

# The NACA's High Speed Flight Research Station and the Development of Reaction Control Systems

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## Reaction Control System Computer Simulations

The modern computing revolution arrived at the NACA High-Speed Flight Station soon after it moved into its new facilities on the west side of Rogers Dry Lake, in 1954. In June of that year the Air Force acquired a Goodyear Electronic Differential Analyzer (GEDA) analog computer to develop flight simulations for the Bell X-2.<sup>1</sup> It also wanted to use the new computer to try and sort out issues of inertia coupling that surfaced that year.<sup>2</sup> The following year the Air Force provided Richard E. Day, Joe Weil, Donald Reisert, Wendell H. Stillwell and several other NACA engineers access to the GEDA.<sup>3</sup> The NACA engineers wanted the GEDA in order to conduct a simulation of a Reaction Control System (RCS): small thrusters to stabilize or redirect a vehicle in a near vacuum. This was unknown territory in every respect: control system design, effects of system lag, control effectiveness, and even how the control stick itself should work. Day, Weil, Reisert and Stillwell developed a simulation based on the Bell X-1B, which was to be used in the actual RCS research flights. The test were set to simulate operation in the presence of low dynamic pressure, and eventually space, so the value of dynamic pressure (referred to as “q”) was initially set at zero pounds per square foot (psf).

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<sup>1</sup> Goodyear's Astrophysics department, a branch of Goodyear Aircraft, developed first version of the GEDA for the Air Force in 1949. It continued to develop the computer over the years, offering the L-2/N-2R2 in 1951 and the L-3/N-3R3 in 1953, for example. L stood for linear, N for nonlinear, and R for recording unit. The GEDA grew out of a need for simulation equipment on the part of Goodyear Aircraft, which had begun making missiles following WWII, the same branch of the tire company that built dirigibles after WWI. <http://www.cowardstereoview.com/analog/good.htm>, accessed August 4, 2014.

<sup>2</sup> Inertia coupling was merely a theory in 1948, advanced by William H. Phillips in an NACA paper, but it wasn't taken too seriously since his theory dealt with a problem that hadn't occurred yet in any aircraft. The Douglas X-3 was the first aircraft to manifest the problem, on a flight in October 1954 (stressing the aircraft to +/-7g—its maximum). The North American Aviation F-100A, which entered service the previous month, experienced the same problem, leading to at least six deaths before being withdrawn from service. The Air Force wanted to use the new computer to simulate the conditions and try and solve the problem. Email correspondence between Christian Gelzer and Robert Hoey, September 26, 29, 2014, and William H. Phillips, *Effects of Steady Rolling on Longitudinal and Directional Stability*, NACA TN no. 1627, (Langley, VA: National Advisory Committee for Aeronautics, 1948).

<sup>3</sup> Gene L. Waltman, *Black Magic and Gremlins: Analog Flight Simulations at NASA's Flight Research Center*, (Edwards, CA: NASA Dryden Flight Research Center, 2000), 8. See also Email correspondence between Christian Gelzer and Robert Hoey, September 26, 29, 2014.

Driving their research was the recently approved X-15 that was then expected to reach 250,000 feet, high enough that standard flight control surfaces would be ineffective because of low  $q$ .<sup>4</sup> The lowest aerodynamic pressure to which any pilot had flown an aircraft was 18.8 psf, and while still controllable, the plane was “unsteady.”<sup>5</sup> [Pressure at seal level on a “standard day” is 2116 psf.] While researchers were unsure at what altitude and speed aerodynamic controls would no longer be effective, they anticipated the need for an alternative would arise when  $q$  reached “on the order of 5-10 pounds per square foot.”<sup>6</sup> The engineers anticipated two alternatives: changing the angular momentum of a rotating flywheel, and jet forces. Those involved with the X-15 program chose the latter, judging the former better suited for items intended for longer durations in space.

By 1956 engineers and designers of the X-15 had some relevant information to draw on, but that and our own familiarity with space maneuvering can obscure just how uncertain almost everything was relating to the problem they faced. Hydrogen peroxide, for instance, the compound chosen to power the Reaction Control Systems on the X-15, was discovered as a chemical compound in 1818 but was only refined in purity to 60-85% and produced in industrial quantities by the German chemical industry starting in the early-1930s. It was the German military that adopted  $H_2O_2$  to power the turbo pumps in the V-2 and as a propulsion system in at least one aircraft and one trial submarine; many of that team would bring the technology with them to the U.S. after the war and apply it to a string of missiles and rockets.<sup>7</sup> When forced over

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<sup>4</sup> The X-15 program was formally launched in 1953 and before its flight program was over the aircraft officially reached 314,750 feet. Unofficially it topped 354,000 feet.

<sup>5</sup> Hubert M. Drake, “Flight Experience with Present Research Airplanes,” *Research Airplane Committee Report On Conference On The Progress Of The X-15 Project: A Compilation of Papers Presented*, (NACA: October 25-26, 1956), 17.

<sup>6</sup> Wendell H. Stillwell and Hubert M. Drake, *Simulator Studies Of Jet Reaction Controls For Use At High Altitudes*, NACA Research Memorandum RM H58G18a, (Hampton, VA: NACA Langley Memorial Aeronautical Laboratory, 1958), 2.

<sup>7</sup> Walter formed Walterwerke in 1935 to develop hydrogen peroxide as a propulsive compound. By mixing it with other chemicals—hydrazine hydrate, methyl alcohol, or kerosene, for example and achieving a higher Isp—or using it as an oxidizer, he produced a 2200 ft/lbs Assisted Take Off motor and a 400hp submarine motor. E. Wernimont, M. Ventura, G. Garboden and P. Mullens, “Past and Present Uses of Rocket Grade Hydrogen Peroxide,” 4-5, [http://www.hydrogen-peroxide.us/history-US-General-Kinetics/H2O2\\_Conf\\_1999-Past\\_Present\\_Uses\\_of\\_Rocket\\_Grade\\_Hydrogen\\_Peroxide.pdf](http://www.hydrogen-peroxide.us/history-US-General-Kinetics/H2O2_Conf_1999-Past_Present_Uses_of_Rocket_Grade_Hydrogen_Peroxide.pdf), accessed September 23, 2014. See also Noah S. Davis, Jr., and John H. Keefe, “Concentrated Hydrogen Peroxide as a Propellant,” *Industrial & Engineering Chemistry*, 1956, 48 (4), pp. 745-748, <http://pubs.acs.org/doi/abs/10.1021/ie50556a025>, accessed September 23, 2014.

a catalyst bed, H<sub>2</sub>O<sub>2</sub> decomposes, shedding the second atom of oxygen; the chemical reaction also produces sufficient heat to turn the remaining water molecule into steam, which can then be used to spin turbines either as pumps or to generate electricity, or it can be used simply as thrust.

All of this was unknown to the Americans during the war, whose use of hydrogen peroxide remained “30-35% by weight in water” throughout the war.<sup>8</sup> In 1951 the NACA decided to modify the X-1 it operated (tail no. 6063) to include a turbo pump powered by highly concentrated hydrogen peroxide as a replacement for the pressurized nitrogen tank. It did so drawing on the NACA’s 1947 Technical Memorandum 1170, *Report on Rocket Power Plants Based On T-Substance*, by Hellmuth Walter, father of Germany’s hydrogen peroxide initiative, and possibly on information available from the Army’s nascent ballistic missile program under way in New Mexico with launches of captured German V-2 rockets (something that began in the spring of 1946).<sup>9</sup> At any rate, the NACA had become aware of hydrogen peroxide’s potential.

There is a relevant side note. Early in his research Walter experimented with hydrogen peroxide jets of some sort on a Heinkel Kadett. “In January, 1937, the first flight of a DVL aircraft with T-substance auxiliary propulsion took place at Alimbsmühle in the presence of Colonel Udet, who piloted the third flight,” wrote Walter. “In June, 1937, the first T-substance rockets were fired (Altenwalde). Then in rapid succession take-off auxiliary, main propulsion, and other rocket drives were brought out in experimental versions.”<sup>10</sup> What he didn’t say explicitly in the first sentence is as important as what he said explicitly in the second and third sentences, since they make clear that the first sentence describes testing something other than rocket propulsion, assisted takeoff, and main propulsion. British researcher P. R. Stokes is certain this refers to “a scientific investigation into the early use as wing 'bonkers' in imposing a

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<sup>8</sup> *A Reference Text Prepared by the Staffs of the Guggenheim Aeronautical Laboratory and the Jet Propulsion Laboratory, GALCIT. California Institute of Technology, for the Air Technical Service Command*, edited by Hsue-shen, Tsien, (n.p., 1946), p. 290.

<sup>9</sup> Hellmuth Walter, *Report on Rocket Power Plants Based On T-Substance*, NACA TM No. 1170, (Washington, D.C.: NACA, July 1947). T-Substance was a literal translation of the German *T-Stoffes*, the shorthand for highly concentrated hydrogen peroxide designated for aircraft and missile use. P. R. Stokes, “Hydrogen Peroxide for Power and Propulsion,” read at the Science Museum, London, 14 January 1998, p. 4, [http://hydrogen-peroxide.us/history-Germany/hydrogen-peroxide-for-propulsion-and-power\\_PR\\_Stokes-1998.pdf](http://hydrogen-peroxide.us/history-Germany/hydrogen-peroxide-for-propulsion-and-power_PR_Stokes-1998.pdf), accessed September 24, 2014.

<sup>10</sup> Walter, *Report on Rocket Power Plants Based On T-Substance*, p. 1.

roll moment for aerodynamic stability study.”<sup>11</sup> If so, and Walter’s specificity in the last two sentences makes Stokes’ assertion quite plausible, this would be the first attempt at a reaction control system—and a hydrogen peroxide based one no less. It ended after three flights on the Kadett, and while no German rocket adopted the system, it would have been suitable for atmospheric flight at slow speeds or high angles of attack.

These were the circumstances in which the NACA engineers at Edwards AFB began working out a simulation for their pilots to try. They provided a control stick for roll and pitch in the standard manner, while yaw control came from a thumb switch on top of the stick instead of rudder pedals. This was not ideal but the pilots soon adapted. A small oscilloscope displayed the simulated pitch and roll to the pilots, while a needle instrument registered the yaw angle: it was not a fancy simulator.

The initial tests simulated flights of a two-minute duration. At the start of the computer run the airplane’s attitude was disturbed slightly, requiring the pilot to stop the motion, then hold an attitude of zero yaw, pitch, and roll. The engineers tried two different control methods. The first was a set of on-off switches that commanded rocket thrust whenever the stick or yaw switch was moved beyond a set point. The second provided that each switch could be either full thrust when the controls were moved, or only half thrust when the stick was first moved, and then full-thrust as the controls were moved further. This was a proportional control system, a somewhat linear increase in thrust based on the amount of control stick movement, much like that of conventional aerodynamic surfaces pilots were familiar with.<sup>12</sup>

The pilots showed they adapted quickly to either system, so the engineers added the effects of up to 10 psf of aerodynamic dynamic pressure and ran a second tests. Aerodynamic controls were still ineffective but the dynamic pressure had a nominal effect on the aircraft’s behavior. Now the pilots found that control of the simulated aircraft at low  $q$  was more difficult than at zero  $q$ . Still, the effects of reduced directional stability were less significant than expected, and simulations revealed the pilots could maintain control even at negative values of directional stability.<sup>13</sup>

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<sup>11</sup> P. R. Stokes, “Hydrogen Peroxide for Power and Propulsion,” p. 4.

<sup>12</sup> Wendell H. Stillwell, “Studies Of Reaction Controls” in *Research Airplane Committee Report On Conference On The Progress Of The X-15 Project*, (NACA: October 25-26, 1956), 175- 177.

<sup>13</sup> Ibid.

Stan Butchart, a WWII veteran and one of the NACA research pilots later recalled: “For the early simulations, the biggest problem I had was with the displays. They didn’t seem real. It wasn’t a true-life thing. It was hard to correlate between real life and looking at a meter. The fellows who rigged them up were the pinball experts who could run them better than we could when we got in and tried to fly ‘em.”<sup>14</sup>

## **The Iron Cross**

The second phase of the RCS research involved a motion simulator, dubbed the Iron Cross. This was to provide a check for the computer simulations and to more closely approximate the pilot’s operating environment.

The Iron Cross was home-built at the High-Speed Flight Station late in 1956 and consisted of two long steel I-beams balanced on a universal joint attached to a supporting strut. It was ballasted to the same inertial ratios as the X-1B. The center of gravity was at the pivot point, with the “cockpit” located a similar distance from the center of gravity as the X-1B’s cockpit. The pilot’s seat was perched on the I-beam.<sup>15</sup>

The instrumentation on the Iron Cross was minimal. The control stick was mounted on the left side of the panel. To give the simulator motion, nitrogen jets were mounted in opposing pairs: one pointing up, one down on the rear arm (pitch), one pointing right, one left (yaw), and two roll jets, pointing up and down, mounted on the right arm. At the end of each arm was a “crash bar:” a steel strip with a skid at its end, which acted like a spring to prevent damage to either the Iron Cross or the floor of calibration hangar (4801). Control was difficult and the ends of the I-beams frequently struck the hangar floor.

Butchart and the other pilots explored basic questions with the Iron Cross, including the design of the special control stick that eliminated the need for rudder pedals. Years later he remembered: “From the pilot’s point of view—the first thing was getting the controls in the right direction. Roll was pretty straightforward; twisting with the wrist, [as was] yaw. When it came to pitch control ... for the nose to go up, I think they [the engineers] had it so that you went down

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<sup>14</sup> Waltman, *Black Magic and Gremlins*, 154.

<sup>15</sup> Stillwell, “Studies Of Reaction Controls,” p. 176, 177, and Stillwell and Drake, “Simulator Studies Of Jet Reaction Controls,” 5, 6.

[with] the stick. It soon became obvious to us that the normal way of thinking was to get the nose up you lifted, as if you had a normal stick for pitch control. That sort of thing didn't take too long to straighten out."<sup>16</sup>

Eventually engineers and technicians put an aluminum enclosure around the pilot's seat, denying him any outside visual cues when "flying," obliging him to work only with the instruments on the panel. The pilot's task during the tests was to maintain a stabilized attitude while flying the Iron Cross. Despite its ungainly, even comically appearance, the Iron Cross revealed control problems that were too subtle for the analog simulator to manifest, such as how important it was to align the thrust axes of the reaction controls.<sup>17</sup>

### **X-1B RCS Research Flights**

The aircraft already selected to carry the first RCS tests was the Bell X-1B rocket plane. This second generation design used the same wing, horizontal tail and XLR11 rocket engine as the first generation X-1, but had a fuselage just over 4½ feet longer than the original design, the maximum length that could still fit in the bomb bay of a B-29 launch aircraft.<sup>18</sup> A more significant change was the airplane's calculated maximum performance, which increased to Mach 2.47 at 70,000 feet. Work on the RCS installation began in February 1957. Not part of the original design, the system had to be shoehorned into the aircraft.

Due to the X-1B's design the placement of the thrusters was unusual, if reminiscent of the Iron Cross, arranged as it was to provide "the largest possible moment arm."<sup>19</sup> The single pair of roll thrusters was mounted in the left wingtip, with one pointing up, the other down. The yaw thrusters were in the rear fuselage, pointing left and right and placed ahead of the empennage. The pitch thrusters' location was the most unusual. One thruster was in the underside of the fuselage, pointing down; placed aft of the center of gravity: it caused the nose to pitch down. The

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<sup>16</sup> Waltman, *Black Magic and Gremlins*, 153, 154.

<sup>17</sup> Stillwell and Drake, "Simulator Studies Of Jet Reaction Controls For Use At High Altitudes," 13, 14. Photos from the period show the Iron Cross in its final configuration with the enclosure.

<sup>18</sup> This also afforded a built-in ejection seat, something not provided in the original X-1.

<sup>19</sup> James E. Love and Wendell H. Stillwell, *The Hydrogen-Peroxide Rocket Reaction-Control System For The X-1B Research Airplane* NASA TN D-185, (Edwards, CA: NASA Flight Research Center, 1959, 5.

other pitch thruster was at the extreme aft end of the fuselage, just above the engine nozzles and behind the rudder, and caused the aircraft to pitch up when fired.

A separate control stick in the cockpit, mounted horizontally on the left side of the instrument panel, was used to fire the thrusters based on the experience from the Iron Cross. Firing the thrusters was an on or off selection, and the thruster's energy level was fixed. When the pilot moved the stick it operated microswitches connected to solenoid valves for each thruster; when a valve opened a solution of 90 percent hydrogen peroxide was forced over silver-coated stainless steel screens. The hydrogen peroxide decomposed into 1,300 F steam which expanded out the thruster. One of its advantages was that it was a monopropellant, but hydrogen peroxide had the disadvantage that it also decomposed on contact with organic materials and was highly corrosive.<sup>20</sup>

In February 1957 work began on instrumenting the X-1B for the RCS research flights and by the end of March the installations and the high-altitude instruments were about 70 percent complete.<sup>21</sup> By the end of April, two ground runs of the four-chamber XLR11 rocket engine had been made; the only thing left was the thruster nozzles themselves, being manufactured by Bell Aircraft.<sup>22</sup>

In July 1957 Neil A. Armstrong joined Butchart as pilot on the X-1B research project. Armstrong transferred to the High-Speed Flight Station from the NACA's Lewis Research Center in 1955, and over the next two years flew a wide range of aircraft at the HSFS. He had been flying an F-51 chase plane when the X-1A exploded, had been the co-pilot on the P2B-1S launch aircraft on March 22, 1956 when that aircraft lost a propeller and suffered severe damage, but he did not yet have any rocket experience.

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<sup>20</sup> Love and Stillwell, "The Hydrogen-Peroxide Rocket Reaction-Control System For The X-1B Research Airplane," 5. The larger advantage of H<sub>2</sub>O<sub>2</sub> was in its non-toxic nature compared to typical rocket propellants such as dimethyl hydrazine or red fuming nitric acid. The concentrated compound was regularly used over the years at the center either as a thruster propellant or to spin turbines via steam, thus generating electricity for an aircraft.

<sup>21</sup> Because H<sub>2</sub>O<sub>2</sub> freezes at 18° F and the X-1B would experience temperatures of -40° to -100° F between launch to flight, engineers and technicians insulated the 2.4-gallon tank and arranged to heat it electrically during flight to ensure the compound did not freeze. Love and Stillwell, "The Hydrogen-Peroxide Rocket Reaction-Control System For The X-1B Research Airplane," 3-4.

<sup>22</sup> X-1B Progress Reports, February 1 to February 28, 1957; March 1 to March 31, 1957, and April 1 to April 30, 1957, File L1-3-11A-1, NASA Armstrong Historical Reference Collection.

Armstrong made his first X-1B pilot familiarization and checkout flight on August 15, 1957, during which no. 2 rocket chamber failed to light after the aircraft was released from the launch plane. Despite this, he reached a speed of Mach 1.32 at an altitude of 45,000 feet on the remaining three chambers. The approach and flare to the lakebed landing was normal but the X-1B touched down nose wheel first; the aircraft skipped and the nose wheel sheared off: as the X-1B skidded across the lakebed the underside of the fuselage and LOX tank were damaged. Such landing problems were not uncommon with the X-1 aircraft. The damage required six-weeks to repair.<sup>23</sup>

On Friday, October 4, 1957 the aircraft was down, “awaiting reaction control wingtips.”<sup>24</sup> That evening, while most of the center’s pilots were down in Los Angeles at the first gathering of the Society of Experimental Test Pilots, the world changed when the Soviet Union launched the first manmade satellite.

### **X-1B RCS Research Flights**

As the post-Sputnik controversy grew, preparations continued for the RCS flights.<sup>25</sup> The first flight to test the system came on November 27 with a new pilot to the program, John B. “Jack” McKay. RCS inputs in flight were limited to roughly one-second duration about all three axes. McKay made the test at Mach 1 and 60,000 feet but the RCS operated poorly.<sup>26</sup> A ground run of the RCS on December 10 went badly and by the time the engineers and technicians sorted out and fixed the problems, rain had closed Rogers Dry Lake.<sup>27</sup> Bear in mind that even if the launch aircraft took off from the main runway at Edwards, the experimental aircraft landed on

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<sup>23</sup> Neil Armstrong pilot report, Flight 14, August 15, 1957, File L1-3-11A-3, and X-1B Progress Reports, August 1 to August 31, 1957, File L1-3-11A-1. NASA Armstrong Historical Reference Collection.

<sup>24</sup> X-1B Log Book, File L1-3-11A-2, and X-1B Progress Reports, September 1 to September 30, 1957, File L1-3-11A-1. NASA Armstrong Historical Reference Collection.

<sup>25</sup> X-1B Log Book. NASA Armstrong Historical Reference Collection. There are no entries between that of October 8, 1957, which states that the work was still in progress, and the November 8 entry about the ground test.

<sup>26</sup> X-1B Progress Reports, November 1 to November 30, 1957. File L1-3-11A-1. NASA Armstrong Historical Reference Collection.

<sup>27</sup> The rocket planes, and many of the other experimental aircraft in the period, operated on and off of the immense lakebed that was the *raison d’etre* of Edwards Air Force Base because of the miles and miles of possible runways in almost any direction. Despite this attribute, seasonal rains often flooded portions of the lakebed and softened the rest, suspending such operations until the lakebed could dry out sufficiently.



the dry lakebed. When the winter rains came they usually flooded portions of the lakebed and softened the rest enough to make them unusable for a time.

With the New Year, the rains held off, the lakebed dried out, and on January 6, 1958, engineers, technicians and mechanics completed ground tests of the rocket engine and the RCS, clearing the way for the second RCS checkout flight.<sup>28</sup>

But it was not until January 16 that the flight actually took place, with Armstrong as the pilot.<sup>29</sup> Nestled in the bomb bay of the B-29 at 25,000 feet he was unable to get pressure readings from either the hydrogen peroxide tank or the RCS, even though the crew of the B-29 and pilot of the chase plane noted the RCS firings. They decided to press ahead but to make the launch closer to the lakebed.<sup>30</sup>

After the drop Armstrong lit the rocket motors and began a Mach 0.76 climb from 26,500 feet, firing each of the six RCS thrusters in turn for one second. He then flew a relatively low-altitude/low Mach number profile, shut down two of the rocket engine chambers, and a third soon after, made a complete set of RCS firings, and came in for a landing, again firing all RCS thrusters on the way in.<sup>31</sup> It was a success.

The resumption of the X-1B RCS flights was scheduled for May 28, but during a preflight inspection of the aircraft they found four cracks in the bottom of the LOX tank. These were welded closed and the areas X-rayed, but equipment failure led to more X-rays and new photos, which revealed persistent internal cracks.<sup>32</sup> The aircraft was parked for good.<sup>33</sup>

## **The JF-104 RCS Research Aircraft**

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<sup>28</sup> X-1B Log Book, File L1-3-11A-2. NASA Armstrong Historical Reference Collection.

<sup>29</sup> Daily Diary 1958, File L3-10-1A-2, NASA Armstrong Historical Reference Collection.

<sup>30</sup> It was not uncommon for one or more of the XLR11's four combustion chamber's not to fire on a flight, so the decision was not as radical as it may appear. At the very least, if no chamber lit, he'd be able to dump his propellant if need be en route to a landing.

<sup>31</sup> Neil Armstrong flight report, X-1B flight 16, January 16, 1958, File L1-3-11A-3, NASA Armstrong Historical Reference Collection.

<sup>32</sup> Daily Diary 1958 and X-1B Progress Reports, January 1, 1958 to January 31, 1958, X-1B Log Book, X-1B Progress Report, May 1 to May 31, 1958. File L1-3-11A-1. NASA Armstrong Historical Reference Collection.

<sup>33</sup> X-1B Progress Reports, June 1 to June 30, 1959. File L1-3-11A-1. NASA Armstrong Historical Reference Collection.

Following the grounding of the X-1B, in June 1958, HSFS chief Walt Williams met with his staff regarding the unfinished program. Among those attending the meeting were Hubert “Jake” Drake, Kenny Klienknecht, Joe Vensel, and Jim Adkins. Williams made it clear, Adkins later recalled, that “we had to have this reaction control program that he had promised and someone had better come up with a way to get the job done.” Adkins commented to Drake during the meeting that he thought they could do the RCS tests using an F-104. After the meeting Drake cornered Adkins and told him to “prove it.” Adkins, who described himself as “just one of many young and foolish engineers with imagination,” set to work.<sup>34</sup>

Adkins gave his briefing three weeks later: it lasted several hours, forcing the attendees to skip lunch. When he’d finished, Williams asked him when could he start, how long it would take, how much it would cost, how many people would be needed, and who they were? To the answers Williams provided \$60,000 in startup money along with help from Keith Anderson and Wendell Stillwell, who’d done early RCS modeling work on the GEDA. Adkins could also call on engineers Jim Love and Perry Row.<sup>35</sup> Within weeks he’d assembled a team of 18 engineers, technicians, and shop personnel.

The first F-104 delivered to the NACA, a pre-production aircraft, was now modified for the RCS program and designated a JF-104, and Joseph A. “Joe” Walker was named the project pilot.<sup>36</sup> Walker had flown P-38s for the Army Air Forces in North Africa during WWII and joined the NACA after the war. He was an accomplished rocket plane pilot by this time and would become the first NASA pilot to fly to the X-15.

The JF-104 gave the RCS project a major advantage over the X-1B. The rocket plane required extensive preparations before flight, not to mention a separate launch platform; the JF-104, on the other hand, was an operational aircraft capable of multiple flights a day. All the modifications were done in-house at the High-Speed Flight Station.

Reflecting everything learned to date, the JF-104 RCS was a more mature design than that in the X-1B. One requirement was that no plumbing with hydrogen peroxide be routed internally. Instead, hydrogen peroxide tanks and tubing were placed in close proximity to the

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<sup>34</sup> Letter from Jim Adkins to Betty Love, n.d., personal collection.

<sup>35</sup> Ibid.

<sup>36</sup> In U. S. Air Force nomenclature the prefix J denotes an aircraft that has been temporarily modified for test purposes.

thrusters, minimizing damage to the aircraft from leaks of the corrosive propellant. The four pitch and yaw thrusters were mounted in the nose cone of the aircraft, along with their spherical hydrogen peroxide tank (in place of a radar). Furthermore, the design of the hydrogen peroxide tanks was similar to that already planned for the X-15. Each wingtip had a pod that contained a downward-pointing roll thruster, tubing, and hydrogen peroxide tank, making them self-contained.<sup>37</sup>

Walker made the first RCS flight on July 31, 1959, taking the aircraft to 30,000 feet, Mach 0.8, and a minimum value of  $q$  of 280 psf. When he pressurized the RCS, the roll rocket blowout discs ruptured, causing the hydrogen peroxide to jettison, leaving only the pitch and yaw rockets to be tested. Nevertheless, he found the aircraft responded to the thruster firings as predicted—at least those that were still functioning.<sup>38</sup>

He flew the JF-104 again on September 16, and on September 21: these structural and stability test flights cleared the way for an operational checkout of the RCS in early October.<sup>39</sup> On October 2, 1959 he took off for the first zoom flight, wearing an Air Force partial pressure suit because of the intended altitude.<sup>40</sup>

Flying west before turning back toward Edwards he made a 3g pull up at Mach 1.92 when he was closer to Edwards than planned, as he later put it, “in the interests of getting the

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<sup>37</sup> Donald Reisert and Elmor J. Adkins, “Flight And Operational Experience With Pilot-Operated Reaction Controls,” *American Rocket Society* (March 13-16, 1961), 4-7, and Joseph A. Walker, “Investigation of Aircraft Control By Use of Reaction Of Small Rocket Motors,” *Society of Experimental Test Pilots Newsletter* (November 1960), 7-9.

<sup>38</sup> J.A. Walker, “Pilot’s Flight Report F-104, No. 96, Subject: Initial flight and ground evaluation and operation of reaction control installation,” (n. d.), F-104 Notebook, NASA Armstrong Historical Reference Collection. File L1-3-10B-1. NASA Armstrong Historical Reference Collection.

<sup>39</sup> Chart: F-104 #961 Reaction Control Airplane, F-104 Notebook, and Reisert JF-104 #961 notebook. File L1-3-10B-3. NASA Armstrong Historical Reference Collection.

<sup>40</sup> This was a precursor to the three Air Force NF-104s, aircraft specifically modified for zoom climbs and intended as trainers for the exoatmospheric portion of flight in the X-15 and Dyna-Soar (X-20). Compared to a stock F-104, the NF-104s had extended wings, RCS, and a Rocketdyne AR2-3 rocket motor (6,000lbs of thrust) added above and just behind the jet exhaust nozzle. Typically starting the maneuver at 35,000 feet, pilots accelerated to Mach 1.9-2 and began the zoom climb. In the JF-104 the climb ended when the aircraft reached an altitude at which oxygen levels were too low to sustain combustion and the jet engine died; not long after this the aircraft exhausted its inertia and descended. The NF-104s pilots did the same and then fired the rocket motor when the jet died of oxygen starvation and continued to climb until its fuel was spent, often cresting above 110,000 feet, where  $q$  was very low indeed and RCS was critical. In spite of its intended purpose, the NF-104 was ultimately used by the Air Force’s Test Pilot School as a teaching and research tool and not as a trainer for the X-15 or X-20 (which was never built). The N prefix denotes a permanent modification to an aircraft in the Air Force nomenclature.

maneuver before leaving the Rogers Lake area.” Holding a steady 4-degree angle-of-attack during the climb, began using the RCS before the aircraft reached peak altitude and found “they performed admirably.” In fact, he used RCS to control his angle of attack during much of the ascent, both to maintain his AoA and to correct divergences.<sup>41</sup> He reached 78,000 feet and Mach 1.18. Q at peak altitude was 62.5 psf.<sup>42</sup> Walker concluded: “this program has at last reached a stage where operational prosecution of the research program can be carried on successfully.”<sup>43</sup>

He went on to make a series of RCS flights in the JF-104 between March and August 1960, after which several other X-15 pilots made flights in the aircraft.<sup>44</sup> Although these flights continued into 1961, the RCS work was coming to a close, having demonstrated the system’s reliability and performance. The aircraft was now being used for pilot familiarization, X-15 weather checks, and X-15 dead stick landing practice. The goal of both the X-1B and JF-104 RCS projects were limited and short term.<sup>45</sup>

### **The X-15 and Mercury RCS Designs**

By the time the JF-104 flights were drawing to a close, the X-15 was beginning its early research flights.<sup>46</sup> The relationship between the data collected from the JF-104 RCS flights and the final design of the X-15's RCS was clear: eight yaw and pitch thrusters were located on the nose of the X-15 while two roll thrusters were positioned near *each* wing tip. Because a failure of the RCS at high altitude could lead to the loss of the X-15, the thrusters were divided into two separate, redundant systems. During the JF-104 flights, engineers tested a Reaction

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<sup>41</sup> Pilots Flight Notes, F-104 #961, January 29, 1960, Chart: F-104 #961 Reaction Control Airplane. File L1-3-10B-2. NASA Armstrong Historical Reference Collection.

<sup>42</sup> The “standard day” parameters, the internationally accepted, arbitrary reference point for aviation and metrology, is 59 degrees F and 14.7 lbs per inch, squared; thus, contrasted with Walker’s 62.5 psf q at 78,000 feet, q at sea level would have been 2116.8 lbs per sq. ft. (after reconciling all of the variables, including the shift to lbs per sq. *foot*).

<sup>43</sup> Pilots Flight Notes, F-104 #961, January 29, 1960, Chart: F-104 #961 Reaction Control Airplane. File L1-3-10B-2. NASA Armstrong Historical Reference Collection.

<sup>44</sup> The X-15 began flying in 1959, and although to that point it was only being flown by North American Aviation pilot A. Scott Crossfield during the acceptance flights, the program’s first group of pilots had already been selected.

<sup>45</sup> Roy Bryant, phone interview with Curtis Peebles, March 16, 2004.

<sup>46</sup> The first X-15 research flight came on March 25, 1960, with Joe Walker at the controls; it was the 9<sup>th</sup> flight of the X-15. Richard P. Hallion and Michael H. Gorn, *On the Frontier: Experimental Flight at NASA Dryden*, (Washington, D.C., Smithsonian Institute, 2003), 407.

Augmentation System (RAS) to increase the stability of the aircraft at low dynamic pressure. North American Aviation, the X-15's builder, proposed a RAS also be added to the X-15. Armstrong, Walker, and Air Force Maj. Robert White (another X-15 pilot) each flew a simulation of the RAS and agreed that it that made the simulation easier to fly. In 1963 a RAS was added to X-15 numbers 1 and 2. By this time, human spaceflight was a reality.<sup>47</sup>

Within a few days of NASA's establishment, on October 1, 1958, Administrator T. Keith Glennan gave his approval to develop Project Mercury.

Like the X-15, the thrusters aboard the Mercury capsule used 90% hydrogen peroxide, and the tanks had pressurized bladders to expel the propellant.<sup>48</sup> The design of the thrusters was also the same as those on the X-15: a cylindrical body with the nozzle pointed to the side. Silver-plated catalyst beds caused the hydrogen peroxide to decompose into steam. The capsule's eighteen thrusters came in three sets of six, with different maximum thrust levels – the 6-pound and 24-pound “high-torque” thrusters, and 1-pound “low torque” thrusters for fine attitude control.<sup>49</sup>

## Conclusion

In terms of design and mode of operation, a single thread runs from the analog computer simulations initiated by the NACA engineers and pilots on the Air Force's GEDA, the Iron Cross RCS, the X-1B RCS, the JF-104 RCS, the X-15 RCS, the Mercury spacecraft RCS. It even extends to the later Lunar Landing Research Vehicle's thrusters fly-by-wire control system, the LLTV, the Gemini and Apollo spacecraft, and the shuttle. If the Mercury flights showed that humans were able to function successfully in weightlessness (to the surprise of some—quite literally), the RCS in all subsequent human populated spacecraft was designed to enable a wider range of activities, including orbital changes and docking with other spacecraft. It started with

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<sup>47</sup> Dennis R. Jenkins, *X-15 Extending: The Frontiers Of Flight*, (Washington, D.C.: NASA SP-2007-562), 414.

<sup>48</sup> The choice of the chemical compound directly reflected the work done at the High Speed Flight Station as well as the early state of affairs: soon H<sub>2</sub>O<sub>2</sub> would be replaced with more energetic fuels by volume. Loyd S. Swenson, Jr., James Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury*, Washington, D.C.: NASA SP 4201, 1998), 195.

<sup>49</sup> *Results Of The First United States Manned Orbital Space Flight*, February 20, 1962, pp. 11, 12, <http://www.hq.nasa.gov/office/pao/History/SP-6/ch1.htm>, accessed July 21, 2013.

the X-15, which demonstrated the RCS's ability to function on a vehicle that eventually flew to space and landed as an aircraft, over and over, long before the shuttle was ever built.

In 1970 Neil Armstrong provided perhaps the greatest testament of the RCS' value when he recounted to members of a review panel at the Johnson Space Center landing on the moon. In the final stages of descent he found the LM headed for a field of boulders the size of cars so he took manual control of the spacecraft and maneuvered it across the moon's surface to a different site. "I will admit that in my approach you'll see a lot more attitude changes and throttle changes than you would like to see; still, I felt very comfortable—I felt at home. I felt like I was flying something I was used to, and it was doing the things that it ought to be doing."<sup>50</sup> He was crediting his experience in the LLRV and LLTV, both of which operated in lunar simulation with hydrogen peroxide powered thrusters. At the time that Day, Reisert, Weil, and Stillwell began working on the first RCS simulation for the GEDA in 1954 they weren't thinking of their thruster system being used prepare someone to land on the moon: they were planning on a reusable vehicle bound for the edge of space. Of course, their system worked on other spacecraft, but variations of it worked on Earth as well as training devices.

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<sup>50</sup> Neil A. Armstrong, NASA MSC Minutes of Meeting of Flight Readiness Review Board, Lunar Landing Training Vehicle, Houston, TX, 12 January 1970.