Current and Near-Term RLV/Hypersonic Vehicle Programs

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SUMMARY

This lecture provides a comprehensive review of current and near-term national and international programs aimed at developing hypersonic flight demonstration vehicles. The paper first explores the motivation for hypersonic vehicle development and potential military and civilian applications for such systems. This provides a proper framework for the discussion of various demonstration programs, which are organized according to national affiliation. Programs in the United States, Europe, the United Kingdom, and Australia are reviewed in detail and those in Japan are summarized. Where possible, context for current programs is provided through a historical perspective of recent national activities and initiatives. For each program, information is provided on the background, overall goal, key program objectives or success criteria, vehicle concept and configuration, concept of operations and/or flight test approach, critical technical challenges, key demonstrations for the flight program, development schedule/milestones and participants and their roles.

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1. INTRODUCTION

This lecture presents a survey of current and near term hypersonic vehicle demonstration programs. An effort has been made to capture most of the major national and international programs currently underway. The goal of this paper is to provide a motivation for, and context within which, technology development needs can be discussed. Many of the other lectures in this series will then focus on those individual technologies.

For the purposes of this discussion, programs will be divided into two general categories, those most closely related to development of Reusable Launch / Reentry capabilities, and those more directly supporting Hypersonic Airbreathing Propulsion. This distinction is arbitrary but useful for grouping programs of similar focus. The scope of the "RLV/hypersonic vehicle" classification in the title of this paper includes rocket and airbreathing reusable launch vehicle programs as well as powered, boost-glide, and un-powered hypersonic vehicle programs.

History has shown hypersonic system development programs and flight demonstration programs to be very dynamic and somewhat unstable. Most programs proposed over the past 20 years have been terminated prior to reaching flight, for example; Hermes, HOTOL, Sanger, the National AeroSpace Plane (NASP) and several recent NASA X-vehicle programs including the X-33, X-34, X-38 and X-43B/C. The system development efforts have often suffered from an immature technology base and the technology demonstrators from a weak connection to future systems.

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Before discussing the individual flight vehicle programs, this paper will briefly explore the motivation for development of *operational* Reusable Launch and hypersonic vehicle systems. By understanding some of the factors stimulating or impeding the support for such systems, we will discover the issues which must be addressed in the technology demonstration programs that must of necessity precede the development of operational systems. If the demonstration programs do not confront and resolve those questions with appropriate test vehicles, then fielding of future hypersonic and RLV systems will remain an elusive goal.

2. MOTIVATION FOR HYPERSONIC VEHICLE DEVELOPMENT

The motivations for high-speed flight have roots in both military and civilian needs. The potential applications have been extensively studied and fall into three general categories; missiles, cruise vehicles, and space access. Several important factors that motivate the consideration of hypersonic or reusable launch system solutions for those missions are;

- the ability to enable a unique capability based on the hypersonic speed
- potential improvements in operational flexibility for accomplishing the mission, e.g. for time critical targets
- potential reductions in operational cost to accomplish the mission, e.g. space launch

The first factor is demonstrated by the fact that where hypersonic flight has provided a unique capability to accomplish a mission, systems have been developed and deployed. For example, hypersonic re-entry vehicles provide a unique capability for rapid delivery of strategic and tactical payloads. Consequently reentry vehicle technology has been developed, demonstrated and deployed by a number of countries. Similarly, hypersonic reentry systems have been developed to support civilian exploration and exploitation of space. Technology has been developed, demonstrated and fielded for both expendable re-entry systems such as Apollo, Soyuz, and interplanetary probe capsules, and for reusable systems, such as the Space Shuttle and Buran. The other current military application of hypersonic technology is in the area of missile defense. Again, the engagement timelines dictate hypersonic speed and consequently, the component and system technologies required to enable hypersonic interceptors have been developed, demonstrated, and fielded.

For military and civilian applications that do not require hypersonic speed or reusable system solutions (space access), hypersonic and RLV concepts have been forced to compete with the alternative approaches. The lack of maturity of many critical hypersonic / RLV technologies, especially light-weight durable thermal protection systems and efficient, reliable, reusable high-speed propulsion, have placed hypersonic/RLV systems at a disadvantage in these competitions. The lack of data on the performance of enabling technologies at the component and integrated system level yields uncertainties in estimates of concept vehicle performance, reliability and cost that far exceed those of competing systems (e.g. Expendable Launch Vehicles). This leads to skepticism on the part of potential customers and policy makers.

To illustrate this point in the context of space access, the reduced operational cost ($/kg to orbit) associated with an RLV will depend critically on the reusability, reliability and operational efficiency of the RLV concept. Given the immature state of understanding of these factors for RLV applications, and the dismal ability to predict such metrics, the paramount objective of a future demonstration should be to characterize these attributes in an appropriate flying testbed. Similar observations can be made with respect to the need to characterize the performance of hypersonic airbreathing propulsion concepts to reduce the associated uncertainty in predicted system-level performance.

It is encouraging that many of the current demonstration vehicle programs reviewed for this survey are seeking to answer these very questions.

3. SUMMARY OF CURRENT FLIGHT DEMONSTRATION PROGRAMS

Before reviewing the individual demonstration programs it is useful to take a broad look at the range of current efforts and to categorize those programs according to their Focus and intended Objective. Classification under program Focus used the two general categories identified previously, Hypersonic Airbreathing Propulsion and Reusable Launch / Reentry. The categorization of Objectives within these classes considered the primary objective of the program or vehicle since many of the demonstration vehicles serve multiple purposes. The following Objectives were selected for the grouping shown in Tables 1 and 2.

Hypersonic Airbreathing Propulsion (Table 1)

- Propulsion Physics - employs generalized elements of a hypersonic propulsion system to understand basic issues such as inlet/isolator performance or combustor performance
- Propulsion System Performance - all the elements of the propulsion system are properly integrated to allow the performance of the isolated propulsion system to be evaluated
- Vehicle Performance - propulsion system is integrated into an airframe allowing the net installed performance of the propulsion system to be evaluated

Reusable Launch / Reentry (Table 2)

- Reentry Physics – utilizes a general configuration to explore basic reentry physics
- Approach and Landing – intended to explore the low-speed flight and approach and landing attributes of a configuration
- Transonic Flight – explores transonic flight characteristics of a configuration
- Hyp/Reentry Performance – intended to evaluate the performance of the vehicle system over a significant portion of the mission envelope including hypersonic flight, launch to, or reentry from, orbit

The tables also have a column to indicate any unique emphasis of the flight demonstration vehicle. In this column HC stands for hydrocarbon fuel, H2 indicates hydrogen fuel.

Table 1: Hypersonic Airbreathing Propulsion

Program	Nation	Objective	Emphasis
HyShot	AU	Propulsion Physics	Supersonic Combustion
ATREX-FTB	JAP	Propulsion Performance	AirTurboRamjet
SHYFE	UK	Vehicle Performance	HC Ramjet
LEA	FR	Vehicle Performance	H2/HC Scramjet
X-43	US	Vehicle Performance	H2 Scramjet
HyFly	US	Vehicle Performance	HC Dual Combustion Ramjet
SED	US	Vehicle Performance	HC Scramjet

Table 2. Reusable Launch and Reentry

Program	Nation	Objective	Emphasis
EXPERT	ESA	Reentry Physics	Aerothermo – Non lifting
IXV Pre-X	ESA/FR	Reentry Physics	Aerothermo - Lifting
Phoenix-1	ESA/GR	Approach/Landing	Autonomous Operations
X-37 / ALTV	US	Approach/Landing	Autonomous Operations
HSFD – Ph 1	JP	Approach/Landing	Autonomous Operations
PRORA-USV (FTB-1)	IT	Transonic Flight	Autonomous Operations
HSFD – Ph 2	JP	Transonic Flight	Autonomous Operations
SOCRATES	ESA	Hyp/Reentry Performance	Operability/Reusability
HERCULES	ESA	Hyp/Reentry Performance	Orbital Reentry
PRORA-USV (FTB-2,3)	IT	Hyp/Reentry Performance	Sub-orbital & Orbital Reentry
X-37	US	Hyp/Reentry Performance	Orbital Reentry
RASCAL	US	Hyp/Reentry Performance	Reusable Small Sat Launch
FALCON/CAV	US	Hyp/Reentry Performance	Boost-Glide Flight

Each of these programs will be discussed in the following sections of this report. Some programs will receive a brief treatment while others will be addressed in some detail. The level of attention is not based on the size/importance of the program so much as the amount of information available to be reported. Availability of that information was dependent upon the courtesy of the organizations executing the program. In general, because of easier access afforded to the author US, Australian and European programs have received greater emphasis. However, since significant activity exists in Japan, an attempt has been made to summarize that work so that it can be put into the overall context. In order to limit the scope, Russian and Chinese programs are not described.

The detailed review of flight demonstrators will be presented in separate appendices dedicated to each program. The summary of the Japanese work will appear within the body of this text.

4. CURRENT AND NEAR TERM PROGRAMS – UNITED STATES

4.1 Recent History

Before surveying the US vehicle programs, significant effort will be devoted to describing the recent history of both reusable launch and hypersonic system technology development and demonstration programs within the United States. This will provide a context within which the particular objectives and the current level of support may be understood and the likelihood of continuation of the demonstrator programs can be gauged.

This perspective will begin with the termination of the National AeroSpace Plane (NASP) program in 1993. NASP was the United States' national initiative to build a flight vehicle to demonstrate airbreathing (scramjet-based), Horizontal Takeoff Horizontal Landing (HTHL) Single Stage To Orbit (SSTO) capability. The demise of the NASP program precipitated a number of vehicle and technology development and demonstration efforts in the Department of Defense (DoD) and NASA. The following sections will address the DoD and NASA efforts considering both hypersonic airbreathing and RLV / Reentry technology programs.

4.1.1 Department of Defense: NASP to Military Space Plane and Operationally Responsive Spacelift

The emphasis of post-NASP activity within the DoD lay in the continued development of critical technologies and flight demonstration of concepts for both rocket and airbreathing-based hypersonic systems.

4.1.1.1 Hypersonic Airbreathing Technology

One immediate successor to NASP was the US Air Force initiated Hypersonic Systems Technology Program (HySTP), whose goal was to provide for an orderly transition and continuation of the scramjet research activities. That program proposed the flight demonstration of a hydrogen scramjet engine at Mach 12-15 using a rocket booster. The lack of support for that initiative led to a further retrenchment and the start of the Hypersonic Technology (HyTech) Program within the Air Force Research Laboratory Propulsion Directorate in 1995. This program has been directed at development of endothermically fueled (hydrocarbon) scramjet technology for operation up to Mach 8, including fuels, materials, structures, and subsystems.

In 1998, the Defense Advanced Research Projects Agency (DARPA) began the Affordable Rapid Response Missile Demonstrator (ARRMD) program. The primary goal of that program was to design and build a missile that could fly at least 400 nautical miles (nm) at Mach 6 and have an average unit flyaway cost of only $200,000 in a production program of 3,000 missiles. To address these goals, two vehicle concepts were developed, one employing a dual combustion ramjet and the other a hydrocarbon scramjet. Although the ARRMD program was terminated in 2000, development of the critical propulsion technology continued under Navy and Air Force research programs. In recent years, the two competing vehicle concepts have been resurrected and are now proceeding toward flight testing as joint DARPA/service funded initiatives under the program designations of HyFly and the Scramjet Engine Demonstrator (SED) respectively.

4.1.1.2 RLV / Reentry Technology

As the NASP program waned, the Ballistic Missile Defense Office (BMDO) created a program to demonstrate rocket-based, Vertical Takeoff and Landing (VTOL) for SSTO. That program, known as Delta Clipper – Experimental (DC-X), was intended to flight-demonstrate critical technologies for highly-operable, affordable, reusable launch. Following its inception in 1991, the DC-X program successfully flight tested a subscale vehicle, demonstrating rocket powered vertical takeoff and landing and powered rotation from reentry attitude to vertical landing attitude, **Figure 1.** Unfortunately, the program was terminated following a landing accident.

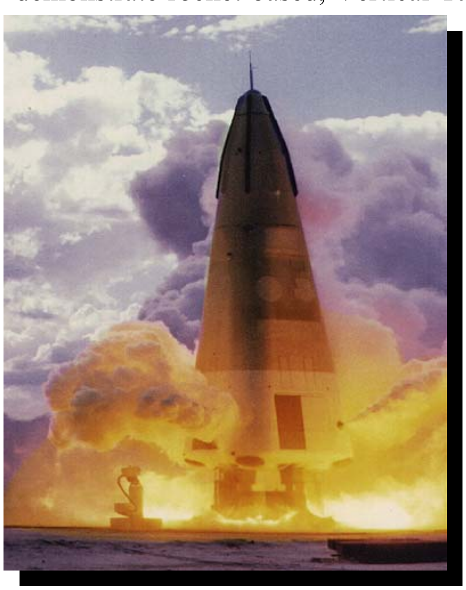

Figure 1. DC-X first flight, 1993.

During this same period, the Air Force began exploring the concept of a Military Space Plane (MSP) architecture comprised of a set of complementary vehicle capabilities, to provide for responsive access to, and operations in space, **Figure 2**. This architecture consisted of several components: A Space Operations Vehicle (SOV) to provide responsive, reusable launch, payloads including a Space Maneuver Vehicle (SMV) which served as a reusable satellite bus for on orbit operations, a Modular Insertion Stage (MIS) for low cost boost to geosynchronous orbit, an Orbital Transfer Vehicle (OTV) for low cost orbital plane change, and a Common Aero Vehicle (CAV) for payload delivery.

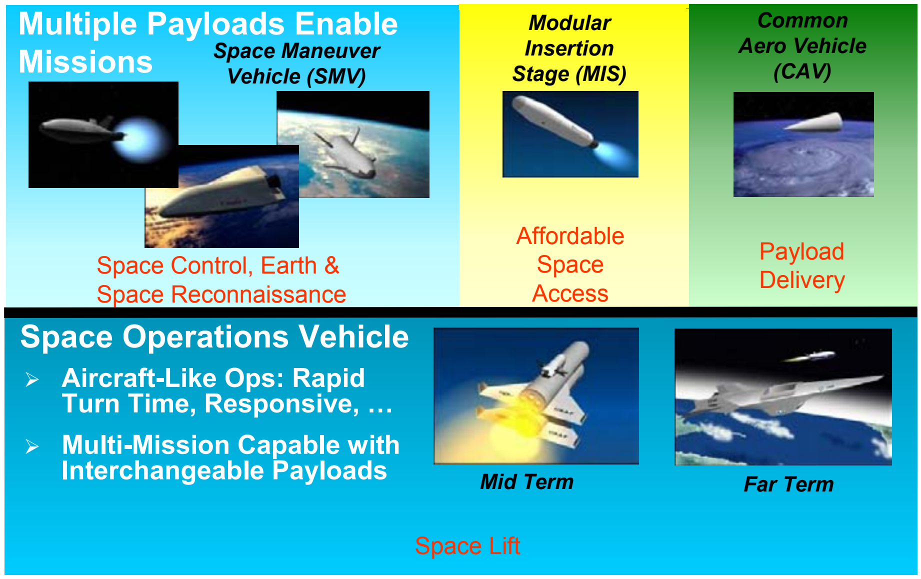

Figure 2. Military Space Plane Architecture.

The MSP architecture has provided a framework for the Air Force to explore the potential cost and benefits of future space access. Vehicle concepts embodying the "capabilities" desired for the various MSP components have been developed to aid in identifying the enabling technologies. Those vehicle concepts have led to several flight test programs demonstrating critical technologies. For example, concept studies for the SMV led to the development of an autonomous approach and landing testbed, the X-40, **Figure 3**. This vehicle was successfully flight-tested by the Air Force and subsequently by NASA until 2001, leading to the adoption of this configuration as a NASA pathfinder vehicle, the X-37.

Figure 3. X-40 flight test vehicle.

4.1.2 NASA – NASP to the Exploration Initiative

4.1.2.1 Hypersonic Airbreathing Technology

At the end of the NASP program, NASA continued internal research efforts to mature hydrogen scramjet technology. Strong progress in this area led NASA to create the Hyper-X program in 1996. The goal of this $250M program was to continue development of, and demonstrate in flight, an airframe-integrated hydrogen scramjet propulsion system. The focus of the program was a sub-scale flight vehicle designated the X-43A. This program, which has survived to the present day, and recently completed its first successful flight test, will be discussed in a later section.

4.1.2.2 RLV / Reentry Technology

Regarding space launch, in 1993, NASA conducted an Access to Space study to investigate future launch alternatives. US National Space Policy directives in 1994 and 1996 dictated that DoD lead future Expendable Launch Vehicle (ELV) development and that NASA should develop flight demonstrators to support a decision by the end of the decade on the development of a next-generation reusable launch system. Consequently, NASA embarked on a program to encourage the *commercial development* of the next generation reusable space launch capability. NASA established an X-vehicle program to demonstrate the critical technologies required for Vertical Takeoff Horizontal Landing (VTHL) rocket-based single stage to orbit. This objective was pursued through a 1996 cooperative agreement between NASA and Lockheed-Martin to build and test the X-33 vehicle, **Figure 4**. NASA also initiated several other flight projects to develop and demonstrate technologies for reducing the cost and increasing reliability of future access to space systems. Those vehicles, supported under the NASA Pathfinder program, included the X-34 and the Bantam small payload launch programs.

Figure 4. Lockheed-Martin X-33 flight demonstration vehicle.

As the decade neared its end, it was clear that the US was not ready to make a decision on the next-generation reusable launch system. NASA sought to create a more coordinated national strategy for guiding the development of future reusable launch capabilities. The agency conducted the Space Transportation Architecture Studies (STAS) with US industry, which led to the first iteration of the Integrated Space Transportation Plan (ISTP) in 1999. This plan called for a five-year competition between clean–sheet RLV designs and vehicles derived from the Space Shuttle. The principal elements of this program included a concept competition and downselect by 2005, a technology risk reduction element for both 2nd generation RLVs intended to fly by 2010 and 3rd generation systems intended to fly by 2025, a number of large-scale integrated ground tests, and flight demonstrations including continuation of the "Pathfinder" vehicles such as the X-34 and the NASA X-38 Crew Return Vehicle (CRV) demonstrator. The intent was that by 2005 NASA would select a single vehicle for full-scale development. If funds were not available to develop a new design then NASA could develop an evolved Space Shuttle for more reliable and lower cost operations.

At this same time, NASA continued to solicit and accept new Pathfinder-class vehicles to demonstrate advanced technologies. In 1999 NASA entered into a four year, $173M cooperative agreement with Boeing to develop the X-37, an orbital and reentry testbed vehicle based on a scale-up of the Air Force/NASA X-40 configuration. This vehicle is still under development and will be discussed in a subsequent section.

In order to develop the content of the ISTP programming, in 2000, NASA formed the 2nd Generation RLV Program Office. This office was to direct system assessments and technology developments for future reusable launch. Contracts were awarded for a "2nd Generation RLV Risk Reduction Definition Program" to identify requirements and technologies for conceptual future launch systems. These studies provided the foundation for the work to be accomplished beginning in fiscal 2001 under the new NASA Space Launch Initiative (SLI) with projected funding over five years of $4.5B.

In early 2001 NASA decided to terminate the X-33 and X-34 programs due to technical problems and rising costs. NASA had spent $912M and Lockheed-Martin an additional $356M on the X-33 program at termination. NASA had invested $205M in the X-34. Later that year, NASA concluded its work on the X-40 program completing the final of seven free-flight autonomous approach and landing tests. The continuation of the X-37 was also in doubt due to a change in launch strategy from the Shuttle to an Evolved Expendable Launch Vehicle (EELV). The cost of an expendable launch was expected to increase the program cost by nearly $100M. With these large program changes looming, the Air Force examined the possibility of providing funding for the X-33, X-34 and X-37 programs, but declined to do so after concluding that none of the demonstrators provided sufficient operational utility to meet Air Force needs. This put future support for the X-37 program in doubt and NASA conducted extended discussions with Boeing to determine the future direction of the program.

In early 2002, as NASA moved ahead with SLI, the Director of Defense Research and Engineering in the DoD, Dr Ron Sega established planning teams to create a new National Aerospace Initiative (NAI). This activity, described extensively below, was intended to coordinate military and civilian efforts in three "pillar" areas, Hypersonics, Access to Space and advanced Space Technology, drawing representatives from DoD Services, NASA, Defense Advanced Research Projects Agency (DARPA), other Government agencies, and industry into the planning efforts. A principal goal was to develop roadmaps for technology development, ground and flight demonstration that would enable revolutionary advances in hypersonic, space access and in-space capabilities. NASA utilized this opportunity to evolve its plans for flight demonstration vehicles for the 2nd and 3rd Generation RLV technology programs. At this same time NASA terminated the X-38 program based on direction from new NASA Administrator Sean O'Keefe that a future crew return vehicle should also have the capability for crew transport.

NASA's 2nd and 3rd Generation efforts under SLI continued until late in 2002 when NASA announced a major change to the SLI program. Based in part on the extreme estimates of 2nd Generation RLV system procurement costs ($30-35B), recognition of the challenges to delivering a new reusable launch capability to replace the shuttle by 2012, and pressures to provide an emergency crew return capability from the International Space Station, NASA decided to restructure the SLI program. The 2nd and 3rd Generation RLV programs evolved into the Next Generation Launch Technology (NGLT) and Orbital Space Plane (OSP) programs. NGLT was intended to continue architecture studies and technology development to support a future RLV development decision, while the OSP program was intended to provide a *near term* (2010) capability for crew rescue from the International Space Station (ISS) with a *longer term* (2012) capability for crew transport to and from the ISS. The OSP program, which was to be provided with up to $2.4B over 5 years, was to be launched using an expendable booster in the near term with the possibility of future launch from a reusable platform if one was developed. The decision regarding the start of a new RLV development program was delayed until 2009. In addition, under the ISTP, funding support for space shuttle life extension was increased substantially and the expected retirement date was extended to at least 2015 with the possibility for operations out to 2020.

Through the SLI restructuring, NASA was able to sustain two flight research programs, the X-37 for orbital and reentry research, and the X-43A for flight demonstration of scramjet propulsion technology. In November 2002, NASA decided to continue development of the X-37 and allocated an additional $301M to the program. The revised program for X-37 called for approach and landing tests in 2004 and a single orbital test in 2006. NASA also initiated funding of the X-43C, a hypersonic scramjet flight test vehicle that used the general lines of the X-43A configuration but employed an engine composed of three separate flowpath modules burning hydrocarbon rather than hydrogen fuel employed by the X-43A. Finally NASA added a new research program, the launch Pad Abort Demonstrator (PAD), to begin development of a full-scale reusable system to serve as a test-bed to demonstrate crew escape technologies.

The most recent change in the NASA program came as a result of the new Space Exploration Initiative announced by the US President in January 2004. This new vision has resulted in the termination of the Space Launch Initiative altogether in order to begin a new initiative for Space Exploration. NASA has taken several preliminary steps to fulfill this mandate. It has created a new Associate Administrator position to lead the Office of Exploration, evaluated the relevance of all NGLT and OSP program activities to this vision, and assigned the SLI budget authority to the new office. NASA will terminate a large fraction of the NGLT programs, continuing only those that are relevant to the Exploration vision, will conduct an orderly termination of the OSP program during 2004, and will begin strategic planning for the systems and technology required to realize the new vision, including the Crew Exploration Vehicle (CEV) to transport astronauts to and through space, **Figure 5**.

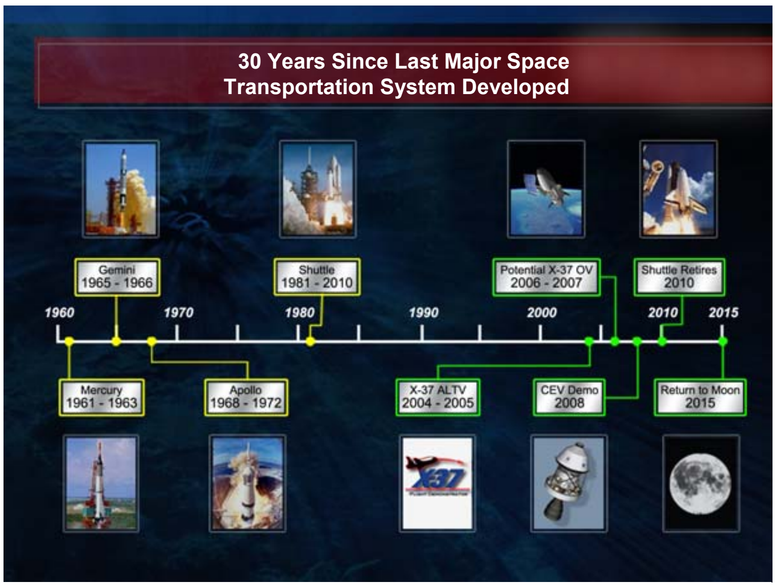

Figure 5. NASA path to the Crew Exploration Vehicle under the Space Exploration Initiative.

4.2. Current Initiatives

4.2.1. DoD/NASA: National Aerospace Initiative (NAI)

Acknowledgement: Some of the information for this section was provided courtesy of the National Aerospace Initiative office. The information contained in this document has been cleared for public release.

As discussed in the preceding history, under the leadership of the Director of Defense Research and Engineering (DDR&E), the DoD and NASA have collaborated on an initiative to enable revolutionary new capabilities for high-speed atmospheric flight, space access and space operations through a program of aggressive technology development, ground and flight demonstration. This initiative provides the framework within which future RLV and hypersonic vehicle demonstrations will be planned and executed.

As noted earlier, NAI was organized along the lines of the three critical aerospace capabilities or pillars. The top-level goals in each capability are:

High Speed/Hypersonics

Flight demonstrations increasing by one Mach number per year reaching Mach 12 by 2012

Space Access

Demonstrate technologies to dramatically increase space access and reliability while decreasing cost

Space Technology

Leverage the full potential of space

For each pillar, NAI identifies general vehicle classes (candidate applications) to focus enabling technology development and flight demonstrations. These vehicle classes are shown in **Figure 6**. Note that the Hypersonics pillar emphasizes vehicles that utilize *airbreathing* propulsion. That pillar addresses both expendable and reusable hypersonic systems and those classifications are broken into sub-classes. Also note that the reusable capability includes an element that falls within both the Hypersonics pillar and the Space Access pillar, the airbreathing first stage of a Two-Stage-To-Orbit (TSTO) system. Similarly, the Space Maneuver Vehicle falls within both the Space Access and Space Technology pillars.

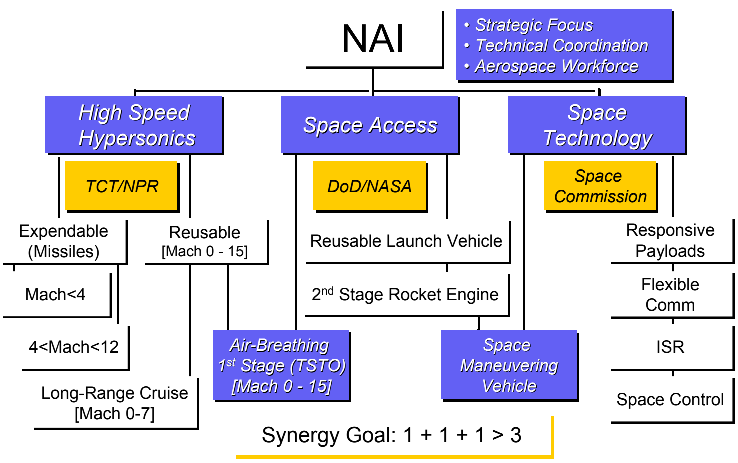

Figure 6. Pillars and vehicle classes of the National Aerospace Initiative.

4.2.1.1 High-Speed Hypersonics Pillar

In order to define meaningful technology programs to build toward these vehicle classes, NAI developed vision capabilities for each pillar. The vision capabilities for the Hypersonics pillar are shown in **Figure 7**. Note that the vision capabilities are time phased and have selected high level metrics to reflect desired system attributes at each point in time. These criteria are then used to define vehicle/system concepts that provide the desired capabilities (represented by the images), and to explore the technology development required to enable those concepts. Using this process, clear traceability can be established from the desired application to the enabling technologies and any required flight demonstration(s).

The history of prior flight vehicles and the vision for flight technology demonstrations under the Hypersonic pillar are illustrated in **Figure 8**. The original vision of the program was to demonstrate an increase of sustained flight by one Mach number per year through 2012. Based on this schedule, plans have been created to guide the component technology development, and programs have been conceived to allow the integration and flight demonstration of those technologies.

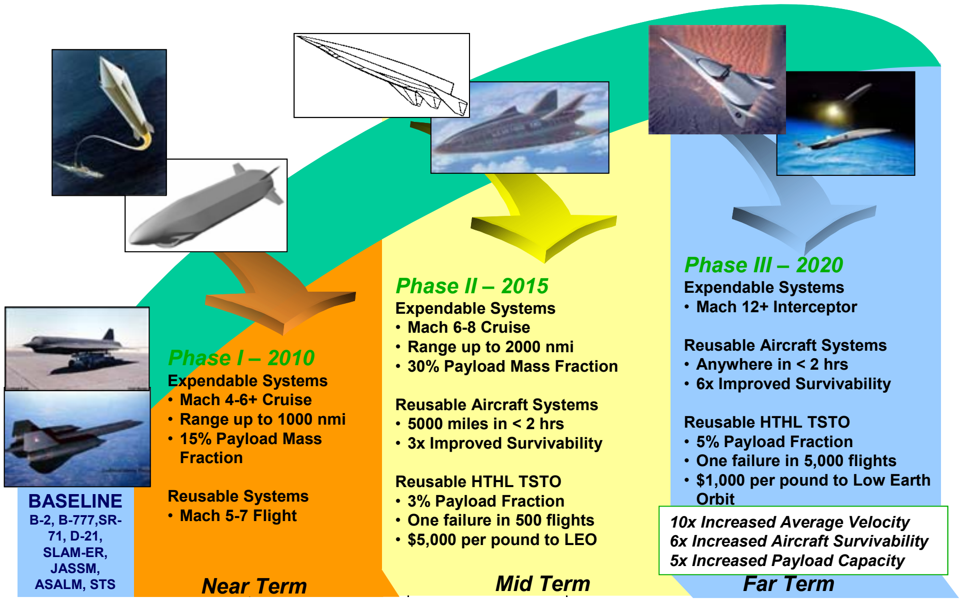

Figure 7. Vision capabilities for the NAI Hypersonics Pillar

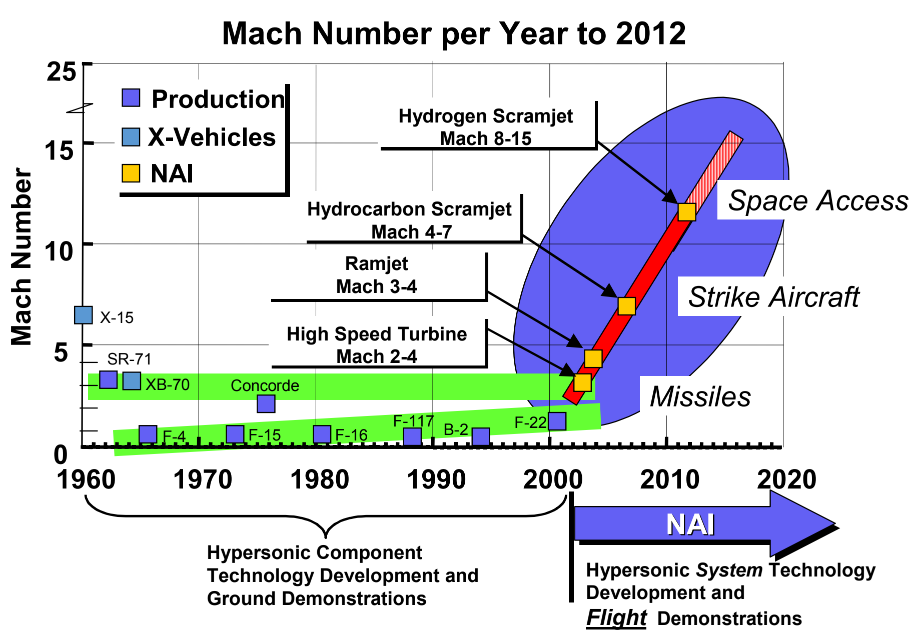

Figure 8. History of flight systems and vision for high-speed flight technology demonstrations.

The top-level flight demonstration roadmap for the Hypersonic pillar is shown in **Figure 9**. This illustrates the major flight programs that are currently envisioned or underway. The programs to be discussed in this survey include the Hyper-X or X-43A, the HyFly, and the Single Engine Demonstrator (SED). The Supersonic Cruise Missile (SSCM) will not be addressed since the program is not hypersonic and the Mach 15 Interceptor, the X-43C, X-43D and Mach 0-12 programs will not be discussed since funded programs do not currently exist for those demonstrators.

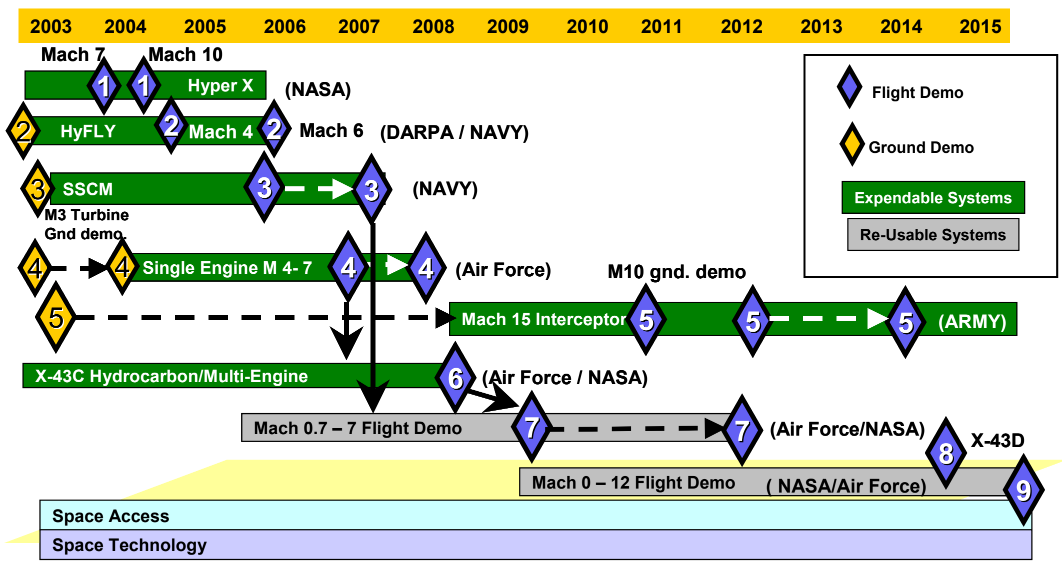

Figure 9. Top level roadmap for Hypersonic pillar flight demonstrations.

4.2.1.2 Space Access Pillar

The objective of the NAI Space Access pillar is to develop and demonstrate technologies that enable responsive, safe, reliable, and affordable access to and from space. The vision capabilities for this pillar are shown in **Figure 10**. Again the capabilities are time phased and reflect key metrics with which candidate system architectures can be assessed. Evaluation of the advanced technology needed to realize these capabilities has led to a very large number of technology development initiatives within this pillar as shown in **Figure 11.** These technologies are broken into four principal areas; Propulsion, Airframe, Operations and Integration, and Flight Subsystems. The critical technologies identified here are the subject of current or proposed research efforts by NASA and DoD. The flight demonstrations proposed for this pillar serve to both focus the development to a specific end and drive the research to produce results in a specific time frame.

The flight demonstration programs for the Hypersonic and Space Access pillars are shown in **Figure 12**. The top section of this figure shows the high-speed hypersonics demonstrators, the middle section shows shared demonstrators, and the bottom section the space unique demonstrators. The high-speed portion reflects the vehicles identified earlier in **Figure 9** with the supersonic cruise missile demonstrator replaced by the acronym RATTLRS.

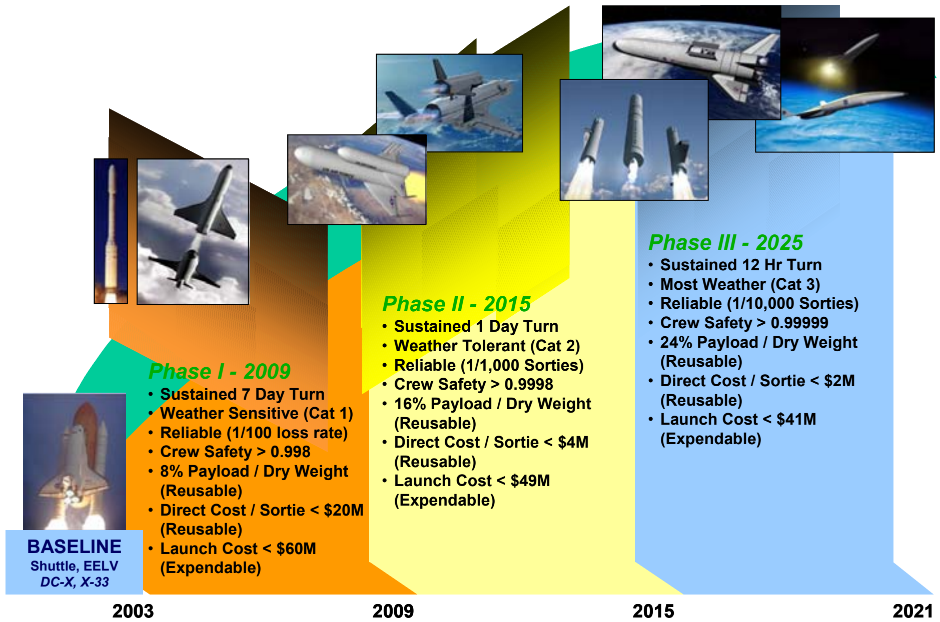

Figure 10. Vision capabilities for the Space Access pillar.

The principal funded flight demonstrators to be discussed are the X-37 program, RASCAL and FALCON. The Small Flight Experiments and Integrated Demonstration activities appearing on the space access portion of the figure are not currently funded.

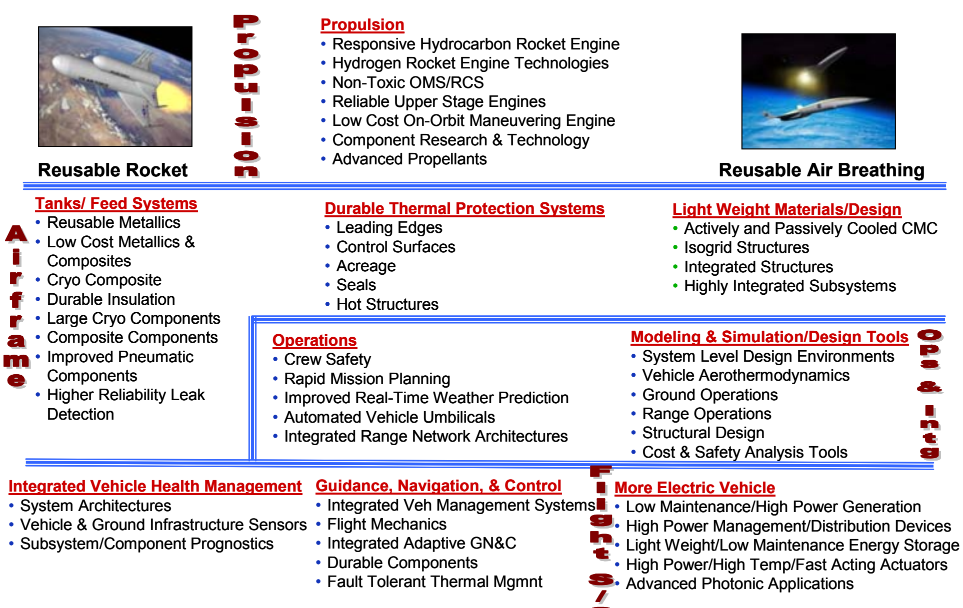

Figure 11. Critical Technologies for the Space Access pillar.

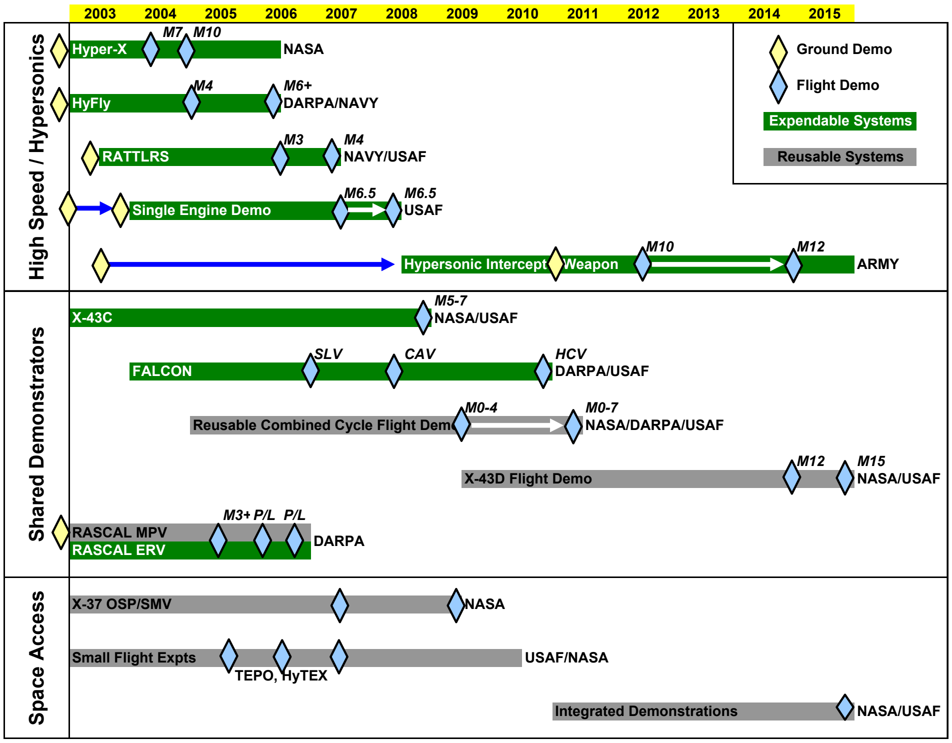

Figure 12. NAI Space Access and Hypersonics flight demonstrations.

4.3 Current Vehicle Programs – United States

As noted earlier, the discussion of the flight demonstration programs is presented in appendices to this document with an appendix devoted to each program. The review of each of the flight demonstration programs will use the following format. The section will first provide a brief **background** on the program and its relevance to any large national initiative. Information will then be provided on the overall program **goal**, key system or technical **objectives** and metrics for success. The **vehicle concept** and configuration will then be discussed along with the **concept of operations or flight testing**. The **critical technical challenges** or technologies will then be identified along with **key technology demonstrations** to be included in the flight program. Information on the current development **schedule and program milestones** will then be presented along with **principal participants** or collaborators. Finally, any relevant information on the current status or recent program accomplishments will be provided.

4.3.1. Reusable Launch / Reentry

The US flight demonstrations that address reusable launch or reentry are the X-37, RASCAL, and FALCON. The X-37 is a reusable orbital reentry testbed under development by NASA. The RASCAL concept is a two-stage partially reusable launch system for small satellite payloads under development by DARPA. The FALCON program is a joint DARPA/AF initiative to develop more operationally responsive expendable boosters and a flight demonstration vehicle for highly efficient aerodynamic gliding reentry. Detailed information for each program is provided in appendices to this document as noted below.

4.3.1.1. ***X-37*** *– Appendix 1*

4.3.1.2. ***RASCAL*** *– Appendix 2*

4.3.1.3. ***FALCON*** *– Appendix 3*

4.3.2. Hypersonic Airbreathing Propulsion

The US flight demonstrations that address hypersonic airbreathing propulsion are the X-43A, the HyFly, and the SED-WR programs. The X-43A is the NASA airframe-integrated hydrogen scramjet flight test program. The HyFly is a joint DARPA/Navy program to demonstrate a dual combustion ramjet powered vehicle. The Scramjet Engine Demonstration – WaveRider (SED-WR) is a joint DARPA/AF program to demonstrate the Air Force HyTech HC fueled scramjet propulsion system. The detailed program information for each program is provided in appendices to this document as noted below.

4.3.2.1. ***X-43A – Hyper-X*** *– Appendix 4*

4.3.2.2. ***HyFly*** *- Appendix 5*

4.3.2.3. ***Scramjet Engine Demonstration (SED-WR)*** *– Appendix 6*

5. CURRENT AND NEAR TERM PROGRAMS – EUROPE

5.1. Recent History

Over the last two decades, there emerged in Europe a strong and diverse program for the development and demonstration of hypersonic technology to support both military applications and European needs for access to space. Initiatives have been undertaken both by individual nations and through partnerships. This history will be reviewed briefly to provide context for the discussion of current vehicle demonstration programs. Recent national programs will be considered first, followed by multinational initiatives through the European Space Agency (ESA).

5.1.1. National Programs

National programs have been conducted to support individual national interests, European program initiatives through the European Space Agency (ESA), and US efforts such as the X-38/CRV.

5.1.1.1 Germany

Two recent initiatives originating in Germany and related to hypersonic flight demonstration include the Technologies for Future Space Transportation Systems (TETRA) program and the Advanced Systems and Technologies for RLV Application (ASTRA) programs, **Ref. Eur-1**.

The TETRA program, started in 1997 and directed by the German national aerospace research organization (DLR), was a German national program to demonstrate new technologies, including hot Ceramic Matrix Composite (CMC) structures, reusable ceramic Thermal Protection Systems (TPS), advanced guidance navigation and control (GNC) and health monitoring on the NASA X-38. This effort was coordinated with the ESA program to participate in the X-38, known as Applied Reentry Technology Program (ARTP). The TETRA program represented 66% of the overall participation of Europe in the X-38 project and was successful in providing the promised structural and flight instrumentation to NASA on schedule.

The ASTRA program, underway since 2000, but on hold in 2004, is a public/private partnership program to conduct RLV system analysis and technology development and position German industry to participate fully in future European launch system development. This program is run parallel to, and in close coordination with, the ESA initiatives. This program has five principal elements, a system investigation and analysis task, technology development programs in propulsion, structures and materials, and avionics/GNC (guidance, navigation and control), and a flight experiment to demonstrate autonomous approach and landing for an RLV representative configuration. The flight demonstrator, known as PHOENIX, is modeled after the HOPPER sub-orbital vehicle concept, which serves as one of the reference concepts for future RLVs in Europe.

5.1.1.2 France

France has maintained a strong research base in both the areas of RLV technology development and hypersonic airbreathing propulsion technology. The RLV activities have generally been aligned with the ESA vision including participation in the ARTP program to collaborate with NASA on the X-38 vehicle development. France is currently conducting studies of a vehicle referred to as Pre-X, a concept to satisfy the goals of the Intermediate eXperiment Vehicle (IXV) demonstrator vision in the Future Launchers Preparatory Program (FLPP).

The hypersonic airbreathing propulsion work has included a number of system concept studies, a comprehensive ground technology development program, and efforts to define and support flight experiments, **Ref. Eur 2-4.** Work has been accomplished through both national efforts, and internationally in partnership with Russia, and with DLR in Germany. France collaborated with Russia on a Wide-Range Ramjet engine concept using a variable-geometry engine to operate between Mach 3 and 12. The work with Germany on the Joint Airbreathing Propulsion for Hypersonic Application Research (JAPHAR) program sought to advance hydrogen fueled dual-mode scramjet technology with the goal of flight testing a vehicle between Mach 4 and Mach 8.

On the topic of flight experiments, between 1993 and 1995, France collaborated with the Russians in the flight testing of an axisymmetric hydrogen-fueled dual-mode scramjet engine mounted to an SA6 booster. One test successfully reached Mach 5.7 but a subsequent attempt to fly at Mach 6.3 was unsuccessful.

Franco-German cooperation on the JAPHAR program sought to define a development methodology for a scramjet propulsion system and then design a flight experiment to validate that methodology. The resulting vehicle however was considered too large for an affordable program. These activities have culminated in the recent action by MBDA France and ONERA to establish a flight test program called LEA. The details of this program will be discussed later in this section.

5.1.1.3 Italy

Italy has recently undertaken a program to mature, through flight demonstration, critical technologies required for future reusable launch systems. This program, known as PRORA-USV, is a major initiative within the Italian National Aerospace Research Program PRORA. The USV program plans to develop three Flying Test Bed (FTB) vehicles to conduct a range of test missions including transonic flight, sub-orbital reentry, hypersonic cruising flight, and orbital reentry. The details of this program will be discussed in a later section.

5.1.2. Multi-national Initiatives

From 1994-1998 the European community conducted a major study to explore future launch architectures through the Future European Space Transportation Investigation Program (FESTIP). A wide range of candidate architectures were considered including reusable launch systems, and two preferred concepts were identified. One concept was a TSTO system, which could be developed in an evolutionary fashion starting with the ARIANE 5 core stage and a fly back booster. Subsequently the ARIANE 5 core could be replaced with a reusable second stage in a Siamese configuration. The other concept was a suborbital HOPPER approach. This winged VTHL system would carry an expendable second stage to a high altitude (160 km) high velocity condition, deploy the stage, and then recover downrange.

The FESTIP vehicle concepts provided a framework within which the need for experimental demonstration vehicles could be considered. Thus the FESTIP study also identified candidate experimental test vehicles to validate design tools and the maturity of advanced technologies, **Ref. Eur-5**. A key recommendation from this study was to build a future European Experimental Test Vehicle (EXTV), which could be used for demonstrating reusability and critical technologies of different potential RLV reference concepts, **Figure 13**. Following this recommendation, a number of companies in the European community advanced proposals for demonstration vehicles to address this need.

During this same time, following the cancellation of the Hermes program, ESA funded the predecessor to the European Aeronautic Defense and Space Company (EADS) Space Transportation to apply the consolidated knowledge acquired through the Hermes program by building and flying a guided and controlled reentry experiment. Thus in 1994, that company led a European industrial team in the effort to build and fly a reentry body. This Atmospheric Reentry Demonstrator (ARD), based on the Apollo capsule shape, was successfully flown in 1998 on the third flight of the ARIANE 5.

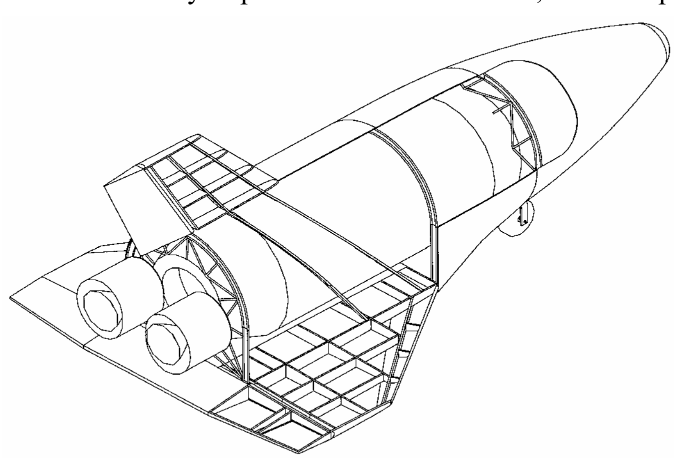

Figure 13. EXTV vehicle concept. Courtesy ESA.

Beginning in 2000, the concepts derived from the FESTIP program were carried forward into the Future Launchers Technology Program (FLTP). The goals of that program were to conduct system and vehicle concept studies, technology development, and demonstrations to further explore the candidate architectures identified in FESTIP. This program was intended to provide additional insight for making a programmatic decision regarding the start of a

European development initiative for the next generation launch vehicle in 2007. The most important objective of this effort was to confirm the value and benefits of reusable future launchers given a consistent and credible set of assumptions regarding the required technologies, **Ref. Eur-6.**

In the spring of 2001, the ESA Director General created an internal working group to develop an overall European vision for reusable space transportation systems, **Ref. Eur-7**. The group was to propose an approach integrating relevant ESA and national efforts, and identify schemes for international co-operation. At the same time the FLTP activities were suspended for review of their relevance. The working group advised continued ESA effort along the lines proposed under the FLTP program but emphasized increased coordination of multinational ESA initiatives with national research programs as well as enhanced coordination with US efforts on the Crew Rescue Vehicle (CRV). The group strongly emphasized the need for focused and coordinated ground and flight technology demonstration efforts directed to address the specific technical challenges faced by a new generation of reusable launch vehicles. One of the most important outcomes was additional clarity in the range of concepts to be considered for future flight test demonstrations. It appeared that the range of demonstrators was narrowing to the following; a vehicle that would investigate lifting reentry physics, another that would demonstrate autonomous approach and landing, a vehicle to explore reusability and operability for cryogenically fueled rocket-based vehicles, and a vehicle to demonstrate flight over the full reentry profile of an RLV-like shape.

5.2. Current Initiatives

5.2.1 Future Launcher Preparatory Program (FLPP)

In May of 2003, the ESA obtained ministerial approval to start a new initiative, The European Future Launcher Preparatory Program (FLPP). This effort, which began in February 2004, follows the lines of previous ESA initiatives in supporting system studies, technology development, and planning for flight demonstration of technologies. The program is broken into three periods. Important milestones include an RLV concept downselect and decision on X-vehicle development during Phase 1 in 2005, a decision on the approach for the next generation launch system concept (RLV vs. ELV) during Phase 2 in 2010, and a development go-ahead decision during Phase 3 in 2013.

Based on the system studies conducted to date, there are several candidate RLV architectures under consideration in Europe; a full reusable TSTO Vertical Takeoff Horizontal Landing (VTHL) configuration, a semi-reusable concept based on a reusable first stage and an expendable upper stage, and the suborbital HOPPER concept mentioned earlier. These concepts present many common and a few unique technical issues that must be addressed through flight demonstration.

In the area of atmospheric reentry, the European community is planning a progression of demonstration vehicles to incrementally build their knowledge and capabilities. This includes the testing of simple, non-maneuvering but highly instrumented vehicle shapes to gain fundamental knowledge on reentry aerothermodynamic phenomena (EXPERT, **Ref. EUR 7-9**), testing of more complex maneuvering reentry vehicles (IXV) to extend that understanding of aerothermodynamics and provide a testbed for other technologies such as thermal protection systems, and finally, the testing of a fully RLV-like configuration to demonstrate all elements of an orbital vehicle design and all phases of flight from de-orbit, through reentry, to approach and landing (HERCULES).

The Europeans also understand the critical need to characterize the reusability and operability of future reusable launch concepts and technology in order to better substantiate potential RLV costs. Consequently they are supporting development of test vehicles to demonstrate autonomous approach and landing (PHOENIX) and a vehicle to explore operations and reuse (SOCRATES). Although the second of these vehicles is not intended to attain orbit, it will demonstrate most of the critical mission phases for a reusable launch system and will provide a test-bed for benchmarking the reusability and cost of operations of a system based on current technology. The relevance of these demonstration vehicles to the critical phases of an RLV mission is indicated in Table 3.

Table 3: Relevance of demonstrators to RLV mission phases.

Mission Phase	Phoenix-1	IXV	SOCRATES	HERCULES
Launch/Horiz. Take-off			X	
Sub/Supersonic Ascent			X	
Hypersonic Ascent			X	
Stage Separation				X
Orbital Maneuver				X
Reentry		X	X	X
Hypersonic Un-powered Flight		X	X	X
Terminal Area Energy Management	X		X	X
Horizontal Landing	X		X	
Reusability/Ground Ops.	X		X	

5.3 Current Vehicle Programs - Europe

5.3.1. Reusable Launch / Reentry

The European flight demonstrations that address reusable launch or reentry are the EXPERT, Intermediate Experiment Vehicle (IXV), Phoenix-1, SOCRATES, and PRORA-USV. The EXPERT and IXV programs are intended to build understanding of reentry aerothermodynamics. The Phoenix is a winged approach and landing demonstrator. The SOCRATES is a reusability demonstration vehicle. The PRORA-USV program consists of three flight test beds to accomplish a range of missions. The detailed information for each program is provided in appendices to this document as noted below.

*5.3.1.1. **EXPERT** – Appendix 7*

*5.3.1.2. **Intermediate Experiment Vehicle (IXV)** – Appendix 8*

*5.3.1.3 **Phoenix-1** – Appendix 9*

*5.3.1.4. **SOCRATES – Phoenix-2** – Appendix 10*

*5.3.1.5. **PRORA-USV** – Appendix 11*

5.3.2. Hypersonic Airbreathing Propulsion

The European flight demonstration that addresses hypersonic airbreathing propulsion is the LEA program. This program will demonstrate an airframe-integrated mixed fuel scramjet in a free flight experiment similar to the X-43A. The detailed information for this program is provided in an appendix to this document as noted below.

*5.3.2.1. **LEA** – Appendix 12*

6. CURRENT AND NEAR TERM PROGRAMS – UNITED KINGDOM

6.1. Current Vehicle Programs – United Kingdom

6.1.1. Hypersonic Airbreathing Propulsion

The UK flight demonstration that addresses hypersonic airbreathing propulsion is the Shyfe program. This program will demonstrate an axisymmetric hydrocarbon ramjet concept in a free flight demonstration. The detailed information for this program is provided in an appendix to this document as noted below.

6.1.1.1. Shyfe – Appendix 13

7. CURRENT AND NEAR TERM PROGRAMS – AUSTRALIA

7.1. Current Vehicle Programs - Australia

7.1.1. Hypersonic Airbreathing Propulsion

The Australian flight demonstration that addresses hypersonic airbreathing propulsion is the HyShot program. This program will conduct tests to collect data on scramjet combustor physics for a number of test article configurations. The detailed information for this program is provided in an appendix to this document as noted below.

7.1.1.1. HyShot– Appendix 14

8. CURRENT AND NEAR TERM PROGRAMS - JAPAN

8.1. Current Vehicle Programs – Japan

Due to the limited availability of information, only a brief summary will be given on Japanese flight demonstration programs.

Over the past two decades Japan has established a comprehensive program to develop technology and expertise in hypersonic airbreathing propulsion and reusable launch. These efforts have been directed by the National Aerospace Laboratory (NAL) and the National Space Development Agency (NASDA), which were recently combined to form the Japan Aerospace Exploration Agency (JAXA). These national efforts have included developing the human capital, the analytical and experimental tools, the component technologies, and the integrated flight demonstrations to make steady progress toward development of future rocket and airbreathing based systems.

In the field of reusable launch and orbital reentry, the Japanese have executed a progression of programs including the Orbital Re-entry Experiment (OREX), the Hypersonic Flight Experiment (HYFLEX) and the Automatic Landing Flight Experiment (ALFLEX). Results from the latest in this series, denoted the High Speed Flight Demonstration (HSFD), were presented recently (**Ref. JPN-1**).

The prime contractor for the HSFD project is the Fuji Heavy Industries Company Ltd (FHI), and the program has two phases. The first phase is to verify approach and landing of a winged re-entry vehicle, while the second is to explore the transonic aerodynamic characteristics of the demonstrator. Both test vehicles derive their shape from the HOPE-X configuration in order to build on the experimental database for that concept. Flight experiments for Phase I, which occur at relatively low altitudes, have been completed successfully. Those tests, utilizing a jet-powered test vehicle, demonstrated fully autonomous flight control design technology for take-off and landing, inertial navigation systems and ground tracking capability.

In Phase II testing, the vehicle is lifted by stratospheric balloon to an altitude of 20 to 30 km and released to achieve transonic speeds. Experiments were conducted in collaboration with the Centre National d'Etudes Spatiales (CNES) of France and were supported by the Swedish Space Corporation (SSC). Problems related to the recovery system were encountered during testing. The experiment nonetheless yielded important data to aid in reducing uncertainties in the extrapolation of transonic aerodynamic properties from ground tests and CFD.

Work has also been reported in the development of various testbeds to demonstrate technologies needed to establish a reusable space transportation system (**Ref. JPN-2**). In this category, programs include the Piggyback Atmospheric Reentry Technology Testbed (PARTT), which consists of a two-part platform including an orbiter and a reentry module, as well as lifting-body and rocket plane concepts.

Japanese research has also emphasized the development of air-breathing propulsion systems for space access. A particularly noteworthy program is the Air-Turbo Ramjet Expander-Cycle (ATREX) engine program for the Japanese TSTO space plane concept. This propulsion approach has a goal of achieving acceleration to Mach 6, and operations up to 30 km. Extensive studies have explored both axisymmetric and non-axisymmetric inlet designs, with single and twin engine configurations. Particular emphasis has been placed on aerodynamic performance, weight constraints and trajectory analysis. Successful ground testing of the prototype core has been completed. Recent work has explored concepts and plans to flight test the engine on a Flying Test Bed (FTB) vehicle, including one based on a solid rocket booster to provide initial acceleration up to Mach 2.

Based on the consistency observed in Japanese progress in hypersonic and RLV technology development and demonstration, it is very likely that additional demonstration vehicles will undergo flight-testing within the next few years. The nearest term tests are likely to be a continuation of the Phase II HFSD transonic flights and flight testing of the ATREX propulsion system.

9. CONCLUSIONS

As this paper demonstrates, a large number of ongoing hypersonic and reusable launch vehicle demonstration programs currently exist. The goals and objectives range from understanding fundamental reentry physics, to demonstrating the system performance on highly complex airframe-integrated scramjets. It is apparent that although a number of these activities seek the same ends they are often un-coordinated, especially when it comes to national boundaries. This is a result in part of international challenges to maintain a competitive advantage, and in part due to the inherent difficulty in integrating such enterprises. However, it is clear from hindsight relative to the collaboration on the US X-38 and the Australian HyShot programs, that international collaboration on demonstration vehicles can benefit all parties without compromising national interests, and result in fiscally realizable demonstration programs.

One hopes the opportunity to collaborate in a similar way on a future program is within the vision of the international aerospace leadership.

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