# THE ART OF THE POSSIBLE

*How the Navy's oldest research institution is preparing drones for the future*

**Abstract**

A team of engineers in the Navy's flagship research lab in Washington, D.C. keep breaking their own records as they take lessons from past prototypes to build new autonomous systems to expand the capabilities and options available to the warfighter. Their mission is to investigate the art of the possible, whether it's powering a drone with a liquid hydrogen fuel cell and making it fly for as long possible, or creating a disposable motorless micro-UAV that can glide in a swarm and create a network of sensors.

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They'd been taking turns gazing up at the sky and waiting for two days and two nights. One of the team's aerospace engineers, Dr. Dan Edwards, wearily returned to ground station for his monitoring shift around 3 a.m., as the aircraft circled steadily and quietly overhead and out of sight on autopilot. At dawn, he could almost make out the unmanned aerial vehicle's (UAV) tiny red and green lights.

When day finally broke on that second morning and Edwards could spot the Ion Tiger aloft with his own eyes, he says it was "unfathomable to realize." His entire career had been about long endurance flight, and this was one of those self-actualizing moments—"it was just an awesome feeling, to see it still up there after two days" he says.

On the crisp spring morning of April 18, 2013, the Ion Tiger UAV completed a 48-hour and one minute flight, crushing the previous flight time best for an electric UAV, a record set four years earlier by none other than the Ion Tiger itself, at 26 hours and two minutes. The difference was entirely in the fuel system.

The team of scientists and engineers out in the field from the U.S. Naval Research Laboratory's (NRL) corporate facility in Washington, D.C., shook hands and congratulated each other on a job well done.

"It was a relief," says Mike Schuette, a senior mechanical engineer and one of Edwards' colleagues from NRL's vehicle research section, which worked on the project in tandem with the lab's chemistry division. "We actually pulled off what we were trying to do."

Part of their mission, sponsored by the Office of Naval Research and spearheaded by Dr. Karen Swider-Lyons, NRL's alternative energy section head, was to demonstrate to the Navy how hydrogen fuel cells and alternative energy storage could do something that would be really useful to the military, in this case, flying a UAV as long as they did, says Edwards.

For a surveillance drone, the ability to spend more time airborne conducting operations was a total game changer. For starters, most damage occurs to UAVs on takeoff and landing, Schuette says, so the endurance improvement of a hydrogen fuel cell would reduce the overall cost as compared to battery-powered aircraft.

"Liquid hydrogen coupled with fuel-cell technology has the potential to expand the utility of small unmanned systems by greatly increasing endurance while still affording all the benefits of electric propulsion," said Swider-Lyons in a 2013 press release.[1] Electric propulsion is nearly silent, starts and stopped instantaneously, and offers a reduced thermal signature—a winning combination for unmanned air vehicles that are meant to be stealthy.

### Far Reaching Implications

More broadly, the achievement marked the first step towards alternatives to hydrocarbon-based fuel. "Shipping hydrocarbon around military installations is very expensive, and it's

1 https://www.nrl.navy.mil/media/news-releases/2013/nrl-shatters-endurance-record-for-small-electric-uav

very dangerous for our military personnel to be driving around giant trucks of gas," Edwards says. With hydrogen fuel cells "you could get away from that." Given the right equipment, a person could even *make* fuel on-site.

A hydrogen fuel cell's only byproduct is water and low-grade heat--it's virtually emission-free. There's no combustion. The system provides an electric power source that's lightweight and super efficient, and operates at a relatively low temperature compared to its antecedents.[2]

Given its high energy density and remarkable efficiency relative to battery power, it's the natural progression for next-generation vehicles. Almost every automaker is actively pursuing hydrogen fuel cell technology. Toyota and Hyundai were among the first to bring hydrogen fuel cell-powered electric vehicles to market in 2015, integrating them into Mirai and Tucson models, respectively.

The U.S. Department of Energy noted in October 2016 that hydrogen and fuel cells are on the verge of a "tipping point."[3] Government-funded research cut the projected-high volume cost of automotive fuel cells 50 percent, and quadrupled the life span of a fuel cell over the last decade.

**Building the Ion Tiger**

The 35-pound Ion Tiger featured a new custom hydrogen fuel cell system designed in-house at NRL. The researchers made every detail as lightweight and efficient as possible to maximize the system's endurance.[4] The cell was constructed with metal-foil bipolar plates bound together by titanium straps; it used liquid hydrogen fuel, which has three times the density of the compressed gaseous hydrogen used to set the previous record. The liquid hydrogen was stored in a custom-built lightweight aluminum cryogenic fuel storage tank, or dewar, with double-walled insulation.

The stored fuel was so cold that it would simply evaporate if exposed to heat too quickly. Even in the vacuum of a specially made dewar, it would lose almost two percent a day.

"Because this was a prototype, it was very difficult to predict the actual boil off process for how long this thing was going to fly," Schuette says. They'd anticipated a 72-hour flight, he says, and up until the second morning, thought they would get there. But when the second morning arrived, their pressure curves indicated that the liquid hydrogen fuel stores had run out.

Swider-Lyons had come to the vehicle research section with a wish list that became the parameters for the Ion Tiger: a long endurance UAV, with a fuel cell that could generate about 500 watts and could carry a five-pound payload—the approximate the weight of a surveillance camera.

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2 https://www.scribd.com/document/255436069/3-D-Printing-in-Hydrogen-Fuel-Cells-for-Unmanned-Systems-Spectra-2014

3 https://energy.gov/eere/articles/verge-hydrogen-tipping-point

4 https://www.nrl.navy.mil/lasr/sites/www.nrl.navy.mil.lasr/files/pdfs/AIAA%20liquid%20hydrogen%20paper%202013%5B12-1231-4608%5D.pdf

Chemists, aircraft designers and engineers took on their tasks, bouncing ideas off each other, in typical NRL fashion.

"There are so many different expertise levels all throughout the different parts of a project that you can arrive at a conclusion that's probably closer to the truth than any place I've ever been," Schuette says. Trade fellows with practical building expertise and doctorates stood side by side in a machine room, the research equivalent of an epic jam session.

"The fact that you can get in the same room the actual mathematical answer and also the practical implication of what that means is very important to fast cycle research and development work," Schuette says.

Every minute detail of the system had to be painstaking engineered to be as lightweight as possible. To help design the regulator that would be used to fill the fuel cell's tanks, they entrusted a young, overly enthusiastic student in the vehicle research section.

**A 'Vital Cog'**

Christine Dailey says she always felt like she had something to prove. Her father had "put her in a bubble growing up," she says, due to her severe dyslexia. Her family lived on a farm, and her parents owned Mega Mix, a Tampa, Florida-based concrete supply company. Her dad felt an obligation to protect her from anything potentially dangerous—most things, in that environment—while her brothers and sisters were free to explore the hazards of heavy machinery and equipment.

The special treatment gave Dailey an inferiority complex, which she says only drove her to work harder. She wanted to show everyone, including herself, that she was capable of great things.

When she designed the Ion Tiger's regulator, Dailey was working full-time at NRL through the lab's Student Temporary Employment program while studying towards master's in mechanical engineering at Embry-Riddle Aeronautical University in Daytona Beach, Florida.

"When I got to NRL, I was nervous about being a girl in the shop, so I would crack jokes to make them comfortable with me," she says. "It was all in my head. I saw my dad in everyone."

As an aspiring boxer and bootcamp instructor, most of Dailey's friends know her as Chrissy the gym rat, not Christine the lab rat. She's blonde, super fit and outgoing. She just doesn't really seem like the type of person one might imagine tinkering with prototype drones in a dingy, secretive government laboratory. But shattering perceptions is kind of her thing.

Soon after arriving at a NRL, Dailey heard Schuette, the vehicle research section's senior mechanical engineer and unofficial mayor of its machine shop, say welding was too difficult to learn. She took that as a personal challenge. "I came in early and often and I made sure he saw me," she says. She was almost surprised that they gave her free reign in the shop. "I assumed they thought I couldn't do it—but they *did*."

"At NRL, I finally felt like an equal," Dailey says, and that's one reason she'll "never leave."

NRL's vehicle research section, which develops technologies for the Navy's autonomous systems, is home to about 35 engineers including Dailey, Schuette, and Edwards, according to the department's head, Alvin Cross, whose 25-plus year career at NRL started with an internship.

"I always challenge my engineers to name their tune," says Cross, who recruited Dailey out of grad school and calls her a "vital cog" in the program. "If they have an idea and it has an application, they'll be encouraged to do it."

**Behind the Scenes: NRL's Vehicle Research Lab**

That philosophy has birthed approximately 400 vehicle platforms since the mid-1970s, and fostered a familial environment that draws some of the nation's brightest minds, despite 20- 30 percent lower pay than the private sector and decidedly unsexy facilities.

Most of the 90 or so buildings on NRL's main campus on the eastern bank of the Potomac River date back to World War II. They could use a paint job, to say the least. Navigating the floors of the building which houses the vehicle research section is a challenge, as maintenance crews routinely cordon off entries and exits.

Dailey, heading down to the machine room, has to double back from a stairwell marked with an asbestos caution sign. It doesn't bother her, she says, quite the contrary. It means the money is going to the research.

It may not look like high-tech lab to the untrained eye, but when Dailey first toured the facility, she "fell in love."

Dailey was demonstrating a robot at a conference being held by the Association for Unmanned Vehicle Systems International (AUVSI), the trade group that champions autonomous systems. Daryl Davidson, an executive directors at the organization, said to her "you have to meet my wife," who worked at NRL at the time.

The young engineer hadn't heard of NRL, and thought Davidson was making a sexist assumption of some kind (there's that self-doubt again). She politely followed him over to NRL's booth. She smiled and nodded at her new female acquaintance as her eyes scanned the display behind her. Dailey quickly realized that this was definitely not girl talk.

Then she was introduced to Alvin Cross, her future boss.

Cross didn't pitch her. NRL doesn't try to compete with the Boeings of the world. In fact, they had never funded a visit from a recruit until Dailey came along, she says. "It's probably just because I had the audacity to ask."

She soon learned of NRL's storied legacy, which dates back to 1923 and includes scientific feats like the principles of radar; the joystick; the Vanguard project, America's first satellite program; and early satellite prototypes of the Global Positioning System (GPS).

Touring the lab as a prospective employee, Dailey says she saw friendly faces, and behind every door, a "playground."

An engineer's playground is messy. Desks hold a clutter of drawings and prototypes, sometimes piled to the ceiling. The engineers don't wear white lab coats; mostly grease stained jeans and dirty, busy hands. Huge dusty storage crates line the hallways like they're ready to deploy, and there are more than a few stray desk chairs strewn about, seemingly abandoned after someone's ah-ha! moment.

Before NRL even offered her a job, Dailey says she called up her other prospective employees and told them no thanks, "I just wouldn't be happy."

It didn't hurt that NRL paid for Dailey to finish her studies.

"They supported me in everything," she says. Dailey received an Edison grant—named after Thomas Edison, who is said to be the figure behind the creation of "a great research laboratory" where "all the technique of military and naval progression" could be developed "without any vast expense."[5] The inventor's 12.5-foot bronze portrait bust, sculpted by Evelyn Beatrice Longman, who also sculpted the wreaths, eagles and inscriptions on the inner walls of the Lincoln Memorial, sits just beyond NRL's security gate, greeting visitors just before they get lost in the labyrinthine facilities.

**No Axe to Grind**

The opportunity NRL gives engineers is to chase any idea that has an application—if they can put together a winning pitch. If approved, the idea is funded and the engineer responsible for seeing it through.

"I pitched this idea for a space program that we all knew was going to get cancelled," Dailey says. It was an exercise machine for astronauts, her dissertation. "I was nervous, but I knew they didn't want to see a bumbling pitch. I wore a jacket so they couldn't see me sweat. I pitched it as something to protect future astronauts."

The idea was approved. Later, Dailey would work on everything from cellular towers to antimissile protections systems, while the bulk of her effort went toward autonomous vehicles.

"This is a proof of concept lab," says Cross. Approximately 40 percent of the vehicle research section's work is considered to be in the category of basic research, whether it's propulsion or deployment systems. Most of it has to do with intelligence, surveillance and reconnaissance.

"There's a lot of license to follow where the research leads you," says Edwards. "You may not know exactly how to get somewhere when you start a project—you have an idea of what you want to achieve. We are here to support the warfighter and to push boundaries—failure, as long as you're coming away with answers and you learn something, is an okay result."

In other words, one of NRL's major value propositions is its ability to investigate the military's current and possible future problems and to build a comprehensive arsenal of solutions.

"Here, we're paying attention to the details," says Schuette. The mission is not about quickly turning around a product to sell for profit, so there's no need to take shortcuts. By investigating fuel cell technology early on, for example, researchers can give the Navy a better understanding of its options as new challenges arise.

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[5] https://www.nrl.navy.mil/about-nrl/history/edison/

"NRL is a good research tool to have in the government toolbox because we don't have an axe to grind," Schuette says. "If anybody ever wants to do a liquid hydrogen flight, we could go back to our notes, give them a better assessment on whether that's their best option, and tell them exactly what they would get in the design."

"Let's face it, warfighters either don't know what they need or they don't understand the art of the possible," says Cross.

**The 'Museum'**

A roughly 600-square foot windowless office space that the staff lovingly calls the "museum" holds a small trove of such options. Prototypes line the walls, resting in cradles and on folding tables, collecting dust like dioramas in a long-forgotten science fair. The Ion Tiger is displayed in a far corner.

"Ninety percent of the items in the museum have flown," Cross says. Accompanying each prototype, a description and news article highlighting one achievement after another.

The first artifact in the museum, almost tucked behind the door, is the Dragon Eye, a five-pound UAV developed in 2001 by NRL and the Marine Corps Warfighting Lab, and manufactured by AeroVironment, a Monrovia, California-based unmanned aircraft systems supplier. It was the smallest unmanned aerial vehicle in action when Marine battalions fielded it during Operation Iraqi Freedom in 2003 and was virtually undetectable.

The Dragon Eye is about the size of a model airplane, and can be launched by hand, or with a store-bought bungee cord. It's Kevlar and fiberglass construction can break into smaller pieces and fit in a Marine's backpack.

The Dragon Eye's purpose was to perform reconnaissance and threat detection for small units—to give a real-time bird's eye view to commanders of the battlefield—providing instant situational awareness and tactical intelligence that allowed for increased maneuverability. Battalions could assess urban battle spaces before descending upon them— as they did before crossing the Diyala Canal, the last obstacle between troops and the capital city of Baghdad.[6]

A few tables down, closer to the center of the room, rests a yellow, palm-sized flying circuit board—a testament to just how much the lab's small-UAV research has evolved since the Dragon Eye. The small glider Close-in Covert Autonomous Disposable Aircraft, or aptly named CICADA, is a low-cost, GPS-guided micro disposable UAV, and another notch in the belt of Edwards, who is credited for developing it with his colleague Aaron Kahn.[7]

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[6] http://www.marines.mil/Portals/59/Publications/With the 1st Marine Division in Iraq, 2003 PCN 10600000000_1.pdf

The CICADA's frame appears inspired by hours of paper airplane experimentation. With no source of propulsion, it's designed to drop from another airborne platform, such as a larger UAV or a weather balloon and glide down to a final crash landing site. To-date, NRL has delivered 150 CICADAs to the NASA Langley Research Center, and was planning "swarm testing"—releasing the micro-UAVs in large numbers to create a sensor network—as of April 2017. [8]

**The Hybrid Tiger**

Many of the museum's past prototypes inform the design of future platforms, and one of NRL's latest endeavors is no exception.

The Hybrid Tiger program, sponsored by the office of the Deputy Assistant Secretary of Defense for Operational Energy, "pulls together autonomous soaring, solar, and all of the hydrogen fuel cell lessons that we learned in the past," says Edwards, "with the intent of being more energy aware in flight."

With an expected first flight of spring 2018, the Hybrid Tiger will be built on essentially the same chassis as the Ion Tiger, Schuette says. "We're recycling as much as we can."

Its wings will be modified to span 24-feet instead of 16; its nose and tail will be totally new; the fuselage will be built from the same mold. To improve its endurance, the Hybrid Tiger will use an algorithm to determine which of its multiple power sources to use – pressurized and liquid hydrogen at night time or solar during the day—which will maximize its endurance, extending the continuous flight time to three and a half days, Edwards says.

"The Ion Tiger flew for 48 hours off a cliff, but it flew in a big circle," Edwards says. The Hybrid Tiger's extended range will make it possible to traverse oceans, or span the entire southern border of the U.S., says Edwards.

"You can fly an awful long way."

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7 https://www.nrl.navy.mil/media/news-releases/2015/nrl-developed-micro-uav-named-popular-science-best-of-whats-new

8 http://www.janes.com/article/69320/navy-league-2017-nrl-eyes-cicada-swarm-tests