AAE 538: Air-Breathing Propulsion

Lecture 1: Course Overview and Introduction

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PURDUE AERONAUTICS & ASTRONAUTICS

PURDUE PROPULSION

Administration and Logistics

Syllabus Review

- Contact Information
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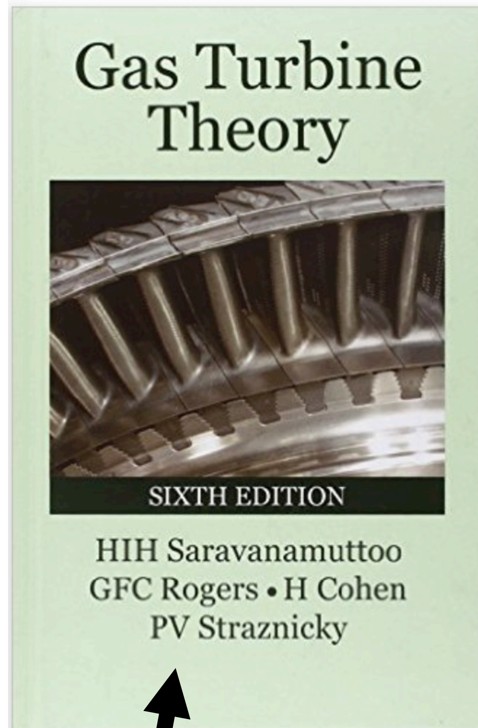
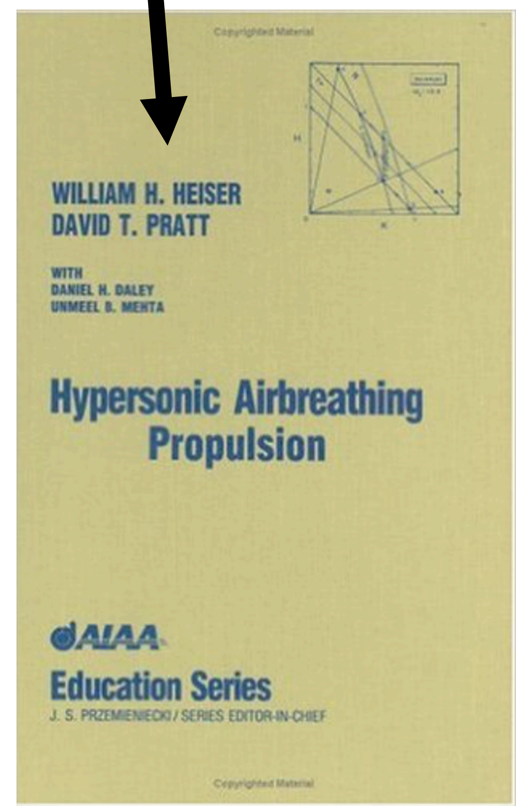


Saravanamuttoo et al. is a good reference text for more advanced analyses.

Heiser and Pratt is available in electronic form through the Purdue Library system



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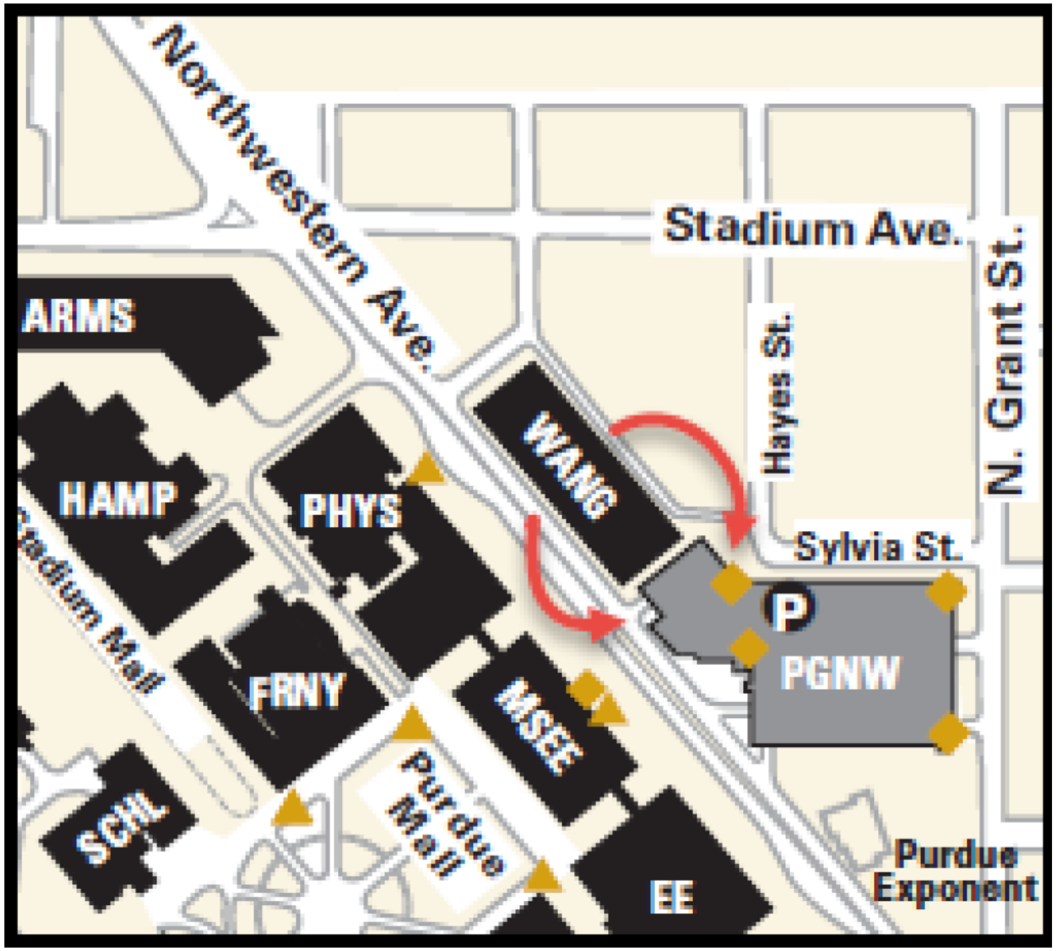
Administration and Logistics

Emergency Plan



Map for EPE/ProSTAR

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Introduction

Air-Breathing Engines

- Nearly all mechanical and electrical processes in the world today are achieved because of some device (an engine) that enables the conversion of chemical energy into thermal energy to perform useful work.
- These devices can take many forms, depending on what we need them to do.
  - For example, shaft work
    - Reciprocating engines achieve a direct conversion to mechanical work with gas expansion, after a constant volume combustion process.

Most automotive transportation applications rely on engines which produce shaft power as the primary mechanism of work output.

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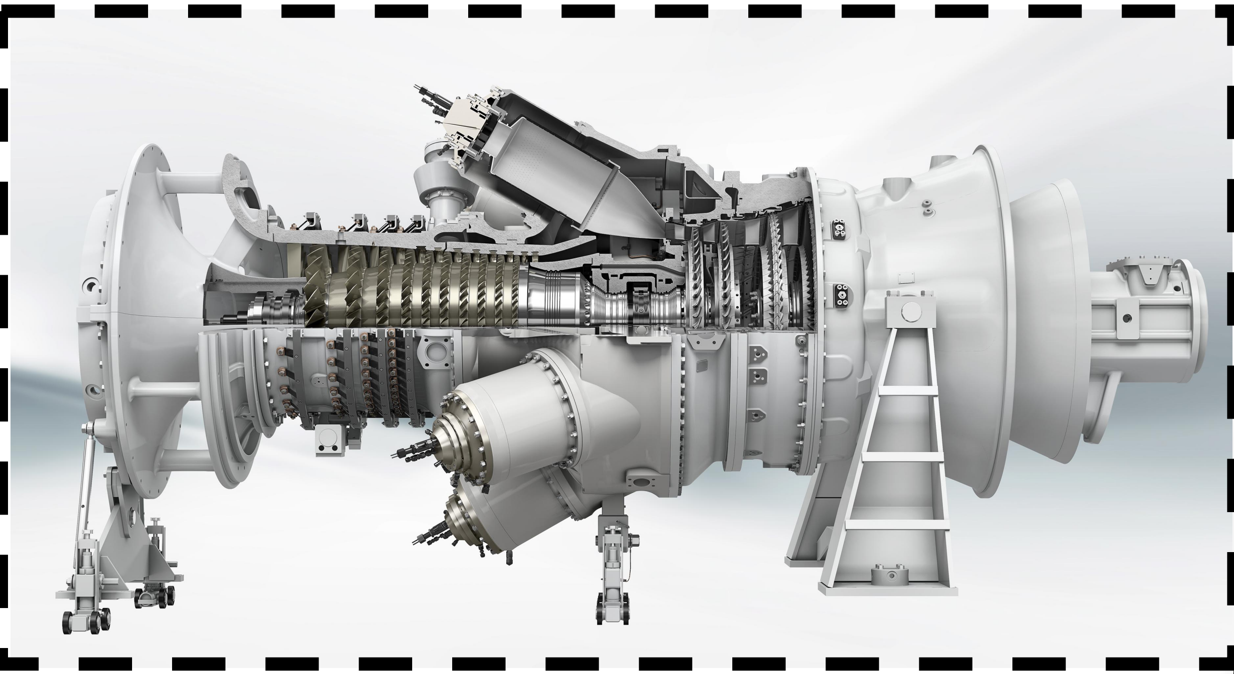
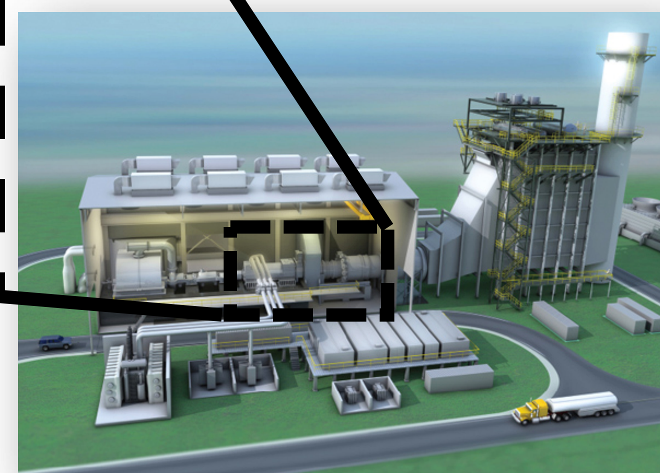
Introduction

Air-Breathing Engines

- Gas turbine engines are also used to generate shaft work. This is accomplished by expansion of high temperature, high pressure gases through the turbine stage, downstream of the (constant pressure) combustion chamber.





Gas turbine power-plants are another case where engines are used to generate shaft work that drives a generator and produces electrical power. These engines are very efficient and can be spooled up quickly in response to changes in the grid load.

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Introduction

Air-Breathing Engines

- Thrust is another output that we might need an engine to produce
  - As a reminder, thrust is a force meaning that is represents a change in momentum with time. Hence, it can be derived from the momentum equation that, in general, the thrust equation can be written as:

$$T = \dot{m}v\Big|_E - \dot{m}v\Big|_I + (p_E - p_I)A_E$$

  - Assuming a perfectly expanded nozzle ($p_E = p_I = p_{atm}$) and a comparatively small change in mass flow rate through the engine ($\dot{m}_E = \dot{m}_I = \rho v A|_I$), then we find:

$$T = \dot{m}(v_E - v_I)$$

  - Therefore thrust is produced as a result of a decrease in core gas density through the engine, which mandates that the exhaust gases must exit the engine with higher velocity than they entered. Where continuity states:

$$\dot{m}_E = \dot{m}_I = \rho v A\Big|_I \quad and \quad v_E > v_I \quad if \quad \rho_E < \rho_I$$

$$for\ constant\ A$$

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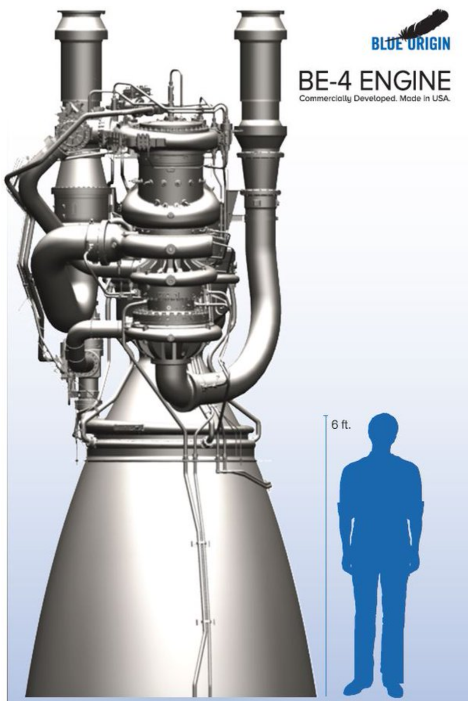
Introduction

(Air-Breathing) Engines

- Rockets are the simplest example of an engine design to produce thrust.
- Rockets carry both fuel and oxidizers on-board for missions beyond earth's atmosphere. To maintain low vehicle size and weight, these propellants are often stored as cryogenic liquids and are, therefore, easily pumped to cycle pressures.
- Although, they are not air-breathing…



Blue Origin BE-4

Rocketdyne RS-25

Saturn 5 Take-Off (Rocketdyne F1)

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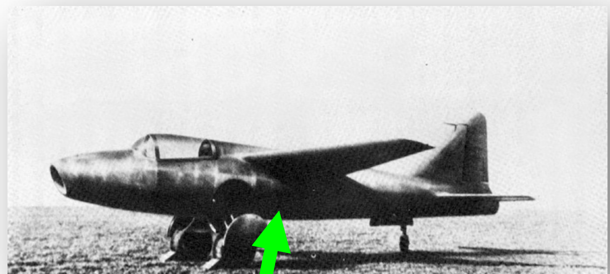
Introduction

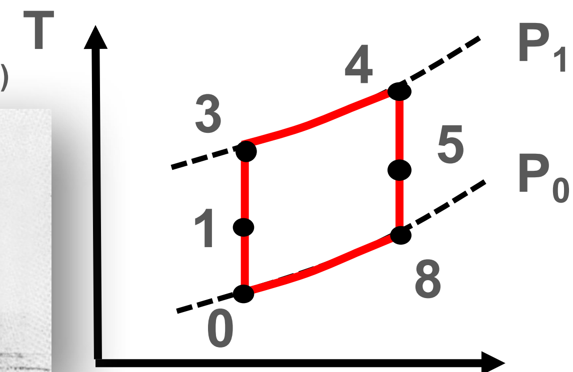
Air-Breathing Engines

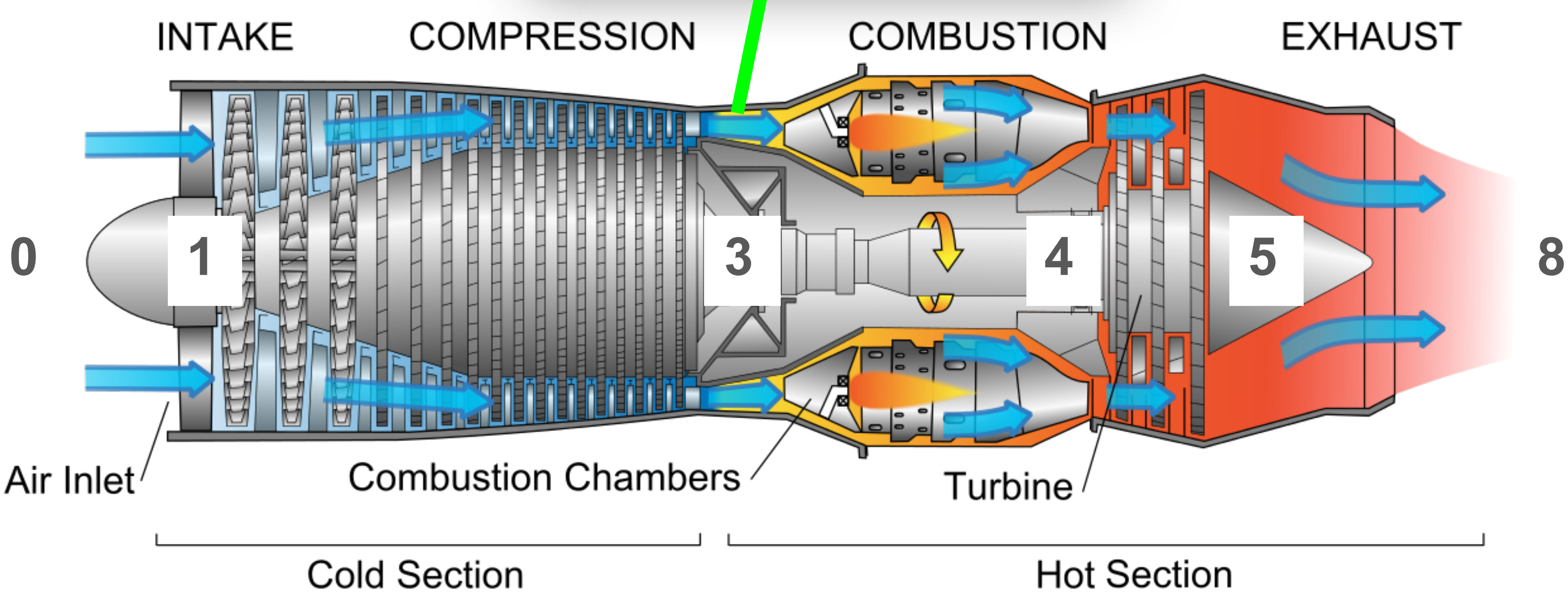
- Turbojets are an example of an air-breathing engine designed to produce thrust.
- This is accomplished using a Brayton cycle, where high-velocity exhaust gases produce thrust, after some expansion has taken place to drive the compressor.

German Heinkel HE 178 (circa 1939)



T-s diagram of an Ideal Brayton Cycle





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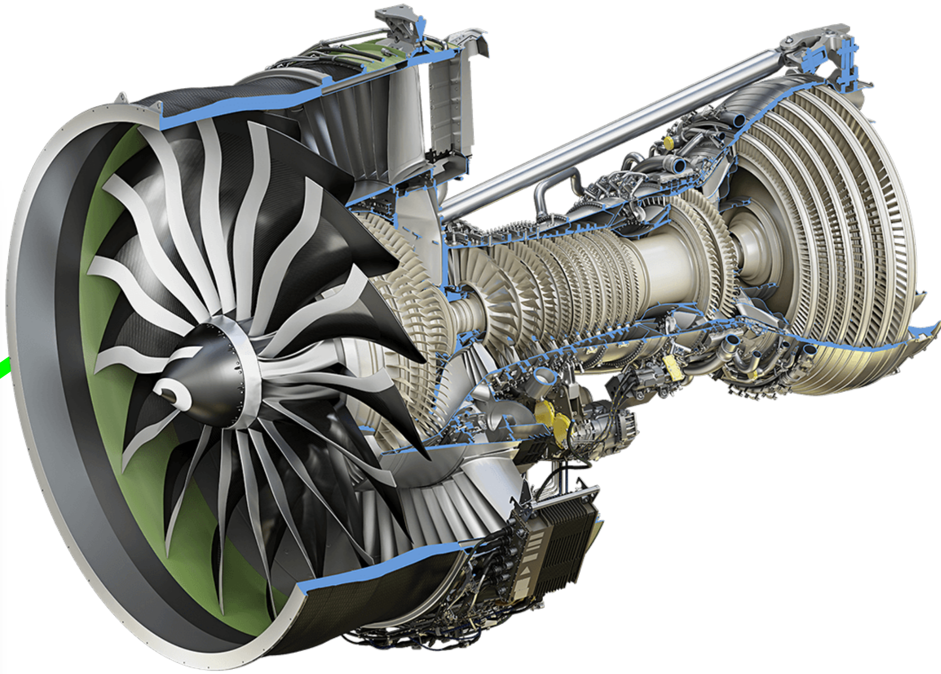
Introduction

Air-Breathing Engines

- In modern aerospace applications, what we typically find is a hybrid configuration that delivers both shaft work AND some level of thrust
  - Turbofans are one example, especially the high bypass ratio engines in commercial airliners.
  - Turbine stage extracts additional work from the exhaust gases to drive the fan as well as the compressor

Boeing 787 Dreamliner



GE Aviation GE-NX Turbofan Engine

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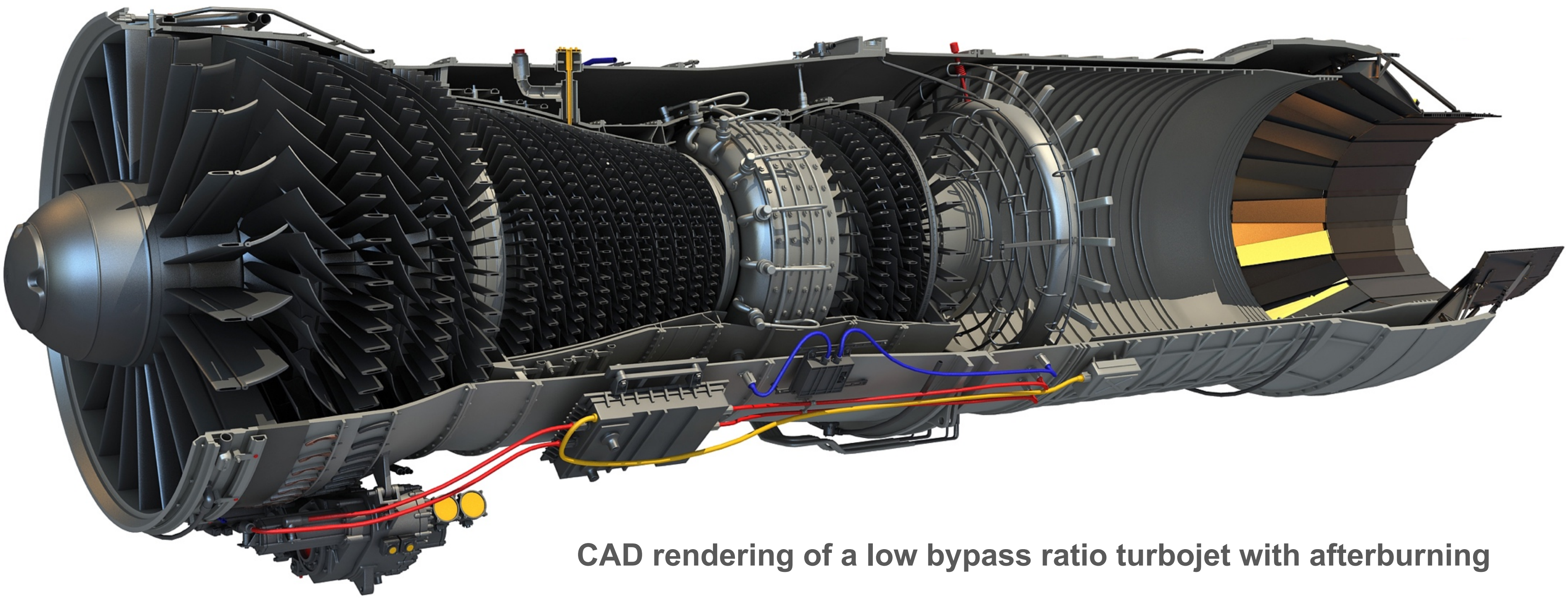
Introduction

Air-Breathing Engines

- Even fighter jets now run turbofan configurations.
  - Supports more efficient afterburning for high-speed flight
  - Better ‘fuel mileage’ during cruise



CAD rendering of a low bypass ratio turbojet with afterburning

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Introduction

Air-Breathing Engines

- In the future, we can expect to see more extended use of these hyrbid cycles
  - STOVL Configurations
  - Ultra-High Bypass turbofans/turboshafts

F35 STOVL configuration with lift fan

Rolls-Royce T406 Turboprop engines on a Bell-Boeing V22 Osprey

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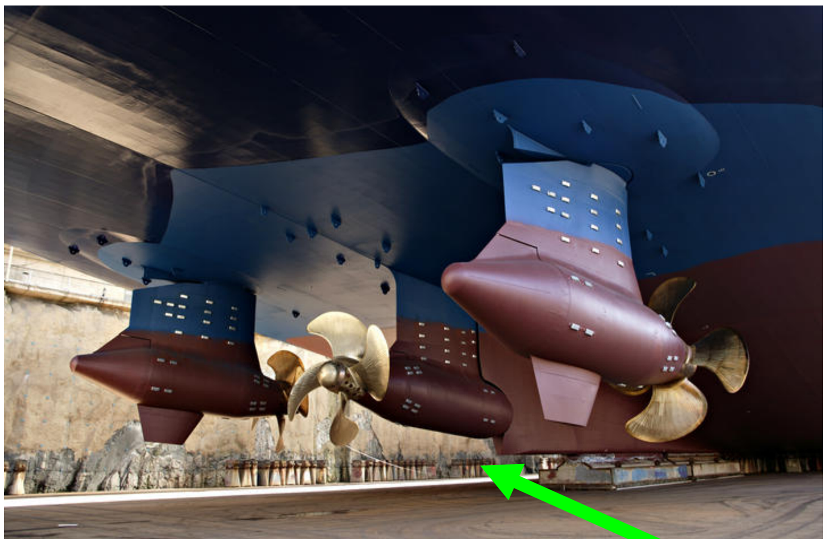
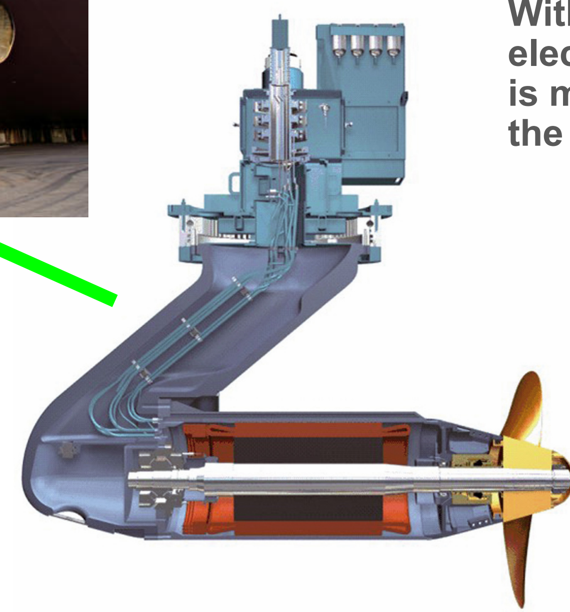
Introduction

Air-Breathing Engines

- In the future, we can expect to see more optimization of these cycles
  - Hybrid-Electric Systems?



With ever increasing need for electrical power on aircraft, this is might be a direction we see in the coming decades…



The Navy and commercial ship-builders have transitioned to a fully-integrated electric propulsion system. Azipods offer full 360 degree ‘thrust vectoring’ while the ships power systems simple spin generators.

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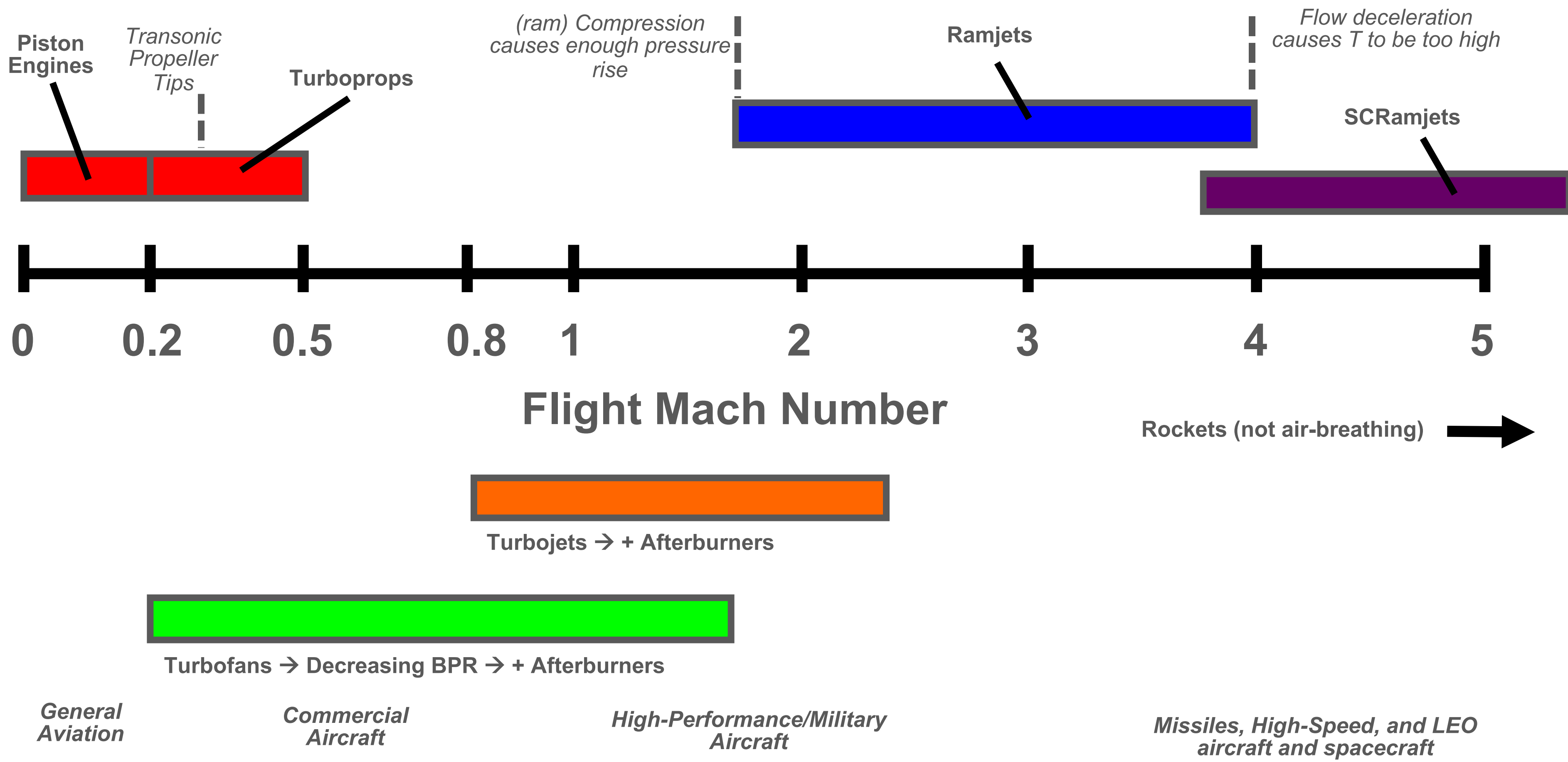
Introduction

- The focus of this course will be turbine engine platforms found in commercial/military aircraft, then extend into super/hypersonic propulsion devices.



Flight Mach number determines the engine platform

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Introduction

Why is the Mach number so critical?

- Unlike in rocket engines, the oxidizer supply to the combustor has to be drawn from the freestream flow.
    - As the free-steam velocity increases, the dynamic component of the total pressure and temperature of the inlet flow increases as well.
- Therefore, changes in the free-stream velocity inevitably impact the way air is handled by the engine inlet system and its condition at the combustor inlet.

Subsonic

Supersonic

Hypersonic

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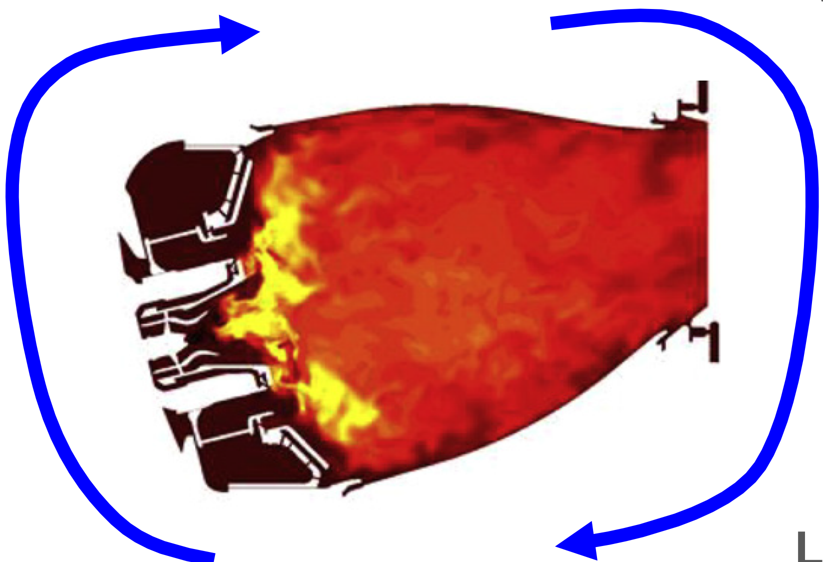
Introduction

- Combustion processes in propulsion applications can be globally-characterized as having a **high power density.**
  - The volumetric heat release rate in a typical steam power plant is on the order of $8\ BTU/ft^3 s$
  - In a jet engines, the this rate can be greater than $12000\ BTU/ft^3 s$
- Multi-scale, multi-physics *design* of turbulent combustion processes is extremely sensitive to inlet conditions

Emissions
Alternative Fuels
Weight
Dynamics
Smoke
Altitude Relight
Reliability
Auto-Ignition
Cost
Fuel Systems
Ground Start
Coking
Exit Profiles
Lean Blow-Out
Pressure Drop
Efficiency



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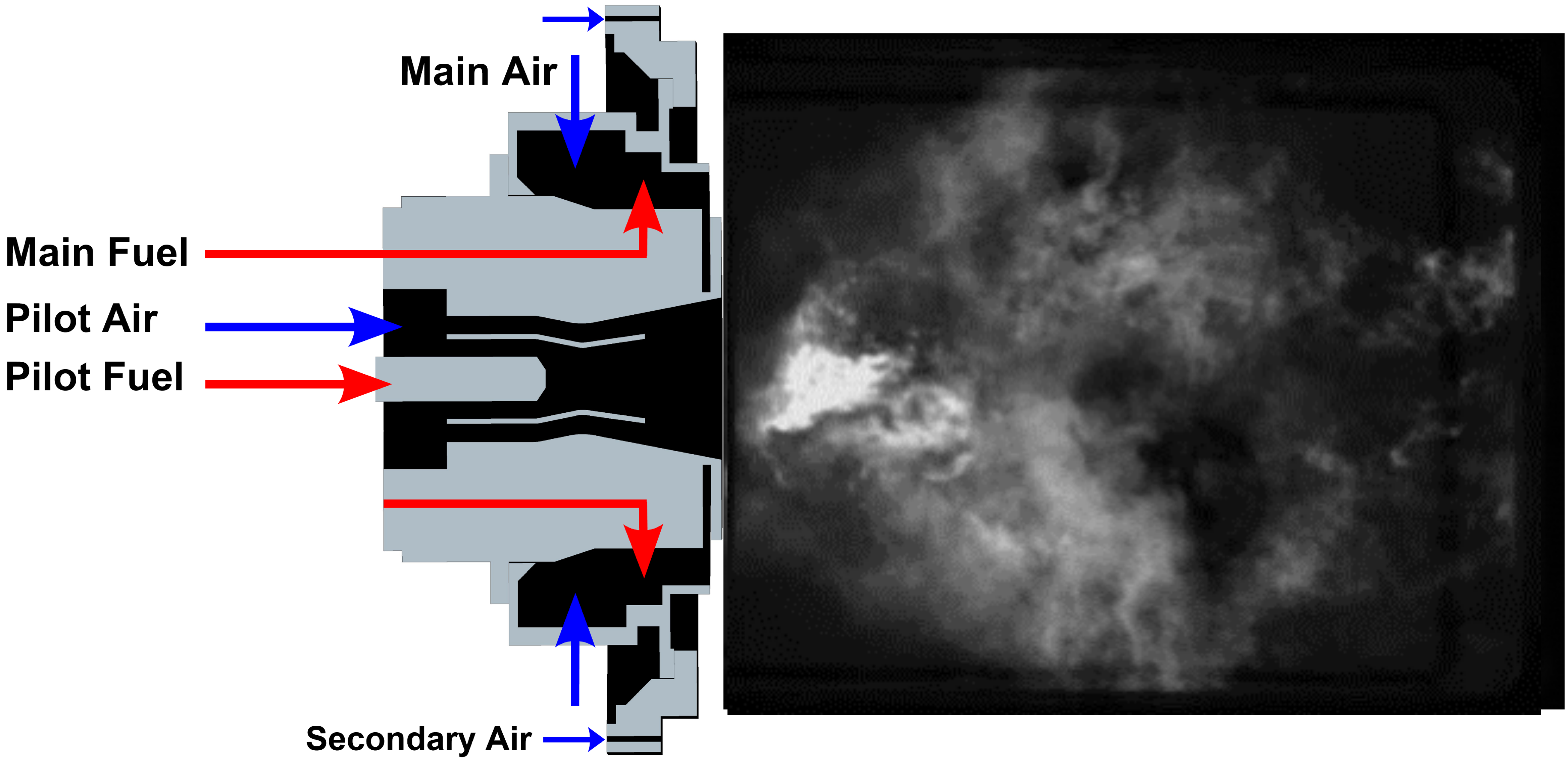
Introduction

Turbulent combustion in engines…



5 kHz imaging of visible light emission from an aeropropulsion injector operating at cruise conditions

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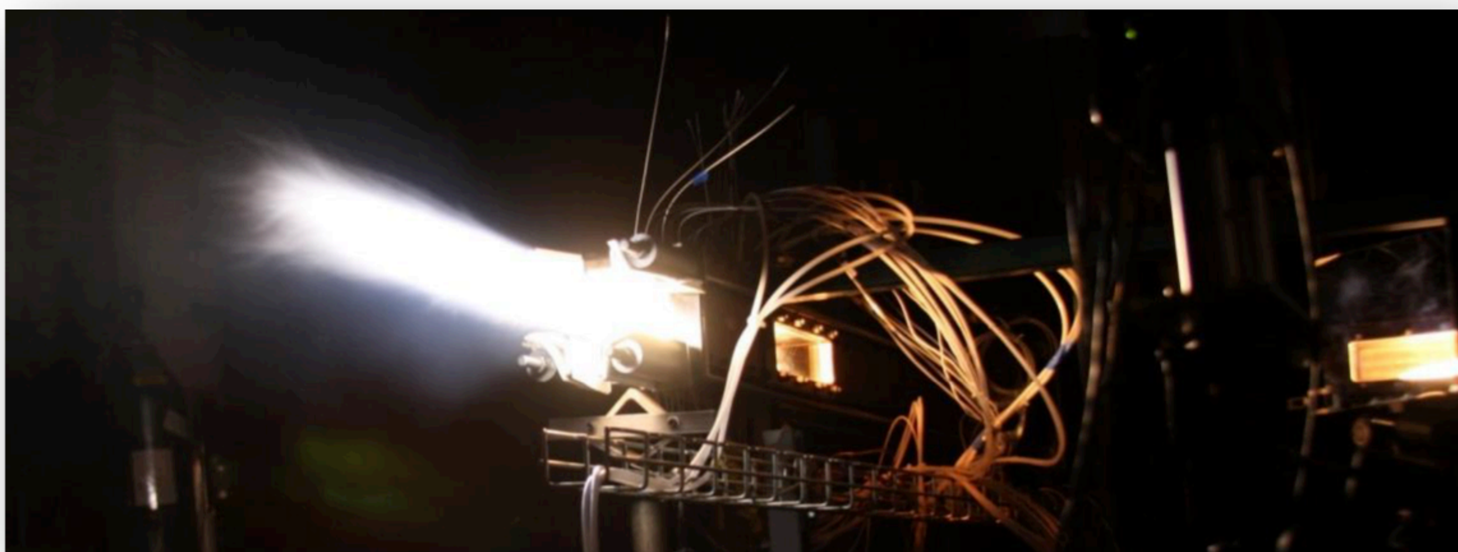
Introduction

Handling the hot gas…

- As we've eluded to, above, once the combustion process is complete the expansion system can vary a great deal as a function of the engines purpose.
  - Turboshaft and turboprop engines, for example, typically generate less than 10% of their overall thrust from the core exhaust. The rest is from shaft work that drives the rotor/propeller, extracted by the turbine stage.
  - The expansion system of a SCRamjet, however, is effectively just a supersonic nozzle. It's often even considered to also act as a combustor.



Purdue SCAB experiment in operation

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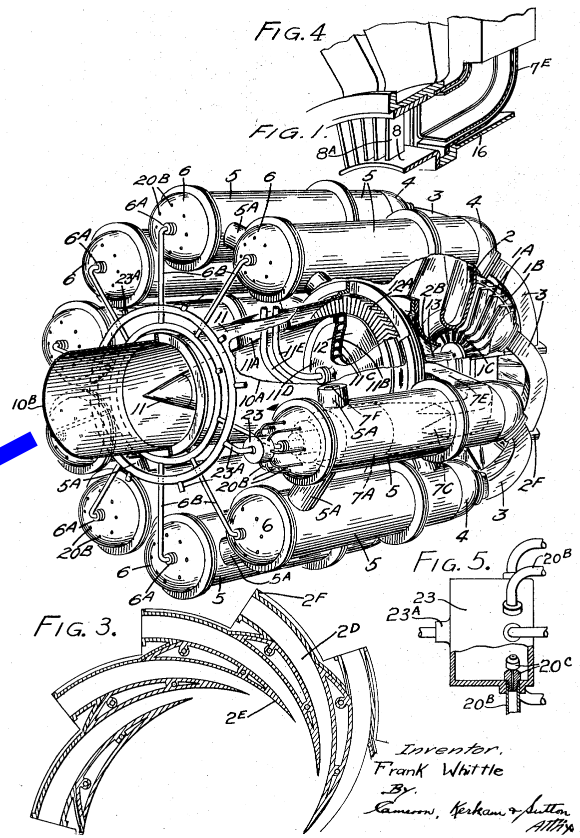
Outline

Where do we even start?

- Air-breathing engines are highly-coupled systems.
  - To fully-understand the physics of each component would take lifetimes
  - To fully-understand their interactions…longer.
- Adding to that, changes in the aviation market, the introduction of new ‘disruptive’ technologies, …

The game is constantly changing and, after 75 years of development, the ‘low-hanging fruit’ is gone.



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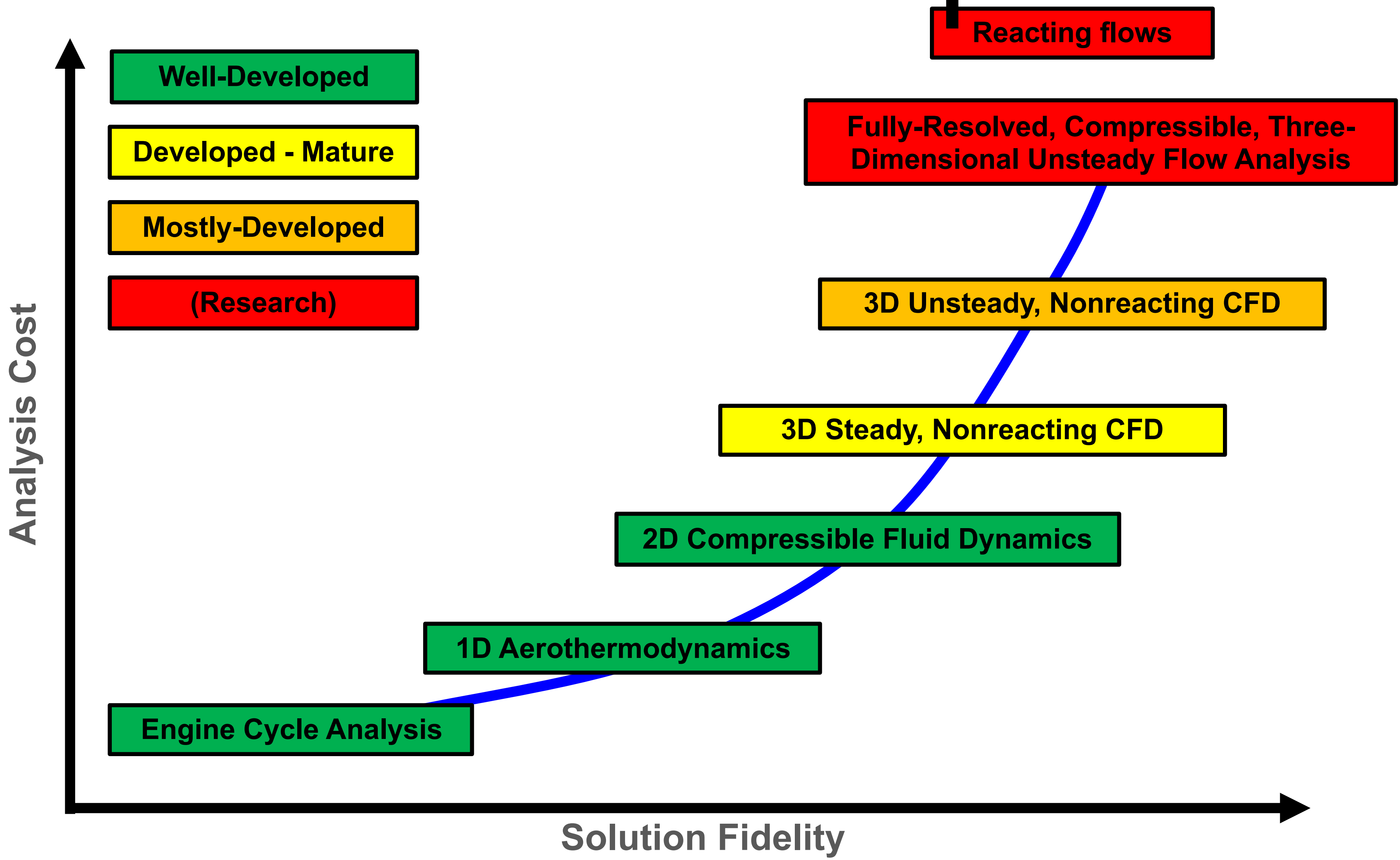
Outline

Simulation Capability in Thermal Science



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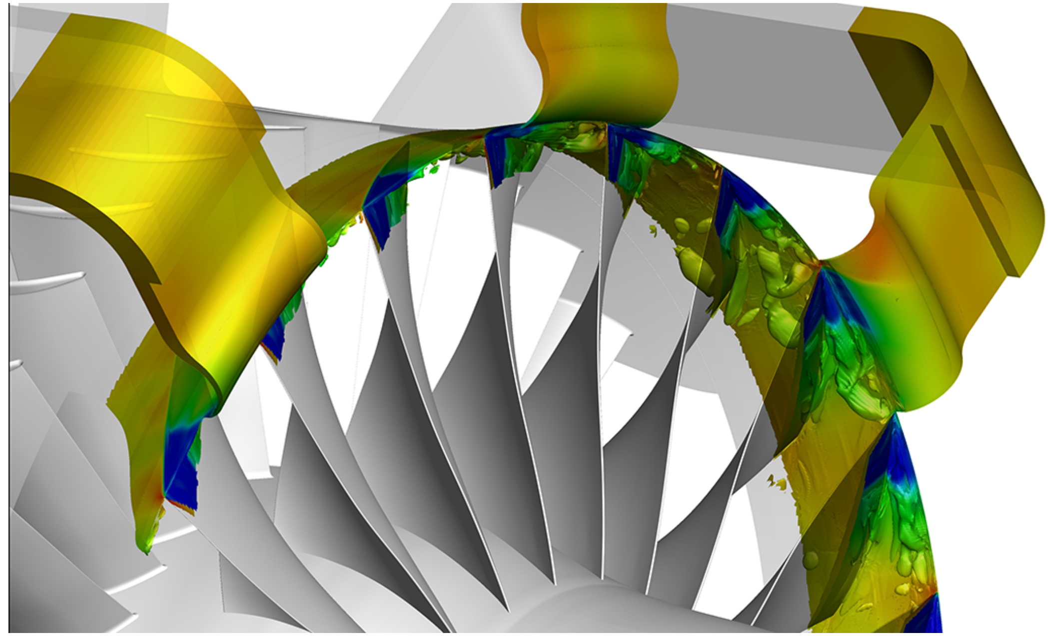
Outline

An example of high-fidelity computation

Oak Ridge Leadership Computing (2014)

'Ramgen Takes Turbomachine Designs for a Supersonic Spin on Titan'

- Investigation of tip injection to extend stall margins in a transonic compressor
    - Stage 67 test case with blades rotating at 16043 rpm
    - 1.5 billion cells
    - 10-100 million core hours of compute time



- DOE supercomputer specs:
    - 18688 Nodes (96 per cabinet)
    - 299008 cores
    - 693.6 TB RAM
    - 4300 ft^2 room
    - 3rd fastest in the world (06/16)
        - 27 petaflops (billion-million)

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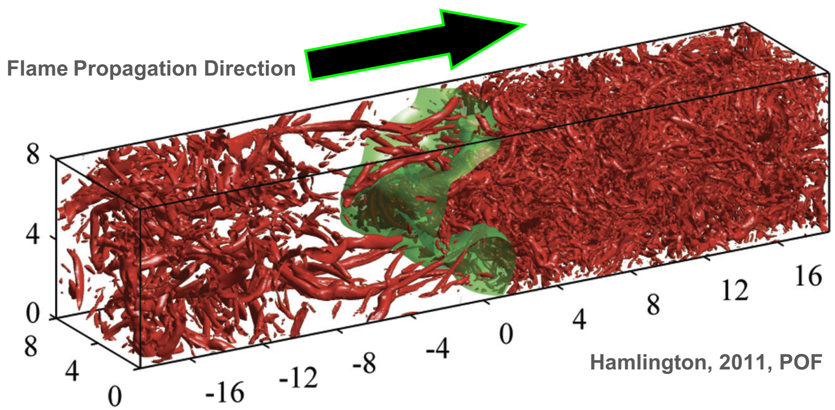
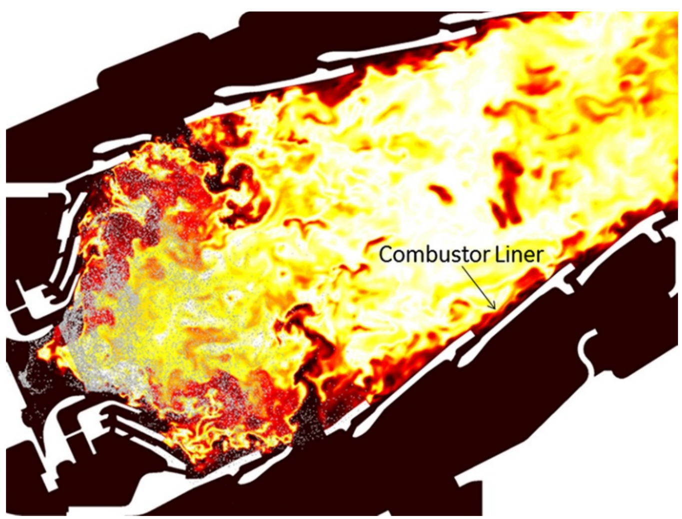
Outline

With chemical reactions…



Hamlington, 2011, POF



Hamlington, 2014,
ALCF Report

- Resolution of turbulence-chemistry interactions requires extreme levels of resolution in space and time.
  - 8 - 40 billion cells
  - 8mm x 8mm x 40mm domain
  - $1M electricity bill (last year)
  - Direct Numerical Simulation
- Component-scale resolution requires the introduction of modeling, accompanied by potential errors.
  - Large-Eddy Simulations

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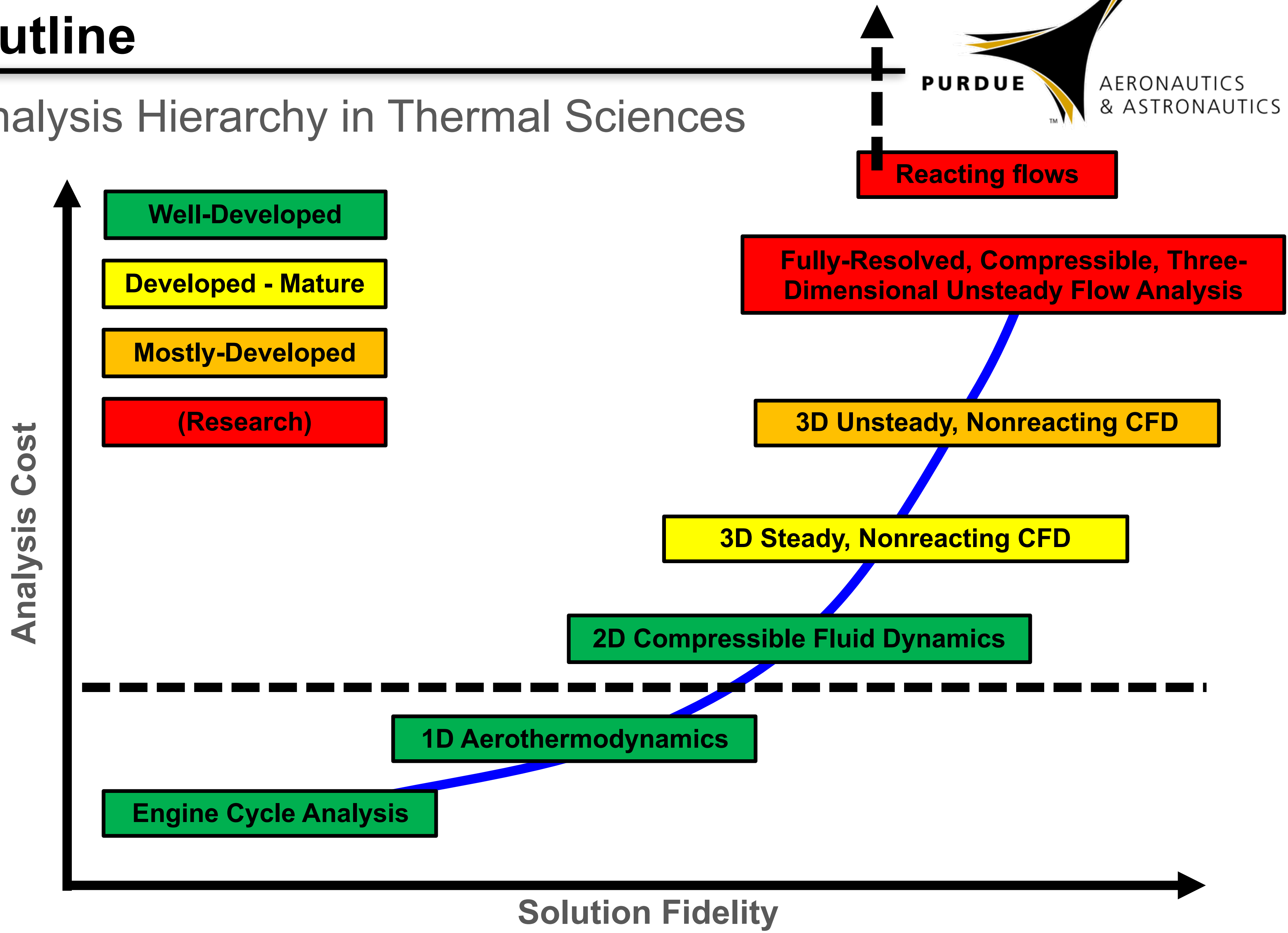
Outline

Analysis Hierarchy in Thermal Sciences



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Outline

The Tools Needed

- Fundamental understanding of engine processes from first-principles
  - One-dimensional analysis developed directly from foundations in:
    - Thermodynamics
    - Compressible Gas Dynamics
    - Heat Transfer
  - Directional sensitivities of engine performance to design changes.
    - Cycle analysis
    - Performance Characterizations
- Expertise in some specific area
  - High-Speed Aerodynamics (turbomachinery)
  - Heat Transfer
  - Combustion
  - Composites, High Temperature Materials, Electronics and Control, …

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Outline

Material Coverage in AAE 538

- Fundamentals of 1D Compressible Flow
- Subsonic Air-Breathing Propulsion Systems
  - Engine Cycles and Performance Criteria
  - Ideal and Real Engine Analysis
  - Component Characterizations
    - Compression Systems
    - Turbines
    - Combustors
  - Component Matching
  - Single- and Dual-Spool Machines
  - On- and Off-Design Performance and Transient Operating Lines
- Supersonic/Hypersonic Air-Breathing Propulsion Systems
  - Inlet Systems, Starting, and Isolators
  - Aerothermodynamics of Combustion
  - Dual-Mode and Combined Systems
  - Burner-Isolator Interactions
  - Expansion Systems

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