

X-51A SCRAMJET DEMONSTRATOR PROGRAM: WAVERIDER GROUND AND FLIGHT TEST

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ABSTRACT

Supersonic combustion ramjet (scramjet) propulsion is a significant advancement in air-breathing propulsion technology. The X-51A WaveRider research vehicle recently set new aviation speed records by employing a scramjet engine in a specialized airframe designed to operate at hypersonic airspeeds. The X-51A was an unmanned scramjet demonstration vehicle designed and developed by the consortium of Air Force Research Laboratory (AFRL), Defense Advanced Research Projects Agency (DARPA), The Boeing Company, Pratt & Whitney Rocketdyne and the National Aeronautics and Space Administration (NASA) to meet the requirements of the United States Air Force (USAF) WaveRider program. The overall test objective of the X-51A program was to demonstrate a scramjet engine using endothermic hydrocarbon fuel, by accelerating a vehicle up to Mach 6+ after the vehicle was boosted to the altitude and airspeed conditions required for engine start. Four X-51A vehicles were built and flown, but only the fourth and final X-51A flight accomplished on 1 May 2013 was fully successful. On that flight the X-51A traveled more than 230 nautical miles in just over six minutes reaching a peak airspeed of approximately Mach 5.1 with a record-setting 210 seconds of air-breathing hypersonic flight. Overall, X-51A flight tests demonstrated the feasibility of an air-breathing scramjet-powered vehicle using hydrocarbon fuel. Flight tests showed the vehicle could successfully be boosted to reach the required conditions for scramjet engine start and the engine could sustain supersonic combustion during autonomous flight operations. The process of preparing to conduct X-51A flight tests was extremely meticulous, in part due to unique constraints of the X-51A test vehicle. This paper presents the attention to detail that was required for the proper planning and execution of X-51A flight tests.

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ACRONYMS, ABBREVIATIONS, SYMBOLS

AFB	Air Force Base
AFRL	Air Force Research Laboratory
ATACMS	Army Tactical Missile System
AVD	Air Vehicle Demonstrator
DARPA	Defense Advanced Research Project Agency
HDAIT	High Desert Assembly, Integration & Test
HSAB	Heavy Stores Adapter Beam
FAA	Federal Aviation Administration
FTS	flight termination system
MCR	mission control room
MSL	mean sea level
PF	powered flight
PID	parameter identification
NASA	National Aeronautics and Space Administration
Scramjet	supersonic ramjet (scramjet)
TM	telemetry

INTRODUCTION

The fourth and final flight of the X-51A Waverider Supersonic combustion ramjet (Scramjet) Engine Demonstrator program occurred on 1 May 2013. This flight was the culmination of a combined effort of personnel from the Air Force Research Laboratory (AFRL), Defense Advanced Research Projects Agency (DARPA), The Boeing Company, Pratt & Whitney Rocketdyne, National Aeronautics and Space Administration (NASA), and the 412th Test Wing at Edwards Air Force Base (AFB), CA. The X-51A was designed to achieve airspeeds of Mach 6+ and travel over 400 nautical miles. The vehicle's scramjet engine was fueled and cooled with JP-7 fuel. The X-51A was launched from a B-52H at an altitude of approximately 50,000 feet and 0.8 Mach number (1). All four X-51A launches were executed from Edwards AFB with the Hypersonic Combined Test Force (HCTF) as the Responsible Test Organization and the 419th Flight Test Squadron as the Test Execution Organization. The test team was presented with unique constraints and applied appropriate test discipline to ensure safe, efficient, and ultimately successful test execution. The X-51A test team demonstrated proactive planning, multi-agency integration, and precise mission timing to achieve four successful launches. The final flight was the most successful in terms of meeting the program's objectives. The X-51A traveled more than 230 nautical miles in just over six minutes, reaching a peak airspeed of approximately 5.1 Mach number with a record-setting 210 seconds of air-breathing hypersonic flight (2) (3).

TEST ITEM DESCRIPTION

The item under test was the X-51A Waverider Scramjet Engine Demonstrator. The B-52H Stratofortress was chosen as the launch platform in order to achieve the desired high-altitude release conditions. Both the X-51A and the B-52H (as configured for the X-51A launch) are discussed in this section.

X-51A

The X-51A program was designed to develop enabling technologies for producing scramjet engines fueled and cooled with hydrocarbon fuel. The air vehicle demonstrator (AVD) consisted of a cruiser, interstage, and a booster as shown in Figure 1 (1).

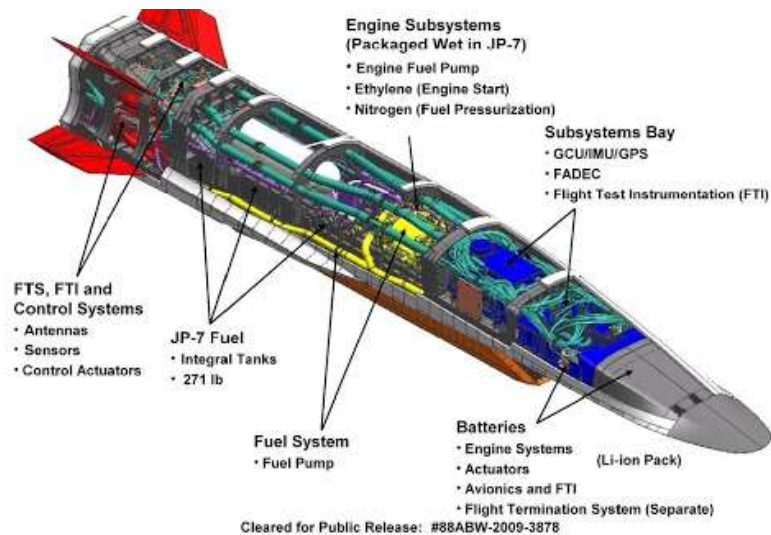


Figure 1 – X-51A (4)

The airframe was built by Boeing's High Desert Assembly, Integration & Test (HDAIT) division in Palmdale, CA, with the scramjet engine built by Pratt & Whitney Rocketdyne (PWR) mounted as a unit into the airframe. The actively-cooled Hypersonic Technology (HyTech) scramjet engine, integrated into the vehicle, used endothermic hydrocarbon fuel (JP-7). The X-51A was designed to be launched from a B-52H at approximately 49,500 feet mean sea level (MSL) and 0.8 Mach number, and accelerated to approximately Mach 4.8 by a solid rocket motor booster. The cruiser portion would then separate from the interstage and booster. Following separation, the scramjet engine would ignite and accelerate the cruiser to Mach number 6+ (1).

The X-51A was primarily composed of standard aerospace materials such as aluminum, steel, Inconel, and titanium. Some of the leading edges contained carbon/carbon composites. For thermal protection, the X-51A utilized a Boeing designed silica-based thermal protection system as well as Boeing Reusable Insulation tiles, similar to those on board the NASA Space Shuttle Orbiters. The X-51A was designed to be a non-recoverable demonstrator, and a total of four vehicles were built for flight test (1).

Booster

The booster was a modified Army Tactical Missile System (ATACMS) solid rocket that accelerated the stack to scramjet operation speeds before the planned separation. The booster had to be thermally conditioned prior to B-52H takeoff to mitigate propellant stress cracks that could have caused booster case rupture. Taking into account aerodynamic heating in addition to the thermal conditioning of the booster, the expected temperatures at the B-52H launch altitude were within the ATACMS design envelope (1).

Interstage

The interstage served as the adapter between the cruiser and the booster. The interstage provided suspension lugs for attachment to the B-52H. The interstage was responsible for the controlled separation of the interstage/booster unit from the cruiser at the conclusion of the boosted flight stage (1). The interstage featured flow-through ducts which were designed to allow the scramjet inlet to start during the boost, thereby providing aerodynamic heating for preheating the fuel prior to scramjet ignition. The interstage also housed the beta vane, which measured sideslip during the boost phase (5).

B-52H

In order to achieve the launch conditions for the X-51A, the test team decided to launch the X-51A from a B-52H Stratofortress as shown in Figure 2.



Figure 2 – X-51A mounted on B-52H (6)

In order to attach the X-51A to the B-52H, a MAU-12 ejector rack was mounted to a B-52H Heavy Stores Adapter Beam (HSAB) on the left wing. The orifices on the MAU-12 were selected to allow for minimal force on the ejection pistons, thereby producing a “near” gravity drop for the X-51A. Due to the weight of the stack, a non-standard fuel waiver was granted for the mission. The non-standard fuel load was among the issues that added constraints to the mission profile and limited flexibility during test execution.

MISSION PROFILE

An X-51A launch mission consisted of the following phases: B-52H take-off and captive carry to the Point Mugu Naval Air Warfare Center Sea Range, safe separation, boost phase, coast phase, engine experiment phase, and the descent phase concluding with vehicle splashdown into the Pacific Ocean (Figure 3).

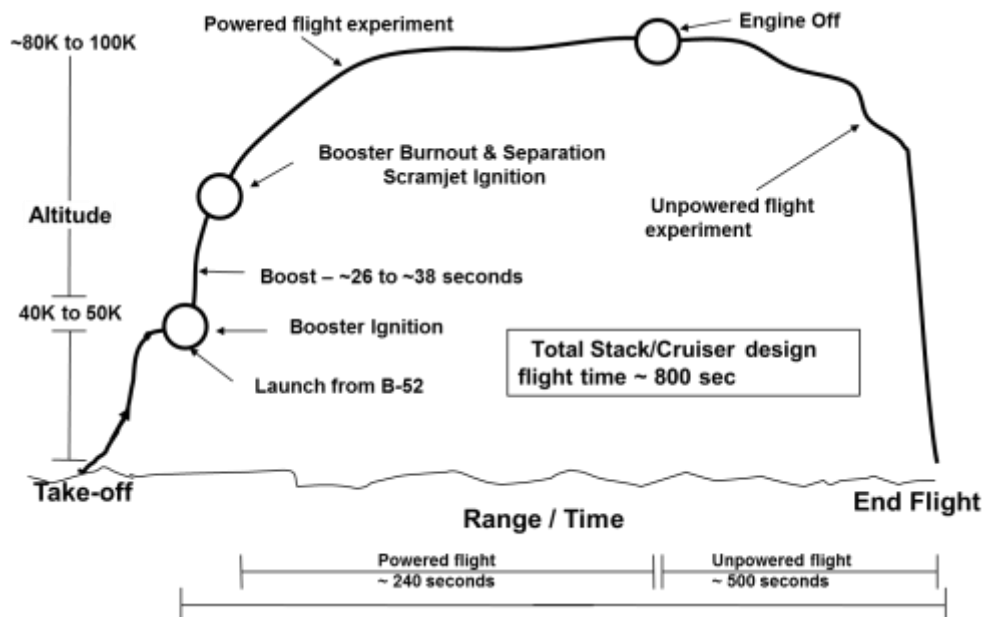


Figure 3 – Mission Profile (5)

Takeoff and Captive Carry to Point Mugu

Launch flight operations began with the B-52H taking off from Edwards AFB with the X-51A attached to the left wing. During the mated portion of the flight no data were received from the X-51A until approximately 24 minutes prior to launch because its avionics were limited to approximately 36 minutes of powered time due to lack of active cooling. Therefore, all checklists, test cards, and software were written accordingly. After release from the B-52H, X-51A telemetry (TM) was transmitted until the vehicle impacted the Pacific Ocean (5).

Safe Separation

Upon release from the B-52H, the booster fins were unlocked and a timer was started. The guidance and flight controls on the booster were enabled after release. Following separation, among the other vehicle actions taking place, the flight termination system (FTS) was armed and booster ignition was initiated. Also, after separation, as the AVD was directly below the B-52H, certain subsystem criteria had to be met within a certain time after the AVD release for the booster to ignite. (2).

Boost

The booster burns were planned to achieve airspeeds of approximately Mach number 4.8. During and following boost acceleration, the JP-7 fuel tank was pressurized and initiated fuel flow through the scramjet engine. The flight control system positioned the AVD for safe separation of the interstage/booster and the cruiser (5).

Coast

The duration of the coast phase was approximately 1 second. During the coast phase the TM transmitter was energized while the cruiser maintained attitude to remain within the scramjet engine start box. (5)

Engine Experiment

During the engine experiment phase, ethylene flow was started to the engine and the scramjet engine start sequence was initiated. Based on a timer started at separation, the cruiser began to roll to an upright position. Shortly after release from the booster, the scramjet engine transitioned from ethylene to JP-7. The engine experiment phase lasted approximately 240 seconds, including the 15 seconds for the engine start sequence. The engine accelerated the vehicle with the goal of achieving a final speed near or above Mach number 6. Once the engine experiment was complete (based upon estimated fuel flow), the engine was turned off (5).

Decent

Following engine shutdown, the cruiser entered a controlled descent phase where the fuel pump power and controller were turned off. Meanwhile, the ethylene and nitrogen tanks also bled down. During the descent phases of PF2, PF3, and PF4, aerodynamic parameter identification (PID) maneuvers were to be performed at Mach numbers 5, 4, 3, and 2. After almost 5 minutes of descent, the X-51A splashed down in the Pacific Ocean, approximately 340 nm downrange (7).

FLIGHT TEST CHALLENGES

Numerous X-51A-related issues raised significant challenges in designing B-52H mission profiles and timing. The challenges were in three main areas: profile constraints, airspace management, and mission control room (MCR) configuration and preparation.

Profile Constraints

The mission profile constraints were defined by the convergence of the requirements and limitations of both the X-51A and the B-52H. The challenges faced by the test team were unique from those faced in envelope expansion or regression flight testing. Figure 4 illustrates the concept of the difference from envelope expansion flight test.

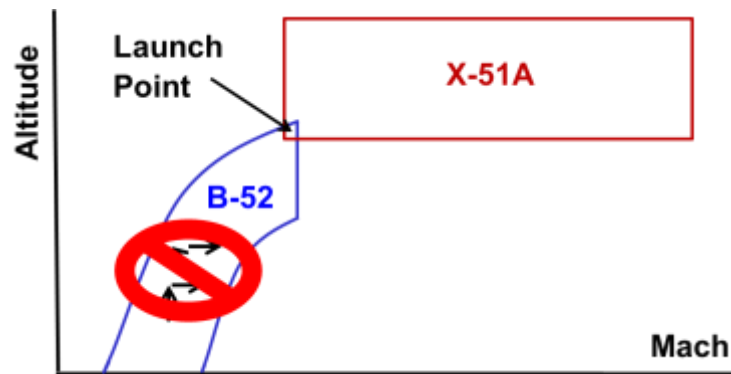


Figure 4 – Representation of the Relative Flight Envelopes

For this mission, the required launch point occurred at the minimal overlap of the flight envelopes of the X-51A and the B-52H. Therefore, the typical “build up and out” flight test approach would not be utilized for this mission. The areas of greatest challenge to the test team were in planning the time to climb, fuel management, maximizing profile proficiency, safety/photo chase constraints, and the limited time to assess X-51A health.

The preferred climb-out for the B-52H had to seek a balance between time to climb and fuel conservation, much like any other mission plan. However, the X-51A added constraints to both time to climb and the fuel planning. Due to the lack of active cooling on X-51A avionics, the time to climb had to be minimized such that the B-52H was at altitude, and on range, before the avionics overheated. The added weight of the X-51A also required a fuel load lower than standard operations, as well as asymmetric loading to account for the weight on the left wing.

The required launch conditions of the X-51A further reduced the flexibility of the B-52H aircrew to execute the mission. The direction, altitude, and speed of the X-51A launch window all contributed to a very small area in time and space where the conditions were satisfied. Due to the limited fuel and time available, only one “dry” run could be flown prior to the single opportunity for a live launch. If the aircraft was not on conditions, the X-51A would not be able to launch.

Due to the nature of the mission, a safety chase was deemed a requirement in order to execute a live launch. To fill the role of safety chase, the F-16s on Edwards AFB had the greatest availability, but were unable to meet some of the mission requirements. The test team decided to utilize F/A-18 and/or F-15B chase aircraft from NASA Dryden Flight Research Center on Edwards AFB. During powered flights PF1 through PF3, NASA F/A-18s were able to meet the demanding nature of the mission profile. However, due to maintenance availability, the lone NASA F-15B was the only safety chase available for PF4. Additionally, the health of the X-51A could be checked on the ground, but not again until on the Point Mugu range.

To mitigate all of the challenges associated with the profile, the test team developed a scripted timing sequence for all mission events and developed specific

training and mission rehearsal scenarios. Table 1 shows a nominal representation of some of the test events.

Time	Event
T/O – 02:30	Step to Aircraft
T/O – 01:45	Remove Environmental Plugs and Covers
T/O – 01:30	Control Room Manned
T/O – 01:20	Anticipated Green Range Call
T/O – 01:20	Remove Booster Heater Blanket and JP-7 Heating Equipment
T/O – 01:10	Engine Start
T/O – 00:35	Green Range Call / Step Chase
T/O – 00:30	Unplug Ethylene Heater
T/O – 00:25	Closeout X-51A/Pull Pins on MAU-12
T/O – 00:12	Taxi
T/O – 00:12	Chase Engine Start

Table 1 – Example Mission Timing Sequence

The scripted timing helped alleviate the time constraints by making obvious decision points. As much as possible, the test team moved the “no-go” calls to occur before takeoff. In order for certain no-go calls to be early in the mission, the test team had to coordinate with multiple agencies including NASA, Edwards AFB tower and airspace controllers, the Federal Aviation Administration (FAA) airspace controllers, and the Point Mugu range controllers. The test team also had to make decisions on critical tradeoffs. For example, in order to maximize the safety chase time on station, the safety chase actually took off after the B-52H. However, to ensure safety chase from start to finish, a separate F-16 conducted the safety chase duties during takeoff until the NASA aircraft were airborne. In order to ensure that the scripting had the greatest chance of success, the team conducted multiple ground rehearsals and mandated one rehearsal mission, without the X-51A attached, prior to the live launch.

In order for test team members to participate in the live launch mission, members were required to attend mission-specific training and have either participated in a previous live launch or the mission profile rehearsal. The rehearsals also allowed the multiple agencies to identify issues early. This lesson was especially true for the airspace management piece of the mission profile.

Airspace Management

The mission profile began with the B-52H takeoff from Edwards AFB, transition through the national airspace to the Point Mugu range and returned to Edwards AFB. Between PF2 and PF3, the mission profile was changed to move the profile closer to the planned divert airfield at Vandenberg AFB as presented in Figure 5.



Figure 5 – Mission Profile

Figure 6 shows the 5 different control agencies for the corresponding airspace. SPORT controls the R-2515 airspace around Edwards AFB and accepts aircraft handed off from the Edwards AFB tower. The R-2515 airspace is where the B-52H climbed to mission altitude with the F-16 safety chase until the NASA safety chase were airborne. The R-2515 airspace is a part of the larger R-2508 complex, controlled by Joshua. Joshua worked the handoff to Los Angeles Center, which controls the transition airspace from R-2508 to the Point Mugu controlled airspace. Plead Control handled the range entry and coordinated the handoff to Plead Mike, who was the controller during the simulated launch (dry pass) and the live launch.



Figure 6 – Mission Profile with Airspace Controller Labels

The restricted airspace managers (SPORT and Joshua in R-2508 and the Point Mugu range personnel) were accustomed to test aircraft traffic and precise test mission requirements. However, Los Angeles Center deals with a large volume of traffic, few of which typically are military aircraft with a test article on a mission like the X-51A launch. Pre-briefing the FAA controllers at Los Angeles Center was a key lesson learned for the X-51A program. The meetings determined that a dedicated controller on the mission frequency was the preferred option for both the X-51A test team and Los Angeles Center. This allowed the test aircrew to keep their focus on the timing and the X-51A rather than working multiple frequency changes. Furthermore, with the FAA agreeing to receive and handoff the B-52H on the mission frequencies eliminated the “chatter” of traffic calls to other aircraft, which reduced distractions to the test aircrew. The NASA chase aircraft rejoin occurred near the transition between the R-2508 and the area controlled by Los Angeles Center. By holding the coordination meetings, the FAA controllers were aware of the two-ship formation (if a safety and photo chase were available) or single chase aircraft that would rejoin with the B-52H in the Los Angeles Center airspace. By including all of the controlling agencies as key members on the test team, routine tasks were mitigated as a source of error, and succeeded in all of the agencies acting as a single test team. The same philosophy also succeeded with the diverse members that made up the mission control room (MCR) team.

MCR Configuration and Preparation

With the focus on the airborne test assets, it could have been easy to overlook the training, qualifications, and proficiency of the MCR personnel. An early focus was placed on the MCR team, and lessons learned were incorporated with each subsequent X-51A mission.

All MCR personnel were trained in their specific crew position. Prior to the airborne mission rehearsal and the live launch, multiple simulations were conducted. The mission aircrew were positioned in a separate room with voice communication to the MCR to simulate the test mission. For PF4, data from previous flights were displayed to offer the MCR personnel a sample of the real-time data they would be observing. Rules of engagement were briefed and practiced including which crew positions made continuation or abort calls. The chain of command and specific terminology were also briefed and practiced during the mission rehearsals. This helped multiple organizations with unique interests work together as a team to execute a successful mission and mitigate any potential for miscommunications.

In order to prepare the MCR team to expeditiously handle abnormal scenarios, MCR personnel and aircrew rehearsed abnormal scenarios and their planned resolution. Some of the abnormal scenarios included a hung store, retained store, loss of B-52H cabin pressure, and abnormal X-51A conditions.

PF4 EXECUTION AND PRELIMINARY X-51A RESULTS

The mission for PF4 was delayed 1 day due to weather near Vandenberg AFB. Certain weather conditions had to exist at Vandenberg AFB in order for the B-52H to consider it a viable option for a divert airfield should there be a hung store. On 1 May 2013, the weather at Vandenberg met the required conditions (as did the weather on the Point Mugu range) and the B-52H took off on time. Immediately after takeoff, the F-16 safety chase noted that one of the B-52H landing gear failed to retract. As part of the mission rehearsal and training, the aircrew had briefed and rehearsed the resolution of this exact scenario. The B-52H aircrew were able to retract the gear and continue the climb without further incident. Following the resolution of the landing gear issue, the single F-15 safety chase ground aborted during takeoff. The chase pilot was able to quickly resolve the issue and lineup for a second attempt. The F-15 successfully took off without major impact to the mission timing. As noted earlier, with the B-52H airborne and the critical timing for the X-51A subsystems already counting, the ability of the F-15 chase pilot to expeditiously resolve the issue and takeoff safely literally saved the mission. The MCR made minor adjustments and communicated the adjustments to the test team. The remainder of the mission profile continued without event. Utilizing the knowledge from the previous live launches and the PF4 mission rehearsals, the release was on conditions and the X-51A separation was successful.

The boost achieved the desired airspeed near Mach number 4.8 followed by a successful transition to JP-7. The boost was sufficiently energetic to cause the B-52H aircrew to feel the vibrations from the rocket booster (6). The maximum airspeed achieved was about Mach number 5.1, and a maximum altitude of about 60,000 feet MSL. The X-51A total powered flight time was 240 seconds with a total scramjet burn time of 210 seconds (1). The PID maneuvers after engine shutdown were executed as planned. The B-52H and F-15B chase aircraft safely returned to Edwards AFB.

CONCLUSION

The successful launch of the longest air-breathing scramjet flight in history was due to the lessons learned during PF1 through PF3. The four live launches combined to show that the vehicle could successfully reach the required conditions for scramjet engine operation. The test team was presented with a unique test article and the integration of that article on the B-52H. The team took the constraints imposed on them by the nature of the mission and applied appropriate test discipline to ensure safe, efficient, and ultimately successful test execution. The X-51A test team demonstrated proactive planning, multi-agency integration, and precise timing to maximize the return on investment and pave the way for future hypersonic research.

LESSONS LEARNED

- The thorough documentation of specific issues during PF1 through PF3 led to those same issues being proactively addressed during PF4 even though much of the PF4 test team was not present for PF1.
- When able, table-top, live-MCR rehearsals, or airborne mission rehearsals greatly helped communication and timing during mission execution.
- Mission rehearsals combined with previous experience led to the proactive identification of issues, such as the B-52H landing gear retraction issue, which could be mitigated and resolved as briefed and practiced.
- The proactive coordination with all of the airspace controllers allowed the B-52H to transit through the national airspace with no adverse impact to the test mission or the precise timing required.

FUTURE WORK

While all 4 X-51A vehicles were expended during flight test, the full impact of the X-51A test program has yet to be seen. The future High Speed Strike Weapon (HSSW) is set to demonstrate flight at speeds of Mach 5.0 and above using air-breathing technology (8) (9).

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BIOGRAPHIES



Maj Chris Rondeau received a M.S. in Electrical Engineering from the Air Force Institute of Technology (AFIT) and an M.S. in Flight Test Engineering from the USAF Test Pilot School. He has worked at the Warner-Robins Air Logistics Center, Robins AFB, GA and the 746th Test Squadron at Holloman AFB, NM. He has served as an airborne test conductor and flight test engineer on the C-12D/J, UH-1, F-16D, B-52H, and B-1B. He is a qualified test director and test conductor supporting B-52H, B-1B, and B-2A flight test operations. He has been a flight commander and is currently the Chief Flight Test Engineer at the 419th Flight Test Squadron at the 412th Test Wing, Edwards AFB, CA.



Lt Col Tim Jorris received a B.S. and M.S. in Aerospace Engineering from the University of California, Los Angeles (UCLA); and his Ph.D. in Astronautical Engineering from the Air Force Institute of Technology (AFIT). He worked at the Munitions Lab at Eglin, is a US Air Force Test Pilot School (USAF TPS) graduate, and worked on the F-15I, B-1, B-52, Global Hawk, X-40A, X-37, X-33, X-51A, and Dream Chaser as a flight test engineer at Edwards AFB, CA. He has served as an Instructor Flight Test Engineer at USAF TPS and an Adjunct Professor for AFIT. He is currently the Director of the Hypersonic Combined Test Force at the 412th Test Wing, Edwards AFB, CA.