The Incredible Rocket-Engine Laser

By JEFF HECHT

Charles Townes's original laser proposal envisioned a low-power coherent light source for communications. Theodore Maiman's demonstration of the first laser at Hughes Research Laboratories in 1960 produced bright pulses of red light and gave great hopes for bigger and better things, especially in the Pentagon. Two years later, a Sunday newspaper supplement feature titled "The Incredible Laser: Death Ray or Hope" illustrated with science-fictional laser cannons, opined:

> The laser may have greater impact than any discovery so far in the burgeoning field of electronics, which has already brought us radar, transistors, satellite tracking networks, [and] TV. The technological revolution it brings about may dwarf any in the past [1].

This historical article traces the invention of the gas-dynamic laser, how it successfully generated high powers, and how it failed to meet the requirements for usable directed-energy weapons and became, in the words of one observer, "a ten-ton watch."

Behind closed doors, military laboratories tried to scale up Maiman's design, in which bursts of light from a coiled flash lamp powered a tiny ruby rod. Hughes Research Laboratories tried making bigger ruby lasers (quoted in [2]). AT&T's Bell Telephone Laboratories developed crystals doped with the rare-earth neodymium, which emitted more light than ruby, but crystals were small and hard to grow [3]. Then Elias Snitzer at American Optical Company added neodymium to optical glass, first in the form of millimeter-thick fibers [4], and later—prompted by military interest—as laser rods a few inches thick [5].

Those advances led the Pentagon to budget $5 million—big money in the early 1960s—for Project SEASIDE to develop pulsed solid-state laser weapons [6]. Air Force Chief of Staff, General Curtis E. LeMay, became a laser enthusiast, briefing a reporter that a speed-of-light laser beam would be invaluable for intercepting Soviet ICBMs [7, pp. 6–7]. A firm called Technology Markets Inc. envisioned a $1.25 billion market in 1970 for "huge lasers, not unlike the anti-aircraft searchlights of World War II, that would roam the heavens, seeking out incoming missiles and destroying or diverting them with the powerful beams of light" [8, p. 25].

Project SEASIDE contractors succeeded in making big laser rods, but they self-destructed when fired [6, p. 122]. "The glass was beautiful from the point of view of optical quality; you could look through a long length like that and could see no thread-like flaws, no ripple at all. [But] when you make laser rods of it, and you start to lase it, you blow it up every time," recalled Snitzer [5]. Tiny metal particles from platinum crucibles left in the laser glass expanded when they absorbed laser light, shattering the glass [6, p. 125].

The solid-state lasers of the mid-1960s had many other problems too. Only a fraction of a percent of the input electrical power emerged as laser energy, so a weapon-grade laser would need gigawatts of input power, and the waste energy would heat the glass so much so that it could not focus the beam. "We showed conclusively that you really just couldn't get there," recalled Donald Lamberson, looking back to his experience as a young Air Force captain in 1963 [8, p. 16].

By then, two other families of lasers had been developed. The first were gas lasers, in which electric discharges through a gas-filled tube excited atoms in the gas to emit laser light. The second were semiconductor diode lasers, in which current

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passing through a semiconductor like gallium arsenide emitted light. Both had mirrors on opposite ends to produce a laser beam, as in a solid-state laser. Early versions of both emitted only milliwatts of coherent light, but that was enough to excite researchers in many fields.

Gradually, the output power of some lasers crept up to watts. Solid-state laser pulses grew powerful enough to measure the range to military targets or designate targets for smart bombs to home in on them.

Yet, no laser came anywhere near military needs for missile defense. In 1965, Project SEASIDE was limping to a close with little to show for its investment. Then the rocket engine laser emerged just in time to revive hope for laser weapons.

I. ROCKET ENGINE CONNECTION

The first step was initiated at the Bell Labs, where Ali Javan, William Bennett, and Donald Herriott demonstrated the first gas laser in 1960 in a helium and neon mixture. In 1963, C. Kumar N. Patel, a young Indian-born physicist at Bell, wondered if molecular gases might be able to generate higher powers because molecules have vibrational transitions that are easier to excite than the higher-energy electronic transitions of monatomic gases like neon. He calculated that carbon dioxide would make a good laser, and pure CO_2 worked for the first time. "We got ten milliwatts on the first shot," Patel recalled. Adding nitrogen made a dramatic improvement. "You put the two things together and the next day you get 10 watts from the same tube that gave you ten milliwatts before." Patel was pleasantly surprised. A series of experiments increased the power to about 200 W by mid-1965, a record power for a continuous laser beam [9].

By that point, military laboratories had gotten interested and were beginning to duplicate his results, with plans to reach kilowatt power by a much bigger tube. Experiments at that level would be classified, but Patel was not yet a U.S. citizen, so he could not get a clearance. With Bell having no interest in competing with military laboratories, Patel turned to experimenting with CO_2 lasers rather than building bigger ones [10].

One military laboratory that had been watching Patel's work was the Avco Everett Research Laboratory near Boston. Its founder, Arthur Kantrowitz, was an expert in gas dynamics, who wondered how he might be able to use that expertise to increase laser power after hearing a talk by laser pioneer Charles Townes [11].

Kantrowitz, born in 1913 in New York City, had earned his doctorate under Edward Teller at Columbia, and then joined the Cornell Faculty [12]. In 1954, he had a fateful cocktail chat with an Air Force officer and the President of Avco Corporation about the difficulty of engineering nuclear warheads to withstand re-entry into the atmosphere. Kantrowitz boasted he could solve the problem in six months. The officer said the Pentagon would pay to solve that problem, and Avco offered to support the laboratory. Kantrowitz picked the Everett site, an old tire warehouse, for its proximity to MIT, Harvard, and good sailing [13, pp. 35–36].

His effort was a huge success, leading to the ablative coverings still used on space capsules returning to Earth [14]. It gave Kantrowitz a reputation as a wizard in the world of fluid and gas flow, important in a wide range of fields, and the head of a well-regarded laboratory where, despite a formal management structure, in practice everyone reported to him [15].

Among them was Edward T. Gerry, an MIT graduate student working part time at Avco while finishing his doctoral thesis, who ran into Kantrowitz's office with a copy of Patel's first article in 1964. Avco was already working on gas flow in lasers, but the laboratory had been stuck with a misconception dating back to the 1930s. Although the three atoms in CO_2 molecules vibrate in different ways, physicists had long thought all three vibrations died down at the same rate, like piano keys held down, so the notes fade slowly. But Patel's experiment showed that the molecular vibrations faded at different rates, as if you took your fingers off some keys but not others.

Kantrowitz quickly realized that Patel's observation meant that expanding hot CO_2 quickly through a nozzle into a low-pressure chamber could produce a population inversion, leading to laser emission. Initially, he thought of zapping the gas with an electric charge, as Patel had, as well as using Avco's expansion technique. But soon Gerry and others at Avco realized that no electrical excitation was needed. The same idea came independently to Nikolai Basov in the Soviet Union and Abraham Hertzberg at Cornell [11].

As a defense contractor, Avco Everett sought lasers powerful enough to kill hard targets like ballistic missiles and nuclear weapons. The CO_2 laser already could deliver the highest power of any laser emitting a continuous beam rather than submillisecond pulses, giving it a head start in the race to deliver lethal energy to potential targets. It emitted near 10 μm, a wavelength in the long-wave infrared at which air is reasonably clear, a crucial attraction for laser weapons because the beam must reach the target, and air is opaque in much of the infrared. But the energy that a 200-W beam could deliver to an incoming nuclear warhead was orders of magnitude below what was needed to shatter the heat shield so it would burn up on entering the atmosphere.

Kantrowitz and Gerry calculated that missile defense would require about a megawatt of laser output that could be focused onto the target for long enough to deliver the energy needed to destroy the target. "Lasers were not that efficient at the time, so you needed to get rid of a lot of waste heat. The best way to do that was to flow it away, the famous garbage disposal principle," said Gerry [16]. Once the gas passed through the nozzle into the laser chamber, it would pass between a pair of mirrors that would extract infrared laser emission from CO_2 molecules to produce a beam that could be focused onto the target. Energy remaining in the hot flowing gas after the laser energy was extracted would be blown out the exhaust, removing the waste heat. The physics behind this was similar to that of a rocket engine, which Gerry and Kantrowitz knew could generate a gigawatt of raw thermal power. “If you could capture one percent, or just a tenth of a percent of the energy in laser light, you were there” with the megawatt-class beam needed for a laser weapon, Gerry said [16].

What Avco called a gas-dynamic laser was simple. It burned cyanogen—a heavy poisonous gas with the formula $(CN)_2$—in oxygen to produce a mixture of hot carbon dioxide and nitrogen [15], which flowed through the system, emitting light after the chemical reaction. The laser worked better with the mixture of nitrogen and CO_2 than with CO_2 alone. “It was a very simple thing, but not an efficient laser,” says Gerry. Yet, efficiency was not essential for demonstrating the potential of a laser weapon. If the gas-dynamic laser could generate a gigawatt of raw power, it only needed to convert a few tenths of a percent of the flow-generated energy into light to make a megawatt of laser power [16].

Experiments started in a shock tube, a small-scale, high-speed version of a wind tunnel, followed by a series of increasingly large combustion-driven lasers. They produced a good quality beam and record power of 10 kW after Gerry accidentally introduced water vapor into the mixture of nitrogen and carbon dioxide [8, p. 17]. By the time their rocket-engine lasers reached 20 kW, they knew they could reach the power thought to be needed for weapons [16].

Avco’s marketing manager, Ben Bova, organized a briefing to inform Pentagon officials of the breakthrough. He was an apt hire; Bova was a budding science fiction writer who had already published two novels [17]. Pentagon scientists had written off gas lasers as unable to generate the needed energy and were stunned to discover that the Avco rocket-engine laser was more like a flamethrower than a flashlight [13, pp. 44–45]. Later, after publishing more novels and becoming editor of *Analog Science Fiction/Science Fact,* the field’s top magazine, Bova told fans at a Boston-area science fiction convention that his job at Avco had been to write a special type of science fiction for military audiences [18].

The Pentagon classified the breakthrough, but ARPA and the Institute for Defense Analyses initially remained wary of the unfamiliar technology. It was partly “not invented here” and partly ignorance. The agencies asked other contractors to scale up electrically powered CO_2 lasers based on Patel’s design. Those lasers converted more of the input power into light, but had no way to get rid of the waste heat and hence became useless behemoths. Hughes needed over 16 m of tubing to generate 1.5 kW for ARPA [19, p. 41]. Raytheon generated 8.8 kW and claimed 13% efficiency, but required about 180 m of tubing [20], [21]. At those sizes and power levels, they could not compete with the rocket-engine laser.

Progress with rocket-engine lasers soon spoke for itself. AVCO cranked the power up to an impressive 138 kW with its MK-5 system in March 1968. United Aircraft’s Pratt & Whitney division also got into the race, trying to win business from the Air Force, and built the XLD-1 laser at its new test facility in West Palm Beach, FL, USA, that reached 77 kW in April. Avco gradually wore down Pentagon committees sent to investigate and its results finally changed minds. “The change from the Pentagon refusing and resisting to fund anything to everybody wanting to fund it took place about 5 o’clock one evening,” Kantrowitz recalled. “Suddenly all the [armed] services wanted to get us under contract” [6, p. 140].

II. EIGHTH CARD

In 1968, ARPA launched a hush-hush classified project to scale up the gas-dynamic laser, code-named EIGHTH CARD, a play on the advantage an eighth card could give in seven-card stud poker [8, p. 24]. Only people invited to work on the project could get information, even if they already had a secret clearance [15]. Even the term “gas-dynamic laser” was highly guarded, and no one in the military called it a rocket-engine laser [22]. At the same time, the Air Force Weapons Laboratory, Kirtland, NM, USA, separately sponsored rocket-engine laser development both at Avco and Pratt & Whitney in Florida [8, pp. 18–22].

The goals of the two programs began to diverge. ARPA continued to focus on defense against Soviet nuclear ballistic missiles. Keenly aware that Basov, who shared the 1964 Nobel Prize in physics with Townes and Alexander Prokhorov for their work on lasers, was working on gas-dynamic lasers [23] and had high-political connections in Moscow [24], ARPA leaders worried about a Soviet breakthrough in laser weapons.

The Air Force Weapons Laboratory, on the other hand, took the lead for the armed services in studying prospects for battlefield laser weapons. In March 1969, it signed a $5.8 million contract with Avco to build three 150-kW rocket-engine lasers, so each service could conduct its own tests. In the summer of 1970, Avco was to deliver one “Tris-ervice” laser to the Weapons Laboratory, a second to the Army Redstone Arsenal in Huntsville, AL, USA, and a third to the Naval Research Laboratory in Washington, DC, USA [8, pp. 20–25]. Avco also built huge pulsed flowing-gas carbon-dioxide lasers powered by lightning-like bolts of electricity, with names like Thumper and Humdinger [25].

Although the Pentagon kept the nature and goals of EIGHTH CARD highly classified for a long time, they declassified the rocket-engine laser concept in 1970—years after Basov published it openly in Soviet journals [26], [27]. Gerry was allowed to disclose the concept at an April 1970 conference of the American Physical Society and followed that with a detailed article in *IEEE Spectrum* that included a low-resolution photograph (see Fig. 1) [28]. But Gerry could not mention that power had exceeded 50 kW, even though Avco had

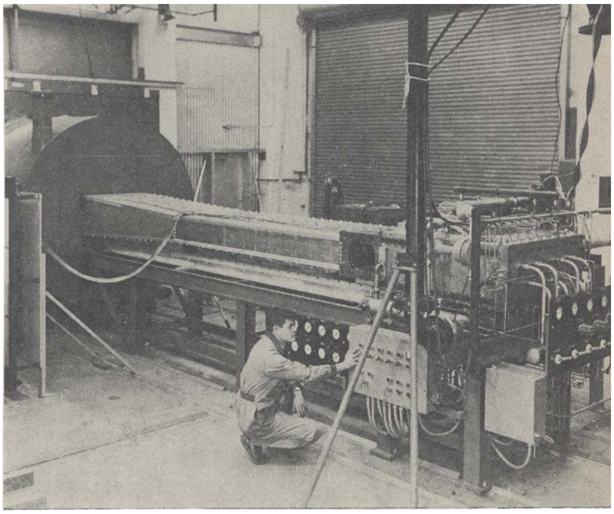

Fig. 1. ***First published photograph of a gas-dynamic laser being tested at the Avco Everett Laboratory, published as Fig. 11 on page 57 of the November 1970 issue of*** **IEEE Spectrum*****. Gas flows along the length of the tube; the infrared laser beam emerges from the circular aperture on the side.***

already passed 100 kW. That left some of his graphs cut off abruptly on the one side at the security limit [15]. At an American Physical Society press conference, Gerry compared the beam's power to that of a small car engine, and he was surprised the next morning to see a headline reading "Laser Powers Small Car" [16].

III. TRISERVICE LASER

The Triservice Laser program was the sort of a bold idea that gets people into trouble. Avco had optimistically thought they could easily scale their earlier rocket-engine to higher power. But once they started, they had to go back to basic physics to work out design problems. It took a year before the first parts of the Air Force version reached the Weapons Laboratory in April 1970, and it took another year and a half to reach the promised laser power. The Army and Navy versions lagged behind. Even then, the beam was so diffuse that it was more like a large searchlight emitting invisible heat rays than a deadly laser weapon [8, pp. 28–29].

Lamberson, who had earned a Ph.D. in aerospace engineering since pointing out the limits of solid-state lasers, had taken over the Weapons Laboratory's laser division in 1969 as a Lieutenant Colonel. He was bright, energetic, and charismatic, but he eventually ran out of patience with Avco. In December 1971, he pushed to take over the project, and within a year, the Weapons Laboratory had greatly improved the beam. They started firing laser shots at slow-moving drones in mid-1973. The first dramatic flash they saw came when the beam scorched metal supports on a water tower. When they improved their aim, they managed to burn through the skin of a drone, causing it to crash with only minor damage. On November 14, 1973, they managed to keep the laser focused on a drone's fuel tank for a little over a second, enough to heat fumes in the tank and trigger a satisfying explosion [8, pp. 30-41].

Details were kept classified for years, but a film of the test was finally shown at an April 1982 laser conference. The infrared laser beam slicing through the air was invisible, but a spot on the drone started to glow as the beam heated it, and eventually caught fire as the fuel tank ruptured. In a second test, the laser cut control wires and caused the drone to crash out of control [29, p. 284]. It was a long way from the instant death of a science-fiction death ray, but it showed the rocket-engine laser's destructive potential and helped convince military leaders to keep supporting laser weapon development [8, pp. 41-42]. Yet, much more remained to be done.

IV. BETTER LASERS THROUGH CHEMISTRY

Gerry's 1970 article on gas-dynamic lasers noted that reacting different chemicals in rocket-engine lasers could produce other laser wavelengths [28]. The most important new chemistry was the reaction of compounds containing hydrogen with others containing fluorine to produce excited hydrogen fluoride (HF) molecules. A 1969 demonstration by The Aerospace Corporation generated up to 630 W of infrared light, about 12% of the energy from the chemical reaction [30]. The chemistry was potentially nasty; the resulting HF is an acid so strong that it can etch glass, therefore, it had to be captured and detoxified. However, the wavelength was only a third that of a CO_2 rocket-engine laser, so the focusing optics could be much more compact, which attracted military interest [31].

One issue was that chemical HF lasers normally emit at 2.6–2.9 μm, which air absorbs strongly. Fortunately, replacing the common isotope hydrogen-1 with the heavier deuterium (hydrogen-2) shifts the wavelength to around 3.8 μm, where air is more transparent [30]. That makes it attractive as a weapon, but a very expensive one because deuterium costs thousands of dollars per kilogram. HF or deuterium fluoride (DF) could generate more power from a rocket-engine laser than CO_2. The size of laser output optics scales with wavelength, so a 3.8-m mirror can focus a DF beam to the same size spot as a 10-m mirror can focus a CO_2 beam. The shorter-wavelength mirror would cover only 13% as much area, making it much lighter.

Chemical rocket-engine lasers had reached the kilowatt level when Gerry moved to ARPA in 1971 to run its laser weapon program. With rocket-engine and discharge-powered carbon dioxide lasers having reached high powers, ARPA turned that technology over to the armed services to focus on developing more advanced lasers. At ARPA, Gerry supported the Baseline Demonstration Laser, the first high-energy chemical rocket-engine laser [16], which exceeded a 100 kW in 1973, leading the way to higher power chemical lasers [32].

He also looked for other lasers that could generate higher powers at shorter wavelengths, which would allow the use of less cumbersome optics. The first success came from firing high-voltage electrical pulses into mixtures of rare gases and halogens. This led to rare-gas-halide "excimer" lasers, such as argon fluoride and krypton fluoride, which were briefly considered for weapon use in the 1980s, but now are widely used in eye surgery and semiconductor production [19, pp. 249–250]. The most promising short-wavelength chemical laser was the chemical oxygen-iodine laser (COIL), emitting on an iodine transition at 1.3 μm, first demonstrated in the 1977 [33].

Rounding up the state of laser progress in mid-1972, *Aviation Week* reporter Philip J. Klass wrote, "Most experts in the field agree that [continuous] power levels of at least a few megawatts should be available by the end of the present decade. There is more disagreement over the question of how big an impact such devices will have in military weapons, strategy and tactics." Although some "enthusiasts" expected laser weapons eventually to be able to block aircraft and missile attacks, he wrote, "even such visionaries agree that this time is at least several decades away" [34].

V. THREE SERVICES GO IN THREE DIRECTIONS

The three armed services took different directions on laser weapons, reflecting their different needs.

The Army, which needs to operate over all terrain, shoehorned an electrical carbon-dioxide into a tank-like vehicle. It shot down drones, but did not seem practical to Army officials, who largely abandoned laser weapons as being too cumbersome to operate in the field by the late 1970s [35].

The Navy was more interested in chemical lasers. Battleships can accommodate large equipment, but they needed a shorter-wavelength laser because water vapor in the marine environment absorbs the 10-μm light from the CO_2 lasers. After ARPA's Baseline Demonstration Laser test, the Navy teamed with the agency to build the Navy Advanced Chemical Laser which reached 400 kW with DF and shot down a couple of small missiles [36]. That laser was cumbersome, occupying a group of small buildings at a TRW test site in the hills east of San Juan Capistrano, CA, USA, but its performance impressed Navy officials [29, p. 285].

TRW then followed up with the Mid-InfraRed Advanced Chemical Laser (dubbed MIRACL) for the Navy (see Fig. 2). A maze of plumbing fed gases that burned to produce DF into reaction chambers where the hot gas emitted a laser beam fed into the SeaLite beam director and its 1.6-m mirror (see Fig. 3). Officially, it was the first megawatt-class continuous-beam laser when it was completed in 1980 [32]. Unofficially, the rocket-engine laser reached a record 2.2 MW [37]. However, by the time MIRACL was up and running in the early 1980s, the Navy had lost interest in it because moist marine air absorbed too much of the 3.8-μm DF beam for use as a shipboard weapon. Congress dropped MIRACL from the Navy budget, but made it the centerpiece of the Pentagon's High Energy Laser Systems Test Facility at the White Sands Missile Range. There, it performed more than 150 military tests over more than 15 years, including shooting down rockets and illuminating orbiting satellites [38]. Yet, the longest single test was 70 s, and the total lasing time during the program amounted to less than 1 h [39].

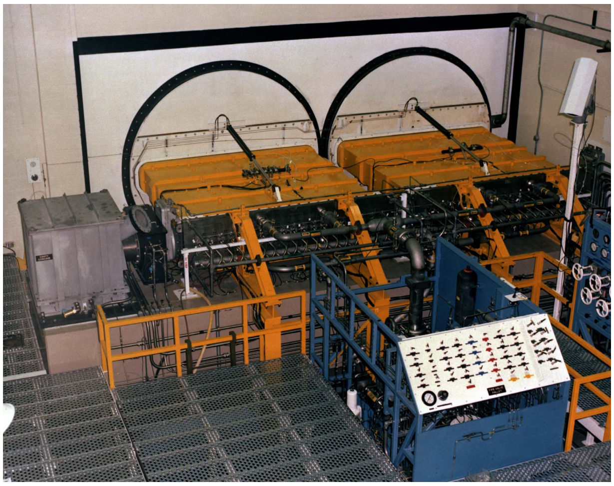

Fig. 2. ***Interior of MIRACL at the National High-Energy Laser Test Range shows the complex plumbing of the gas flow in a deuterium-fluoride rocket-engine laser (courtesy of U.S. National Archives).***

VI. GETTING THE AIRBORNE LASER LABORATORY OFF THE GROUND

The Air Force Scientific Advisory Board pondered the potential of laser weapons for much of 1969 and 1970. In the spring of 1971, the group met at Kirtland Air Force

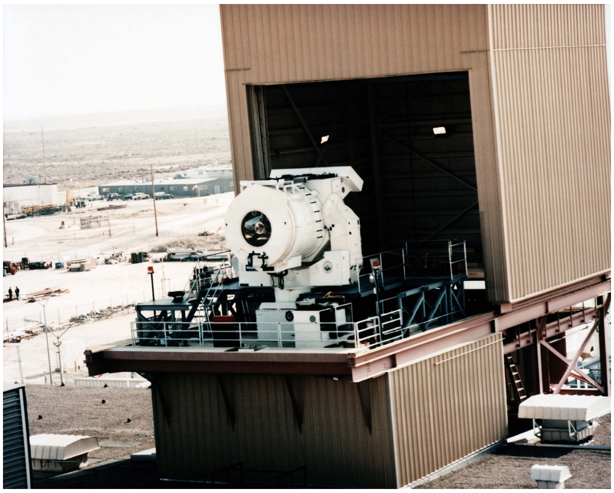

Fig. 3. ***Sea Lite beam director for MIRACL was steerable to aim at targets. The laser itself and the beam path to the beam director are out of sight inside the building (courtesy of U.S. National Archives).***

Base, where they limited their discussions to laser technology [8, p. 63]. Laser power had reached the 100-kW range, reviving excitement about laser weapons and other high-energy laser applications.

William McMillan of UCLA suggested creating a national laboratory for laser defense modeled after the Manhattan Project [8, p. 64]. In an opening talk, nuclear physicist Edward Teller urged the Air Force to "pay early attention to lasers and the changes that the existence of this instrument could bring about." He walked around the stage, gesticulating, envisioning an undefeatable "great laser battleship in the sky," and proposing a laser program for the 1970s on a scale to match the U.S. development of long-range nuclear missiles in the 1950s. Others lauded prospects for developing powerful rocket-engine and electric-discharge lasers [8, p. 65].

Lamberson, who took charge of the Weapons Laboratory laser program in March 1969 [40], wound up as a voice of moderation. Although a great fan of lasers, he warned that any laser program should be systematic and based on sound technology. He opposed "Manhattan or multihundred megabuck programs" until the technology was ready. His comments reflected both his knowledge of the state of laser development and his concern that super-sized plans would take the laser program away from the Weapons Laboratory [8, p. 64].

In the end, the panel recommended a modest laser project at the Weapons Laboratory [41]. The roots of that plan traced back to a 1967 discussion between two laboratory officers with very different backgrounds. Lieutenant Colonel Howard W. Leaf was a fighter pilot who had moved up the chain of command to fly a desk in the research bureaucracy. First Lieutenant Petras V. Avizonis was a Lithuanian-born Ph.D. in physical chemistry with an interest in lasers inspired by a talk by Charles Townes. Leaf wanted to give pilots more firepower, particularly on otherwise defenseless AWACS radar planes, and thought that "bits and pieces" of laser technology being developed at the Weapons Laboratory could be demonstrated on an airborne testbed. Avizonis liked the idea [8, pp. 15–18].

Lamberson knew laser science and technology very well and was a very good manager and leader [15]. He also had a gift for finding very bright people and helping them work together on tough projects like getting the Air Force's TriService Laser up and running. However, the Airborne Laser Laboratory faced a much tougher challenge than demonstrating a big laser to work in the laboratory. Its mission was a system-level test of operating a laser weapon in an airplane. That meant the laser and all the equipment it needed to destroy targets had to operate in a constantly vibrating environment and keep the laser beam on the target long enough to deliver lethal energy.

The first step was to prepare a military version of a Boeing 707 to house a CO_2 rocket-engine laser emitting about 400 kW, powerful enough to be lethal, yet small enough to fit into the plane. It also required a fire-control system to identify and track targets and optics to focus the beam onto the target. They could not use glass optics; they needed materials that reflected or transmitted at the laser's 10-μm wavelength. They also had to install a movable turret to point the beam at remote targets. It all had to work together as the plane flew through the turbulent atmosphere [41].

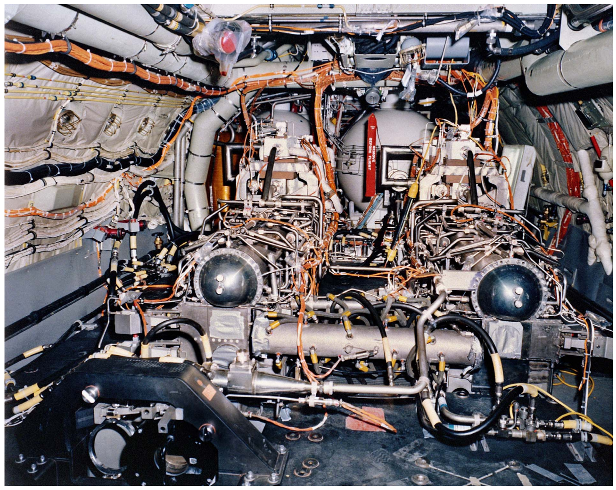

Fig. 4. ***Laser part of the Airborne Laser Laboratory, with the fuel tanks in back (courtesy of U.S. National Archives).***

The modified plane was delivered at the start of 1973, and the Weapons Laboratory began testing the optical and aircraft systems with a lower-power CO_2 laser, while Pratt and Whitney built the high-energy laser (see Fig. 4). It took years to install it into the plane, where the laser occupied the front third of the interior behind the pilot. The power supply and fuel occupied the middle, and the rear third held computers and control systems, as shown in Fig. 5 [29, p. 286]. Customizing the plane to fit the laser required cutting holes and changing the fuselage so much so that some doubted whether it could fly properly. Odd vibrations plagued the plane on early flights, requiring diagnosis and adjustments [8, pp. 123–125]. The Air Force got the laser-laden plane off the ground in 1978 for a photograph, but it still needed work.

A seasoned traveler takes aircraft vibrations for granted. Optical systems do not. Laser optics must be carefully aligned for the laser to work properly. Airplanes in flight vibrate continually, and the shaking affected components, making the laser beam jitter and drift off target.

Atmospheric transmission also proved a problem. The CO_2 rocket-engine laser was the most powerful laser available in the early 1970s. But water vapor and CO_2 molecules in the air absorbed its 10-μm wavelength, heating the air. Heating was strongest in the center of the beam, and as the air warmed, it expanded, reducing the refractive index at the center of the beam. This transformed the air into a negative lens, spreading the beam across a wider area, an effect called thermal blooming, which dispersed the laser energy instead of focusing it onto the target. Air turbulence also scattered or bent the laser beam.

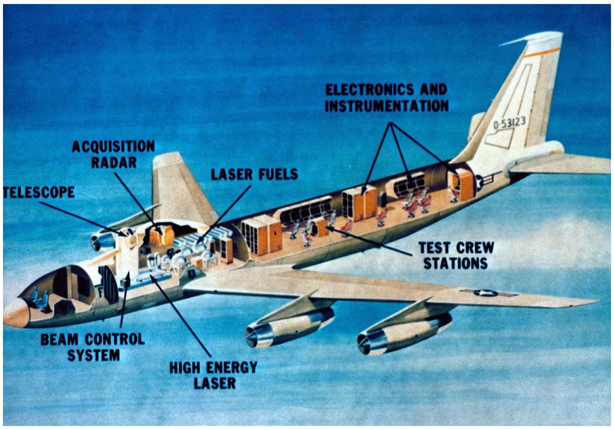

Fig. 5. *Layout of the Airborne Laser Laboratory. The laser itself is shown in Fig. 4. The control systems, including 1970s' vintage computers, are in the back part of the plane (courtesy U.S. National Archives).*

The optics could only focus light onto targets within a few kilometers of the plane, inadequate for many potential missions [42, p. 224]. The laser's metal mirrors absorbed so much laser light that they had to be cooled with flowing water [42, p. 212]. The powerful laser beam ignited dust particles, producing "fireflies" in the air that traced the path of the invisible beam. The beam also burned dust on optical surfaces, damaging them, so components had to be disassembled and serviced in clean rooms [8, p. 237, photo of clean room]. Critics came to scoff at the whole venture, calling the Airborne Laser "a ten-ton watch" or saying it was so massive that its only conceivable use would be to drop it on the enemy [29, p. 25, 30].

The rules of military bureaucracy also forced a change in the management, as crucial tests approached. Over a period of nine years, Lamberson had grown the laser program from 25 people with a $6.5 million budget to a team of 350 and a budget of $86.8 million. By military standards, that was an exceptionally long time in the same post. When he was promoted to brigadier general on February 2, 1978, Lamberson was forced to move on because the head of the laser program had to be a colonel [8, p. 206]. But the laser was still years away from its ultimate goal of shooting down moving targets while in flight.

Not until September 4, 1980, could the laser team report that all vital hardware worked, and the laser could produce light, although it had not yet emitted a focused beam. Exhaust from the rocket-engine laser emerged as a key issue because it produced thrust in the opposite direction, as in a rocket. The laser vented downward, so the thrust pushed the plane's nose upward, and the pilot had to compensate while flying to keep the aircraft on course. The cooling system ran hotter than desired. The biggest question was whether vibrations would disrupt beam alignment, but that could only be answered by firing the Airborne Laser at targets [8, pp. 234–235].

The pressure was high. The program would be in danger if the laser could not bag a target soon. Ground tests found leaks in the cooling system, so equipment had to be removed, repaired, and reinstalled. Ronald Reagan's defeat of President Jimmy Carter in the November elections added to the time pressure. Air Force Secretary Hans Mark, a staunch advocate of the Airborne Laser Laboratory, would be out of job when Reagan took office in January. Mark and another program advocate, New Mexico Senator Harrison Schmitt, were scheduled for a visit on January 15, so the Weapons Laboratory rushed to show them the laser firing a high-power beam [8, pp. 235–237]. For over a week in early January, workers worked around the clock to set up the laser [8, pp. 235–236].

The Weapons Laboratory had planned two test firings the day before the planned visit, but gas-flow problems stopped both prematurely. The laser beam did fire into the open air during the second test, an important milestone. But it also damaged a critical mirror that could not be replaced in time to repeat the demonstration the next day. Mark and Schmitt understood that the previous day's experiment had been a partial success, but the Weapons Laboratory team was disappointed [8, pp. 237–239].

Another round of private tests followed, and a crucial demonstration was scheduled for late May 1981 at Edwards Air Force Base in California. Their goal was to shoot down a missile with the plane in the air. That required keeping the beam focused for 2–4 s on the nose of a missile three to 5 km away. Although the laser could generate 400 kW, only about 75 kW were expected to reach the target, making it harder to destroy the target. Officials were optimistic, but everything had to go just right.

Bad weather spoiled results on the first of three days of planned tests. On the second day, the beam briefly hit the target when the laser ran for 1.2 s, but did no damage. On the final day, the laser locked onto the missile for the full 1.8 s that it fired, but the beam did not stay on target long enough to report a kill [8, pp. 248–253].

Had the tests been conducted in secret, the Weapons Laboratory would have quietly noted the lessons learned and come back to try another day. But this test was public, and the press reported that the laser had "flunked a test" [43, p. 63]. The Air Force was annoyed, but they should not have been surprised [8, pp. 248–253]. Movie death rays always worked for the good guys, but in the real world, Murphy's law saw to it that something would go wrong!

A Pentagon official, when asked about the next step, said there would be no announcement until the Airborne Laser Laboratory shot something down. That took two years. Pentagon brass minced no words with Airborne Laser Laboratory program manager Colonel Jerry Janicke after he briefed them before planned tests at Edwards Air Force Base in May 1983: "Do not embarrass us, and get it done" [8, p. 279]. After a series of test shots, the Airborne Laser Laboratory shot down its first two missiles on May 26

Fig. 6. ***Donald Lamberson, the driving force behind the Airborne Laser Laboratory, shown after being promoted to major general in the 1980s (courtesy U.S. Air Force).***

[8, pp. 286–289]. The staff could finally report proof of the principle of an airborne laser weapon.

VII. SHIFT IN FOCUS

Tests continued until September, but it was clear that the Airborne Laser Laboratory was far from a practical weapon system, and Air Force brass abandoned the quest for airborne rocket-engine lasers. On May 4, 1988, Lamberson, by then a major general (see Fig. 6), joined hundreds of others to watch the Airborne Laser Laboratory leave from Kirtland for the Air Force Museum in Dayton, OH, USA [8, pp. 306–310]. It was listed as in storage in 2015, but its current status is unknown [44].

The Reagan's Administration's Strategic Defense Initiative, first announced in March 1983, had a different mission for rocket-engine lasers, in orbiting robotic laser battle stations intended to block Soviet nuclear attack. It spent several years building a remarkably compact chemical rocket-engine laser called Alpha, which was intended as a prototype for the battle station. However, by the time it reached megawatt-class output in 1989, the Cold War was winding down, and Soviet laser scientists got a tour of the Alpha facility at TRW's San Juan Capistrano facility [45].

VIII. POSTSCRIPT

Chemical lasers were tried again in the 1990s to evaluate the potential of lasers for two new missions, blocking ballistic missiles launched by "rogue states" and defending against rockets, artillery, missiles, drones, and small boats launched by insurgents. They looked promising for defense against insurgent weapons, which are relatively easy targets because they can be engaged at kilometer-scale range and are loaded with fuel or explosives that laser energy can ignite or detonate. However, field operations specialists did not want chemical lasers on the battlefield for logistic reasons. Not only were the lasers massive and the chemicals fuels dangerous, but the chemical lasers would be useless without ample supplies of the special fuels they burn to power the laser. Field operations specialists wanted a different type of laser, a solid-state electrically powered laser that could run on current from the diesel-fueled generators already in the field. In 2009, a laboratory solid-state laser built by Northrop Grumman generated a 100-kW beam for five solid minutes, meeting military targets [46]. Since then, industrial fiber lasers have been scaled to tens of kilowatts and are now in testing [47]. Serious challenges remain, but the giggle factor is gone for laser weapons on the battlefield.

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