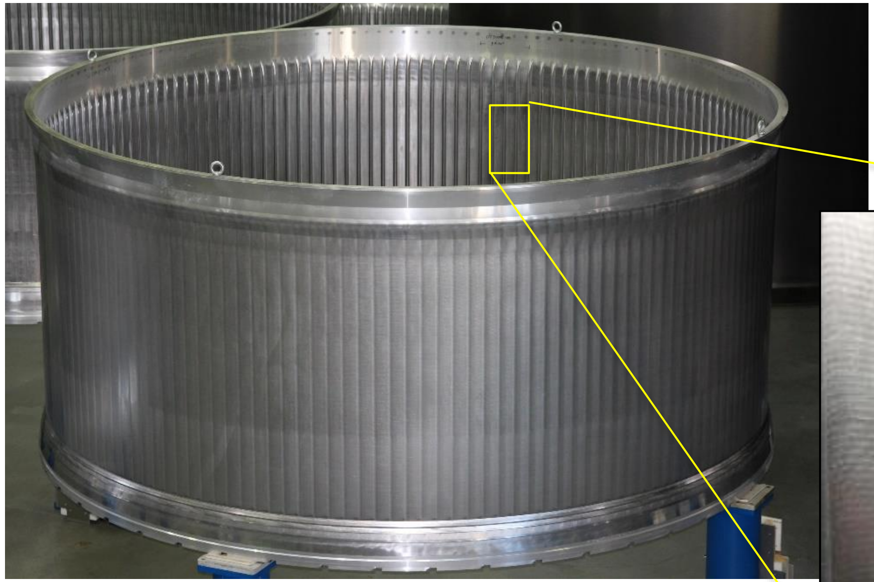
Demonstration of How Manufacturing Innovations Challenge Conventional Structural Design



10-ft diameter, 5-ft tall ISC formed in 1.5 hours, January 2019

Close-up of stiffeners

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Background: Space Shuttle Cryogenic Tank Manufacturing

Problem

- Machined/welded construction of launch vehicle cryotanks is expensive, wasteful, and risky

Integrally Machined

- 90% scrap rate
- Approx. 540,000 lbs. chips/tank
- $8M chips/tank

Welded Structure

- Approx. 0.5 miles of welds
- Material property knockdown
- Defects
- Welds require 100% inspection

Solution

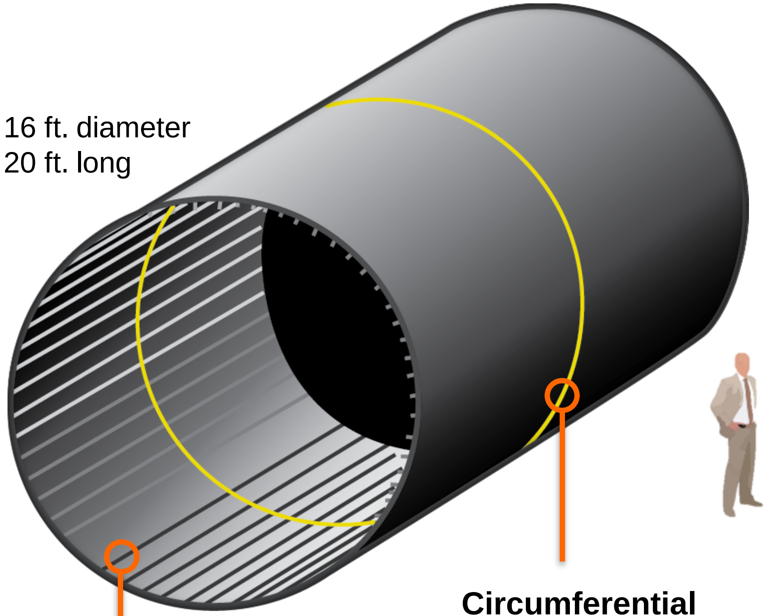
- Use Advanced Near Net Shape Technology (ANNST) to manufacture cryotanks which are cheaper, lighter, with fewer welds
- Single-piece stiffened barrel in one processing step via **Integrally Stiffened Cylinder (ISC) process**

Capital investment to establish U.S. ISC capability ~ $8M (equivalent to the scrap from *one* Shuttle External Tank)

Integrally Stiffened Cylinder (ISC) Process for Launch Vehicles

<u>Integrally Stiffened Cylinder (ISC) Process</u>:

- Flow form cylinder against grooved mandrel
- Material flows into grooves to form integral longitudinal stiffeners
- Single-piece stiffened cylinder formed in hours



<u>Projected Benefits*</u>

- 50% cost reduction
- 60% schedule reduction
- 25% increase in buckling load
- 10-20% mass reduction

** Stoner, et al. NASA/TM-2016-219192.*

Can these benefits be transferred to aircraft structures?

<u>Lab to Commercial Scale in 5 Years</u>

Proof of Concept, 2012

8 in. diameter, 6 in. long

Sounding Rocket Flight Demo, 2015

17 in. diameter, 20 in. long

Commercial Manufacturing Demo, 2017

10 ft. diameter, 3 ft. long

Conventional Aircraft Structural Design

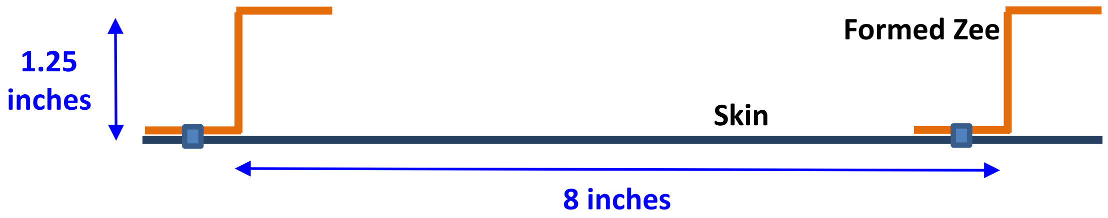
Interior structural details of riveted fuselage construction in a state-of-the-art commercial transport

- Aluminum aircraft have been assembled using rivets and fasteners for nearly 100 years
- 1928 - Ford Tri-Motor: first passenger plane bolted aluminum construction
- Typical single aisle commercial transport has >400,000 rivets
  - Overlaps, rivets increase weight
  - Jigging, drilling, and riveting dominates assembly rate
  - Holes prone to becoming crack initiation sites

Approach:

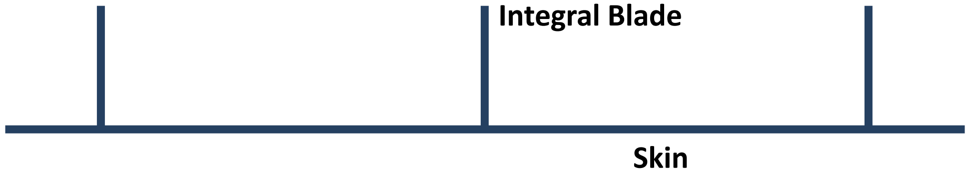
- Examine structural performance (analytically) to optimize structure fabricated with new manufacturing approach
- Conduct trade study to identify compatible assembly technologies
- Fabricate 10-ft. diameter lightweight metallic fuselage manufacturing demonstration article to validate concepts
- Identify next steps to further optimize materials, manufacturing, and structures. Address durability and certification concerns.

Aircraft Fuselage: Longitudinal Stringer Cross Sections Considered



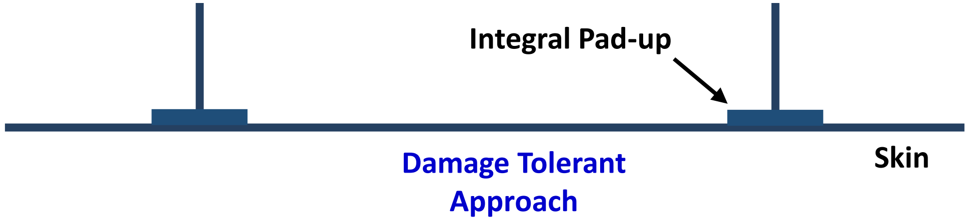
Industry Standard:

- Industry uses rivetted zee and inverted hat (omega)
- 2524-T3 Skin, 7150-T7751 Stringer
- Study limits number of zee gauge selections (0.02-inch increments)



Integral Blade:

- 2524-T3 Skin and Blade
- Spacing from 2.5 inches to 8.0 inches
- Effect of blade height limitation studied to guide flow forming

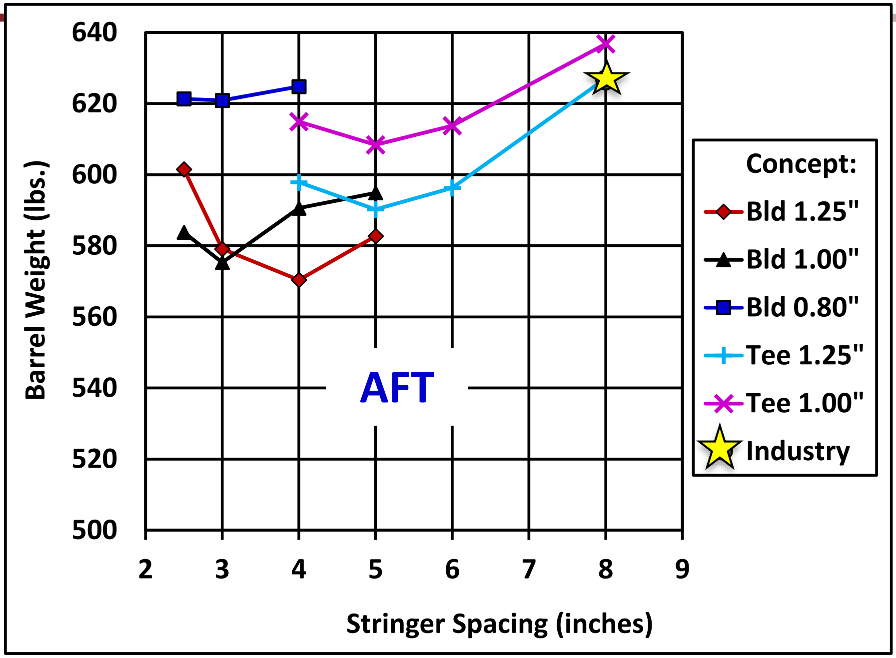


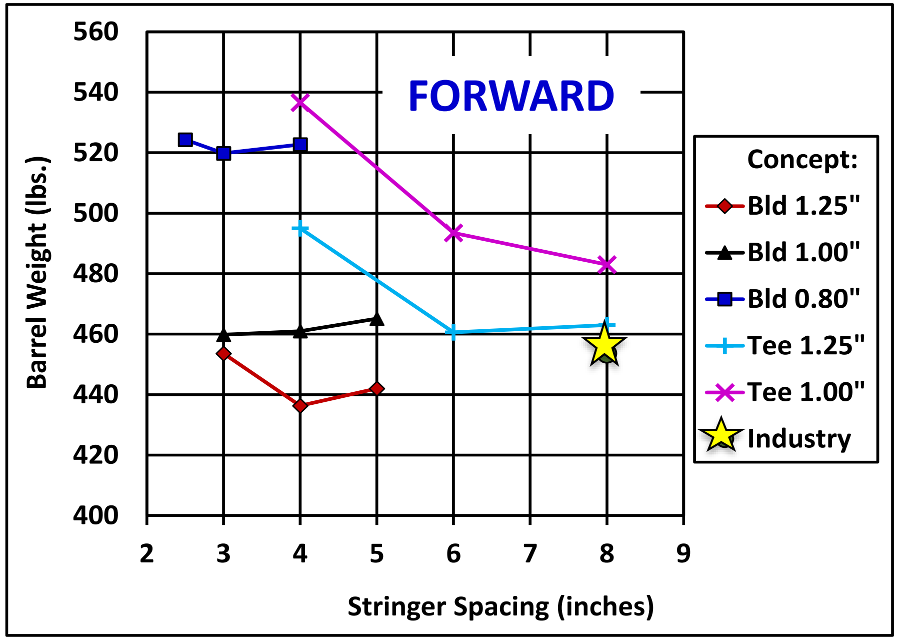
Integral Tee:

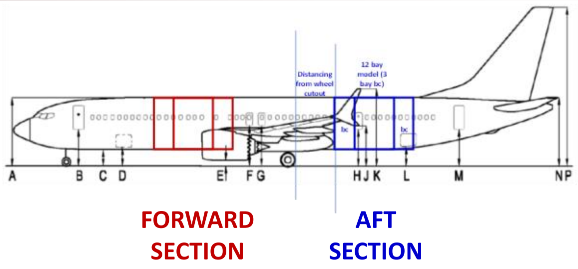
- 2524-T3 Skin and Tee
- Spacing from 3.0 inches to 8.0 inches
- Pad-up at least 2.35x skin thickness – to promote crack turning
- Pad-up 1.00 inch wide

Industry prefers wide spacing for cable runs, but integral stringers at moderately wide spacing and no interference with inner flange could be beneficial

Sizing Summary: Constant ISC Stiffener Cross-Section and Spacing



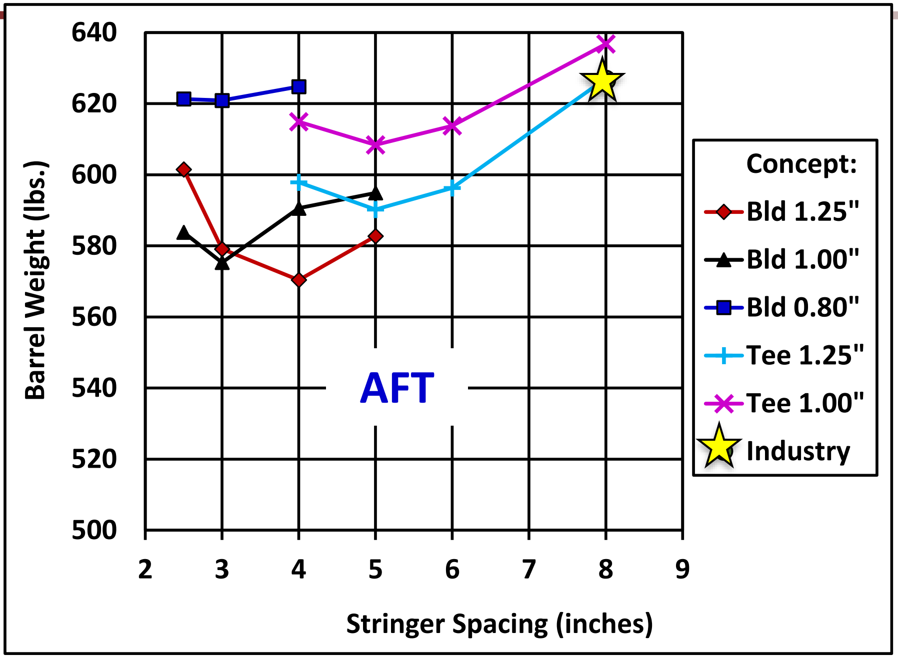


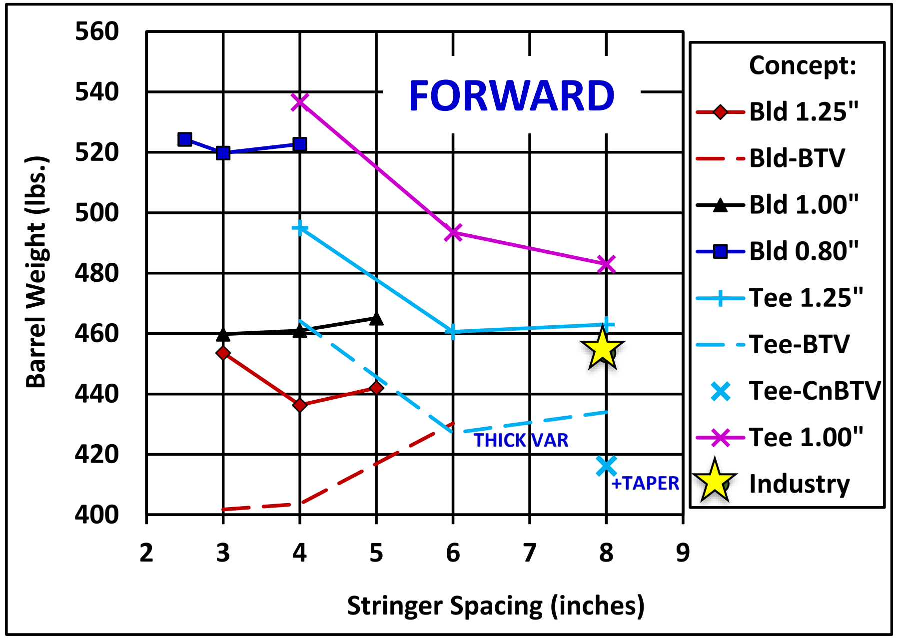


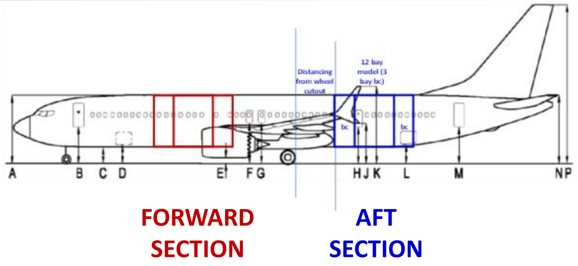
- Sizing study iterated between NASTRAN detailed finite element analysis and HyperSizer panel sizing
- For <u>**constant ISC stiffener cross section**</u> and spacing:
  - Best integral blade cylinders were lighter than industry standard **(-9% aft, -4% fwd)**
  - Integral tee cylinders were a little heavier (-6% aft, +1% fwd) compared to industry standard weight
- ISC can be weight competitive with large stringer spacings (even 8 inch)
- Larger stringer spacing allows standard ring frame approach

Constant ISC stiffener with narrow blade spacing gives rise to predictions 4-9% lighter than conventional designs

Sizing Summary: Allowing ISC Stiffener Variations







- Sizing study considered ability to change stiffeners by modifying mandrel in ISC:
  - Closer spacing for energy absorption, stiffness at keel
  - Wider spacing for shear along window belt
- In all cases, allowing ISC cross section and spacing variation is beneficial
- Examples shown for forward section (dashed lines and X) where:
  - Blade thickness allowed to vary circumferentially
  - Then blade thickness allowed to taper longitudinally
- Similar approach can be used to make shorter blades (~1 inch) competitive (not shown)

Designs incorporating ISC cross section and stiffener spacing variations further reduces fuselage weight

Manufacturing Trade Study

Objective:

Assess advanced manufacturing processes (welding and additive manufacturing) for integration of structural ring frames, window frames, and floor beams into ISCs

Trade Study Goals:

- Fabricate blade stiffened panels to evaluate manufacturing processes and resulting joint properties
- Compare candidate processes using ***Analytical Hierarchy Process*** to identify candidates for manufacturing demonstration article
- Compare processes based on maturity, scalability, performance, ability to integrate into ISC, and projected manufacturing complexity, rate, and cost

Candidate Assembly Processes

Baseline: Riveted Assembly

Welding Processes

- Laser Welding (LW)
- Refill Friction Stir Spot Welding (RFSSW)
- Friction Stir Welding (FSW)

Additive Manufacturing (AM) Processes

- Additive Friction Stir (AFS)
- Laser Metal Deposition (LMD)
- Laser Hot Wire AM (LHW)
- Cold Metal Transfer AM (CMT)

Materials Characterization Methodologies

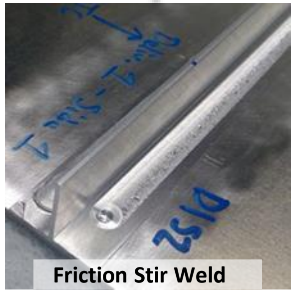
- Tensile Testing *ASTM E8*
- RFSSW Pull Off Test *ASTM C297*
- Microhardness *ASTM E384*
- Microstructural Analysis *ASTM E3*
- Coordinate Measurement for Distortion
- NDE – X-ray radiography

Welding processes equate to greater maturity, faster assembly rates, fewer post-processing requirements and better structural performance

Welding Processes

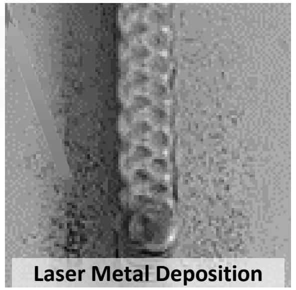

Laser Weld

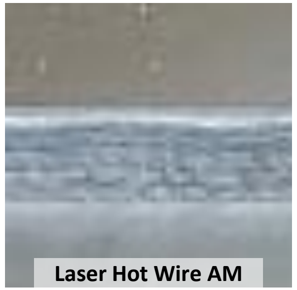

Refill Friction Stir Spot Weld


Friction Stir Weld

Additive Manufacturing (AM) Processes


Additive Friction Stir


Laser Metal Deposition

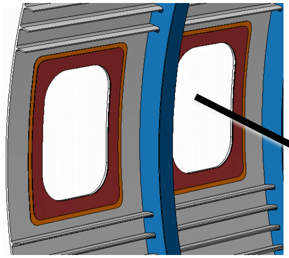

Laser Hot Wire AM

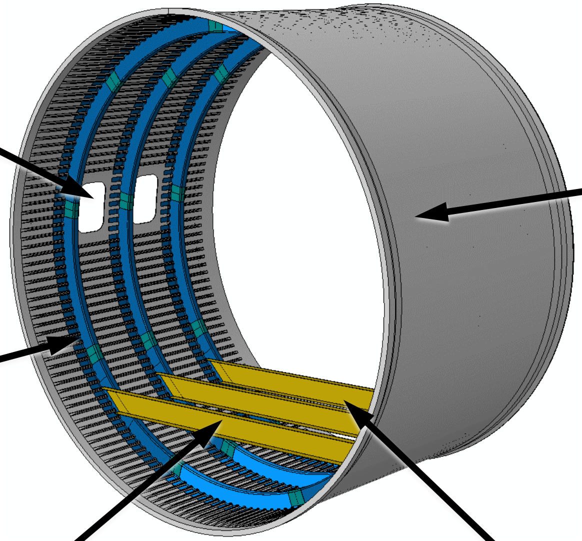

Cold Metal Transfer AM

Lightweight Metallic Fuselage Manufacturing Demonstration

2) Window areas machined (MSFC)

Window upper/lower transoms and floating window frames





1) ISC formed barrel (*MT Aerospace*)

Flow-formed integrally stiffened skin and stringer fuselage

Stretch-formed Z-ring frames and shear clips

3) Ring frames RFSSW installation (*Lincoln Electric Automation*)

4) Floor beams riveted installation (LaRC)

Brake-formed C-channel floor beams

Extruded J-stiffened floors (not shown)

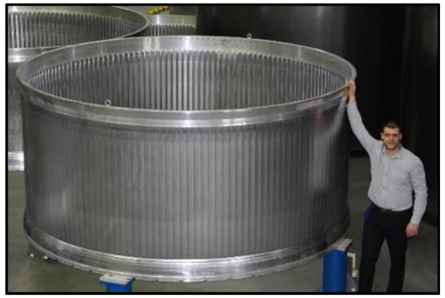
5) Floor panels bolted installation (LaRC)

Extensive use of different forming and assembly techniques to reduce manufacturing time and cost

MDA Component Fabrication – Single-Piece Forming Operations

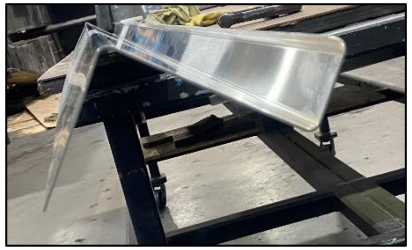
Integrally Stiffened Cylinder
(skin + blade stringers)

Flow forming

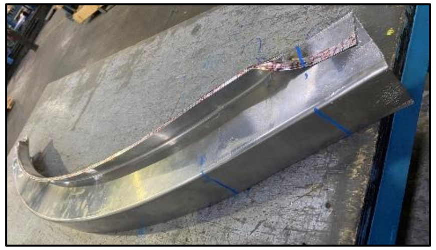


Machining

Ring Frames
(Z-frames)

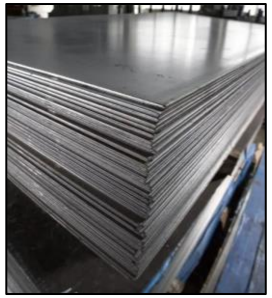


Stretch forming



Machining

Floor Beams
(C-channels)



Brake forming

Floor Panels
(skin + J-stringers)

Extrusion and flattening

Machining

Cost and Rate Sensitivity Study

Cost Rate

Case	DOC/seat-mile Impact (2020$) (- is good)	Probability of DOC Reduction	Investment Cost Impact (2020$M) (- is good)	Fuselage T1 Production Cost Impact (2020$M) (- is good)	Fuselage Production Rate Impact (units/mo.) (+ is good)	Fuel Economy Impact (seat-miles/gal) (+ is good)
Baseline	*0.0525*		*271,841*	*25.1*	*31.0*	*78.0*
Basic ISC, no weight impact, no maint impact	-0.0001	100%	-1,062	-1.7	18.6	0.0
5% outer shell weight reduction with resizing	-0.0003	100%	-2,379	-1.8	18.8	0.3
20% outer shell weight reduction with resizing	-0.0008	100%	-6,272	-2.0	19.4	1.3
5% outer shell weight reduction with resizing and fuel at $4.07/gal	-0.0004	100%	-2,366	-1.8	18.6	0.3
5% outer shell weight increase with resizing	0.0001	2%	299	-1.6	18.9	-0.3
5% outer shell weight increase with resizing and fuel at $4.07/gal	0.0002	0%	300	-1.7	18.7	-0.3
Heavy maintenance interval increased from 96 mo. to 108 mo.	-0.0003	100%	-1,265	-1.7	18.9	0.0
Heavy maintenance interval decreased from 96 mo. to 84 mo.	0.0001	0%	-828	-1.7	18.9	0.0
ISC section circumferential joints riveted rather than welded together	-0.0001	100%	-1,221	-2.0	20.3	0.0
ISC section length 15’	-0.0001	100%	-1,174	-1.9	22.1	0.0
ISC section length 20'	-0.0001	100%	-1,237	-2.0	31.5	0.0
Spot weld v. rivet cost factor = 0.2	-0.0001	100%	-1,171	-1.9	40.4	0.0
Spot weld v. rivet cost factor = 0.8	-0.0001	100%	-945	-1.6	6.5	0.0
Post-formed ISC thickness = 0.072	-0.0001	100%	-1,059	-1.7	19.0	0.0
Post-formed ISC thickness = 0.036	-0.0001	100%	-1,440	-2.3	26.0	0.0
75% Robotic Riveting	-0.0001	100%	-907	-1.5	22.8	0.0
98% Automatic riveting	-0.0001	100%	-761	-1.3	25.4	0.0

- Implementing ISC technology with the use of FSW to connect the ISCs yields about a **60% increase** in rate.
- Riveting ISCs together using traditional methods instead of FSW yields about a **65% increase** in rate.
- Increasing ISC length to 15’ yields a **71% increase** in rate and 20’ ISC yields a **102% increase** in rate.
- Replacing rivets with RFSSW for integrating ring frames into ISCs yields a **163% increase** in rate.
- ISCs reduce manufacturing costs by 0.4%, representing **~ $1B savings** across the entire fleet of single aisle transports.
- 9% reduction in weight results in additional 1.9% operational cost reduction (reduced fuel burn) over the lifetime of the aircraft. Total cost reduction of 2.3% equates to **~ $6B savings** over the fleet lifetime.

Sensitivity studies were conducted to assess the effect various parameters have on manufacturing rate and cost of ISCs compared to riveted aluminum aircraft

Summary

State-of-the-art compares advanced composite construction with aluminum manufacturing processes that have not changed appreciably for >50 years

Advanced aluminum manufacturing approaches reduce manufacturing rate, cost, and weight

- Predicted 60-130% increase in manufacturing rate with use of ISCs and optimization of RFSSW compared to state-of-the-art riveted aluminum construction (6-8 times greater manufacturing rate that composites)
- Predicted 2.3% cost reduction (**$6B savings over lifetime of aircraft**)
- >9% weight reduction reduces fuel burn and approaches weight reductions claimed for composite structures
- Inspection and repair may use conventional practices/trained mechanics
- Enhanced sustainability through reduced weight (reduced fuel burn), reduced manufacturing waste, and recyclability of aluminum alloys (aligns to Sustainable Flight National Partnership; US Aviation Climate Action Plan)

Advanced metallic processes are cross-cutting and applicable to aerostructures beyond aircraft fuselage

- Relevant to cryogenic storage and fuel tanks:
  - Low-cost access to space for launch vehicles
  - Single-piece forming leads to fewer joints for leakage in cryogenic storage tanks on Earth and future exploration applications on Moon and Mars
  - Fuel tanks for hydrogen-fueled aircraft (proposed from Advanced Air Mobility platforms to commercial transports to meet Zero-Carbon Emission Goals in 2050)

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- Libby Urig, NIA/AMA
- John Wagner, D307 (retired)
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<u>Organizations</u>:
D307 – Advanced Materials and Processing Branch
D312 – Structural Mechanics and Concepts Branch
D313 – Non-Destructive Evaluation Branch
E1A – Aeronautics Research Directorate
AMA – Analytical Mechanics Associates
NIA – National Institute of Aerospace

Questions?