Chapter 1 – SUMMARY OF TASK GROUP ACTIVITIES AND ACCOMPLISHMENTS

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1.1 SCIENTIFIC CHALLENGES IN AEROTHERMODYNAMIC PREDICTION AND THE NEED FOR FLIGHT RESEARCH

In the upcoming decades military capabilities based on hypersonic flight systems will become increasingly important to NATO members as the need for time-critical responses evolves. Fast strike capabilities with conventional munitions on both tactical and global scales will facilitate the engagement of time-critical and mobile targets while minimizing the threat to associated launch assets. Responsive, efficient space access will ensure both the rapid sustainment and replacement of critical space systems and the time-critical deployment of Intelligence, Surveillance and Reconnaissance (ISR) capabilities. While a broad spectrum of technology development is required to realize such planned capabilities, the development of essential hypersonic systems will be paced by the ability to accurately predict the extreme aerothermodynamic environment.

One of the primary technological challenges to the development of hypersonic capabilities is the management of the substantial thermal loads associated with the aerothermodynamic environment. Conservative approaches to thermal protection systems increase vehicle weight at the expense of performance, while aggressive, low-weight designs increase the potential risk for structural failure. At the heart of this problem lies the current inability to accurately predict the complex fluid dynamic, thermodynamic and chemical phenomena associated with hypersonic flows.

Unsteady and non-equilibrium aerothermodynamic phenomena are the source of the dominant acoustic and thermal loads experienced by hypersonic systems, effecting changes in the environment both locally and over large regions of the vehicle surface. A few examples of the broad spectrum of such phenomena include laminar-turbulent transition in the boundary layer, shock wave / boundary layer interactions, and catalytic heating resulting from non-equilibrium gas-surface interactions. Laminar-turbulent transition in the boundary layer increases surface heat transfer by almost an order of magnitude, making accurate estimation of the onset of transition a critical need for the design of efficient thermal protection systems. Local flow separation resulting from shock wave / boundary layer interactions generates extreme heat transfer rates in the region where the separated flow is reattaching and can be the source of significant acoustic loads if the interaction is unsteady. Finally, non-equilibrium thermodynamic processes and chemical reactions in the flowfield and at the system surface can substantially impact surface heat transfer by determining the availability of energy transferred to the vehicle from the flowfield through catalytic surface heating. Through the rigorous exploration, modelling and exploitation of these and other physical phenomena, the research community is attempting to develop accurate methods for the prediction and mitigation of the extreme aerothermodynamic environment.

High-fidelity numerical methods, large-scale computational simulations and advanced laser-based time- and space-resolved diagnostics are providing unprecedented insight into the fundamental phenomena associated with hypersonic flows. Despite this advantage, progress in modelling and exploiting critical phenomena is limited due to the inability of ground test facilities to duplicate the entire flight environment and the complex interactions that contribute to critical aerothermodynamic phenomena (for example, the influence of non-equilibrium thermophysics on laminar-turbulent transition). Ground test facilities typically excel in reproducing one aspect of the hypersonic environment at the expense of another

parameter, as illustrated by the following examples. Shock tunnels generate high-enthalpy flows but at the expense of potential non-equilibrium of the facility freestream. Arc-heated facilities used for thermal protection system material testing can provide very high heat flux into the material, but typically do so at subsonic or low supersonic conditions which do not reproduce the strong shock waves and high shear rates associated with hypersonic flows. Finally, a class of low-disturbance "quiet" wind tunnels has been developed for the exploration of boundary layer transition. Such facilities provide flight-like disturbance environments in the test sections by delaying the onset of transition in the nozzle but only in low-enthalpy flows at low Reynolds numbers. While computations have no such physical limitations, the utilization of high-fidelity, unsteady numerical simulation for the analysis of turbulent flows is currently limited to relatively low Reynolds numbers due to the excessive computational demands of such computations. Additionally, as with any numerical model, verification and validation of the solution accuracy is dependent on detailed comparison with well-characterized and resolved "real" experimental data. Unfortunately, the extraordinary expense and complexity associated with flight experiments in the hypersonic environment precludes the option of utilizing such an approach as the primary source of new insight into fundamental physical phenomena.

Given the challenges described above, there is significant need for reliable approaches to the extrapolation of numerical simulations validated at ground test conditions to application at actual flight conditions. One philosophical approach to the problem recently employed by a number of research organizations is the "Triangle" model illustrated in Figure 1-1. In this model, ground test, numerical simulation and flight research are all utilized in concert to provide an integrated approach to the identification and modelling of critical phenomena. As indicated in Figure 1-1, ground test and numerical simulation form the strong base of the triangle, a reflection of the fact that the bulk of the new insight required to develop essential knowledge will be acquired through these disciplines. Flight research, at the vertex of the triangle, provides a focus to the integrated research efforts and the opportunity to feed back critical "real world" observations to the foundational efforts of ground test and computation. The HIFiRE – Hypersonic International Flight Research Experiment – program jointly executed by the United States Air Force Research Laboratory and the Australia Defence Science and Technology Organisation was developed based on the triangle model and characteristics of such an approach are clearly evident in a number of other international flight research programs [1], most notably the DLR SHEFEX and ESA EXPERT efforts.

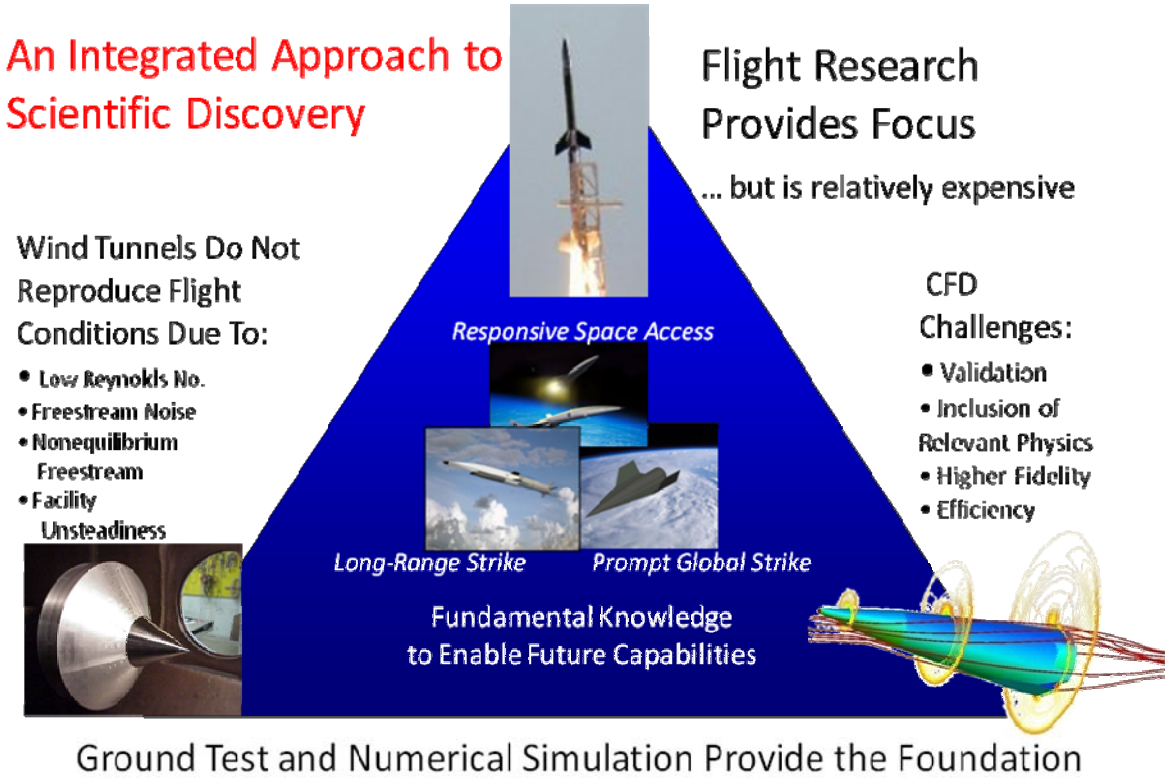

Figure 1-1: The "Triangle" Model for Scientific Discovery Integrating Ground Test, Numerical Simulation and Flight Research.

There have been several notable prior attempts by RTO to address the issue of critical aerothermodynamic phenomena. AGARD/FDP WG18 [2] explored a number of critical phenomena including laminar-turbulent transition, shock wave / boundary layer interactions, rarefied flows, real gas flows and extrapolation from ground test data to flight conditions based on the space shuttle. More recently, RTO-AVT-WG10, *Technologies for Propelled Hypersonic Flight*, [3] addressed the areas of plug nozzles, scramjet combustion and CFD validation for hypersonic flight. These prior efforts led to significant improvements in predictive capabilities as evidenced by comparison to ground test data and helped guide the research directions of the scientific community. However, continued improvements in physical and numerical modeling, computational efficiency, and experimental techniques, coupled with a new generation of flight research programs now present a unique opportunity to assess and improve our aerothermodynamic flight prediction capabilities. This report presents the work of AVT-136, *Assessment of Aerothermodynamic Flight Prediction Tools Through Ground and Flight Experimentation*, which attempted to leverage current flight research programs based on the triangle model to advance the extrapolation of ground test and numerical simulation to flight conditions.

1.2 OBJECTIVES AND ORGANIZATION OF AVT-136

In 2005 the RTO Applied Vehicle Technology panel approved the organization of Task Group AVT-136, *Assessment of Aerothermodynamic Flight Prediction Tools Through Ground and Flight Experimentation.*

The objective of the Task Group is to *assess and improve the understanding and prediction of aerothermodynamic phenomena and aerothermal loads for space transportation and earth/planetary entry systems through ground and flight experimentation*.

The following activities were undertaken by the group:

- Define data needed from ground-based and in-flight experiments for assessment/calibration of computational aerothermodynamic tools for space transportation and earth/planetary entry.
- Assess/document lessons learned from past ground-based experiments and demonstrator flights, including measurement uncertainties.
- Assess aerothermodynamic prediction tools using the available database and quantify simulation uncertainties. Identify gaps in the experimental database.
- Assess the current state of the art in measurement techniques for flight/ground experimentation for addressing critical aerothermodynamic phenomena.
- Where possible, conduct additional ground and flight experiments, with well-defined test conditions and measurement uncertainties. Pay special attention to address gaps.
- Where possible, conduct computational simulations for the experiments.
- Document both experimental and computational results and make recommendations for the future work.

To achieve the above, AVT-136 organized its efforts around the following six scientific topic areas broadly relevant to the development of planned hypersonic capabilities. Each topic area functioned as a semi-autonomous group by independently establishing a program of work consistent with the objective and defined activities of the Task Group. Contributions to the topic programs of work were organized and led by pairs, or in a few cases, individuals, who were recognized leaders in the area and capable of motivating the community to significant contributions. A summary of the topic areas is provided below.

Table 1-1: AVT-136 Scientific Topic Areas and Leadership.

Topic		Lead – Organization	Co-Lead – Organization
1	Nose and Leading Edges	Brian Hollis – NASA Langley	Salvatore Borelli – CIRA
2	Shock Interactions and Control Surfaces	Doyle Knight – Rutgers U.	Jose Longo – DLR
3	Shock Layer Properties and Radiation	Joe Olejniczak – NASA Ames	
4	Boundary Layer Transition	Steve Schneider – Purdue U.	
5	Gas/Surface Interactions	Georg Herdrich – U. Stuttgart	
6	Base and Afterbody Flows	Michael Wright – NASA Ames	Louis Walpot – AOES

To facilitate the development of scientific contributions to the six thrust topics, AVT-136 elected to structure the program of work to initially emphasize the assessment of numerical simulation capabilities through comparison with high-quality archival experimental data sets, although in several cases new experimental data was collected as part of the AVT-136 effort. After completion of the initial validation stage, numerical simulation capabilities were to then be extended to comparison with flight research data made available by the various flight research programs from the participating countries. A schematic illustrating how this process was planned for utilization in the Boundary Layer Transition topic is shown in Figure 1-2. After assessment of the capability of semi-empirical estimation methods to predict transition in well-characterized ground test experiments, the method was to be evaluated against a series of data from planned flight research efforts characterized by increasing three-dimensionality in both geometry and flow characteristics. The flight data was to be provided by the AFRL/DSTO HIFiRE 1 (axisymmetric geometry), NASA HyBoLT (flat with rounded sides) and HIFiRE 5 (elliptic cross-section) flight experiments. Unfortunately, unforeseen issues related to the availability of the flight research data prevented the Task Group from accomplishing this goal.

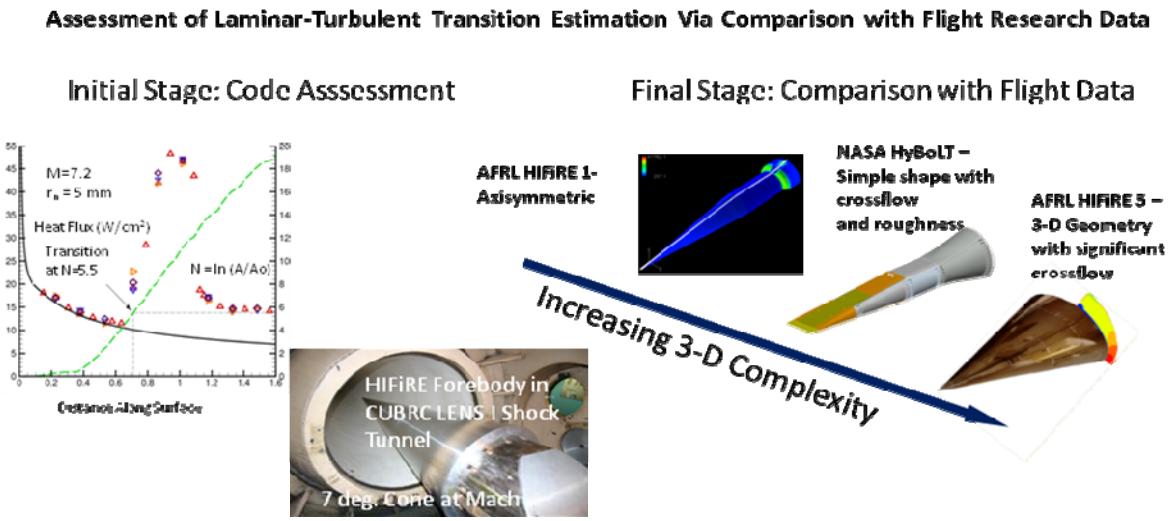

Figure 1-2: Example of the AVT-136 Planned Program of Work Comprised of Initial Code Assessment Followed by Comparison with Flight Research Data.

1.3 CHALLENGES ENCOUNTERED BY THE TASK GROUP

Although it was recognized from the onset of AVT-136 activities that reliance on flight research data yet to be collected posed significant risk to the achievement of Task Group objectives, the group concluded the significant benefit to be derived from comparison of computational simulations with flight data warranted pursuit of such a program of work. AVT-136 planned to acquire the following flight research data to facilitate accomplishment of the group objectives.

Table 1-2: Flight Research Data AVT-136 Planned to Utilize.

Flight Program	Agency	Flight Data to be Used by AVT-136
HIFiRE 1	AFRL/DSTO	- Boundary Layer Transition on cone forebody
		- Shock / Boundary Layer Interaction data generated by flare at aft of experiment
HyBoLT	NASA	- Boundary Layer Transition data
HIFiRE 5	AFRL/DSTO	- Boundary Layer Transition on elliptic shape

Unfortunately, both the HIFiRE and HyBoLT (Hypersonic Boundary Layer Transition) programs experienced significant technical difficulties that prevented AVT-136 from gaining access to the data. Following a series of unforeseen technical challenges associate with range access, telemetry and data acquisition issues, HIFiRE 1 is scheduled for launch in March, 2010, almost two years after it was originally planned. It is planned that the boundary layer transition and shock wave / boundary layer interaction flight data generated by HIFiRE 1 will eventually be provided to the research community for assessment of computational capabilities. As a result of the delays associated with HIFiRE 1, HIFiRE has also been pushed back beyond the scope of the AVT-136 effort. Finally, the HyBoLT experiment was launched aboard a developmental booster in August, 2008. The booster strayed from the planned trajectory and was destroyed on the ascent of the vehicle prior to achieving experimental conditions, resulting in no collection of experimental data.

AVT-136 keenly kept abreast of the developments associated with both the HIFiRE and HyBoLT programs. When it first became apparent that HIFiRE 1 was going to be delayed, a request for a one-year extension was made to the RTO AVT Panel. The request was granted and the Task Group proceeded with plans to quickly analyze the data when it finally became available. When HIFiRE 1 was delayed again in late 2008 it became apparent that flight data would not be available for use by AVT-136 and the group restructured its program of work to emphasize the comparison of numerical simulations with benchmark experimental data sets and eliminate plans to assess capabilities against flight data. Many members of the Task Group hope to eventually accomplish the flight data comparison goals, unfortunately, it will be outside the scope of the AVT-136 effort.

1.4 TASK GROUP CONTRIBUTIONS

Despite the unavailability of flight research data in accordance with the original AVT-136 program of work and the need to alter the program to emphasize the simulation assessment component, most of the scientific topic areas developed by the Task Group made significant progress in the assessment of current capabilities. The chapters following this introduction document the program of work and contributions of most of the topic areas and, thus, specific scientific conclusions and contributions will not be discussed here. However, it should be noted that the activities of AVT-136 generated substantial interest within the international scientific research community and the work of the Task Group was prominently featured in a total of six invited sessions dedicated to AVT-136 in the Sixth European Symposium on Aerothermodynamics for Space Vehicles and the 48th (2010) AIAA Aerospace Sciences Meeting. Section 6.4 of this report provides a list of the 33 conference papers presented by AVT-136 contributors at these two conferences.

1.5 SUMMARY OF TASK GROUP MEETINGS

A summary of the meetings of AVT-136 is presented in Table 1-3 below.

Table 1-3: Summary of Meetings of AVT-136.

Location	Date	Summary of Activity
Goettingen, GER	Spring 2006	Define PoW Technical Issues
Washington, DC	Fall 2006	Finalize PoW and Contributions
Florence, IT	Spring 2007	Review Progress on Contributions
NASA Ames	Fall 2007	Review Progress on Contributions
Loen, Norway	Spring 2008	Review Progress on Contributions
Versailles, FR	November 2008	Review Progress on Contributions
		6th European Aerothermodynamics Conf
VKI	July 2009	Review contents of draft final report
Orlando, FL	January 2010	Orlando AIAA Aerospace Sciences Meeting

1.6 REFERENCES

[1] Erbland, P., “Current and Near-Term RLV/Hypersonic Vehicle Programs”, RTO/AVT VKI Lecture Series on “Critical Technologies for Hypersonic Vehicle Development”, Brussels, Belgium, 10-14 May 2004.

[2] Muylaert, J., Kumar, A. and Dujarric, C., "Hypersonic Experimental and Computational Capability, Improvement and Validation", AGARD Advisory Report 319 (Final Report of AGARD Fluid Dynamics Panel's WG18), December 1998.

[3] "Technologies for Propelled Hypersonic Flight", NATO-RTO-AVT-WG10, 1998 – 2002.