CONFIGURATION CONCEPT
This is an artist's rendition of the Boeing Transonic Truss-Braced Wing configuration — a possible idea for commercial use in the 2030s.
IMAGE: NASA

X-66A: Bracing for the Next Big Wing

Years in the making, a demonstrator airplane with a truss-braced wing configuration may go big in the next decade

BY MAKS GOLDENSHTEYN

Don't tell his landlord. Zach Hoisington built his own wind tunnel — in a courtyard at his apartment building in California. With the help of 16 box fans and plywood walls, the young aerospace engineer tested sections of his paraglider prototype after work.

So when Hoisington found himself in a room with nine like-minded engineers in Boeing's Huntington Beach, California, offices in late 2007, seven years after he joined the company, he felt right at home.

Challenged by since-retired Boeing Technical Fellow Marty Bradley, the small Boeing Research & Technology team looked for novel ways to lessen the environmental impact of commercial aviation.

With whiteboards lining the conference room walls, the attendees pitched designs that ran the gamut of aircraft concepts and technology ideas.

DIGITAL BRAINSTORM

Engineers Marty Bradley, Christopher Droney and Zach Hoisington reviewed an early idea around 2010.

PHOTO: BOEING

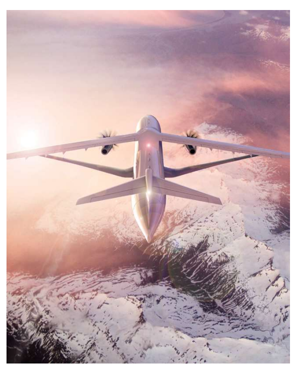
Hoisington floated the idea of an airplane configuration with high, long, thin wings that could be braced by diagonal struts, or trusses, attached to the lower part of the fuselage.

"I've always been drawn to lighter, externally braced structures," Hoisington said recently.

Part of the draw was a childhood interest in paragliders, which are essentially wings with strings, the simplest form of external bracing. At age 14, he took paragliding lessons with his father.

X IS FOR EXPERIMENT

X-planes are experimental U.S. aircraft designed to test and evaluate new aerodynamic concepts. They are intended to test technologies that can be adopted into other aircraft designs, not serve as prototypes for full production.



IDEA IMAGES

Early aircraft concepts became known for their transonic flying speeds and truss-braced wing airframe configuration, gaining the name Transonic Truss-Braced Wing.

IMAGES: BOEING

FUTURE FIRST X

A Boeing MD-90 flies to Palmdale, California, to begin its transformation into the first X-66A.

PHOTO: NASA

GRANDMOTHERLY INSPIRATION

In the early 1950s, Grace Bambauer Butler worked three jobs so she could afford flying lessons. After getting her license, she bought an inexpensive, storm-damaged Piper J-3 Cub. After fixing it, she sold the plane in the late 1950s. It later became an inspiration for her grandson Zach Hoisington, a Boeing engineer.

PHOTO: COURTESY OF ZACH HOISINGTON

It also happened that Hoisington's grandmother, a pilot, had once restored a Piper J-3 Cub, a type of strut-braced monoplane produced between 1937 and 1947. Hoisington heard stories about the restoration growing up.

Part of the plane lived on his grandmother's RV, as the altimeter found a permanent home on the dashboard. In 2007, Hoisington took her paragliding after she turned 90.

A Formidable Challenge: Size and Speed

Like Grandma Butler's J-3, several smaller, slower-flying, externally braced airplanes — both monoplanes and biplanes — debuted starting in the early 20th century. Some of the wings were braced by struts, others by cables.

Yet, translating the aerodynamic efficiency benefits to a commercial airliner-sized aircraft flying at transonic cruising speeds was a challenge for the aerospace industry.

Engineer Christopher Droney, who also attended Bradley's 2007 brainstorm, said the limited computing power available before the late 1990s was a primary reason. It was difficult to model the effects of real-world operating conditions — including payload, speed and altitude variations — on aerodynamic performance and operability.

"I don't think we had the computing capability to solve the structural dynamics and aerodynamics problems simultaneously," Droney said. "And by the early 2000s, it was only going to be a matter of, 'Who is going to get there first with enough fidelity and seriousness to solve it?'"

High-Flying History: The Long and Thin of It

The principle that longer, thinner wings may reduce drag and add lift for overall aerodynamic efficiency has long been established in the world of aviation.

Maurice Hurel

One notable example of a concept that incorporates elements of both is the Hurel-Dubois HD.31 prototype designed and flown by French naval pilot and airframer Maurice Hurel in 1953.

PROTOTYPE PIONEER

The only HD.31 built was on display at the 1953 Paris Air Show.

PHOTO: NATIONAL ARCHIVES CATALOG

Hurel's wind tunnel tests showed that monoplanes with long wingspans supported by lift-inducing struts could more than offset the weight penalty associated with the longer, heavier wings. Many of his prototypes, including the propeller-powered HD.31, were referred to as "flying letter openers."

Werner Pfenninger

In 1954, Swiss-born aerodynamicist and member of the NASA Hall of Honor Werner Pfenninger established that an airliner with a truss-braced wing configuration flying at transonic speeds* would see improved aerodynamics and lift compared to an airliner with a traditional cantilever wing configuration.

*Mach 0.80 is a typical cruising speed for single-aisle commercial airplanes today that approaches the speed of sound.

Good Timing: NASA Requesting Ideas

In early 2008, Bradley's team reconvened to refine their ideas. They dubbed their project the Sustainable Ultra Green Aircraft Research program, or SUGAR. This groundwork came at an opportune time.

Later that same year, NASA Aeronautics issued a solicitation for advanced-aircraft research ideas. Each concept was evaluated for its potential to influence reductions in fuel burn and emissions.

"This seemed like a perfect fit for what we had funded internally and what NASA was now asking for," Bradley said.

In late 2008, NASA awarded initial research contracts to a Boeing-led team that included various industry and university partners. NASA adopted the SUGAR moniker for this first phase, though the "Sustainable" in Boeing's version of the acronym was switched to "Subsonic" to match NASA's solicitation language.

> "This seemed like a perfect fit for what we had funded internally and what NASA was now asking for."
>
> **MARTY BRADLEY, RETIRED BOEING ENGINEER**

The work lasted through March 2010, at which point the Boeing-led team focused on the two most promising approaches, each coupling a truss-braced wing configuration with other carbon-reducing technologies. The concepts were called SUGAR High and the hybrid-electric SUGAR Volt.

News of the SUGAR Volt concept helped popularize the idea of pursuing hybrid-electric technology in aviation.

Within Boeing, the aircraft concepts became synonymous with their airframe configuration and the speed at which they would be flown — becoming known as the Transonic Truss-Braced Wing, or TTBW. The research also included advanced propulsion concepts.

TAKING SHAPE
In 2013, Hoisington shared the small-scale model of the concept vehicle.
PHOTO: BOEING

MODEL BEHAVIOR
In 2013, engineers Timothy Allen, Droney and Bradley worked with an under-construction truss-braced wing concept model ahead of wind tunnel testing at NASA's Langley Research Center.
PHOTO: BOEING

> "Adding the truss underneath the wing makes a big triangle. It stabilizes the whole inner part of the wing. The part that's deflecting the most is the part outboard of that. The center is more rigid and the outboard part is more flexible, which mirrors what you see on regular airplanes with cantilevered wings that come out of the fuselage."
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> **MARTY BRADLEY, RETIRED BOEING ENGINEER**

Studies around the SUGAR High and SUGAR Volt efforts became the basis for a second NASA contract, SUGAR Phase II.

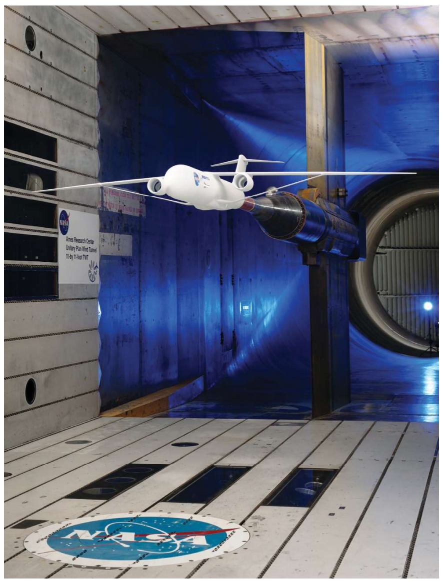
Phase II: Model Behavior in the Wind Tunnel

The Phase II team, including technical lead Droney, continued to define the TTBW airplane's architecture and configuration from 2012 to 2014. With a better understanding of its drag and structural characteristics, they built a first wind tunnel model out of fiberglass.

At the Transonic Dynamics Tunnel at NASA's Langley Research Center in Hampton, Virginia, Boeing tested a 15% scale model without trusses to understand the wing design's baseline aeroelasticity, or flexibility, in flight conditions. Afterward, the trusses were secured, and the same tests were performed again.

The results were promising.

> **“** We surprised ourselves, because the performance actually got better. That’s a classically harder thing to go do, the faster you go. But we kept getting smarter on the problem.**”**
>
> **CHRISTOPHER DRONEY, ENGINEER, BOEING RESEARCH & TECHNOLOGY**



SUSPENSE

From 2014 to 2016, Boeing teams tested a truss-braced wing model at NASA’s Ames Research Center to simulate Mach 0.745 speeds.

PHOTO: NASA

“Adding the truss underneath the wing makes a big triangle,” Bradley explained. “It stabilizes the whole inner part of the wing. The part that’s deflecting the most is the part outboard of that. The center is more rigid and the outboard part is more flexible, which mirrors what you see on regular airplanes with cantilevered wings that come out of the fuselage.”

In 2014, Boeing began studying the idea of a TTBW-based flight demonstrator under NASA’s Ultra-Efficient Subsonic Transport plan, setting the stage for future developments.

Phase III: Idea Comes to Life

Encouraged by the initial findings, the team took what had once been a kernel of an idea and transformed it into a testable concept in Phase III.

Until this point, detailed aerodynamic and structural designs had not been completed. It was time to translate textbook theory into a functional design — and during wind tunnel testing, to see whether it could actually demonstrate the expected performance gains.

During this phase of SUGAR, from 2014 to 2016, researchers used digital modeling to advance the shape of the wings, the struts and their interaction — including airflow in the narrow channel between them — to ensure aerodynamic efficiencies were in the target range without incurring extra drag.

“If you’re looking to make performance estimates for a regular airplane, well, we’ve built tons of those,” said Neal Harrison, Boeing TTBW principal investigator and the program manager for multiple phases of SUGAR.

“We know how to estimate their performance and get really close. But with the truss-braced wing, there’s really no available information on which to make those guesses with a high degree of confidence. We had to actually shape all of this from scratch.”

Boeing designers tested a new model during a low-speed test at NASA’s Ames Research Center, but at Mach 0.745, slower than the typical cruising speed of today’s airliners.

TUNNEL VISION

Boeing engineer Neal Harrison checks a model ahead of Mach 0.80 wind tunnel testing at NASA’s Ames Research Center in 2019.

PHOTO: NASA

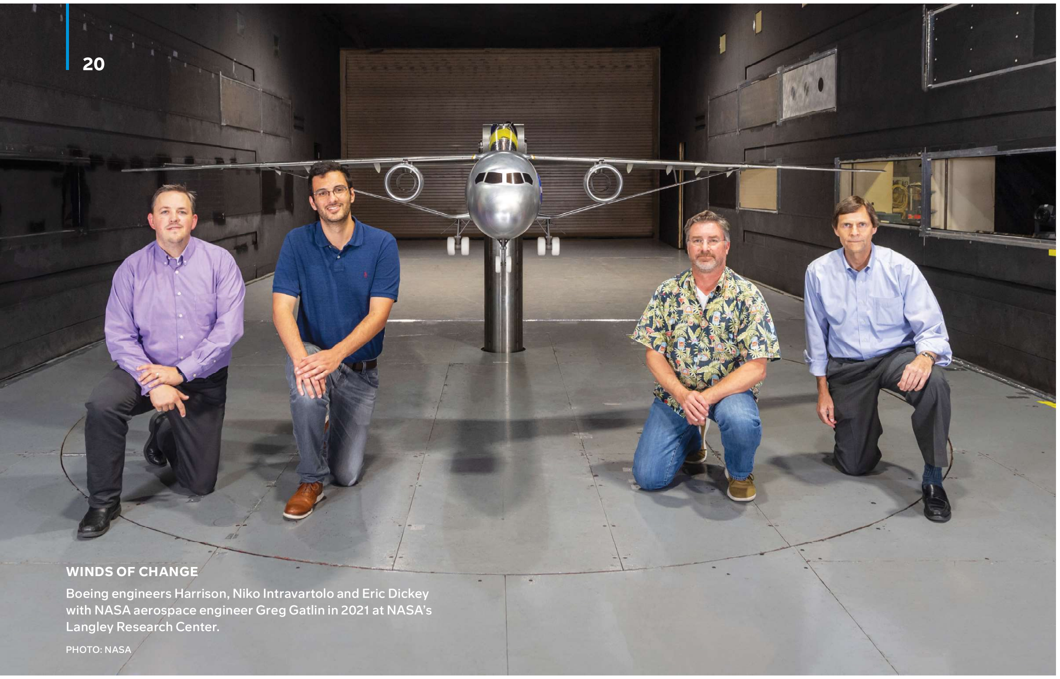
Phase IV: Speed Surprise

As the configuration concept matured, the SUGAR team optimized the aircraft cruise speed to better match the demands of the market. By Phase IV, conducted from 2016 to 2020, the team again tested wind tunnel models at Mach 0.80 — including a first test of a high-lift system.

“We surprised ourselves, because the performance actually got better,” said Droney, who led Boeing’s work on the contracts for SUGAR Phase III and part of Phase IV. “That’s a classically harder thing to go do, the faster you go. But we kept getting smarter on the problem.”

By this point, one of the key learnings was that a single-aisle aircraft designed with a truss-braced wing configuration could see fuel consumption drop by more than 5%. Future studies would show the predicted benefit to be 10% or even higher, depending on the mission and the advanced technology paired with the airframe.

The theoretical concept vehicle being tested had a wing-span of 170 feet (52 meters) and included a folding wingtip to account for existing airport taxiways and to fit within a standard gate. Improvements included changes to the sweep and thickness of the wings, as well as re-aligning the trusses from the center of the wings to their rear.



WINDS OF CHANGE

Boeing engineers Harrison, Niko Intravartolo and Eric Dickey with NASA aerospace engineer Greg Gatlin in 2021 at NASA's Langley Research Center.

PHOTO: NASA

Increasingly, Boeing Research & Technology teams were collaborating with colleagues from the Boeing Commercial Airplanes Product Development team, requiring a coordinated effort across sites and business units.

Phase V: Detailing a Demonstrator

SUGAR Phase V included high-speed buffet testing to check against vibrations incurred at Mach 0.80 and faster, including the highest speeds the aircraft would experience (like during an emergency maneuver). Given the configuration's unusual geometry, it was important to assess airflow between the wing and the truss.

Phase V also included more low-speed testing, which looked at the effects of icing and the performance at takeoff and landing.

With this phase complete, Boeing anticipated an opportunity to validate years of development and testing with a full-scale demonstrator vehicle through NASA's Sustainable Flight Demonstrator (SFD) program.

> "We've answered many of the biggest conceptual questions. Now you have to take a big step forward in detail and really start actually designing parts — literally down to the nuts and bolts."
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> **NEAL HARRISON,**
> **ENGINEER,**
> **BOEING RESEARCH & TECHNOLOGY**

> "Along with NASA and our partners, we're building a flying test bed to validate technologies that we've seen great promise in for some time. This is how we're creating the capabilities to address the needs of our customers and the wider industry."
>
> **MIKE SINNETT,**
> **SENIOR VICE PRESIDENT AND**
> **GENERAL MANAGER OF**
> **PRODUCT DEVELOPMENT,**
> **BOEING COMMERCIAL AIRPLANES**

The Real Deal: Flight Tests This Decade

In January 2023, NASA announced its award of a $425 million Funded Space Act Agreement to Boeing and industry partners — to design and build an SFD with a TTBW configuration. Boeing and its partners will contribute an estimated $725 million to fund the endeavor.

In June, the U.S. Air Force conferred an X-plane designation for the demonstrator vehicle, with the name X-66A. NASA and Boeing applied for this designation because the SFD will continue a long history of one-of-a-kind experimental aircraft brought to flight to validate a breakthrough design.

The demonstrator is expected to take to the sky for flight tests in 2028 and 2029. Boeing is using elements from existing MD-90 airplanes and will integrate them with all-new components.

"We've answered many of the biggest conceptual questions," Harrison said. "Now you have to take a big step forward in detail and really start actually designing parts — literally down to the nuts and bolts."

The TTBW airframe allows the demonstrator to have more underwing space than a typical airliner, allowing it to accommodate an advanced propulsion system. Combined with expected improvements in propulsion, materials and systems architectures, the TTBW configuration could yield up to a 30% reduction in fuel consumption and emissions relative to today's most efficient single-aisle airplanes, depending on the mission.

Together with Boeing's other work on future-flight concepts, such as studying hydrogen and hybrid-electric propulsion, advanced technologies like those demonstrated aboard the SFD are parts of several key levers that Boeing believes will be required to achieve commercial aviation's goal of net-zero emission by 2050.

"Along with NASA and our partners, we're building a flying test bed to validate technologies that we've seen great promise in for some time," said Mike Sinnett, senior vice president and general manager of Product Development for Boeing Commercial Airplanes. "This is how we're creating the capabilities to address the needs of our customers and the wider industry."

The SFD's first flight test will represent the culmination of a two-decade effort on the part of numerous engineering teams and individuals, including those who gathered for that 2007 impromptu brainstorm session. It will have added meaning for those who have advocated for the idea from the initial concept to its current stage. This includes Droney, now the SFD deputy chief engineer, and a host of others who helped sustain the project within Boeing Research & Technology and Boeing Commercial Airplanes.

"This will certainly go down in my book as probably the career accomplishment," Droney said. "Certainly something I've been chasing and pushing for so long."

Technical challenges remain before the SFD takes flight, and not every outstanding question can be answered through the flight-test program alone. Boeing is currently under contract for SUGAR Phase VI, during which teams will continue to examine aspects of the TTBW configuration that set it apart from typical tube-and-wing aircraft.

The SUGAR Phase VI, SFD and Boeing Commercial Airplanes Product Development teams are working in parallel to mature the TTBW technology and develop the data and analysis needed to determine its viability in the market.

For Bradley, who retired from Boeing in 2020 and now works as an aerospace consultant and a lecturer at the University of Southern California, news of the Boeing SFD award in early 2023 seemed like a good teaching moment. In a class he led a few days after Boeing received the award, Bradley took students down memory lane to the heady days that started it all.

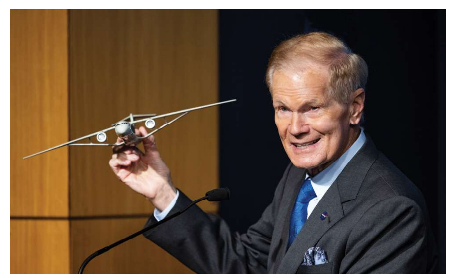
"It was a lesson about the time it takes to bring good ideas to fruition," he said. **IQ**

FUTURE FLIGHT PLANS

NASA Administrator Bill Nelson, right, discusses the X-66A with Boeing teammates Grace Lee, Samuel Jayagaran, Nate Bakala and Susan Champlain in 2023. To build the X-66A, Boeing will convert an MD-90 into a full-scale demonstrator aircraft.

PHOTO: BOEING

In Their Words



PHOTOS: NASA

At NASA headquarters in Washington, D.C., leaders celebrate NASA's 2023 selection of Boeing and its industry team to develop and flight-test a full-scale Transonic Truss-Braced Wing demonstrator aircraft.

"One of the key outputs of this activity is really the learning, the knowledge. What, at the integrated airplane level, will the benefits be? The results of this effort and market conditions, that'll dictate whether this shows up on the next commercial product."

Todd Citron,
Boeing Chief Technology Officer

"We've been advancing and exploring these advanced technologies, and we've been testing them at simulations at NASA wind tunnels. We're now moving to that next stage — demonstrating this promising technology in-flight."

Bob Pearce,
Associate Administrator,
NASA Aeronautics Research
Mission Directorate

"That is a revolutionary design, and this is going to be flying in 2028. It's our plan to demonstrate this extra-long, thin wing, stabilized by the braces. And in addition to the design, the Sustainable Flight Demonstrator will integrate multiple other related green technologies."

Bill Nelson,
NASA Administrator