

# Innovation Quarterly

2017 May  
Volume 1, Issue 4

## **How We Fly**

The science behind  
the experience

## **Demonstrating**

Performance

## **Always Learning**

Solid foundation for a  
structural career

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George Ndayizeye is a Boeing structural engineer working on the 777X program in Everett, Washington.

PHOTOGRAPHY BY GAIL HANUSA

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Boeing's pioneering efforts in the development and application of durability and damage tolerance methods are evident in terms of significant safety improvements and considerable reductions in service actions on airplanes designed since the 1980s. Managing an aging fleet and the adoption of new regulations affecting maintenance planning have been, and continue to be, challenges. New materials and assembly methods, and the ever-constant quest for productivity gains in the factory, are all further shaping the way durability and damage tolerance are being assessed and implemented.

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Boeing played a major role in the development of the Finite Element Method, Lanczos Eigenvalue Extraction and Craig-Bampton Reduction. These three numerical simulation methods revolutionized large system structural dynamic analysis, and outside of Boeing, these methods are commonly applied in a multitude of other industries producing consumer products and heavy machinery.



# The wonder of flight

If you've stood still to watch a Boeing airplane fly overhead, then you know how amazing flight still is to us.

Yet there's another thing better than watching an aircraft climb skyward — and that's to experience the wonder of powered flight for yourself. This capability is the end result of our extensive and ongoing work in improving the flight experience, which is the theme of this edition of IQ.

The members of Boeing's technical team continue to raise the standards for the flight experience. For instance:

- Our versatile Commercial Airplanes product line lets our airline customers meet the public's desire to travel nonstop, or "point-to-point," instead of changing flights at large airports.
- We developed the striking and stylish Boeing Sky Interior. You'll find it not only on our Commercial Airplanes, but also on the CST-100 Starliner next-generation space capsule.
- We made overhead bins bigger to help our airline customers give passengers options.
- Thanks to its many new technologies, the Boeing 787 Dreamliner offers significant improvements in the flying experience, such as bigger windows, lower cabin humidity, and improved interior aesthetics.
- Our products continue to advance in fuel efficiency and other environmental improvements. Airplanes that use less fuel and are also quieter for communities near airports.

Yet there's more to come. Among the developments in work are features on smart devices that could allow passengers to control their onboard personal environment. They may also let crew members monitor cabin systems during flight—and even lock and unlock electronically controlled overhead bins.

We remain committed to improving the flying experience, to strengthen our stature as a leader in aerospace and innovation. **IQ**



**GREG HYSLOP**  
Boeing Chief Technology Officer  
Senior Vice President, Engineering, Test & Technology

## Recognizing Advanced Developments and Research

# Technology RADAR

People working in Boeing's Technology Intelligence and Trends community of practice are human sensors in the world of science and technology. We make it our business to watch for innovations in practice, new business models and new ways of thinking. Here's a peek at a few signals on the screen.

### Predicting Metallic Defects

**LOCATION**  
Berkeley, California

**PROJECT URL**  
[nature.com](http://nature.com)

**MESSAGE**  
Lawrence Berkeley National Laboratory researchers have developed machine learning algorithms that can predict metallic defects accurately. This method can reduce the computational cost of understanding materials defects, thereby aiding research of advanced alloys and new materials.

### Robot That Replicates Bat Flight

**LOCATION**  
Urbana, Illinois

**PROJECT URL**  
[csl.illinois.edu](http://csl.illinois.edu)

**MESSAGE**  
Engineers from the University of Illinois and the California Institute of Technology have achieved autonomous flight of Bat Bot, a flying robot that mimics the morphology of bat wings. The soft, flexible wings of bat-bots could present safety and other advantages compared to current aerial robots such as quadcopters.

### Roses Turned Into Supercapacitors

**LOCATION**  
Linköping, Sweden

**PROJECT URL**  
[liu.se](http://liu.se)

**MESSAGE**  
Scientists at the Laboratory of Organic Electronics at Linköping University have made roses into supercapacitor energy storing devices by forming conducting threads throughout the plant. The electronic "power plant" shows promise toward autonomous energy systems.

### UAV Taxi Takes off in Dubai

**LOCATION**  
Dubai, UAE

**PROJECT URL**  
[is.mpg.de](http://is.mpg.de)

**MESSAGE**  
In July, Dubai's Roads and Transit Authority (RTA) will be launching autonomous aerial vehicles (UAV) taxi service. Piloted from a central command center, the UAVs will cover a 40-to-50 kilometer area and can carry one passenger. Dubai will use the Ehang 184 UAVs developed in China.

### Criminal Intent Brain Scan

**LOCATION**  
Roanoke, Virginia

**PROJECT URL**  
[research.vtc.vt.edu](http://research.vtc.vt.edu)

**MESSAGE**  
Using non-invasive brain imaging, scientists can detect the state of knowledge of a criminal activity. Research conducted by researchers at Virginia Tech and Yale University, determined brain activities that indicated if subjects knew they were breaking the law. In the legal context, such knowledge can be the difference between "knowingly" or "recklessly" committing a crime, which can affect sentencing and penalties.

### New Methods for Nano-Swimmers

**LOCATION**  
Stuttgart, Germany

**PROJECT URL**  
[is.mpg.de](http://is.mpg.de)

**MESSAGE**  
Two methods for propelling micro- and nano-robots in fluid have been developed by researchers at the Max Planck Institute for Intelligent Systems. One method relies on bubble propulsion; the other, a enzymatic reaction.

### Unidirectional Wave for Mini Mass Transport

**LOCATION**  
Tokyo, Japan

**PROJECT URL**  
[iu-tokyo.ac.jp](http://iu-tokyo.ac.jp)

**MESSAGE**  
An autonomously moving synthetic polymer developed at the University of Tokyo could potentially support application in nanomachines. The unidirectional "wave" motion could serve as mass transport for miniscule substances.

BOEING PHOTO



“The ecoDemonstrator program reflects our core belief that ‘learning by doing’ will accelerate the implementation of environmentally progressive technologies into our stream of new products and services.”

**MIKE SINNETT,**  
VICE PRESIDENT OF PRODUCT DEVELOPMENT,  
BOEING COMMERCIAL AIRPLANES

# Flights of innovation:

## Proving readiness helps speed new technologies to market

**Boeing, Embraer wrap up latest ecoDemonstrator testing.**

**BY DOUG CHRISTENSEN, ASSOCIATE TECHNICAL FELLOW AND ECODEMONSTRATOR PROGRAM MANAGER  
BOEING COMMERCIAL AIRPLANES**

Boeing and Embraer, the Brazilian-based airplane manufacturer, worked together on the Boeing ecoDemonstrator program late last year to test emerging technologies that will improve the environmental performance and safety of airplanes of the future.

The ecoDemonstrator program is focused on accelerating the testing, refinement and completion of new technologies, methods and materials to improve aviation environmental performance. The program is in its fourth generation involving several airplanes that serve as flying testbeds. The most recent testing involved three weeks of technology innovation flight tests in Gavião Peixoto, Brazil, aboard an Embraer E170.

“The ecoDemonstrator program reflects our core belief that ‘learning by doing’ will accelerate the implementation of environmentally progressive technologies into our stream of new products and services,” said Mike Sinnett, vice president of Commercial Airplanes Product Development. “We are on a journey to learn how to efficiently take the best new ideas and transform them into implementable product and service improvements that reduce the environmental footprint of commercial aviation.”


The collaboration between Boeing and Embraer is part of a five-year cooperation agreement signed in 2016. It is part of a broader relationship that began in 2012, when the companies announced they would cooperate in ways to create value for both companies and their customers. This collaboration allows the two companies to combine resources and accelerate technologies that improve the performance and safety of their products. Boeing and Embraer leaders continue to investigate opportunities for advanced technology acceleration on the next ecoDemonstrator program, which is expected to involve a 777 aircraft in 2018.

The companies have worked together to improve runway safety and continue to support Embraer’s KC-390 defense aircraft program. Boeing and Embraer also opened a joint center in São José dos Campos, Brazil, in 2015 to coordinate biofuel research with Brazilian universities and other institutions.

“It was an honor for Embraer to conduct this fourth generation of the ecoDemonstrator on an Embraer E170 aircraft,” said Fernando Ranieri, Embraer’s Technology Development vice president. “By doing this program

together in a very tight schedule and in a true partnership, engineers of both companies developed mutual respect and admiration.”

One of the most promising technologies tested, he said, is an optical air data system using LIDAR (Light Detection and Ranging). LIDAR technology, which uses lasers, offers the potential to save weight and drag and provide a reliable and separate architecture backup source for air data from pitot tubes. Pitot tubes or inlet probes protrude from the fuselage and measure air speed, atmospheric pressure, external temperature and other parameters.

“Those of us from Embraer and our counterparts at Boeing realize we’ve completed something special,” said Luiz Nerosky, Embraer ecoDemonstrator project manager. “I hope this paves the way for future collaborations.” 

## Flight tests range from ice-phobic paint to sugarcane biofuel

**The combined Boeing-Embraer team flew more than 15 flights totaling more than 35 flight hours in 2016. These are some technologies demonstrated.**

### ON THE TARMAC

Boeing and Embraer collaborated on three weeks of flight tests in Gavião Peixoto, Brazil, aboard an Embraer E170 in 2016.

BOEING PHOTO



BOEING PHOTO

### Ice Phobic Paint

Today’s paints require regular airplane washing and do not provide ice phobic characteristics. This new coating was applied to the nose of the test aircraft and its performance for ice release and the ability to require less washing was evaluated.

The testing for the new ice phobic paint was broken into two focus areas.

Embraer’s focus was to test the application, appearance and in-service durability of the testing. Embraer engineers monitored the application process to understand how the new paint worked in the existing application system, and it was determined that the paint was compatible with their existing paint equipment and hangers. They also measured the appearance of the paint after application. The paint produced an acceptable appearance and passed the testing required by the manufacturer. The test aircraft will continue to fly in Embraer’s test fleet. The paint will be monitored to measure the in-service durability and appearance.

Boeing’s focus was on the lab testing of the paint for rain erosion durability and ice phobic characteristics. Leading edge samples were painted with the new paint product, and then tested in Boeing’s Whirl Arm rain erosion test facility. Engineers examined its ability to meet tough durability requirements for use on aircraft surfaces that face the direct flow of air. The results were mixed and additional future testing will be required.

Small bar test hardware was also painted with the new product and tested at the Anti-icing Materials International Library centrifuge ice test facility in Quebec, Canada. While there were signs of improvement, true ice-phobic paint is still years ahead of us.

—DIMITRIOS PRIFTIS,  
BOEING RESEARCH & TECHNOLOGY,  
LADSON, SOUTH CAROLINA

### Slat noise cove fillers

New leading-edge slat designs reduce unsteady air flows, which would lower noise for communities as the airplane is on approach. Boeing and Embraer co-led the design for a new slat shape for the E170 prototype aircraft.

Teams of engineers from both companies evaluated new slat shapes for high-lift performance and noise-reduction characteristics. Computational fluid dynamic codes were used to design the shape and predict the amount of noise reduction for the aircraft.

Two configurations were designed, analyzed, built and tested on the prototype aircraft. Initial indications show that the noise due to air flow around the leading edge slat can be reduced by as much as 10 decibels.

—RACHELLE SPETH,  
BOEING RESEARCH & TECHNOLOGY,  
ST. LOUIS

BOEING PHOTO



### SHOWING PROMISE

A new, leading edge slat (above) was introduced and tested, while an experiment on paint (above left) to repel ice showed improvement.

## Boundary Layer Data System

Flight tests demonstrated the installation and application of an autonomous Boundary Layer Data Measurement System (BLDS) to measure airflow on a laminar wing or tail surface at commercial aviation flight speeds and altitudes.

Boeing partnered with U.S.-based university experts to develop a flight-test device that could be attached to the external surface of an airplane and, in conjunction with airflow rake instrumentation hardware, measure airflow characteristics at flight speeds and conditions. Embraer provided the flight test vehicle and the predicted airflow characteristics to which the device data could be compared.

The device recorded the data autonomously, which removed the requirement to run flight-test wiring, significantly reducing the cost of flight-test instrumentation. Results of the data show an excellent match to the predicted characteristics and demonstrated that the device could be attached externally (without fasteners) and record data at all commercial aircraft flight conditions.

This device provided low-cost data to improve the efficiency of flight-test data acquisition, resulting in less fuel use and lower emissions.

—KEVIN MEJIA,  
BOEING TEST & EVALUATION,  
SEATTLE

## Sustainable Aviation Fuel

Boeing and Embraer contracted with a Brazilian company to provide biofuel for all of the flight testing in Brazil. The ecoDemonstrator program used a 10 percent blend of this biofuel made from waste Brazilian sugarcane.

Biofuels reduce lifecycle emissions by 50 to 80 percent when compared to fossil fuels. This demonstration highlighted to the aviation industry that local biofuels are available and can be used to fuel aircraft from any facility.

—ONOFRE ANDRADE,  
BOEING RESEARCH & TECHNOLOGY,  
BRAZIL

BOEING PHOTO



EMBRAER PHOTO



### MEASURING DATA

Methods to more efficiently collect data, coupled with the potential use of biofuels, could lead to more efficient flying—also tested on the latest ecoDemonstrator.

## Optical Air Data

Utilizing Light Detection and Ranging (LIDAR) technology, the Boeing and Embraer ecoDemonstrator program demonstrated the ability of lasers to measure air data parameters such as air speed, atmospheric pressure, temperature and others.

Boeing and Embraer worked with an industry supplier to acquire flight hardware to test the ability of LIDAR to measure air data at a variety of flight profile conditions and, more importantly, a variety of atmospheric conditions. The supplier equipment was installed and tested on the ground to investigate the ability to integrate onto a flight test vehicle.

After the system was validated on the ground, the flight demonstrator flew a series of test conditions over several days and weather conditions to record data and compare to the ship system.

LIDAR systems continue to show promise for the aviation industry and this test provided valuable data to advance LIDAR technology. Potential use in the aviation industry includes flight test data system improvements, engine inlet probe replacements, aircraft performance benefits, and turbulence detection and mitigation.

—DUNCAN WEBER,  
BOEING COMMERCIAL AIRPLANES,  
SEATTLE

## Proven record for improving technology

Boeing has a history of conducting demonstrator projects to test and prove technology readiness for promising innovations. The ecoDemonstrator program was a follow-on to the Boeing Quiet Technology Demonstrator program. Through that earlier program in the early 2000s, Boeing and Rolls Royce developed the quieter engines that became a competitive advantage for the 787 Dreamliner.

The ecoDemonstrator program was introduced in 2012 to support the long-term sustainable growth of aviation. Once proven mature, ecoDemonstrator technologies and processes can be incorporated into existing production models, made available for in-service fleets and applied to new airplane development programs.

### ECODEMONSTRATOR 737 FIRST GENERATION, 2012

The ecoDemonstrator Program formally began in 2011 in cooperation with American Airlines and the FAA. With an inaugural flight in 2012, 15 new technologies were tested on an American Airlines Next-Generation 737-800 airplane. Technologies tested included:

- Natural laminar flow
- Variable area fan nozzle
- Regenerative hydrogen fuel cell
- Flight trajectory optimization
- Carpet made from recycled materials
- Blended biofuel

### ECODEMONSTRATOR 787 SECOND GENERATION, 2014

The ecoDemonstrator Program used 787 Dreamliner ZA004, a company-owned airplane, for flight tests beginning in mid-2014. Partners included the FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program, NASA's Environmentally Responsible Aviation (ERA) Project, Japan Airlines, Delta Air Lines, Rolls Royce, Honeywell, Rockwell Collins, General Electric and Panasonic, among others.

Boeing and FAA CLEEN, a competitively bid five-year program with costs shared by participants, completed testing of the Ceramic Matrix Composite (CMC) engine nozzle. Made of high strength, heat resistant ceramic, the CMC nozzle is designed to enable engines to operate at a higher

temperature, improving fuel efficiency while decreasing emissions and noise.

More than 25 technologies were evaluated to make flights more fuel efficient and quieter. They included aerodynamic and flight control improvements; ice-phobic wing coatings to reduce ice accumulation; and software applications and connectivity technologies that can improve flight planning, fuel-load optimization, in-flight routing and landing.

NASA also tested its Airborne Spacing for Terminal Arrival Routes technology, based on Flight Interval Management, to help achieve precise spacing between aircraft upon landing. The technology is intended to increase landing frequency and reduce holding patterns, saving fuel, emissions and time.

The world's first flight using "green diesel," a sustainable biofuel that is widely available and used in ground transportation, was completed on the ecoDemonstrator 787.

Other technologies tested: touch-screen displays in the flight deck, wireless sensors that can reduce wiring, and outer wing access doors made from recycled 787 carbon fiber.

### ECODEMONSTRATOR 757 THIRD GENERATION, 2015

In March 2015, the ecoDemonstrator 757 took to the skies to evaluate new technologies to improve commercial aviation's efficiency and reduce noise and carbon emissions. Boeing collaborated with TUI Group and NASA on these 757 tests. Boeing worked with NASA to test active flow control technology to improve airflow over the rudder and maximize its aerodynamic

BOEING PHOTO



### USE AND RE-USE

A Boeing 757 flew in 2015 to not only test flight technologies, but also to demonstrate recycling out-of-service aircraft.

efficiency, and "bug-phobic" coatings that can reduce drag from insect residue. The ecoDemonstrator 757 was flown using a 5 percent blend of "green diesel" produced in the United States, to support ongoing industry efforts to approve this biofuel for use in commercial aviation.

Also tested were solar and thermal "energy harvesting" to power electronic dimmable windows, as a way to reduce wiring, weight, fuel use and carbon emissions; and a 3D-printed aisle stand made from excess carbon fiber from 787 production, an example of efforts to repurpose aerospace-grade carbon fiber and reduce airplane weight and factory waste.

Boeing collaborated with Stifel's aircraft finance division, which owned the airplane, as well as the Aircraft Fleet Recycling Association and an airplane demolition company in Burnsville, Minnesota, to dismantle and recycle the 757 using environmental best practices. Including parts and materials, about 90 percent of the airplane (by weight) was reused or recycled, with 10 percent going to a landfill.

# Structural Integrity

**With a passion to learn and eagerness to work hard, a talent emerges from the other side of the world.**

BY DAN RALEY, BOEING WRITER | PHOTOGRAPHY BY GAIL HANUSA

George Ndayizeye was only 12 years old when machete-wielding tribesmen attacked his boarding school in Burundi. He hid in the clergy living quarters overnight until military troops intervened, blocked the surrounding roads, and scattered the intruders.

He didn't feel out of danger until he was airlifted from Gitega to Bujumbura by the United Nations—his first airplane flight.

"I almost died," he recalled of that time in East Africa in 1993. "There was no communication. My parents thought I was killed."

But "out of danger," did not yet equate to "safe." Violence continued in the region throughout the 1990s.

Later, using a student visa, he joined an older brother and sister who had migrated to Charlotte, North Carolina. He applied for asylum once he arrived in the United States in 2001, and it took a year of Ndayizeye explaining his situation for authorities to let him stay.

Today, Ndayizeye finds normalcy in Washington state, on the other side of the world from his native Burundi. As a structural analysis engineer for Boeing, he works on the

777X program, on a new joint that connects the forward fuselage to mid-fuselage of the twin-aisle jetliner. He performs static and fatigue analysis, and supports the design team. He says he feels at home there.

"America is so open-minded," he said. "You can come in with new ideas and make a product. You are as limited as the sky. You are part of a team and it's diverse—and it's very safe."

Ndayizeye rises at 4:30 a.m. and exercises in a gym. He has breakfast and is at work by 7. With increased responsibilities, he interacts with several teams as they ready the 777X for the marketplace. The management team recognized him for his key contributions on enhancements made to 777X floor-frame loads. He was previously singled out for his work on a 787-9 wing-to-body faring design that helped it come in ahead of schedule and budget. And he was recently awarded with a Black Engineer of The Year – Science Spectrum Trailblazer Award.

Mark Clayton, deputy chief engineer for 777X fuselage integrated product team, was one of Ndayizeye's first managers and mentors at Boeing. Working together on the 787 program, Clayton recalls a young engineer who was willing to do whatever was necessary to fit in with his unfamiliar surroundings.

For example, Ndayizeye took a class on public speaking simply to be able to communicate better with others



“I used to see airplanes passing by and wonder, ‘how does that work?’”

GEORGE NDAYIZEYE

on the job. Approached by Boeing for his perspective on African market possibilities, the engineer sat down and wrote a detailed paper on opportunities in the region, Clayton said.

"What I thought was impressive about him was how he approached work, especially with English as a second language," Clayton said. "He faced some unique challenges, like transitioning from telecommunications to commercial airplane structures. I noted his willingness to always self-improve, to always learn."

Stability for Ndayizeye extends well beyond his employment. He married a Burundi woman he happened to meet in Texas. He gained American citizenship in 2014. He became a father.

And, with the help of Boeing's Learning Together Program,

he is finishing a master's degree in aerospace engineering from the University of Washington, with a concentration on composite materials.

"I used to see airplanes passing by and wonder, 'how does that work?'" he said.

His journey from East Africa to Boeing's largest production site was a long and determined one, requiring equal amounts courage and patience. He proved to be an excellent student, drawn to math and science, and he took as many extra courses as he could at whatever school he was privileged to attend.

Yet, Ndayizeye realized early on that teaching likely was the highest profession he would attain in his country, which remains one of the poorest worldwide. He wanted more

“America is so open-minded. You can come in with new ideas and make a product. You are as limited as the sky.”

GEORGE NDAYIZEYE

#### ON A NEW FIELD

George Ndayizeye (right), who grew up in the Burundi countryside, now plays recreational league soccer with other professionals in Everett.



in a career, though the budding engineer didn't necessarily know he would wind up in aerospace.

Raised in the East African countryside, Ndayizeye tended cows, up to 20 at a time. Armed with a stick and youthful resolve, he gently steered these animals to grassy areas and water during the day, and he repeated the process when the sun went down. This was his childhood until he moved to a city where his parents prospered in business.

Ndayizeye grew up in Burundi's, southernmost province of Makamba, in a dwelling without electricity or running water. While it remains a sleepy rural setting in many ways, his homeland for decades has been immersed in civil war—and it forced him to flee.

The long-running strife between Burundi's Hutu and Tutsi tribes—Ndayizeye belongs to the latter—finally proved too unsettling for him. The boarding school terror was unforgettable.

“War was still going on in Burundi,” he said. “There was no way I was going back.”

Once in the states, Ndayizeye, who speaks English, French, Swahili and Kirundi, moved from community college to the University of North Carolina at Charlotte, impressing people with his scholastic dedication and productivity.

He became an undergraduate research assistant, working with professors and graduate students on bioengineering

research projects, with whom he shared citations. His determination to succeed was his biggest attribute, said Robin Coger, former UNCC mechanical engineering professor and dean of the college of engineering at the North Carolina A&T State University.

“Is he a great story in overcoming adversity? Absolutely,” Coger said. “But he's also a great story because he wanted something, and he was willing to work for it. All George needed was a chance.”

At UNCC, Ndayizeye conducted research on liver cells and how they could be used to mimic an organ transplant—both in simulating death and in their revival—while he held down an outside job to pay for his education. Some of his research data is still in use, according to Charles Lee, director for the Center for Biomedical Engineering and Science at UNCC.

“I applaud him because I knew what he did while he was here: He would put in a seven- to eight-hour day in my lab and then go to work to earn money during the summer. It's rare to have such a motivated and devoted student,” Lee said.

After graduating with a mechanical engineering degree from UNCC, Ndayizeye received an internship from Corning, in Hickory, North Carolina, and a short time later, he accepted a full-time job at the company's manufacturing plant in nearby Winston-Salem. He helped develop a new fiber-optic cable used for communications. Challenged to come up with ideas for preventing underground water seepage inside the cable, he solved the problem quickly on a white board, and shares in patents and patent applications by Corning Cable Systems.

The aviation world soon beckoned Ndayizeye. In 2008, he attended a week-long National Society of Black Engineers convention in Orlando, where Boeing had a job fair booth. Ndayizeye randomly stopped and asked about a design job.

He was interviewed on the spot by company recruiters who subsequently recommended that he would be good fit for structural analysis. They asked if he would be willing to move to the Seattle area. Two weeks later, he received a Boeing job offer in the mail. It all happened so fast.

“I knew Boeing, but I didn't know I would ever work for Boeing,” he said.

George Parker, a Technical Fellow who leads Boeing's chemistry and failure analysis and testing division, met



#### UP TO THE TASK


Ndayizeye frequently consults with technical mentors at Boeing, such as Mark Clayton (left), deputy chief engineer for the 777X integrated product team, structures.

Ndayizeye at an engineering conference and has mentored him for more than a year now. He has encouraged the engineer to keep advancing through the company, and to pursue the Technical Fellowship.

Ndayizeye has found many benefits to life in America. Some are very basic, but reassuring. For example, he sees how people are able to band together and create and produce commodities, like Boeing does in building airplanes.

According to the 2017 World Happiness Report published annually by the United Nations, the Republic of Burundi was ranked 154, second from last on the list. The United States is ranked 14.

Still, Ndayizeye said he misses Burundi at times, especially the culture. To stay connected to his roots, he mentors young children in his native country, sharing his success through recorded messages. He encourages fellow Africans to follow his lead, to consider life-changing alternatives.

“It's a matter of having a vision and sticking to it, and he's a man of perseverance,” Parker, his mentor, added. “He still hasn't accomplished all of what he'd like to accomplish—but he's a man on a mission.” 



# Blake Emery talks Boeing's cabin design philosophy

**More than just a smooth ride and a comfortable cabin, the Boeing flying experience depends on continual research and advancements in science and technology.**

BY NATE HULINGS, BOEING WRITER | PHOTOGRAPHY BY TIM MCGUIRE

**Q&A** with the differentiation strategy director for commercial airplanes who leads cross-cultural research with the flying public to develop interior and exterior improvements

**Q** How are Boeing commercial airplane cabins designed? Is it more art or more science?

**A** Nothing that you'll find in a Boeing airplane cabin is random or just feels like a good idea. Boeing cabin design is based on passenger-focused research, and is intentional, based on what we discover from that research. Every idea is vetted to see if it does indeed improve the passenger experience. So it's probably more science.

**Q** So what have you learned improves the passenger experience?

**A** Let's talk about passenger windows as an example. Our approach to windows reflects the heart of our cabin philosophy, which is: airplanes by design, for people, always connected to sky. That's been true since the 707 jetliner that took to the skies in 1958.

Six decades ago with the 707, Boeing improved the view to the outside by providing more windows. To improve the connection to the sky, the 707 had dome lights to simulate stars, sunset and sunrise—key elements associated with the sky.

User experience testing confirms what intuition suggests: people sitting at the window seat rated the flying experience higher than those further away from the windows. That's why those window seats fill up first!

But why? Research shows that people feel the connection to the sky is special—that holds across the world's cultures.

#### INTERIOR INSIDER

Blake Emery, develops differentiation strategy for Boeing Commercial Airplanes.

**Q How has technology further enabled this approach?**

**A** Pulling a window screen down essentially turns a window into a wall, breaking the connection with the sky. On the Dreamliner, you can dim the window and still not lose the connection to the sky. We innovated by seeking out technologies that enabled the window to dim, and allowed the passenger to choose the opacity of the window.


**Q Fliers typically face the “window or aisle” dilemma. How can every seat get more window?**

**A** The obvious answer is to have the windows be larger and higher in the fuselage. The problem was that would bring additional weight to the aircraft.

For the 787, and the decision to move to a composite fuselage, the engineers were able to eliminate the heavy window reinforcing band, thus enabling larger windows. The window band is necessary on metal airplanes to prevent stress fractures and their propagation. Composite structure does not propagate cracking the way metal can, which allowed us to eliminate that band.

**Q And what about the interior lights?**

**A** The Boeing Sky Interior uses modern LED lighting. We also incorporate a proprietary method of harmonizing the lights with the architectural lines to help the passenger subconsciously feel as if they are truly in the sky.

Every little bit of light in a Boeing airplane has been carefully thought through right down to the engineering to allow or create that light. The interiors design strategy continues to be driven by the “by design” aspect of our cabin philosophy. Research and engineering come together to create the preferred passenger experience. 



BOEING ILLUSTRATION

## Special seating

**Three new, state-of-the-art seat designs for the 787 Dreamliner family were introduced in April through a collaboration by Boeing and two suppliers.**

The new offerings, an economy class seat by LIFT and two premium business class seats by Jamco, are part of Boeing’s effort to collaborate closely with suppliers to address capacity and performance issues in the seat and interiors categories—a concern for Boeing and the industry, according to Boeing leadership.

These types of collaborations have another major benefit—seats designed spatially, structurally and aesthetically for the Boeing Sky Interior and the 787 Dreamliner.

“The passenger experience is enhanced when you have a space that has total design harmony,” said Blake Emery, director of differentiation strategy for Boeing Commercial Airplanes.

# Selections from the Boeing Technical Journal

The Boeing Technical Journal is a peer-reviewed periodical for Boeing subject-matter experts to capture and leverage knowledge. Research coverage includes all manner of commercial and defense product development, and products and services spanning land and sea, to air and space, and cyberspace.

The Journal is a proprietary publication, but the articles on the following pages are summaries of technical papers approved for public release and available online at Boeing.com.

### Contributing Authors

**LEAN BY DESIGN:  
THE SYNTHESIS  
OF LEAN AND  
DESIGN THINKING**



**Miriam Grace** is a Boeing Technical Fellow and senior systems architect supporting sales and marketing for both commercial and defense work.



**David L. Smith** is a systems architect focused on combining modern innovation approaches with model-based system engineering methods.



**Liz Juhnke** is a Boeing designated expert in user experience and a designer supporting manufacturing and quality systems.



**Steve Dalton** is a Boeing designated expert in Lean methodology working in service and program integration.

**FORTY YEARS OF STRUCTURAL  
DURABILITY AND DAMAGE  
TOLERANCE AT BOEING  
COMMERCIAL AIRPLANES**



**Steven Chisholm** is a Boeing Associate Technical Fellow and the director of structures engineering in Commercial Airplanes.



**Antonio Rufin** is a Boeing Technical Fellow and senior lead engineer in the structural damage technology group for durability and structural fatigue in Commercial Airplanes.



**Brandon Chapman** is a structural analyst involved in the development of durability and damage tolerance analysis methods and allowables.



**Quentin Benson** is a Boeing Associate Technical Fellow and structural analyst in the 777 aft fuselage group.

**AN HISTORICAL PERSPECTIVE  
ON BOEING’S INFLUENCE ON  
DYNAMIC STRUCTURAL ANALYSIS  
NUMERICAL SIMULATION**



**Jack Castro** is a Boeing Associate Technical Fellow providing leadership and consulting on best practices and application of finite element methods across the company.

# Lean by Design: The Synthesis of Lean and Design Thinking

## Summary

MIRIAM GRACE | DAVID L. SMITH | LIZ JUHNKE | STEVE DALTON

Boeing employees have learned, from hard-won experience, innovation at the scale of aerospace requires functional groups to work together.

Technologically advanced systems must interoperate in a system-of-systems context. Design Thinking is particularly effective in situations where there are multiple dimensions to consider, layers of meaning that challenge linear logic, and many gaps in understanding. And it provides a solution to one of the thorniest leadership questions of the innovation movement: How to do innovation?

Subsequently through Lean, Boeing has maintained competitive advantage with continuous incremental improvements to its products and services by eliminating waste. In the traditional practice of

Lean as institutionalized at Toyota, seven types of waste are identified: overproduction; inventory, waiting, motion, transportation, rework and over-processing.

But in the first chapter of the book, "Lean Thinking," authors James Womack and Daniel Jones identify an eighth waste type: goods and services that do not meet the needs of the customer. When that which is produced is a poor fit or unsuitable as measured against what the customer values, it is usually because the producer has disregarded or is totally unaware of the value opportunity.

This is where the concepts of Lean and Design Thinking can merge to create a synergistic multiplying effect between product and process, resulting in greater quality and

higher value for less cost.

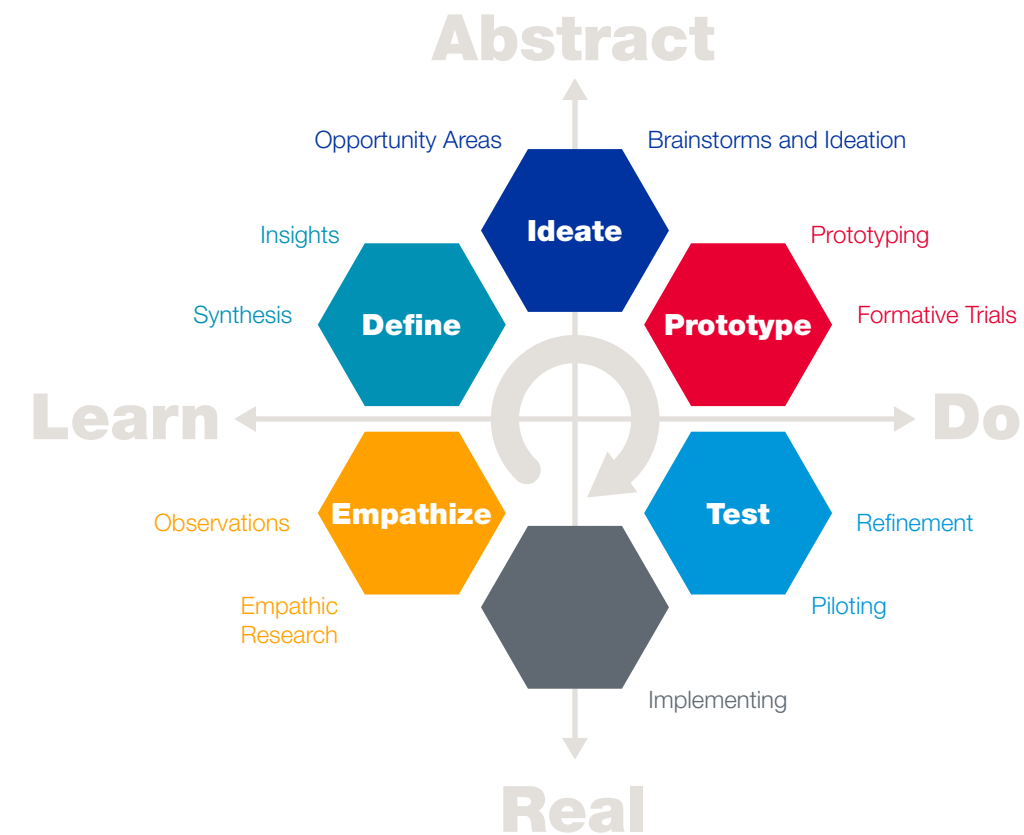
Those already familiar with Lean methods can help facilitate the melding of Lean and Design Thinking in service of Boeing's vision to out-innovate the competition. Finding the synergies and blending the strengths to maximize and leverage both is clearly an opportunity. The goal of this article is to encourage stronger dialog between Lean and Design Thinking practitioners and to find ways to unify these methods.

The concept is simple: bring the product and value-chain stakeholders together in a unified design process where products are developed together with the operations that will produce them. This will provide the flexible knowledge base for innovators to work toward achieving the best alternative outcomes for each respective area; ultimately bypassing costly post-production changes.

Today's business environment is about receiving more for less. The expectation is that businesses must provide more valuable products and services at lower costs. The idea of "better, faster, safer, cheaper" has dominated business thinking since the early Lean movements of the 1970s.

But today customers equate value with products and services that are not just simply better, but innovatively better. The market is calling for game changers. Further, the expectation is

The writing on the wall suggests innovative is the new better, with faster, safer and cheaper simply expected.



**FIGURE 4.** Design thinking methods iterate in a continuous feedback loop to foster innovation.

SOURCE: BOEING

that those innovations should resonate with why a company is delivering them in the first place. The why must map to a shared belief between both the supplier and the customer that the service or product truly has additional value. The writing on the wall suggests innovative is the new better, with faster, safer and cheaper simply expected.

This emergent paradigm is not just about the ability to innovate faster, but to be able to do it over and over again; quickly, reliably and with high quality. Customers reward the speed of development for innovative new solutions only when the solution

resonates with their perceptions of value.

The Design Thinking learning curriculum had its origins in a joint program started at Stanford University in 1958 between the departments of Mechanical Engineering and Fine Arts. The deeply collaborative Design Thinking methodology, with its human-centered focus, enables the shift to customer-centricity.

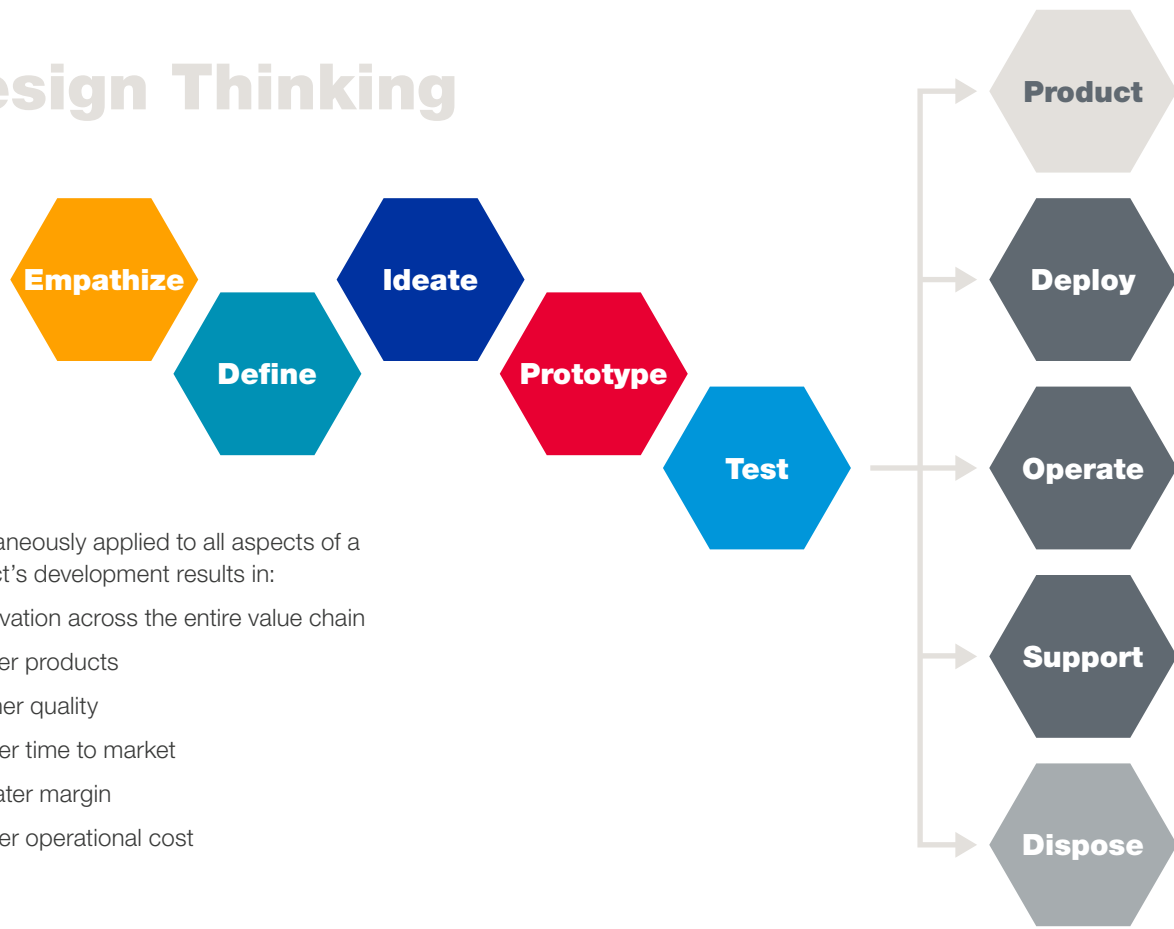
Twenty-first century businesses embrace design methods as a way of accessing and leveraging the creative consciousness of employees. Figure 4 shows the Design Thinking process

flow as taught inside Boeing, with key actions at the various phases, against the backdrop of a reference framework.

The development of human-centered design standards (ISO 9241-11:1998, ISO 9241-210:2009, and ISO 26800:2011) introduced a broad definition of usability, closely aligned with business objectives, and laid out fundamental principles for designers to follow in system design contexts. These include:

- Ensure the project integrates the users' wants or needs and the environment in which they work or live.

# Design Thinking



Simultaneously applied to all aspects of a product's development results in:

- Innovation across the entire value chain
- Better products
- Higher quality
- Faster time to market
- Greater margin
- Lower operational cost

**FIGURE 6.** Design thinking methods applied across the value chain.

SOURCE: STANFORD UNIVERSITY AND BOEING

- Ensure designers know who the users are and how the system should fit into their lives or their work.
- Make the demonstration of usability (in the broad sense of quality-in-use) the objective of the design team.
- Form a flexible team that will understand and address all aspects of the users' experience with the system.

While Lean methods apply to business optimization, streamlining processes and eliminating waste, Design practice is focused on business transformation

and is driven by innovation in all areas of the business.

From a Design Thinking perspective, innovation endeavors begin with more than just detailed customer knowledge; a level of insight often referred to as "customer empathy" is also required. In this mindset, employees are challenged to:

- Start by developing deep understanding of the customer, their feelings about the context within which they operate, and their key business challenges and opportunities.

- Use that empathy to envision a better world on their behalf.
- Set discrete goals that will give life to that vision.
- Then innovate to make it so.

Design Thinking is also inclusive of a systems paradigm (aka systems thinking) and shares principles with the systems sciences, such as:

- Holism as a methodology.
- Integration as a direction.
- Humanism as a task and responsibility.

- Openness as an ecology.
- Purposefulness as behavior.
- Choice as a driver.
- Multidimensional as structure.
- Counter-intuitive as an understanding.
- Emergence as a property.

Thus, useful innovation starts with customer empathy and a vision derived from that empathy. By developing detailed customer knowledge, we understand the why that motivates a particular customer, and this gets to the heart of anticipating their needs. Starting with why leads to discovery of the what.

This approach of targeted innovation is counterintuitive. Asked to describe a process for innovating, many people start by talking about ideas. Companies and organizations striving for innovation often sponsor idea fairs. Such exercises are wasteful and perhaps even destructive to the organization's ability to achieve their innovation goals. What should come first is getting to the right articulation of a customer value-creation challenge. Getting this right is the secret sauce to outperforming the competition and is foundational to the creation of a culture of innovation.

Design Thinking offers a range of powerful and standardized tools that guide the user toward development of a deep understanding of the why. Further, it facilitates a smooth process for evaluating iterations in thinking, building and learning to identify what and how. This is an innovation paradigm.

Ultimately, the task is not simply designing something and making it work well at the least cost. Rather, it is to design the right something and communicate the connection between

that thing and the target customers' or users' activities or feelings. Discovering customer needs takes time and requires intentional activities like observing and conversing with them, forming relationships, and gaining insights into the rough spots in their daily lives.

Design Thinking can be taught and mentored, and is a repeatable process. But how do we take advantage of this? How can we be innovative and lean simultaneously?

This synergy can be realized through the blending of Design Thinking and Lean practice at the very onset of product development, more specifically, with the direct and intentional application of design principles and practice to Lean. In fact, Lean already has a practice that approaches that ideal—the Production Preparation Process, or 3P.

Instead of just using Lean to fix existing problems in the manufacturing or delivery process, 3P takes Lean upstream for integration into new product design from the start. This is where Lean can have the most influence on both the product and its value-chain. The addition of Design Thinking to Lean methods provides

the advantages of deeply understanding human needs and developing alternative designs that create breakthrough value.

Designing the value-chain at the onset of the innovation process using proven Lean principles has benefits. It results in products that are more valuable, require less initial capital investment, and have lower ongoing cost for production. This facilitates achieving the very essence of the concept of more for less.

To read and download the complete Boeing Technical Journal paper titled:

“Lean by Design: The Synthesis of Lean and Design Thinking”

Please visit [boeing.com/IQ](http://boeing.com/IQ).

# Forty Years of Structural Durability and Damage Tolerance at Boeing Commercial Airplanes

## Summary

STEVEN A. CHISHOLM | ANTONIO C. RUFIN | BRANDON D. CHAPMAN | QUENTIN J. BENSON

Pioneering efforts in structural durability of aircraft, which saw significant advances in the 1970s and 1980s with the development of comprehensive internal technology standards, continue to evolve at Boeing.

Successes are evident in terms of significant safety improvements and considerable reductions in service actions on airplanes designed since that time. Managing an aging fleet and the adoption of new regulations affecting maintenance planning remain some of the greatest challenges.

New materials—both composite and metallic—and assembly methods are all further shaping the way durability and damage tolerance are being assessed and implemented. The full version of this paper, which can be accessed at [www.Boeing.com](http://www.Boeing.com), reviews the progress made over the past 40 years in the development and application of durability and damage tolerance methods across the Boeing Commercial Airplanes product line.

In that time, durability and damage tolerance (DaDT) have had to keep pace with major developments in materials and manufacturing

processes. Composites, for example, saw their first primary structure application at Boeing in the early 1990s on the 777 empennage. Today, they are used on the new Boeing 787 and 777X in areas of the airframe that previously were the exclusive domain of metals.

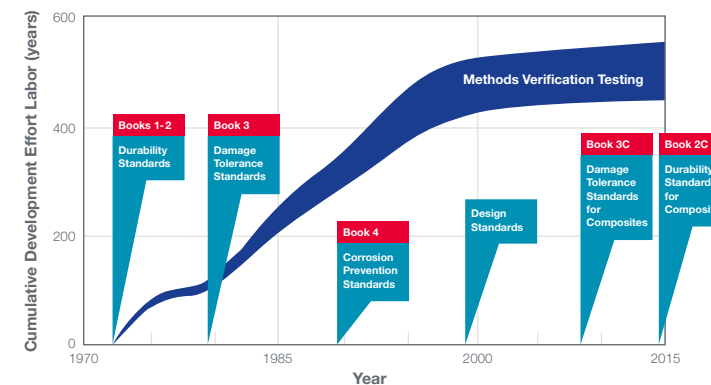
The most important outcome from the early developments and their evolution is the steady advance in commercial aviation safety that has been achieved since the advent of commercial jet transport in the 1950s. Progress in commercial aviation safety has always been entwined with the evolution of design requirements that are mandated by the regulatory agencies. The introduction of fail-safe design on the Boeing 707, design and testing for durability starting with the model 727, and incorporation of DaDT methods, and more active corrosion prevention and control measures starting with the 757 and 767 airplanes, have all played a role in bringing about a significantly safer, more durable and more economically viable fleet.

One notable success story has to be how Boeing developed supplemental structural inspections in the late 1970s and early 1980s and integrated them

into operator-applied maintenance programs, essentially converting fail-safe certified airplanes into damage-tolerant ones. The success of these programs is evidenced in the ever-improving fleet safety record of the commercial airplane fleet, the majority of which consists of Boeing airplanes.

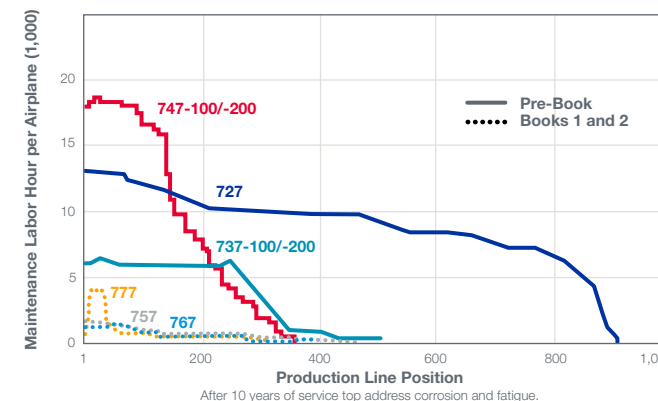
In another major accomplishment, and supporting these developments, Boeing has created industry-leading technology methods and standards that provide a Boeing Commercial Airplanes product-wide uniform approach to design and analysis for fatigue, damage tolerance and corrosion prevention and control (Fig. 3).

The standards capture lessons learned and are periodically updated to incorporate new methods, which can then be adopted in new designs or as design improvements. Furthermore, since their inception, these standards have been built for ease of use both in terms of prerequisite analysis skills and tools, and reliance on a manageable number of variables. Embodied in Book 1, Book 2 and Book 3 (and their composite counterparts), the compendia of these standards are considered



**FIGURE 3.** Evolution timeline and resources required for Boeing structural DaDT technology standards.

SOURCE: BOEING



**FIGURE 6.** Impact of new design and analysis practices on fleet maintenance hours.

SOURCE: BOEING

The size and longevity of the Boeing active commercial fleet (as illustrated by Table 1) is a testament to a quality achieved only as a result of decades of development and experience.

Airplane Model	EIS <sup>1</sup> Date	Airplanes (Active Commercial Fleet Only)			High Time Airplanes	
		Delivered	In Service	Average age, yrs.	Flights <sup>2</sup>	Hours <sup>2</sup>
727	1964	1,827	24	37.2	87.7	93.2
737-100/200/300/400/500	1968	3,098	895	22.8	97.3	102.2
737-600/700/800/900	1993	5,659	5,384	7.6	46.7	64.4
747	1970	1,489	501	14.8	36.1	136.5
757	1963	1,043	715	21.4	45.6	104.2
767	1962	1,061	738	17.9	50.0	125.0
777	1995	1,396	1,333	8.8	38.7	92.4
787	2011	378	378	1.7	6.4	17.9
DC-9	1965	927	2	36.0	108.1	109.3
MD-80	1980	1,191	351	25.2	60.3	90.0
MD-90	1995	116	71	19.0	40.9	56.9
717	1998	155	151	14.2	57.1	46.6
DC-10	1971	366	48	38.4	46.7	131.0
MD-11	1990	198	117	21.8	19.3	109.4

<sup>1</sup> Entry into service  
<sup>2</sup> In thousands

**TABLE 1.** Boeing Commercial Airplane usage statistics, based on May 2016 data.

SOURCE: BOEING

living documents that are periodically revised to adopt the latest improvements in analysis, loads, materials, and structural concepts, as well capturing new test and service data as it becomes available.

Initially developed in the early 1970s, and first implemented with the 757 and 767 models, the Boeing durability analysis standard, commonly referred to as “Book 2,” along with its design companion, “Book 1,” were first introduced with the overall objective of assuring a competitive economic life for aircraft structure. This goal was specifically defined as an absence of

significant fatigue cracking in the first 20 years of service (defined as a probability of cracking of less than 1 percent with 95 percent confidence), and at least 30 years of service before fatigue related maintenance begins to measurably escalate (defined as a nominal probability of cracking of 5 percent with 95 percent confidence). This meant that the airframe truly remains economically viable for a minimum of 30 years.

Book 1 provides specific design and analysis guidance collected from service and full-scale fatigue test data to help designers and analysts

avoid known issues and adopt best practices. Book 2 provides a comprehensive summary of design values for fatigue analysis, as well as the procedures and constituent factors used to determine them.

The Boeing damage tolerance analysis standard, commonly referred to as “Book 3,” was first introduced in 1979 in response to new requirements. Book 3 provides a method and design data for damage tolerance analysis of metallic structure. Similar to the Boeing durability method, the Boeing damage tolerance approach was first implemented for new design with



**FIGURE 39.**  
The Boeing 777 FAUB fuselage assembly process.

SOURCE: BOEING



the 757 and 767 models. Book 3 was also used concurrently for supplemental structural inspection programs on the 727, 737 and 747 models.

The introduction of the durability method as well as active corrosion prevention programs has had a dramatic and almost immediate effect on fleet maintenance, as Fig. 6 shows. The 757 and 767 were the first models to take advantage of the Books, resulting in a drastic reduction of maintenance service hours. This trend has continued on newer airplanes, the 737 NG and 777, further enhanced by improvements to the methods and the continuous learning process afforded by fleet observations. This trend is also clearly evidenced in the many full-scale fatigue tests successfully completed since then.

Boeing has a monitored fleet in which events are evaluated using a common damage tolerance methodology, and maintenance programs are adjusted as necessary, while the airplanes are operated out to their 30-year life expectations and beyond. Recent indications from the worldwide commercial airplane fleet are that average airplane ages may be peaking, but much of the current pool remains advanced in age. The size and longevity of the Boeing active commercial fleet (as illustrated by Table 1) is a testament to a quality

achieved only as a result of decades of development and experience. These statistics are also a reminder of the continuing challenges associated with aging structures and the value of design for durability.

The DaDT methods whose foundations were laid down at Boeing decades ago have continued to prove themselves through service and test experience. As the regulatory environment has evolved and technology has progressed, these methods have had to keep pace or expand into new areas. Although the basic analysis principles employed today are not substantively different from past methods, the tools and processes used have been refined over these past 20 years. Looking ahead, these processes will seek more efficient use of engineering resources, greater accuracy, and incorporate service experience acquired from an ever-expanding fleet:

- **Materials and basic part fabrication**

Although much of the current focus in structural materials development is on composites, metals will continue to play a significant role in many areas of the airframe, and for the foreseeable future, will likely remain the dominant choice in short-haul, high-production-rate airplanes.

Additional efficiencies can be gained by implementing advanced

fabrication techniques. For metals, this is especially true for titanium, an impact that is compounded by the rising use of titanium alloys on new airplanes such as the 787. Because of the intrinsic cost of titanium, even a moderate reduction of the buy-to-fly ratio (the ratio of the weight of the raw material used for a component and the weight of the finished component) can lead to significant cost savings. Welding, powder metallurgy and additive manufacturing are among the technologies being explored in pursuit of this goal.

- **Assembly processes**

With fuel costs having doubled in the past decade as a percent of total operating costs and the new generation airplanes being able to deliver much improved fuel consumption, lower emissions and lower environmental noise, orders for new and replacement aircraft are expected to grow at an extraordinary pace. The result is that production rates will grow to unprecedented levels.

On the 737 airplane family, the existing wing panel assembly process, which rivets wing skins and stringers while the wing is held in a stationary horizontal position, is being replaced with a new high-precision automated system termed (vertical) PAL (Panel Assembly

Line). PAL assembles the panels on a moving line at higher rates and in a vertical attitude, eliminating flow-intensive temporary fastening and overhead crane movement of parts. Qualification of the new PAL assembly system included a comprehensive fatigue test program, the goal of which was to show that for fatigue-critical areas of the wing, the new system meets or exceeds the fatigue performance of the older legacy processes. A similar fatigue test program has recently begun to evaluate and qualify the new 737 Spar Assembly Line (SAL).

On the Boeing 777 program, the focus is on a radically new fuselage one-up assembly process, FAUB, or Fuselage Automated Upright Build (Fig. 39). With FAUB, aluminum major fuselage sections are now built using pre-programmed, guided robot pairs that fasten the panels of the fuselage together with only minimal fixed tooling. Automated drilling operations will eventually install approximately 60,000 fasteners that are today installed by hand. In addition to benefiting production rates, FAUB will improve workplace safety and increase product quality.

- **Analysis methods**

One area that has been the object of considerable attention over the past decade has been the development of finite element analysis best practices in their application to both fatigue and damage tolerance assessments. Experience shows that the value and versatility of finite element analysis as an adjunct to DaDT evaluations can only be truly realized when the proper modeling strategy (both the type of analysis and physical model) is tailored to the specifics of the problem and evidence from either test or other previously accepted analyses can be used to validate the results.

For composites, some of the greatest current challenges are in NDI (Non-Destructive Inspection), particularly in the application of the technology to large composite surfaces, and in its ability to reliably detect degraded bondlines or interlaminar disbands. Boeing has been developing NDI methods that put energy into the structure transverse to the critical interfaces, scanning the structure as the energy pulse is applied. This technique has been shown to be capable of finding weak bonds or delaminations that are on the verge of damage nucleation and growth, but it is not yet ready for deployment in the field.

- **The human connection**

One challenge that is easy to overlook is the industry's ability to maintain skill continuity in this highly specialized (and sometimes subjective) technical discipline. Although U.S. government projections indicate relatively low (less than 1 percent) annual employment growth rates in aerospace engineering over the next decade, the reality is that the industry is faced with significant turnover due to age demographics, globalization, shifting skill needs and competition from other

industries. These are expected to become particularly acute issues in the fields of composite and stress engineering (including fatigue and damage tolerance), systems integration, and manufacturing/production engineering.

Boeing is actively engaged in efforts to maintain an experienced workforce through efforts in training and mentoring. In the DaDT field, training curricula have been developed and are being used across the company's design centers worldwide. Between 2006 and 2014, nearly 85,000 hours of specialized DaDT training were imparted to engineers supporting Boeing projects.

Many challenges remain, not all of which are purely technical—for example, how experience and past lessons learned are preserved and built upon. Maintaining that continuity in the midst of a major engineering generational transition will be one of our greatest future challenges yet. **IQ**

To read and download the complete Boeing Technical Journal paper titled:

“Forty Years of Structural Durability and Damage Tolerance at Boeing Commercial Airplanes”

Please visit [boeing.com/IQ](http://boeing.com/IQ).

# An Historical Perspective on Boeing's Influence on Dynamic Structural Analysis Numerical Simulation

## Summary

JACK F. CASTRO

The convergence of the Finite Element Method, Craig-Bampton Reduction and the Lanczos Eigenvalue extraction method formed a foundation that has improved the development and performance of every modern Boeing airplane, along with a multitude of consumer products familiar to all, such as automobiles and washing machines.

This paper is a reflection on Boeing's influence on the development and deployment of several numerical solution methods pervasive in the field of structural dynamics.

### Boeing and the finite element method

Today within Boeing, the finite element method is pervasive with several thousand engineers applying this technology on a regular basis. With regard to structural analysis, it is central to loads and dynamics analysis, as well as stress analysis and testing. It turns out that it was Boeing's need to improve flutter prediction that led to the development of the finite element method.

Jon Turner, the supervisor of the Structural Dynamics Unit at Boeing

in Seattle in the 1950s, brought the modern finite element method into everyday use. According to Carlos Felippa, who writes in the "The Origins of the Finite Element Method", Jon Turner "forcefully got Boeing to commit resources" to the Direct Stiffness finite element method while other aerospace companies were mired in the Force Method which eventually died out.

In the early 1950s, with the growing popularity of jet aircraft, and with demands for high performance military aircraft, delta wing structures presented new modeling and analysis problems. Existing unidirectional models (i.e. beam models) did not provide sufficient accuracy. Instead, two-dimensional panel elements of arbitrary geometry were needed.

While Turner's application for the direct stiffness finite element method was vibration calculations to facilitate flutter and dynamic analysis, Ray Clough, from the University of California at Berkley, partnering with Boeing, realized that this method could be applied to stress analysis. Many others contributed to the development and popularization of today's modern

finite element method, in particular, J.H. Argyris, O.C. Zienkiewicz and E.L. Wilson.

In 1964, NASA also recognized that the future of structural analysis was the finite element method. And in July, 1965, NASA issued an RFP for NASTRAN, which stands for NAsa STRuctural ANalysis. While Boeing did not bid on NASTRAN, the company contributed several state-of-the-art substructuring techniques. One of these was component mode reduction, a technique for reducing a finite element model of a component down to a set of boundary matrices that approximates the dynamic characteristics of the component. The reduced component is generically referred to as a substructure, but currently the term "superelement," coined by commercial finite-element-analysis software providers, is more prevalent.

### Craig-Bampton component mode reduction and synthesis

There are a litany of component mode reduction and reduced order modeling techniques, but one technique stands out for its widespread use and deployment in the popular

commercial Finite Element packages (e.g. MSC Nastran, NX Nastran, ABAQUS and ANSYS). The "Craig-Bampton" (C-B) component mode reduction method is applied to a wide variety of dynamic simulations not only in aerospace, where it was conceived, but in virtually every industry where structural dynamics has a large influence on the product design and performance.

The seminal paper on the C-B method was published as "Coupling of Substructures for Dynamic Analysis" in July 1968 in the AIAA Journal by Roy Craig, of the University of Texas, and Mervyn Bampton, a Boeing structures engineer.

Within Boeing, the Craig-Bampton technique is central to the aeroelastic process, which is used for flight loads and flutter analysis. Of significant importance to the flutter community is that the C-B methodology enables rapid frequency variation studies and insertion and tailoring of assumed modes. The C-B method is also extensively applied in propulsion dynamics for windmilling, fan blade out loads and engine vibration related noise (EVRN) analyses.

The EVRN analysis is a coupled vibro-acoustic analysis where C-B reduction is performed to reduce

the airframe and acoustic fluid model down to the interface with the engine. Of significance, is that this C-B superelement package can be delivered to the engine manufacturers in the form of boundary matrices and output transformation matrices (OTMs), thereby preserving all Boeing trade secrets, while enabling the engine companies to determine how different engine bearing and mount designs effect the interior cabin noise.

C-B reduction with OTMs is also central to coupled loads analysis for Boeing spacecraft. Coupled loads analysis, in this context, is essentially the dynamic structural analysis of the complete space structure.

Another class of dynamic analysis performed in the automotive industry, and also across virtually every other industry (including aerospace) that analyzes dynamic systems, is Multi-Body Dynamic (MBD) simulation.

MBD is a numerical simulation method in which systems are composed as assemblies of rigid and/or elastic bodies. Connections between the bodies are modeled with kinematic joints or linear/nonlinear springs/bushings/dampers. If inertia (mass) is eliminated, and all bodies are rigid links with kinematic constraints, then the multibody analysis reduces

down to a kinematic mechanism analysis. However, when mass is included, the analysis is inherently dynamic.

For the dynamic case with flexible bodies, the challenge is to bring the flexibility of each body into the system simulation in an accurate and efficient manner. The standard methodology used to create the "flex body" is to perform a C-B reduction where the body is reduced down to the interface degrees of freedom that connect the body to its surrounding joints. Additional transformations may be done to put the interface matrices in a form compatible with the formulation of the MBD software system. However, the first step is typically the C-B reduction. All the popular commercial finite element packages have the ability to generate "flex bodies" of components from finite element models of the component and the C-B method is used to create the reduced mass and stiffness matrices that are processed to generate the flexible body.

### Lanczos method of eigenvalue extraction

The computation of a structure's or substructure's natural frequencies and mode shapes is of fundamental importance to dynamicists because they use them to understand dynamic behavior and interplay of components in a dynamic system.

From a mathematical perspective, the calculation of natural frequencies and mode shapes is an eigenvalue extraction problem in which the roots (eigenvalues) and associated mode shapes (eigenvectors) are computed from the dynamic equation of motion with the assumption of harmonic motion, while neglecting damping and applying no loading.

Eigenvalue/eigenvector calculation is also a requirement of the C-B reduction method. The C-B method uses the natural frequencies and mode shapes

In many cases, engineers are using these technologies today within a modern graphical user interface oblivious to the underlying solution methods and algorithms at play.

## Dynamic structural analysis numerical simulation timeline

### 1950s

**1950:** Cornelius Lanczos published the "Lanczos eigenvalue extraction method" used in the popular finite element programs for vibration and buckling modes.

**1952-53:** Jon Turner oversaw development of the first continuum based finite elements.

**1956:** Turner, Clough, Martin and Topp publish seminal paper which summarized a procedure called the Direct Stiffness Method (DSM).

### 1960s

**1960:** Ray Clough penned "Finite Elements for Plane Stress Analysis," which both adapted the DSM method for stress analysis and simultaneously coined the phrase "Finite Element."

**1960s:** Boeing engineers commence development of finite element codes on digital computers, including the ATLAS system, a large-scale computing system for linear and nonlinear, metallic and composite, structural optimization.

**1964:** The finite element method is recognized by NASA as the "future of structural analysis, particularly for complex aerospace structures."

**1965:** NASA begins development of its own finite element program, NASTRAN, in partnership with MacNeal-Schwendler Corporation (MSC) and Computer Sciences Corporation.

**1968:** Roy Craig and Mervyn Bampton, publish "Coupling of Substructures for Dynamic Analysis," which became known as the Craig-Bampton component modal synthesis.

### 1970s

**1970:** Boeing's military and commercial airplanes mathematicians come together to form Boeing Computer Services (BCS).

### 1980s

**1989:** Boeing and Cray are awarded the Society of Industrial and Applied Mathematics (SIAM) Gordon Bell Award for implementing a general sparse matrix factorization on an eight-processor Cray Y-MP computer.

of a component constrained at its interface to generate the dynamic portion of the reduced stiffness, mass and loads matrices. So, a robust and efficient C-B reduction requires a robust and efficient eigenvalue/eigenvector calculation.

Cornelius Lanczos, a colleague of Albert Einstein, was inspired to study and improve matrix methods and numerical eigenvalue extraction of linear systems while working at Boeing in 1946-1949. Shortly after leaving Boeing to join the National Bureau of Standards, he published the method in 1950.

The Lanczos eigenvalue extraction method is by far the most prevalent eigenvalue extraction method used today in the popular finite element programs for vibration and buckling modes. It is the bread and butter of dynamicists, whether used directly for computation of natural frequencies and mode shapes, or used indirectly with similar methods that are based upon automated component modal synthesis of very large systems.

Before the commercial availability of the Lanczos method in the mid-1980s, dynamicists spent a large amount of thought and time in determining

how to reduce a model down to a size that could be efficiently solved with their finite element program and yield an accurate, albeit approximate solution. This is precisely why the C-B and other dynamic reduction techniques were created. However, the underlying weakness of all these methods was an accurate, efficient and robust eigenvalue extraction method for the reduction process.

#### Boeing Computer Services

During the 1980s and early 1990s the Boeing Computer Services math/software team was directly responsible

for the first significant robust and efficient Lanczos method deployed in a commercial FEA package. In 1985, The MacNeal-Schwendler Corporation (MSC) released Nastran V65 with Boeing's Lanczos eigensolver, and in the decade following, similar implementations were deployed in most of the other popular finite element packages.

Taking the Lanczos method from an unstable, impractical methodology to a highly practical, robust and efficient methodology was the result a many researchers and the coalescence of

several key breakthroughs—block algorithms, stability correction only as needed, shifting, and integrating all of these with a smart algorithm for choosing shifts.

The work of the BCS math team cannot be overstated when it is recognized that 30-35 years after their heroic efforts, the Lanczos method is still prominent in the popular commercial FEA packages. We attribute much of the performance improvement in finite element solutions to computing hardware improvements. However, in the late 1980s, between the Lanczos and Sparse Solver methods, engineers realized order of magnitude gains in solution performance independent of any hardware improvements. These two performance improvements meant that many models that had previously required substantial substructuring and complex dynamic reduction, could now be solved directly with the Lanczos method.

The finite element method was invented roughly 60 years ago. Craig-Bampton reduction was invented roughly 50 years ago and the modern Lanczos and Sparse solver methods

were deployed into commercial FEA packages roughly 30 years ago.

The fact that after multiple decades, these technologies persist, albeit in often simpler and automated implementations, is a testament to the significance of these methods. Yet, in many cases, engineers are using these technologies today within a modern graphical user interface oblivious to the underlying solution methods and algorithms at play. [IQ](#)

To read and download the complete Boeing Technical Journal paper titled:

"An Historical Perspective on Boeing's Influence on Dynamic Structural Analysis Numerical Simulation"

Please visit [boeing.com/IQ](http://boeing.com/IQ).



# Skywriting to the MAX

**How creative engineering and expert flying confirmed the new 737 up to the challenge.**

**BY ANDREAS WEISWEAVER, FLIGHT TEST ENGINEER  
BOEING TEST & EVALUATION**

The airplane known as 737 MAX 1A004 had just completed a week of round-the-clock hot and humid testing for extended operations. It was mid-February, and the 737-8 flight test program was nearing the end of its certification schedule. Now the test team faced the challenge of demonstrating the plane's ability to accomplish a maximum-duration flight.

This particular task calls for a single flight spanning more than nine hours, while also allowing for minimal fuel reserves.

To go nine hours would have been unheard of in the 1980s; historically, the 737 would go six hours and 30 minutes in the air, not including the climb.

But MAX is ready for the challenge. The 737 MAX boasts multiple innovations—including high efficiency wingtips and industry leading CFM International LEAP 1B engines—that provide 50 percent more time in the air than the classic 737.

The Flight Test teams at Boeing have a history of making long duration flights interesting. Both the 787 and 747 teams spelled out the airplane model names using the jets' flight paths over the continental United States. The drawings show up on flight-tracking software that lay digital lines over a geographic map.

The 737-8 team intended to follow suit and started dreaming up concept art weeks before the nine-hour test flight. Simply tracing out 737 seemed derivative. And flying the Boeing logo had been done before. The airplane needed to act as a pencil drawing continuously across the

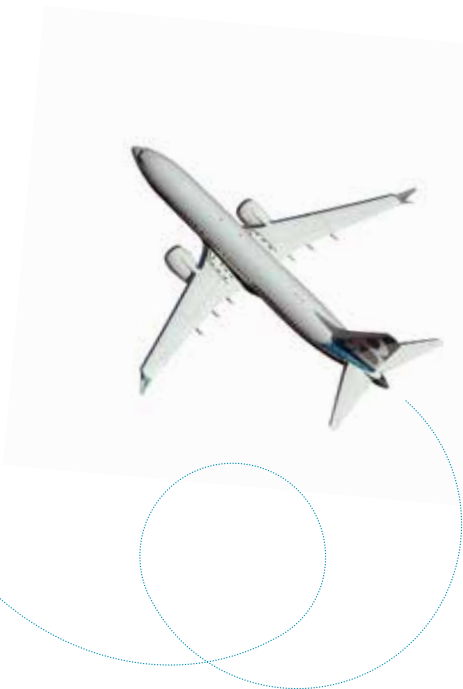
Northwest sky. The drawing had to be done with a single, well-choreographed motion.

The team settled on something that proved technically feasible, would commemorate the airplane model, and be a nod to the particular test we were flying. The finalist was a hand-drawn flight path spelling out the word MAX in distinct block lettering. This would honor the new 737 MAX model and act as a reminder that Boeing was demonstrating the maximum duration flight capabilities of the jet.

Each section of each letter would be represented by a flight leg with course changes accomplished using latitude and longitude point coordinates. With the concept complete, the next phase was to lay out details for the flight plan.

The hand-drawn letters were replaced by the more familiar Boeing Stratotype font and a draft MAX template was overlaid on navigational sectional charts. The flight was to be further bounded by a working range within the Seattle and Salt Lake Air Route Traffic Control Centers' airspaces to minimize administrative workload.

Boeing Flight Dispatch began coordinating this preliminary plan with air traffic control days before the test. Flight planning



tools using a typical cruise mach number yielded the first-cut flight time of over 14 hours; a bit excessive. Flight variables affecting the plan include fuel burn rates, leg distances, winds aloft, cruise altitude, aircraft weight and power settings (cruise speed), to name a few.

Dialing in these variables required calling on the knowledge of the 737 aero performance engineers. This team had been carefully analyzing endurance data from the previous months of testing and ably provided the airplane cruise settings needed for the flight. With cruise settings in-hand, a rescaled flight plan yielded a nominal test time of nine hours with 37 GPS waypoints to connect during the journey.

Further, a keen observer may have noted a long section suspiciously resembling the trailing cones used by the flight test group to measure high accuracy static pressure data. This was to allow for variability during the day of test.

Before going all-in on the plan, the chief test pilot reviewed the full flight plan detailing every minute spent and every pound of fuel burned. With the necessary final coordination

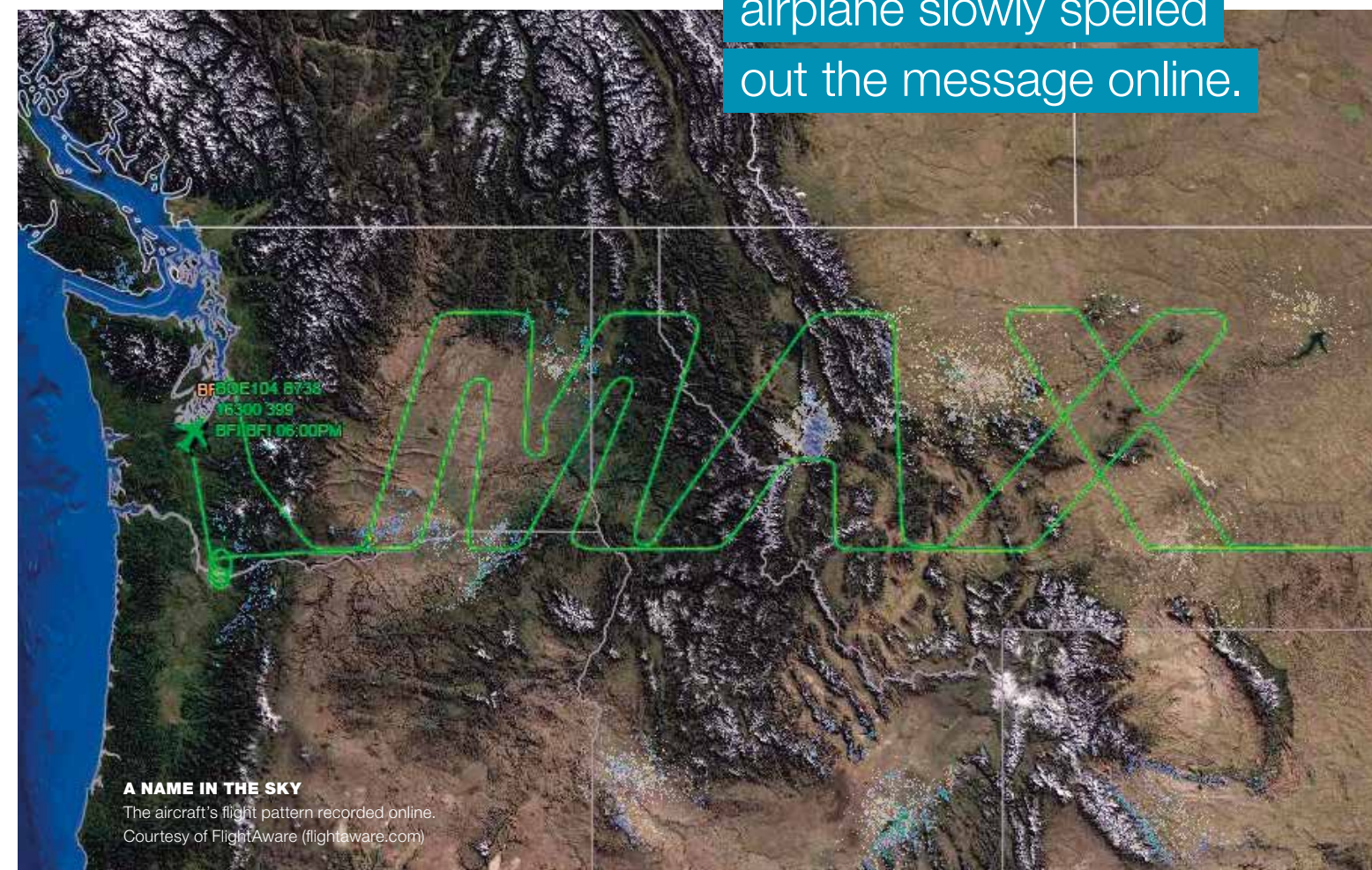
between dispatch and air traffic control, the eight-person test crew boarded 737 MAX 1A004 on Feb. 11, at 7:45 a.m. and departed Boeing Field for the nine-hour mission.

Each turn was executed with precision as the airplane slowly spelled out the message online. Lower than forecasted headwinds saw the airplane due to arrive ahead of schedule, which caused the crew to exercise a number of victory laps just north of Portland, Oregon, before returning home.

The airplane landed back in Seattle having been aloft for 9 hours and 13 minutes of continuous flight with ample fuel remaining.

The mission complete, Boeing had yet again proved its airplanes could go the distance. **IQ**

Each turn was executed with precision as the airplane slowly spelled out the message online.

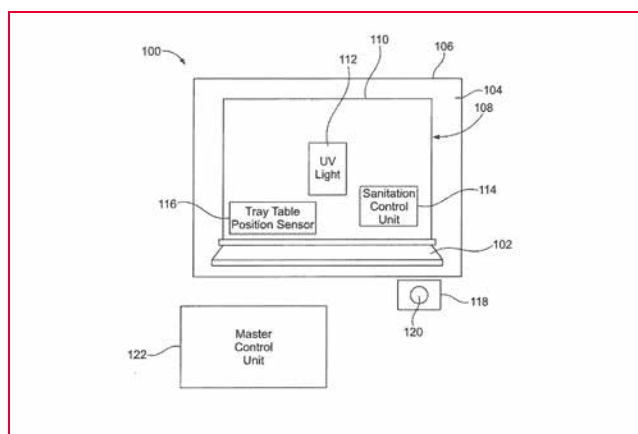


# Patent Spotlight

A few of Boeing's latest ideas and technical breakthroughs recently granted or published by the U.S. Patent and Trademark Office.

“When it comes to developing and nurturing a strong innovation portfolio, consistency is key, and those who can harness it are rewarded for their efforts.”

CLARIVATE ANALYTICS,  
TOP 100 GLOBAL INNOVATORS REPORT

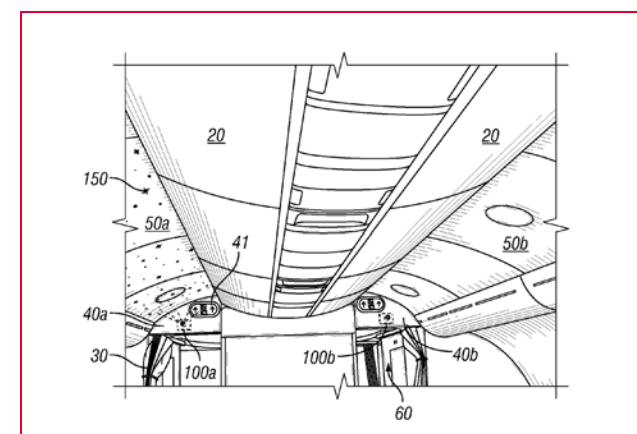


Systems and methods for sanitizing a tray table

**U.S. PATENT PENDING**  
**INVENTOR: STEVEN MACKIN**

During a typical flight, the tray tables fixed to the backs of airplane seats could become contaminated by spills, food crumbs or other germs from a passenger either using or being near the tray. While cleaning crews do try to clean the entire cabin, there might not be sufficient time to do a thorough cleaning during each flight turnover. In a closed setting, like an airplane cabin, passengers appreciate every effort made to provide a clean environment.

The U.S. Patent and Trademark Office has recently allowed an application, and a patent should be granted in the next few months to Boeing, for a system for sanitizing a tray table using ultraviolet light. Protection for additional aspects of the invention is also being considered. This patent describes a sanitation assembly coupled to the tray table. This sanitation system could be built into the seat or into the tray itself. The process could be done using a sanitation control unit coupled to the UV light source that could be automated or operated manually. The sanitation control unit operates the UV light source to emit the UV light onto the tray table when the table is secured in an upright position, and prevents the UV light source from emitting the UV light when the tray table is not secured in the upright position.

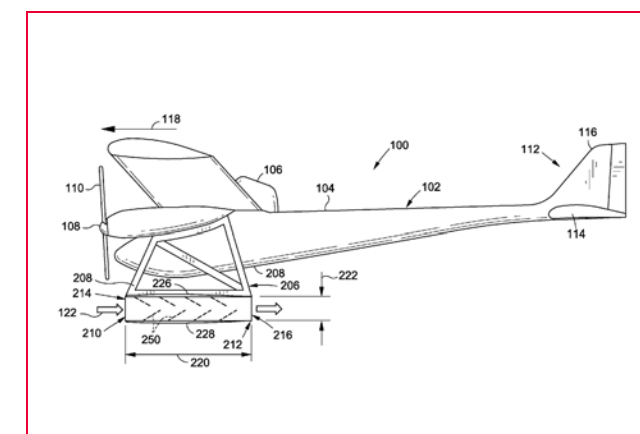


Unique system and method of creating scenes within a moving vehicle such as an aircraft

**U.S. PATENT PENDING**  
**INVENTOR: JAGDISH MADHAV**

It is becoming increasingly common for aircraft to use LED lighting to create a theme or mood within the cabin. For example, Boeing's Sky Interior uses LEDs extensively to create a harmonious visual environment for passengers. However, the schemes might be limited, and changing the LED lighting to upgrade to the appearance of starry skies or constellations might require a significant effort.

This patent application proposes using tiny projectors to create moving pictures or unique graphical scenes on the ceiling of a vehicle, like an airplane. Projectors could be positioned adjacent to the ceiling, such as at the top front panel of a cabin, near the tops of curtain assemblies, or between side overhead bins. The projectors could be the size of pico-projectors or micro-projectors. The system may include a control panel that controls the operation of the projectors in conjunction with an onboard sound system, if any.



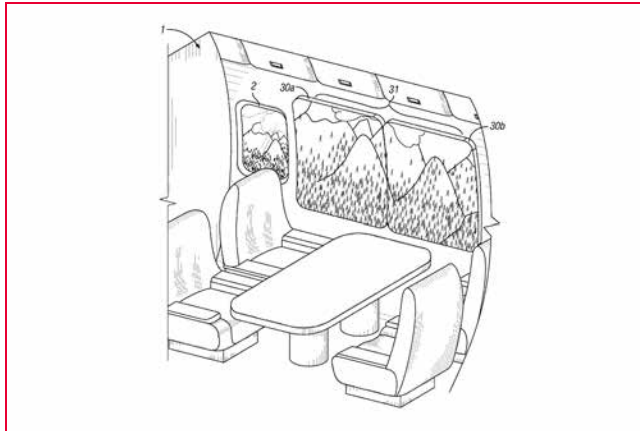
Airborne system and method for removing pollutants from a volume of air

**US PATENT: 9,555,882 B2**  
**INVENTOR: MINAS TANELIAN**

Air pollution is a significant problem for many cities. Pollution in the air today could include noxious gases, liquids and particulates, or conditions involving all of them, like smog. While current solutions for reducing air pollution mainly include minimizing sources of pollutants, these methods don't address removal of the pollutants already in the atmosphere. Air pollution, like smog, can sometimes stick around for a long time until natural weather phenomena move the pollutants.

This patent granted to Boeing in January, discusses attaching a bank of air filters to an aircraft that would sweep the sky to remove pollutants. The air filter bank may include a housing with an air intake at a forward end and an air exit aft. The air filter may be configured to remove pollutants entrained in a volume of air entering the air intake and impinging on the filter surfaces prior to exiting the air exit.

The patent doesn't specify the exact type of air vehicle used, but suggests that it could be a fleet of solar-powered or otherwise environmentally sustainable, unmanned aircraft flying in formation to clear the air of pollution. Such pollution might be trapped under inversion layers above cities, over industrial operations, surrounding forest fires or around volcanic activity.

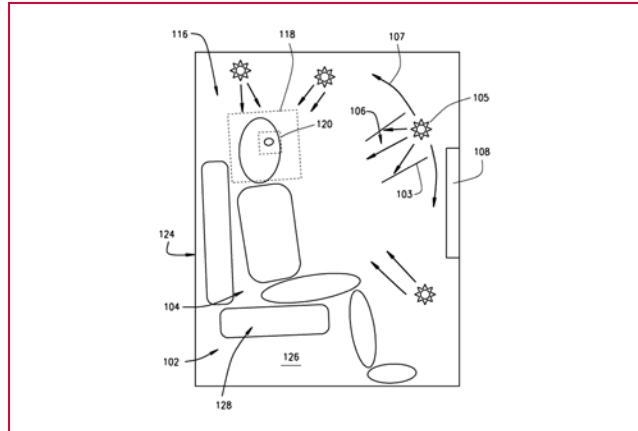


### Airplane cabin panoramic view system

**U.S. PATENT PENDING 20160325836 A1**  
**INVENTOR: DAVID TEO**

Almost everyone wants a window seat. On an airplane, the views can be spectacular; so, airplane cabins are designed with this desire in mind. However, airplane windows have always been somewhat limited in size due mainly to structural constraints.

Through a recently published Boeing patent application, there could be an alternative. Boeing has developed a system to implement panoramic views within existing aircraft designs. The airplane cabin enhanced viewing system uses cameras, flat panel displays and window plugs in place of transparent windows. Display screens would be configured to fit into the existing window spaces of an airplane model, and would include a camera positioned to capture video outside of the aircraft. The camera and screen are connected to a processor to display the captured video, and could include controls to manipulate the operation of the camera and display—to pan and zoom, for example. More than one camera and more than one display screen could be connected to the processor, which could combine the captured videos to create a single panoramic view on a single display or multiple displays.



### Ambient lighting system to mitigate the impact of travel across time zones

**U.S. PATENT 9,493,112 B2**  
**INVENTORS: LISA C. THOMAS, RICHARD J. LOFTIS, ANDREW L. ARMATORIO, COLIN W. HART**

There is a retinal photoreceptor in eyes called “melanopsin” that detects light and uses it to help regulate melatonin production, which is involved in initiating the sleep cycle in humans. Visible light, including wavelengths from approximately 390 nm to approximately 700 nm on the electromagnetic radiation spectrum, is known to have measurable effects on the melanopsin photoreceptors. Additionally, the duration of light exposure, the intensity of light and the time of day of the exposure contributes to the regulation of a person’s circadian rhythm.

The body’s natural circadian rhythms, which are partially mediated by local day-night cycles and exposure to light, become disrupted when the day-night cycle at a new location doesn’t match what the body is used to. This effect is circadian desynchrony, part of the effect known colloquially as “jet lag.” It occurs when someone travels across a number of time zones in a period of time that is shorter than the body’s ability to acclimate. People differ in their ability to adapt to this change, but on average, if a person has rapidly traveled across three time zones, it will take approximately three days before that person’s circadian rhythm readjusts to the new light cycle.

Boeing has a patent on technology that provides a customized ambient lighting environment for travelers that can be automated or manually adjusted for the provision of light that closely simulates the ambient light exposure in a desired time zone. The lighting may be adjusted such that it emits specific wavelengths at appropriate times to provide the user’s body with the experience of light exposure in the desired time zone.

## Boeing IP News

### Top 100 Global Innovator for 2016

Boeing has once again been named to the Top 100 Global Innovators list for the sixth consecutive year. The list, which analyzed factors from 2015, uses a proprietary formula to measure companies around the world engaging in innovation through research and development, intellectual property protection and commercialization.

The 2016 analysis by Clarivate Analytics found that many of the Top 100 Global Innovator companies tended to file for fewer patents, presumably focusing on invention quality over quantity. Other trends indicated by the report included a tendency for technology diversification, globalization and increasing investment in innovation.

“Together, the firms on the list generated more than \$4 trillion in revenues in 2015. That massive figure is supported by more than \$227 billion spent on R&D,” the report states.

The Top 100 Global Innovator program was formerly conducted by the information media company Thomson Reuters through its IP & Science business, but was sold last October and became a new company—Clarivate Analytics.

Clarivate relies on a variety of data to come up with its Top 100 Global Innovators index, including a scientific and peer-reviewed scoring system of proprietary patent-related metrics and methodologies.

“Pinning down the specifics of how to quantify innovation often feels like a moving target,” said David Brown, executive vice president of Clarivate Analytics. “With the Top 100 Global Innovators program, now in its sixth year, we look to eliminate any ambiguity as to what makes an organization innovative and celebrate those who have made meaningful gains to usher in the next era of global innovation.”

**For a complete list of the top 100 visit:**  
**<http://top100innovators.stateofinnovation.com>**

## World Intellectual Property Indicators

2016 report  
on 2015 data

**PATENT APPLICATIONS:**  
**2.9 million**  
**Increase of 7.8%**

**TRADEMARK APPLICATIONS:**  
**6 million**  
**Increase of 15.3%**

**INDUSTRIAL DESIGN APPLICATIONS:**  
**872,000**  
**Increase of 2.3%**

SOURCE: WORLD INTELLECTUAL PROPERTY ORGANIZATION

# Developing Airplane Systems Faster and with Higher Quality through Model-Based Engineering

## Performance and productivity improvements from Europe

BY EDUARDO CARRILLO DE ALBORNOZ-BRAOJOS | BASTIAN FIGLAR | RAMON GOMEZ | GRZEGORZ KAWIECKI  
BOEING RESEARCH & TECHNOLOGY, EUROPE

When Boeing began developing the Air Data Reference Function for the 777X, our engineers had the opportunity to work faster, reaching higher first-time quality through model-based engineering. The ADRF is a key avionics function, processing signals from pressure and temperature probes and computing aircraft state parameters like airspeed and altitude. Early integrated testing of the model in the simulator helped to verify and correct the system's interfaces and behavior, long before such testing could be achieved on the design through conventional development.

Model-based systems engineering and development (MBSE/MBD) is one of the focus areas for Boeing's research in Europe. The development of systems, comprising different engineering disciplines and stakeholders is traditionally facilitated by document-based communication. The ever increasing complexity of systems and demand for shorter development cycles and lower costs require a more efficient and less error-prone communication and development approach.

Boeing's European research—with presence in Spain, Germany,

the UK, and several other locations across Europe—has been strategically placed in an area which is not only an extensive source of knowledge and advanced technology, but also provides important locational advantages to develop solutions in areas such as materials and manufacturing, data-driven airline services, and, as in this example, avionics model-based systems engineering. Most of this work is done within the framework of research consortia consisting of European research, industrial and academic institutions. It leverages the access to talent, extensive supplier base and other high-tech and commercial opportunities of Europe.

Model-based systems engineering intends to centralize all information about the system in a model, often called the "single source of truth." The model supports the system's entire life cycle from requirements documentation to validation and verification exercises to maintenance and training purposes, just to mention some. Stakeholders like decision makers and suppliers as well as the development teams can access the model at different views and levels of detail, to access data according

to their needs while consistency of the information is guaranteed.

The approach requires a sophisticated common modeling environment, including tools, good practices and industry standards that are currently investigated by applying MBSE methods on a smaller scale during the development of selected avionics systems.

The expertise gathered and the tools developed by working on dedicated systems are transitioned to the programs and applied to other systems, moving to a truly model-centric, highly efficient and agile development culture.

The ADRF project for the 777X proved that a MBSE approach improves quality and communication, de-risks the program and significantly reduces development cost and time. Requirements could be validated at an early stage in the program, avoiding ambiguities, erroneous information and other specification flaws.

Advanced cooperative technology development with European industry leaders and the proximity to European suppliers further facilitate reductions of development cost and time. This increases first-time quality and opportunities to explore and incorporate MBSE standards developed by European industry and academia. 

## Global Scale

Here is a snapshot of a few of the technical projects in work with dozens of joint research centers and consortia worldwide.

### Boeing in South Africa and Kenya

Boeing continues to expand its international presence with new offices opening in Johannesburg, South Africa; and Nairobi, Kenya. The offices were established to support the growing commercial aviation, security and defense needs, and opportunities on the African continent. The offices will also support burgeoning technological platforms, such as the recent development in South Africa of a tobacco-based sustainable aviation biofuels supply chain in partnership with South African Airways and other partners.

### Collaborative investment for Korean technology sourcing

Since April 2016, in conjunction with the South Korean government, Boeing has been working with potential Korean suppliers to identify candidate technologies and parts from their consumer electronics and automotive applications to adapt to aerospace purposes. Following a carbon fiber braiding pilot project in 2016, two new projects on thermoplastics and composite interiors are being funded by the South Korean government and industry in 2017. Additional investments by government and companies in titanium applications for aerospace are also launching in 2017, with discussions to define titanium parts and alloy needs. As part of the mutual investment, Boeing is expected to fulfill supplier engagement commitments and sharing requirements.

### Full fidelity simulator training for C-17 in the UAE

Expanding its international training portfolio, Boeing provides C-17 Globemaster III aircrew and maintenance instruction along with logistics and simulator maintenance support for the United Arab Emirates' (UAE) inventory of realistic Weapons System Trainers. These are full fidelity motion-based simulators that are a replica of the C-17 flight deck crew station and equip pilots for airland and airdrop missions, tactical missions, aerial refueling, emergency procedures and mission rehearsal. This most recent award is the first standalone prime services contract for Boeing to perform this work in the Middle East Region. Currently, there are 32 Boeing-delivered C-17 simulators at training centers around the globe.

### What is Model-Based Systems Engineering?

Traditional systems engineering stored data in static documents; MBSE recasts the data as a set of object models, then creates relationships between the individual objects within the model.

MBSE's digitized architecture makes real-time updates accessible by all users and enables virtual system integration and test, reducing development costs, as well as the risk of design problems.



**DAN NEWMAN,**  
SENIOR TECHNICAL  
FELLOW

# Technology Readiness and the Valley of Death

**Innovation requires safely crossing technology over many paths.**

The modern established metric for technology maturity has been the TRL, or “technology readiness level,” which originated at NASA headquarters in 1974 using a scale from 1 to 9.

For many in the research and development community a technology is generally “proven” when it reaches Technology Readiness Level 6, at which point it has achieved “System/subsystem model or prototype demonstration in a relevant environment.” And once proven, there should be no reason why the technology isn’t available for use in every relevant application, right?

Well, not really.

In reality, there is a colossal distance between being technically proven and having a successful implementation. This difficulty in transitioning a new technology or approach is affectionately referred to as “The Valley of Death.”

In industrial practice, there are many factors threatening the livelihood of technologies that are “ready.” There is an established Manufacturing Readiness Level (MRL) scale, adopted by the U.S. Department of Defense in 2005, that addresses the feasibility and affordability of producing the technology at the required scale and rate. There are also integration maturity metrics used to assess an Integration Readiness Level (IRL) scale. And both of these contribute to a System Readiness Level (SRL).

While TRL is known and used by most, these other scales are not so common. More often, the term “ilities” refers to the many important attributes of a design, product or system regarding form, fit and function.

Among the most often mentioned for complex systems are *reliability*, *availability*, *maintainability* and *supportability*. For military aircraft, add *transportability*, and *survivability* (itself defined as *susceptibility* and *vulnerability*). And for everything, add *affordability*, although not usually included in the technical *ilities*. (The author here wanted to mention *plausible deniability*.)

After TRL 6, there is a significant cost to mature the abilities of products and systems so that those seeking to use them can be confident that they will work as advertised. This cost and risk is the first part of the Valley of Death that makes it hard to transition a new technology or approach to real life.

**Even if a new invention works as intended, there is still enormous cost and risk before a successful implementation on or as a product.**

For example, the Internet of Things—that is everything in our lives using sensors and intelligence, connecting

to everything else, and being managed using data analytics—has been just around the corner for quite some time.

Another issue is the basic human philosophy of “if it ain’t broke, don’t fix it.”

Even if a product or system is working inefficiently, most often the user is otherwise satisfied with the fact that it is, indeed, working. The user might not change, even if the change promises to address the inefficiency and offer more. Making a change to a working system means new hardware and software, documentation, training, facilities and support equipment. It means the loss of all the valuable experience and intuition for all the people who use it, and sometimes the need to replace all trusted tools and relevant data. The case for change requires benefits that not only offer better functioning once in place, but so much better that the cost of changeover is warranted.

Add to that the time it takes to put new equipment in place. The time to turn over an entire fleet or inventory can be long. Both old and new systems must be in place and functioning until the entire change is complete. Often it is necessary that a new component must be compatible with some or all interfacing parts or systems, as well as the existing infrastructure. For example, a new US Navy aircraft must be compatible with the current air-capable ships, and the new ships must be compatible with all the existing aircraft. This backwards

compatibility’ requirement limits the freedom to improve.

Sometimes, it’s the customers who are not ready, as in the unsuccessful introduction of Skeelers in-line skates in 1972, and the very successful Rollerblade 15 years later.

Similarly, the iPad, introduced in 2010, had extraordinary success compared to the Letterbug (1986), EO Personal Communicator (1991), Apple Newton MessagePad (1993), the GRIDPad tablet (1989), Compaq Concerto (1993), Palmpilot (1996), NewsPad (1997), Fujitsu Stylistic 1000 tablet (1996), Intel Web Tablet (1999), Microsoft Pocket PC 2000 (2000), Microsoft Tablet PC (2002) and so on.

Sometimes the technology is nearly there, and the customers are ready, but the regulators are not. Unmanned aircraft are proven extensively in the military, but to date, drone pizza delivery is still limited to New Zealand. Similarly, the advent of urban air taxis is a ways off, according to civil regulators.

As the aerospace industry relies so heavily on the support and approval of these necessary partners—both military qualification and civil certification—I offer that we need to develop and establish a Regulatory Readiness Level (RRL) as another risk measure.

The Valley of Death is wide and deep, and risky to cross. But technologies do make it now and then, sometimes sponsored by the government and sometimes at private investment. Boeing has certainly developed its share of sci-fi-movie-like technologies for which the world was not ready. But it turns out that merely inventing a solution and proving the technology are not the hardest parts. Being ready in all aspects to traverse the Valley is the real work in innovation. **IQ**

Dan Newman is a Senior Technical Fellow for configuration development, and chief engineer of Phantom Works Rotary Wing Aircraft, in Boeing Defense, Space & Security.

## Technology Readiness Levels Explained

The maturity of technology is commonly measured by Technology Readiness Levels (TRL). A project is evaluated against set parameters for each TRL and is rated based on its progress. There are different standards bodies that define their own TRLs. However most observe nine levels, with similar concepts. TRL 1 is the lowest and TRL 9 is the highest.

### The following are TRLs defined by NASA

<b>TRL 9</b>	Actual system “flight proven” through successful missions operations.
<b>TRL 8</b>	Actual system completed and “flight qualified” through test and demonstration (ground and space).
<b>TRL 7</b>	System prototype demonstration in a space environment.
<b>TRL 6</b>	System/subsystem model or prototype demonstration in a relevant environment (ground and space).
<b>TRL 5</b>	Component and/or breadboard validation in relevant environment.
<b>TRL 4</b>	Component and/or breadboard validation in laboratory environment.
<b>TRL 3</b>	Analytical and experimental critical function and/or characteristics proof-of-concept.
<b>TRL 2</b>	Technology concept and/or application formulated.
<b>TRL 1</b>	Basic principles observed and reported.



“ Inspiring to see students apply STEM knowledge to make those gliders fly! ”

**JIM WIGFALL,  
BOEING SHARED SERVICES GROUP**

PHOTO: JIM WIGFALL



PHOTO: AMERICAN PHYSICAL SOCIETY



PHOTO: GENE YANO



BOEING PHOTO

**From the top, left to right:**

**STUDENTS OF EMBRY-RIDDLE AERONAUTICAL UNIVERSITY,** winners of the Boeing Flight Competition at the National Society of Black Engineers annual conference, received congratulations from Jim Wigfall, a Boeing vice president and emcee of the event held in April. That evening, Wigfall also accepted NSBE's Corporate Diversity Leadership award on behalf of Boeing.

**IN MARCH, ALLEN ADLER,** (middle) was inducted as a Fellow of the American Physical Society by Jeffrey Hunt (left), Boeing Technical Fellow and chair of the APS Forum on Industrial and Applied Physics, and Barbara Jones of IBM, outgoing FIAP chair.

**BOEING'S KEN UMEDA ACCEPTS A DISTINGUISHED ACHIEVEMENT AWARD** on behalf of the company's Authorized Representative (AR) team, in recognition of developing a certification process to support the entire fleet, including heritage models such as 727s and Douglas DC-8s. ARs are certified to have the technical acumen, regulatory knowledge and impartiality to make compliance findings on behalf of the FAA when airplanes are altered or repaired.

**TED COLBERT AND GREG HYSLOP,** Boeing's chief information officer and chief technology officer, respectively, open the Boeing India Engineering & Technology Center in Bangalore in March. The BIETC supports such areas as the development of advanced environment friendly coatings, data analytics for next-generation airplane health management tools, and software tools for airlines and airports to improve their operations and reduce costs.



From the Innovation Video Playlist

# Twenty more years of life

Boeing is leveraging its more than half-century of expertise in designing, manufacturing and maintaining jetliners to convert well-used passenger jets into freighters that can efficiently fly for another 20 years — avoiding the scrap yard and providing additional value to owners.

Each modification is no small task. All of the seats, stow bins and lavatories come out, a large hole is cut into the side of the airplane, and a cargo door is installed. Oftentimes, the floor structure is replaced with a stronger one capable of accommodating heavy freight containers. Once done, it looks like a brand new airplane.

View this video and other Boeing Short Films on [boeing.com/innovation](http://boeing.com/innovation).



**FROM THE PRESENT TO THE FUTURE**  
**A BETTER WAY TO FLY.**

There's a promise built into every Boeing plane that transcends route maps and data points. It's a promise to innovate beyond the needs of today. To exceed efficiency standards. To craft superior experiences for passengers. To ensure that our planes will continue to be the most advanced and reliable in the world. To always deliver a better way to fly.

[boeing.com/commercial](http://boeing.com/commercial)

 **BOEING**