Behind the Curtain: Design and Manufacturing Technology For 21st Century Commercial Propulsion

Alan Epstein

Vice President, Technology & Environment
Pratt & Whitney

The 12th Israeli Symposium on Jet Engines and Gas Turbines
Haifa, November 2013

Outline of this Talk

- Why commercial aviation is important
- Aircraft propulsion in the 21st century
  - Evolution and refinement verses revolution
- Aero engines are a great home for advanced technology
  - Historically, most technology focused on product design
  - Manufacturing technology now offers new opportunities

Commercial Aviation

In One Year…

2.97 billion
passengers

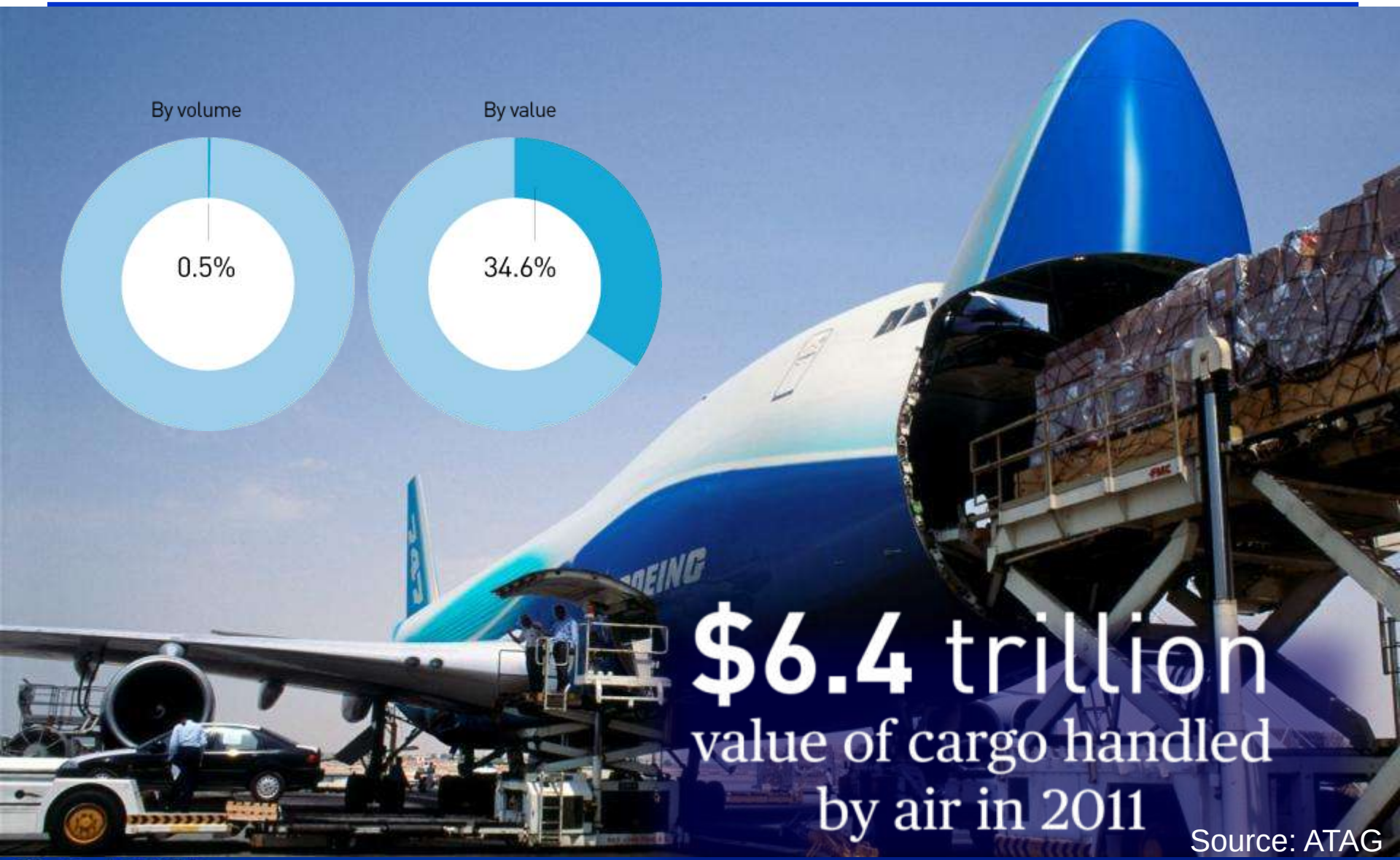
34,765
city-pair routes

28.5 million
aircraft movements

5.4 trillion
passenger kilometres

Source: ATAG

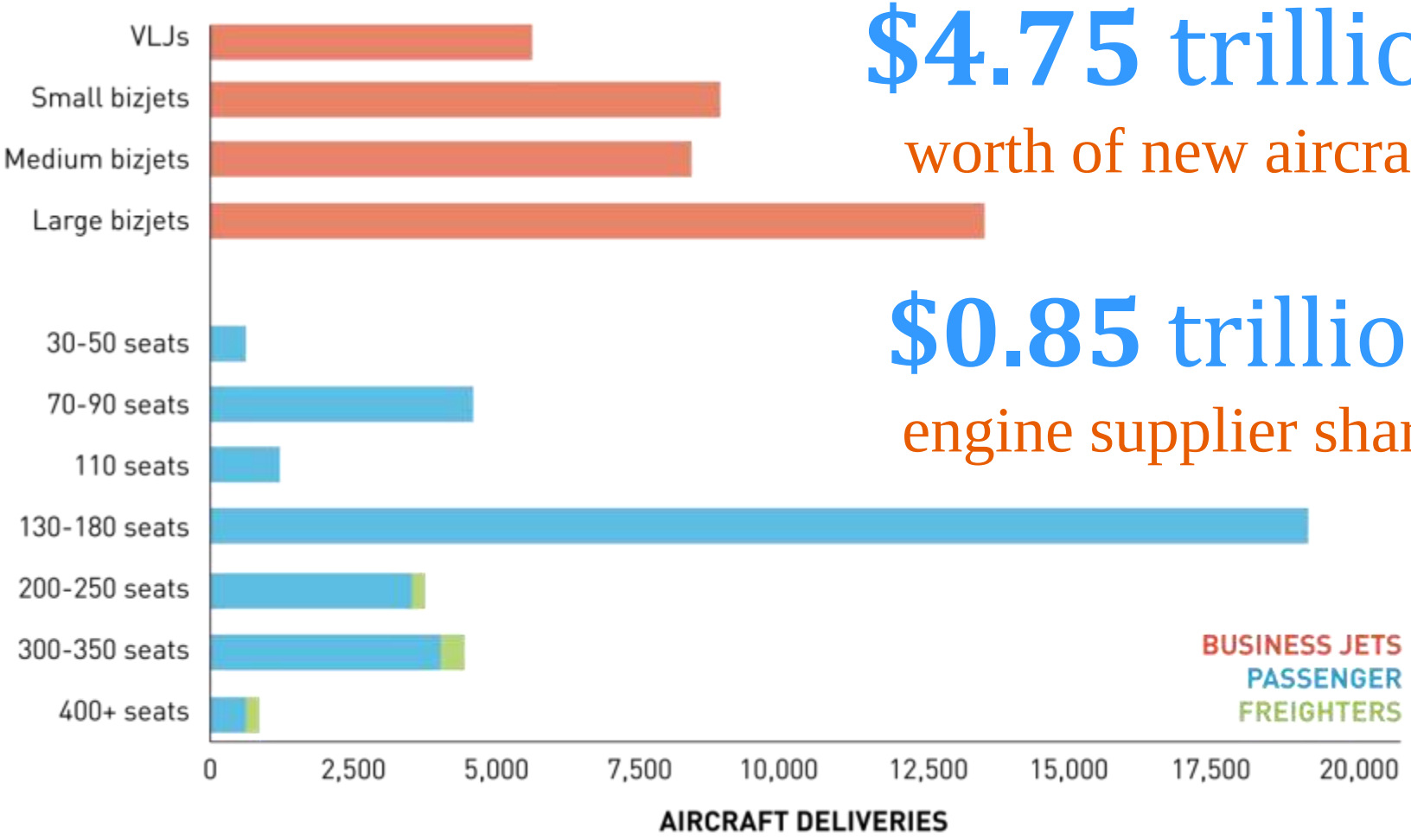
Aviation: World Trade



Source: ATAG

Deliveries Going Forward: 2012-2031

68,000 New Aircraft Across a Range of Sizes



$4.75 trillion

worth of new aircraft

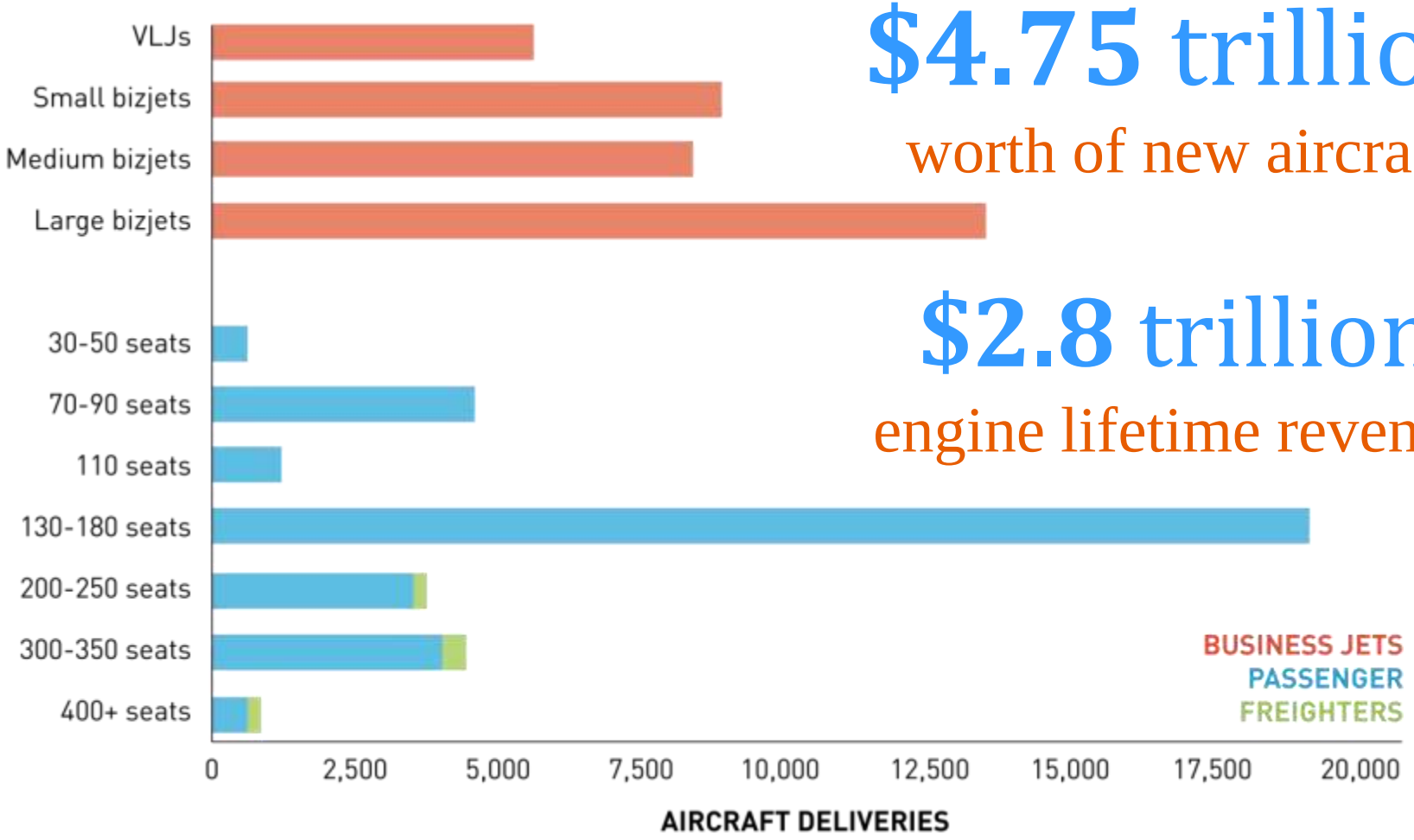
$0.85 trillion

engine supplier share

Source: ATAG

Deliveries Going Forward: 2012-2031

68,000 New Aircraft Across a Range of Sizes



$4.75 trillion

worth of new aircraft

$2.8 trillion

engine lifetime revenue

Source: ATAG

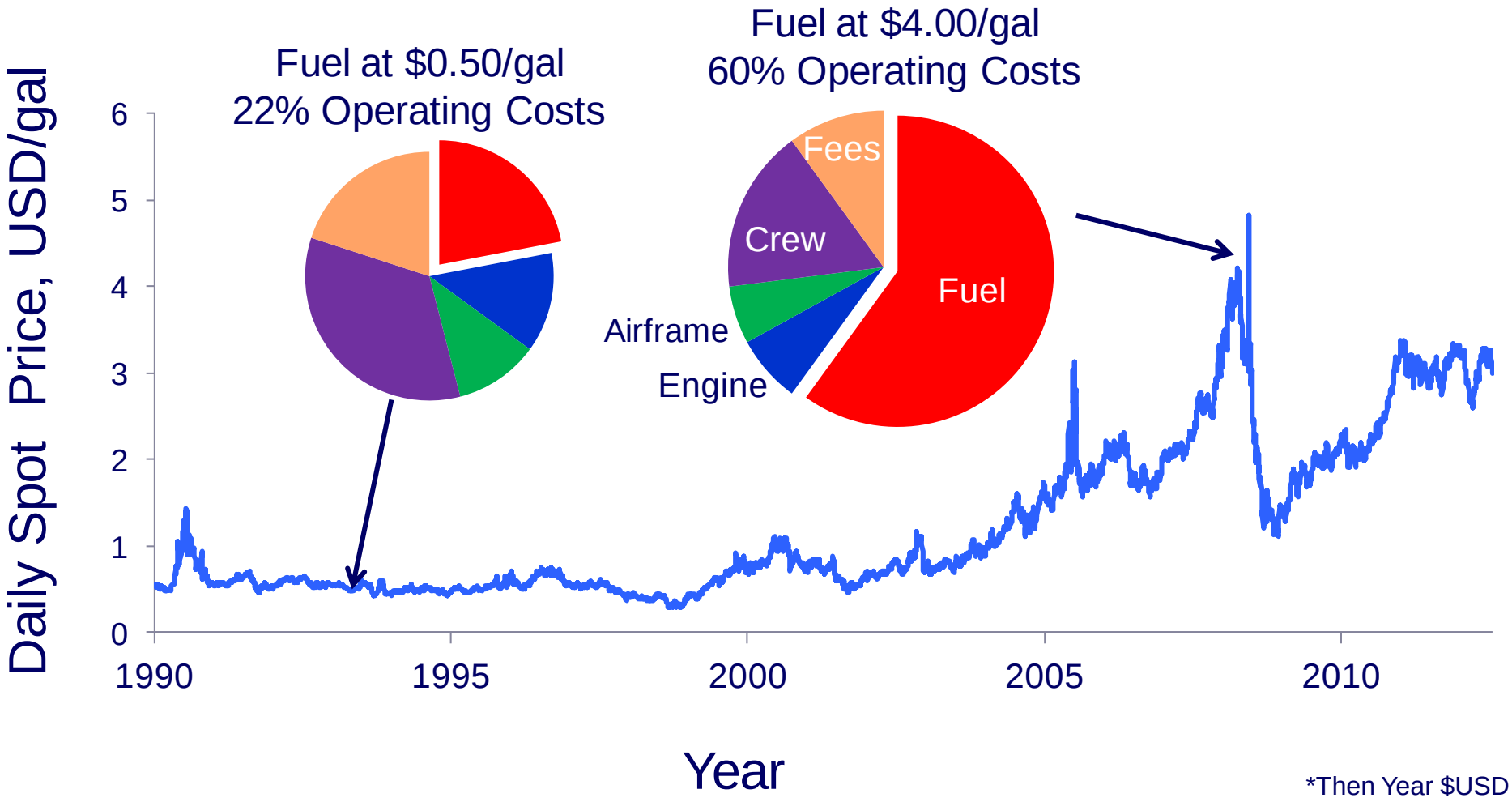
What's New?

"There is nothing new in the world except the history you do not know."

Harry S. Truman

External Driver Spurs Innovation – Cost of Fuel

Twin Aisle Aircraft Costs (excludes capital)



*Then Year $USD

Meeting the Climate Change Challenge

"The world cannot regulate its way out of global warming; it must innovate."

Tom Friedman,

Columnist, *New York Times*

Author, *The World Is Flat*

Innovation vs. Novelty

- Innovation
  - "The alteration of what is established by the introduction of new elements or forms"*
- Novelty:
  - "An…amusing object…relying for its appeal on the newness of its design"*

*Source: *OED*

Reducing the Cost of Fuel

These Aircraft Fly Well, but…

Human Power

Solar Power

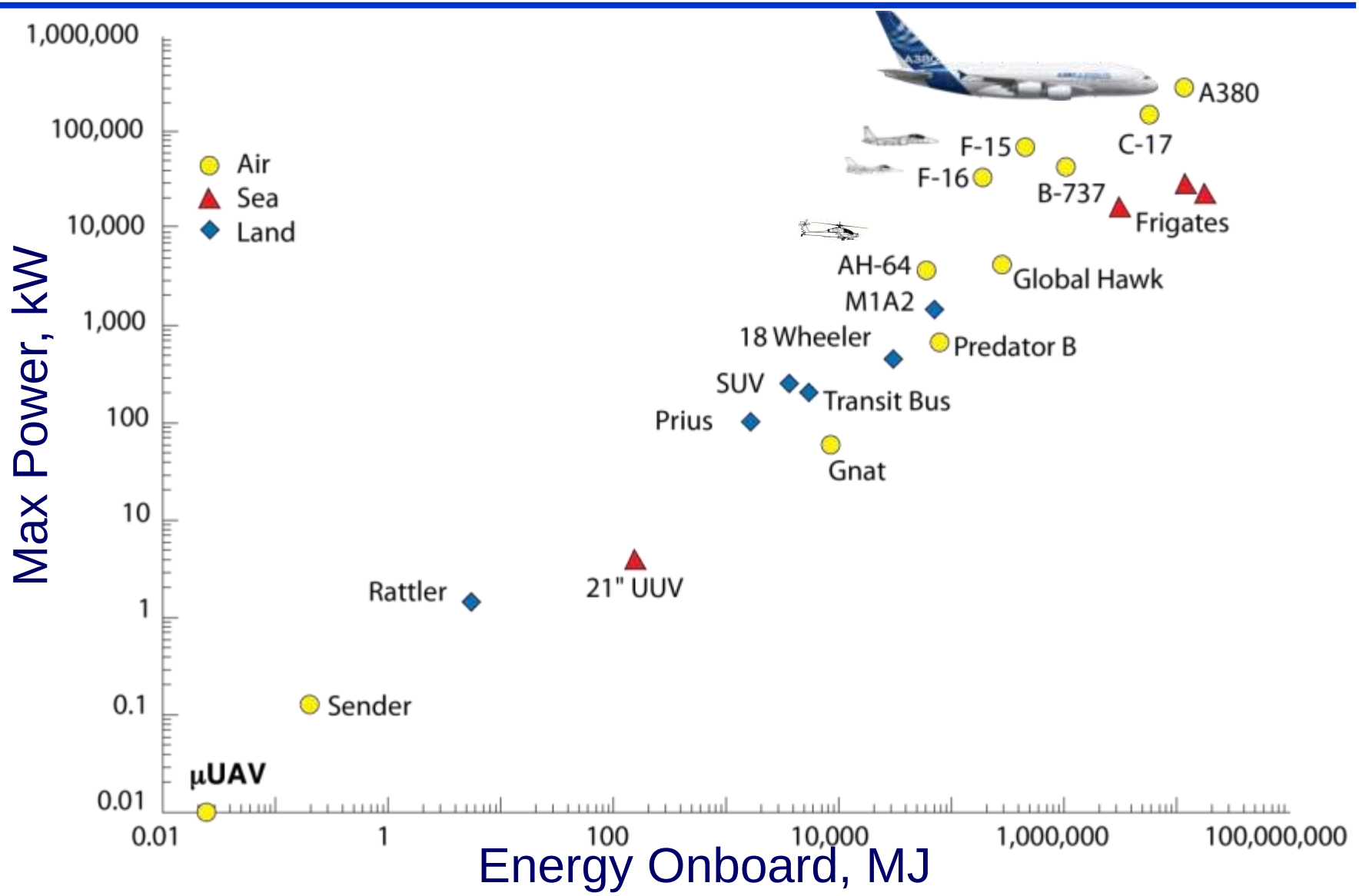
Novelty verses innovation
Is there economic value?

Airplanes of the Future?

Future Airplane is Unclear, Future Motor is Not

Source: ATAG

Vehicle Maximum Energy and Power



Evolution of Motor Efficiency

Shaft Power Delivered per Unit of Power In

25 MW of Shaft Power

680 tonnes

1.6 tonnes

=

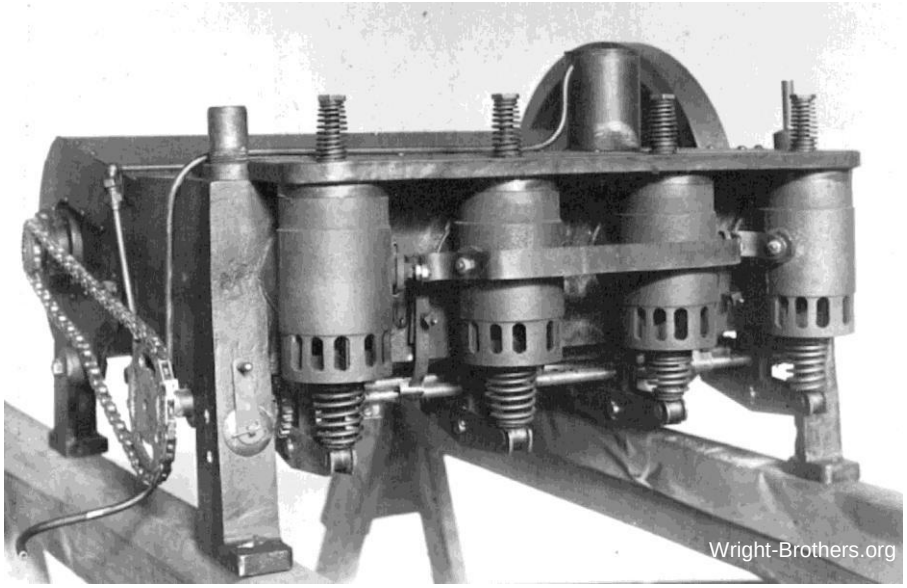
Same Power

Better Efficiency
Lower Emissions

Aero Engine Demands Push Engineering Limits

Power to Weight Requires *Very* Expensive Material

Wright Flyer



Wrights' engine used aluminum, then 100 times the cost of steel

Advanced Materials are at the Heart of Propulsion

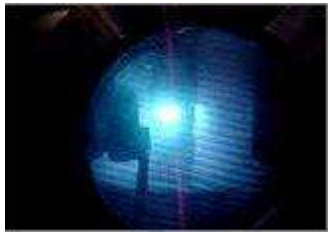
Enabling Performance, Weight, and Life

Advanced Single Crystal Casting

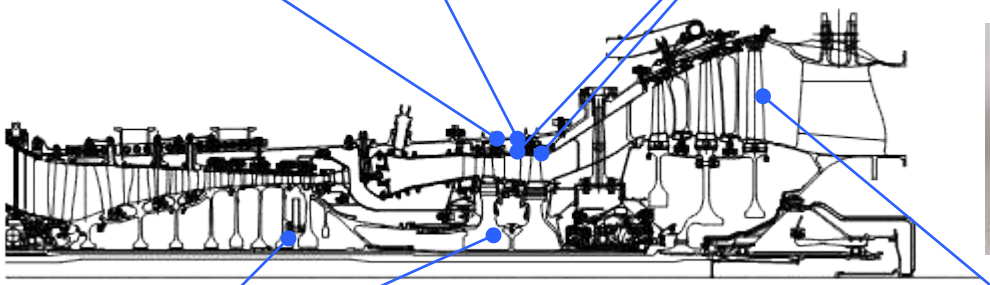
6th Generation Oxidation Resistant Single Crystal Airfoil Alloys

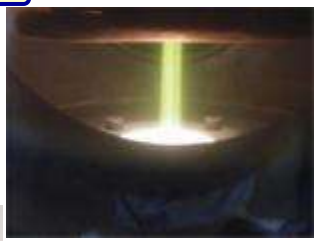
5th Generation Turbine Coating Technology

Microcircuit Casting / Cooling Technology



Cathodic Arc Bond Coat



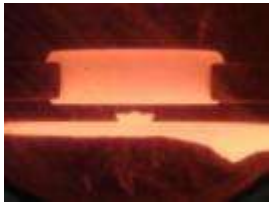


Electron Beam TBC

TiAl LPT Blades

Suspension Plasma TBC

6th Generation Powder Metal Materials

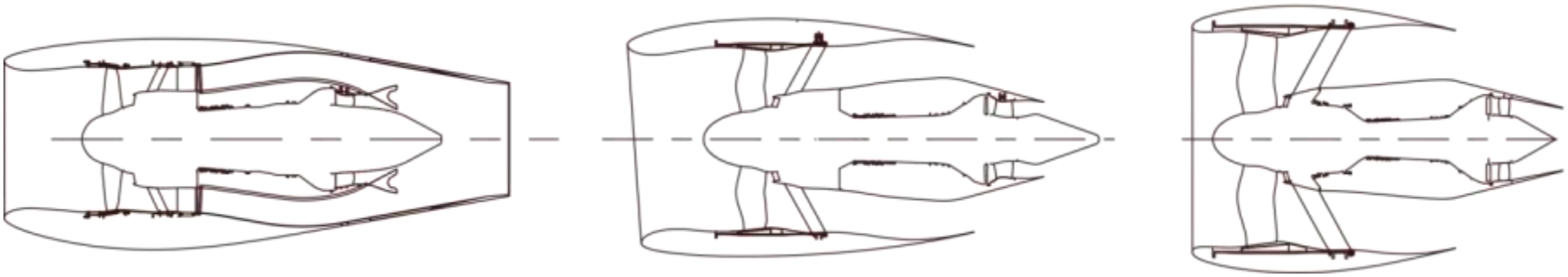


Advanced PM HPT disk

High Strength Forged TiAl Airfoil Alloys

Evolution of Bypass Ratio and Efficiency

In Service	2013-16	Longer Term
BPR = 5	BPR ~ 12	BPR ~ 15-18
Fuel Burn Reference	-15%	-20-30%

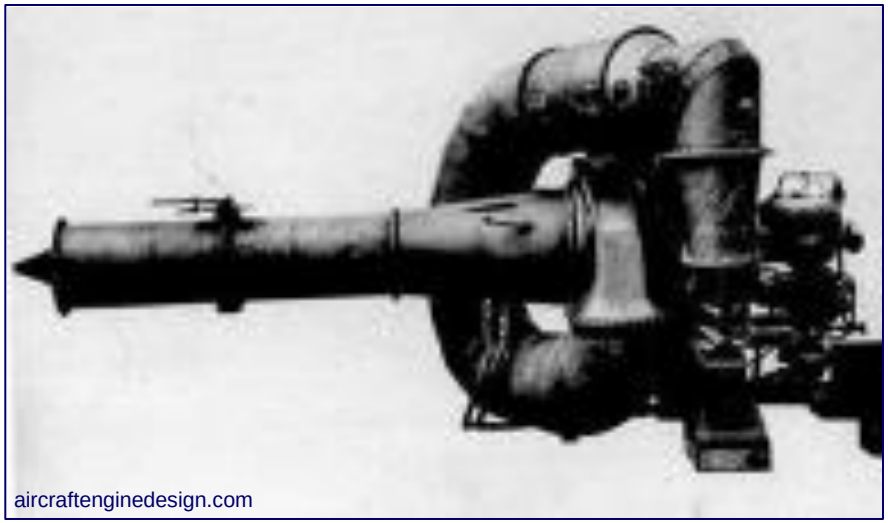


How We Make Engines Today

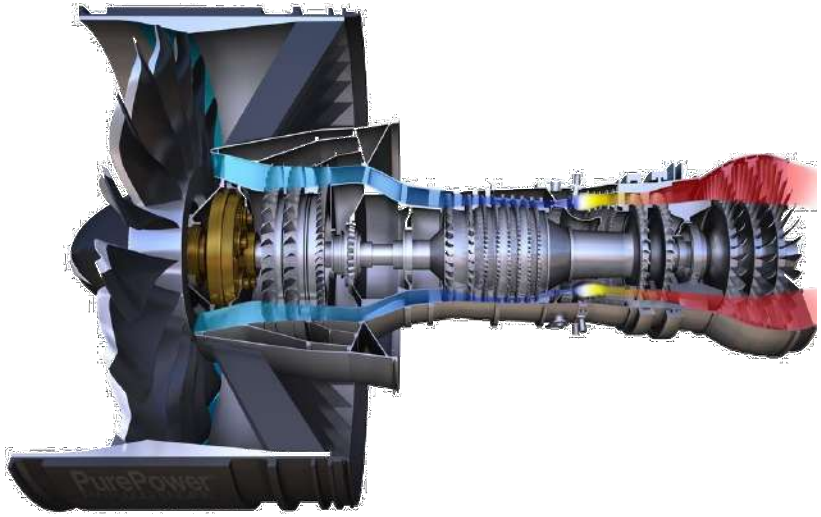
Manufacturing a Jet Engine

Processes Much the Same Then and Now

State-of-the-Art 1937



State-of-the-Art 2013



Jet engines have been largely made by…

- Forging
- Machining
- Casting
- Welding

Forging Enhances Metal Properties

Refining the Process Over Time

2000

1860 A.D.

Iron Dagger at
Alaca Hoyuk
(Turkey)

Modern Forging

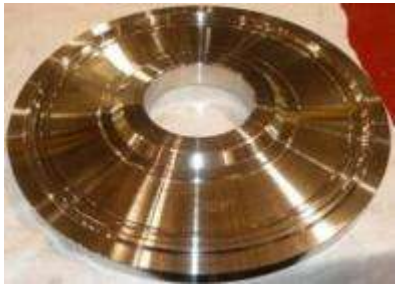
500-350 B.C.

Bronze Laminated Swords
Iron and Steel Swords
Dual Alloy Swords
(Warring States Period, China)

2200 B.C.

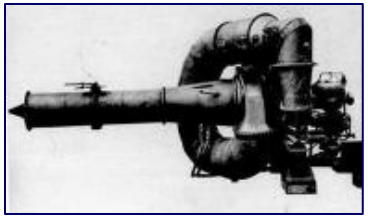
Engine Disks are Unique in Aviation

Always Forged for Strength, Machined for Shape



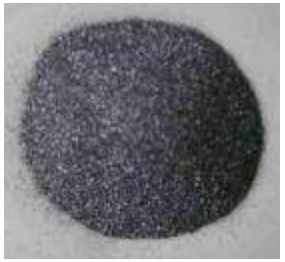
1990

1970



Whittle Engine

1937

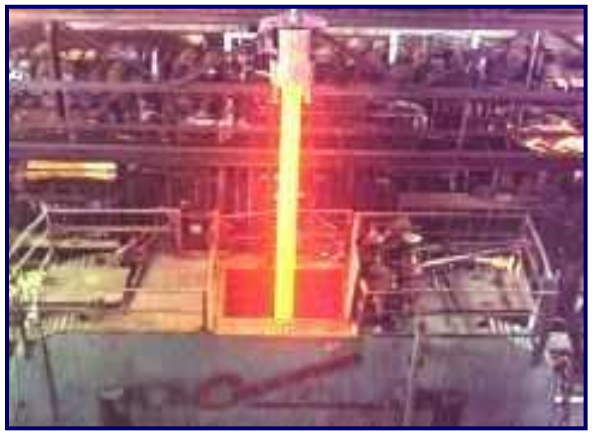


Metal Powder

Powder Metallurgy Manufacturing Process

P&W's Vertically Integrated Supply Chain

Alloy Powder Atomization



Billet Extrusion

Rotor Isothermal Forging

Casting for Shape

Popularization of Investment Casting

1960

Turbine Blades

1900

Cast Iron Plowshare
Han Dynasty, China

300-500 A.D.

Cast crucible steel in India

200 B.C-200 A.D.

Cast Copper
Mesopotamia*

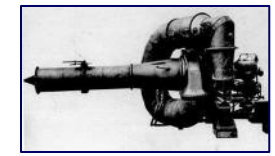
~450 B.C.

Earliest Cast Iron
Jiangsu, China

3200 B.C.

* Image courtesy of the American Foundry Society

Turbine Blades – From Wrought to Cast



Whittle Engine

1940

Wrought

1960

1970

Cast

1980

Cast Single Crystal

1st single crystal research blade

Improved single crystal

Machining for Shape

Computations Drove More Complex Geometries

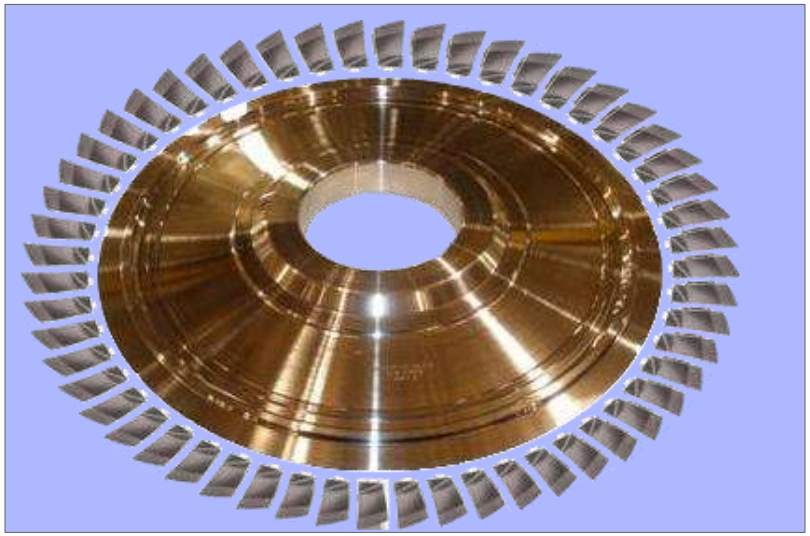
Traditional
2-D Airfoils

Recent
3-D Airfoils

Machining for Shape

Reducing Part Count and Cost, Improving Performance

Traditional Approach



Separate Disk, Airfoils
57 pieces

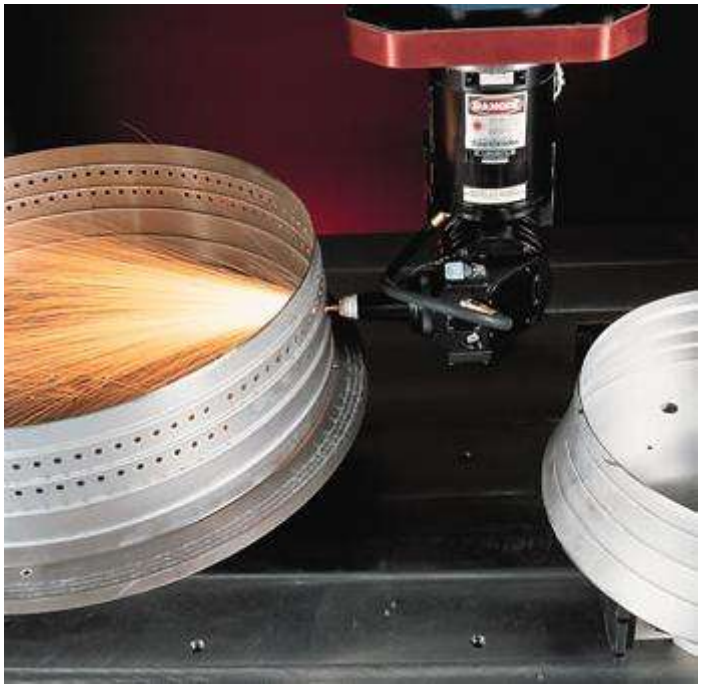
Preferred Approach

Integrally Bladed Rotor (IBR)
One piece

New 20th Century Manufacturing Technology

Cutting and Hole Drilling Tough Material

Laser Drilling



[Courtesy LAI International]

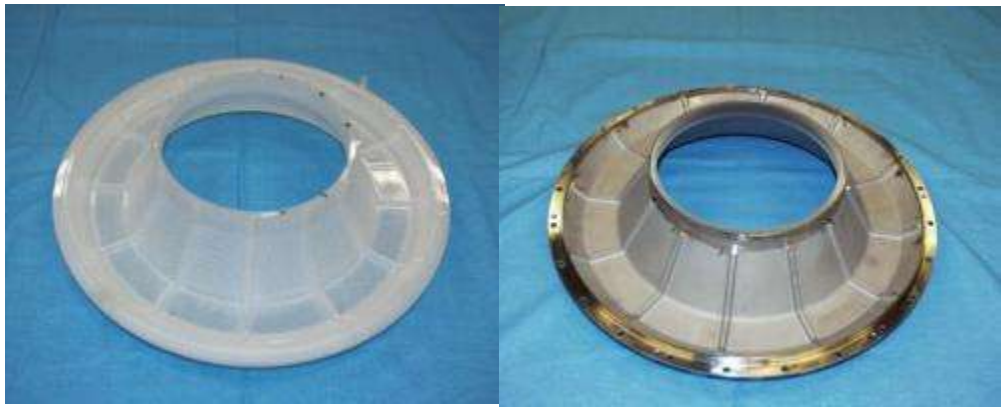
Electrical Discharge Machining (EDM)

[Siemens press picture]

Stereolithography – Shape, but not Properties

New Tech of the 1980s

Seal Model



Compressor Rear Case
Master and Wax Patterns

New Manufacturing Technologies

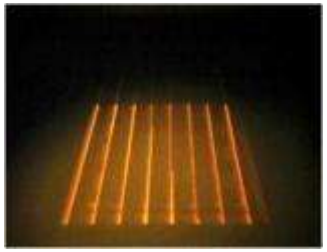
Emerging Opportunities

Manufacturing Technology to Create Value

A Few 21st Century Advances

Direct Metal Laser Sintering

Intelligent Cells



Electron Beam Melting

Thermoplastics

Automation

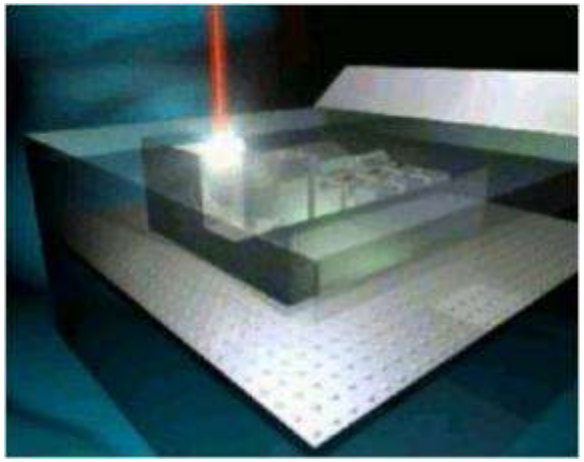
Machine Monitoring

Advanced processes reduce cost and weight

Direct Metal Laser Sintering (DMLS)

An Emerging Technology

Metal Powder



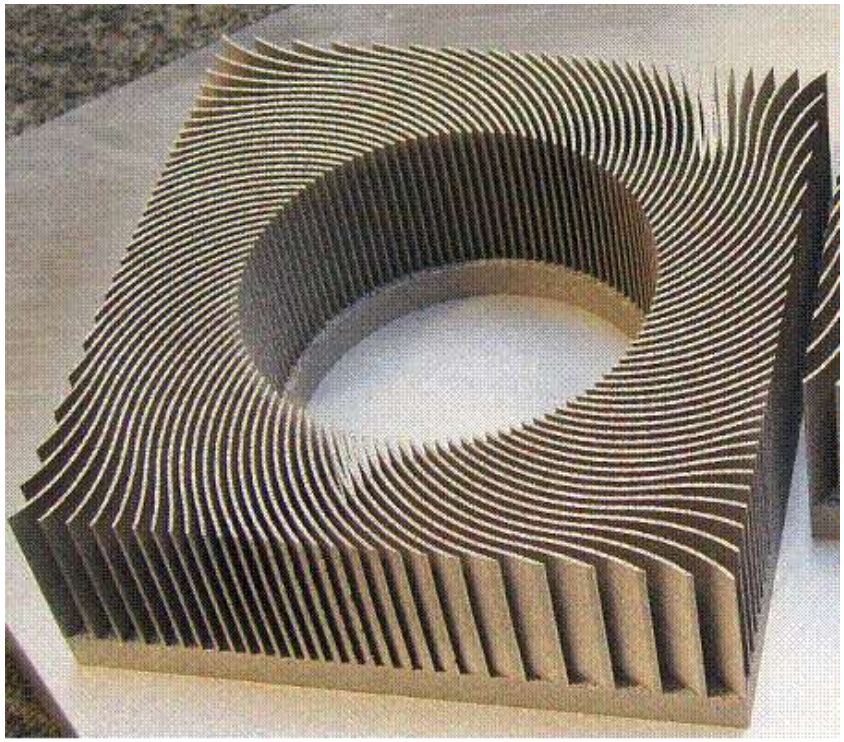
Laser or E-Beam Sintering

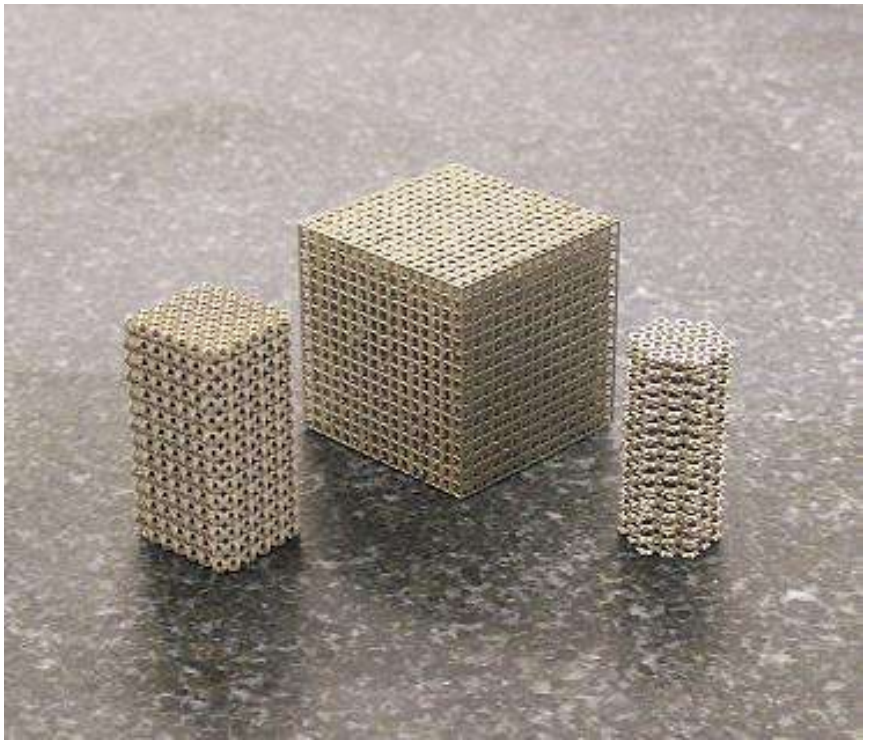
Part

[Images courtesy of Morris Technologies]

Manufacturing by Adding One Layer at a Time

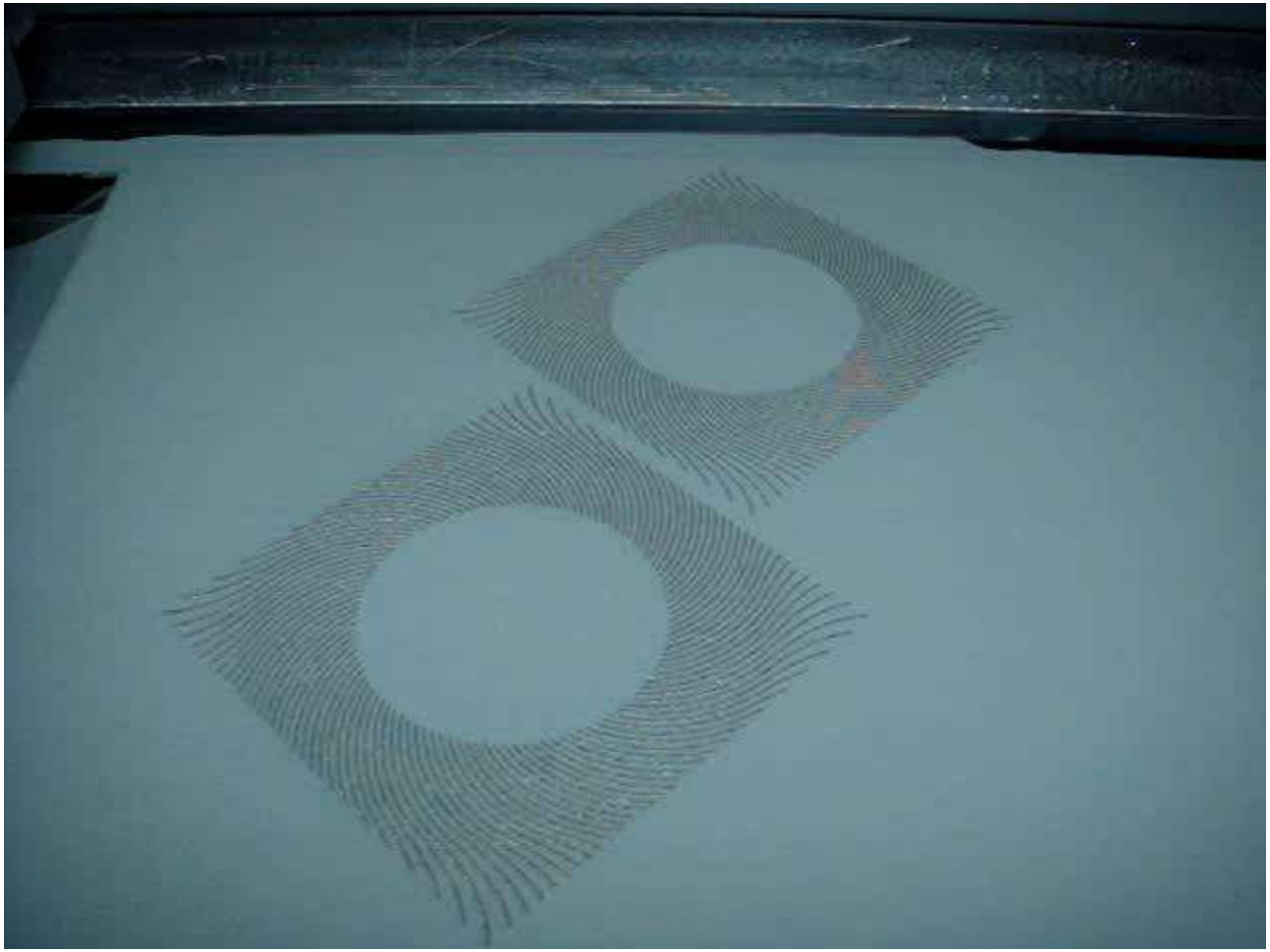
Both 2-D and 3-D Shapes Possible





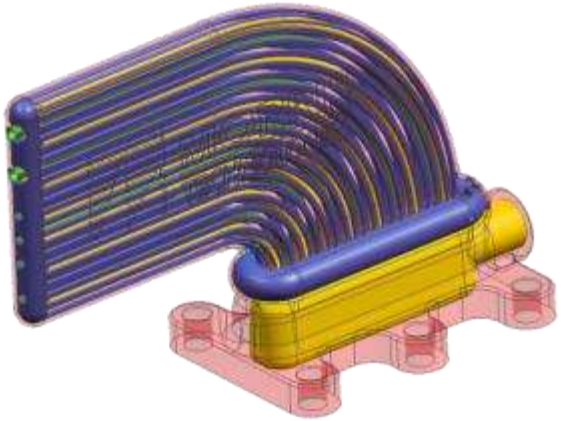
[Image courtesy of Morris Technologies]

DMLS Demonstration



Near Term Applications of DMLS

Low Stress, Geometrically Complex



[Images courtesy of Morris Technologies]

Process Dependent Design and Materials

Different Outcomes by Process and Properties

Design for the cold spray process

Design for direct metal laser sintering (DMLS)

[El-Wardany et al, 2nd World Congress on Integrated Computational Materials Engineering]

Challenges for Additive Manufacturing

Jet Engines Care About Shape and Properties

[Image courtesy of EOS]

- Shape accuracy not yet adequate
  - Finish processing needed
- Product properties can be improved
  - Strength at temperature
  - Corrosion
  - Fracture toughness, etc.
- Ensuring Quality
- Material systems available
- Powder quality and availability

Summary

- Gas turbines are the future of commercial aviation
  - Most efficient engines on the planet
  - Lowest emissions
  - Lowest cost of ownership
- Jet engines manufactured with legacy approaches
  - Innovation is opening new manufacturing opportunities
  - Manufacturing technology is an exciting investment area