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14. ABSTRACT
The AFRL liquid engine mission is developing the technology trade space for high performance, affordable rocket engines. This can be accomplished by increasing design space – not point designs; integrated technology demonstrators; and a systems engineering approach – tech selection and execution. Tools need to be developed to enable model driven development that will replace empirically-based tools with physics-based tools, enable new technologies, and reduce development costs. Technology may be developed during engine cycle via oxygen-rich staged combustion, expander, and innovative cycles – Ex-Hex, and Aerospike. Or it may be developed within the component, in hydrostatic bearings, combustion stability and ignition.

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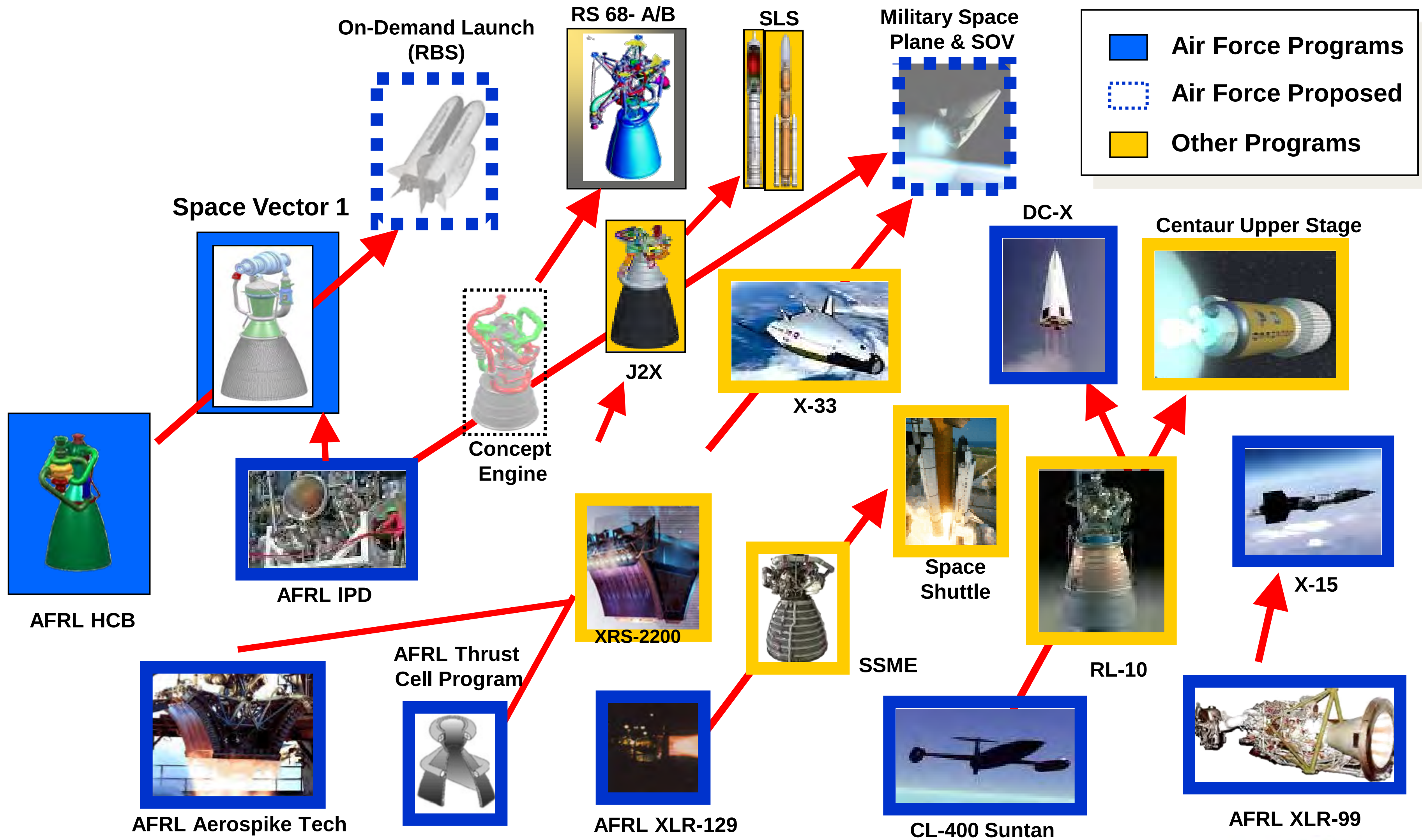
Hydrocarbon Boost Technology for Future Spacelift

15 Feb 2012

Dr. Richard Cohn
Chief, Liquid Rocket Engines Branch
Propulsion Directorate
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

AFRL Edwards Rocket Site: Liquid Rocket Technology Development



AFRL Liquid Engine Mission

Developing the Technology Trade Space

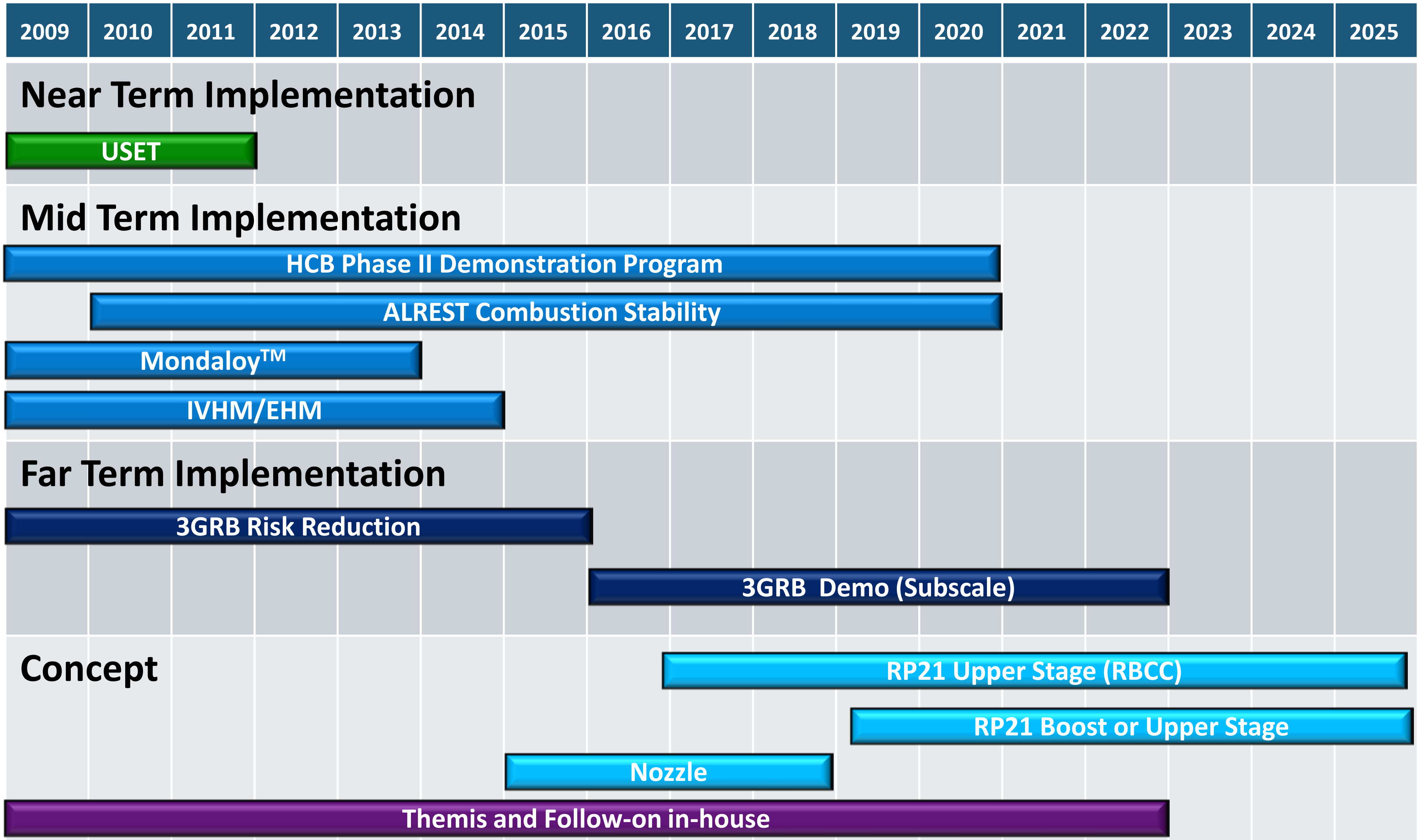
- Develop the trade space for high performance, affordable rocket engines
  - Increase design space – not point designs
  - Integrated technology demonstrators
  - Systems engineering approach – tech selection and execution

- Develop the tools – enable model driven development
  - Replace empirically-based tools with physics-based tools
  - Enables new technologies
  - Reduces development costs

- Develop the technology
  - Cycle
    - Oxygen-rich staged combustion
    - Expander
    - Innovative cycles – Ex-Hex, Aerospike
  - Component
    - Hydrostatic Bearings
    - Combustion Stability
    - Ignition

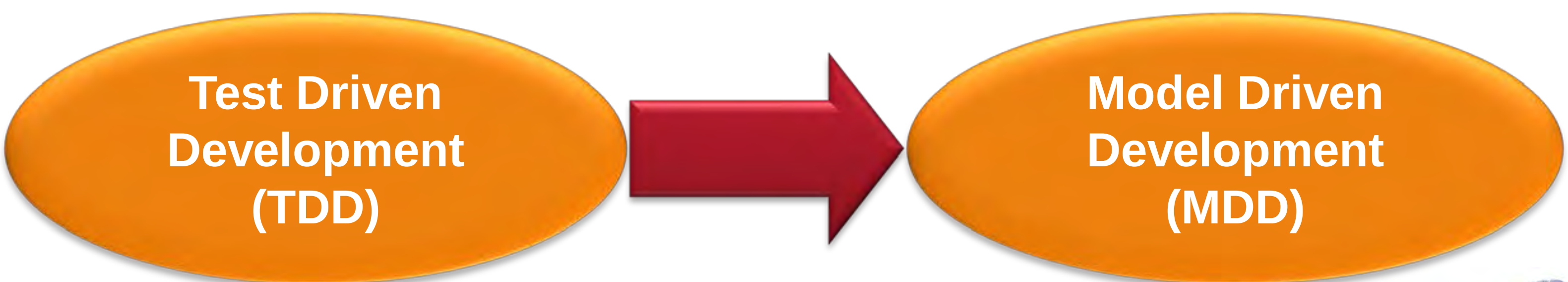
AFRL/RZSE LRE Roadmap

As of FY12 PB



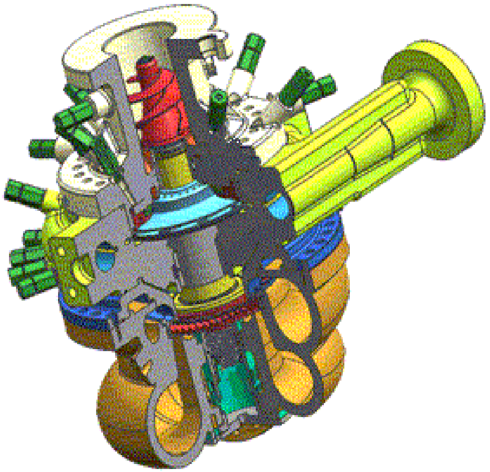
Drive Towards Model Driven Development

- **Industry standard modeling, simulation, and analysis tools need to be updated**
  - Existing empirically based tools require hundreds of tests
  - Could not handle new technologies like hydrostatic bearings
  - Major contributor to failure of prior R&D tech demo effort
  - Industry losing greybeard design and analysis experience
  - Current computational capabilities enable physics-based tools
  - Testing drives the cost of rocket programs
    - Necessary
    - Need to be smart



Upper Stage Engine Technology

- Liquid Rocket Engine development has utilized TDD process
  - The RL-10: 707 pre-flight test firings
  - SSME: 4,566 component tests on 56 different engines
  - The F-1 Engine development cost: $2.77 Billion (2007 $)



- USET developed MDD tools
  - Demonstrated liquid hydrogen turbopump

- Completed test campaign
  - 29 tests–Steady and transient performance, pump mapping, suction performance, cavitation testing
  - 332 instruments—most highly instrumented turbopump ever!!!

Models validated on USET are being used on HCB and provide critical risk reduction for EELV

Hydrocarbon Boost Overview

- Demonstrator pursuing performance and operability goals
  - Expendable and reusable
  - Tech applicable and necessary for both applications
- Develops crit tech for domestic LOX/RP ORSC rocket engines
  - Ensures domestic sources
  - 250k lbs skid-based demo
    - Optimized for data collection
    - Scalable to 1.6 Mlbf thrust
- 14 year, funding limited effort
  - System testing completes in FY19
  - Prime contractor: Aerojet
- Cost-effective, MDD

HC Boost establishes a new SOTA in Domestic LOX/Kerosene Engines

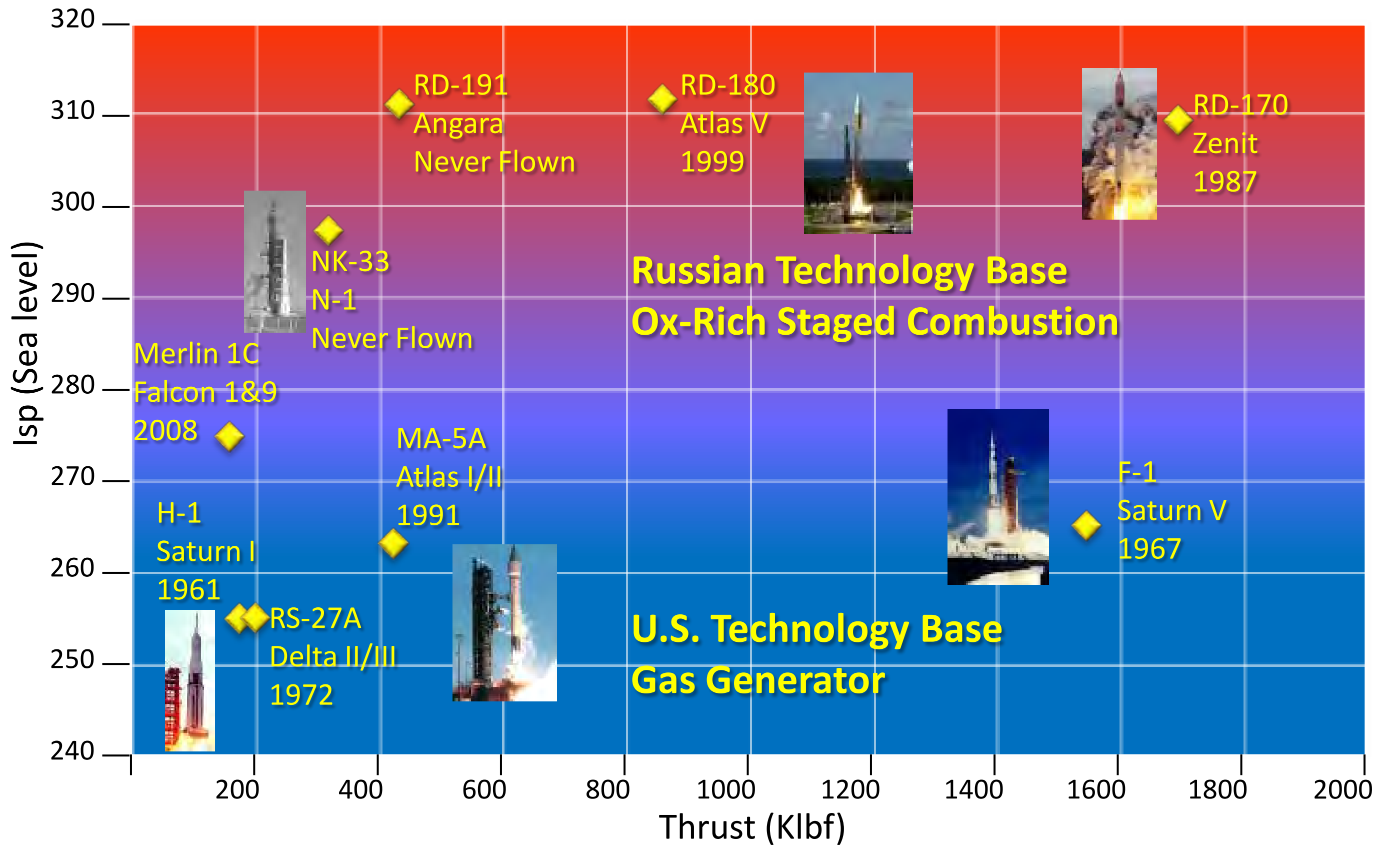
Hydrocarbon Boost
State of the Industry and Program Goals

Domestically

- No large domestic HC engines
  - > 250 klbf thrust
- NASA HC efforts ended in 2005
  - RS-84 & TR-107
- Space-X has integrated 9 GG LREs (Merlin 1C)
  - Demonstrated 6/2010
  - Designed for re-use

Internationally

- RD-151 (de-rated RD-191) reusable engine flown on Naro-1



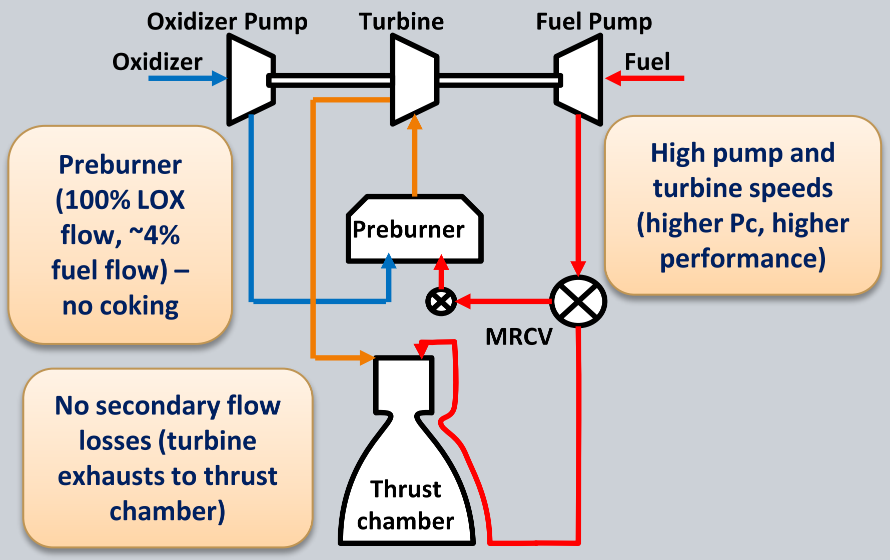
HCB Upgrades the Domestic Technology Base

AFRL

What is Oxygen-Rich Staged Combustion?

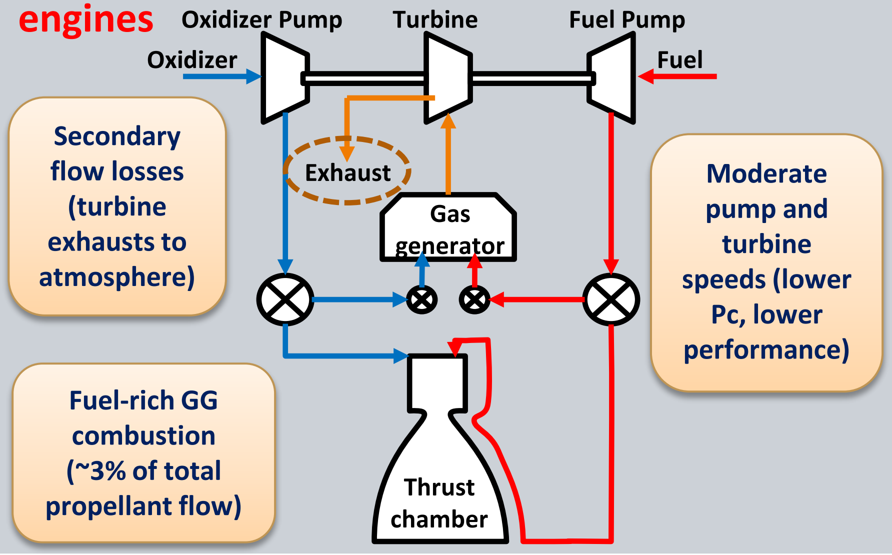
Staged Combustion Cycle

- High flow, high pressure preburner powers pumps
- Ox-rich staged combustion pioneered by Russia – maximum performance cycle
- Challenging environments with hot oxidizer flows (e.g. metallurgy)
- **U.S. has never produced a LOX/HC staged combustion cycle engine**



Gas Generator (GG) Cycle

- Low flow, low pressure gas generator powers pumps
- Relatively simple design
- Heritage to 1950's and 1960's U.S. engines (Delta, Atlas, Titan, Saturn)
- **U.S. has extensive experience in both LOX/LH2 and LOX/HC GG engines, including recent Falcon engines**



ORSC is a higher performance cycle, providing a smaller launch vehicle or an increase in delivered payload

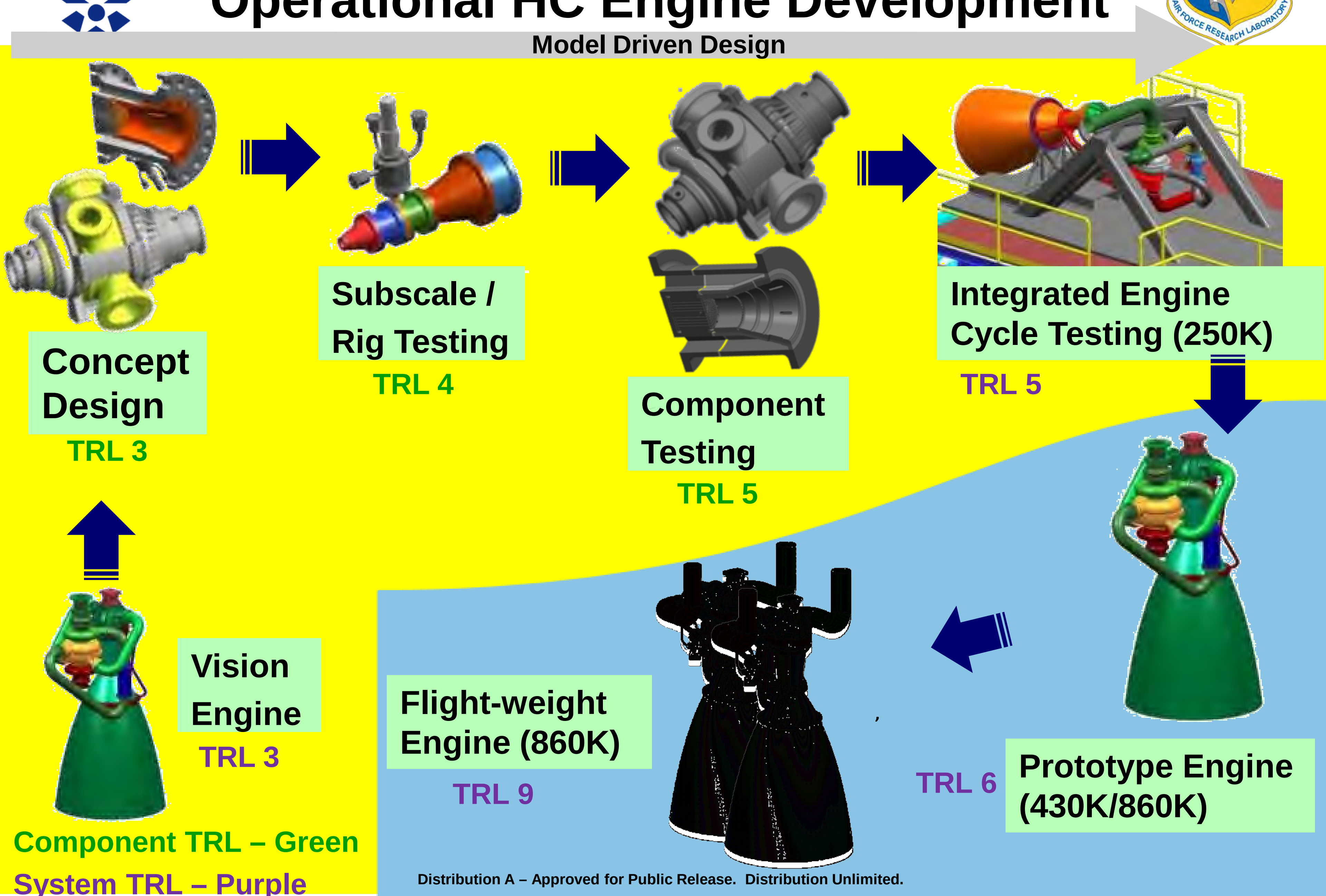
HCB Goals
Jointly Developed through IHPRPT

GOALS	HCB Demo
Isp* (seconds) Sea Level/Vacuum	+15%
Thrust to Weight* Sea Level/Vacuum	+62%
Production Cost	-50%
Failure Rate	-75%
Mean Time Between Replacement (Cycles)	defined
Mean Time Between Overhaul (Cycles)	defined
Turnaround time (hrs)	defined
Throttle range	defined
Sustainability	Must derive from sustainable materials and processes

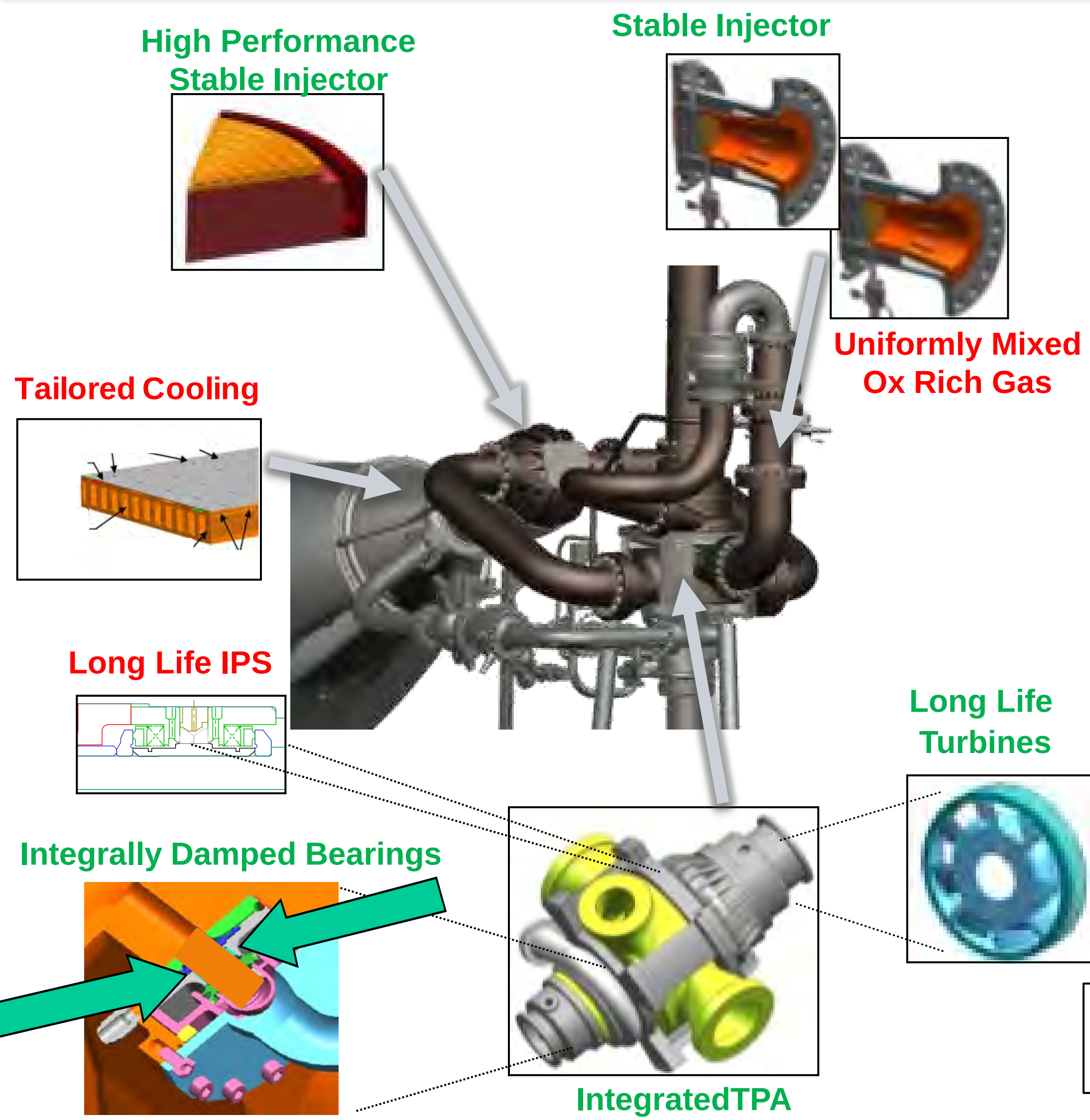
- **Integrated High Payoff Rocket Propulsion Technology**
  - **Develops goals for Rocket Tech**
  - **Liquids, Solids, & Spacecraft**
  - **3-phased tech development**
  - **Began in 1996**
- **Steering Committee**
  - **OSD and NASA Hq Co-Chair**
    - **OSD**
    - **DoD Services**
    - **NASA**
    - **Industry**
- **Semi-Annual Meetings**
- **Goal: Achieve TRL 5**

HCB Provides a Reusable, Robust, and High Performance Engine Required for Current and Future Spacelift Concepts

Systems Engineering Approach to Operational HC Engine Development



HCB Demonstration Engine



Engine Level Technologies

- ORSC is Overarching Technology
- US Derived High Strength Ox Resistant Material

Ox Rich Preburner

- Combustion Stable Injector
- Uniformly Mixed Ox Rich Gas

Turbopump Assembly

- Integrated Design
- Long Life Turbine
- Long Life Interpropellant Seal
- Integrally Damped Bearings

Thrust Chamber Assembly

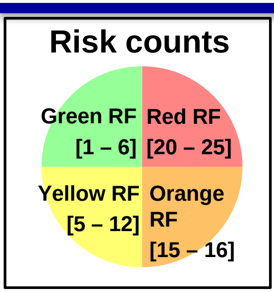
- High Performance, Combustion Stable Injector
- Tailored Cooling

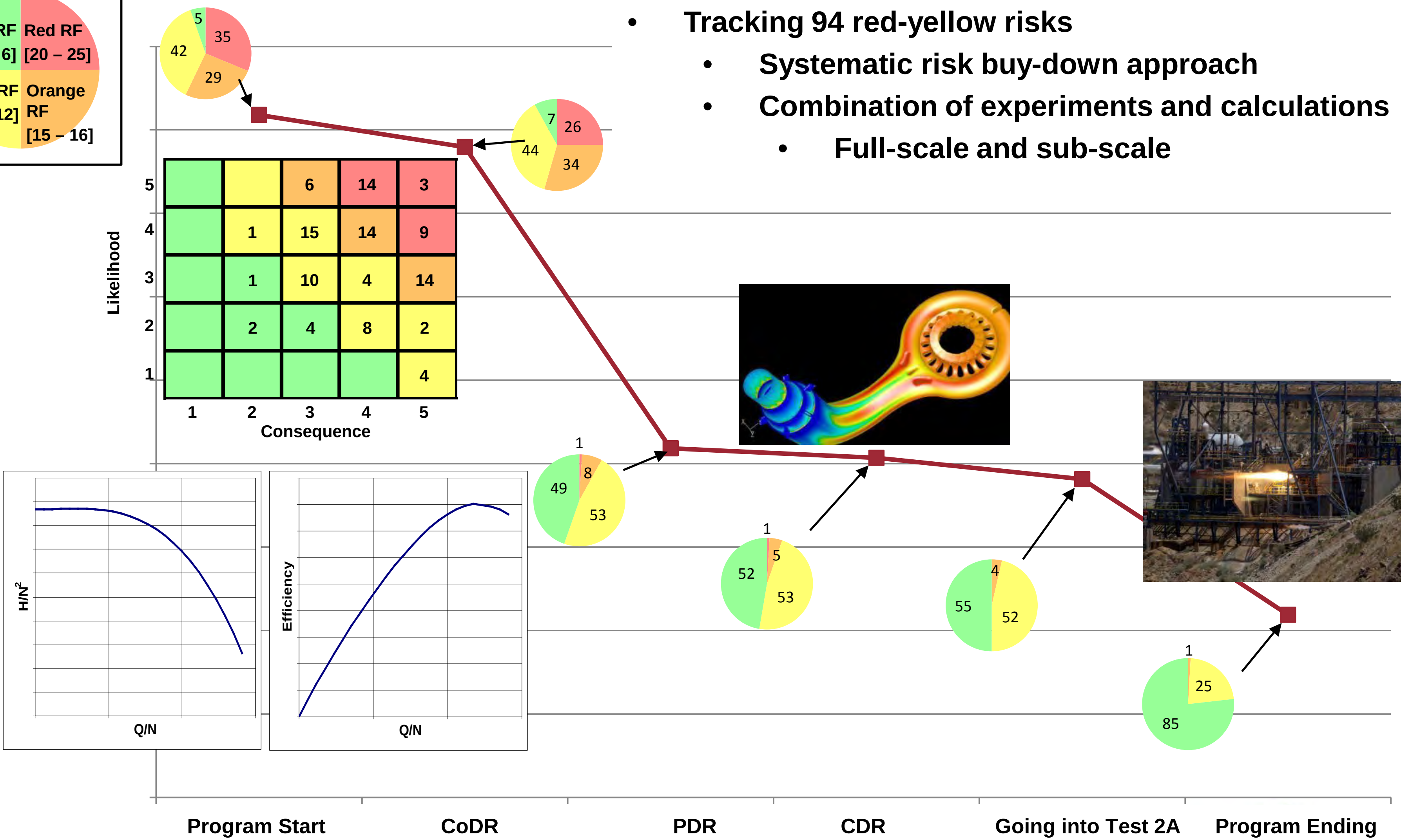
Reusable Liquid Rocket Engine tech
Reusable & expendable rocket engine tech

Technical risk buy-down plan

Within HCB

- Thorough Risk Evaluation Process
- Tracking 94 red-yellow risks
  - Systematic risk buy-down approach
  - Combination of experiments and calculations
    - Full-scale and sub-scale





Likelihood \ Consequence	1	2	3	4	5
5			6	14	3
4		1	15	14	9
3		1	10	4	14
2		2	4	8	2
1					4

NASA/AFRL Collaborations

Collaborations

Project	AF Program
Water Rig Testing	HCB
Aero-spike Nozzle Testing	3GRB
Real Time Vibrational Monitoring System	USET
Ox rich Preburner Combustion Stability Assessment	HCB
ALREST	HCB
Promoted Combustion Testing & Oxygen Compatibility Assessment	HCB

Leveraging technical expertise for oversight

Project	AF Program
General Fluid System Simulation Program	HCB
Technical Advisors	USET/HCB
AFRL Turbomachinery Independent Review Board Members	USET/HCB

Hydrocarbon Boost
Key Supporting Technology Efforts

Materials
- CRAD: AFRL/RX, PWR, Aerojet, Questek
- SBIRs: Synertech, CalRam
- In-House: On-site contract support

Fuels
- Fuels
- CRAD: NIST
- In-House: RZSA
- Academia: Stanford

Health Management
- CRAD: FTT
- SBIRs: Wask,Turbosolutions, FTT, Frontier tech, Impact

HC Boost Components & Demo Engine
CRAD: Aerojet, FTT

Combustion Stability
- CRAD: Aerojet, PWR, STA
- SBIRs: Metacomp, In-Space
- Academia: UTenn Chattanooga, Purdue, Penn State

Cavitation
- SBIRs: FTT, CRAFT, Barber Nichols
- Aerospace, CFDRC
- Academia: Clarkson

Injectors & Igniters
- SBIRs: Orbitec, Sierra
- In-House: RZSA
- Academia: Penn State, Purdue, Navy Post Grad School

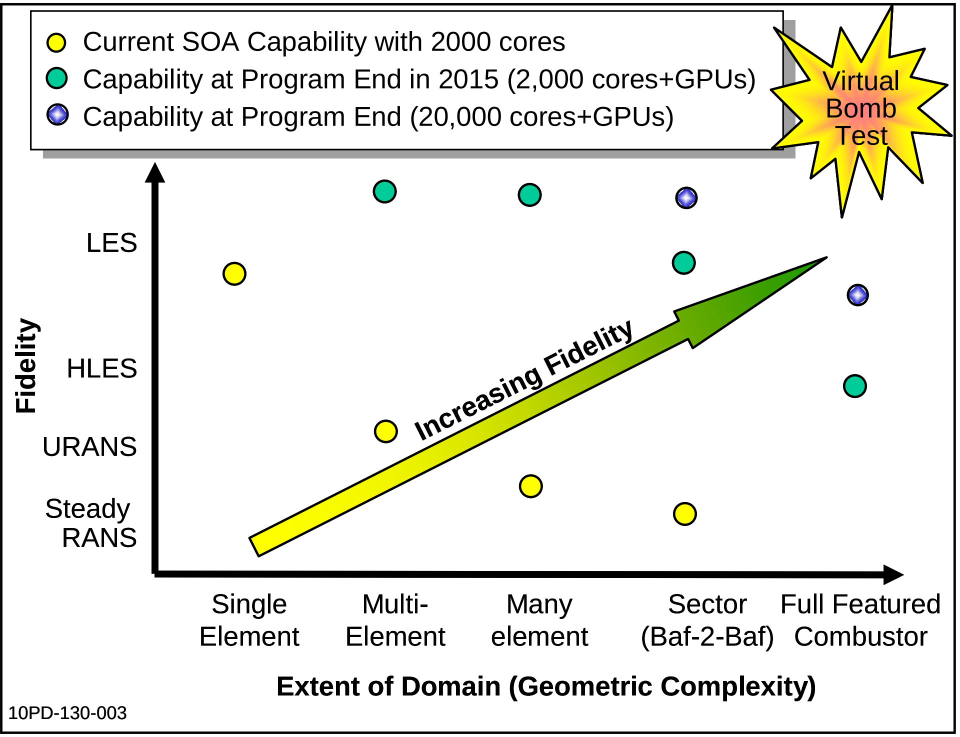
Additional Risk Reduction
Combustion Instabilities

- Combustion instabilities are a key risk to any rocket engine development program
- Can be extremely destructive and can destroy the engine and the test stand
- Complex interaction between many phenomena

Destructive Instabilities

Advanced Liquid Rocket Engine Stability Technology (ALREST)

Develop a suite of multi-scale combustion stability models



Combustion stability is high risk

ALREST program models key physics

- **Kinetics**
- **Hydrocarbon mixtures**

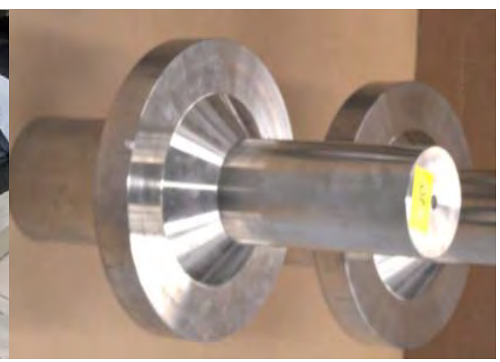
Tools developed can be extended

- **Military and commercial rockets**
  - **Solid and liquid**
- **Gas turbines**
  - **Flight and land based power**
- **Other combustion systems**

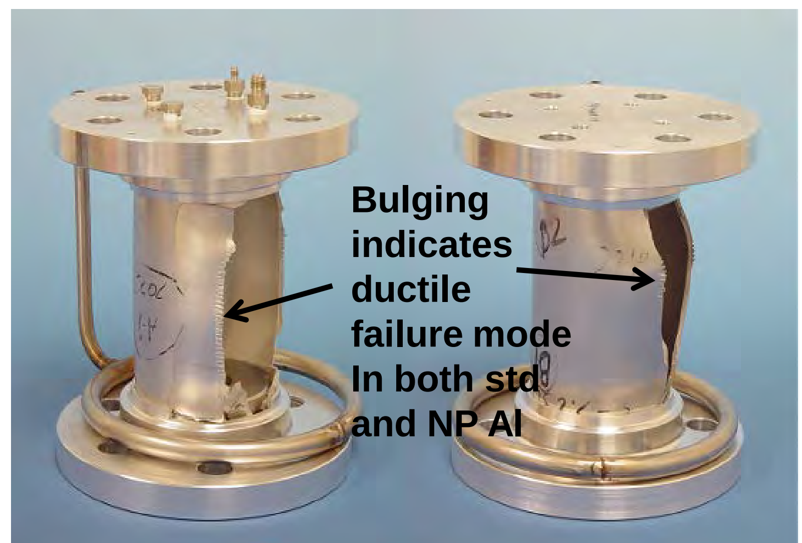
Multi-scale physics based modeling mitigates combustion stability risk and reduces development costs

Additional Risk Reduction
Materials Research

- **Spearheaded development of Mondaloy™, a new, high strength, oxygen compatible metal**
  - **Required for reusable high pressure ox-rich staged combustion engine**
- **Spearheaded development of nano-aluminum which has greater strength than typical aluminum alloys**



Full-scale turbine housing & high speed rotor



Conclusions

- **AFRL/RZS is leading the development of the next generation of rocket engine technology**
  - **Drive towards model driven development**
  - **Strong emphasis on Systems Engineering**
  - **Working both cost and technologies**
- **Pursuing performance and operability goals in support of Air Force space access (expendable or reusable)**
  - **Critical tech for high performance domestic ORSC liquid rocket engine**
  - **Program goals defined by DoD, NASA and industry partnership**
  - **Strong focus on systems engineering**
  - **Periodic data transfer to industry throughout the program**
  - **Collaborations with NASA fully leverages domestic expertise and facilities**