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Hypersonics Into the 21st Century: A Perspective on AFOSR-Sponsored Research in Aerothermodynamics

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This paper documents the programmatic context and considerations that have shaped the development and execution of a number of research initiatives implemented by the Air Force Office of Scientific Research Aerothermodynamics and Turbulence portfolio since 2001. The National Hypersonic Foundational Research Plan has been developed in concert with NASA and Sandia National Laboratories to coordinate strategic planning in the scientific disciplines relevant to hypersonic technologies. The HIFiRE program has provided flight data to provide insight into the behavior of critical phenomena in-flight and helped address several key objectives identified in the National Hypersonic Foundational Research Plan. The STAR initiative facilitated the transition of knowledge and capabilities from basic research to technology development and has made key contributions to national-scale programs and Test and Evaluation capabilities. In the future the portfolio will focus on energy transfer mechanisms between kinetic, internal and chemical modes as a potential approach to new flow control capabilities and to expand the contributions of the portfolio to other areas of interest to the Air Force.

I. Introduction

THE last decade has witnessed incredible advancements in the technology and foundational scientific knowledge base essential for the development of efficient future hypersonic capabilities. The basic research community has played a vital role in the development and transition to application of innovative methods and foundational insight that have guided progress, and in this area researchers sponsored by the Air Force Office of Scientific Research (AFOSR) have been at the forefront. In celebration of the 60th Anniversary of AFOSR and to acknowledge the basic research community that drives innovation, this manuscript examines the major themes of the AFOSR Aerothermodynamics and Turbulence Portfolio during the period from 2001-2013. It should be noted that this work is not intended as a review of the state-of-the-art, but is instead provided as a reflection on the programmatic context and priorities that led to the evolution of several notable initiatives that have influenced scientific progress. Although this text will focus on the discipline of aerothermodynamics, it should be understood that parallel AFOSR programs in combustion, diagnostics and materials research have also made substantial contributions to the realization of current capabilities. Additionally, the crucial role of researchers from NASA and Sandia National Laboratories must be mentioned in this perspective. Many of the most significant accomplishments stemming from AFOSR-sponsored research in the last decade have been the result of collaborative efforts between these three organizations. As always, it is the scientific insight and inventiveness of the world-class basic research community in academia, government, and small business that inspires and drives technological progress and both this paper and the special session in which it is presented are intended to acknowledge and celebrate the critical contributions of this community.

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A. Motivation - Why Hypersonics?

Superior speed and range have long been recognized by military scholars as game-changing advantages and the benefits of hypersonic capabilities have inspired us in this manner for almost half a century. In the last decade the envisioned applications of hypersonic capabilities have focused primarily on the rapid response to time-critical targets and, to a lesser extent, on potential alternatives for economic access to space. Currently, the DoD strategic shift described as the *Pivot to the Pacific*[1] motivates interest in weapons capable of covering long-distances rapidly. The potential benefit of a hypersonic weapon can be realized in terms of rapid responsiveness, increased survivability in contested environments and efficient range coverage. However, when all these advantages are considered together, a persuasive argument may be made for the *economic efficiency* of hypersonic systems.

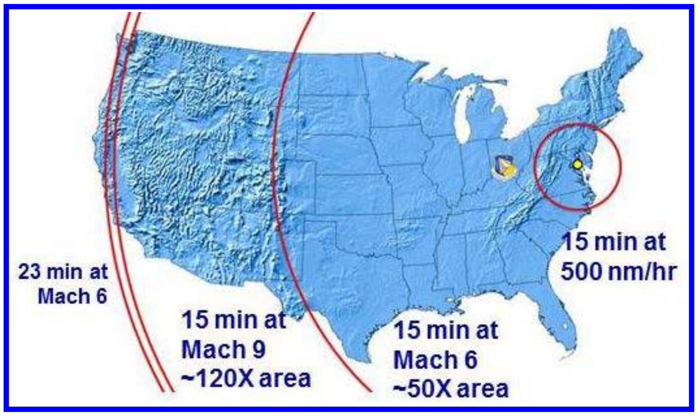

Figure 1. Comparison of range and area covered in 15 minutes for conventional and hypersonic systems.

An indication of the estimated range covered in 15 minutes using the United States as a geographical reference is plotted in Fig. 1. From an origin in Washington D.C., a conventional system can cover much of the mid-Atlantic region in 15 minutes while a system capable of Mach 6 can reach to the Rocky Mountains and a system capable of Mach 9 flight can almost reach the West Coast. In terms of potential area covered in a fixed amount of time, the Mach 6 capability provides roughly 50-times the area coverage of a conventional system and the Mach 9 capability provides almost a factor of 120 increase. When it is considered that approximately 50 conventional systems and the associated infrastructure, supply and personnel support would have to be deployed to provide the same area/time coverage as a Mach 6 capability, the argument for the superior potential economic efficiency of hypersonic systems becomes increasingly compelling.

B. Technical Challenges to Hypersonic Capabilities

From an extremely simplified perspective the realization of planned hypersonic capabilities is highly dependent on the ability of the science and technology community to integrate advancements from various disciplines. Powered hypersonic systems that have flown have primarily been highly-integrated lifting bodies where the aerodynamic and propulsion functions have been strongly interdependent while the thermal protection of unpowered reentry systems has required the multidisciplinary consideration of aerothermodynamics, material response and structural loads. Analogously, the scientific challenges to the advancement of hypersonic capabilities also require the integration of contributions from a variety of scientific disciplines including fluid dynamics, thermophysics, high-temperature materials, chemistry, and computational science. The aerothermodynamic environment defines the boundary conditions that drive the scientific challenges and parameter space for many of these disciplines. Thus, the ability to efficiently and accurately predict the aerothermodynamic base state becomes a key driver for the advancement of system design and analysis capabilities.

Figure 2 provides a non-quantitative estimate of the relative position of a number of recent hypersonic technology development programs within a notional space defined by Mach number and extent of nonequilibrium effects. Within this space recent systems can essentially be represented as two basic groups: those dominated by engineering challenges related to system integration and those dominated by scientific challenges related to unknown thermophysical phenomena. Within the group challenged by integration issues, noted in the blue-shaded region in Fig. 2, most of the systems are driven by air-breathing propulsion. Key technical issues associated with this group are driven by aero-propulsion integration considerations and common challenges include understanding the behavior and impact of laminar-turbulent transition and unsteady shock interactions. Within this group freestream Mach numbers are typically low enough that the effects of thermochemical nonequilibrium are not significant. In contrast, thermochemical nonequilibrium resulting from the dissociated environment behind high Mach number shocks poses the dominant challenge for the group of gliding systems composing the buff-colored region in Fig. 2. For these systems rate-dependent thermochemical processes determine the release of energy from excited internal states into thermal energy and the accurate prediction of aerothermodynamic phenomena is paced by the accuracy of relevant reaction rates required for simulations. Within this region the interaction between the nonequilibrium gas environment and reactive material surfaces also becomes a challenge for which predictive capabilities are dependent on accurate knowledge of the rates of fundamental thermochemical reactions that occur in the gas, at the gas-surface interface, and within the near-surface region of the material.

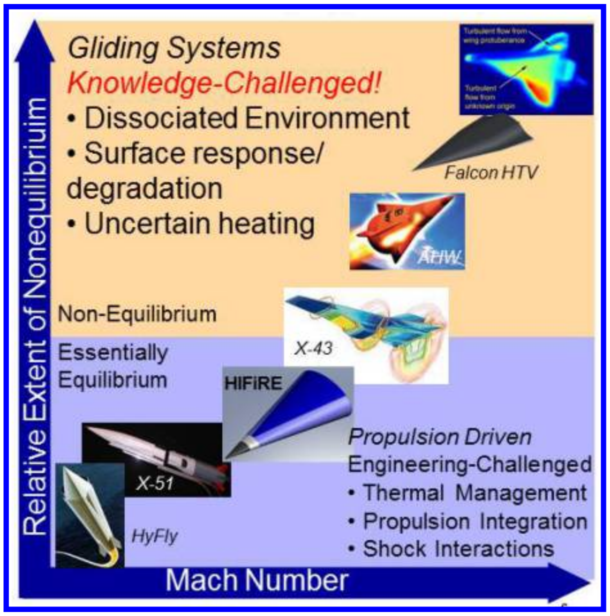

Figure 2. Releative comparison of recent hypersonic technology development programs in a notional Mach Number vs Extent of Nonequilibrium Effects space

C. The AFOSR Aerothermodynamics Strategy

The Air Force Office of Scientific Research is responsible for the investment and management of the United States Air Force basic research budget. In this role, AFOSR emphasizes the identification and support of innovative, unique research that has the potential to provide game-changing capabilities for the future American warfighter. The AFOSR Aerothermodynamics & Turbulence portfolio has responsibility for fluid dynamics research associated with high-speed and high-energy flows of interest to the Air Force. Current emphasis areas within the portfolio include the fundamental physics of turbulence and boundary layers, shock-dominated flows – especially shock/boundary layer and shock-shock interactions, and flows in thermochemical nonequilibrium.

The dual objectives of the Aerothermodynamics & Turbulence portfolio are to identify and foster the development of innovative science with the potential to lead to transformative new capabilities while simultaneously championing the technology transfer of research breakthroughs to application within technology maturation programs. Since 2001 the portfolio has supported a number of notable initiatives that have contributed to the maturation of the state-of-the-art in applied research, coordination of research efforts among the agencies sponsoring scientific research relevant to hypersonics, and identification of new research directions for the hypersonic scientific community. These initiatives have included the following:

- HIFiRE – the Hypersonic International Flight Research and Experimentation program has integrated the efforts of the Air Force Research Laboratory, NASA, and the Australian Defence Science & Technology Organisation in the execution of a flight research program intended to support foundational research in the hypersonic sciences
- STAR – the STability Analysis for Reentry initiative teamed scientific subject matter experts with industry to provide critical analysis supporting the AF/DARPA Falcon HTV-2 and X-51 programs while simultaneously promoting the development and transition to application of advanced numerical simulation capabilities for use in applied research and development.
- The National Hypersonic Foundational Research Plan (NHFRP) identified and provided near-, mid- and far-term scientific objectives for the common research interests of the Air Force, NASA and Sandia National Laboratories relevant to hypersonics.
- Basic research initiatives in the integration of aerothermodynamics, high-temperature materials, and high-temperature chemistry research and the identification and exploitation of fundamental mechanisms of energy transfer that influence the macroscopic behavior of high-speed flows

Although many publications document the scientific accomplishments that have been derived from the investments of the portfolio, this paper attempts to provide a contextual description of the programmatic considerations that led to the pursuit of these initiatives. In the following text these initiatives are described in an order that facilitates the logical flow from one topic to another, but does not represent the chronological sequence of events. The topic of laminar-turbulent transition appears as a recurrent theme throughout this paper. The tremendous achievements of the transition research community during the last decade provide a compelling example of what can be accomplished when outstanding researchers and motivated funding agencies work together to address critical scientific challenges that limit progress towards planned national capabilities.

II. HIFiRE

The HIFiRE (Hypersonic International Flight Research and Experimentation)[†] program was envisioned and developed during 2005-2006 to address a diverse range of challenges to the advancement of hypersonic capabilities. From a scientific perspective, the availability of scientifically-oriented flight research data would both help resolve issues regarding how critical phenomena behave under actual flight conditions and provide vital data to guide the development of methods for extrapolating the results of ground test and numerical simulations to application at flight conditions.[2] Programmatically, there was concern at this time that the large-scale expensive demonstration projects were focusing on single-shot demonstrations of technology concepts for which the research and development had already been accomplished and as a result there were few opportunities to obtain new scientific insight from the resulting flight data. In response to this perception, HIFiRE was intended to be a multiple-flight, economically efficient flight program with the goal of accepting increased technical risk to facilitate the collection of critical scientific data that would shape the development of future programs. One final motivation for the program was the desire to provide flight research experience for the current generation of aerospace scientists and engineers. It is anticipated that the development of future hypersonic systems will require a greater utilization of flight data as the scales of the envisioned systems are rapidly outgrowing the physical space available within our current ground test infrastructure. Increased experience with flight research and enhanced capabilities to extrapolate knowledge of critical phenomena gained from ground testing to flight conditions are anticipated to be essential for the development of future systems.

A. Programmatic Inspiration

A number of people and programs inspired the creation of HIFiRE, a few of which may be considered to be nontraditional with regard to aerospace program development. One of the principal inspirations and champions for the program was Dr. Mark Lewis, who was the Air Force Chief Scientist during the time the program was developed. In a variety of presentations Dr. Lewis noted the need for scientifically-driven flight research and the willingness to accept technical risk to increase the probability of achieving useful scientific data and insight. One of the past examples often noted by Dr. Lewis was the X-15 program, which over the course of 199 flights helped provide key foundational knowledge – occasionally via flight failure – for the advancement of hypersonic capabilities. For example, the failure of a pylon supporting a simulated ramjet engine on one of the flights of the X-15-2 research vehicle focused the attention of the scientific community on the severe environments generated by shock interactions.[3]

Professor Allan Paull from the University of Queensland (and who is currently at the Australian DSTO) not only played a vital role in inspiring the program, but serves as the program Principal Investigator. Paull's historic and economically-lean HyShot academic scramjet flight research program challenged the prior paradigm that flight research was only possible via large, complex, government programs and inspired the community reflect on what could be accomplished using small, affordable sounding rockets.[4] Paull's later work with DARPA on the HyCAUSE[5] program helped solidify the idea that academia and government could work together on scientific flight research. It was during one of Prof. Paull's visits to DARPA to brief the HyCAUSE program the he and the author met over lunch and the HIFiRE program was – literally – sketched out on the back of a placemat.

One of the unconventional influences that profoundly shaped the HIFiRE program was the AFRL RSATS (Responsive Space Access Technology Study)[6] effort. RSATS examined a number of technical issues related to operationally responsive space and one concept that resonated across technology areas was the concept that program costs could be reduced by exploiting economies of scale and system commonality instead of building each individual vehicle as a stand-alone unique system. This philosophy shaped the initial planning within the HIFiRE program to standardize as much of the vehicle launch system as possible and to attempt to focus experiment-specific configurations and optimization within the scientific payload. Although each flight experiment has a unique

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[†] The HIFiRE program was originally called FResH – Fundamental Research in Hypersonics. This was primarily due to the author's opinion that there were more than enough hypersonic program names starting with "Hy"and a "fresh" approach to the program name would reflect a new perspective regarding flight research. In retrospect the name FResH was not very inspiring and it is fortunate that wiser colleagues at AFRL and DSTO prevailed in changing the program name to HIFiRE.

scientific objective, many of the HIFiRE flights utilize common components and hardware and the exploitation of economies of scale have helped the program maintain control over escalating costs.

Finally, there have also been a number of prior government and academic research efforts that have influenced the philosophy of HIFiRE and warrant mention in this perspective on the program. The work of Fisher and Dougherty[7] to examine the role of disturbance levels in ground test facilities on laminar-turbulent transition on a cone and to compare those results with data taken in flight on the same model established an impressive precedent for scientifically-driven flight research. Additionally, the availability of relevant hypersonic flight data from NASA programs such as Reentry F[8] has provided strong motivation and inspiration for the academic study of foundational scientific issues relevant to hypersonic systems and inspired the HIFiRE program to seek the open publication of as much data from the program as current policy will allow. The AFRL University Nanosat program[9], which has provided opportunities for educational research teams to participate in the development and launch of small satellites, has helped shape the HIFiRE philosophy with regard to coordination with academic research institutions. Lastly, the ESA EXPERT[10] program, which sought to explore fundamental scientific issues associate with reentry systems via a series of independent experiments integrated within a common vehicle, shaped much of the perspective of the international research community regarding science-oriented hypersonic flight research in the years immediately prior to the development of HIFiRE.

B. The Pyramid Approach

One of the foundational premises of the HIFiRE program is the idea that flight research is a complementary component to numerical simulation and ground testing and when the three methods are used in concert there is tremendous potential to advance the understanding of critical scientific phenomena. The concept is conceptually illustrated in Figure 3. Numerical simulations and ground testing provide the foundation of the research program – graphically represented as the base of the pyramid – upon which the rest of the program will be "built". Flight research provides an opportunity to focus and integrate the contributions from numerical simulations and ground testing, in addition to providing essential insight into the behavior of critical phenomena under actual flight conditions. Comparison with flight data provides critical feedback for the refinement, validation and scaling of knowledge learned from the simulation and ground testing components, but due to practical and economic limitations associated with flight research, the detailed, deep knowledge of the critical physical phenomena will most likely originate from within the simulation or ground test contributions. As a whole, the integrated contributions from all three vertices of the pyramid combine to provide fundamental knowledge for the development of hypersonic systems and capabilities.

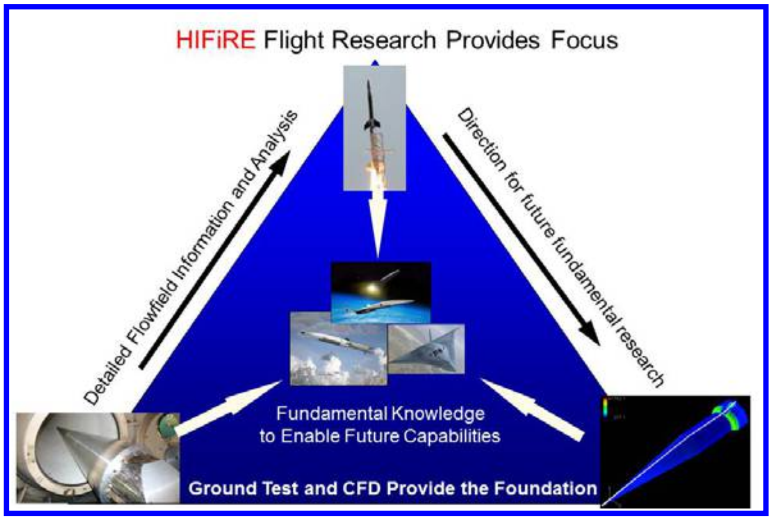

Figure 3. Illustration of Pyramid Approach to the Integration of Ground Test, Numerical Simulation and Flight Research

C. A Brief Summary of HIFiRE Accomplishments

The HIFiRE flight research schedule is comprised of nine research flights addressing a broad variety of hypersonic scientific challenges and one engineering risk reduction flight designed to address vehicle attitude control issues. A comprehensive summary of the program is provided by Dolvin[2] while Kimmel and Adamczak[11-12] provide a review of the aerothermodynamic objectives of the program. To date, the engineering risk reduction flight, HIFiRE 0, and research flights HIFiRE 1, HIFiRE 2 and HIFiRE 3 have been successful. HIFiRE 5[‡] failed

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[‡] Note: The HIFiRE flights are not numbered in chronological order. The sequence of flights so far has been HF0, HF1, HF2, HF5 and HF3.

to reach the designed test Mach number due to an unusual failure of one of the booster stages, but still provided flight data outside the intended experimental window.[13] The 80% success rate for the program so far is much higher than that typically achieved for a flight research program and is a credit to the Program Manager, Mr. Douglas Dolvin from AFRL, and the rest of the HIFiRE team.

HIFiRE Flights 1 and 5 comprise the portion of the program dedicated to aerothermodynamics. For these flights, the test article is boosted towards a parabolic flight trajectory by a two-stage sounding rocket and the experiment remains connected to the experiment in a captive-carry configuration. Near the apogee of the trajectory the experiment is reoriented from a nose up to nose-down position and the experiment then accelerates downward under the force of gravity to reach hypersonic conditions as it returns to earth. An illustration of such a trajectory is presented in Figure 4. Although other HIFiRE flights may utilize different trajectories, this parabolic flight path is common to the aerothermodynamic experiments of flights 1 and 5.

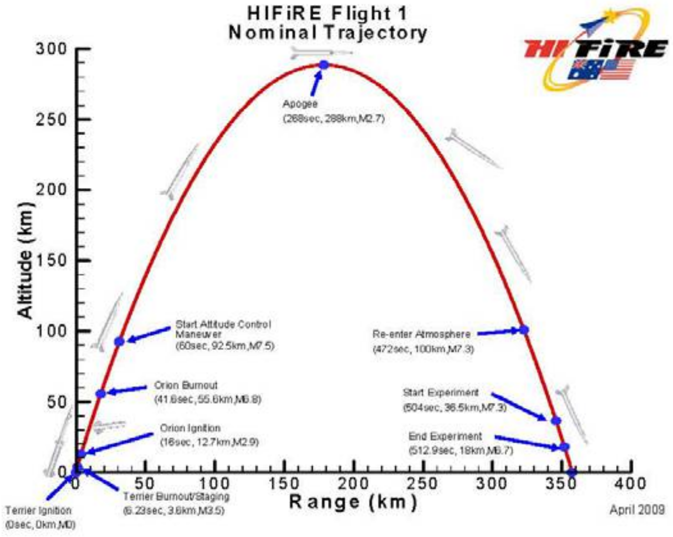


Figure 4. HIFiRE Flight 1 Nominal Trajectory.[14]

Two critical scientific challenges associated with the development of hypersonic systems are the accurate estimation of laminar-turbulent transition and the modeling of unsteadiness in shock/boundary layer interactions. Both phenomena are significant sources of aerothermodynamic heating or acoustic loads and strongly influence the design of the vehicle structure. HIFiRE 1, represented schematically in Figure 5, is designed to provide clarifying flight data on both topics. The flare on the back of the configuration is designed to generate the axisymmetric analog to the spanwise symmetric shock/boundary layer interaction generated by a normally-oriented ramp on a flat plate. The normal ramp configuration has been widely studied with regard to the structure and dynamics of the shock/boundary layer interaction that it generates near the corner junction of the ramp and flat surface.[15] A number of researchers have studied the unsteadiness of this interaction and although substantial progress has been made towards understanding the phenomena, to the author's knowledge, no prior investigation has examined the fundamental unsteadiness of shock/boundary layer interactions in flight and there are open questions regarding the role of the incoming boundary layer and dynamics of the interaction at flight Reynolds numbers.

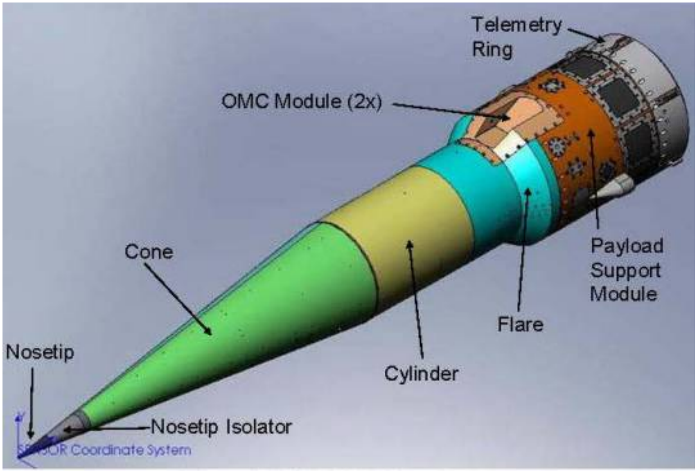


Figure 5. Schematic of the HIFiRE 1 Test Article[14]

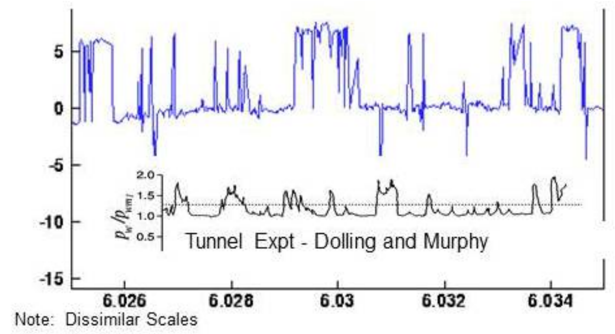


Figure 6. Qualitative Comparison of Fluctuating Pressure Histories from HIFiRE 1 and Dolling and Murphy[16]

Time histories of fluctuating pressure signals taken from the HIFiRE 1 flight data and the ground test experimental compression ramp data of Dolling and Murphy[16] are compared in a qualitative manner in Figure 6. Although there are considerable differences in the freestream conditions and Reynolds numbers for both experiments, both dynamic pressure signals contain characteristics of the bimodal distribution associated with the intermittent passage of a shock wave. Comparison of normalized power spectra of the HIFiRE 1 data with the ground test data of Dolling and Or[17] in Figure 7 reveals the significant low-frequency content that has been widely studied in association with this configuration is also evident in the flight data.[18] It is believed that this is one of the first, if not the first, verification of unsteadiness in shock/boundary layer interactions in flight.

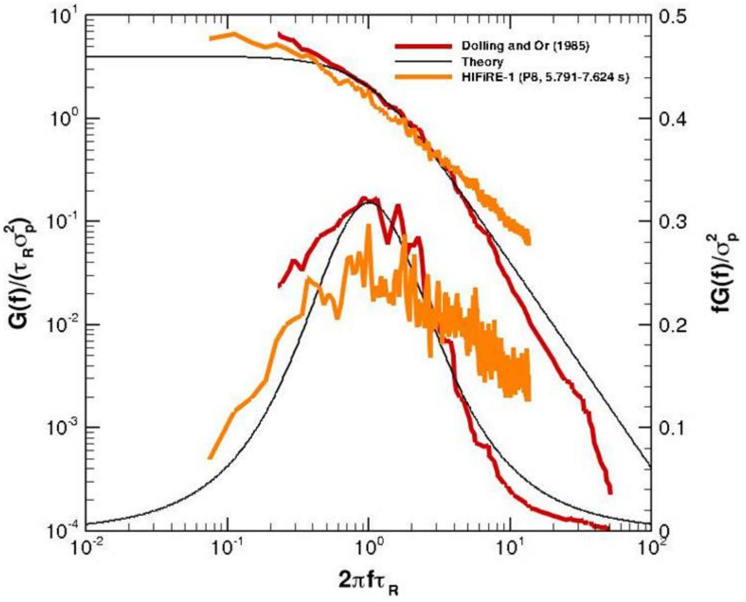


Figure 7. Comparison of normalized power spectra from the wind tunnel experiments of Dolling and Or with Flight Data from HIFiRE 1. (From Ref. 18)

The forebody of HIFiRE 1 is designed to examine laminar-turbulent transition under flight conditions. The forebody shape is a round circular cone chosen to facilitate comparison with a significant number of earlier wind tunnel experiments.[19] Cross-flow and Mack second-mode instabilities are the dominant mechanisms that drive laminar-turbulent transition on hypersonic configurations of this type and the experiment was designed so that both types of instabilities could potentially occur on the vehicle. During ascent, low angle-of-attack transition consistent with the second-mode instability[20] occurred. Although descent occurred at a higher than intended angle-of-attack, this phase of the flight yielded both cross-flow and second-mode induced transition.[47] Analysis of the transition data obtained from HIFiRE 1 has been reported in a number of publications, including References 12 and 20.

The intent of HIFiRE Flight 5 was to complement the data taken on an axisymmetric body in Flight 1 by obtaining similar measurements on a body with significant three-dimensional boundary layers and strong cross-flow. As with the HF1 configuration, the HIFiRE 5 forebody was chosen to facilitate comparison with a significant body of prior ground test experiments. The elliptic cone shape chosen for the experiment, shown in Figure 8, has been the previously studied by a number of groups due to its relatively simple geometric configuration yet significant similarity to the configuration of more complex lifting body shapes utilized in technology demonstration programs. The elliptic cross sectional shape of the cone generates a strong pressure gradient from the major to the minor axis of the cone which results in significant cross-flow within the cone boundary layer. Unfortunately, the second stage booster for Flight 5 failed during the experiment and HF5 did not achieve the designed flight window for the experiment. Reduction of the data collected outside the intended experimental window is ongoing, as are plans to potentially re-fly the experiment at a later date.

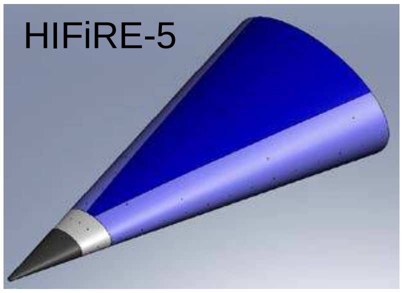


Figure 8. Schematic of the HIFiRE Flight 5 Configuration

In summary, the HIFiRE program has played a considerable role in extending the legacy of HyShot and HyCAUSE and shaping the current philosophy towards economically-efficient flight research. The success rate of the HIFiRE flights, as well as those from the DLR SHEFEX[21] program which shares a similar philosophical foundation with HIFiRE, have led to the appearance of smaller-scale risk mitigation flight research components in the current generation of major hypersonic technology demonstration programs such as the proposed DARPA IH program. Additionally, flight research programs led by academia, such as the University of Virginia/Virginia Tech High-V program[22] are emerging.

III. STAR: Fostering Technology Transition

As noted earlier in this text, one of the objectives of the AFOSR Aerothermodynamics & Turbulence portfolio is to champion the technology transition of advancements from basic research to application within technology maturation programs. In 2003, Dr. Peter Erbland from AFRL who was detailed to the DARPA Falcon Hypersonic Technology Vehicle (HTV) program[23] presented the portfolio with a significant opportunity in this area. Erbland and the Falcon management team were concerned with the significant uncertainty associated with the estimation of laminar-turbulent transition in the industrial design approach for maneuvering reentry shapes such as those planned for the Falcon program and the resultant impact on system thermal protection system requirements. The Aerothermodynamics & Turbulence portfolio was invited to work closely with the Falcon management team to try to address this issue and improve the state-of-the-art in the estimation of hypersonic laminar-turbulent transition.

In response to this challenge, the portfolio adopted a two-pronged strategy of developing and transitioning advanced numerical methods that were easily implemented and integrated with existing industrial design processes and making subject matter experts on the topic of laminar-turbulent transition readily available to applied research organizations and industry that were supporting the Falcon program. The effort was named STAR – STability Analysis for Reentry – and included Prof. Steven Schneider from Purdue University, Prof. Graham Candler and Dr. Heath Johnson from the University of Minnesota, Prof. Helen Reed from Texas A&M University and Dr. Roger Kimmel from AFRL. The STAR team initially held several workshops to inform the technology development community with regard to the maturing basic research tools that were potentially applicable to the Falcon program and later consulted with various groups on technical issues related to laminar-turbulent transition. As the Falcon program progressed the STAR team provided critical insight towards the verification of the vehicle configuration and trajectory and helped identify key events and phenomena that contributed to in-flight incidents. In addition to supporting the Falcon HTV-2 program the STAR team also contributed to the resolution of key challenges for the X-51 program and the transition of methods developed by the team has facilitated unprecedented new capabilities within the Test & Evaluation community.

A. Critical Guidance Provided to Technology Development Programs


Figure 9a. Temperature Sensitive Paint on HTV-2 Forebody Tested in Purdue Quiet Flow Ludwieg Tube[48]

The STAR team proved that it could make a valuable contribution to technology development programs through the support it provided to the Falcon team in the pre-flight assessment of the HTV-2 configuration and confirmation of the planned vehicle trajectory. Ground test data obtained on the HTV-2 forebody in conventional wind tunnels indicated that boundary layer transition could potentially occur further upstream than originally considered in the vehicle and trajectory design, significantly increasing the risk of thermal protection system failure. The STAR team examined the issue in an integrated computational and experimental assessment. Experimental data collected in the flight-like disturbance environment of the Purdue Quiet Flow Ludwieg Tube indicated that in a low disturbance environment the onset of transition was significantly further downstream than that observed in the higher-disturbance environment of the earlier conventional tunnel tests. Computational analysis from the University of Minnesota provided insight into the development of streamlines in the nose region that led to the possible formation of instabilities. Based on the integrated insights from both the experiments and simulations, the program developed a modification to the nose shape that resulted in a further delay of the onset of transition on the vehicle surface. As a result of the

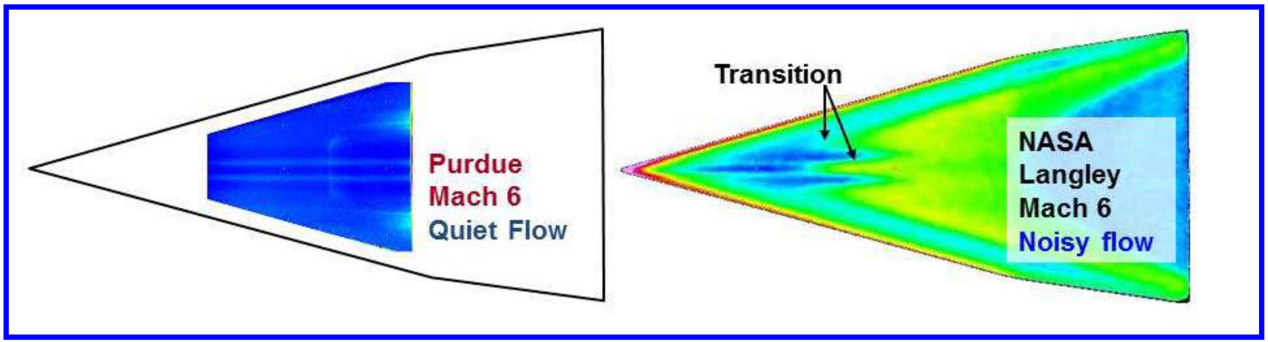


Figure 9b. Comparison of transition locations observed under Quiet and Conventional facility noise levels.[48]

STAR team's contributions in verifying the designed trajectory and improving the nose-tip design, the HTV-2 program proceeded to flight.

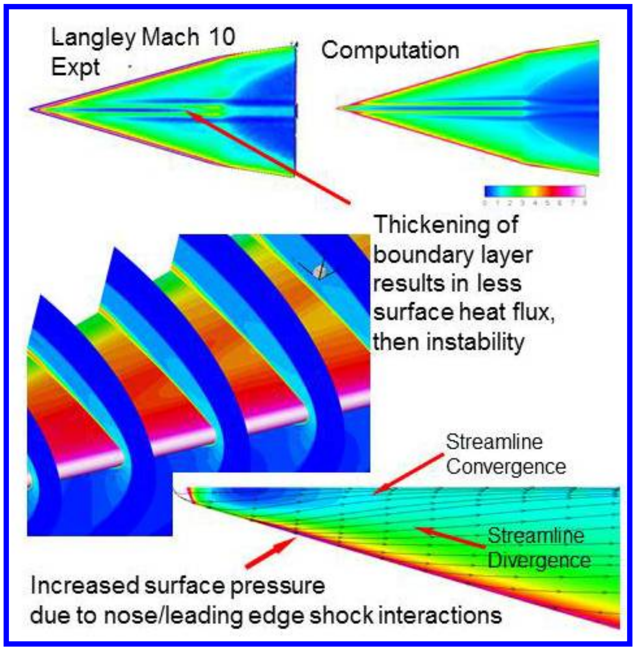


Figure 9c. Numerical Simulation of Critical Phenomena on HTV-2 Forebody, from the University of Minnesota.[48]

Although this contribution from the STAR team to the HTV-2 program has not been published prior to this paper, the team's contributions were presented by MGen Bedke, the AFRL commander, during the 2010 AF/AIAA T&E Days conference.[48] Figures 9a-c, extracted from Bedke's briefing illustrate the accomplishments discussed in the preceding paragraph.

Following both the first and second HTV-2 flights the STAR team provided significant support to the Falcon program by aiding in the post-flight analysis that identified the critical physical phenomena that led to the in-flight incidents for both flights. Although the team's specific contributions are not presented here, it can be stated that the team's contributions played a critical role in aiding the program contractor and management team in understanding the underlying scientific phenomena that drove the extreme conditions experienced by the vehicle during both flights.

In a similar manner the STAR team also supported the Air Force X-51 program. Data from the Purdue Quiet Flow Ludwieg Tube indicating the effectiveness of boundary layer trips on a scaled model of the X-51 inlet forebody is shown in Figure 10. The upper image shows a thermal image obtained from temperature sensitive paint indicating that in a flight-like disturbance environment the inlet trips would have a delayed effectiveness – as seen by the increased surface heating resulting in transition six inches downstream of the inlet ramp corner which is indicated as a dotted line in the image. The lower image shows the effectiveness of the trips in the higher disturbance "noisy" environment typical of conventional ground test facilities. Under noisy conditions the trips lead to transition at the inlet ramp corner, as seen by the sudden increase in surface heating associated with turbulent flow immediately downstream of dotted line. The insight from this analysis helped the X-51 designers understand and account for the influence of high-disturbance tunnel environments when considering the data from larger-scale ground test facilities used for the pre-flight assessment and development of the X-51 system. Following the incident in Flight 2 of the X-51 program, the STAR team again supported the program by providing a detailed computational investigation of the state of the boundary layer developing within the inlet. Although details remain unpublished, in a private communication the X-51 program manager has indicated that the STAR team analysis was essential to the resolution of an open question regarding the state of the inlet boundary layer and the program was able to incorporate the results of the analysis in planning for the successful flight on May 1, 2013.

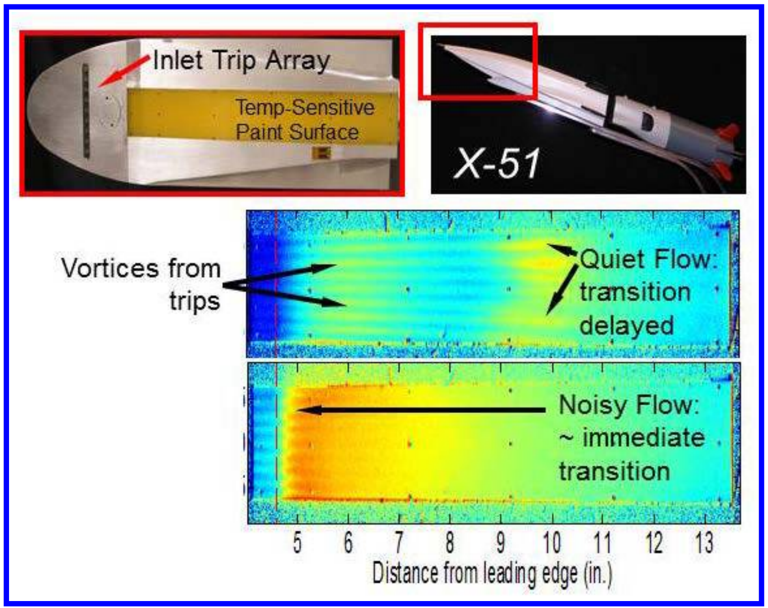


Figure 10. Temperature Sensitive Paint Images from Purdue Quiet Flow Ludwieg Tube Revealing X-51 Trip Inlet Effectiveness in Quiet and Noisy Freestream Conditions[49]

B. Development and Transition of Advanced Simulation Tools

The second thrust of the STAR strategy was the development and transition of advanced simulation tools to applied research. Around 2003, when the STAR initiative began, the state-of-the-art for inclusion of transition considerations in the design of hypersonic vehicle designs was to estimate the onset of transition via a correlation based on mean flow parameters. Some approaches also estimated an altitude for which transition would occur, an idea which had its roots in the design of ballistic systems and can be shown analytically to be consistent with some of the mean flow correlations.[24] Unfortunately, the transition process is driven by the initiation and growth of instabilities in the boundary layer and mean flow parameters do not accurately represent the key physics of the process. (See the review by Schneider[25] for additional information on this topic.) Thus, there are inherent and considerable uncertainties associated with mean flow correlations for transition and the method is generally insufficient for the accurate estimation of transition.[§]

Research methods based on linear stability theory or the parabolized stability equations (PSE), which predict the growth of instabilities within a base mean flow solution, had been utilized by the scientific community for several decades[26], but seemed to lack acceptance for technology maturation. It should be noted that several prior attempts to transition methods based on stability theory have been made, but the methods have generally not been widely adopted within industry. It was the author's opinion, based on several anecdotal conversations with various members of the community, that prior efforts to transition stability-based methods faltered because the technology maturation community was not yet ready to utilize them but in 2003 with the recent significant advancement and utilization of large-scale computational methods the applied research community was perhaps finally ready to move to a stability-based approach.

Under prior sponsorship from AFOSR, Johnson and Candler at the University of Minnesota had developed a PSE method called PSECHEM which included the capability to consider finite-rate gas chemistry within the analysis.[27] Although there were several other PSE methods in use within the research community at the time, most notably the NASA LASTRAC code, the fact that PSECHEM included gas chemistry effects critical for the analysis of hypersonic flows motivated its choice as the basis for a technology transition initiative. Johnson took the lead in reconfiguring PSECHEM as an easily-integrable, user-friendly stability analysis tool designed for transition to the applied research community. Significant effort was invested in ensuring that the tool could be readily installed and integrated with existing computational solvers and that the code could be run in a training or development mode with an easy to interpret graphical user interface. Johnson also spent a considerable amount of time supporting installation and education for potential users. The resulting tool was renamed STABL – STability Analysis for Boundary Layers – and both utilized and refined in the STAR team contributions to the analysis of the HTV-2 and X-51 programs.

In a parallel effort, Candler's research group developed an improved unstructured version of the NASA hypersonic workhorse DPLR (Data Parallel Line Relaxation)[28] which was originally developed by Wright and Candler. The new unstructured code, called US3D[30], incorporated kinetic energy preserving flux reconstructions[29] to facilitate improved resolution of small-amplitude fluctuations while retaining the computational efficiency of lower-order algorithms. US3D was designed to be easily coupled with STABL and other specialized companion solvers that address multiphysical phenomena such as gas-surface interactions and ablation.

Not all the methodology advancements developed by the STAR team were computational. During 2007 a collaboration between Purdue and TU Braunschweig[31] refined the use of unconventional sensors (originally employed by Fujii in 2005) to characterize second-mode instabilities in hypersonic boundary layers. The PCB sensors utilized in this effort had traditionally been utilized, among other things, for sensing seismic disturbances and strain waves in naval artillery pieces. The stiff sensing element required for the sensor to withstand such measurements resulted in the transducer being sensitive to very high-frequency fluctuations such as those associated with second-mode instabilities which can occur at several hundred kHz. Although the PCB sensors have proven difficult to calibrate, their use has enable the detection of second-mode instabilities in the boundary layer generated on test articles in a wide variety of ground test facilities. As a result, research scientists and test engineers have a new capability to conveniently detect the presence of critical instabilities within the hypersonic boundary layer.

[§] The author has tried to consistently use the term "estimation" with regard to the prediction of laminar-turbulent transition. Due to the fact that the critical physical phenomena that initiate instabilities and drive the transitin process, including freestream perturbations and surface roughness, are impossible to precisely model for any flight, transition will never be truly predicted. Instead, the most likely paths to transition will be estimated and the uncertainty bounds associated with transition will be minimized to a tolerable range that can be accommodated within the vehicle design. The author is unsure of the source of this philosophy, but he generally attributes it to both Dennis Bushnell and William Saric.

C. Technology Transition Resulting from STAR

At the beginning of the STAR initiative it was envisioned that once the benefits of the advanced methods demonstrated by the team were evident to the technology development community there would be a rapid adoption of the methods and tools within industry and government laboratories. Unfortunately, this was not the case and for several years the STAR effort existed primarily as a support program to the major technology demonstration programs. However, over the last five years there has been a substantial increase in the number of technology transition events derived from the STAR effort, as the team's expertise and methods have continued to consistently make valuable contributions to the resolution of key scientific challenges.

The computational tools developed by the Candler group at the University of Minnesota have been transitioned to a relatively large number of organizations and the codes are starting to see extensive use. STABL has been adopted by more than 25 organizations including multiple groups within the Air Force and NASA, Sandia Laboratories, most of the major airframers and several universities. The basic research version of STABL continues to be developed at the University of Minnesota while an offshoot government-only version intended for the Test & Evaluation community is being further developed under support from the DoD Test Resource Management Council in a partnership with GoHypersonic, Inc. US3D has been transitioned to more than 15 organizations including many of those that have adopted STABL. The numerically-efficient resolution of critical physical scales achievable with the code has made it attractive for the simulation of system- and component-scale flows over hypersonic systems and the code architecture facilitates integration with other methods such as STABL or material response modules. The code is receiving considerable attention from a number of government agencies and is poised to be one of the workhorses for the development of the next generation of hypersonic systems.

Although industry and government research laboratories were the original intended beneficiaries of the STAR effort, the Test & Evaluation (T&E) community has played a critical role in the utilization and adoption of tools and methods developed under the initiative. In retrospect, this was a logical evolution for the effort since many of the technical challenges experienced by major development programs are addressed and resolved in the large-scale T&E facilities. John Lafferty, Dan Marren, and the staff of Arnold Engineering Development Center (AEDC) Tunnel 9 recognized the potential of the STAR effort to transform T&E capabilities early in the initiative and worked closely with the STAR team members and program management to coordinate the transition of emerging tools for use in the T&E environment. Although a number of technology transitions have resulted from this collaboration, perhaps the most impressive has been the integration of a number of the STAR-developed advancements to yield new capabilities for assessing the evolution and impact of boundary layer transition on a model tested in Tunnel 9. In this integrated approach US3D is used to simulate the mean flow over the model and the results are utilized by STABL to determine the most probable instability mechanisms that will develop within the flowfield. The PCB sensors capable of detecting second-mode instabilities are utilized to verify the presence of the predicted instabilities within the model boundary layer and temperature sensitive paint capabilities developed internally at AEDC are used to characterize the global footprint of transition on the vehicle surface. As a result of these integrated methods, T&E engineers can now predict, verify and assess the global impact of instabilities that drive the transition process on hypersonic systems, a significant advancement over prior approaches that inferred the effect of transition from force and moment data and surface heat transfer measurements.

In summary, the STAR team has provided crucial scientific expertise to a number of major technology development programs, including Falcon HTV-2 and X-51, driven the transition of new capabilities to government and industry, and facilitated new capabilities within the T&E community. An attribute that has played a vital role in the success of the initiative has been the interest and effort the participants in the program from academia, industry, and government have invested in closely collaborating on the program. The STAR team members prioritized outreach to the members of the technology maturation community and industry and government engineers have actively sought the advice and counsel of the team. On the government side, program managers from AFOSR, AFRL, DARPA and AEDC have worked very closely to coordinate the efforts of the team and to facilitate the transition of technology into application. Without this teamwork at the program management level the success of the STAR initiative would not have been possible. Finally, in addition to the methods and tools developed under STAR, a number of students trained under this initiative and proficient with these tools have begun careers within government and industry where they will continue to contribute to the advancement of hypersonic technologies. This next generation of engineers and scientists are among the most important technology transitions to sprout from the basic research investments of AFOSR.

D. Notable Efforts Outside of STAR

In addition to the STAR initiative, the AFOSR Aerothermodynamics portfolio has also supported a number of other initiatives intended to facilitate the discussion of critical research issues and foster the advancement and transition of leading-edge scientific methods. Among the most significant efforts of this type have been the portfolio's support of research contributions to NATO Research and Technology Organisation (RTO) efforts in hypersonics since the late 1990s. Under RTO Working Group 10 (1998-2002),[41] a number of researchers sponsored by the portfolio contributed to an effort addressing the *CFD validation of Hypersonic Flight*.[42] Although the portion of this effort that addressed shock-shock interactions was led by two consecutive program managers of the Aerothermodynamics & Turbulence portfolio[43], the most notable effort in this area addressed the ability of various computational methods to simulate laminar shock/boundary layer interactions occurring within high-enthalpy flows.[44] As part of the activities associated with this topic, a number of leading experts in numerical simulations were invited to participate in a "blind" validation study of the flow generated by a double-cone configuration. Surprisingly, there was generally poor agreement between the results of the numerical simulations and experimental data, an outcome that generated considerable attention and discussion within the aerothermodynamics research community. Further investigation of the sources of discrepancy between the simulations and experiments over the next few years led to significant new understanding of the role of nonequilibrium effects within high-enthalpy facilities and improved methods for the simulation of such flows.[45]

Following Working Group 10, RTO working group AVT-136: *Assessment of Aerothermodynamic Flight Prediction Tools through Ground and Flight Experimentation*[46] continued efforts to assess and validate numerical simulation methods. Although this working group was organized with the objective of assessing how computational methods extrapolated to flight conditions, delays in launch dates for programs slated to provide the flight data led to a redefinition of the group objectives to focus on an evaluation of the current state-of-the-art in computational methods for a variety of topics critical to hypersonic systems. Despite this setback, the efforts of the group were featured in more than 40 conference papers in six invited sessions at the Sixth European Symposium on Aerothermodynamics for Space Vehicles and the 48th (2010) AIAA Aerospace Sciences Meeting and the final report of the group was published as a special edition of *Progress in Aerospace Sciences.*[46] Three current RTO groups addressing Catalyzed Gas-Surface Interactions (AVT-199), Sources of Aeroheating in Hypersonic Systems (AVT-205), and Hypersonic Laminar-Turbulent Transition (AVT-200) have also grown out of the work of AVT-136.

Experimental data from the CUBRC team led by Dr. Michael Holden have played a critical role in the success of these activities, as well as a variety of others. Holden's team has been responsible for multiple experimental investigations of the double-cone flowfield that have enabled progress in the characterization and simulation of nonequilibrium effects in high-enthalpy flows, assessment of key aerodynamic phenomena on a variety of flight demonstration configurations, and preliminary experimental analysis of the HIFiRE flight 1 and 5 configurations. For HIFiRE 1, the CUBRC team played a significant role in the determination of the flare configuration and a preliminary assessment of transition estimation methods on the forebody.

IV. The National Hypersonic Foundational Research Plan

Throughout the history of hypersonic technology development investments in essential supporting scientific efforts have been closely aligned with the technology system or application of interest at the time. In its 2000 report "Why and Whither Hypersonics Research in the US Air Force?"[32] the Air Force Scientific Advisory Board (SAB) described the roughly 15-year boom-and-bust cycle hypersonic technology development has endured in the United States and observed that as a result of the close-coupling between technology and basic science funding the base of scientific expertise in areas supporting hypersonic development has been slowly diminishing. The SAB observed that experts seeking alternative research areas during each bust cycle were not being recovered or replaced with each new boom period.

In 2003 program managers from AFOSR, NASA Langley and Sandia National Laboratories recognized the fact that, while each organization had a unique mission and technology objective, similar foundational science capabilities and investments were required. As a result, efforts began to coordinate the research investments of each agency in the area of laminar-turbulent transition with the goal of promoting collaboration and maximizing the limited resources available. By 2005 the effort has seen sufficient preliminary success that, when DoD senior leadership suggested that a national initiative coordinating hypersonic research would be well-received, it was adopted as the basic model for the National Hypersonic Foundational Research Plan. Although there have been several prior efforts to coordinate hypersonics research on a national scale, the intent of the National Hypersonic

Foundational Research Plan was to employ a slightly different approach by focusing on scientific, not technology, challenges.

A. NHFRP Objectives

The National Hypersonic Foundational Research Plan (NHFRP) was motivated by the observation that the federal organizations supporting the maturation of hypersonic technologies frequently shared common goals regarding the development of foundational sciences, despite having different missions and applications. The perspective of the Air Force SAB regarding the sustainment of the hypersonic knowledge base provided additional motivation. The goal of the NHFRP was to identify scientific research objectives critical to the development of hypersonic capabilities but independent of specific technology programs. The decoupling of scientific research funding from technology development trends was intended to foster the long-term sustainment of the critical knowledge base and ensure that critical subject matter expertise was readily available to new technology development initiatives during the initial rise of future boom cycles. This concept is schematically illustrated in Figure 11 which attempts to reproduce several of the graphics illustrating trends developed by the SAB on the left side of the illustration, while communicating the goals of the development of a stable base of expertise on the right side.

B. NHFRP Thrust Areas

The NHFRP was organized along the lines of six scientific thrust areas deemed by program managers from the participating agencies to be critical and unique to the development of hypersonic capabilities. Although contributions from many more than six areas are required to realize hypersonic systems, disciplines where other applications outside hypersonics could potentially drive scientific progress were not included in the plan. The six thrust areas of the NHFRP include the following:

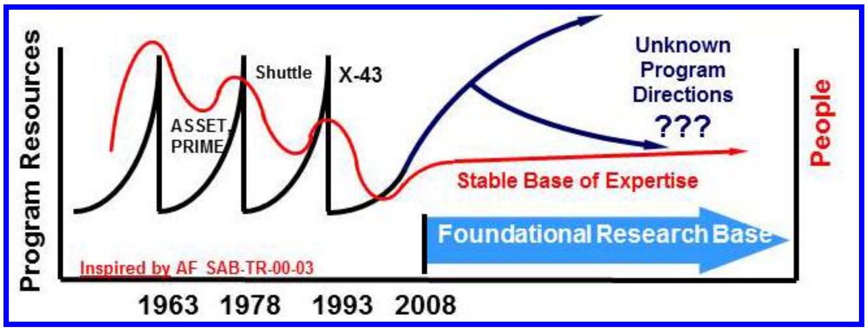
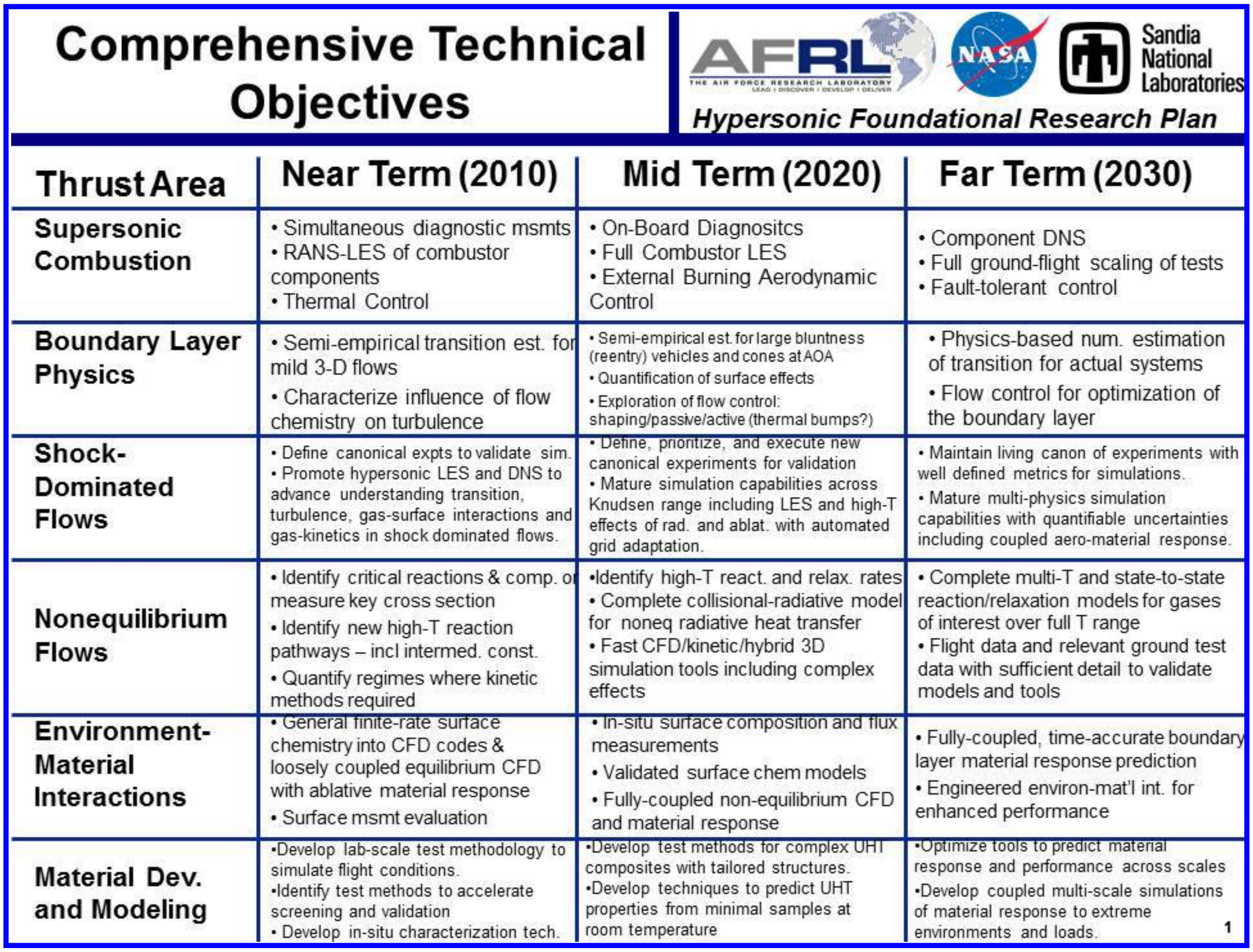


Figure 11. Illustration of trends reported in 2000 SAB report and objective of NHFRP

- Boundary Layer Physics
- Shock-Dominated Flows
- Nonequilibrium Flows
- Supersonic Combustion
- Environment, Structures and Material Interactions
- High-Temperature Materials and Structures

To formulate the NHFRP thrust plans, in 2007 leading subject matter experts from the Air Force, NASA, Navy and Sandia National Laboratories were invited to participate in a workshop at NASA Langley where near-term (2010), mid-term (2020) and far-term (2030) scientific goals were identified for each thrust area. For each thrust area a panel of 8-10 subject-matter-experts participated in the identification of goals, with roughly 50 participants participating in the workshop. Two tiers of goals were developed as part of the planning effort, a top-level comprehensive set of goals intended to communicate the plan to leadership and the general aerospace community, and a specific set of goals for each thrust area intended to inform and shape the research directions of the research communities supporting the thrust. The objectives were reviewed and updated with minor revisions in a second workshop occurring during the summer of 2009. The top-level goals from the 2009 version of the NHFRP are listed in Figure 12.



Comprehensive Technical Objectives

Hypersonic Foundational Research Plan

Thrust Area	Near Term (2010)	Mid Term (2020)	Far Term (2030)
Supersonic Combustion	• Simultaneous diagnostic msmts • RANS-LES of combustor components • Thermal Control	• On-Board Diagnositcs • Full Combustor LES • External Burning Aerodynamic Control	• Component DNS • Full ground-flight scaling of tests • Fault-tolerant control
Boundary Layer Physics	• Semi-empirical transition est. for mild 3-D flows • Characterize influence of flow chemistry on turbulence	• Semi-empirical est. for large bluntness (reentry) vehicles and cones at AOA • Quantification of surface effects • Exploration of flow control: shaping/passive/active (thermal bumps?)	• Physics-based num. estimation of transition for actual systems • Flow control for optimization of the boundary layer
Shock-Dominated Flows	• Define canonical expts to validate sim. • Promote hypersonic LES and DNS to advance understanding transition, turbulence, gas-surface interactions and gas-kinetics in shock dominated flows.	• Define, prioritize, and execute new canonical experiments for validation • Mature simulation capabilities across Knudsen range including LES and high-T effects of rad. and ablat. with automated grid adaptation.	• Maintain living canon of experiments with well defined metrics for simulations. • Mature multi-physics simulation capabilities with quantifiable uncertainties including coupled aero-material response.
Nonequilibrium Flows	• Identify critical reactions & comp. or measure key cross section • Identify new high-T reaction pathways – incl intermed. const. • Quantify regimes where kinetic methods required	•Identify high-T react. and relax. rates • Complete collisional-radiative model for noneq radiative heat transfer • Fast CFD/kinetic/hybrid 3D simulation tools including complex effects	• Complete multi-T and state-to-state reaction/relaxation models for gases of interest over full T range • Flight data and relevant ground test data with sufficient detail to validate models and tools
Environment-Material Interactions	• General finite-rate surface chemistry into CFD codes & loosely coupled equilibrium CFD with ablative material response • Surface msmt evaluation	• In-situ surface composition and flux measurements • Validated surface chem models • Fully-coupled non-equilibrium CFD and material response	• Fully-coupled, time-accurate boundary layer material response prediction • Engineered environ-mat'l int. for enhanced performance
Material Dev. and Modeling	•Develop lab-scale test methodology to simulate flight conditions. •Identify test methods to accelerate screening and validation • Develop in-situ characterization tech.	•Develop test methods for complex UHT composites with tailored structures. •Develop techniques to predict UHT properties from minimal samples at room temperature	•Optimize tools to predict material response and performance across scales •Develop coupled multi-scale simulations of material response to extreme environments and loads.

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Figure 12. Top Level Comprehensive Goals of the National Hypersonic Foundational Research Plan (May 2009)

An example of how the investments of the various agencies integrate to support progress towards the objectives of the NHFRP is illustrated in Figure 13. As indicated in Figure 12, one of the near-term goals in the area of Boundary Layer Physics for the topic of laminar-turbulent transition has been the development and validation of semi-empirical transition estimation methods for three-dimensional flows. Such methods would include STABL, LASTRAC, and other methods for which the predicted instability amplitude growth rate is calibrated with existing data to provide an estimate of the magnitude of the instability growth that will result in transition. To complement ground test data, flight research experiments supported by the Air Force and NASA provide a progressive series of vehicle geometries on which validation data for semi-empirical methods was to be obtained. The progression of flight research configurations with increasingly three-dimensional geometries and resultant boundary layer flows is shown in the left side of Figure 13.

The mid-term goal of the Boundary Layer Physics thrust plan is to "quantify surface effects" and begin to extend semi-empirical methods to account for realistic surface conditions including roughness and manufacturing discontinuities. Although specific efforts to provide validation data in this area are still under development, the recent efforts of NASA to image the Shuttle Orbiter during reentry via the HYTHIRM[33] program provide some insight into how such efforts could proceed. Infrared thermal images of the Shuttle during reentry from the HYTHIRM program are compared with simulations from Candler in the right-hand portion of Figure 13. Within both sets of images, the impact of surface defects can be seen in the wedges of turbulent flow that follow disturbance sites. Understanding the impact of such realistic conditions on the development of the transition process will be key to extending semi-empirical methods towards a more general transition estimation capability.

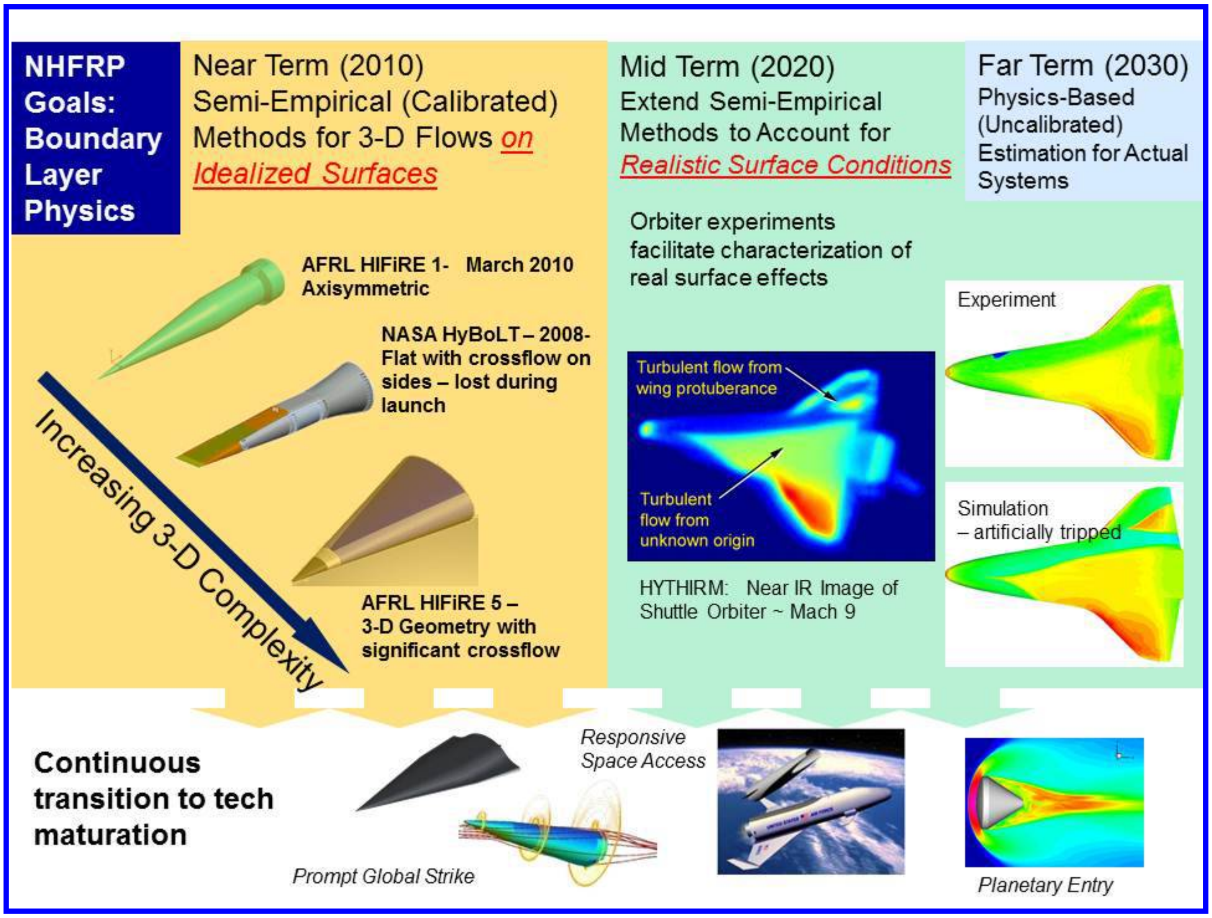

Figure 13. Illustration of the integration of various government research efforts towards achievement of the scientific goals defined in the NHFRP for the Boundary Layer Physics topic of laminar-turbulent transition.

C. Summary and Impact of the NHFRP

To date, the NHFRP has been reasonably successful in defining and communicating a unified national vision for the advancement of scientific disciplines that are essential for the realization of planned hypersonic capabilities. As part of the coordination facilitated by the plan, in 2009 NASA and AFOSR jointly invested almost $30 million over five years in three academic research centers addressing the NHFRP thrust areas of Boundary Layer Physics, Supersonic Combustion, and High-Temperature Materials and Structures. The three National Hypersonic Science Centers (NHSCs) developed under this initiative supported more than 100 graduate students at 18 universities in areas essential to the development of future hypersonic capabilities. The NHFRP has also been adopted by the DoD Joint Technology Office for Hypersonics as the DoD basic science plan for the maturation of hypersonic technologies. The NHFRP is intended to be an evolving document that is updated periodically as research progress allows advancement towards the goals defined in the plan. Since the plan was originally drafted in 2007 it has been updated once in 2009 and is scheduled to be revised and updated again in 2013.

V. Future Research Directions

Although most of this paper has focused on the programmatic activities that have allowed the AFOSR Aerothermodynamics & Turbulence portfolio to guide the scientific research community and facilitate technology transition, the most important role of the portfolio is to foster the discovery and advancement of innovative science with the potential to lead to transformational Air Force capabilities. This final section will focus on the envisioned future research emphasis of the portfolio: energy transfer between kinetic, internal and chemical modes in a gas and how the characterization, modeling and control of such mechanisms at the molecular- and meso-scales may enable the management of flow behavior at the macroscopic subsystem or vehicle scale. This emphasis area was chosen based on the observation that many of the scientific challenges in aerothermodynamics can be considered within the scope of this topic but in the past the work has typically been motivated and presented in terms of the relevant system issues. By emphasizing the fundamental science issues of the research, the portfolio hopes to focus the attention of the community on the scientific challenge and facilitate the extension of research within the portfolio to a broader range of applications of interest to the Air Force, including thermal management and directed energy systems.

A. Notable Research Accomplishments that Shaped the Program Direction

As noted above, much of the recent progress in aerothermodynamics has been made based on new insights into the transfer of energy between various modes – kinetic, internal or chemical. Four examples of such work include Saric's use of discrete spanwise roughness elements for cross-flow instability control[34], Rasheed, et al's use of acoustic-absorptive surfaces for second mode instability control[35], Martin and Candler's simulations of the effect of chemical reactions on turbulent fluctuations within the boundary layer[36], and Leyva, et al's studies of the role of CO_2 on the attenuation of second mode instabilities[37]. Each of these AFOSR-sponsored efforts has provided new insight into fundamental energy transfer mechanisms or interactions that have affected the macroscopic behavior of the flow and as a whole they strongly influenced the perspective of the author.

Saric's approach to cross-flow instability control on swept wings is to place discrete finite disturbance elements at subcritical spanwise wavenumbers near the leading edge of the wing. A variety of disturbance configurations including roughness, holes, and plasma actuators have been utilized. The underlying theory behind the control concept is that the subcritically-spaced elements perturb the base flow in a way that promotes the development of the associated subcritical instabilities and, thus, hampers the development of critical instabilities. This tailoring of the flowfield to favor the most benign instabilities exploits the competition between various instability modes within the flow and in the context of the new programmatic paradigm can be considered as an approach that favors the distribution of kinetic energy into modes that are the most favorable to the desired flow state.

Candler and Martin examined the role of endothermic and exothermic reactions within a turbulent boundary layer and noted that with the release of energy in exothermic reactions the intensity of turbulent fluctuations increased while conversely endothermic reactions resulted in a decrease in turbulence intensity. This work illustrated the potential for interaction between chemical and kinetic energy modes within the flowfield.

The work of Hornung and Rasheed experimentally verified the theoretical predictions of Malmuth and Federov that an acoustically absorptive surface could be utilized to attenuate second-mode instabilities within a hypersonic boundary layer. By covering one side of a cone with blind holes which served as acoustic dampeners and leaving the other side as a smooth surface, Hornung and Rasheed demonstrated that the transition Reynolds number was almost 50% greater on the side of the cone with holes compared to the smooth side. Later, Bres, Colonius and Fedorov[38] examined the phenomena in an integrated theoretical and computational approach and verified the effect of the blind holes on the attenuation of the second-mode instability. In the context of energy transfer mechanisms, this effort illustrated the effect of controlling the availability of the kinetic energy within the instability to delay transition and, thus, shape the macroscopic state of the flowfield.

The final example of work that has influenced the emerging research directions of the portfolio is a similar effort of Leyva, et al,[37] to examine the effect of the presence of CO_2 on the growth of second-mode instabilities in air. In early experiments, Hornung's group at CalTech sought to explain the approximately factor of four difference in transition Reynolds numbers on a cone between flows of CO_2 and flows of air and N_2[39], as illustrated in Figure 14. It was theorized that the effect was the result of an overlap in the spectral ranges for the occurrence of second-mode instabilities and molecular acoustic absorption in CO_2, since such overlap does not occur in air. (Figure 15) Later experiments by Jewell, et al[51] indicated that the injection of CO_2 into a Mach 5 freestream air boundary layer could for certain conditions delay the onset of transition and simulations by Wagnild and Candler[40] verified that the delay of transition resulting from the CO_2 injection was the result of absorption of the energy from the second-mode instability into the internal vibrational modes of the CO_2. In this case, the energy transfer from the kinetic energy of the instability into the internal vibrational mode of the gas resulted in a delay in transition location in the cone boundary layer.

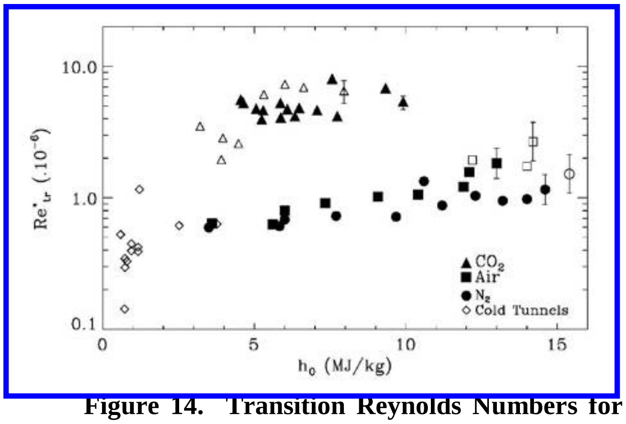

Figure 14. Transition Reynolds Numbers for Air, CO2 and N2 on a Cone for various flow enthalpies. From Ref. 39

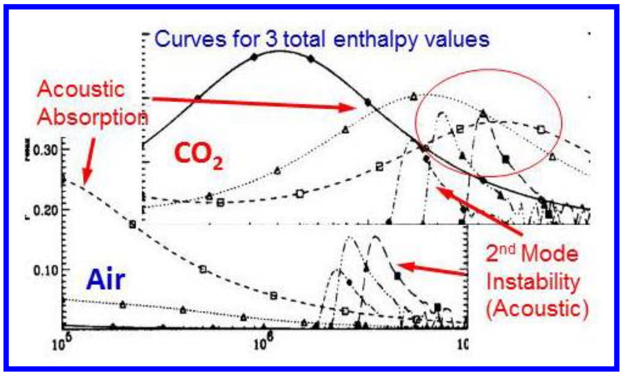

Figure 15. Comparison of 2nd Mode Instability and Acoustic Absorption bandwidths for Air and CO₂. Ref. 50 and I. Leyva, private communication

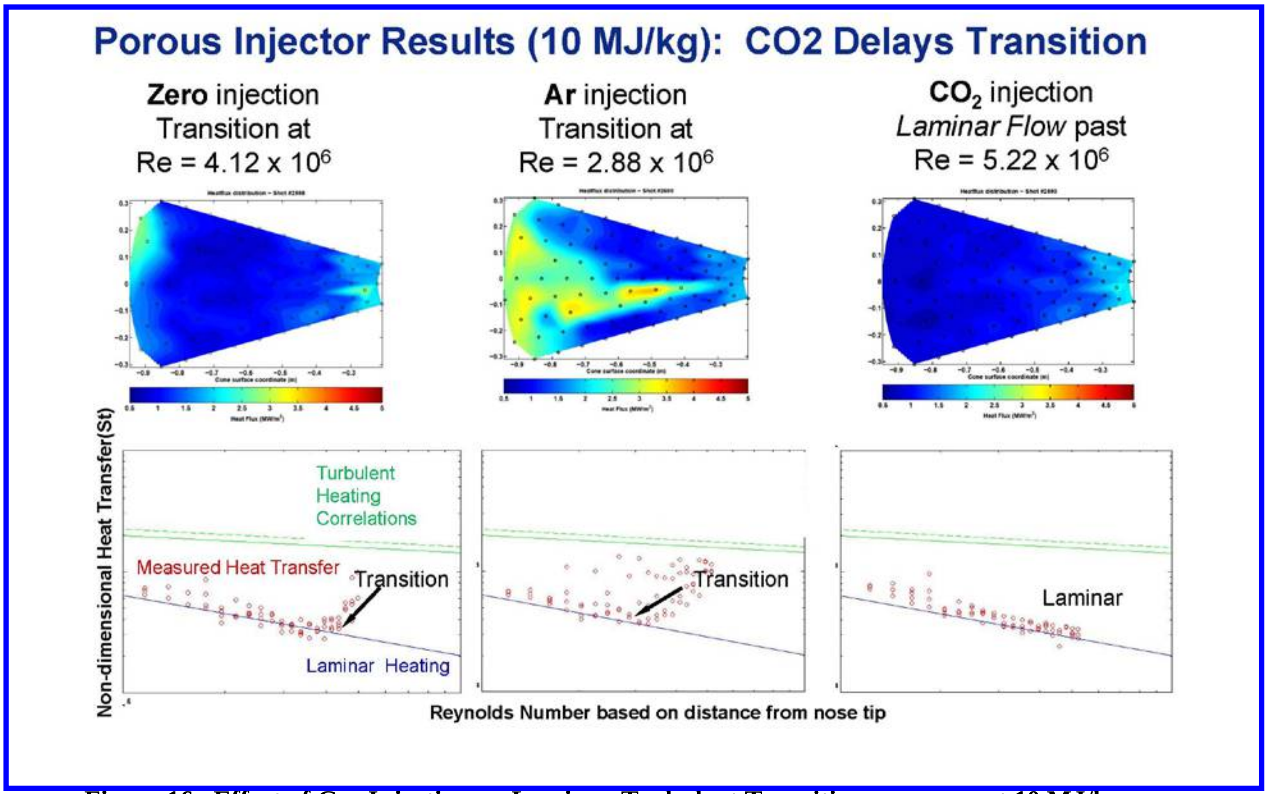

Figure 16. Effect of Gas Injection on Laminar-Turbulent Transition on a cone at 10 MJ/kg. From Ref. 51, Courtesy I. Leyva

B. New Opportunities for *Inherent* Flow Control

Although individually the research highlights noted above are impressive, when considered as a group it is the opinion of the author that they are absolutely game-changing. Once identified, knowledge of dominant energy transfer mechanisms can potentially be exploited to enable a revolutionary approach to the control of macroscopic flow behavior. Specifically, flowfields could be *designed* to favor preferred energy transfer mechanisms that result in an application-optimized flow state. To the authors' knowledge this perspective has not been programmatically emphasized within the scope of prior fluid dynamics research and a broad spectrum of technological benefits could be realized by breakthroughs driven by progress in this area. Previous efforts, particularly those related to gas lasers and plasma processes, have explored the creation of excited energy states within the flowfield. Prior knowledge from these areas will be leveraged to explore the generation and control of specific flow structures and phenomena. In this manner, a new branch of flow control that addresses the exploitation of energy transfer mechanisms and rates to create flows that *inherently* tend to evolve towards a designated end state may be possible. With the assistance of breakthroughs in large-scale parallel computing and highly-resolved optical diagnostic methods, researchers are now equipped to explore and characterize rate-dependent micro- and molecular-scale energy transfer processes and the critical role they play in shaping the macro-scale behavior of the flowfield.

VI. Summary

Even with evolving global political and military challenges, the ability to rapidly and economically cover large areas remains an invariant goal for the warfighter. The objectives of the Air Force Office of Scientific Research *Aerothermodynamics and Turbulence* portfolio are to provide the foundation for the achievement of this warfighter capability by discovering and advancing the necessary science that will enable future technologies and fostering the transition of innovative breakthroughs to further maturation and utilization within the technology development and demonstration community. This article has documented the programmatic considerations and context that have driven the development of several significant initiatives that have motivated scientific progress relevant to hypersonic technologies since 2001.

A major emphasis area of the portfolio has been partnership and collaboration with other agencies and organizations- to develop scientific strategy, support research, and transition new capabilities to application. Thus, close coordination with and contributions from program managers from a variety of other organizations have been critical to the advancement of the portfolio objectives.

The National Hypersonic Foundational Research Plan (NHFRP) has been developed in concert with NASA and Sandia National Laboratories to identify and communicate near-, mid-, and far-term scientific objectives in the disciplines relevant to hypersonic technologies. The NHFRP is intended to decouple the support of scientific research from the cyclic fluctuation of hypersonic technology development for the purpose of providing a sustained knowledge base relevant to a broad spectrum of future high-speed capabilities. NASA and AFOSR have supported a number of joint efforts within the framework of the NHFRP, including three National Hypersonic Science Centers which support multiple academic institutions. The plan has also been identified as the DoD basic research plan for hypersonics by the Joint Technology Office for Hypersonics.

The HIFiRE (Hypersonic International Flight Research and Experimentation) program supports flight research intended to provide key insight into the behavior of critical phenomena in flight and to guide the extrapolation of ground test and numerical simulations to application at flight conditions. The program utilizes a pyramid-style philosophy where ground test and numerical simulation provide the foundation for the advancement of knowledge and flight research provides the focus and feedback to inform the foundational effort. The aerothermodynamic portion of HIFiRE is structured to provide critical insight into laminar-turbulent transition on a series of flight configurations with evolving three-dimensional complexity, which will address one of the objectives in the area of boundary layer physics defined in the NHFRP.

The STAR (STability Analysis for Reentry) initiative was organized to facilitate the transition of essential scientific knowledge and capabilities from the basic research to technology demonstration communities. The subject matter experts involved with this initiative have provided innovative insight and analytical tools which have been utilized to resolve potentially show-stopping challenges to several national-scale technology demonstration programs. The methods transitioned to application under this initiative have been embraced by the Test and Evaluation community to result in transformational new capabilities for the ground testing of upcoming hypersonic systems.

In the future the portfolio will be emphasizing research that explores the discovery, modeling and exploitation of energy transfer mechanisms at the molecular- and meso-scales that can potentially shape the macroscopic behavior of the continuum flowfield. A number of recent notable accomplishments in fluid dynamics may be viewed within this context and the new initiative is intended to focus the scientific dialog on key pacing issues. If successful, this initiative will lead to new methods of inherent flow control where energy transfer between kinetic, internal and chemical modes is utilized the shape the flow, as well as increased contributions from aerothermodynamics to other areas of Air Force interest including thermal management and directed energy.

In conclusion, the AFOSR Aerothermodynamics portfolio has worked closely with other agencies to envision and develop a comprehensive set of initiatives that have guided the strategy, performance and transition of essential science in support of current and future hypersonic technology development. This achievement would not be possible without the exceptional contributions of the outstanding researchers supported by the portfolio. Within this group, the students who are being prepared to lead the development of the next generation of hypersonic capabilities represent the most important technology transition from the portfolio.

Acknowledgments

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