X-43A Fluid and Environmental Systems:

Ground and Flight Operation and Lessons Learned

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Abstract

The X-43A Hyper-X program demonstrated the first successful flights of an airframe-integrated scramjet powered hypersonic vehicle. The X-43A vehicles established successive world records for jet-powered vehicles at speeds of Mach 7 and Mach 10. The X-43A vehicle is a subscale version of proposed hypersonic reconnaissance–strike aircraft. Scaled down to a length of 12 ft (3.66 m), the lifting body design with high fineness ratio resulted in very small internal space available for fluid systems and their corresponding environmental conditioning systems. Safe testing and operation of the X-43A fluid and environmental systems was critical for mission success, not only for the safety of the flight crew in the NASA B-52B carrier aircraft, but also to maintain the reliability of vehicle systems while exposed to dynamics and hostile conditions encountered during the boost trajectory. The X-43A fluid and environmental systems successfully managed explosive, pyrophoric, inert, and very high pressure gases without incident. This report presents a summary of the checkout and flight validation of the X-43A fluid systems. The testing used for mission assurance is summarized. System performance during captive carry and launch flights is presented. The lessons learned are also discussed.

Nomenclature

^oC	=	degrees Celsius
CST	=	combined systems test
^oF	=	degrees Fahrenheit
FMU	=	flight management unit
ft	=	feet
GH2	=	hydrogen, gaseous
GHe	=	helium, gaseous
GN2	=	nitrogen, gaseous
GSE	=	ground servicing equipment
HXLV	=	Hyper-X launch vehicle
HXRV	=	Hyper-X research vehicle
kPa	=	kiloPascal
kPad	=	differential kiloPascal
LLIS	=	Lessons Learned Information System
m	=	meters
P	=	pressure measurement, referred to by number
PID	=	parameter identification
psf	=	pound-force per square foot
psi	=	pound-force per square inch

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psid	=	differential pound-force per square inch
RV	=	relief valve, referred to by number
s	=	seconds
T	=	temperature measurement (thermocouple), referred to by number
VP	=	oxygen sensor, calculated oxygen concentration, referred to by number

I. Introduction

THE X-43A Hyper-X Program successfully demonstrated and validated the technology, experimental techniques, and computational methods for design and performance predictions of a hypersonic aircraft with an airframe-integrated, dual-mode scramjet engine. Ground testing, flight testing, and analysis were integral elements for ensuring a successful program.[1] The flight-test portion consisted of three short-duration scramjet tests using the X-43A autonomous, free-flying, expendable Hyper-X research vehicles (HXRV) at speeds of Mach 7 and Mach 10. The X-43A vehicle is shown in Fig. 1. All three vehicles were virtually identical, with the main difference being the internal engine flowpaths of the Mach 7 and Mach 10 configurations. Each research vehicle was delivered to the test condition by a modified Pegasus® (Orbital Sciences Corporation, Dulles, Virginia, U.S.A.) booster rocket, known as the Hyper-X launch vehicle (HXLV) which was launched from the NASA B-52B, tail number 008, shown in Fig. 2. An adapter provided the interface between the HXLV and the HXRV and contained the fluid systems used during the boost phase of the mission. The entire configuration was referred to as the X-43A stack. The X-43A propulsion system consisted of the aerodynamic shaping of the fuselage, the scramjet engine itself, and associated fluid systems for fueling and protecting the engine.[2] The goal of the fluid system development effort was to assure leak-tight operation of these systems for flight safety and provide performance to meet mission requirements. The goal of the environmental system development was to prevent air intrusion, inert the vehicle in the event that leaks developed in the fluid system, and provide modest thermal control.

The first vehicle was intended to be flown at a speed of Mach 7 on June 2, 2001. The flight was terminated approximately 49 s after launch due to a loss of control of the booster rocket. (See X-43A Mishap Investigation Board, *Report of Findings: X-43A Mishap,* http://www.nasa.gov/pdf/47414main_x43A_mishap.pdf). The second vehicle was successfully flown to a speed of Mach 6.8 on March 27, 2004 and demonstrated positive acceleration of the HXRV under its own power while climbing. The third and final mission of the program successfully cruised at a speed of Mach 9.7 on November 16, 2004.

The following provides a basic timeline of events for the two successful scramjet experiments. After reaching the launch altitude and airspeed (roughly Mach 0.8), the X-43A stack was released from the wing of the B-52B. After falling approximately 1000 ft (305 m), the HXLV rocket motor ignited, propelling the stack to the desired separation altitude and Mach number. At a dynamic pressure of approximately 1000 psf (47.88 kPa), pistons in the HXLV adapter explosively separated the HXRV from the HXLV. The cowl door on the HXRV opened 2.5 s after separation. This was followed by 2 s of unpowered, trimmed flight to obtain a baseline of all forces acting on the vehicle. The igniter and hydrogen were then injected into the engine, and supersonic combustion was maintained with hydrogen for approximately 10 s. After engine shutdown, another baseline was obtained of all forces acting on the vehicle for a period of several seconds before the cowl door was closed and a recovery maneuver was initiated. An unpowered deceleration and descent trajectory was flown to a splashdown in the Pacific Ocean. A series of parameter identification (PID) maneuvers were performed as the vehicle slowed from test conditions to a speed of Mach 2.[3]

The HXRV could not be recovered after each mission. Data from onboard sensors was telemetered and collected at a number of land-based sites along the coast of the state of California, U.S.A. A U.S. Navy P-3 aircraft, stationed north of the flight path of the HXRV, was critical for obtaining data during the later stages of the launch flights, when the HXRV was beyond line-of-sight of the California coast. This report examines the evolution of the fluid and environmental systems for the three X-43A vehicles, summarizes the results of ground and flight tests, and presents lessons learned.

II. Vehicle Systems Description

Two main systems within the X-43A vehicle will be discussed in this report. The fluid systems are comprised of the hardware used to provide consumable quantities to the X-43A scramjet engine and the enclosure purge. The environmental system used the enclosure purge gas and onboard sensors to mitigate any hazards posed to the vehicle or personnel.

A. Fluid Systems

The X-43A propulsion system consisted of the scramjet engine itself and the associated fluid systems. A high-pressure gaseous hydrogen (GH2) system fueled the engine. An igniter system, containing a pyrophoric mixture of 20 percent silane and 80 percent GH2 by volume, initiated combustion. Regulated gaseous nitrogen (GN2) was supplied from ground servicing equipment (GSE) during ground operations. The B-52B provided GN2 for cavity purge during captive carry flight. A GN2 system in the adapter provided cavity purge and coolant pressurant during boost. An onboard supply of GN2 in the research vehicle provided vehicle cavity purge, coolant pressurant and propellant systems purge during free flight. The research vehicle water coolant system provided active cooling for the engine leading edges during free flight. A glycol–water coolant system in the adapter provided engine cooling during boost. The GH2 heat exchangers, igniter tank and HXRV GN2 tank used thermostatically-controlled resistive heating elements to maintain their temperatures at approximately 150 ^{o}F (65.6 °C).

B. Environmental Systems

The environmental systems were designed to keep personnel and hardware safe by controlling oxygen intrusion, propellant leaks, and internal temperatures. Figure 3 shows the placement strategy for the environmental sensors and purge orifices. The vehicle internal cavity was inerted to maintain 1.5 percent oxygen volume fraction or less, precluding combustion in the event of GH2 or igniter leakage. Four oxygen sensors inside the HXRV verified the cavity environment was adequately inert. Bulkhead cutouts and vent lines were designed to create a purge path, or flow direction, carrying leaking propellants aft and overboard. The vehicle cavity was pressurized to reduce intrusion of high temperature outside air, which could be damaging to vehicle internal systems. The vehicle internal temperatures were passively controlled to provide an acceptable thermal environment for all internal systems. Thermocouples in the vehicle cavity monitored internal temperature and could detect fires. Numerous thermocouples were also located on the vehicle systems. Tank heaters and GSE were also used to control vehicle temperature. Mizukami discusses the design of aerospace environmental systems in detail.[4]

III. Ground Testing

Exhaustive ground testing was completed on all fluid and environmental systems. These tests were conducted on configurations that ranged from components to subsystems and assemblies to the combined systems test (CST), which simultaneously involved the B-52B, HXLV, adapter, and HXRV. While all these tests contributed to the success of the X-43A, certain tests deserve particular attention because of their significance or complexity. These tests were run on all three research vehicles.

A. Integrated Coolant–Purge Tests

The objective of this test was to verify that the coolant and purge system would perform as desired during boost and free flight. This test included simulation of the separation event where the coolant and purge source transitions from the adapter to the HXRV.

The HXRV and adapter were physically connected to each other, including fluids systems. The interconnected coolant and purge systems were run according to predicted boost and free-flight timelines, using actual consumables. The hydrogen and igniter systems were not run, but were pressurized with helium. Ground test valves were used to simulate adapter flow cutoff caused by separation.

The integrated coolant–purge tests were successful on all three research vehicles. Each test demonstrated acceptable transition from adapter to HXRV fluid systems. Performance data was projected to flight conditions, considering acceleration, coolant viscosity, engine thermal effects, and ground test hardware differences. Uncertainty and dispersion effects were also considered. The ground test and uncertainty analysis for the Ship 1 coolant flow duration indicated that the margin was only 0.6 s. The Ship 2 ground test verified a comfortable margin for all flow rates and consumable flow duration. The flowrate demonstrated during Ship 3 testing was used to set the coolant turn-on time for the Mach 10 flight based on a heating analysis.

B. Integrated Leak and Functional Tests

Fluid systems leak and functional tests were conducted between significant events and hardware changeouts. The first objective of the leak and functional test was to verify the general particulate cleanliness of the X-43A gaseous systems. This included all GSE used in conjunction with these tests. The second objective was to verify that the fluid systems met leak rate requirements. Components and fittings must be bubble-tight, to the extent they can be tested while installed in the vehicle. High-pressure tank assemblies had to meet operationally allowable preflight leak rates, which satisfied safety and mission success requirements with margin. The third objective was to check the functionality of components in the HXRV fluid systems, as much as possible while installed in the vehicle. The final objective was to exercise the regulators installed in the vehicle to eliminate any potential stiction problems. Additional objectives were added as needed.

C. Cavity Purge Tests

Cavity purge tests were performed to ensure the environmental systems could prevent and detect oxygen intrusion, detect fuel leaks, inert contaminated cavities, provide modest thermal control, and maintain an internal pressure higher than ambient. The cavity purge test for Ship 1 was the most rigorous, as the operation of the integrated systems was assessed for the first time. Numerous changes had to be made to optimize performance. This test was conducted as part of the Ship 1 CST. As confidence in the systems was gained and procedures developed, subsequent X-43A vehicles received less rigorous testing.

A component thermal management issue was identified during the Ship 1 CST, when the S-band unit reached the maximum rated operating temperature (165 ^{o}F) (73.9 ^{o}C) before completing the nominal mission timeline. The CST results brought to question the mission success of the S-band transmitter during the primary mission. Through investigation with the equipment manufacturer, the maximum operating temperature was revised to a limit of 185 ^{o}F (85 ^{o}C). To further ensure the life of the unit, the heat sink for the transmitter was modified to operate in a forced convection mode with the use of a cavity purge orifice directed into the heat sink cooling fins. To ensure mission success, operating procedures were developed to assure the S-band temperature was limited to 150 ^{o}F (65.6 ^{o}C) during ground operations and 140 ^{o}F (60 ^{o}C) at launch.

D. Combined Systems Tests

The combined systems tests were the final validation test of the propulsion systems prior to flight, and involved all three vehicles – the B-52B, the HXLV, and the HXRV – mated together with interconnecting fluid systems. The objectives of these tests were to:

1) complete the verification of the manual vent functionality with inert gas
2) complete the verification of the emergency vent and purge sequence with inert gas
3) complete the verification of the instrumentation and control room displays
4) complete the verification of the tank heater control
5) verify the system integrity during ground and taxi operations
6) verify and rehearse the ground servicing procedures.

For these tests, the flight operations were simulated as closely as possible, short of servicing the HXRV with actual propellants and flying the mission. The entire X-43A stack was mounted to the B-52B, as if for flight. All gas systems were serviced with inerts (GHe and GN2). The B-52B purge system was exercised for cooling and to validate good flow rates in the HXLV and in the HXRV. At the conclusion of the each CST, the GH2 and igniter tanks were vented to demonstrate the function of the manual and automatic vent modes. The automatic vent mode was commanded by the onboard flight management unit (FMU).

All three CSTs were successfully conducted. Because of scheduling conflicts, the CST for Ship 2 was actually conducted as part of the captive carry flight. During each CST, the control room was fully operational, with displays running as if for flight. When applicable, the CST data were used to adjust operating limits on monitoring displays, maximizing the chances of detecting problems while minimizing false alarms.

IV. Flight Tests

The flight tests of the X-43A served many purposes. The captive carry flights checked out all combined systems with the X-43A stack mounted on the B-52B wing, but with no launch conducted. The launch flights resulted in the actual release of the X-43A from the B-52B.

A. Captive Carry Flights

The launch flights of the X-43A vehicles were each preceded by a captive carry flight. These flights allowed for a complete checkout of critical systems, procedures, and timelines for the entire launch mission. For the captive carry flights, the propellants were replaced with inert gases and the B-52B flew a simulated launch flight. Fluid and environmental systems objectives for the flights were to:

1) verify the manual vent and emergency vent and purge operations from the B-52B HXRV monitor station
2) verify that the fluid system was leak-tight in the captive carry flight environment
3) verify the adequacy of the vehicle thermal control
4) verify the adequacy of the cavity inerting and pressurization

5) verify the performance of the B-52B GN2 system
6) verify the functionality of the scramjet static pressure sensors and thermocouples
7) verify that the coolant system temperatures were acceptable.

1. Ship 1

From a fluid systems standpoint, the Ship 1 captive carry flight was essentially a repeat of the CST, with all upper surface panels installed, servicing equipment removed, and an actual flight conducted. Success criteria included meeting all established leak requirements, and the completion of a nominal vent and purge sequence (both manually and FMU-commanded).

The Ship 1 captive carry flight marked the first flight test of several environmental sensors, including oxygen and hydrogen sensors. The flight was the first time that all environmental systems, including purge duration, cavity purge pressure, vehicle sealing, and oxygen and hydrogen detection, were exercised as if for a launch flight.

Cavity purge tests continued with this flight, validating that the vehicle seals and purge system adequately maintained inert, oxygen-free cavities at altitude (low static pressure) and cruise speed (high dynamic pressure). The electrolytic oxygen sensors indicated 0.0 to 0.3 percent oxygen in an inert cavity. Catalytic oxygen and hydrogen sensors were also installed for research purposes, with mixed performance results. Selected GN2 system tanks onboard the B-52B carried nitrogen gas that was seeded with hydrogen. This gas was introduced into the X-43A cavities during the flight. Although the seed gas was a 1-percent hydrogen in nitrogen mixture that, when mixed with additional nitrogen onboard the B-52B, was less than 1 percent hydrogen, the hydrogen sensors indicated just under 2 percent hydrogen during the flight.

An important lesson was learned with this test. This test was improperly performed, as the hydrogen likely embrittled the tanks on board the B-52B, and the tanks had to be replaced. The material properties of all aerospace systems must be well understood, even for heritage systems. Had the X-15 heritage GN2 system onboard the B-52B been thoroughly understood, hydrogen embrittlement of the B-52B tanks could have been avoided.

2. Ship 2

The same success criteria for the captive carry flight with Ship 1 applied to Ship 2. The cruise–launch altitude for Ship 2 was increased from 25,000 to 40,000 ft (7,620 to 12,192 m), which directly affected the cold soaking of both the Hyper-X stack and the B-52B (specifically the onboard GN2 tanks). The HXRV was very cold internally during this flight, and changes were made postflight to help balance heat soaking on the ground during preflights with the predicted cold soaking that would occur during the cruise out to the launch point. The B-52B GN2 regulated pressure was decreased to help reduce the amount of cold GN2 forced into the HXRV during the flight. The captive carry flight demonstrated sufficient internal cavity pressure to allow the regulated pressure to be reduced without allowing oxygen intrusion.

The electrolytic oxygen sensors did not perform as expected during the flight. As altitude increased, the sensors experienced what appeared to be a partial pressure effect, in which the sensors showed increasing noise in the signal as the cavity pressure decreased with altitude. Essentially, the sensors lost the ability to provide quality detection of the presence of oxygen, and their effective accuracy was reduced. This effect was not seen in Ship 1. Extensive troubleshooting and recalibration could not correct this signal noise, which persisted throughout subsequent flight tests. The corrective action was procedural and control room training was used to familiarize everyone with the characteristics of the sensors.

3. Ship 3

All systems on Ship 3 performed as well as they did for Ship 2 except for the cavity pressurization. The captive carry flight showed a ground cavity pressure of 0.3 psid (2.07 kPad), which was unusual because it was believed that with each additional ship, the crew became more adept at sealing the vehicle and improving all potential leak areas. Exhaustive testing and additional sealing corrected this problem postflight. Many small seams were filled with a room temperature vulcanizing silicone (RTV), and the cavity pressure improved to 0.55 psid (3.79 kPad) on the ground for the launch flight.

B. Launch Flights

Table 1 summarizes the timing of mission events for the three launch flights. This table can be used to match fluid system changes shown in Figs. 4 through 9 with critical mission events. Note that the coolant was left on 15 s longer for the Ship 2 flight than for the Ship 3 flight. This important detail will be discussed further in the Ship 3 "Coolant System" section below.

Table 1. Mission events timeline for all three flights.

Mission Event	Ship 1	Ship 2	Ship 3
Launch	0	0	0
Coolant On	45	49	43
Separation	49	94	88
Cowl Open	--	96	91
Cowl Closed	--	133	111
Coolant Off	--	133	112
Splash	78	603	810

All event times are shown in seconds after launch

1. Ship 1

Flight 1 Summary. All ground operations and the captive carry flight phase to the launch point were nominal. Shortly after launch from the B-52B, booster control was lost, and the mission was terminated 49 s into the flight. However, important insight was gained into the fluid systems, both while the X-43A stack was attached to the B-52B and during the short boost flight.

Coolant System. During the boost, the adapter GN2 regulator failed to regulate pressure. As a result, the coolant system was pressurized, but the solenoid valves were not commanded open. The adapter GN2 pressure (A023) was not regulated to the nominal value and exceeded the transducer upper limit [Fig. 4(a)]. At these pressures, the adapter GN2 relief valve would have opened and vented the excess gas overboard.

The rapid pressure increase detected by the coolant supply pressure sensor (P113) after launch indicates the coolant system briefly became active. Coolant flow likely started at close to 45 s after launch, but was pressurized for only 5 s. If the flight had continued, thermal analysis shows that there may have been sufficient coolant onboard to allow the engine to survive long enough to conduct the experiment.

Fuel and Igniter Systems. The fuel and igniter systems remained leak-tight throughout the captive carry phase of the launch flight. Due to booster failure, the X-43A was not delivered to the proper test conditions, and the fuel and igniter systems were not operated after inadvertent separation occurred.

B-52B and X-43A Nitrogen Systems. The relationships between B-52B GN2 regulated pressure, HXRV adapter GN2 purge pressure (A023), HXRV coolant pressurant (P117), and HXRV cavity purge pressure (P281) for Flight 1 are shown in Fig. 5(a). Note the pressure drop between the B-52B GN2 pressure and the HXRV cavity pressure (P281), attributable to line losses in the lengthy B-52B GN2 system. As mentioned previously, the adapter GN2 regulator failed wide open and did not regulate pressure after launch from the B-52B. The adapter GN2 relief valve would have opened and vented the excess gas overboard, creating a small exhaust jet. Mizukami, et al. discuss this event and the effect on vehicle aerodynamics in detail.

Hyper-X Research Vehicle Internal Cavity Purge System and Oxygen Sensors. Environmental data obtained during the launch flight indicated that environmental improvements could be made to the X-43A design. With minor modifications, the potential for air intrusion was reduced, which also reduced the potential for flammability and thermal loading of critical equipment in subsequent flights. Incremental testing led to a design that maintained inert cavities for the duration of the ground and captive carry operations. For flight safety, an inert cavity was required to have less than 1 percent oxygen volume fraction. This provided an inherent margin of safety because the flammability limits for hydrogen and oxygen in a nitrogen atmosphere are both 4 percent volume fraction.[5–7] The reliability of the catalytic oxygen sensors was unacceptable and they were removed from subsequent vehicles. The electrolytic oxygen sensors indicated oxygen levels were less than 0.2 percent for the ground and captive carry portions of the launch flight. Upon release of the stack from the B-52B airplane, oxygen levels began to increase. Oxygen indications continued to increase at all sensors through the remainder of boosted flight, through termination, and until splashdown at 77.6 s.

The cavity pressure differential was positive during the first 3.5 s of the launch flight, and the large initial oxygen indications by the catalytic oxygen sensors are believed to be false positives. These false positives are likely caused by the very high rate of depressurization of the inert vehicle cavities when the purge was terminated at launch. Additional testing and improvements in the pressure compensation algorithm were warranted, but not conducted as the sensors were dropped from subsequent flights.

With the cavity pressure differential decreasing to less than zero on the underside of the vehicle approximately 3.5 s after launch, seeing oxygen levels increasing at sensor VP09 first was not surprising. This sensor was mounted closest to where the fuel feed lines descend through a bulkhead cutout from the hydrogen bay into the engine cavity. During ground operations, significant purge leakage could be felt venting through the engine–vehicle interface. Thus, when the pressure differential on the underside of the vehicle decreases to less than zero in flight, air intrusion into the hydrogen bay by way of the fuel line feedthrough is highly likely without increased sealing around the engine and fuel feed lines. This leak path was corrected in subsequent vehicles. The placement strategy for the electrolytic oxygen sensors was successfully tested during this brief flight, as air intrusion was detected during the controlled portion of the boost trajectory that could be corroborated through analysis.

All the fluid systems remained leak-tight and operated according to specifications throughout the Ship 1 flight mishap and after the termination command. The systems maintained integrity even while the X-43A stack was tumbling and the HXRV inadvertently separated from the HXLV adapter.

Hyper-X Research Vehicle Internal Cavity Thermal Control. The S-band transmitter temperature was 160 ^{o}F (71.1 ^{o}C) at takeoff, cooling to 120 ^{o}F (48.9 ^{o}C) at launch. Internal cavity temperatures were between 80 and 100 ^{o}F (26.7 and 37.8 ^{o}C) at launch, with T058 and T059 about 20 ^{o}F (11.1 ^{o}C) cooler, likely due to cold purge gas blowing directly on the thermocouples. The internal temperatures are shown in Fig. 7(a). Refer to Fig. 3 for the location of all sensors. The S-band and cavity temperatures were notably higher for the first launch flight than subsequent flights.

2. Ship 2

Flight 2 Summary. All fluid systems remained leak-tight throughout all phases of flight and performed nominally during the engine experiment. Vehicle thermal control was improved from the Ship 2 captive carry flight. The internal cavities were fully inerted during captive carry and the engine experiment, which was successfully carried out at a speed just below Mach 7.

Coolant System. Because low cavity temperatures were measured during the Ship 2 captive carry flight, the HXRV thermal environment was carefully conditioned during ground operations and monitored during the launch flight to ensure the coolant system was not threatened by freezing temperatures. Special care was taken to ensure that water did not leak from the coolant tank into the small-diameter coolant lines in the engine and cowl, which could freeze at altitude and threaten mission success. The coolant system successfully supplied the required coolant beginning at the Mach 3 flight condition until the cowl door was closed. The coolant system was allowed to remain flowing until the onboard supply was exhausted, lasting through the engine experiment and the postexperiment cowl-open PID maneuvers. In Fig. 4(b), note that the coolant supply pressure drops rapidly at 132 s after launch, when the onboard coolant is exhausted. This occurs about one second before the coolant valve is commanded closed. Coolant duration for water onboard the HXRV was almost 38 s. The HXRV coolant system duration was slightly short of expectations, but within the predicted uncertainties and was sufficient to meet test objectives.

Fuel and Igniter Systems. The performance of the fuel and igniter systems matched predictions. A time history plot of fuel and igniter pressures during the engine experiment is presented in Fig. 8(a). To start the engine, the igniter, which is a mixture of 80 percent hydrogen and 20 percent silane by volume, is first injected to the flowpath to establish a stable flameholder region. The hydrogen fuel is then injected into the flowpath, and increased in two stages. The regulated pressures, P108 and P112, were within expected limits and all systems performed nominally. Downstream line temperatures, T83 and T79, were higher than upstream line temperatures, T77 and T75 respectively, during portions of the propellant and igniter flows.

All fuel and igniter system temperatures behaved as expected, and are shown in Fig. 9(a). After the heater was turned on, igniter and HXRV GN2 gas temperatures reached nominal levels in about 20 min, and decreased during captive carry flight. Heat exchanger temperatures took about 40 min to reach nominal levels, and also decreased during captive carry flight.

B-52B and X-43A Nitrogen Systems. All purge pressures were nominal during the launch flight. The B-52B GN2 system maintained nominal pressure, which was reduced to mitigate colder temperatures experienced during the Ship 2 captive carry flight. Comparing Flights 1 and 2 [Figs. 5(a) and 5(b)], note that the drop in purge pressure immediately after launch was quite dramatic for Flight 1 [essentially to zero psi (zero kPa)], but less abrupt for Flight 2, especially measured at A023. This improvement in performance was due to the addition of a plenum in the adapter that blew down through a small-diameter orifice into the HXRV in the time from launch to the activation of the adapter GN2 system, about 49 s into the flight. The HXRV purge pressure was nominal after separation from the HXLV.

Hyper-X Research Vehicle Internal Cavity Purge System. The HXRV internal cavity pressure was slightly lower during the launch flight than it was for the captive carry flight. This lower pressure was expected because the B-52B regulated purge pressure was reduced to decrease the amount of cold soaked GN2 pumped into the HXRV during the captive carry portion of the launch flight. Overall, cavity inerting and pressurization exceeded expectations. Cavity pressure remained 0.5 psid (3.45 kPad) above ambient for most of boost phase. The internal pressure was lowest just after drop, falling to 0.4 psid (2.76 kPad) when supplied only by the adapter plenum tank. An internal pressure of approximately 0.7 psid (4.83 kPad) was provided during the scramjet experiment. Overall performance was much higher than predicted during boost. This result was attributable to a new pressure distribution over the upper surface of the HXRV at transonic and supersonic speeds that was not accurately predicted by the simple cavity pressure model.

Oxygen Sensors. The electrolytic oxygen sensors performed as expected, similar to the captive carry flight. The sensors became noisier at higher altitudes, indicating oxygen levels oscillating from 0 percent up to 0.7 percent at the 40,000 ft (12,192 m) cruise altitude. This signal oscillation is attributed to a low pressure sensitivity, and not actual oxygen intrusion. The vehicle remained inert throughout the captive carry portion of the flight with no oxygen intrusion detected. The heater blankets around the sensors maintained proper temperatures. The locations of these oxygen sensors within the HXRV, labeled VP09 through VP12, are identified in Fig. 3.

Figure 6(b) presents flight data for the oxygen sensors. There are two unambiguous occurrences of oxygen intrusion during the flight, prior to exhaustion of onboard purge. The first indication of oxygen intrusion occurred immediately after drop, when the onboard purge was supplied only by a small plenum in the adapter. Oxygen levels increased for 20 s, reaching 7 percent at the forward end of the hydrogen bay (VP09). The other three sensors detected 2 to 4 percent. The intrusion detected by VP09 began to decrease before the other sensors showed a decrease in oxygen levels. The oxygen detected by VP10 through VP12 decreased only after the adapter GN2 supply was activated. The cavities were completely inert within one minute after the intrusion was detected.

The second intrusion occurred immediately after the conclusion of the engine experiment. This intrusion appeared to have originated in or around the hydrogen bay. Cavity pressure was relatively high, at 0.8 to 0.9 psid (5.5 to 6.2 kPad), and was not believed to be a contributing factor as it was for the first intrusion. Sensor VP10 measured oxygen levels approaching 9 percent at the aft end of the bay. Sensor VP09 also detected oxygen at the forward end of the bay, but at a level of only 4 percent. The other two sensors, VP11 and VP12 did not detect oxygen intrusion during this event. The oxygen intrusion was reduced to below 3 percent about one minute after the intrusion was first detected.

Before this intrusion could be completely inerted, the oxygen levels detected by all four sensors began increasing. This is due to the gradual depletion blowdown of onboard purge. After the FMU vent and purge cycle, the onboard purge depleted gradually, and oxygen levels gradually rose to ambient (21 percent measured oxygen).

Hyper-X Research Vehicle Internal Cavity Thermal Control. The ground purge was used successfully to manage S-band transmitter temperature before flight. Cavity temperatures were benign during ground operations. After starting with a temperature at takeoff of 150 °F (65.6 ^{o}C), the S-band temperature decreased due to vehicle cold soaking during the cruise out to the launch point, reaching 85 ^{o}F (29.4 ^{o}C) at launch.

Cavity fire detect thermocouples measured temperatures generally above 60 °F (15.6 ^{o}C) for the duration of the flight, with only T058 and T059 below that. Those thermocouples are directly above purge orifices, and are artificially cooled by the cold soaked B-52B GN2. As shown in Fig. 7(b), cavity temperatures were benign during boost and free flight, even though the vehicle leading edges reached 1700 °F (927 ^{o}C), and air intrusion occurred during boost and descent. Fluctuations in measured temperatures appear to be directly related to the flow of adapter and HXRV purge. The S-band temperature increased 12 ^{o}F (6.7 ^{o}C) during boost [to 97 °F (36.1 ^{o}C)], and increased at a constant rate of 0.1°F/sec (0.056 ^{o}C/sec) for the duration of the free-flight, reaching a maximum of 140°F (60 ^{o}C) at splash.

3. Ship 3

Flight 3 Summary. All fluid systems remained leak-tight throughout all phases of flight and performed nominally. Vehicle thermal control and sealing was greatly improved from the Ship 3 CST and captive carry flight. The internal cavities were fully inerted during captive carry and the engine experiment, which was successfully carried out at a speed just below Mach 10.

Ground Operations and Servicing. The planned flight on November 15 had to be cancelled very late in the day-of-flight checklist. All panel closeouts had been completed and permanently installed on the HXRV and HXLV adapter. With the flight rescheduled for the following day, normal procedures call for GSE to be plugged into the HXLV adapter side panel and various external systems used to monitor the HXRV overnight in a standby mode. With all panels closed out for flight, a unique challenge was created for monitoring onboard systems and controlling fluid system temperatures and pressures overnight until another launch flight attempt could be made the following day, November 16. Simply powering up the HXRV in this configuration turned on all HXRV systems, including the telemetry transmitters, which posed a hazard to ground crews. A work-around was developed, in which the HXRV was powered up every few hours by way of the B-52B HXRV monitor station to check fluid system temperatures and pressures. The HXRV tank and line heaters were turned on from the B-52B HXRV monitor station as needed to maintain an approximate 75 ^{o}F (23.9 ^{o}C) internal cavity temperature throughout the night, during which outside temperatures dropped to approximately 45 ^{o}F (7.2 ^{o}C). In addition, thermal control was aided by the use of a thermal cover (nicknamed the "banana") to insulate both the HXLV and HXRV, and the GSE to blow hot air into the cover. This ad hoc monitoring and insulation worked very well, and the vehicle cavities remained at approximately 75 ^{o}F (23.9 ^{o}C), as desired, throughout the night and early morning.

All systems were aggressively serviced, with as much fuel and nitrogen placed on board as was deemed possible using available fuel servicing curves. As a result, the HXRV GN2 system pressures approached the maximum pressure of 8500 psi (58,605 kPa) during the captive carry flight, however, the pressures were easily controlled by turning off the HXRV heaters when pressures approached maximum and turning the heaters back on when pressures declined.

Coolant System. The HXRV internal thermocouples around the coolant tank and line registered cavity temperatures above 32 °F (0 ^{o}C) for the duration of the flight. There was no threat of freezing the water onboard the HXRV in either the tank or lines. This was aided by the thermal conditioning the night before flight.

Figure 4(c) presents coolant system data for the third launch flight. The coolant flow for Flight 2 continued 23 s longer than Flight 3, as Ship 2 performed cowl-open PID maneuvers that were not repeated with Ship 3. The coolant system was activated just after Mach 4 flight conditions were reached, and flowed until the cowl door was closed. The command to close the cowl door was the trigger for stopping coolant flow for this flight. Postflight analyses hint that the cowl leading edges became deformed during the latter phase of the third flight. At speeds approaching Mach 10, the thin leading edge structure of the engine and cowl door were much more susceptible to melting. In hindsight, knowing there was ample water margin onboard, this flow should have been allowed to continue a few seconds longer to provide continued protection of the cowl from high temperatures.

Adapter coolant temperature remained constant throughout the captive carry and boost stages of the flight. Not surprisingly, the adapter coolant tank temperature increased immediately after the separation of the HXRV from the HXLV, rising about 20 ^{o}F (11.1 ^{o}C) in 30 s.

Fuel and Igniter Systems. Early hardware and software testing identified two problems with the Mach 7 igniter subsystem controller when applied to the Mach 10 flight. First, when the hydrogen fuel flow was initiated, the igniter system venturi became unchoked. As a result, the propulsion system controller reverted to an open loop mode during the igniter flowrate schedule, which caused an unsteady igniter mass flowrate. Second, wind tunnel testing found a concern for sustaining ignition. To prevent the unsteady flowrate and sustain ignition in flight, the propulsion control software was modified to run the igniter subsystem in an open loop mode.

The fuel and igniter pressures during the Mach 10 engine experiment are presented in Fig. 8(b). Compare this figure with Fig. 8(a) to illustrate the different fueling schedules for Flights 2 and 3. The igniter regulated pressure is reduced at different stages when fueling both vehicles. Hydrogen control valve downstream pressure is set to several different plateaus for both vehicles, matching the desired fueling schedules. The regulated pressures, P108 and P112, were within expected limits and all systems performed nominally. The differing pressure profiles for the igniter control valve downstream pressure is attributable to trapped pressure in the igniter supply line. Downstream line temperatures T83 and T79 were higher than upstream line temperatures T77 and T75, respectively, during portions of the propellant and igniter flows. All fuel and igniter system temperatures behaved as expected, as detailed in Fig. 9(b), and were similar to Ship 2 data.

B-52B and X-43A Nitrogen Systems. All components of the B-52B GN2 system performed nominally. The relationships between B-52B GN2 regulated pressure, HXRV adapter GN2 purge pressure (A023), HXRV coolant pressurant (P117), and HXRV cavity purge pressure (P281) are shown in Fig. 5(c). Shown is the known pressure drop from the B-52B into the HXRV, which is consistent with Ships 1 and 2.

Hyper-X Research Vehicle Internal Cavity Purge System. For the Ship 3 captive carry flight, cavity pressure was approximately 0.4 psid (2.76 kPad) at takeoff. A maximum internal cavity pressure of 1.1 psid (7.58 kPad) was demonstrated at about 39,500 feet (12,040 m). For the launch flight, internal pressure was 0.55 to 0.65 psid (3.79 to 4.48 kPad) at takeoff, increasing to just over 1.4 psid (9.65 kPad) before drop, which was the highest cavity pressure achieved in flight for any of the three X-43A vehicles.

The internal cavity pressure increased as expected as the vehicle climbed and accelerated to the test condition, and in general the vehicle cavity pressure performed much better than expected. The internal pressure remained above 0.5 psid (3.45 kPad) for duration of the boost and experiment. The flapper valves [which open at 0.45 psid (3.10 kPad)] likely remained open during all phases of the flight, ensuring that a good purge flowpath was always established in the vehicle. During the boost phase, internal pressure was influenced greatest by the transition from sub- to supersonic airflow (shock formation) and by the application of adapter purge. Data from the launch flights of

Ships 2 and 3 support the conclusion that a supersonic pressure distribution over the upper surface of the HXRV produces a favorable increase in cavity pressure.

Oxygen Sensors. The electrolytic oxygen sensors performed as expected during the captive carry phase of the final launch flight. The vehicle remained inert throughout captive flight with no oxygen intrusions. The heater blankets around the sensors maintained proper temperatures.

Figure 6(c) presents unfiltered flight data for the oxygen sensors at 25 Hz. The data is plotted as a function of time from launch from the B-52B. There are four occurrences of oxygen intrusion after launch, identified by arrows. The engine experiment (fuel on) was conducted from 94 to 105 s after launch.

As expected, significant oxygen intrusion occurred immediately after drop, when onboard purge was supplied only by a small plenum in the adapter. Oxygen levels increased for 20 s, reaching almost 17 percent in the hydrogen bay, and up to 5.5 percent in the silane bay. At 31 s into the boost phase of the flight, the adapter GN2 supply was activated, increasing the internal cavity pressure, flushing the intruding oxygen molecules aft and overboard, and helping to return the cavities to an inert state. At 9 s after adapter GN2 started flowing, a second intrusion of oxygen was detected at just over 7 percent in the igniter bay. This was inerted after 35 s, just prior to the separation event. A third intrusion occurred in the hydrogen bay just after the cowl was opened. This intrusion was 10 s in duration, with maximum intrusion of 6.7 percent, and was inerted midway through the engine experiment. The fourth and last noted intrusion began between engine off and cowl closed. It was 17 s in duration with maximum intrusion of 9 percent. After this intrusion was inerted, the cavities maintained their measured oxygen levels until all the systems were vented and purged, at which point all onboard purge was depleted, and oxygen levels gradually rose to ambient (21 percent measured oxygen).

Hyper-X Research Vehicle Internal Cavity Thermal Control. Cooler ambient temperatures and aggressive use of ground purge managed the S-band temperature before taxi. Recall that the S-band began transmitting immediately when the vehicle was powered up. Vehicle closeouts occurred the previous day before the aborted first-flight attempt, and excessive heating was a concern. The S-band temperature increased 22 ^{o}F (12.2 ^{o}C) during the final day-of-flight checks, reaching 125 ^{o}F (51.7 ^{o}C) when the ground purge was removed. During taxi to takeoff, a time span of approximately 50 min, the temperature rose an additional 10 ^{o}F (5.6 ^{o}C), reaching 135 ^{o}F (57.2 ^{o}C) at takeoff. The S-band temperature cooled to 70 ^{o}F (21.1 ^{o}C) by launch, increased 12 ^{o}F (6.7 ^{o}C) during boost [(to 82° F) (27.8 ^{o}C), and increased at a constant rate of 0.1 °F/s (0.056 ^{o}C/s) for the duration of the free-flight, reaching a maximum of 157 °F (69.4 ^{o}C) at splash. The reduced B-52B regulated purge pressure appeared adequate to maintain the required S-band cooling.

Cavity fire detect thermocouples measured temperatures generally above 40 °F (4.4 ^{o}C) for the duration of the flight, with only T058 and T059 below that. Those thermocouples are directly above purge orifices, and are artificially cooled by the cold soaked B-52B GN2. Temperatures dropped continually during the flight as altitude increased and the HXRV (and B-52B GN2) cold soaked.

A closer detail of the temperature data during the third launch flight is presented in Fig. 7(c). Immediately after drop, when the purge flowrate drops, T059 showed an immediate increase in temperature. This increase in temperature is attributable to the lack of cool purge blowing directly on the thermocouple. Once the adapter and HXRV purge systems were activated, internal temperatures remained relatively constant. After the engine experiment, the igniter bay temperatures, measured by T057 and T058, increased at a greater rate than did the other areas inside the vehicle after the engine experiment. This disparate behavior was not demonstrated during the Ship 2 flight.

V. Lessons Learned

With any experimental vehicle as complex mechanically and programmatically as the X-43A, many problems develop which could hinder the success of the experiment. Tracking these problems and their solutions and documenting them for future generations as lessons learned, is an invaluable tool that was developed during this program. The X-43A fluids and environmental systems were critical contributions to the first flight of an airframe-integrated scramjet at speeds of Mach 7 and Mach 10. Many lessons were learned that are provided in this report as guidance to the future development of aerospace vehicles. A detailed listing of lessons learned for the fluid and environmental systems of the Hyper-X Program and the X-43A configuration are presented in the appendix. Though the Hyper-X Program is currently not listed, NASA maintains a database of lessons learned throughout the agency, available online through the Public Lessons Learned System (PLLS), available at http://llis.nasa.gov/llis/plls/index.html.

VI. Conclusions

Even though the scramjet experiment was not performed, useful data was obtained from the first launch flight of the X-43A, leading to design improvements to the fluid systems. The HXRV fluid systems performed better than required for the final Mach 7 and Mach 10 engine experiments, with no mass losses, valve leakage, or regulator anomalies. On the Ship 2 launch flight, the coolant system supply was exhausted prior to the cowl closing, but this occurrence did not affect the engine experiment or vehicle maneuvers and was within the predicted system performance, taking into account uncertainties. For the Ship 3 flight, the coolant system was shut off before the onboard coolant had been exhausted, possibly allowing damage to occur to the engine leading edges after the primary engine experiment. The damage could have been prevented by allowing the coolant flow to continue.

Thermal control of the vehicle internal cavities and S-band transmitter improved with each subsequent flight. Ground purge was used successfully to manage S-band transmitter temperature before flight. Cavity inerting and pressurization were adequate throughout all phases of flight, for all three vehicles. Electrolytic oxygen sensors performed adequately, though noise levels increased with altitude and each subsequent vehicle. Explainable intrusions of oxygen were detected after launch during all three launch flights at low purge flowrates. The intrusions were successfully inerted or reduced by the purge flow.

Lessons were learned with each vehicle and with each flight. Each lesson was documented and applied to the next flight and the next vehicle. The third and final launch flight of the X-43A configuration had no leaks in the fluid systems, experienced no oxygen intrusions during ground operations and captive carry flight, was thermally controlled to room temperature [roughly 75^{o}F (23.9 ^{o}C)] during ground operations and captive carry flight, and had all fluid systems perform as designed during the engine experiment.

If at all possible, “Test what you fly, fly what you test,” even if it seems inconvenient or unnecessary at the time, because this approach to hardware and software testing is the best way to accurately foresee in-flight system interactions that may otherwise be missed.

Appendix

X-43A Fluids and Environmental Systems

Lessons Learned

1) Improve the engine-to-vehicle interface seal to reduce air intrusion into the area between the fuselage and the engine flowpath.
2) Take advantage of any existing supply margin, and increase the boost phase purge mass flow, or start the purge earlier during the boost.
3) Catalytic oxygen and hydrogen sensors are not yet ready for the flight safety role in aerospace applications.
4) Use proven hardware, when possible: a troublesome pressure regulator was replaced with one of flight-test-proven design.
5) When using two sensors to compare similar readings, use sensors with comparable accuracy.
6) The material properties of all aerospace systems must be well understood, even for heritage systems. Had the X-15 heritage GN2 system onboard the B-52B been thoroughly understood, hydrogen embrittlement of the B-52B tanks could have been avoided.
7) Because sufficient margin was available, the B-52B GN2 regulator was adjusted as needed to provide increased–reduced vehicle thermal control.
8) Adjusting tank heater times on and off helped regulate internal temperatures.
9) Requirements and procedures were modified to assure adequate cleanliness levels of the fluid systems to assure proper functionality.
10) Even when meticulous cleanliness procedures are followed, known and unknown system behaviors necessitate the use of in-line filters to protect sensitive system components, such as pressure regulators.
11) Pyrovalves were opened simultaneously (within 0.04 s) at about 45 s after launch, in order to not operate the adapter GN2 pressure regulator near the low end of its flow rate capability range.
12) An accumulator plenum and a metering orifice were added to the purge supply line in the adapter, to bridge the loss of purge pressure immediately after launch until the adapter purge system is activated, at 45+ s into the flight.
13) A check valve was added to prevent GN2 in the adapter supply from backflowing into the plenum during boost.
14) Cavity purge and relief vent ports on the adapter were made to be symmetric, to preclude any possibility of asymmetric forces due to nominal or anomalous venting.
15) Thermal control GSE was furnished for better control of vehicle temperature: a liquid nitrogen heat exchanger for ground purge to provide cooling, and a cover for the vehicle for use with heated air.
16) The igniter shutoff valve was modified to incorporate a Vespel® (a polyimide resin with graphite filler) (E. I. du Pont Nemours and Company, Newark, Delaware, U.S.A.) soft seat instead of a hard metal seat, to provide better leak tightness at operating pressure levels.
17) An inert gas should be used to keep a positive pressure within the hydrogen heat exchanger at all times to prevent corrosion of a critical flowpath between checkouts.
18) With margin available, leave coolant system activated to keep the engine leading edges cool during PIDs at high speeds, even though the primary engine experiment has concluded successfully.
19) Understand that some ground test operations are more strenuous on the flight hardware than the actual flight test.
20) Remain flexible, but vigilant, when establishing procedures for handling unexpected events.
21) The cavity pressure achieved by Ship 3 during the CST "surprised" many during the test because it was so much lower than anticipated. It was assumed that the vehicle would be assembled better than the previous two ships, so a full-up environmental test was never done. Never assume anything, always test what you fly, fly what you test.

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Figures

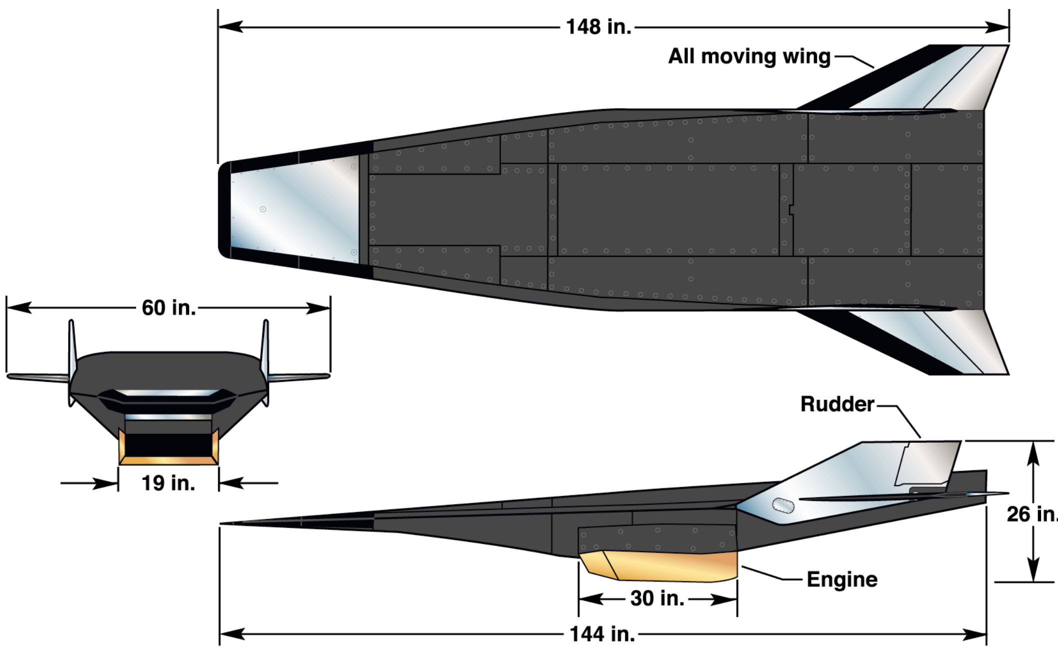


Figure 1. Three-view of the X-43A.

Figure 2. The X-43A stack and the NASA B-52B.

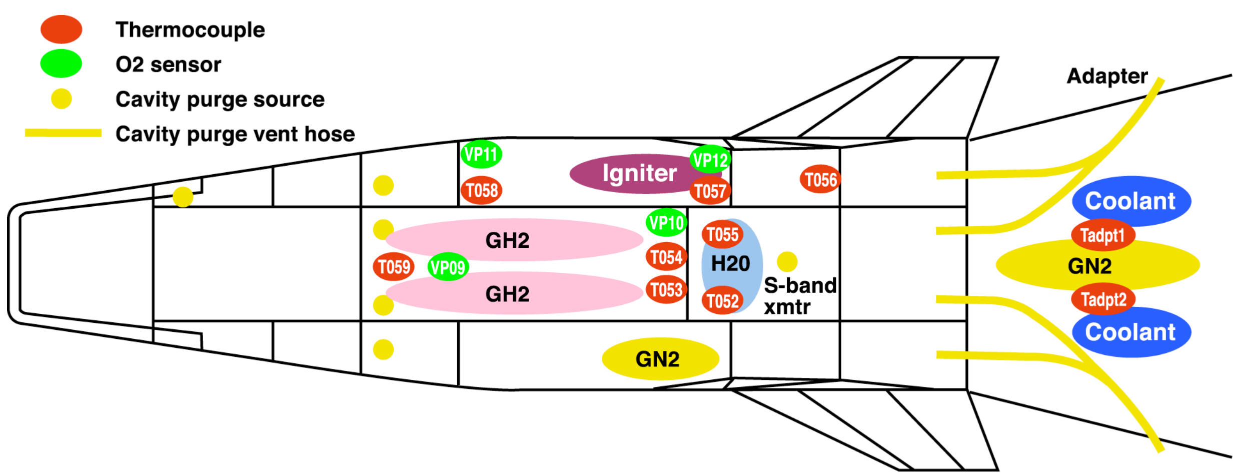
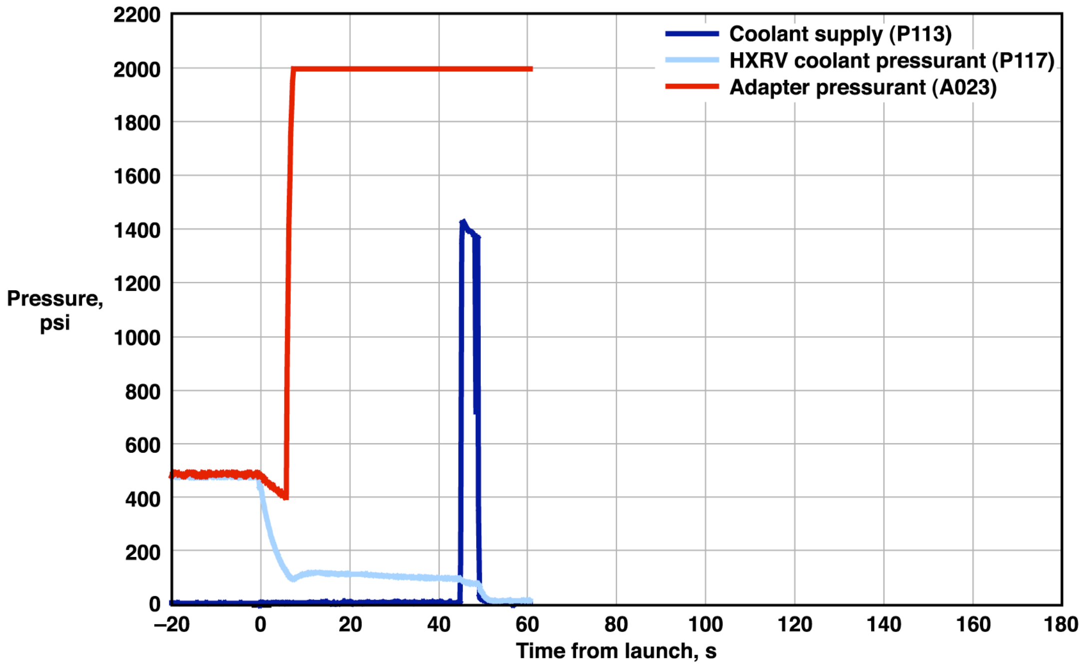
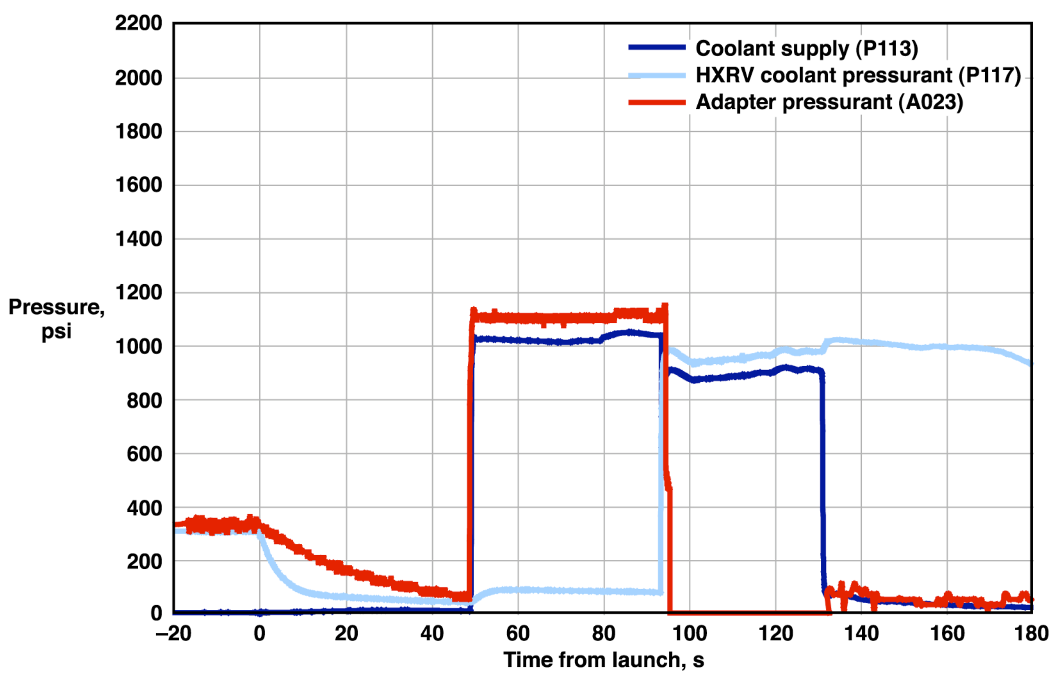


Figure 3. X-43A environmental sensors schematic.

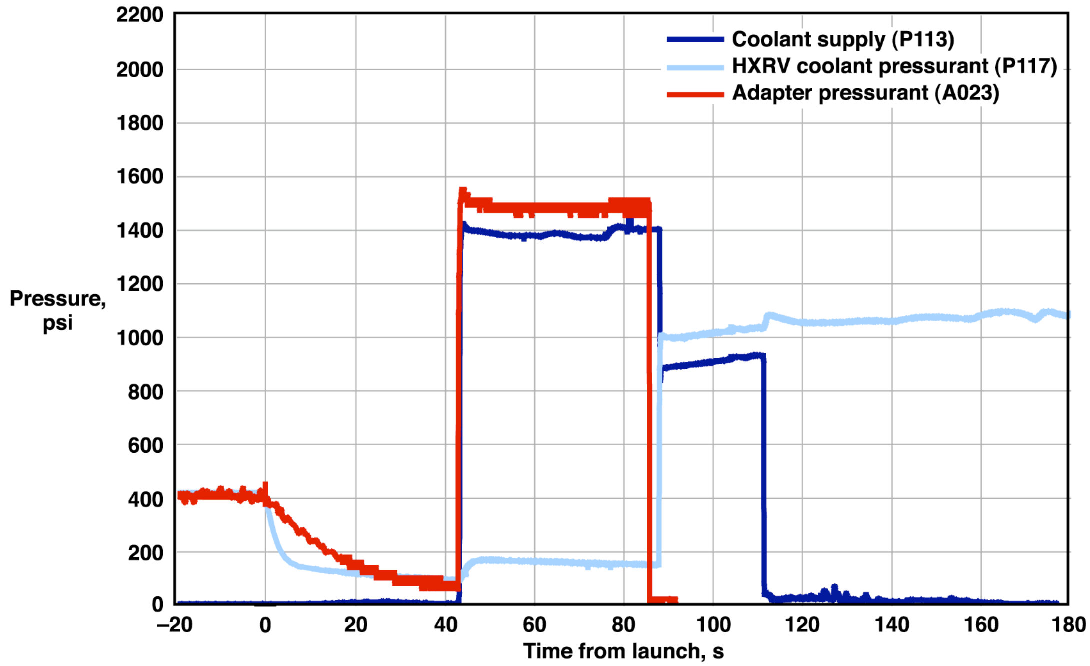


(a) Flight 1 coolant system pressures.



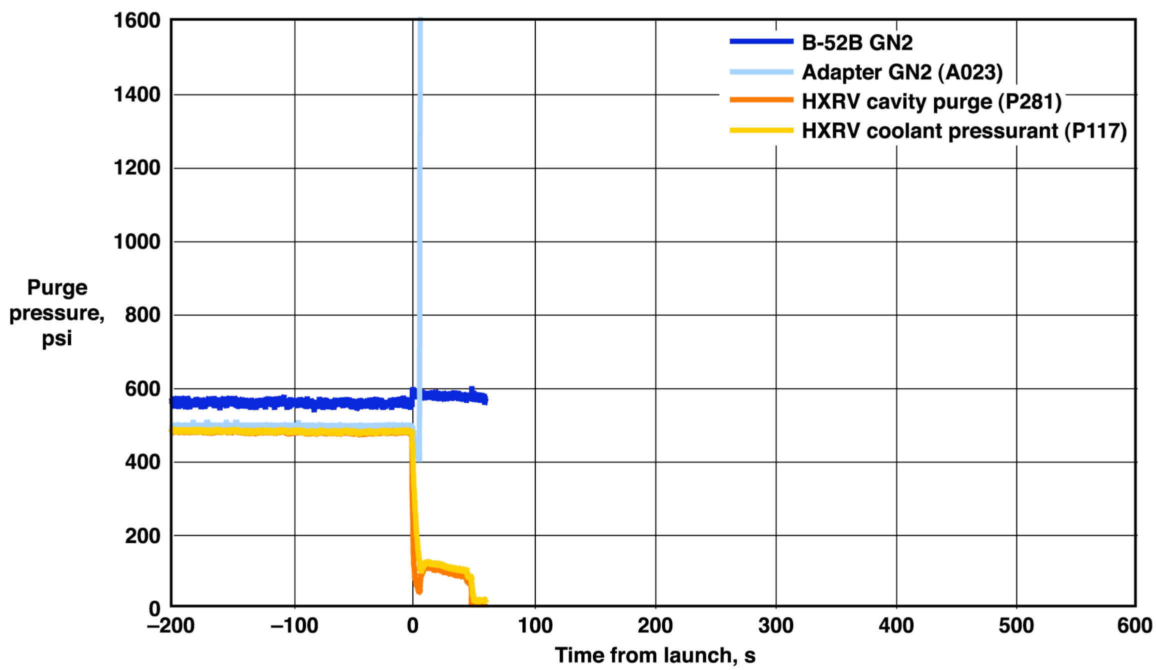
(b) Flight 2 coolant system pressures.

Figure 4. X-43A coolant system pressures.



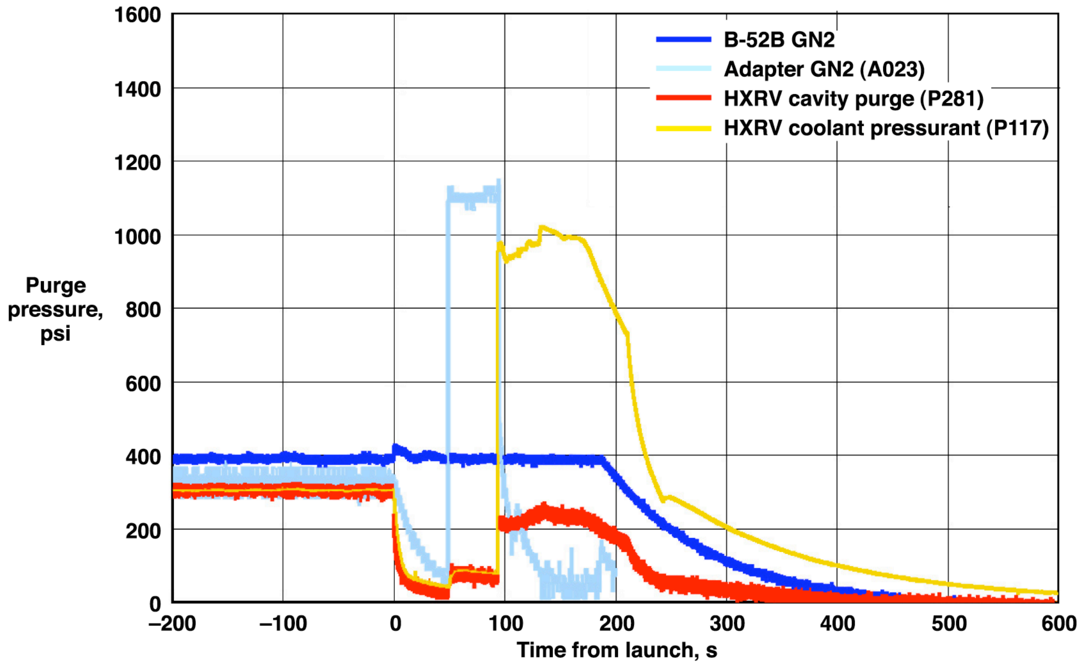
(c) Flight 3 coolant system pressures.

Figure 4. Concluded.

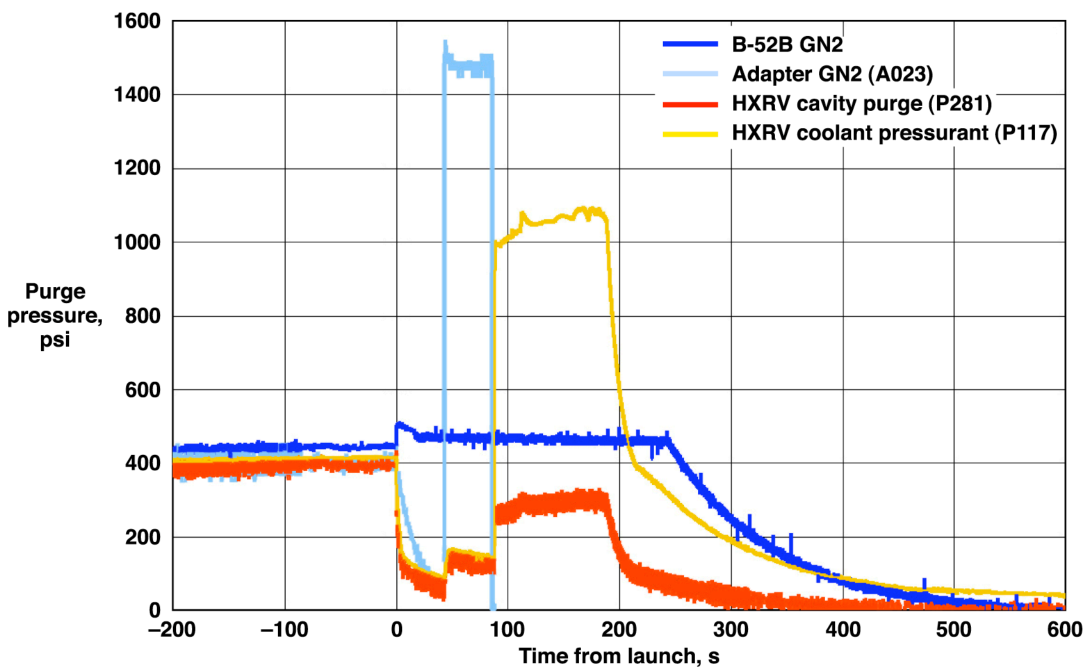


(a) Flight 1 purge system pressures.

Figure 5. X-43A purge system pressures.

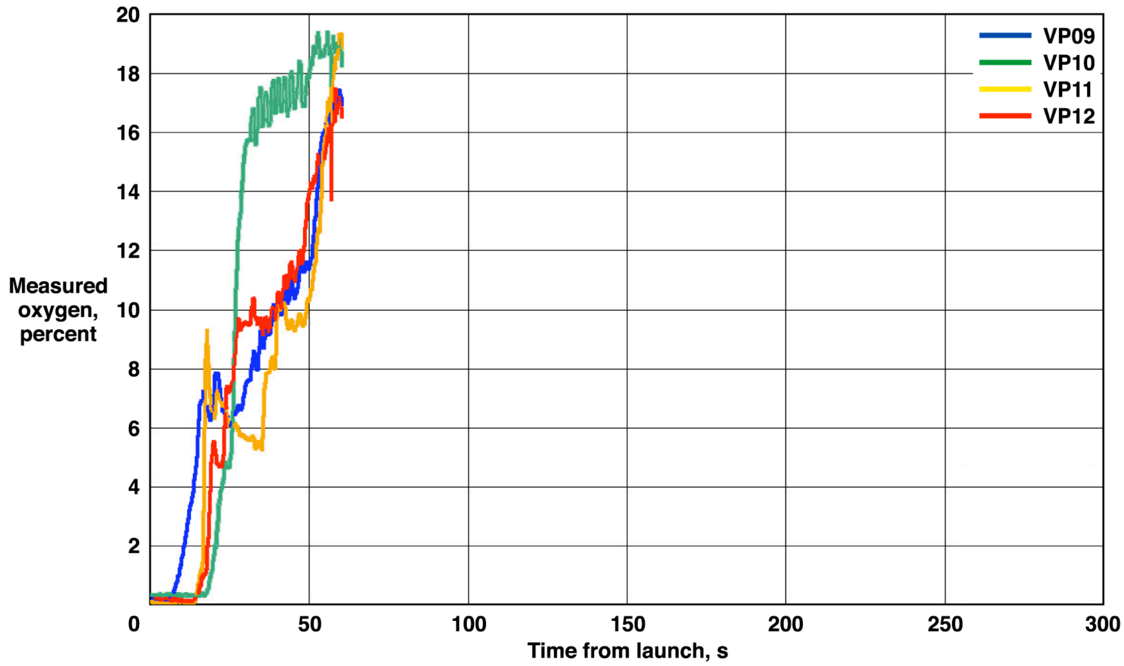


(b) Flight 2 purge system pressures.

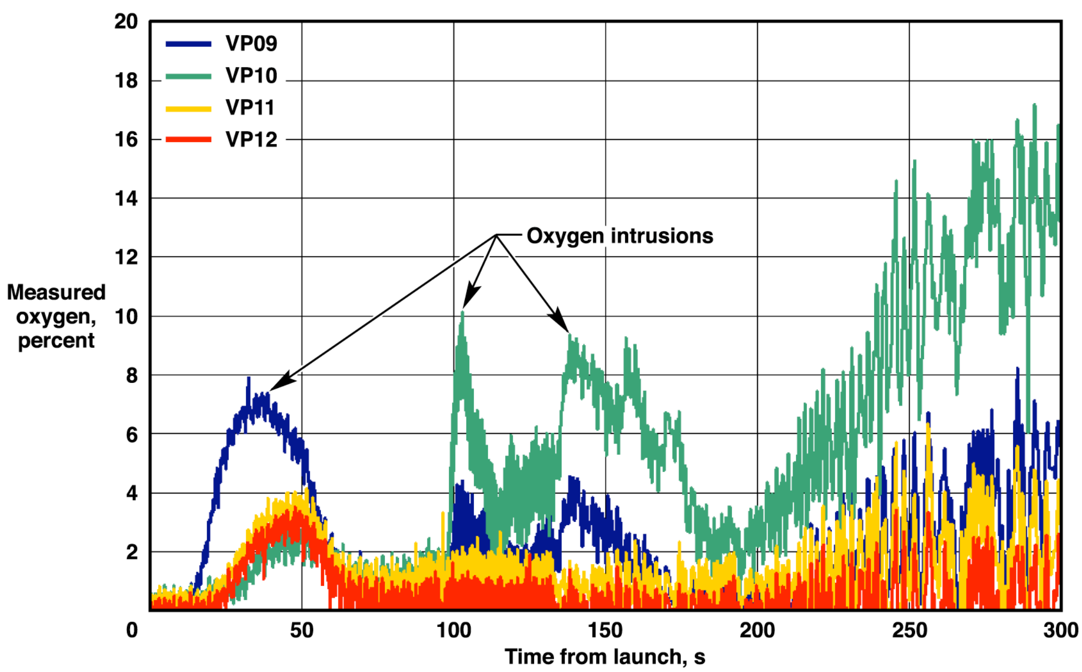


(c) Flight 3 purge system pressures.

Figure 5. Concluded.

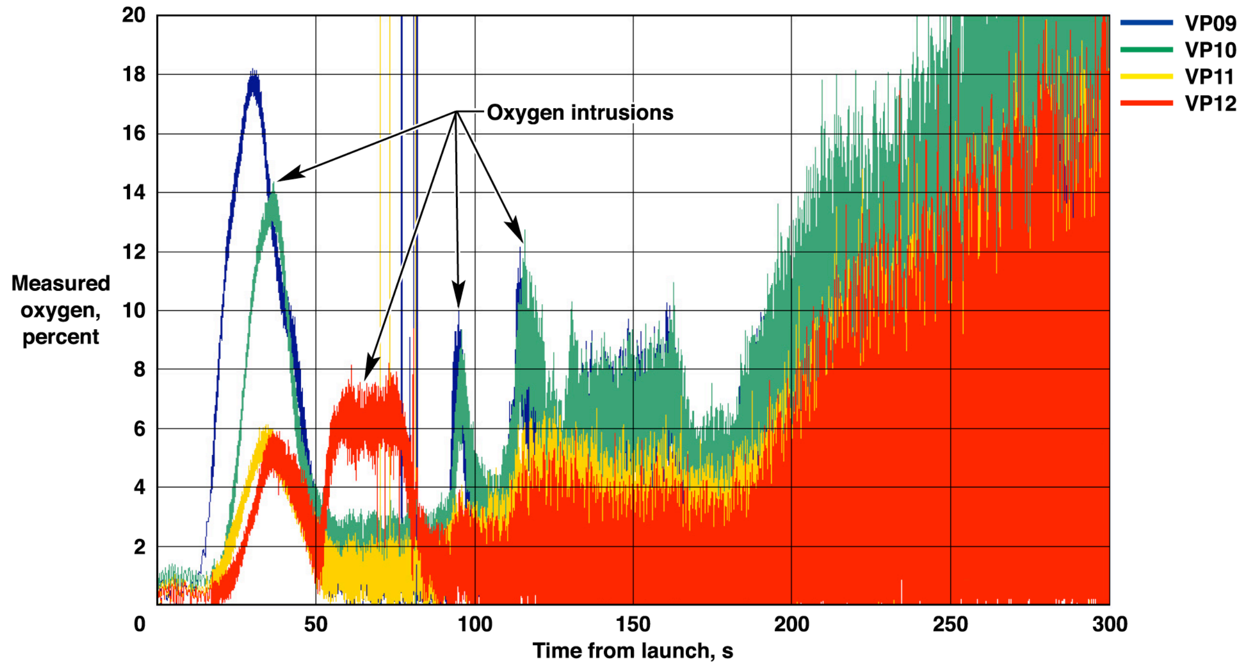


(a) Flight 1 oxygen levels.



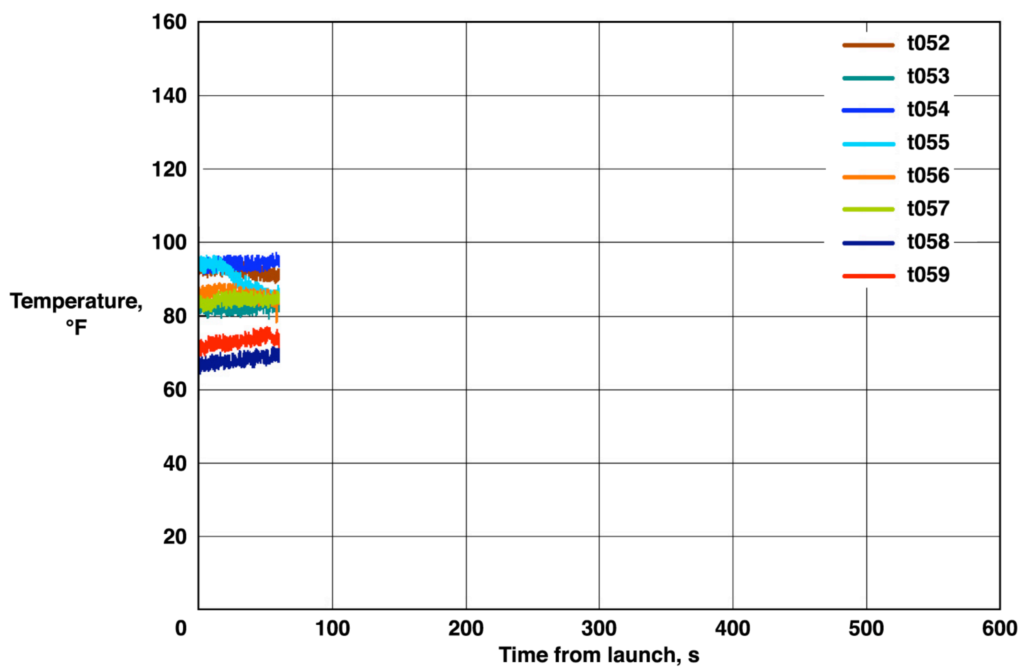
(b) Flight 2 oxygen levels.

Figure 6. X-43A oxygen levels from drop through the engine experiment (refer to figure 3 for sensor locations).



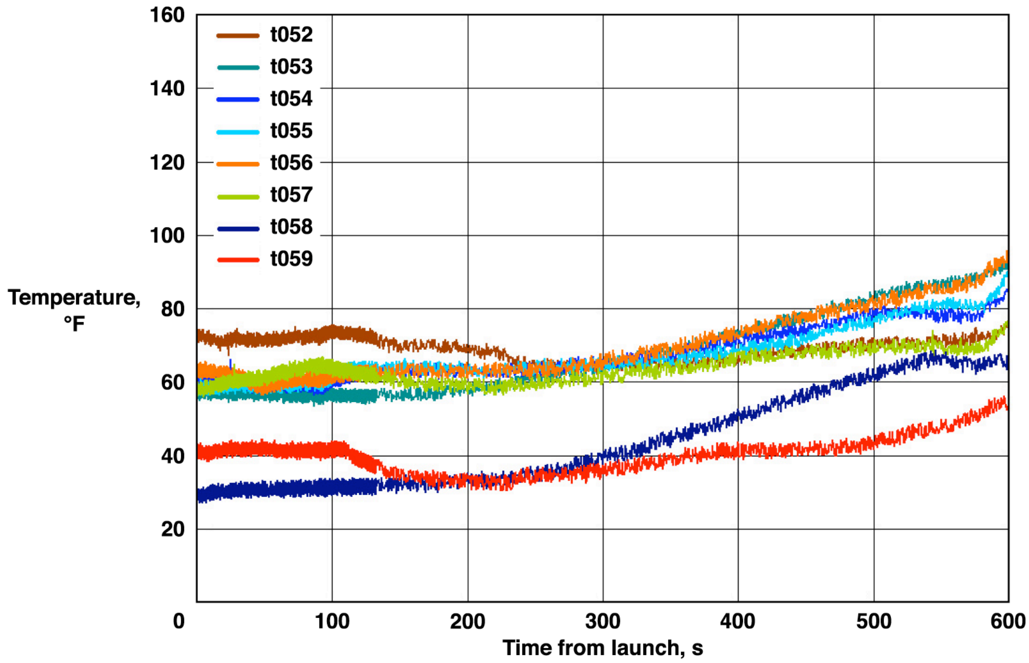
(c) Flight 3 oxygen levels.

Figure 6. Concluded.

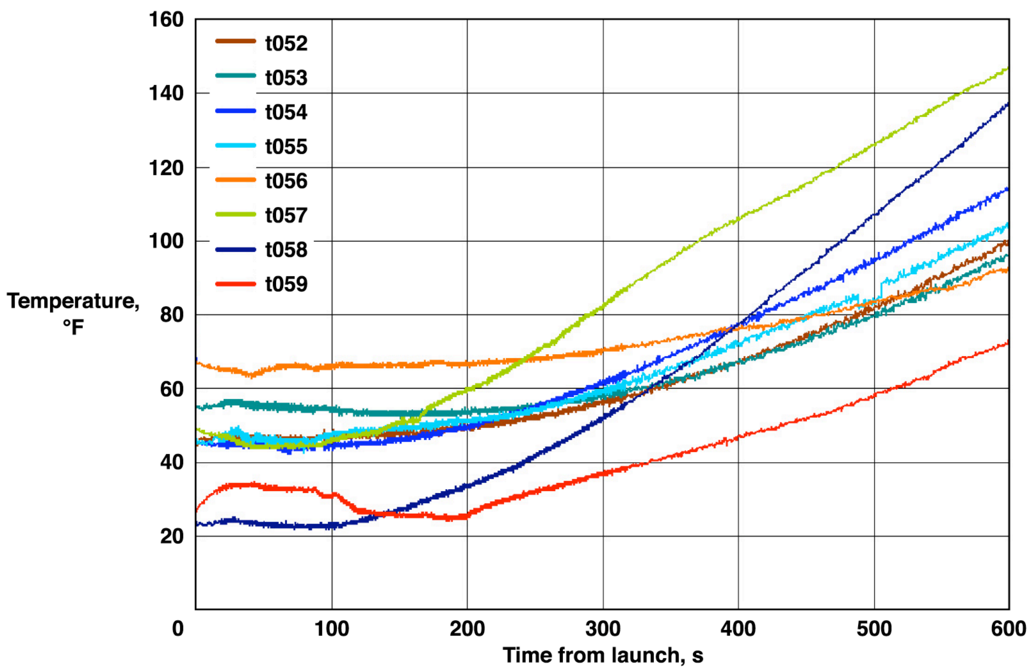


(a) Flight 1 cavity temperatures.

Figure 7. X-43A cavity temperatures (refer to figure 3 for sensor locations).

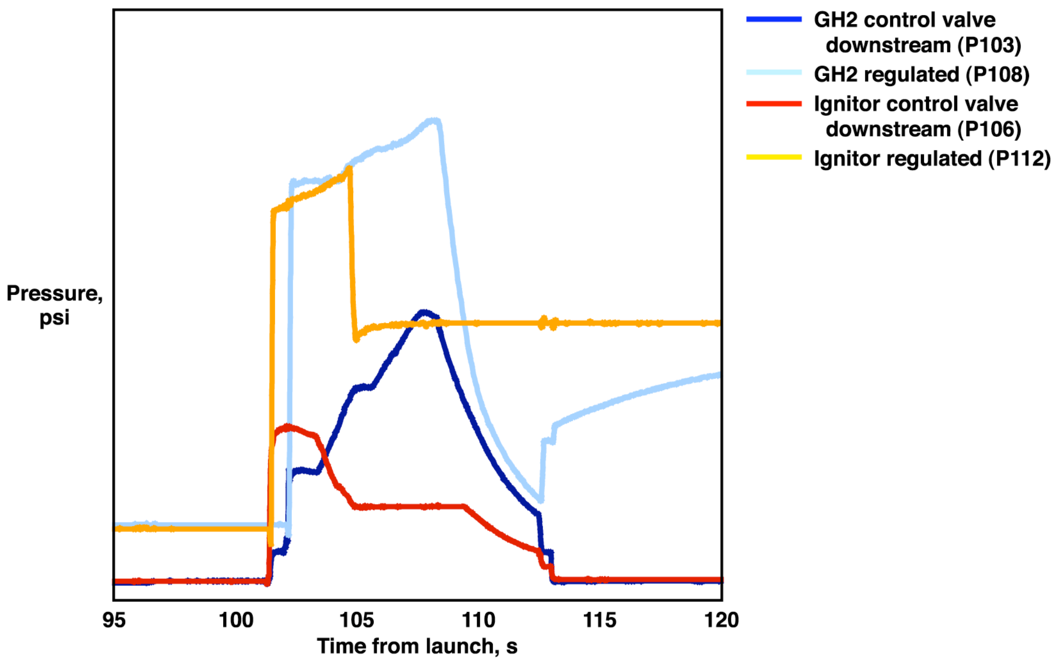


(b) Flight 2 cavity temperatures.

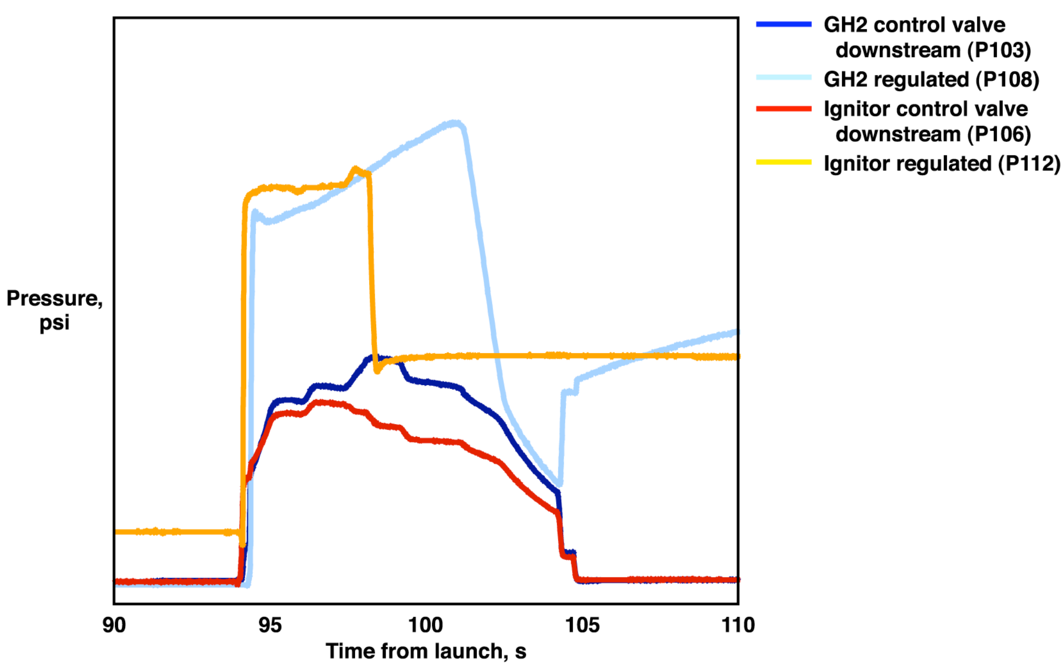


(c) Flight 3 cavity temperatures.

Figure 7. Concluded.

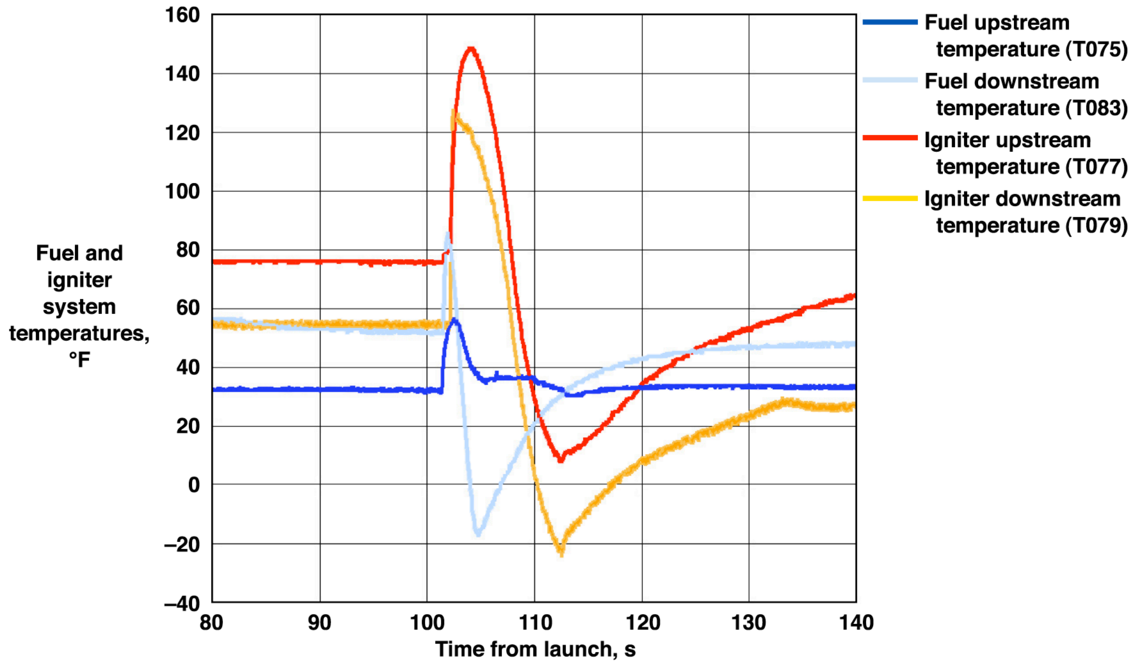


(a) Flight 2 fuel and igniter systems pressures.

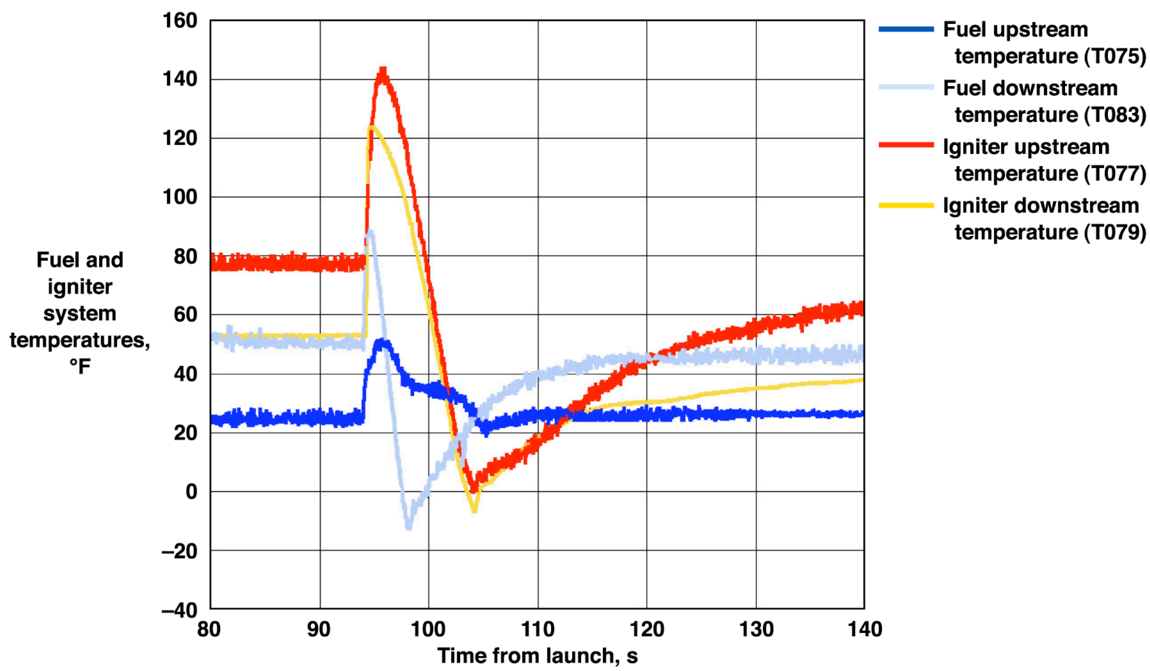


(b) Flight 3 fuel and igniter systems pressures.

Figure 8. X-43A fuel and igniter systems pressures.



(a) Flight 2 fuel and igniter system temperatures.



(b) Flight 3 fuel and igniter system temperatures.

Figure 9. X-43A fuel and igniter temperatures time history.