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Hyper-X Stage Separation—Background and Status

David E. Reubush
NASA Langley Research Center, Hampton, VA

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David E. Reubush[1]
NASA Langley Research Center, Hampton, VA

ABSTRACT

This paper provides an overview of stage separation activities for NASA's Hyper-X program; a focused hypersonic technology effort designed to move hypersonic, airbreathing vehicle technology from the laboratory environment to the flight environment. This paper presents an account of the development of the current stage separation concept, highlights of wind tunnel experiments and computational fluid dynamics investigations being conducted to define the separation event, results from ground tests of separation hardware, schedule and status. Substantial work has been completed toward reducing the risk associated with stage separation.

INTRODUCTION

The development of reusable launch vehicles holds great promise as the key to unlocking the vast potential of space for business exploitation. Only when access to space is assured with a system which provides routine access with affordable cost will businesses be willing to take the risks and make the investments necessary to realize this great potential. The current NASA X-33 and X-34 programs are steps on the way to enabling the routine, scheduled access to space. Unfortunately, while a great improvement over current systems, the cost per pound delivered to orbit for currently proposed systems will still be greater than that required to exploit space for many business uses. One of the limiting factors in potential cost reductions for chemical rockets is the Isp limit.

The use of airbreathing engines holds potential for very significant increases in Isp which could result in a significantly lower cost per pound to orbit. The National Aero-Space Plane program (NASP), which was canceled in 1995 as unaffordable at that time, was a joint NASA/U.S. Air Force effort to develop a single-stage-to-orbit, airbreathing vehicle. However, while the NASP was never completed, the NASP program developed a significant number of technologies which only await demonstration before they will begin to be accepted for use in future aerospace vehicles. Key among these technologies is airbreathing engines for hypersonic flight. NASP brought the materials and design methods for scramjet (supersonic combustion ramjet) engines to the point that efficient engines and practical vehicles which use them can be developed. One of the major requirements to have these technologies accepted is a flight demonstration. In the spirit of "Faster, Better, Cheaper," NASA has initiated the Hyper-X program to demonstrate that scramjet engines can be designed, constructed, and will operate at the high Isp levels necessary for use in access to space vehicles as an initial step to this end.

The NASA Hyper-X program employs a low cost approach to design, build, and flight test three small, airframe-integrated scramjet powered research vehicles (X-43) at Mach numbers of 7 and 10. The research vehicles will be dropped from the NASA Dryden B-52, rocket boosted to test point by a Pegasus first stage motor, separated from the booster, and then the scramjet powered vehicle operated in autonomous flight. Tests will be conducted at approximately 100,000 ft. (depends on Mach number) at a dynamic pressure of about 1000 psf. To the program's knowledge there has never been a successful separation of two vehicles (let alone a separation of two non-axisymmetric vehicles) at these conditions. Therefore, it soon became obvious that the greatest challenge for the Hyper-X program was, not the design of an efficient scramjet engine, but the development of a separation scenario and the mechanisms to achieve it. This paper will discuss highlights of the genesis of the separation concept and the many efforts (involving wind tunnel testing, computational fluid dynamics analyses, kinematic analyses, structural analyses, simulations, and hardware testing) to validate its effectiveness to date.

SYMBOLS AND ABBREVIATIONS

AOA	Angle Of Attack
DFRC	Dryden Flight Research Center
FCGNU	Flight Control, Guidance, and Navigation Unit
fps	feet per second
GASP	General Aerodynamic Simulation Program
HXLV	Hyper-X Launch Vehicle

[1] Hyper-X Stage Separation Manager, NASA Langley Research Center, Associate Fellow, AIAA

HXRV	Hyper-X Research Vehicle
INU	Inertial Navigation Unit
Isp	Specific Impulse
LaRC	Langley Research Center
LVDT	Linear Variable Displacement Transducer
M	Mach number
MDA	McDonnell Douglas Aerospace
NASP	National AeroSpace Plane
psf	pounds per square foot
q	dynamic pressure
RVDT	Radial Variable Displacement Transducer

BACKGROUND

The precursor for Hyper-X was a study, conducted by McDonnell Douglas (now Boeing), (with Pratt & Whitney as a major subcontractor) in cooperation with NASA Langley Research Center which began in 1995. The purpose of the Dual-Fuel Airbreathing Hypersonic Vehicle Study (Refs. 1-3) was to evaluate the technology readiness for and the benefits to be accrued by the use of airbreathing scramjet engines in vehicles for use in the current two most likely missions for hypersonic aircraft: deep strike/reconnaissance and/or as the first stage of a two-stage-to-orbit launch system. The deliverable from this study was conceptual designs for such aircraft. The second phase of the study was to have been an attempt to merge the two vehicles and thus to serve both missions with a single vehicle. An option to this study was the conceptual design of an X-airplane which could demonstrate the critical technologies needed for the mission vehicles.

While the first phase of the Dual-Fuel study was underway it became apparent to the management of what was then the Hypersonic Vehicles Office of NASA Langley Research Center that there was a building interest on the part of NASA Headquarters in using flight tests to demonstrate NASA developed technology, and, at the same time, improving the technology readiness levels (TRL) of the technology. As a result, the second phase of the Dual-Fuel study was postponed and the option for development of a conceptual design for a demonstrator vehicle was exercised. As things developed, NASA Headquarters soon solicited proposals from the NASA Research Centers for flight demonstration candidates. One of Langley’s proposals was the hypersonic demonstrator being fleshed out in the option to the Dual-Fuel study. The combination of the advanced state of development of the vehicle design compared to the competition and the interest by Headquarters in means to reduce the cost of access to space resulted in the Langley proposal being selected as one of the two flight tests to be funded. This, then, became the Hyper-X program.

STAGE SEPARATION CONCEPT EVOLUTION

The Hyper-X program began with the separation concept that was developed during the Dual-Fuel option study. The proposed hardware is illustrated in figures 1 to 3. This concept had the research vehicle being attached to the booster adapter by a pair of explosive bolts in the research vehicle base. At the center of the research vehicle aft bulkhead and at the forward end of the adapter the research vehicle rode on three "ejection rails." The purpose of the rails was to both hold the research vehicle before separation and guide it during the ejection process. Ejection was accomplished by use of a pair of pistons pushing on the base of the research vehicle with the ejector force directed through the vehicle’s center of gravity. (Fig. 2) The pistons were actuated by a pyrotechnic 3 cartridge breech which provided high pressure gas. (Fig. 3) A portion of the high pressure gas was also to be exhausted out the top of the adapter to help counteract the nose up moment on the booster resulting from the loss of the large research vehicle mass forward of the booster cg. Also being considered was a flap on the top of the ballast avionics module (BAM – located between the Pegasus first stage motor and the research vehicle adapter) or, alternatively, a small rocket motor located in the tail of the Pegasus either of which could be actuated to help counteract the nose up moment. It was estimated that the separation event would require on the order of 0.6 second before the aft end of the research vehicle was no longer overlapping the forward part of the booster adapter.

It had been realized all along that stage separation was one of the "long poles" in the Hyper-X tent. So, shortly after the Hyper-X fabrication contract was awarded to the Micro Craft team in March, 1997, a joint government/contractor team was formed to examine the existing separation concept and make recommendations for possible improvements. The team initially brain stormed and came up with a number of possible alternate separation concepts. Some of those suggested were a hinged adapter lower surface (Fig. 4), an integrated rail/ejector (Fig. 5), two two-stage separations (Figs. 6 and 7), and an inverted separation (Fig. 8). Unfortunately, all of the suggested concepts had deficiencies which precluded their use.

The separation "tiger team" also contacted a number of organizations with experience in vehicle stage separation and made site visits to both Redstone Arsenal and Sandia National Laboratory. While no organization was found that had experience with high Mach number (7 and above), high dynamic pressure (approx. 1000 psf), non-axisymmetric separations the general consensus was that the 0.6 second separation time was too long. Sandia suggested three alternative separation methods. Their first choice was for Hyper-X to do an exo-atmospheric separation to avoid the risks due to high dynamic pressure. Unfortunately, while this scenario appeared to be very attractive, later studies showed that, for Mach 10, the heat load exceeded the capabilities of the research vehicle thermal protection system tiles. They also suggested a fairing on the front of the Pegasus with the Hyper-X ejected downward similar to bomb ejection from an aircraft (Fig. 9). The prime difficulty with this concept was the fact that the research vehicle would have to pass through the bow shock of the Pegasus and there was significant concern that the research vehicle control system would not be able to handle the upset. Sandia's third suggestion was to split the adapter with pyrotechnics and push the two halves laterally to limit the time the research vehicle and adapter overlapped (Fig. 10). This suggestion appeared to be the best of any seen by the team and was accepted as a basis on which the separation scenario could be built. Sandia also strongly recommended that the rails be eliminated as their experience base said that, no matter how well they performed in ground tests, the rails would bind in flight.

By the time of the Hyper-X Manufacturing Readiness Review (MRR) held at DFRC in June of 1997 the separation team had settled on a concept based on the Sandia suggestion (Fig. 11). In this scenario the forward part of the adapter would be a clamshell built in two halves with hinges at the aft end. The research vehicle would be pushed forward away from the adapter and when it had moved forward two inches the two adapter halves would then be pushed apart laterally by pyrotechnic pistons or springs. The hinges were added to the Sandia concept to avoid having two relatively large free-flying pieces of hardware which might possibly impact the research vehicle and to allow their drag to help decelerate the launch vehicle away from the research vehicle.

There was significant discussion of the separation scenario during the MRR. One of the concerns expressed was that there would still be significant time required for the two halves to clear the research vehicle wings and any roll upset of the research vehicle during this time would risk impact of a wing on one of the clamshells. It was during discussions of this concern that a suggestion was made that instead of splitting the forward adapter like a clamshell perhaps the forward adapter could swing down as a single piece. Doing this would shorten the research vehicle/adapter overlap time. Subsequently, this concept (soon to be known as the "drop-jaw") was accepted as the baseline separation concept for the program and, for which, significant development occurred.

The drop-jaw concept remained the program baseline until developments in early 1999 resulted in its abandonment, but too late to impact the construction of the booster adapter. (The developments which resulted in the abandonment of the drop-jaw will be discussed later.) Solid models of the current adapter design are shown in figures 12 to 16. The research vehicle is held to the adapter by 4 Pacific Scientific explosive bolts. One is at the forward end of each of the two jaw beams and attaches the jaw beams to the research vehicle keel beams in the nozzle area of the research vehicle. Two are in the base of the research vehicle and attach the research vehicle station 144 bulkhead to the adapter station 144 bulkhead. There were also two explosive bolts attaching each jaw beam to the aft part of the adapter. The adapter features two pairs of pyrotechnically actuated pistons with a powered stroke of 7 inches and a full stroke of over 9 inches adapted from surplus B-1 missile ejector racks to both push off the research vehicle and drop the jaw (jaw pistons now inactive).

The current separation scenario begins with the launch vehicle INU sensing zero or less axial acceleration for 200 ms at which time the launch vehicle flight control computer notifies the research vehicle that it is ready to separate. After a number of actions, such as switching purge flows from tanks in the adapter to tanks in the research vehicle, which occur over a time period of 3 sec. the research vehicle notifies the launch vehicle to initiate separation. On this command the launch vehicle ordinance driver module (ODM) initiates the explosive bolts and the pyrotechnics which drive the vehicle ejection pistons and would have driven the jaw pistons. After a delay of on the order of 4 or 5 ms. the bolts and piston pyrotechnics fire and after a further delay of on the order of 25ms the pistons start to move and drive the research vehicle forward and would have driven the jaw down. It is currently anticipated that the separation event will be over in less than 250 ms.

In the slightly over two year's time since the MRR there has been much work done on the drop-jaw concept including wind tunnel tests, CFD analyses, structural analyses, kinematic analyses, and multi degree of freedom simulation development and analyses. This work is the subject of the balance of this paper.

WIND TUNNEL TESTS

There have been a number of wind tunnel tests dedicated to investigating the aerodynamics of the separation event.

Even before the Hyper-X contract was awarded a test was conducted with an early research vehicle/adapter configuration in the 20" Mach 6 and 31" Mach 10 tunnels at Langley (Fig. 17). In this test the research vehicle was mounted on a sting which passed through the adapter. The relative position of the adapter could be varied on the sting to simulate the movement of the research vehicle away from the adapter. While this test did yield data as a function of research vehicle axial position relative to the adapter there was a concern that the presence of the relatively large sting would have an adverse effect on the reliability of the data so additional tests were desired.

After the drop-jaw concept was selected there was concern that the shocks which would have formed in front of the drop-jaw during its operation would adversely affect the aerodynamics of the research vehicle by pressurizing the nozzle area and thereby impart a nose down moment that the vehicle control system might not be capable of handling. To investigate this phenomenon and to improve the reliability of the separation aerodynamic data the program arranged for a test at Mach 6 in the Arnold Engineering Development Center's (AEDC) von Karman Facility Tunnel B utilizing the facility's CTS rig (Captive Trajectory System). This system allowed the independent movement of and determination of loads on the research vehicle and the launch vehicle. A photograph of the model in the tunnel is shown in figure 18 while a typical schlieren (for the jaw at 90 deg. of rotation) is shown in figure 19.

Since the AEDC CTS rig required the use of a blade mount for the research vehicle there was a need to determine the interference effects from the presence of the blade on the vehicle as well as a desire to understand the sting interference effects from the original tests in the LaRC 20" Mach 6 tunnel. As a result, additional tests have been conducted in the 20" Mach 6 tunnel with a model capable of being mounted both by sting or blade with either a dummy blade or dummy sting to assess the support interference effects (Fig. 20). The previous data have now been corrected for the support interference effects.

COMPUTATIONAL FLUID DYNAMICS

In addition to the experimental investigation of the separation event there has also been a very significant CFD effort aimed at understanding the event. Solutions have been obtained utilizing the SAMcfd code from ResearchSouth (refs. 4 and 5), GASP from AeroSoft (ref. 6), and Overflow (ref. 7). The experimental data have all been obtained with the research vehicle and adapter held in fixed positions relative to each other and, as a result, are steady state approximations of a very dynamic event. While to date no time accurate, three-dimensional solutions have been obtained with the CFD, efforts are underway to obtain real time solutions in which the statically determined kinematics of both the launch vehicle and research vehicle are allowed to be influenced by the flow field.

Examples of some of the CFD work done to date are shown in figures 21 and 22. Figure 21 shows flow field contours obtained with SAMcfd for the drop jaw at a rotation angle of 90 deg. which duplicates one of those tested in the AEDC wind tunnel test. As can be seen, there are shocks which form in front of the dropping jaw which, in turn, influence the aft portion of the research vehicle. Also observe the similarity between the CFD determined shock patterns and those from the schlieren of figure 19. (Note that CFD is at $M = 7.1$ while wind tunnel test was at $M = 6$.) Figures 22 and 23 show a comparison of the experimentally determined normal force and pitching moment coefficients for the research vehicle with that obtained from the SAMcfd CFD solutions for the same positions.

SIMULATIONS

In order to assess the viability of the separation event a 6(research vehicle) + 6(booster) + 3(drop jaw and pistons) degree of freedom simulation tool has been developed under contract to LaRC by Analytical Mechanics Associates. This tool incorporates the kinematics of the separation event and the aerodynamic data base utilizing an Adams solver (ref. 8).

While a full set of Monte Carlo simulation runs has not yet been completed the simulations have already yielded significant impacts on the separation. It was found that the large normal force on the aft end of the Hyper-X resulting from the jaw drop yielded a nose down moment that the vehicle control system was not able to handle. Alternate scenarios of delaying the drop-jaw until the vehicle pistons were at half stroke and full stroke were also investigated with similar results. Typical examples of the divergent pitch and roll oscillations are shown in figure 24. This discovery resulted in the abandonment of the drop-jaw. Fortunately, the simulation has also shown that, by setting the Hyper-X wings to 6 degrees (either prior to the piston push or at the time of break wire trip) the vehicle is controllable and the risk of re-contact with the adapter is minimized. (See figure 25) The exact risk will not be quantified until the complete set of Monte Carlo runs is completed sometime later this year.

HARDWARE TESTS

The first hardware tests to be conducted were of the forward jaw to research vehicle explosive bolt joint. A portion of the structure on both sides of the joint was constructed and held together with one of the proposed explosive bolts. Unfortunately, when the bolt was fired the joint did not separate. The test was repeated with a similar result. After consultation with a number of organizations with experience in explosive bolt joints a modification to the counterbores around the bolt suggested by Sandia was tried. This new design was successful, however, the doubt cast by the first failures and the desire to have as stiff a joint as possible led the program to canvass the industry for possible replacement bolts. This study led to the decision to replace the original bolts. The new bolts were tested in test fixtures simulating each of the three different bolted joints (forward jaw to research vehicle, station 144 adapter bulkhead to research vehicle aft bulkhead, and jaw to aft adapter) to assess their performance in each application. They performed flawlessly in all three applications.

The second hardware test was of the drop jaw mechanism. In this test a mass simulator was constructed which duplicated the moment of inertia of the jaw to within 0.2% and the jaw and drive pistons were mounted in a framework and the pyrotechnic cartridges which activate the pistons were then fired. Instrumentation included LVDT’s on the two pistons, an RVDT on the jaw hinge, a pressure transducer to measure the driving pressure for the pistons, and load cells to measure the force produced by each piston as well as video and still photography. A photograph of the apparatus during the piston push is shown as figure 26.

There was concern that the shock from the explosive bolts would be greater than the vehicle FCGNU, actuator controllers, and actuators have been qualified for. Therefore an airframe shock test was conducted utilizing the adapter for the first flight and the second research vehicle. This test identified the shock levels felt at a number of locations in the vehicle airframe.

Following the airframe shock test tests of the performance of the pyrotechnic pistons which push the research vehicle were conducted. Mass simulators mounted on air bearings were utilized for simulation of both the launch vehicle and the research vehicle (Fig. 27). The mass simulators were mounted upright and the pyrotechnics fired to enable the assessment of any lateral motion caused by differences in piston push of the two pistons. This test was conducted twice and in neither instance was there an indication of any yaw due to uneven piston push.

The ejection piston test was followed by a test of a single piston with an applied side load to evaluate the capability of the pistons to operate in the event the vehicles are at some angle of pitch or yaw at separation and a side load on the pistons results (Fig. 28). Tests with side loads from 500 lb. to 2000 lb. in 500 lb. increments were conducted at NASA Dryden. While the higher side loads did result in damage to the piston and cylinder there was nothing seen in these tests to indicate that the pistons would not perform as desired; even with levels of side load much greater than that expected in the actual separation event.

The final separation hardware test was held on September 16 of this year. In this test the second airframe, ballasted to flight weight and cg location, was attached to the first adapter with flight explosive bolts (Fig. 29). All flight pyrotechnics, initiators, and separation instrumentation (break wires, LVDT’s, etc.) were installed as they would be in the actual flight. An engineering version of the FCGNU was installed to verify the shocks from both the explosive bolt firing and piston push would not adversely affect it. One of the two video cameras to be installed in the adapter for flight was included to also verify its insensitivity to the shocks. After separation the vehicle was supported by an overhead crane, with a sufficiently long support cable to minimize effects on the vehicle path. Preliminary results from this test indicate that the FCGNU was unaffected by either shock event, the video camera functioned as desired, all instrumentation functioned as expected, and the LVDT’s indicate no yaw was imparted to the vehicle by the piston push. These results further support the conclusion that, in flight, the separation should occur as desired with no adverse effects on the vehicle.

CONCLUDING REMARKS

This paper discussed highlights of the stage separation activities for NASA’s hypersonic technology program, Hyper-X. Flight test plans call for the first Hyper-X research vehicle (X-43) to fly at Mach 7 about June, 2000. There has been much work done to ensure that the non-axisymmetric separation at extreme conditions designed for this program will be successful. At this point in time the program has conducted extensive hardware, wind tunnel, and CFD efforts to insure that the separation event will occur as desired. The remaining activities will include numerous runs of the 15 DOF simulation and a formal risk assessment activity to further assure the success of the separation event.

ACKNOWLEDGMENTS:

The author would like to recognize all those who have contributed to the understanding of the separation event. On the government side: Scott Holland and Bill Woods for support in aerodynamic testing; Walt Engelund, for support in aero data base development; Doug Dilley (NYMA, Inc.), Peter Pao (NYMA, Inc.), Pieter Buning, and Tin-Chee Wong (NYMA, Inc.) for CFD support, Paul Moses (NYMA, Inc.) and Frank Vause (NYMA, Inc.) for structures and kinematics evaluations; John Martin and Jeff Robinson of Langley, and Renji Kumar of Analytical Mechanics Associates for simulation support; Bruce Swanson from Sandia National Lab for many helpful suggestions based on the Sandia corporate knowledge; and Yohan Lin for providing the Dryden flight research perspective. On the contractor side: Wayne Blocker from Micro Craft for almost super-human effort in design and manufacturing of the adapter as well as supervision of the ejection systems test program; Kevin Bowcutt and B. F. Tamrat from Boeing for contributions to the development of the drop jaw concept and aerodynamics support respectively; and Gary Garcia and Ed Silvent from Orbital Sciences for development and conduct of the ejection systems test program.

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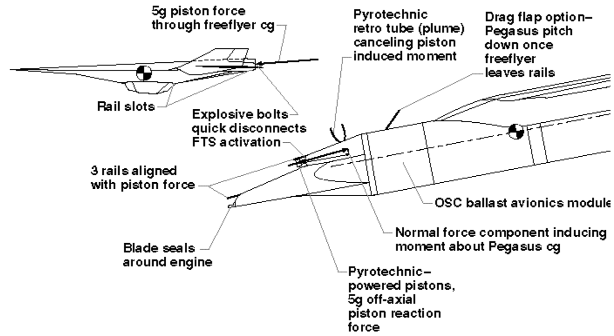

Figure 1. Proposed stage separation process from dual-fuel study.

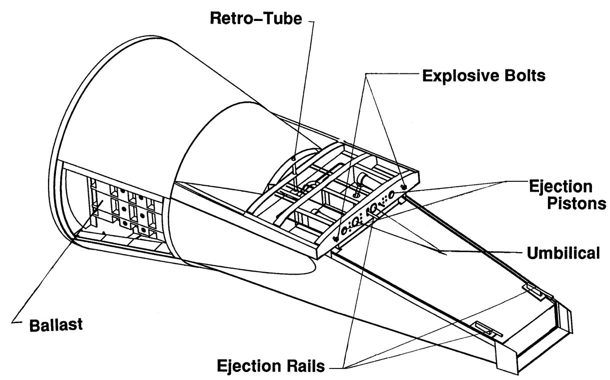

Figure 2. Proposed booster adapter with ejection system.

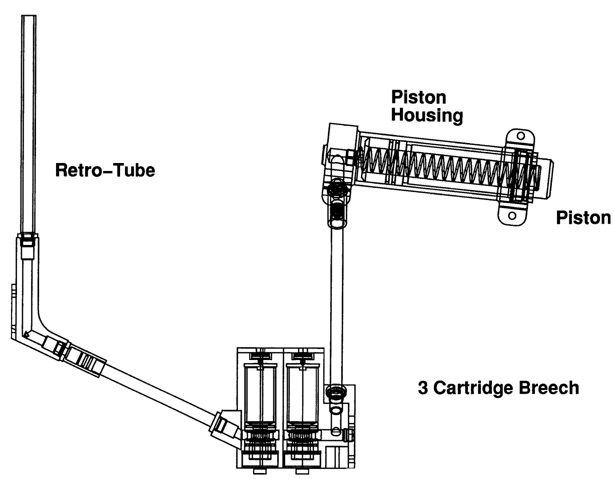

Figure 3. Proposed pyrotechnic ejection system.

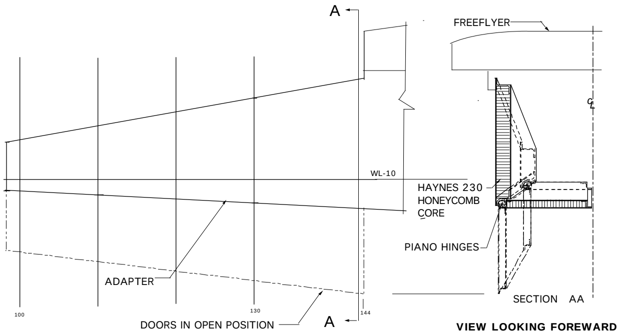

Figure 4. Proposed hinged adapter.

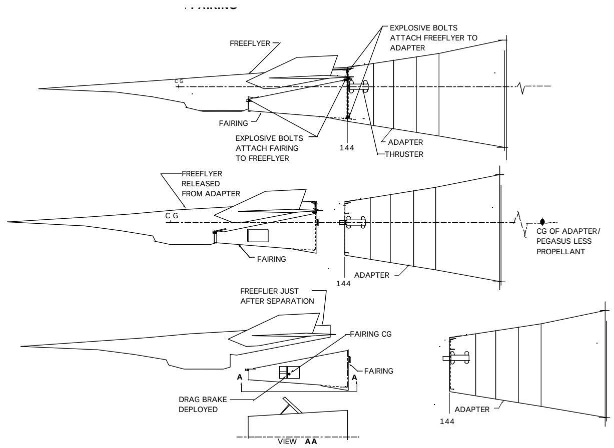

Figure 7. Proposed two-stage separation with drag brake.

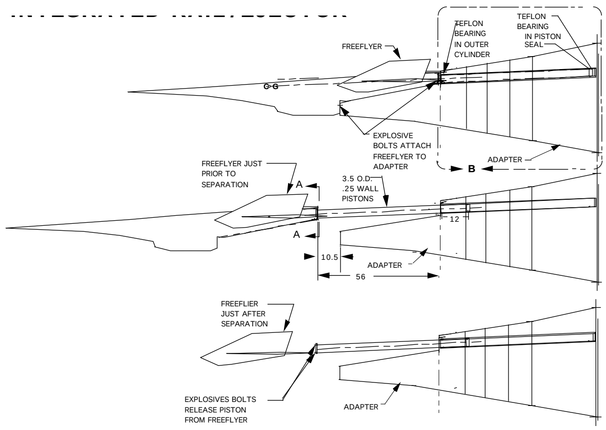

Figure 5. Proposed integrated rail/ejector.

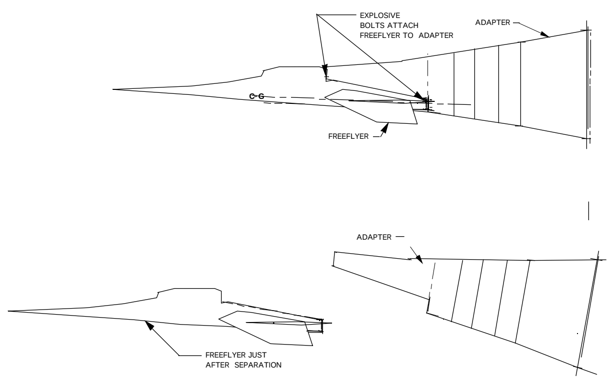

Figure 8. Proposed inverted separation.

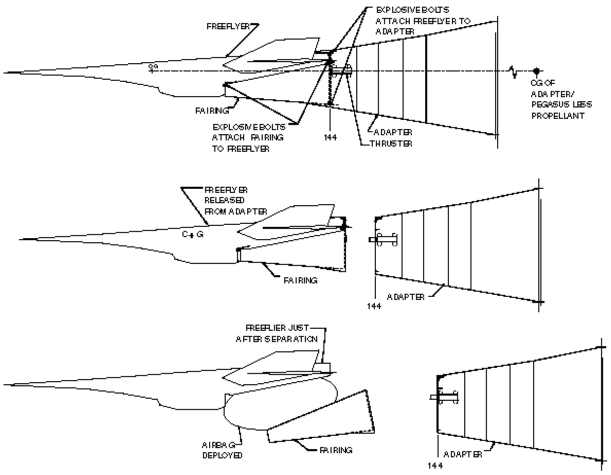

Figure 6. Proposed two-stage separation with air bag.

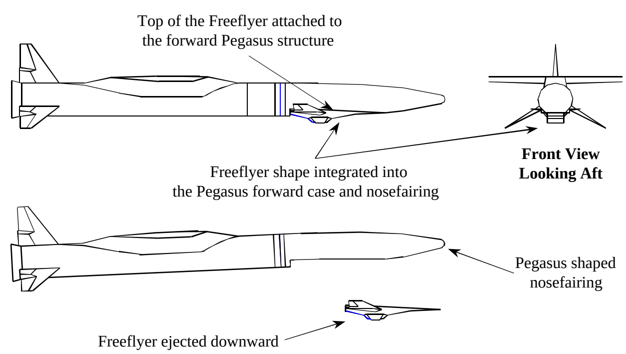

Figure 9. Sandia proposed stores separation concept.

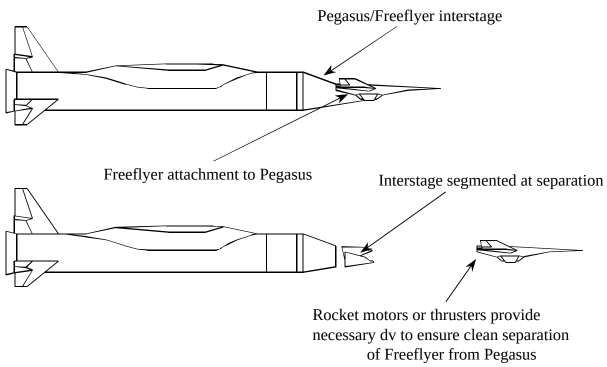

Figure 10. Sandia proposed split adapter concept.

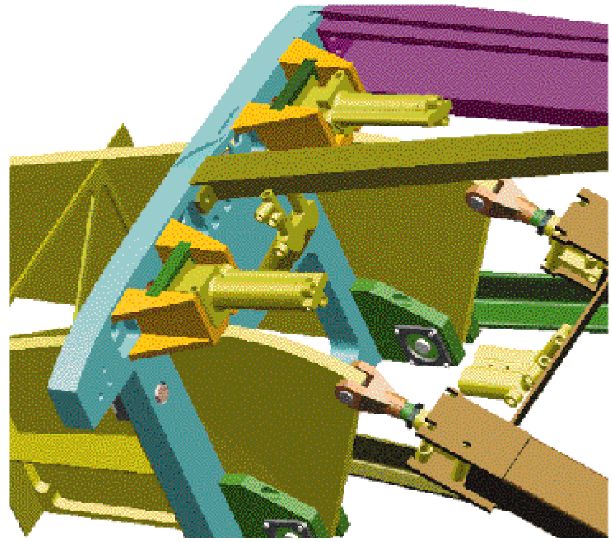

Figure 13. Solid model of drop jaw adapter showing flyer ejection mechanism.

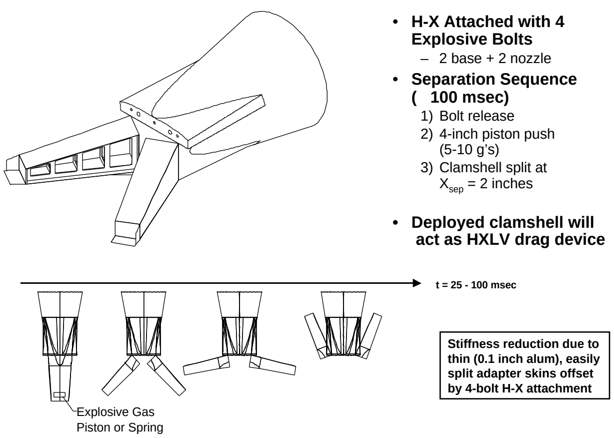

Figure 11. Clamshell adapter proposed at MRR.

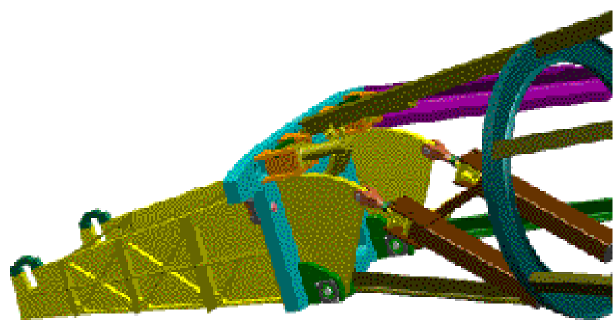

Figure 14. Solid model of drop jaw adapter showing jaw and jaw ejection system.

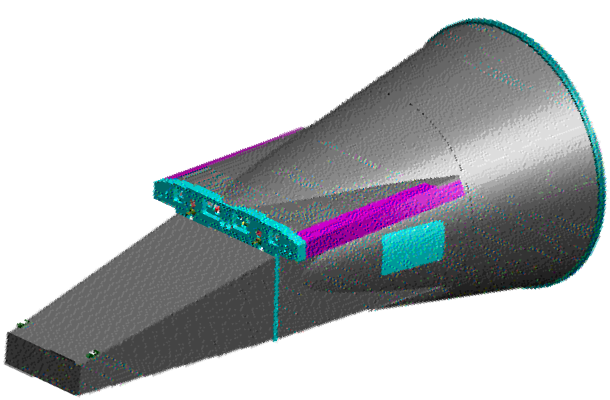

Figure 12. Solid model of drop jaw adapter.

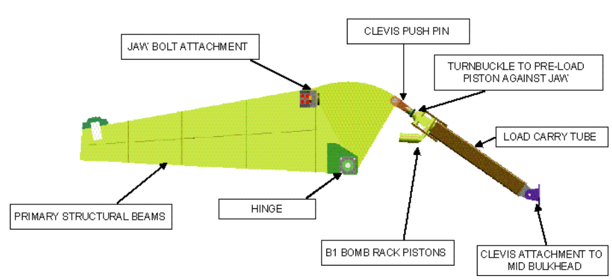

Figure 15. Drop jaw and ejection system with parts call-out.

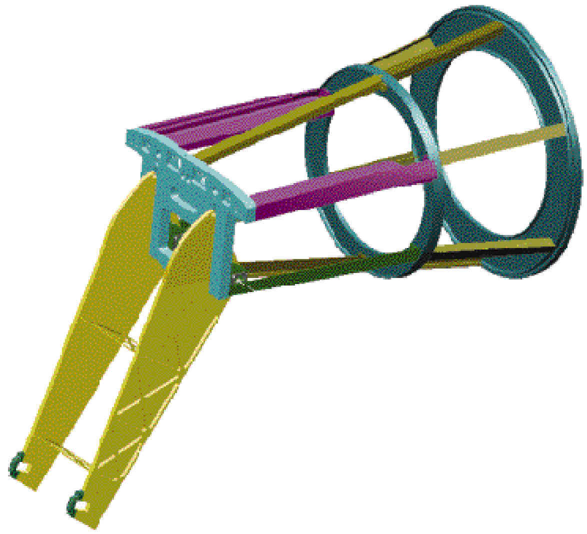

Figure 16. Solid model of primary structural members of drop jaw adapter.

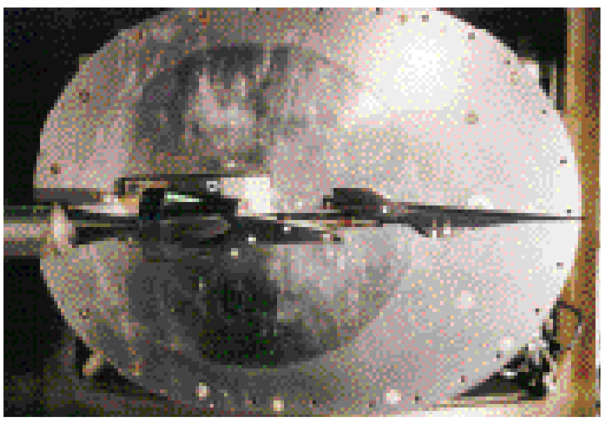

Figure 17. Model used in early separation tests at LaRC at M = 6 & 10.

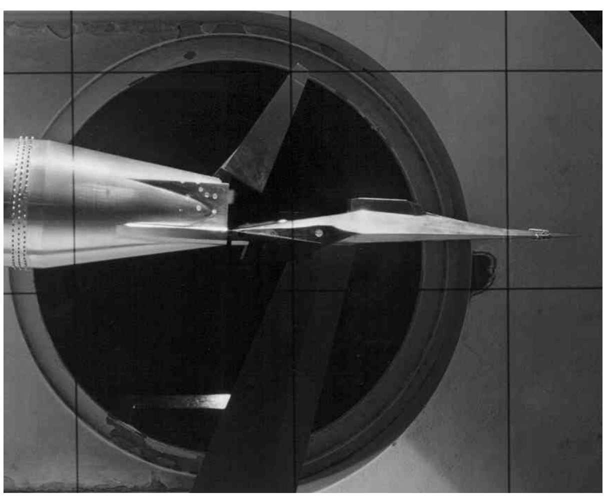

Figure 18. Models used in separation tests at M = 6 in AEDC VKF Tunnel B.

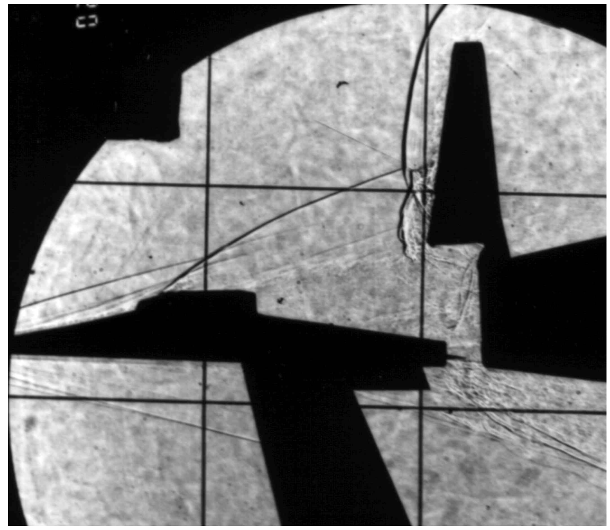

Figure 19. Schlieren from AEDC test for drop-jaw at 90 degrees.

Figure 20. Model used at LaRC to evaluate support interference effects for AEDC tests.

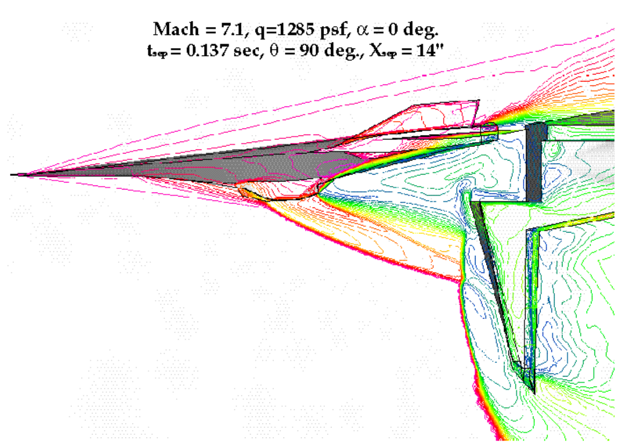

Figure 21. Flowfield contours obtained from SAMcfd solution for drop-jaw at 90 degrees, M = 7.1.

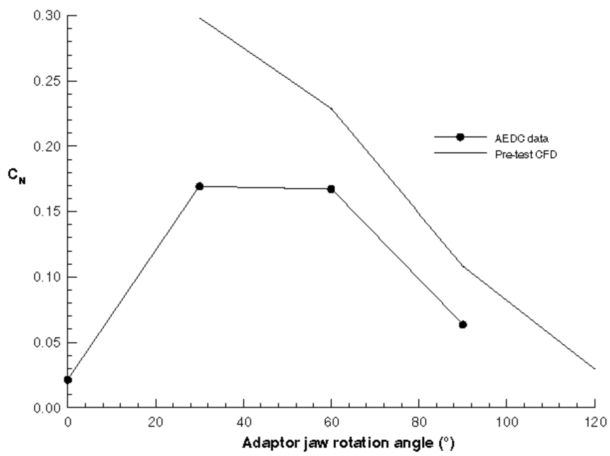

Figure 22. Comparison of research vehicle normal force coefficients as a function of drop-jaw angle from SAMcfd solutions with those from AEDC wind tunnel test.

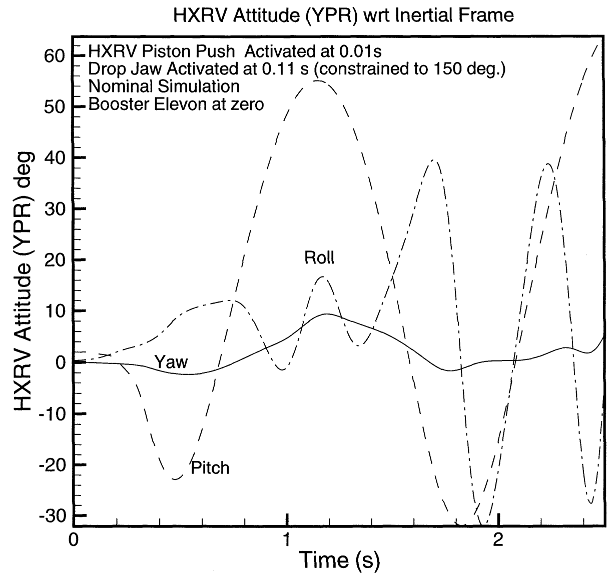

Figure 24. Research vehicle pitch angle as a function of time for a non-optimum separation obtained with simulation tool.

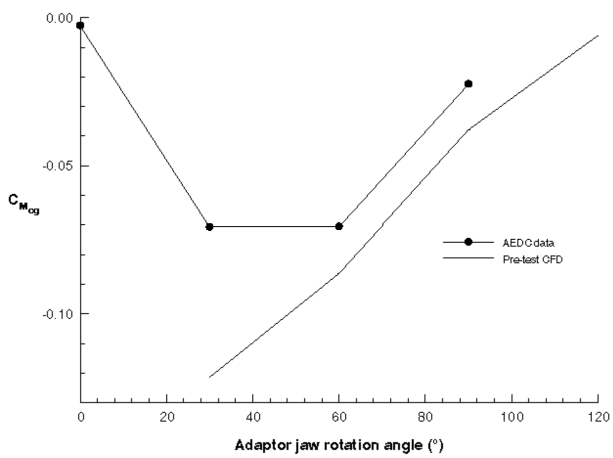

Figure 23. Comparison of research vehicle pitching moment coefficients as a function of drop-jaw angle from SAMcfd solutions with those from AEDC wind tunnel test.

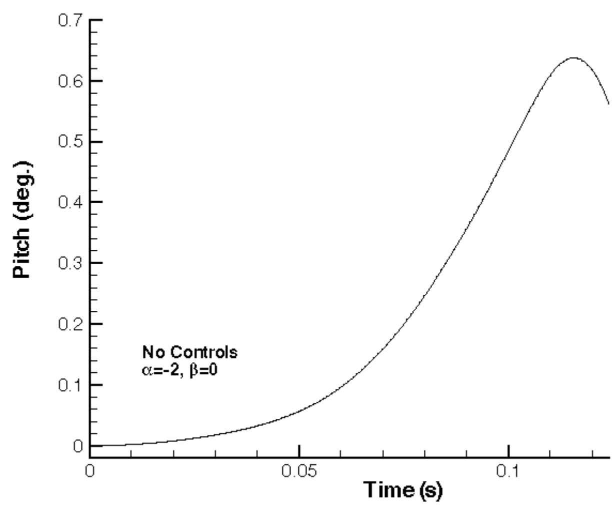

Figure 25. Booster pitch angle as a function of time for a non-optimum separation obtained with simulation tool.

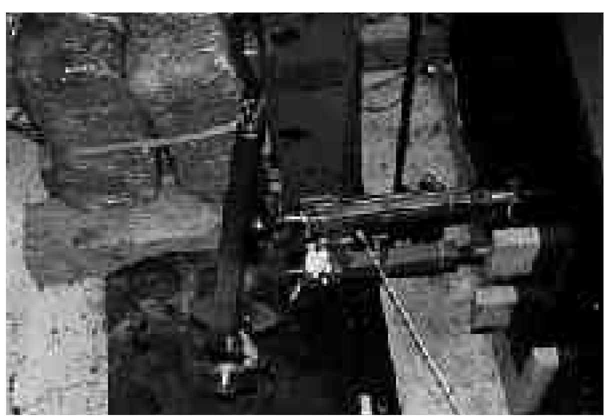

Figure 26. Top view of drop-jaw test apparatus during piston push.

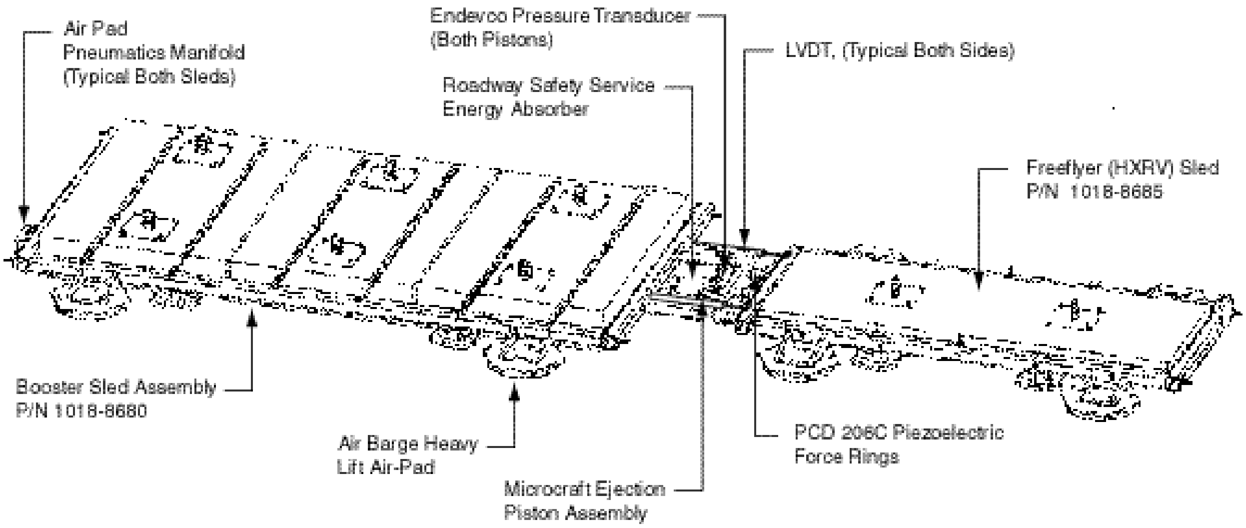

Figure 27. Ejection piston test set-up with mass simulators for launch vehicle and research vehicle.

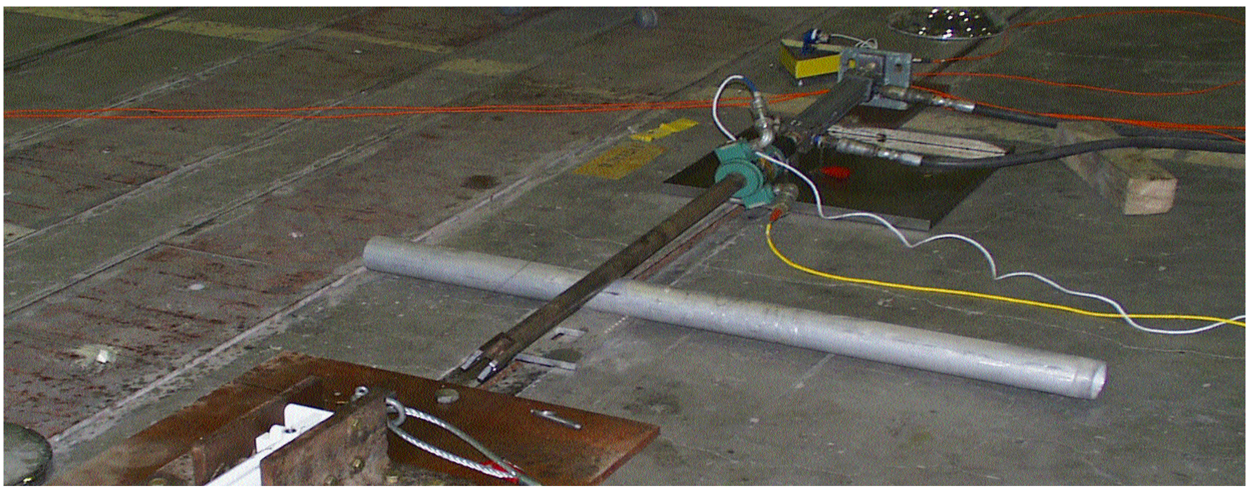

Figure 28. Ejection piston side-load test set-up.

Figure 29. Full-scale separation hardware test set-up.