind-tunnel testing needs

The need of hot shot facilities comes from the desire to avoid the ORBITER problems and to reduce uncertainties related to testing only in cold hypersonic W.T ; the comparisons of U.S. Shuttle flight data with predictions show :

. A longitudinal trim discrepancy (figure 2)
. A leeside heating with vortex scrubbing underpredicted by cold wind-tunnels.

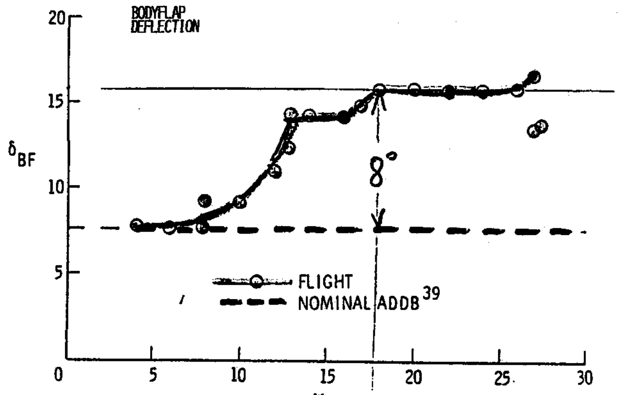


FIGURE 2 - ORBITER LONGITUDINAL TRIM DISCREPANCY

. A windward heating with non-catalytic effects = thermodynamic non-equilibrium.

In order to approach flight conditions one must reproduce :

. The flight speed U_∞ , therefore the total enthalpy.

. The binary chemical kinetics parameter = flow density x lenght

Two new facilities are now under development :
. An arc-heated facility at Toulouse (France) called F4.
. A shock-tube facility at Göttingen (Germany) called H.E.G. (High Enthalpy Göttingen)

The figure 3 shows that these new facilities are complementary : F4 will go up to 5.6 km/s with test duration longer than 20 ms, and H.E.G up to 8 km/s with a shorter duration about 1 ms.

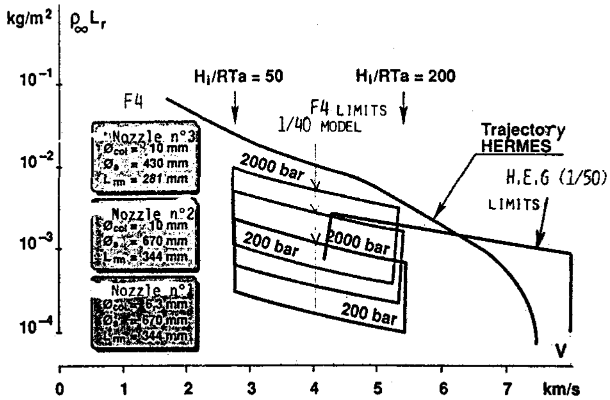


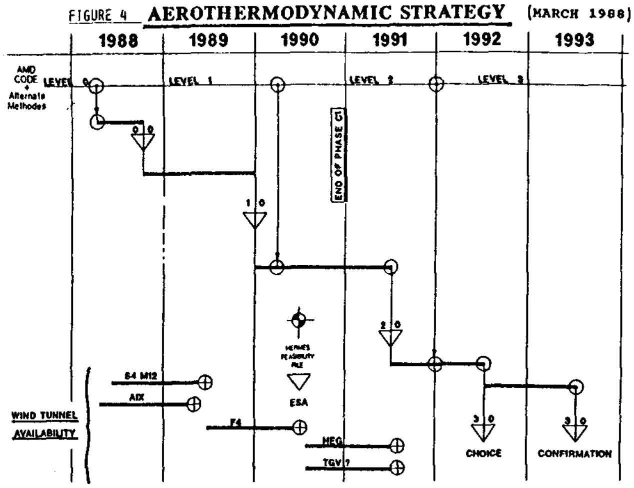
FIGURE 3 - CHEMICAL KINETICS SIMULATION

4 - The part of hypersonic facilities in the development strategy

As already seen, these facilites are not able to duplicate exactly the flow behaviour during reentry, specially the hot part, due to air pre-dissociation in the high temperature chamber.

Therefore, it is necessary to develop theoretical means to transpose the results from wind-tunnel to flight, and to design a new definition, after a series of calculations and tests.

FIGURE 4 **AEROTHERMODYNAMIC STRATEGY** (MARCH 1988)

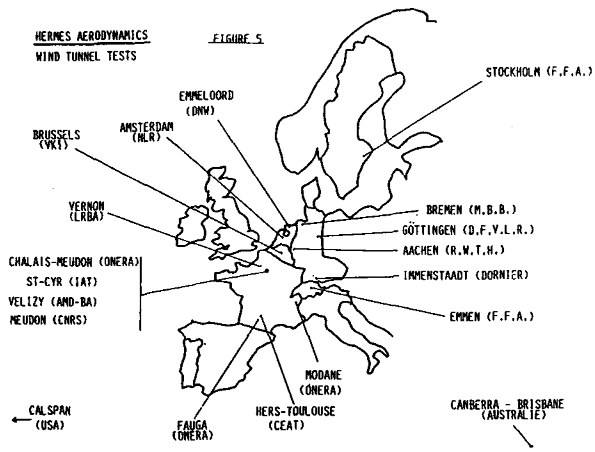


The figure 4 shows the strategy involving a parallel development of experimental and theoretical means, and successive spacecraft definitions.

The hypersonic tests have 3 targets :

- To give a complete data set on the stability and control, the pressures and heat fluxes, the controls hinge moments,...
- To validate (or not) the codes by comparison with calculations of forces and moments (first step of validation).
- To sweep a large number of variables in order to put in light the sensitivities of difficult items like boundary layer transition.

HERMES is an European project involving co-operation with a lot of Companies and Research Centers, located anywhere in Europe (figure 5), which supposes big efforts of co-ordination in order to minimize the delays : for thermal testing, the total delay-including model specifications, agreements, model study and manufacture, equipment, customs, tests and data processing, can reach twenty months in the worst case. Therefore, it is a big problem.



5 - Description of hypersonic facilities required for HERMES development

TABLE 1

HYPERSONIC FACILITIES SELECTED FOR HERMES AEROTHERMODYNAMICS TESTING–MAIN CHARACTERISTICS AND TYPES OF TESTS

TYPE	USED	NAME	NOZZLE DIAM (MM)	STAGNATION MAX. PRESS. (BAR)	STAGNATION TEMP. (°K)	MACH	MODEL LENGTH (CM)	CORRESP. REYNOLDS x 10-6	MAIN TYPES OF TESTS
COLD	*	CHALAIS MEUDON R3	347	170	1 050	10	15	1.9	(M,Re)SIM-(F,M) + THCOL
	*	MODANE S4	685	40	1 100	6.4	26	9.3	(M,Re)SIM-(F,M)
		"	1 100	150	1 500	10-12	33	2.5-1.6	(M,Re)SIM-(F,M) + (T,P)
TESTING	*	GOTT.LUDWIEG B	500	36	650	6.8	15	2.4	Liquid crystals vizualisation
	*	FFA HYP 500	500	120	800	7.1	26	10	(M,Re)SIM-(F,M)
	*	CHALAIS MEUDON R2	327	75	630	5-6-7	15	10-4.6	(M,Re)SIM-(F,M)
		KOLN-H2K	600	45	1 400	6-8.7-11.2	22	7-1.3-0.1	(M,Re)SIM-(F,M)
RAREFIED	*	GOTTINGEN V1G	250	100	1 500	7-10-22	9.6	.02-.08	$M/Re^{1/2}$ Simul.(F,M)
		" V2G	400	40	870	11-15	9.6	.006-.02	Idem
GASES		C.N.R.S. SR3	230	120	1 300	15-20	9.6	.05-.07	Idem + heat flux
			360	3.5	1 100	20	9.6	.003	by infrared camera
HOT	*	VKI LONGSHOT	360	4 000	2 200	15-20	26.	1. to 5.	(M,Re)SIM-(F,M) + (T,P)
	*	VERNON C2	1 068	30-350	1 850	16.	40	0.1 to 1.2	$M/Re^{1/2}$ simul-(F,M) + (T,P)
TESTING	*	AACHEN TH2	571	670	5 150	6.3	26	1.0	(ρ,V)simul.First approx. of RGE
AERO -	*	CALSPAN 96 IN.	1 219	1 300	6 100	10	43	0.34	Idem
THERMO-	*	CANBERRA T3	267	380	27 MJ/KG	6.2	43 (nose)	0.20	(ρL,V)simul-RGE on (T,P)
	0	FAUGA F4	670	2 000	16	9.	39	0.24	Idem
DYNAMICS		H.E.G.	700	1 000	30	7.5	65 (nose)	0.5	Idem

(M,Re) SIM = Mach-Reynolds simulation
(F,M) = Force and moments measurements - (T,P) = temperature and pressure measurements
THCOL = Thermocolor paints - RGE = real gas effects
* Already used W.T

The table 1 gives a first idea of the diversity of the means already used (or under development) and the main types of tests made in each facility.

So we have mainly blowdown tunnels with useful time of many seconds for low energy flow, then shock tubes with time of some ms for middle energy flow, and finally an arc-heater powered by an impulse generator, or a two-stage shock tube, for high energy flow.

TABLE 2

HYPERSONIC FACILITIES WITH A STAGNATION TEMPERATURE > 1 800° K

MEAN OR HIGH ENTHALPY LEVEL

Location Name	Nozzle		Max. usable enthalpy Stagnation values			Free Stream		Useful test time (ms)	Test Velocity m/s	Test gas	Hermes model ref. length mm	NOTES
	Exit mm	Shape	Po bars	To K	Ho/RTa (H_o MJ/K)	Mach Numb	Reynolds* x10-6					
VKI Longshot	360	Conical	4000	2350	30 (2.35)	15	6.2	10	2000	N2	236	Gun tunnel N2-N2 with heavy free-piston compression heater
"	450	Contoured	2200	2300	28.7 (2.25)	15	3.4	10	1960	N2	236	Idem
LRBA C2	1068	Contoured	350	1850	26.4 (2.06)	15.8	1.0	10	1760	N2 or air	433	Shock tunnel with light separation piston - Helium driver
AACHEN TH2	572	Conical	670	5150	97.5 (7.64)	5.8	1.1	1.	3650	Air	236	Shock tunnel-Helium driver
CALSPAN 96"	D 1219	Contoured	1360	6100	120 (9.4)	10.	0.34	1.	4.100	N2	433	Shock tunnel-Hydrogen driver

* Based on model reference length

The tables 2 and 3 show the real or expected maximum performances of mean or high enthalpy level facilities, and the working principle.

TABLE 3

HYPERSONIC FACILITIES WITH A STAGNATION TEMPERATURE > 7 000° K

VERY HIGH ENTHALPY LEVEL (SUITE)

Location Name	Nozzle		Max. usable enthalpy Stagnation values			Free Stream		Useful test time (ms)	Test Velocity (ms)	Test gas	Hermes model ref. length mm	NOTES
	Exit mm	Shape	Po bars	To K	Ho/RTa (HoMJ/KG)	Mach Numb	Reynolds* x10-6					
FAUGA F4	670	Contoured	2000	8600	200 (15.7)	9	0.24	17.	5.450	Air	390	Arc heater supplied by impulse generator
CANBERRA T3	267	Contoured	380	10000	351 (27.5)	6.2	0.20	0.05	6.600	Air	Nose 1/30 but ref.433	Helium driver heated by heavy piston in a 6 m compression tube
BRISBANE T4	254	Contoured	185	14000	532 (41.7)	5.2	0.20	0.16	7230	Air	Nose 1/30 433	Idem - except 26 m. compression tube
GOTTINGEN H.E.G.	700	Contoured	1000	10000	383 (30)	7.5	0.5	1	6.800	Air	Nose 1/20 650	Idem- except 28 m. compression tube-Designed for longer useful time, and reduced Helium contamination

* Based on model reference length

6 - Critical analysis of these facilities

6.1. In shock tunnels and arc-heated facilities the main testing difficulties come from the short duration and pollution ; for example :

- . The metallic particles in high pressure shock tubes destroy the thin films put on the model lower surface.

- . The very short duration of hot shots makes very difficult or even impossible forces and moments measurements.

In most of the shock tunnels the test section flow is mainly known by calculations from the stagnation conditions, computed from the shock speed and a pressure gage signal. So the uncertainties about the uncoming flow are sometimes large, and to improve the flow knowledge the shock tubes currently used for HERMES have been equiped with a Pitot pressure and stagnation enthalpy (thermocouple on a sphere) measurements.

In addition, in hot-shot facilities one must measure the pre-dissociation of the test gas in front of the model, the rotational and vibrational temperatures, and the stagnation enthalpy. Reducing the measured surface heat fluxes to Stanton coefficients requires the knowledge of the test density, velocity and recovery enthalpy.

So there is a very difficult measurements problem in hot-shot facilities, and new means are now tested in the European Research Centers :

- . Strioscopy with phase contrast and holographic interferometry for density measurements
- . Laser-induced fluorescence for OH, O2, H2O dosages and vibrational, rotational temperatures
- . U.V. and visible spectroscopy fo O2 and NO dosages
- . Langmuir probe for electrons density and temperatures
- . Electron beam fluorescence for velocity, density, N and O local concentrations

and many others means(CARS)

6.2. About the existing rarefied gases facilities, the main critics are :

- . Reynolds number too low, therefore viscous parameter too high for simulating the hot part of the reentry, going from 80 down to 60 km altitude

- . Poor ratio of core diameter/nozzle exit diameter, leading to very small models

- . The existing conical nozzles give high longitudinal and lateral Mach gradients

- . Balances problems due to high heat flux.

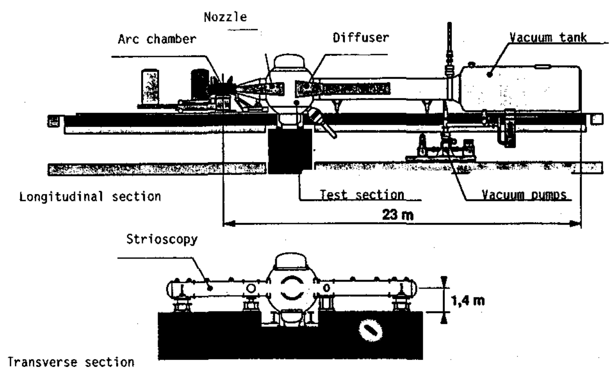


FIGURE 6 - F4 AERODYNAMIC CIRCUIT

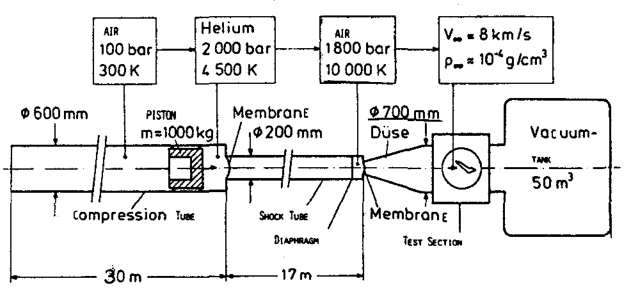


FIGURE 7 - HIGH ENTHALPY GOTTINGEN AERODYNAMIC CIRCUIT

7 - Possible improvements

7.1. Shock tunnels

- To increase the test duration by lenghtening the tube, and so increasing the shock travel time - and by tailoring conditions.

- To reduce the test section gradients by making new contoured nozzles instead of the conical ones

- To improve the measurements, using the new systems indicated upper, which are to-day tested in laboratories, and proved means as thermocouple on a sphere, for stagnation enthalpy measurement.

7.2. Rarefied gas facilities

- To increase the maximum stagnation pressure in order to decrease the viscous parameter

- To design and build new contoured nozzles suited to well defined working conditions

- To make new balances more isolated, and more sensitive to forces and moments.

8 - Another approach : the hyperballistic gun with a pressurized tunnel

In order to avoid blowing on a model with pre-dissociated air, and using complex codes, difficult to validate, to transpose the results from hot-shot facility to flight, one can throw a little model using a light gas gun in a tunnel equiped with optical measurements able to record the model trajectory.

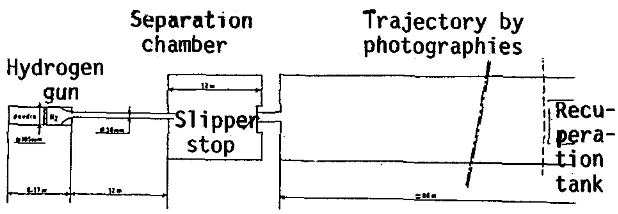


Figure 8- HYPERBALLISTIC TUNNEL - GENERAL VIEW

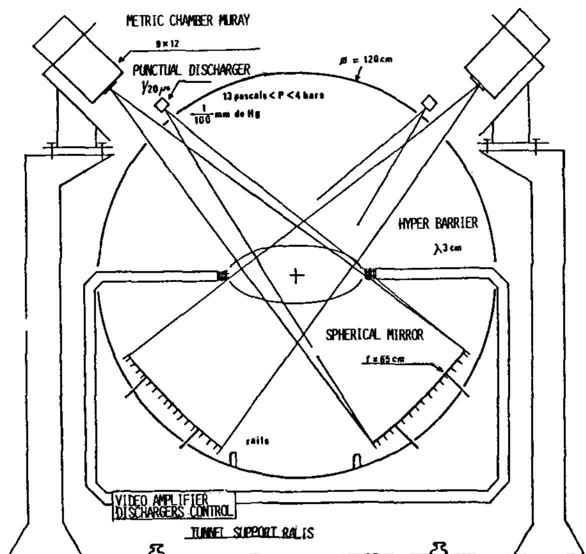


FIGURE 8 BIS - HYPERBALLISTIC TUNNEL - MEASUREMENTS SECTION

If the tunnel pressure is controlled one can duplicate the choosen flight point since the velocity V and the product density ρ x lenght L can be kept as in flight, and therefore the Reynolds number $\frac{\rho V L}{\mu(T)}$ is very near the flight, because the static temperature T in the tunnel is not far from the flight one. In addition, the stagnation enthalpy level is maintained.

Of course, there is some limitation of the velocity due to gun power and model resistance to mechanical stresses and thermal loads.

Today our target is a 5000 m/s velocity obtained in a hydrogen gun with a maximum acceleration of about 200.000 g. We have begun the feasibility tests and demonstrated that a 1/340 model holds this acceleration, using a powder gun.

9 - Conclusion

So the hypersonic facilities already used - or which will be used - are very miscellaneous, and so are the problems to solve. To day it seems that the most difficult one are the measurements in the hot-shot tunnels, specially the flow knowledge ; also the flow quality and the forces measurements in rarefied gas tunnels need improvements.

In addition, it happens that some comparisons of test results are puzzling, due to the diversity of test conditions. So, one of the main problems is the results interpretation.

References :

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2 - Moyens hypersoniques du L.R.B.A, by A. Desgardin. Paper presented at the 22 th Applied Aerodynamics Conference - Lille, France, November 1985.

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