Special X-43A Edition

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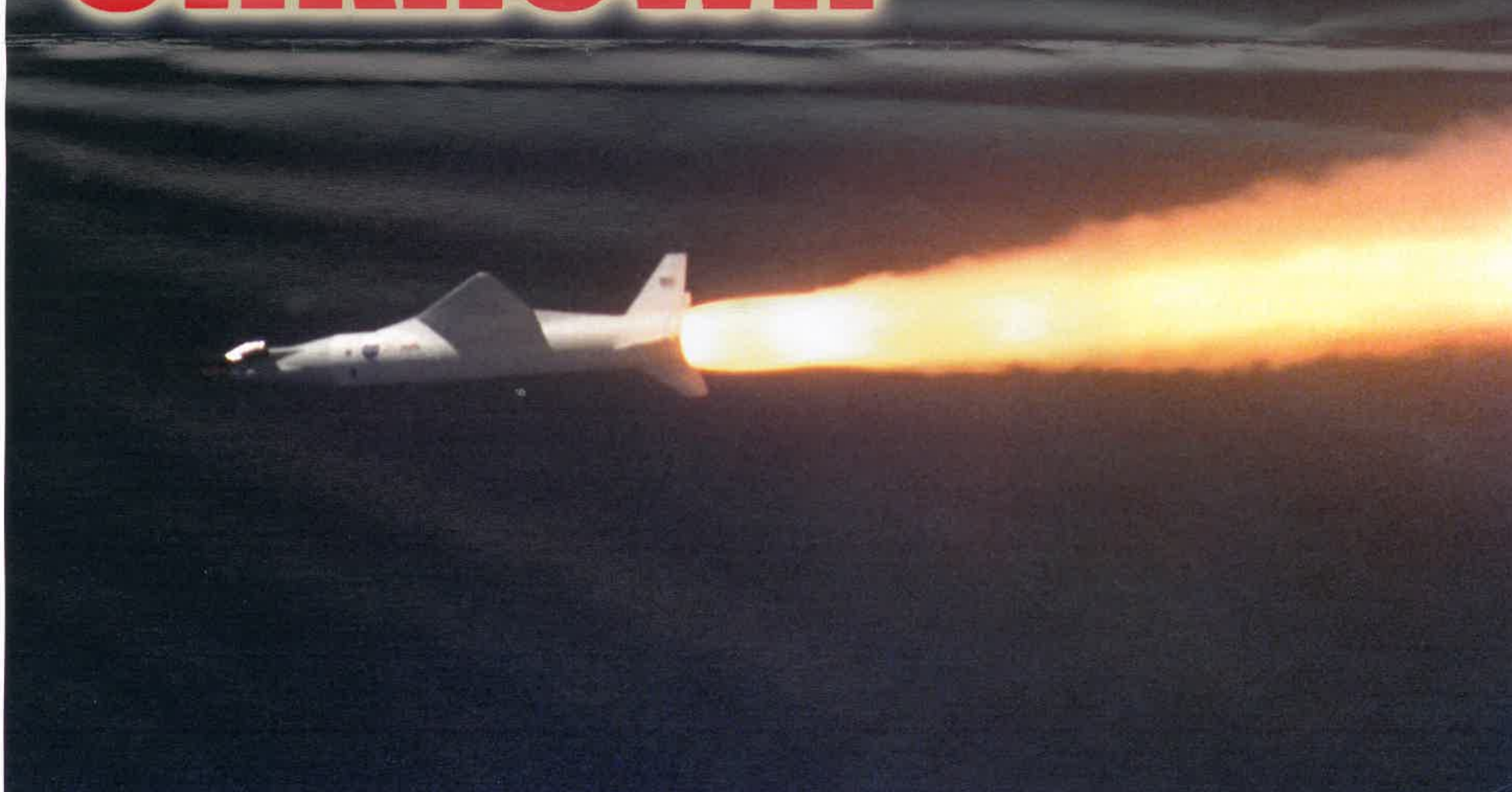
11 Seconds into the Unknown



Forging New Frontiers

With proof scramjets work, what's next?

EC04 0095-38 NASA Photo by Tom Tschida

By Jay Levine
X-Press Editor

It all came down to 11 seconds. Researchers have labored for more than four decades using wind tunnels and equations to open a door in aeronautics that has been breeched but never fully opened. But with the March 27 flight of the X-43A, the real and the imagined in hypersonic research were separated in 11 seconds. That's the amount of time the X-43A scramjet engine fired, validating the models and tools developed to enable an aircraft with a supersonic combustion ramjet – or, scramjet – to operate in the hypersonic regime.

What makes the flight even more remarkable is that the scramjet achieved positive thrust in a fully integrated aircraft; previous experiments had attempted to fire scramjets affixed only to a rocket.

Three central figures in NASA's X-43A program recently explained some of the intricacies of hypersonic exploration, including Hyper-X program manager Vince Rausch, who is based at Langley Research Center, Hampton, Va., Dryden X-43A project manager Joel Sitz and Dryden's deputy X-43A project manager, Paul Reukauf.

"The objective of the program is to benchmark the tools, facilities and techniques used to design these kinds of vehicles," said Reukauf. "The X-43A airframe is essentially a design that was done by McDonnell Douglas (now The Boeing Company) for the X-30 National Aero Space Plane (NASP). It was one of the candidate designs during that program and, in that configuration, was 250 feet long and weighed half a million pounds. This project scaled down that concept (to make) the X-43A 12 feet long, five feet wide and two feet thick, but it's a true optimized hypersonic shape – it's not just some vehicle we stuck a scramjet on."

A team of Dryden and Langley employees competed in a 1995 NASA X-Plane competition and were winners with the X-43A, which was funded a year later. The goal of the competition was to produce a significant aeronautics achievement for about $200 million and do it in less than three years. Using data gathered in the X-30 NASP project, Dryden and Langley put together a program to explore the engine integration problem that had plagued the earlier effort. McDonnell Douglas scaled down the size of their initial NASP vehicle, while Langley and partner ATK-GASL (formerly MicroCraft Inc.) worked further to develop an engine design.

EC04 0091-39 Photo by Tony Landis

Top photo, from left, celebrating a successful flight are Dryden mission controller Brad Neal, NASA Associate Administrator for Aeronautics J. Victor Lebacqz, Dryden X-43A deputy project manager Paul Reukauf, Dryden Center Director Kevin L. Petersen, Ryan Warner (seated), Dryden X-43A chief engineer Griffin P. "Griff" Corpening (seated), Dryden X-43A project manager Joel Sitz, Robert Shannon, Tom Horn and David Dowdell. Above, the sun rises on mission day.

Each X-43A is a separate research vehicle attached to the nose of a modified Orbital Sciences Pegasus booster rocket and carried under the wing of the NASA B-52B. The configuration is called the "stack" and it is air-launched, with the X-43A coming to a final rest in the ocean.

"With the March flight of the X-43A at Mach 7, the NASA Langley/Dryden team, along with their contractor team members, achieved a 40-plus year dream of proving that scramjet propulsion really does work as advertised," said Langley's Rausch. "This achievement will pave the way for more robust, affordable access to space and more efficient high-speed flight in the atmosphere."

The successful flight took the talents of both NASA centers and help from partners ATK-GASL, Orbital Sciences and the Boeing Phantom Works, he added. In addition, he said, X-43A officials had many thanks for the Code R Vehicle Systems Office at NASA Headquarters, which provided the financial backing for the mission's flight into the unknown.

To put the accomplishment in a time frame, Reukauf said researchers were familiar with the concept of ramjet and scramjet engines as early as the 1930s, with the first operational ramjet used in missiles in the 1950s and early 1960s.

"It's a simple concept, but the devil is in the details," he said.

Third flight

With the success of the Mach 7 flight, preparations are well under way for the third X-43A vehicle to embark on a Mach 10 flight late this fall. The third vehicle in the X-43A series differs from the previous two with its enhanced thermal protection systems on the vertical tails – to ensure it will survive the heat of a Mach 10 flight – and minor changes to the scramjet's geometry to accommodate the higher Mach number.

Vince Rausch
Langley Hyper-X Program Manager

"(The new vehicle) has a slightly different design in the propulsion system to demonstrate that the scramjet can work at Mach 10," said Sitz. "The feeling is that scramjets can work all the way up to Mach 15. We've demonstrated a Mach 7 flight; this will be a Mach 10 mission. At some point we'd like to fly a future research vehicle on a Mach 15 flight to see what the window is, to define the limits of scramjet operation."

For the third flight, the testbed's carbon-carbon leading edges will be treated with a different coating to protect against higher temperatures. There also will be software changes and a condensed schedule.

"We know what's ahead of us," Sitz said. "And we know that what's ahead of us is very hard because it's been a lot of work to get to this point – we're not going to relax or let our guard down at all on this mission. We're going to use all the same processes and analysis techniques that we knew worked for the second mission, and apply those to the third mission."

With preparations for the third vehicle, it's so far, so good.

"The research vehicle is essentially completed with the exception of some minor modifications we want to make to the fluid systems that drive the engine," he said. "Then we'll put all the systems into the vehicle and do what we call an 'integrated blowdown,' meaning we attach the research vehicle to the launch vehicle adapter and pressurize all the fluid systems with an inert gas. And then we do a 'blowdown' to simulate the engine experiment, which also simulates the hand-off from the RV (research vehicle) adapter to the RV fluid systems during the separation event."

Flight One

The team had little time to revel in the success of flight two before concentrating on the upcoming one. But the success proved the resilient team's ability to rebound from the June 2, 2001, first flight, when the first X-43A vehicle was lost moments after release from the wing of the NB-52B. Following booster ignition, the combined booster and X-43A stack deviated from the flight path and were deliberately destroyed. Investigation into the mishap showed that there was no single contributing factor, but the

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X-43A 101: What it is, what it does and the partnerships that make it go

By Jay Levine
X-Press Editor

After more than 40 years of work by researchers, a joint NASA-industry team enjoyed the payoff when the X-43A testbed separated from a rocket booster at approximately Mach 7 – about 5,000 mph – and its engine fired successfully, producing positive thrust.

The flight, conducted jointly by Dryden and Langley Research Center marked a world record and the first time an integrated airbreathing supersonic ramjet (scramjet) engine exceeded hypersonic speed (about Mach 5). Concepts developed on the ground and researched in wind tunnels were proven in flight for the first time, proving that the engine technology works and that it could be a component in the kind of advanced propulsion system required for future exploration and commercial aircraft.

"The challenge for NASA and industry will be to build on this success, to keep advanced airbreathing technology moving forward," said Dryden X-43A project manager Joel Sitz.

Prior to the record-breaking flight that marked several firsts in aeronautics, the triple-supersonic SR-71 was the fastest known airbreathing engine aircraft. The fastest rocket-powered aircraft flight within the atmosphere was the Mach 6.7 flight in 1967 by William J. "Pete" Knight in the X-15. A bullet fired from a gun travels at roughly Mach 3, though a Mach number designation takes into account altitude and atmospheric conditions as well as speed.

"The return to flight was a long, tough effort that built on a great deal of work that preceded it. One of the most satisfying aspects of accomplishing it so successfully is to see the hard work and dedication of so many people over so many years finally come to fruition," said Langley's Luat Nguyen, X-43A deputy manager for technology.

The X-43A is an unpiloted 12-foot-long vehicle. It was air-launched from the wing of the NASA B-52B mothership and rocketed to its research altitude of 95,000 feet and Mach 7 speed by a modified Orbital Sciences Pegasus booster rocket. From there, the ATK GASL-built X-43A separated from the booster and performed the engine test as well as several aerodynamic tests before reaching the intended end of its journey in the Pacific Ocean.

Simple in concept but exceedingly difficult to design and demonstrate, a scramjet engine is not much more than a hollow tube with few moving parts. While the X-43A flew at Mach 7, air was flowing through the engine at about half that speed. Among many of the daunting challenges involved: introduce fuel, ignite it and achieve combustion in the millisecond each individual molecule of air spends in the engine – a task only slightly more difficult than lighting a match in a hurricane.

"The team really worked together. It has been a real pleasure working on this project and with the people on it, both NASA and contractor members," said Lowell Keel, ATK-GASL vice president of X-vehicle programs. "It's people that make it happen, and these people put their hearts and souls into the hardware and the project. I worked here at Dryden on the F-111 TACT in the mid 1970s and it's a real pleasure to come back home and to be a part of another success."

On the surface, the 11 seconds of data gathered during the flight might not seem like much, but it's an eternity to researchers who have gained valuable data they'll now compare to models and paradigms developed on the ground during the past four decades, Sitz said.

The team sees the flight as the beginning of hypersonic-realm exploration; X-43A vehicle number three is presently at Dryden and undergoing preparation for flight test this fall. The X-43A is not a reusable aircraft, so a different vehicle is used for each flight – all of which end in the ocean. Reusable aircraft would have raised costs exponentially for the experiment.

"We achieved positive acceleration of the vehicle while we were climbing, and maintained outstanding vehicle control," said Larry Huebner, Langley Hyper-X propulsion lead. "This was a world-record speed for air-breathing flight. We had outstanding vehicle control through the entire scramjet portion of the experiment.

"To put this in perspective, a little over a hundred years ago a couple of guys from Ohio flew for 120 feet in the first controlled, powered flight. Today, we did something very similar in the same amount of time but our vehicle, under airbreathing power, went over 15 miles," he said. "Now it's time to roll up our sleeves and start looking at some data."

Brad Neal, Dryden mission controller, shared Huebner's enthusiasm.

"It went without a hitch. It was a big operation and we've been working on it for a lot of years, and this last week we've been working around the clock," Neal said of flight week. "We like to have these kinds of finales to these types of operations."

"The X-43A team believes this flight will pave the way for a new future during the next two decades," said Dryden X-43A chief engineer Griffin P. "Griff" Corpening. "We've shown we can fly out there (in the hypersonic realm)."

Because the X-43A theory and design methodology is now backed up by flight research, Corpening said industry and military interests in hypersonic vehicles can be pursued much more confidently.

For now, however, researchers want to savor a moment that was not reached easily.

"It was all the sweeter for the challenges we had to step up to over the life of the program," said Corpening.

Tom Harsha, Boeing Phantom Works X-43A project manager, agreed the flight was spectacular.

"It was a long time coming. There were an awful lot of people who worked on it and we're overwhelmed by the scope of this success. We were looking to do two things that had never been done: separate an aircraft at Mach 7, and fly that aircraft's scramjet engine to produce thrust," Harsha said.

The successful flight was the second in the X-43A project. On June 2, 2001, the first X-43A vehicle was lost moments after release from the wing of the NB-52B.

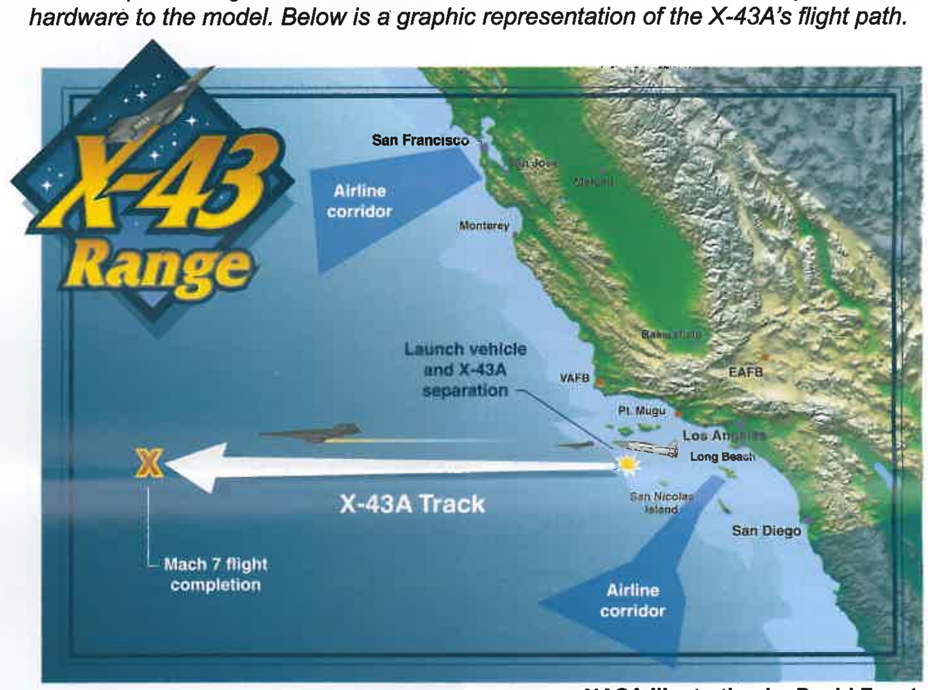
"The thing is that two years and nine months ago we had our doubts as the return-to-flight plan began," said Phillip Joyce, Orbital Sciences Corp. hypersonic and suborbital programs director. "Dryden was told, 'OK, go do it.' That to me is the most inspiring – NASA was willing to do what it takes to get it right, and as a result we had an extremely great flight."

ATK-GASL (formerly MicroCraft Inc.), based in Tullahoma, Tenn., built both the vehicle and the engine, and The Boeing Company's Phantom Works, Huntington Beach, Calif., designed the thermal protection and onboard systems. The booster is a modified Pegasus rocket built by Orbital Sciences Corp., Chandler, Ariz.

Leslie Williams, Gray Creech and Keith Henry contributed to this report.

Photo courtesy of Jeff Caplan Langley Research Center

In the Langley Research Center wind tunnel are, from left, Larry Heubner and Earl Andrews performing surface calibration checks while technician Robert Kyle attaches hardware to the model. Below is a graphic representation of the X-43A's flight path.



NASA Illustration by David Faust

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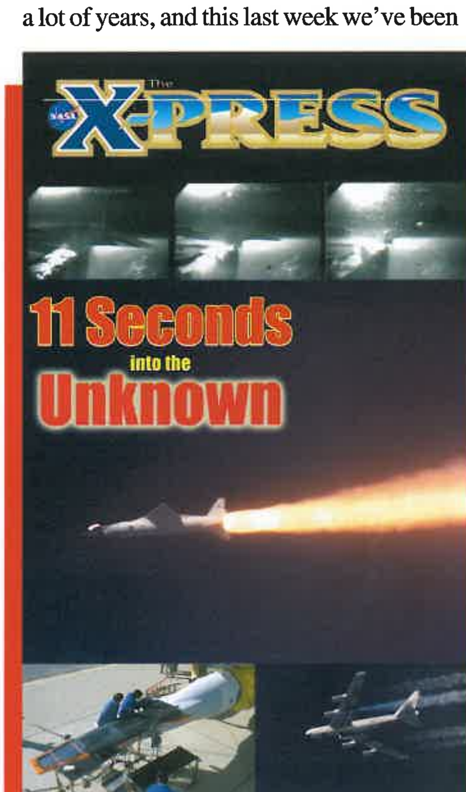


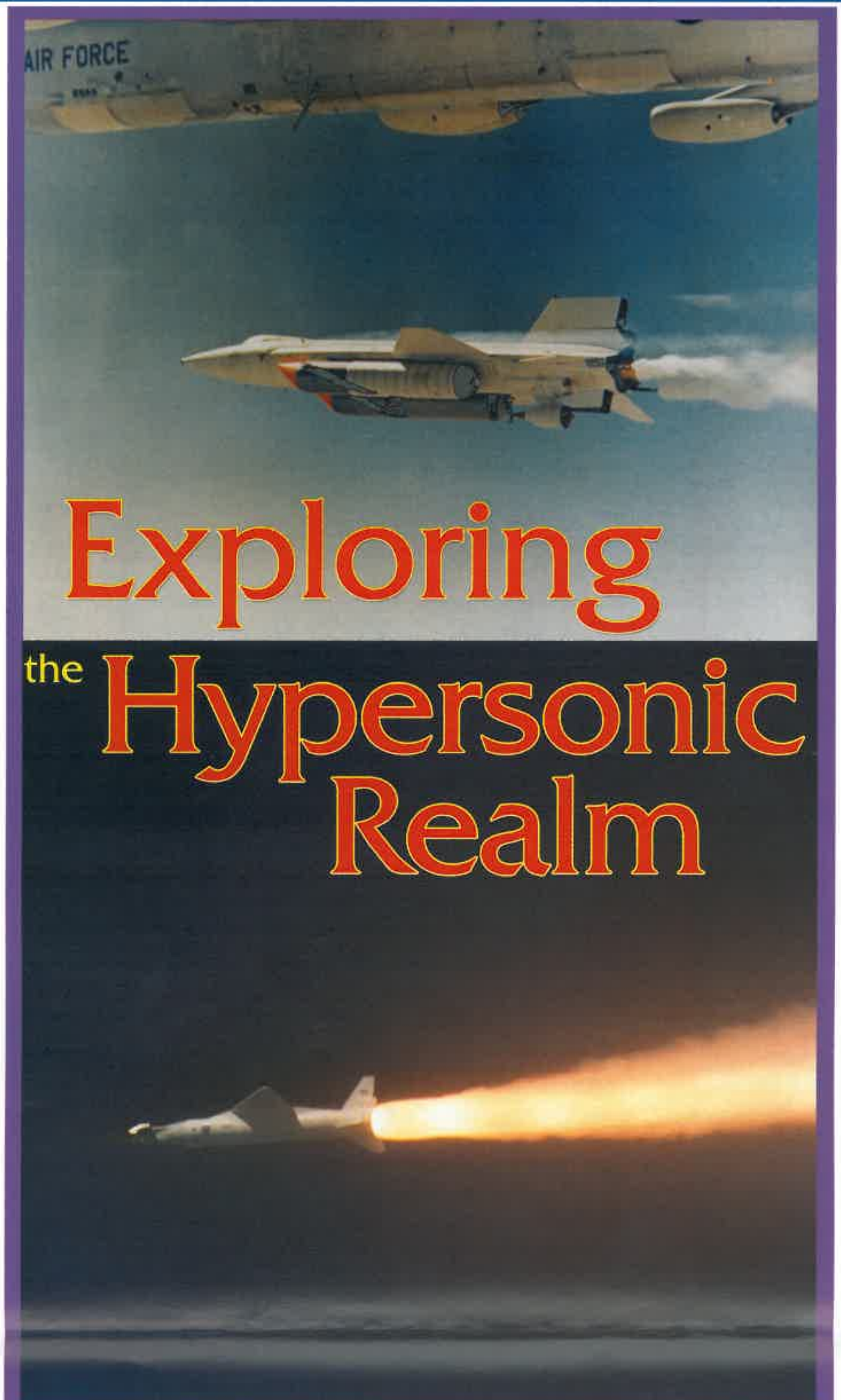
About the cover ...

When the X-43A successfully completed its mission March 27 it marked the beginning of a new era in hypersonics research.

Counterclockwise from bottom left, the cover of this special edition features the aircraft on the ground under the wing of its host NB-52B with crew members (clockwise from bottom) Mark Davis and Dale Edminister of NASA and Boeing's Duoc Tran. The next frame shows the "stack's" air launch from the NB-52B mothership. The booster portion of the stack ignites, center, and finally, a combination of explosive bolts and pistons on the rocket booster sends the X-43A on its way to a successful flight (top three panels).

This special edition is a tribute to the X-43A, to the pioneers of hypersonic research and to the men and women who make it all happen.

Exploring the Hypersonic Realm



NASA boasts a long history of hypersonic research. At top is the X-15, which William J. "Pete" Knight piloted in 1967 to Mach 6.7 to become the "fastest man alive" (EC68-1889). Above is the X-43A "stack," comprised of the rocket booster and testbed, on its record-breaking March 27 flight. (EC04 0092-31 NASA Photo by Jim Ross.)

By J.D. Hunley
Former Dryden Historian

Since the 1950s, what is today the Dryden Flight Research Center has been heavily involved with hypersonic flight research—flying and gathering data from research vehicles traveling faster than five times the speed of sound (Mach 5). The first hypersonic research airplane was the X-15, designed to fly to a speed of Mach 6 and an altitude of 250,000 feet. In a joint program involving NASA's Langley and Dryden research centers, the Air Force, the Navy and North American Aviation, the rocket-powered X-15 exceeded both design goals. NASA pilot Joe Walker flew to 354,200 feet (more than 67 miles) on August 22, 1963, and Air Force Maj. William J. "Pete" Knight flew a modified X-15 with additional propellant tanks and an ablative coating to a speed of Mach 6.7 (4,520 miles per hour) on October 3, 1967.

In the course of almost 10 years of flight research from 1959 to 1968, the X-15 yielded a vast amount of new data about hypersonic aerodynamics and aerothermodynamics, among other disciplines. This field was still in its infancy in 1954, when the X-15 program won approval. The few hypersonic wind tunnels then in existence were small and unable to simulate the conditions of actual flight at speeds above Mach 5. The seemingly realistic fear at the time was that testing in them would fail to produce valid data. As it turned out, nearly all of the hypersonic flight forces and pressures turned out to be in close agreement with the low-temperature wind-tunnel predictions. This general validation, although broadly confirmed by some missiles and spacecraft, came primarily from the X-15; it made the conventional, low-temperature, hypersonic wind tunnel an accepted source of data for configuration development of hypersonic airframes.

This was a very significant confidence builder for designers but, at the same time, the X-15 overturned several beliefs aerodynamicists had held since the mid-1950s. One was the theoretical presumption that the boundary layer (the thin layer of air close to the surface of an aircraft) would be highly stable at hypersonic speeds because of heat flow away from it. This presumption fostered the belief that hypersonic aircraft would enjoy laminar (smooth) airflow over their surfaces. Because of this, many designers computed performance and heating for the case of laminar flow. At Mach 6, even wind-tunnel extrapolations indicated extensive laminar flow. However, flight data from the X-15 showed that only the leading edges of the airfoils exhibited laminar flow and that turbulent flow occurred over the entire fuselage. Small surface irregularities, which produced turbulent flow at transonic and supersonic speeds, did so equally at speeds of Mach 6. Thus, designers had to abandon their expectations of extensive laminar flow.

A similar reversal of expectations occurred with turbulent heat transfer. Predictions from 1956 and 1960 about such transfer proved to be too high, with the actual flight results in 1961 averaging about 35 percent lower than the predictions. Most specialists in fluid mechanics refused to believe the data. But repeated measurements in flight completely substantiated the initial findings. This led aerodynamicists to undertake renewed ground-based research to complete their understanding of the phenomena involved – highlighting the value of flight research in doing what Hugh Dryden had predicted for the X-15 in 1956: that it would "separate the real from the imagined."

This discovery and the resultant wind-tunnel testing led NASA Langley Research Center to arrive at the Spaulding-Chi model for hypersonic heating. It enabled NASA and industry to design lighter vehicles with less thermal protection that could more easily be launched into space. The design of the Apollo command and service modules was one result. The X-15 flight research also led North American Aviation to develop an automated mathematical model for aerodynamic heating designated Hypersonic and Supersonic Thermal Evaluation (HASTE) that provided a workable approximation for design work. North American used it directly in the initial Apollo design effort.

On three separate occasions, excessive aerodynamic heating of the X-15's nose-wheel scoop door caused structural deformation. This permitted superheated air to flow into the wheel well, stagnate, and burn the tires. Although the metal wheels stayed intact, the disintegration of the rubber tires made landings very rough. The lesson from this to designers of aircraft and spacecraft likely to be subjected to extensive heating was to take precautions to avoid the possibility of external, heated air leaking into the fuselage.

Other problems from aerodynamic heating included windshield crazing (internal cracking due to pressure), panel flutter and skin buckling. Arguably, designers could have prevented these local problems through more extensive ground testing and analysis of possible mechanisms for heating, but a key purpose of flight research is to discover the unexpected, which it did in these cases as in many others. The truly significant lesson from these problems was that simple non-critical design features of subsonic or supersonic aircraft can become much more critical at hypersonic speeds.

There were other corrections to and validations of ground-test data and theory from the X-15, but it is sufficient to say here that results of the X-15 flight research helped provide the data and the confidence to proceed with placing humans in space and ultimately on the moon. This included the design of the Space Shuttles, which had to carry humans into space and back the first time, as expected, without the cautious "envelope expansion" employed with the X-15 and other flight research vehicles at what became the Dryden Flight Research Center.

Dryden made other contributions to the Space Shuttles, the first of which, Columbia, landed at Edwards Air Force Base on April 14, 1981. Although Dryden did not have as major a role in shuttle flights as did Johnson and Kennedy Space Centers, Dryden researchers were significantly involved (as were other NASA centers) in analyzing data from the shuttle flights, which provided data at much higher Mach numbers and altitudes than had the X-15.

In 1981, Dr. William L. Ko, Bob Quinn and other Dryden researchers compared preflight predictions of structural temperature distributions on the Shuttle during re-entry with data from the initial shuttle flight. They found "an unpredicted rapid cooling 1800 sec into entry" that they attributed to "inaccurate assumptions of structural heat dissipative properties or flow conditions" during that part of the flight. They also discovered "additional discrepancies in descriptions of heating of the upper fuselage" resulting from "lack of knowledge of the complex flow patterns existing over that area of the Shuttle body."

Also in 1981, engineers Ken Iliff, Rich Maine, and Johnson Space Center's D.R. Cooke examined selected stability and control derivatives from Columbia's first re-entry, reporting data for a range of speeds from Mach 25 down to Mach 1.5 and altitudes descending from 515,000 to 50,000 feet. As they stated, Columbia was "the first vehicle to maneuver over a wide range of hypersonic velocities, yielding data on flight characteristics from previously unexplored regimes." They validated "the general trends in the Shuttle derivative predictions...with the greatest disagreement with predictions found in the reaction control system jet aerodynamic interaction effects." In a subsequent paper dealing with the same subject for the first three Shuttle re-entries, Maine and Iliff again found that "most of the flight-derived estimates agreed fairly well with predictions, considering the lack of experience in these new flight regimes." Here, "the most notable exception was the aerodynamic interference caused by firing the reaction control jets in the atmosphere. The flight results showed this interference to be considerably smaller than predicted."

Space does not permit even a cursory summary of over a dozen analyses of Shuttle hypersonic data by Dryden researchers including Harry Chiles, Tony Whitmore, Leslie Gong, Jerry Jenkins, Al Carter and Mary Shafer, but among other findings, as Iliff and Shafer have written, the Shuttle's "flight stability and control derivatives were significantly different from...predictions." Analysis of them led to "flight determined estimates [that] were used to modify the flight simulator significantly." Simulation studies then resulted in modification of a bank reversal maneuver flown on Columbia's second mission (STS-2), with nearly identical maneuvers flown on subsequent flights of the Shuttle fleet. Again, flight research separated the real from the imagined—this time with the Shuttle operating as if it were a flight research vehicle.

Iliff and Shafer also discussed areas other than those included here where the data from Shuttle flight differed from values predicted by ground testing. They then pointed out, based in part on analysis of the X-15 and the Shuttle flight data, "how the correlation and validation of ground test and flight [we]re used in a complementary fashion to improve the results of each."

Dryden began dropping Pegasus launch vehicles from its venerable B-52 No. 008 in 1990. In conjunction with Orbital Sciences Corp. (designer of the Pegasus in a joint venture with Hercules Aerospace under contract from the Defense Advanced Research Projects Agency), Dryden launched six Pegasus vehicles.

The first Pegasus vehicle—rolled out in August 1989 and launched by the B-52 on April 5, 1990—successfully placed two spacecraft into orbit, an Advanced Research Projects Agency/U.S. Navy experimental communications satellite and a NASA Goddard Space Flight Center, Greenbelt, Md., bus containing two experimental canisters and a payload-environment instrument package, both of which remained attached to the third stage of Pegasus. The remaining five B-52 launches followed through August 1994, after which Orbital's L-1011 assumed launch duties.

On the first Pegasus flight, Dryden researchers Gregory Noffz, Bob Curry and Ed Haering together with Ames researcher Paul Kolodziej gathered temperature data up to speeds above Mach 8 and calculated heating rates on the fuselage in the area where the wing shock interaction occurred. These and other Dryden and contractor engineers including Robert Meyer and Tim Moes gathered further aerodynamic and aerothermodynamic data from Pegasus flights and compared them with predicted data.

Dryden engineers also collaborated with Orbital Sciences on the Pegasus Hypersonic Experiment (PHYSX) project, which sought to gather aerodynamic information at speeds from Mach 5 to Mach 8. To obtain this information, researchers attached a steel glove to the right wing of a Pegasus first stage. On October 22, 1998, the glove, outfitted with sensors, gathered data as the Pegasus dropped from beneath Orbital Science's L-1011 aircraft and launched a commercial satellite into orbit, beginning the flight from Cape Canaveral Air Force Station, Fla. PHYSX yielded valuable information about the transition from laminar to turbulent airflow as the Pegasus first stage accelerated to Mach 8 at an altitude of approximately 250,000 feet. PHYSX also provided useful data about aerodynamic and aerothermodynamic flow phenomena that could be helpful in designing future hypersonic airbreathing vehicles.

Meanwhile, by the time PHYSX had flown, NASA had inaugurated a limited effort to gather data benchmarking the design tools used on the X-30 program for a single-stage-to-orbit, airbreathing flight vehicle called the National Aero Space Plane. (Both Langley and Dryden worked on this project, which never flew but did contribute both knowledge and materials to the nation's store of knowledge about hypersonics.) A series of working groups and committees, including representatives of Langley Research Center, met at NASA Headquarters. These meetings resulted in a proposal that NASA inaugurate a flight research project involving an airbreathing supersonic combustion ramjet (scramjet) engine integrated into an airframe. The goal was that it be comparatively simple so as to keep the costs and consequent risks low. It would provide valuable data about the operation of an airbreathing scramjet integrated with an airframe operating at hypersonic speeds.

The upshot of all the discussions at NASA Headquarters was the Hyper-X project. Langley became the lead center with responsibility for program management and technology applications. Dryden became the lead center for flight research with the added responsibility for managing the subsequent contracts with MicroCraft Inc. (for fabrication of the three X-43A flight research vehicles) and Orbital Sciences Corp. (for modified Pegasus first stage launch vehicles that would be carried aloft and dropped from B-52 008). GASL Inc., which built the scramjet engines and their fuel systems, and Boeing, which provided the avionics system and final structural design, were subcontractors.

While the Hyper-X project got underway with requests for proposals from potential industrial partners in 1996,

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EC04 0092-39 NASA Photo by Jim Ross

NASA's B-52B air-launched the stack comprised of a modified Orbital Sciences Pegasus booster rocket with the ATK-GASL X-43A testbed attached to its nose.

From the beginning

X-43A chief engineer recalls effort to prepare the hypersonic vehicle

By Leslie Williams
Public Affairs Specialist

"The importance of the Mach 7 flight scramjet test could turn out to be one of the major events in present-day flight-testing and research."

Griffin "Griff" Corpening
Dryden's X-43A chief engineer

NASA's scramjet engine test began when the rocket ignited and shoved the 12-foot-long X-43A research vehicle to an approximately 100,000-foot altitude, where two small pistons separated the experimental craft from its booster.

The flight concluded in the ocean but not before the cowl door on the scramjet had opened to allow supersonic air to enter and fuel was injected into the engine, producing thrust – demonstrating the air-breathing engine that NASA has been researching for decades in ground facilities.

From the moment the X-43A "stack" – the research vehicle and launch vehicle with adapter – dropped from NASA's B-52B mothership, the project's chief engineer, Griffin "Griff" Corpening, said he held his breath until he heard the wonderful words "the research vehicle is stable" from controls engineer Cathy Bahm, after the testbed had separated from the booster and was flying under its own power.

Corpening has worked on the X-43A project since its 1997 inception at Dryden. Reflecting on the challenges that have faced the project team in preparing a hypersonic prototype to make aviation history, he said being part of a hypersonic flight program had been one of the main reasons he joined NASA.

Corpening studied hypersonics at the University of Maryland as a graduate student and worked at Johns Hopkins University Applied Physics Laboratory in Maryland in the mid-1980s. At that time, high-speed research was a priority for both government and private industry in a quest to expand access to space.

As Dryden's chief engineer on the project, Corpening oversaw both technical operations and research objectives for the vehicles. He also coordinated work activity with project team counterparts at NASA's Langley Research Center and industry partners ATK-GASL, Orbital Sciences Corp., and The Boeing Company's Phantom Works.

NASA's last major effort in hypersonic research was the National Aerospace Plane (NASP) program of the early 1990s, a project that attempted to incorporate multiple new technologies into a full-scale prototype and was ultimately canceled when the Air Force withdrew from the program. For the Hyper-X program, of which the X-43A is a part, the major objective has been to prove that the scramjet engine works in flight.

"NASP activity was the genesis for Hyper-X," Corpening explained. "People were trying to sell different projects and ideas for a couple of years after NASP ended. Dryden and Langley were instrumental in developing the flight test approaches. One idea that rose to the top was doing a sub-scale flight test."

Langley's Hampton, Va., facilities and the expertise of its personnel blazed the trail for many of America's scramjet milestones. Corpening said that it is there and at facilities like the Applied Physics Laboratory where many hypersonic design methods and tools were developed during the NASP program – through wind tunnel tests, computer modeling of system performance predictions, and a sea of analysis – but never flight tested and proven.

"Unlike past, larger hypersonic research vehicle concepts, the X-43A fit nicely in Langley's 8-foot-high tunnel," turning the experiment into a good selling point in the bid for funding from NASA Headquarters, he said. "This allowed for a direct comparison between a wind tunnel model and a flight vehicle."

Corpening said that, early on, a tremendous amount of resources went into ensuring a very stiff joint between the research vehicle and the adapter required by the launch vehicle control system. He added that the biggest challenge was probably figuring out how to separate the research vehicle from the adapter-booster combination while flying at Mach 7.

Project officials conducted an extensive search of the country to locate anybody with experience separating vehicles at X-43A speeds and conditions, to no avail. Complicating the flight planning was the irregular shape of the X-43A. It was an engineering feat that had never been attempted.

Corpening said the team met in 1997 to examine options. One option considered was to boost the vehicle into orbit, where the atmosphere is thin and forces are low, detach the testbed from the booster there and then fly it back to the Mach 7, 100,000-foot test point required for the scramjet experiment. Engineers investigated this option seriously but determined additional thermal protection would be needed for re-entry. Since the vehicle's outer shape could not be changed, however, the need for added protection would mean a correlating reduction in the testbed's internal volume; there was no way to do this effectively, he said, so the option was scrubbed.

Another option that was studied extensively was to rotate the forward part of the adapter immediately after separation so that it was out of the research vehicle's way. Engineers thought this would minimize chances of the research vehicle coming back into contact with the adapter as the vehicle flew away from the booster. Extensive wind-tunnel testing, however, revealed that this approach produced large forces on the aft end of the vehicle that would cause it to

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EC04 0027-74 NASA Photo by Tony Landis

Crew chief Mike Bony, center, talks with Joe Kinn, as Dyncorp's Charlie Nichols, at left, completes another task on the day of flight.

EC04 0091-36 NASA Photo by Tony Landis

EC04 0027-18 NASA Photo by Tony Landis

Above, from left, Boeing employees Travis Findley, Patrick Briney and Duoc Tran prepare the X-43A research vehicle. At left, instrumentation technician Casey Tull and Joe Kinn, right, ready the vehicle for flight.

EC04 0029-18

The NB-52B flies a captive-carry mission with the X-43A "stack" comprised of the modified Orbital Sciences

Preparing for Su

By Jay Levine
X-Press Editor

Before the X-43A headed into the skies to make history, crews worked around the clock – sometimes in gusts exceeding 60 mph in the early hours of the morning – to prepare NASA B-52B and its under-wing payload.

NB-52B mothership preparations and those for the "stack" are complex. The stack, comprised of the Orbital Sciences Pegasus booster rocket with the X-43A testbed on its nose, is attached to an adapter under the wing of the NB-52B. The round-the-clock preparation procedure is split into two 12-hour shifts and begins on Monday of flight week to ensure everything is ready for Saturday's mission.

Tasks are time-consuming and require patience and caution. The handoff from day to night crews and back again is like the passing of a baton in a relay race – the footing must be firm, the motion perpetual, and the right steps are essential along the path in order to claim victory.

Volumes of details and procedures leading to the day of flight rival the thickness of a good encyclopedia set. Here's a condensed look at the Monday-through-Friday schedule, with special emphasis on the cold night before the history-making event and the day the X-43A flew.

Monday

The rocket and vehicle are housed in Vehicle Assembly Building 4847, near the Dryden dispensary. X-43A preparation is complete and the stack is ready to be mated to the NB-52B.

"The B-52 is parked diagonally on the ramp with the nose pointed toward the lakebed; the airplane is level, with plumb bobs hanging off the center hook on the pylon," explained crew chief Michael Bondy. "We draw a chalk line to 100 feet past the airplane. Pylons are 10 feet to 12 feet in the air, so we put a mark on the ground to show where we need to bring the trailer to line up under it. It's not real forgiving. You have to be pretty close when you pull under that pylon to mate (the stack to the pylon)."

What comes next is the kind of thing that keeps antacid makers in business.

"The crew 'airs up' the struts so there are about 12 inches of struts instead of two – that's to give us enough height so when the rocket comes underneath, the wing of the X-43A misses the rear landing gear doors and the vertical tail of the Pegasus will miss the B-52's horizontal stabilizer. You're talking about inches. Then we shore up the wingtips and hope the winds stay steady. We can mate (the stack and the NB-52B) in 10- to 15-knot winds, depending on the direction of the wind, but we can't mate in 20-knot winds," Bondy said.

There's no time for respite in the process, as day melds into night and the next shift takes over.

"Their big job for the night is to move the rocket and X-43A combination to the flight line," Bondy said, noting that the procedure involves opening gates and stopping traffic so is best suited to being an evening activity.

Tuesday

Following a safety meeting, it's time to begin the mating process. Safety briefings are common before any procedures begin; briefings allow mission leaders to clearly define who's doing what in order to eliminate confusion during execution of the tasks. Pre-mate checks, consisting mostly of instrumentation checkouts, ensue after the stack on its trailer is situated underneath the pylon and elevated to where electronic connections between the vehicles can be made. I
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NASA Photo by Carla Thomas

egasus booster rocket and the ATK-GASL X-43A research vehicle.

EC04 0027-28 NASA Photo by Tony Landis

Above, the ATK-GASL X-43A is attached to the modified Pegasus booster rocket. Here, the booster hangs on hooks from the NB-52B aircraft that air-launched it into the hypersonic realm. Below, from right, Winnie Chen (Boeing), Pete Hogenson (Boeing), Noah Risner (ATK-GASL), Larry Berger (ATK-GASL) and Patrick Briney (Boeing) are at work on the X-43A leading-edge thermal protection system.

EC04 0086-15 NASA Photo by Tony Landis

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can then be mated ly.

ke your time, have the chalk t, position the stack, bring it and keep it in line, it's not so / said. "But you can't bring it . If you miss by an inch, you (the trailer and stack) out and can take three hours or up to Closing the hooks on the ıckles takes a matter of t's the preparation to get to ınd the electric checkouts ıd after it is mated ly (that is time-consuming). 's always giving a sigh of all the hooks are closed and is hung."

y, Thursday and Friday

ıtack and bomber mated, the ıys involve inspecting and ıechanical, electrical and mission-critical elements at Delta, the area near the runway where the checkout of the NB-52B and the stack are performed. Delta essentially becomes a large campsite that is set up and staffed until the NB-52B returns from the mission. Enormous hoses, cables, tanks, equipment, tools, ladders, power units, stands, air conditioners and a daunting list of other materials are assembled to assist the crew that will be on site around the clock until the mission is complete.

Instrumentation, control room interface, avionics and other procedures begin as the vehicle comes ever closer to taxiing. ATK-GASL's Dale McKill completes work with thermal protection panels and is on hand to assist in the handling of those sensitive elements of the X-43A. McKill also assists Dryden mechanic Joe Kinn with other mechanical

See Preparations, page 8

EC04 0091-09 NASA Photo by Tony Landis

Clockwise from left, Jake Vachon, Charlie Nichols (Dyncorp), Casey Tull, Dale McKill (ATK-GASL), Monte Hodges and Joe Kinn work on the morning of flight day to wrap up preparations for the X-43A team's history-making mission. Although the night crew had endured a cold, windy shift, their replacements arrived the next morning to an operation that was on time and moving smoothly toward take-off.

EC04 027-59 NASA Photo by Tony Landis

ATK-GASL's Dale McKill, left, and Dyncorp's Charlie Nichols seal up one of the panels on the modified Orbital Sciences Pegasus booster rocket. These close-out tasks on flight day were among the last before the aircraft taxied out for a successful March 27 mission.

EC04 091-23 NASA Photo by Tony Landis

From left, Dryden propulsion lead Tom Grindle, Dale McKill, Joe Kinn and Jake Vachon begin final preparation of the X-43A for its groundbreaking flight to Mach 7. X-43A team members worked around the clock to insure readiness on flight day.

Preparations ... from page 7

elements of the mission as systems and instrumentation teams complete their assignments.

To "seal" the panel screw holes in the testbed following the panel installation, Boeing employees apply what Bondy refers to as "pancake mix" to the half-inch-deep holes that are about an inch in diameter. Once the holes are filled, workers carefully sand and glaze the surface so that filled spots match the areas surrounding them. Then the surface is allowed to cure overnight, ensuring that thermal protection is even in flight. Once the sealing work is complete, the night shift crew can start fueling and address any "squawks" – troubles identified by the day crew – about any of the vehicles.

A cold night

Herman "Chico" Rijfkogel is the nightshift crew chief. He reads and drives the procedures for the 10- to 12-hour fueling process – 10 to 12 hours, that is, if all goes well. To complicate matters, a steady 20- to 25-mph wind and gusts up to 60 mph welcome the night crew.

"We do the servicing of the vehicle in the evening with the use of a fuel servicing cart," he explained. "The fuel cart monitors vehicle systems, pressures and temperatures. Normally, everything is fine, but as evening approached the wind started to blow and the servicing cart started to move, making it difficult to use without people holding it. Dane Lariosa started adding 25-pound shot bags to the cart until the cart was stable."

Rijfkogel said he could not recall an instance where such a move was necessary during preparation for a research mission. Wind and cold, however, did not hinder the crew's resolve.

"Practice and procedures were specific and we were ready for anything. In fact, we did the procedure with zero red line," he said, meaning that no major complications arose.

"When we came in, the wind was supposed to let up. But it started kicking up and lasted all night. We later found out that the winds died down a half hour after we left (the next morning)," Rijfkogel added.

"Anyone involved with the fueling operation is required to wear a Nomex fire-retardant suit and gloves due to the presence of a fire hazard. Many of us had to throw on an extra jacket underneath to stay warm," he said.

The winds notwithstanding, crew members Steve Robinson and Ken Wilson work the line hookups and perform leak checks. At the same time, Jerry Cousins runs four nitrogen purges to clear oxygen from the lines. Trucks are used to keep nitrogen flowing, especially in the cavity (the interior of the X-43A research vehicle), so no oxygen will settle in those areas.

EC04 091-118 NASA Photo by Tony Landis

The NB-52B crew on mission day included, from left, Orbital Science's John Pomroy, Dryden chief pilot Gordon Fullerton, co-pilot Dana Purifoy and flight engineer Dave McAllister.

Systems for the X-43A and the NB-52B are checked using inert gases during the week because substances required for flight – many of them hazardous – must be carefully pumped into the aircraft. The systems, which previously have been pressurized with nitrogen, now are pressurized three times with actual fuel to guarantee the absence of nitrogen and that the system is prepared as procedures dictate.

Lariosa and Randy Wagner monitor the 'D-com,' or decommutator, which translates instrumentation data into information technicians can read about such elements as fuel and pressures. Clint St. John does the work of three people that night due to a personnel shortage on his shift, acting as fuel servicing cart operator, propulsion engineer representative and operations engineer.

Night crew members also include ATK-GASL's Shannon McCall and Eddie Pool and Dryden's Gary Pacewitz and Ron Wilcox.

Day of flight

Despite a difficult evening, everything is uncharacteristically on schedule. Charlie Nichols, Dyncorp, and Casey Tull begin day-of-flight avionics and instrumentation checks, while Art Cope takes over nitrogen operations. Kinn also checks for mechanical issues that could hinder aircraft departure.

"There's always a bunch of things that come up and all the procedures have to be signed off in something we call the 'Big Book,'" Bondy said, adding that Dale Edminister assures that the procedures are complete.

Dan Bain, Jeff Doughty, Monte Hodges, Rich Young and Dyncorp's Larry Harper are in charge of maintenance, servicing, preflight activities and clearing the squawks.

Orbital Sciences mechanical lead Burt Nelson and mechanical engineer Ed Silvent remove the yellow raincoat, or blanket, on the rocket booster used to keep it at 72 degrees F. The rocket's fuel is the texture of road tar. Air conditioners are hooked up to the booster, and hot or cold air is pumped in to keep it at operational temperature. Temperature changes in propellant will cause it not to burn according to predictions, which could jeopardize the flight, Bondy said.

Bruce Wise, Kay & Associates, assists with this part of the process. Wise is involved in ground support activities such as monitoring of equipment like the air conditioner for the Pegasus rocket and fuel temperature. Jeff Lloyd, also of Kay & Associates, is the day shift representative.

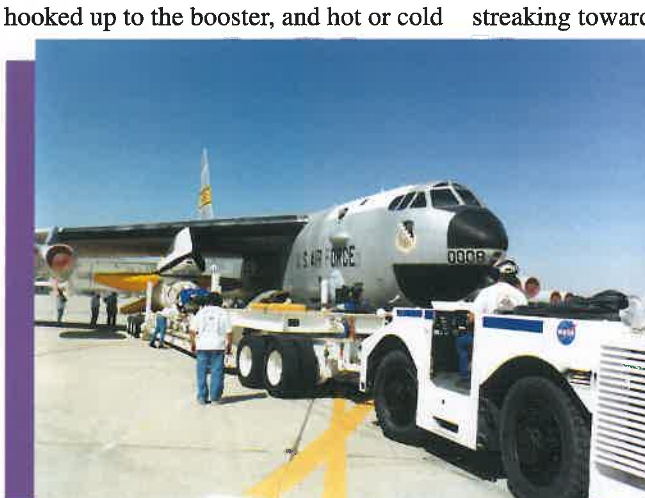
Protective covers are removed from the carbon-carbon leading edges of the X-43A. The surface was examined carefully hours before and then re-covered until now – the final stage of flight preparations. Hoses and power lines are disconnected and final panels are closed up, including a main panel on the rocket booster that is a three-eighths-inch-thick aluminum panel sealed both with bolts and RTV, a rubbery sealant.

When Mission Control is ready, NB-52B pilots arrive and preflight operations continue. The mothership's engines are started. Crew members continue to clear unnecessary tools, machines, hoses or other non-critical items from the area.

Once the research aircraft and its payload begin to taxi, the maintenance crew's work is done until the NB-52B returns. Most of the equipment remains; when the aircraft returns – or the mission aborts – the crew can quickly hook everything back up.

Before the aircraft heads down the runway, maintenance crews take another look at the aircraft in an area called, appropriately enough, "Last Chance."

The ground shakes and the air behind the gigantic aircraft is distorted by the heat and exhaust of the engines. The NB-52B builds speed as it rumbles down the runway and lumbers into the sky, streaking toward its date with destiny.



The stack consisting of the X-43A and the Orbital Sciences booster rocket are lined up to be hung from the hooks of the NB-52B.

EC03 252-34 NASA Photo by Tony Landis

Practice makes perfect

Using the art of simulation, Mission Control staff gets ready

By Sarah Merlin
X-Press Assistant Editor

On flight day in Mission Control, practice makes perfect.

Or, more precisely, practice makes "prepared." When it's show time for a mission like the X-43A, Mission Control staff members know they're ready because a rigorous series of simulation runs has helped them get that way.

A staple of every mission at Dryden is the process through which project managers, engineers, technicians, ground and flight crews develop a game plan for day-of-flight activity. Before research aircraft ever leave the ground, everything possible is done to familiarize the entire team with mission protocols – and to de-fang the element of surprise.

By the time the NASA B-52B carrying the X-43A stack left the runway, mission crew members had undergone as many as eight simulation drills over a period of months. The idea, according to Dryden lead operations engineer Brad Neal, is to avoid getting into any situation where something goes wrong and someone in Mission Control has to say, "Can somebody help me here?"

While it's not possible to predict the specifics of every potential problem, Neal said, it *is* possible to have procedures in place that will enable mission staff to address problems efficiently. During months of roundtable discussions, mission controllers develop a system of handling activity at every stage of the mission no matter what unexpected events crop up.

"We have a series of emergency procedures where we've sat down as a team and said, 'These are the things that could go wrong, and this is how to deal with them,'" he said. "We make sure we've molded a team that's working as one big unit; who makes what calls, how everything's to be done in a timely fashion – the idea is that, whatever it is that's happening, everybody knows what their role is and that everybody gets the right info at the right time" to address situations as they might arise.

ED04 019-10 NASA Photo by Tom Tschida

From left, Tony Kawano, Brad Neal, Griff Corpening, Joel Sitz, Dave Dowdell, Jessica Lux, Bill McMullen and, top left, Paul Lundstrom (Spiral Technology) monitor a captive-carry flight of the X-43A. The captive flight is a dry run in which researchers perform every step and procedure as if it were the actual mission, minus air-launching the research vehicle.

It's a big job, considering the amount of information being monitored.

With the X-43A's second flight, two NASA control rooms full of engineers and technicians plus personnel at Point Mugu Naval Air Station and Vandenberg Air Force Base collaborated to watch as the mission – in this case, virtually a picture-perfect one – unfolded. All told, some 1,500 types of data flickered across the banks of computer screens under the watchful eyes of Mission Control staff.

Some are responsible for range safety issues – ensuring that the designated path of the testbed's Southern California trajectory is clear from desert launch to splashdown at sea. Others oversee the telemetered research data streaming in from the NASA B-52B mothership, launch vehicle and research vehicle. Still others keep a weather eye on performance data about the vehicles' propulsion systems, structures, temperatures and pressures, and then there are the video streams coming from the chase plane, the NB-52B and the camera mounted on the X-43A's adapter. Radar data about the vehicles' ground and space positioning, location and altitude occupy another set of screens.

In such a detail-intensive atmosphere, and with so much at stake, adrenaline plays a significant role. But the simulation drills give staff the tools they need to allow calm heads to prevail. In mission-specific exercises created by engineers whose job it is to devise scenarios containing potential crises, the Mission Control team spends a substantial amount of time practicing the art of, well, mission control.

"Even during the sims, when there's no real hardware involved, it does get your blood pressure up," Neal admits. "Especially during the last minutes before launch. From about nine minutes on down, we're extremely busy.

"But that's one of the main reasons we run them – to familiarize everyone with that sense of urgency. Especially the new leads. For old hands, the Mission Control experience maybe isn't new, but there are different faces on every mission."

Newcomers use the simulation drills to master the efficient, compacted language patterns used in the control room, and to familiarize themselves with basic operational equipment like radios and headsets.

Above all, everyone has to know what it feels like to be ready, should the time come, to deal with an anomaly under pressurized conditions – a scenario in which the X-43A team thankfully never had to prove itself on the project's second flight.

Frontiers ... from page 2

booster's control system was identified as the root cause of the problem.

"Working with the caliber of people we have on this team has been great," Sitz reflected. "People kept the goal and significance of the goal as their focus, and stayed motivated. We knew it was going to be hard but that's why most of them – if not all of them – came to work for NASA. We had a really positive attitude and we started the accident investigation that afternoon. There were a number of challenges in terms of budget, but all the way up the chain people realized what we were trying to do was so significant – we were given the priority to continue and complete the program."

And despite the loss of the first vehicle, there were many lessons to be learned from its brief flight.

"From a technical standpoint, I think we relearned a lesson that we've learned time and time again for Dryden and for anyone who flies airplanes – you can't take *anything* for granted," Reukauf said.

"We treated the booster almost as if it were a commercial off-the-shelf item. We talked to (Orbital Sciences engineers), but we didn't ask many questions. We were not the experts on solid rocket boosters, and of course that's the part that broke. We flew (the booster) in a different configuration than it had been flown in before. So, why in the world did we treat it like an off-the-shelf item?

"In the end, all we can say is we shouldn't have."

Future

The next major challenge in the exploration of hypersonic flight is to demonstrate the transition from a turbine engine to a ram/scramjet engine in flight, in a reusable fashion, so it can be researched through multiple flights, Sitz said.

"We've established the last remaining piece of a combined cycle system that can get you from the ground to space in the most efficient way, and that's the scramjet. We know turbines work. We know ramjets work. We know scramjets work – now. We know rockets work. But nobody has ever put all four elements together in an integrated propulsion cycle. We need to start working on that part of that puzzle," he said.

Other steps could include more research with aircraft flying at Mach 4 and Mach 5, use of new materials that can withstand the heat of hypersonic travel and continuing current NASA research aimed at making hypersonic aircraft quieter and more environmentally friendly. Ultimately, technology developed and matured by NASA could provide the data a private company will need to build these aircraft for commercial use, Sitz said.

Until some of those questions can be answered, however, development of a hypersonic aircraft for use by the general public isn't likely to progress.

"If national leadership focused on using reusable vehicles to flight-validate combined propulsion cycle integration concepts we could get there sooner rather that later, but there (currently) are higher priorities," Sitz said.

While X-43A research represents significant progress, Reukauf said none of it resolves aspects of the problems related to manned aircraft. A materials revolution and acceleration of technology development are needed to safely transport people on these aircraft of the future, he said. For now, NASA is developing research tools and models designed to enable industry to accomplish this for future application in a commercial market.

While NASA grapples with the direction of its hypersonic research, the U.S. Defense Advanced Research Projects Agency (DARPA) could tap Dryden for assistance on some of its work in the hypersonic realm. Already a DARPA partner on the X-45 Unmanned Combat Aerial Systems project, Dryden officials are ready to assist the federal agency by sharing X-43A research data and the Center's systems integration capabilities.

The most promising hypersonic project in which Dryden could play a role, one tentatively slated for fiscal year 2005-06, is that of the Responsive Access, Small Cargo Affordable Launch, or RASCAL.

As envisioned, the RASCAL testbed would be an F-15-sized vehicle with a reusable first stage that uses an aircraft engine with mass injection pre-compressor cooling. Using a modified F-100 turbojet propulsion system to power the first stage, the vehicle would launch small, low-cost orbital satellite payloads. The goal of the project is to cool air before it enters the engine's compressor as a means of preventing the blades from melting, which would allow the aircraft to retain structural integrity while providing power sufficient to reach Mach 4 and 100,000 feet.

Readying for Flight 3

By Jay Levine
X-Press Editor

Among its many accomplishments, the record-breaking X-43A flight helped validate research models and tools for designing hypersonic aircraft and systems. It also provided valuable lessons that the X-43A team members will draw on when they venture into the unknown once again this fall, hoping to reach Mach 10 in another flight.

Having two flights under their belt and a working familiarity with the people and procedures on the project will enhance the team's experiences with a third X-43A. But significant challenges lie ahead.

"The biggest concern is that in the course of testing we damage something, or something will go wrong. That's the kind of thing that can hurt us the most," said Laurie Marshall, who was launch vehicle chief engineer on flight two and will serve as Dryden's X-43A chief engineer for flight three.

The team learned many lessons from the first two flights. The first X-43A flight, on June 2, 2001, was lost moments after release from the wing of the NASA B-52B. Initially, the project team was stunned.

"(The) flight one (mishap) was so unexpected – there was no reason to believe that we would find ourselves in the situation we found ourselves in," Marshall reflected. "To be in the control room and watching the flight and watching the data was overwhelming. It was a complete surprise."

However, from the disappointment and ensuing mishap investigation the groundwork for flights two and three was built, while the vehicles were simultaneously being prepared. Better interdisciplinary communication was refined as more independent analysis and a solid training program were developed, Marshall said. In overcoming flight one's challenges, the success of the second flight was that much sweeter.

"(Flight two) had an even larger impact for all of us because we lived through flight one and lived through the mishap investigation and did all this work toward a success. But at the same time we were doing all of that (preparation for flight two), we were thinking that we felt really good *before* (on flight one) – we thought we did everything that needed to be done, but was there something else to do? We didn't think so," Marshall said.

With flight two safely in the rearview mirror, the team is now focused, laser-like, on the third flight.

"With the flight data (obtained in flight two), we might not have to look under every rock before flight three. We'll use a trajectory very similar to flight two, with a little extra to get it to the test conditions. People are aware of the shorter time frame and are working with due diligence," she said.

ED04 019-16 NASA Photo by Tom Tschida

Above, from left, Ross Hathaway (partially hidden), Jake Vachon and Tom Jones watch monitors at the propulsion station in Dryden's gold control room during a captive-carry flight of the X-43A. Below, clockwise from lower left, Casey Tull, Jerry Cousins, Noah Risner and Randy Wagner work on an X-43A vehicle.

NASA Photo

Control Laws

One challenge with the next flight is designing new control laws to drive the third X-43A, the first time in five years the team has focused on that issue. To that end, information gathered on flight two will assist in refining models used to develop the control law software. That's where Dryden flight control lead Ethan Baumann's group comes in. Cathy Bahm, flight control lead on flight two and currently Dryden's X-43A deputy chief engineer, summed up the work ahead.

"Our challenge is getting the updates for the controller and guidance in the time we have. With the compressed schedule, we need them quickly. We need to develop and test the new control laws and make sure they're robust," Bahm said.

Engineers at Langley are responsible for the separation of the X-43A from the rocket booster, so the focus for Dryden's flight controls group is control of the vehicle at Mach 10 and during descent.

"We're hoping the vehicle control performs as well or better than (it did on) flight two and that during descent we can do maneuvers to validate our models," Bahm said.

Baumann noted the critical roles played by Ray Dees and Jeanette Le in the simulation process used to develop flight controls.

"They're the simulation experts," he said. "They integrate each IPT's (integrated product team) models into the sim and make sure all of the pieces work together. The sim is then used for mission analysis, training and hardware-in-the-loop testing. We couldn't do our job without the simulation, and Dryden's simulation wouldn't be the same without them," he said.

From the first two flights, the X-43A team drew lessons in the value of good models on which to base flight controls and analysis. And flight two delivered hangars full of data, some of which will be used to validate models and enhance the third flight.

Structures

At the same time, Tom Horn, Dryden's X-43A structures lead, said his team works to ensure that the NB-52B and the stack containing the modified Orbital Sciences booster rocket and the X-43A research vehicle are structurally ready to perform the mission. Horn's team monitors issues such as stack weight, research vehicle and booster thermal protection and loads on the NB-52B hooks from which the X-43A hangs.

Three high-temperature strain gages capable of withstanding 1,500 degrees Fahrenheit will gather structure data about the vertical tail for the higher-temperature Mach 10 flight, Horn said. The vertical tail is made of solid Haynes (a high-temperature metal alloy capable of withstanding temperatures of up to 2,400 degrees Fahrenheit) and carbon-carbon that can withstand up to 3,000 degrees Fahrenheit.

Flight one issues required additional testing. Engineers incorporated modifications resulting from those tests simultaneously onto the second and third X-43A vehicles. As a result of data gained, much of the testing required to validate the structure for flight already is complete on the third testbed.

"We just reviewed the temperature model and it certainly validated a lot of our design philosophy. In many cases, we predicted trends pretty well. Now, Langley researchers are going to take the X-43A trajectory through predictive tools and tell us how close we were," Horn said.

One of the unique things about the program is the breadth of technology it incorporates, he added. Technologies ranging from the 50-year-old aluminum-and-rivet NB-52B to carbon-carbon and Haynes hot structures on the X-43A are used. Somewhere in between is the graphite and epoxy rocket booster, he noted.

Propulsion

When the subject is X-Plane propulsion, Tom Grindle, Dryden's X-43A propulsion lead, said his team members are the go-to guys. Their work amounts to mimicking on the ground what the engine will experience in the sky – to minimize surprises.

Before the research vehicle is ready to fly, the leak and functional testing, combined systems testing and captive-carry flight can eliminate some of the unknowns. And for flight two, relevant procedures had been re-written six or seven times for maximum efficiency in carrying them out, Grindle said. That means things are in good shape for flight three.

But, "Even with our flight two success, we can't become lax in following our procedures and safe practices," he stressed. "We want to remain diligent – we want to be sure that procedures are followed and we don't miss something."

After enjoying a success, he said, " you have to remain observant to make sure everything is the way it should be and the way we want it to be."

Aerodynamics

With flight three ever closer, Mark Davis, Dryden's X-43A aerodynamic lead, said his team is anxious to add to the hypersonics database for validating models and tools for future aircraft.

"Unless we model the right things, we might not get the right answers," he said. "After two flights, we have a good idea of what we're looking for in the X-43A data. This data is important because there's not much information at these higher Mach numbers and because wind tunnels can't match all of the physics as seen in flight. We'll rely on data from flight two to validate our models so we can have more confidence in using our models for the third vehicle.

"Our research partners at Langley performed a number of wind tunnel tests to develop the aerodynamics models used for the test vehicle," Davis continued. "The flight data collected by Dryden was then used to validate the wind tunnel data. Computational Fluid Dynamics, or CFD, used the information from the wind tunnel and will use the flight data provided by Dryden, to validate their models. These models from CFD will be used to develop future hypersonic vehicles."

Also a success was the Flush Air Data System, or FADS, which gathered air data – the condition of the vehicle in flight – for models developed and used by controls and systems engineers. The beauty of the FADS, developed by Dryden researchers, is that it eliminated the need for a pitot tube, a device used to collect air

See Flight Three, page 12

X-43A Team

EC04 093-01 NASA Photo by Tom Tschida

Realm ... from page 5

Dryden and Langley had already gotten involved with a Russian scramjet project. In late 1990, Russian aerospace leaders visited several NASA centers, including Dryden, and the director of the Central Institute of Aviation Motors in Moscow extended an invitation to Dryden's John Hicks to take part in a joint effort to do flight research on the Russian experimental scramjet project. The invitation finally led to a formal contract in which NASA provided $1.8 million for a redesign of an existing Russian scramjet engine that had flown to Mach 5.5 and 5.35 in two previous tests aboard an SA-5 high-altitude surface-to-air missile without achieving full supersonic combustion. The contract also called for modification of the SA-5.

Dryden managed the program for NASA with Langley providing analytical support. The project had an interesting connection to the X-15 in that the scramjet engine was a takeoff of the Hypersonic Research Engine (HRE) that Langley had developed and intended to fly on the X-15A-2. This was a scramjet design that never actually flew, but a dummy HRE flown on the Mach 6.7 flight of the X-15A-2 caused severe heating from a little understood shock wave interaction with the boundary layer, damaging the lower empennage of the aircraft severely. Tunnel testing of the engine achieved supersonic combustion but with a drag penalty that exceeded the thrust produced. The Russian engine produced less drag than the HRE but benefited from its data and design. On February 12, 1998, it flew on the improved SA-5 from the Republic of Kazakhstan and reached a speed of Mach 6.48 while operating for 77 seconds.

Australia's University of Queensland personnel performed another significant scramjet test program called HyShot. On July 30, 2002, they achieved a successful launch of a Terrier Orion Mk 70 rocket containing a scramjet payload at the Department of Defence's Woomera Instrumented Range, 500 kilometers (about 311 miles) north of Adelaide, in the South Australian desert. The aim of the HyShot program was to provide in-flight tests of scramjet technology, validating experiments held in ground test facilities. The HyShot launch was designed to take the scramjet engine to a speed of Mach 7.6 for the experiment. The rocket and payload reached an altitude of 314 km (about 295 miles) before the rocket was configured to fly in a new trajectory pointing the payload back toward Earth. The flight experiment took place within only the last few seconds of the flight.

Illustration Courtesy Langley Research Center

This graphic illustration shows the separation of the X-43A from the Pegasus booster.

For this test two identical scramjet engines were flown side by side, one fueled and one not, so that a direct comparison could be made between powered and unpowered operation. Post-flight data analysis indicated that supersonic combustion had been achieved and the Australians have shared their data with the international scientific community for peer review.

What the Russian and Australian tests did not provide was information about airframe interference and interaction with the scramjet engine. However, the PHYSX experiment did provide information on forebody transition from laminar to turbulent airflow that was useful to Hyper-X. Additionally, Dryden's experience with launching Pegasus from the B-52 provided the basis for the X-43 operational concept. The pylon used to launch the X-15 is used with an additional adapter to launch the X-43A. Computer codes used to design the X-43A benefited from aerodynamic and aerothermodynamic data gathered on the hypersonic vehicles and projects already discussed (X-15, shuttle, X-30, Pegasus, PHYSX and the Russian scramjet).

The first X-43 launch attempt occurred on June 2, 2001,with drop from the B-52 at approximately 0.5 Mach number and 23,000 feet. The drop and Pegasus ignition were successful but control was lost eight seconds after ignition, causing the loss of the vehicle. Two and a half years of investigation and changes to the Pegasus followed the accident. The launch profile also changed, with the drop now taking place at approximately 0.8 Mach number and 40,000 feet.

The loss of the first X-43A underscores the inherent risk of flight research. Exploration of the unknown carries with it real and great risk of failure, as illustrated in events from the death of Otto Lilienthal in an 1896 glider crash to the loss of the Space Shuttle Columbia and its crew during re-entry in 2003.

Fortunately, on March 27, 2004, the Hyper-X team overcame these risks and successfully flew the X-43A to a speed of Mach 7. Launched by the B-52 and propelled to roughly that speed by the modified Pegasus rocket, the unpiloted X-43A separated from the Pegasus and operated on its own for a short period, burning its hydrogen fuel in its supersonic combustion ramjet engine. The Mach 7 speed marked a record for air-breathing flight. More important, the vehicle gathered propulsion, aerodynamic and other data that could be critical for further development of technology for use in future air and spacecraft. As such, Hyper-X continued Dryden's distinguished record of research flight, including work involving hypersonic research. It also continued a long tradition of successful collaboration between Dryden and Langley research centers dating to Langley's important involvement in X-1 flight research in the 1940s that led to the first known supersonic flight by Air Force pilot Chuck Yeager in a joint project with Dryden's predecessor, the Muroc Flight Test Unit.

X-43A deputy project manager Paul Reukauf and Dryden historian Curtis Peebles contributed to this article.

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pressure data, which would melt at hypersonic speeds.

Instrumentation

For the aerodynamics group and many others, the role performed by Dryden X-43A instrumentation lead David Dowdell and his group is a vital one. Without accurate data collected by the instrumentation, Dowdell said, "there wouldn't be anything to analyze." So, Dowdell and his team are careful to make sure they come through with the required data and then communicate clearly with researchers at Langley, ATK-GASL and Boeing who are waiting for the data stream to commence.

"We have a couple of extra, unique research sensors positioned near vehicle three's engine that we didn't have on flights one and two – skin friction and heat flux gages for the propulsion folks," Dowdell said.

Trong Bui, a propulsion engineer, explained the new sensors.

"Skin friction gages measure the wall shear stress on the engine wall surface and the heat flux gages measure the heat transfer rate to the engine wall. We place the sensors in the internal nozzle section on the research vehicle body side," Bui said.

Two skin friction gages are located on the starboard side. The heat flux gages are directly across from the skin friction gages on the port side. Measuring the skin friction and the heat transfer simultaneously allows researchers to deduce what's called a Reynolds Analogy Factor – the ratio between the skin friction and heat transfer rate, important in aerodynamics. When one of those numbers is known the other can be determined. Skin friction measurement helps researchers determine the amount of skin friction drag, which can be significant at hypersonic speeds.

"I'd like to see how big a force that (skin friction drag) is," Bui said. "That would be the first time that will have been done in flight; it's been measured in wind tunnels for the last 20 to 30 years. In flight, we could use the data to verify models and tools for the next hypersonic vehicle."

Flight Systems

Everyone knows their roles and all are ready to make some more history with the third X-43A flight, said Matt Redifer, Dryden X-43A flight systems lead for flight two. Yohan Lin will handle those duties on flight three. The experiences of the first two flights set the stage for success on the third.

"For flight systems, our main mission-success objective was to design a sequence of ground validation tests for the launch vehicle, the adapter – including the separation system – and the research vehicle that would give us the highest probability of success without taking too much time, breaking the bank or damaging the flight hardware," Redifer said.

Lessons from the first two flights will impact preparations for the next flight.

"We added additional systems tests, performed really in-depth analysis on the test results and created high fidelity models," he said. "The best thing we learned from flight two is that persistent, meticulous attention to the details is the recipe for success."

Corpening ... from page 5

pitch downward and into uncontrollable flight. This option too was discarded. In the end, engineers opted instead for a process of simply "pushing the two vehicles away from one another" at as fast a rate of speed as possible, he said.

When the first of the program's three research vehicles arrived at Dryden in October of 1999, the challenges facing engineers had morphed from those of paper airplane theory into those involving the actual hardware of a small hypersonic aircraft with unique systems that required testing and integration. Corpening said some of the more formidable challenges could not be foreseen or dealt with until the vehicle had arrived and engineers could begin validation testing of the various onboard systems.

"I look at this vehicle as more like a Ferrari than a Ford pickup that you can beat to death," Corpening said. "Because of volume constraints and mission requirements, and (in order) to capture the data we need, all the systems are highly optimized and customized to our needs. There isn't a whole lot of room for error."

By the time the second vehicle arrived in February of 2001, Corpening said many of the lessons learned through construction and flight of the first X-43A had been incorporated by the manufacturer. However, the first flight failure caused the team to re-examine all elements of the research and launch vehicles.

The team reviewed all the computer models and databases used to design control laws for both the launch and research vehicles, and conducted more wind-tunnel testing to validate changes for flight two. When the Mishap Board made its final recommendations, the team then put together the return-to-flight plan.

Corpening said the mishap was obviously very difficult for the team. Many had worked on the project for years and made significant sacrifices, including extended time away from their families. But the disappointment led to a collective resolve to identify the problems and fly again.

For the second flight, he said, major changes included removal of propellant from the booster since the vehicle would be dropped at an altitude of 40,000 feet instead of 23,000 feet, as it was in the first flight, requiring less propellant. This would allow the launch vehicle to fly a trajectory that more closely resembled that of a standard Pegasus booster rocket, reducing the forces and moments on the launch vehicle fins.

A second motor was added to the fin actuation system to give it added torque capability. Numerous other modifications also were made to help mitigate the still inherently risky project.

With the successful second flight under the team's belt, Corpening said the historical significance of the flight has yet to be realized. "The importance of the Mach 7 flight scramjet test could turn out to be one of the major events in present-day flight-testing and research," he said.

Ultimately, he hopes the experiment will lead to more efficient space access vehicles. But he says that in addition to a potential lack of funding, other major challenges for future scramjet operations include development of a thermal management system necessary for the high temperatures the vehicle encounters and achieving a thorough understanding of the engine's operability under a variety of conditions. To really understand scramjet-powered airplanes, Corpening said, the ideal would be development of a reusable vehicle similar to the X-15.

"It's an outstanding team," he said of those who have brought the project this far. "They have all done exceptional work, down to a person. It's an honor and privilege to work with them."

As the project prepares for its last flight, Corpening hands over the chief engineer baton to launch vehicle engineer Laurie Marshall, who will oversee preparations for the Mach 10 flight. Corpening will remain on the project as senior advisor.

A song for the unsung heroes

This special edition of the X-Press is possible thanks to Dryden X-43A Project Manager Joel Sitz and PACE Chief Michael Gorn. Thanks also go to Dryden's partners at Langley Research Center, Hampton, Va., ATK-GASL (formerly MicroCraft Inc.) based in Tullahoma, Tenn., The Boeing Phantom Works, Huntington Beach, Calif., and Orbital Sciences Corp., Chandler, Ariz.

Many people make the X-43A a success. Some of those who do not appear in the main text but who made important contributions are noted here. A special thanks to Keith Henry from the Langley Public Affairs office for compiling the Langley list of X-43A contributors.

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