THE OXFORD T6 STALKER TUNNEL: PERFORMANCE, UPGRADES & NEW MODES OF OPERATION

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ABSTRACT

The T6 Stalker tunnel is a multi-mode high enthalpy pulse facility for testing of aerothermodynamics for high speed flight. It operates with a free-piston driver and can be coupled to several different components downstream to become a shock tube, reflected shock tunnel or an expansion tube. This allows for a wide range of testing from subscale model testing to exploration of fundamental high-speed flow processes. Its development was initiated in 2014 with its first commissioning beginning in 2017. Eight years from its conception, has seen its successful commissioning in all modes of operation. Research has been conducted in several fields including shock layer thermochemistry and radiation, convective heating and boundary layer transition. Additional hardware has been developed to expand its capability and operability. This paper will highlight the performance of the facility in each of its modes now that it has been operated against the overall performance map for the facility. Some of the research performed in the facility, including radiation testing, satellite demise and sub-scale planetary probe testing, is also presented.

Index Terms— High Enthalpy, Ground Test Facility, Shock Tunnel, Aerothermochemistry

1. INTRODUCTION

Further development of next-generation high-speed vehicles, such as air-breathing access-to-space vehicles and atmospheric entry craft, requires a greater understanding of hypersonic flow phenomena. Whilst fight testing remains the most desirable source of experimental data, the prohibitive cost limits the availability of relevant results for the multitude of possible fight trajectories. Ground test facilities can undertake hypersonic experiments at a fraction of the cost of fight test programmes, providing valuable data to inform vehicle development, understand the aerothermodynamic environment, and improve computational models. Figure 1 presents several archetypal fight trajectories of interest to hypersonics research. The peak heating conditions for all of the vehicle trajectories shown occur where there are significant thermochemical effects in the flow. Additionally, the majority of these missions pass through high altitudes at significant speeds resulting in large non-equilibrium regions around the vehicle. Such flow fields require accurate spatio-temporal reconstruction during ground testing. High-enthalpy test facilities are therefore required to properly recreate the fight environment and enable relevant data to be obtained.

Stalker [1] estimated that a continuous ground test facility capable of simulating re-entry conditions could require gigawatts of input power. This is evident in Figure 1 which shows that continuous facilities are currently limited to maximum speeds of around 1 km/s. Achieving higher enthalpy test conditions therefore requires a shift to transient facilities, albeit with a general reduction in achievable test time. Hypersonic pulse facilities of varying types are operated worldwide, by universities, space agencies and private companies [2], and all continue to provide invaluable data for vehicle development. However, for trajectories such as those shown in Figure 1, it is not possible to simulate the entirety of the fight path in any one type of ground test facility. This has led to the relatively recent conversion of existing ground test facilities to be multimodal; examples include HEK-X [3] and X3R [4]. This challenge has also formed a core motivation for the development of the T6 Stalker Tunnel described herein.

This paper describes the University of Oxford T6 Stalker tunnel. This includes detailing its operation and performance in each mode since the conception in 2014 to the current state of the operation. New hardware since the previous FAR conference for T6 is detailed, including a Mach 10 nozzle, two shock tubes of different internal diameters for shock layer radiation and infrastructure to handle flammable gases for Ice Giant entry testing. Three experiments that have been undertaken recently in T6 are highlighted: Shock layer radiation measurements for Lunar & LEO return; Subscale model testing for convective heating during Ice Giant entry; spatial measurements of convective heating during satellite demise at true flight Knudsen and enthalpies.

2. T6 FACILITY OVERVIEW & CAPABILITY

The T6 Stalker Tunnel is a multi-mode, high-enthalpy, transient ground test facility [6]. It is the first of its type in the UK and is the highest speed wind tunnel in Europe. The facility combines the original free-piston driver from the T3 Shock Tunnel (originally developed by late Prof. Ray Stalker at the Australian National University) with modified barrels from the Oxford Gun Tunnel (originally the Bristol Sidley

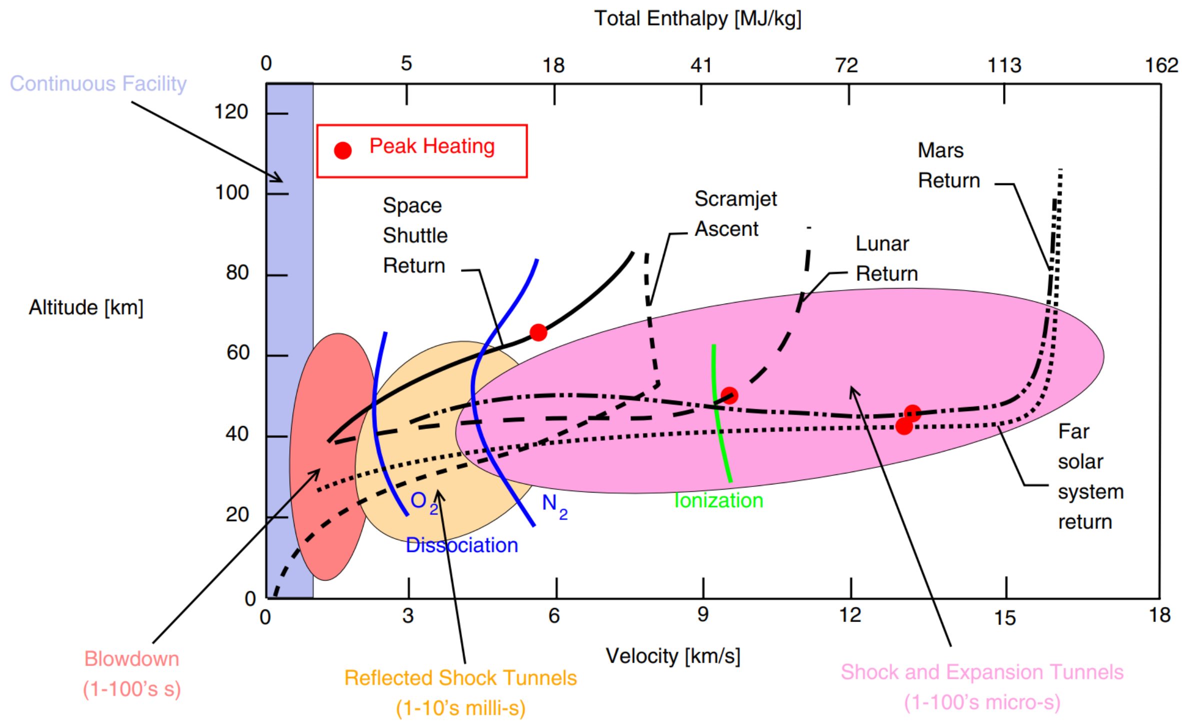

Figure 1: Selected mission trajectories and approximate test facility capabilities (adapted from Fletcher [5]).

Gun Tunnel). Depending on test requirements, it can operate as a shock tube, reflected shock tunnel or expansion tube/tunnel (Figure 2). With funding from the EPSRC National Wind Tunnel Facility, the T6 facility was re-engineered from the main components from these two facilities and installed between 2014 to 2018. Commissioning of the facility began in 2018 [7] which led to the first successful experiments to investigate air shock layer radiation [8]. Table 1 details the leading dimensions of the facility.

Table 1: Leading dimensions of the T6 Stalker tunnel. * means these are altered for some nozzles/configurations.

Section	Length (m)	Internal diameter (mm)	Outlet diameter (mm)
Reservoir	2.8	342.9	300.0
Compression Tube	6.0	300.0	76.2†
Shock Tube 1	2.8	96.3	96.3
Reflected Shock Tunnel	5.3*	96.3	220.0*
Expansion Tube/Tunnel	6.0*	96.3	236.0*
Steel Shock Tube	6.0	96.3	96.3
Aluminium Shock Tube	7.1	225.0	225.0

T6 has two different weight free pistons, allowing for better piston tuning for over-driving and soft landing conditions. Six driver conditions have been produced, with varying fill compositions possible. The highest conditions tested to date has a rupture pressure of 45 MPa and 4500 K for pure Helium.

2.1. Reflected Shock Tunnel Mode

This mode of operation is typically used for model tests from 2.5 to 4 km/s, where test time is required (for example, scramjet combustion test) and model sizes are large. The test gas is processed by an incident and reflected shock, stagnating before passing through a converging/diverging nozzle which sets the freestream Mach number. T6 has two nozzles, a Mach 7 and 8 nozzle. As seen in Figure 3, T6 can match a large proportion of the flight enthalpies and dynamic pressures required for scramjet combustion work.

2.2. Expansion Tube/Tunnel Mode

When the speed becomes larger than 4 km/s, both chemical and thermal free-out occurs in the nozzle expansion of a reflected shock tunnel. Additionally, above 4.5 km/s, the total pressures become too high to contain and the heating to the nozzle throat requires actively cooled throats to avoid throat ablation. An expansion tube overcomes this by never stagnating the gas and using an unsteady expansion process

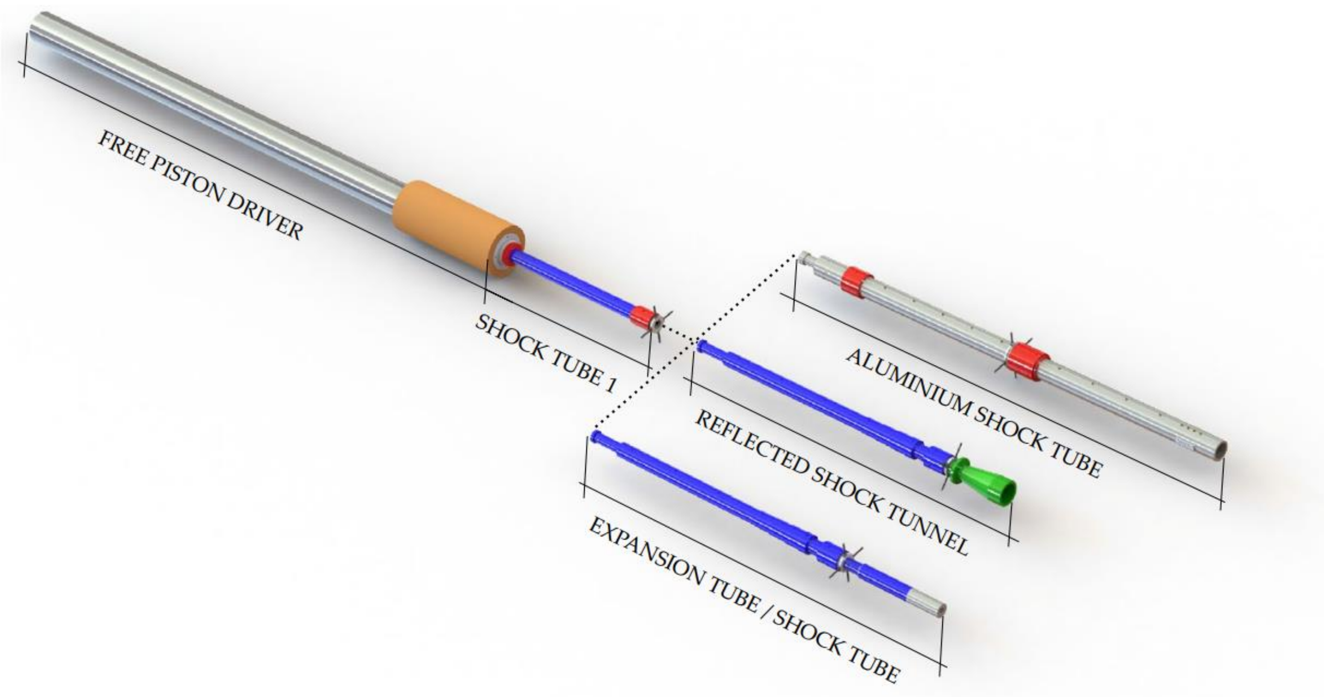

Figure 2: Diagram showing different T6 facility modes.

to increase the total pressure and total enthalpy of the test gas. This comes at the cost of test time, flow quality and test core diameter. An expansion tunnel allows for some recovery of the test flow core by allowing steady expansion of the test gas at the cost of density-length capability. Additionally, this can be used to achieve lower pressure conditions and avoid damage to smaller models by mounting off centerline. T6 currently has a nominally Mach 10 nozzle dependent on the inflow Mach number. Figure 4 shows the performance in expansion tube/tunnel mode for a variety of driver and flight conditions.

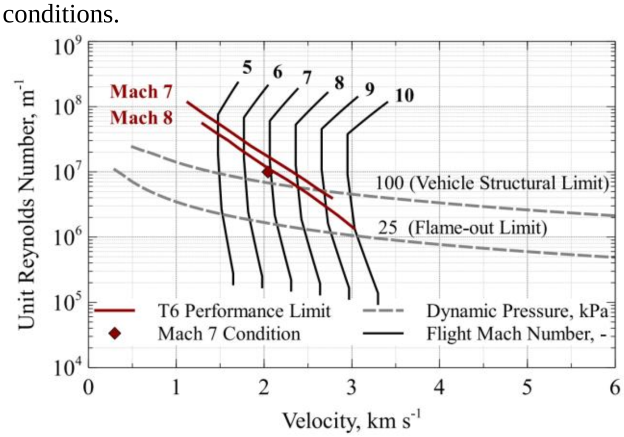

Figure 3: Unit Reynolds number performance of T6 in RST mode vs scramjet flight path.

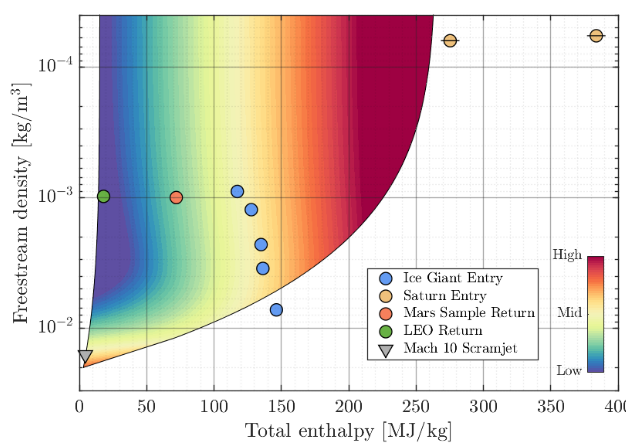

Figure 4: T6 performance envelope in expansion tube/tunnel mode. Colour gradient indicates most appropriate driver condition.

2.3 Shock Tube Mode

This mode of operation, does not use a model, rather establishes a travelling shock through an initial fill composition of gas and pressure. By matching the shock speed and density to a planetary trajectory point, the shock heated gas is similar to the vehicle's stagnation line thermochemistry and radiation. There are two shock tubes for the T6 facility: a steel shock tube at 96.3 mm and an aluminium shock tube at 225 mm internal diameter. Figure 5 shows the performance of the two modes in comparison to relevant Earth return missions. The aluminium tube can cover most conditions for LEO, Lunar return and asteroid return missions, though the steel shock tube is needed to explore the conditions of higher speed Mars return missions.

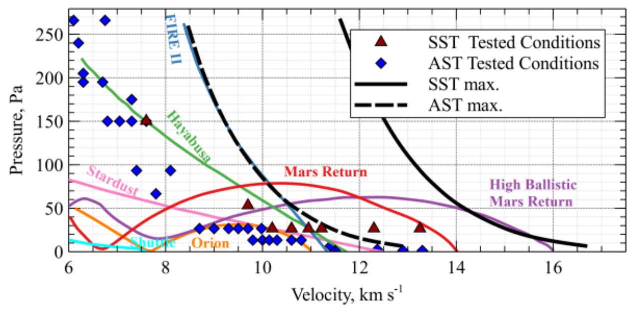

Figure 5: Performance map of T6 operated in shock tube mode for Earth entry vs representative trajectories. SST is steel shock tube and AST is aluminium shock tube.

3. UPGRADED INFRASTRUCTURE

3.1. Steel Shock Tube

A new barrel has been manufactured to connect to the end of the facility to enable measurements of shock layer radiation in the tube (Figure 6). This has an inner diameter of 96.3 mm, keeping constant from the rest of the driven tubes. It features 190 mm long windows on either side of the facility matching the already existing aluminium shock tube. It incorporates 8 axial locations to mount shock timing stations, which at 5 locations feature holes on both sides of the tube. The tunnel features a large port hole downstream of the measurement windows to decrease pumping resistance and allow for high purity experiments. This has successfully been fitted to the existing infrastructure and passed hydraulic testing at 175 bar. It is to be used in upcoming Neptune entry studies, where it is challenging to pump down and maintain cleanliness due to the light gases in the test mixture (H_2 and He).

Figure 6: Picture of steel shock tube.

3.2. Aluminium Shock Tube

An aluminium shock tube (AST) was developed to explore low radiative conditions and high altitude conditions. The larger diameter (225 mm) allows for larger integration lengths for spectroscopy and minimizes the effects of boundary layers on the measurement, but also the test slug length (Mirels effects), especially at low fill pressures. Construction from aluminium minimizes outgassing and thus, Carbon contamination of the test gas. After initial commissioning and comparison to historical data for validation, the AST has been applied for a range of Earth, Mars and Titan testing.

Figure 7: Picture of T6 during air shock layer radiation tests in Aluminium Shock Tube mode.

3.3. Mach 10 Expansion Nozzle

An expansion nozzle was developed for larger model testing. The contour of the nozzle was scaled from the University of Queensland X2 nozzle to the larger inlet diameter of the T6 facility. This has an outlet diameter of 236 mm, producing core flows of 180 mm in diameter, with a nominal entry Mach number of 7.3 and exit Mach number of 10. Attachment points have been included at nozzle exit to allow for measurements of exit static pressure. This has been successfully commissioned with both air and Hydrogen mixtures and applied to convective heating experiments for planetary entry and satellite demise.

3.4. Flammable Test Gas

To allow the use of Hydrogen as a test gas, modifications to the operation of the tunnel and related infrastructure were required. This included the inclusion of a Nitrogen purge system, modifications to the logic of the facility PLC, test gas pre-fill cylinder, and a dedicated vent and a gas detection system. This has been successfully implemented for both shock tube and expansion tube modes. With simple modifications, it should also allow for combustion studies to be undertaken in the test section.

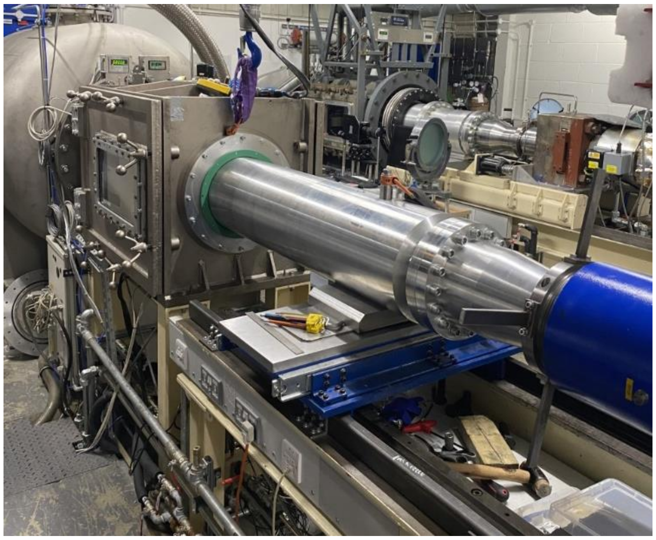

Figure 8: Picture of Mach 10 expansion nozzle

4. RECENT TESTING

4.1. Shock Layer Radiation

As shown above in Figure 5, the aluminium shock tube has covered a large of entry conditions from Lunar to LEO return. The testing to date has used calibrated emission spectroscopy setups covering the range from 200 to 850 nm, mostly taking broad wavelength measurements at 7.5 km/s to 12 km/s. An example of this measurement is presented in Figure 9, where the average spectral radiance is shown in the equilibrium region with the spatial variation of the wavelength integrated spectral radiance showing the clearly higher radiance in the non-eqiulibrium region. Initial testing focused on the equilibrium region to validate the setup against well characterised test cases from the NASA EAST and Ecole Centrale plasma torch facility. This showed generally good agreement with both when differences in diameters and conditions were accounted. This was then expanded to look at a wider range of conditions and the non-equilibrium region. An investigation of the effect of shock speed variation showed the importance on the spatial radiance history, particularly in what should be the equilibrium region. This clearly demonstrated that the shock speed history is important and needs to be included in any analysis of shock tube measurements.

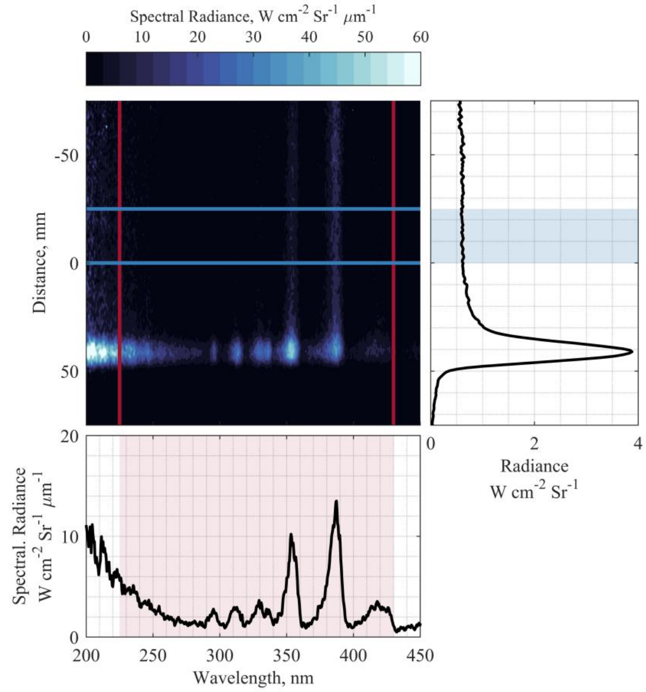

Figure 9: UV shock layer radiation for an air test at 7.7 km/s, 66.6 Pa.

Testing has now been performed at lower speed air conditions (5-7 km/s) [9], where radiative heating is not dominant, to explore the thermochemistry of LEO return. This showed an offset in the measured radiance in the equilibrium region. It is unclear if this offset is a measurement issue, boundary layer effect or a reflection of reality. A small offset in the UV was seen in the testing at higher speeds, though could be present within the uncertainty. This will be explored in the steel shock tube as a comparator, though further higher resolution spectra is required. Additionally, testing has been performed at a range of conditions for Martian entry (Figure 10) and Titan entry (Figure 11). This data is yet to be analysed.

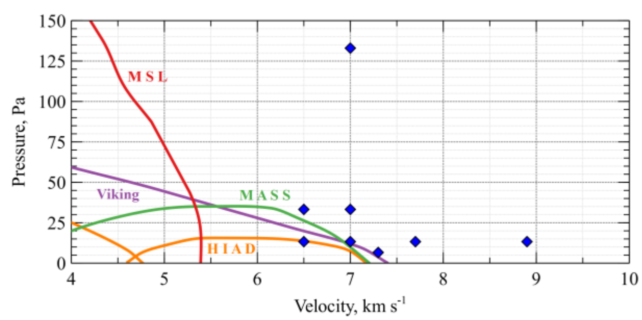

Figure 10: T6 shock layer radiation tests for Martian entry vs flight trajectories.

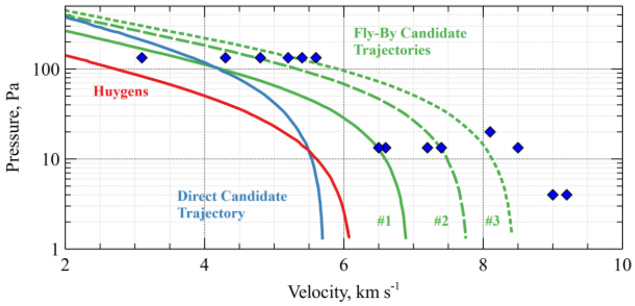

Figure 11: Shock layer radiation tests for Titan entry vs flight trajectories.

4.2. Ice Giant Entry Convective Heating

Planetary entry probe missions to the Ice Giants were proposed in 2010 by NASA and ESA and more recently, the 2023 - 2032 Decadal Survey recommended that NASA's highest priority new flagship mission should be a Uranus orbiter and probe with a launch date in the early 2030s. The Oxford T6 Stalker tunnel is the only facility in Europe capable of replicating the high speeds required for Ice Giant entry for convective heating (Figure 12) and is therefore a key stepping stone on the path to realising the goal of an Ice Giant mission. Preliminary tests have demonstrated the capability to match lower speed Ice Giant trajectories but there is still significant scope to further increase performance by utilizing higher performance driver conditions and lower acceleration tube fill pressures.

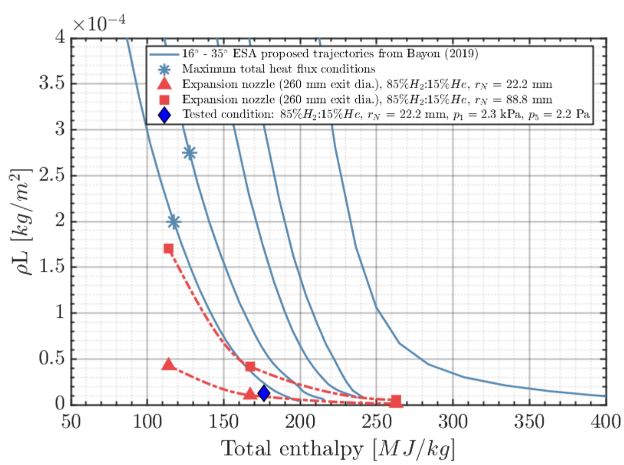

Figure 12: T6 expansion tunnel tests for Ice Giant entry vs flight trajectories

As seen in Figure 13, a 1:10 scaled model of the Galileo probe has been tested at Ice Giant entry conditions. The model is instrumented with coaxial thermocouples to measure the heat flux from stagnation point out around the model. Initial testing has shown promising heat flux and condition results (Figure 14) and successfully utilized the expansion nozzle and flammable gas infrastructure.

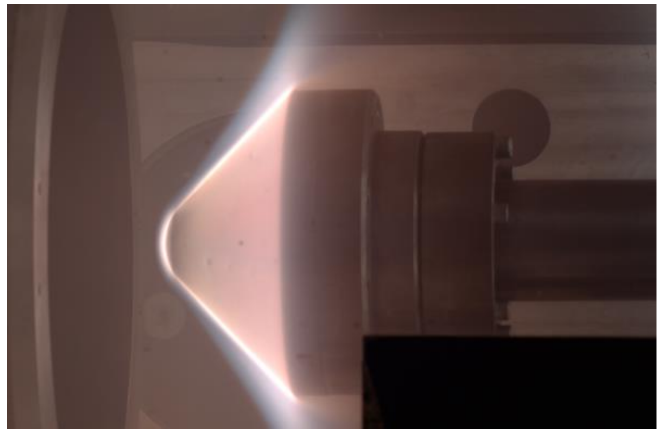

Figure 13: Luminosity during test of Galileo subscale model at 18.0 km/s in 84.5% H_2 / 15% He / 0.5% CH_4.

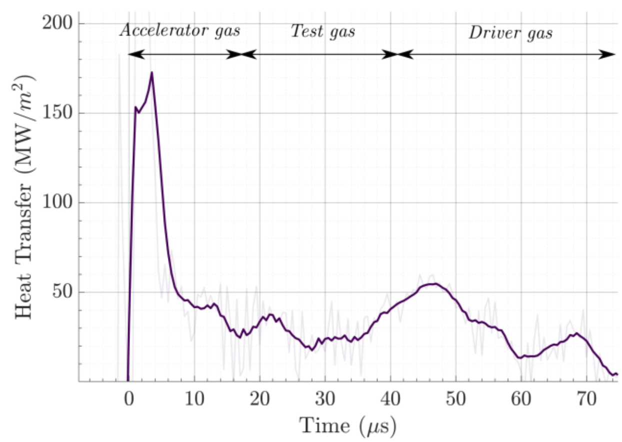

Figure 14: Heat flux measured at the stagnation point of a Galileo sub-scale model at 18.0 km/s in 84.5% H_2 / 15% He / 0.5% CH_4.

4.3. Satellite Demise

Defunct satellites must be removed from Low Earth Orbit through uncontrolled re-entry into Earth's atmosphere. Ideally, satellite components `burn up' due to the aerothermal heating loads at hypersonic velocities. Computational models to predict debris trajectories and demise rates to minimise the risk to the global population require validation data which represents flight. In order to model surface heat flux successfully, thermochemical conditions in the shock layer must be known. This effect is hard to model given the possibility of thermochemical non-equilibrium, particularly in rarefied upper atmosphere flow conditions. There is a distinct lack of experimental data available to verify and improve these models, especially at true flight enthalpies and Knudsen numbers.

Conditions were created in expansion tunnel mode at 6.5 km/s and post-shock Knudsen numbers relevant for flight of large components (> 0.2 m). This speed was chosen as there is little change in satellite components in the upper atmosphere. Figure 15 plots the post shock density length at different altitudes and cylinder diameters. The red dashed line shows the post shock density-length product for the flow condition using 10 mm diameter models. This shows a large range of relevant cylinders can be explored (0.5 to 2.5 m).

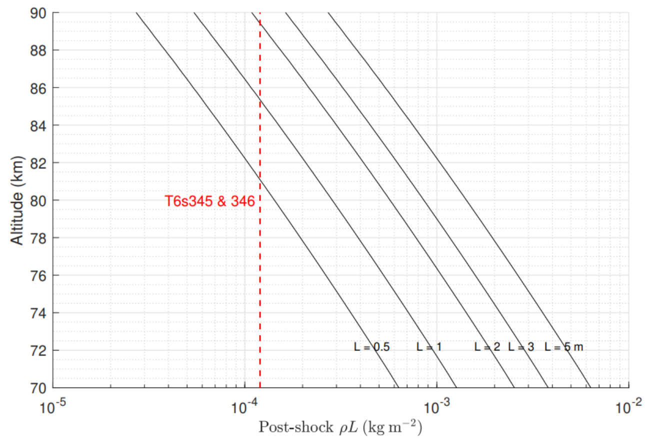

Figure 15: Scaling of tests in T6 replicating satellite demise conditions at 6.5 km/s.

The cylindrical models were manufactured from MACOR and painted with platinum thin film heat transfer gauges (Figure 16). which can respond in the short test times and have high sensitivity and spatial resolution. They were coated in Silicon Dioxide to avoid corruption from free-electrons the slightly ionized shock layer. The gauges were placed at different locations so a spatial heat flux distribution could be achieved. These could be mounted in different orientations, initially trialed in axial and cross flow orientations.

A novel mounting was created, where up to 12 models are situated in a ring (Figure 17). This places all gauges at the same radial location, avoiding any radial non-uniformity in the flow and maximizing the output for each test. This also keeps the delicate models outside of the line-of-sight of the barrel where high Stokes number diaphragm fragments predominately pass. As this is mounted onto the traverse, sweeping of angles of attack and yaw can then be easily achieved whilst keeping the model centroids close to stationary.

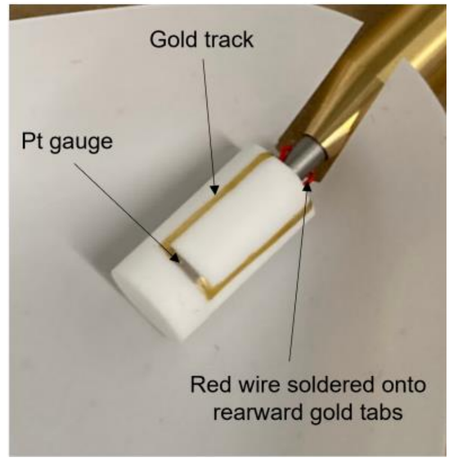

Figure 16: Picture of thin film heat transfer gauge on an axially mounted MACOR cylinder.

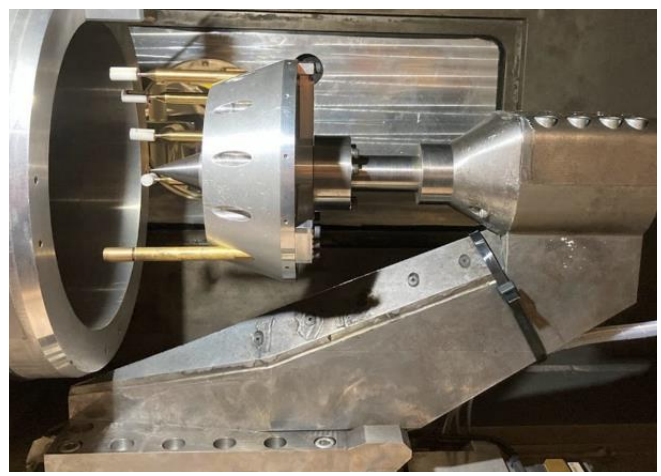

Figure 17: Picture of ring of models for satellite demise testing in T6.

Figure 18 shows a comparison between the measured Pitot pressure and the heat flux on an axially mounted model with the gauge on the cylindrical section of the model. These demonstrate both the quality of the condition and challenges of achieving meaningful data from tests in expansion tunnels due to short duration, ionized flows and potential for particulate damage. This development is seen as a future testbed, where different shapes and could be tested over a range of orientations to garner unique and high quality convective heating data for satellite demise codes.

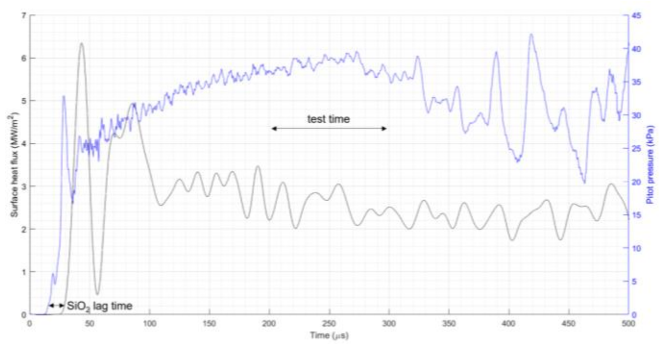

Figure 18: Pitot pressure and heat flux measured on axial mounted cylinder at 0° AoA on cylindrical surface for Earth entry at 6.5 km/s.

5. CONCLUSION

This paper summarises the current operation of the multi-mode Oxford T6 Stalker tunnel. It has been commissioned and operated to run in three modes: a reflected shock tunnel, an expansion tube/tunnel and a shock tube. There have been multiple upgrades to the infrastructure in recent years, which expand the facilities capabilities to perform high speed vehicle testing and fundamental exploration of thermochemistry and radiation. The new infrastructure includes a new steel shock tube and larger diameter aluminium tube for shock layer radiation studies, a Mach 10 expansion nozzle to increase test core sizes and infrastructure to handle flammable test gases. This has now been applied to a range of testing, all of which is challenging to achieve in these facilities. This paper highlighted the shock layer radiation testing and convective heating studies for both Ice Giant entry and satellite demise.

The future outlook is extremely positive, with the facility now operating full-time in the full suite of modes proposed in 2014. However, further developments are needed to expand its capacity and capability including a new test section, larger reflected shock tunnel nozzles and extension of the free piston driver.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the UK National Wind Tunnel Facility for their support in the development of the T6 Stalker Tunnel under grant EP/L024888/1. Thanks also to the Oxford University John Fell Fund and Fluid Gravity Engineering for their support in the development of the aluminium shock tube. The authors would like to thank the ESA/UKSA for funding these development of the steel shock tube, expansion nozzle and flammable gas infrastructure. Funding for the shock radiation testing and Ice Giant testing was provided by ESA/UKSA. The authors would like to tank the dedicated work of the Oxford Thermofluids Institutes installation team, mechanical technicians and instrumentation technicians. Without their efforts, this work would not have been possible.

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