"Advanced Solid Fuel Ramjet Demonstrator"

Coalition Warfare Program

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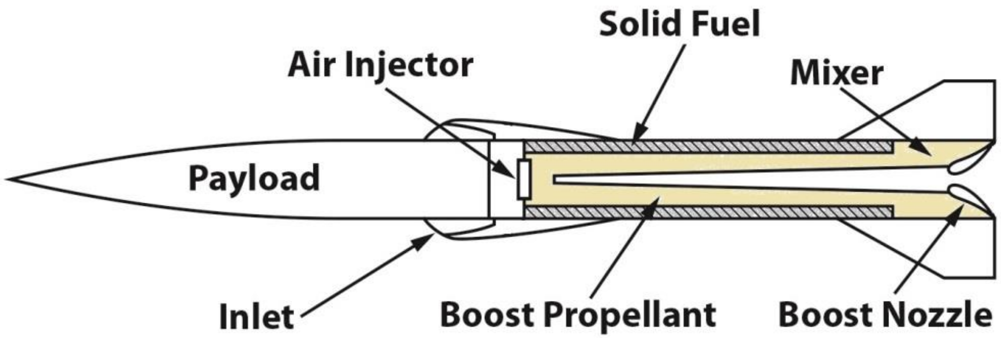
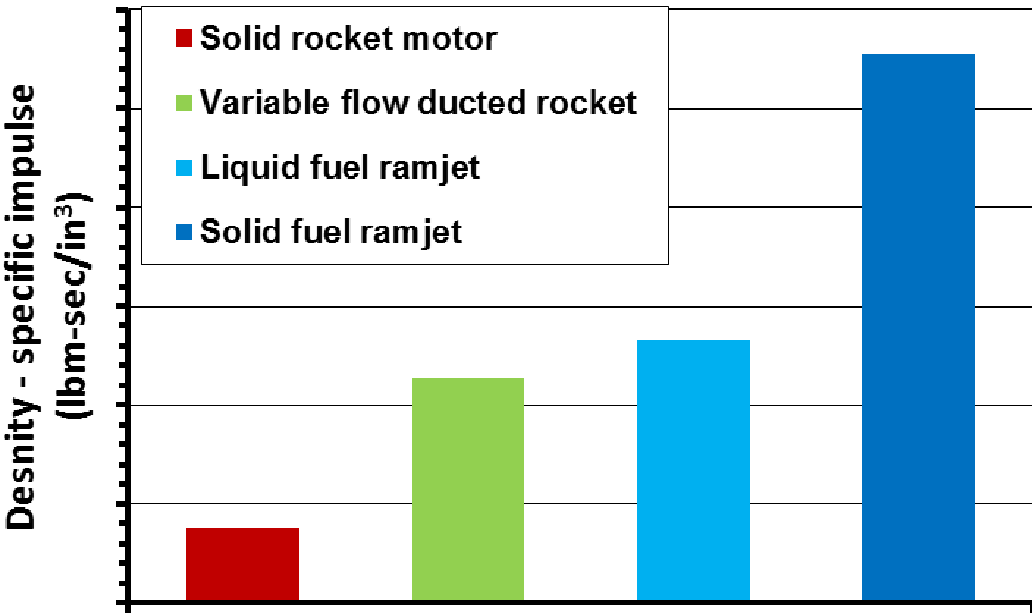
Project Motivation: Long Range Propulsion

- Density specific impulse (ρ*Isp) is an indicator of range potential for propulsion systems
  - Thrust per fuel mass flow rate
- SFRJ have greatest range potential. Solid metalized fuels have higher energy density than liquids (JP-10)
- SFRJ are mechanically simple and can readily be scaled over tactical sizes (Recent 3.0" flight demonstrated at NAWCWD)





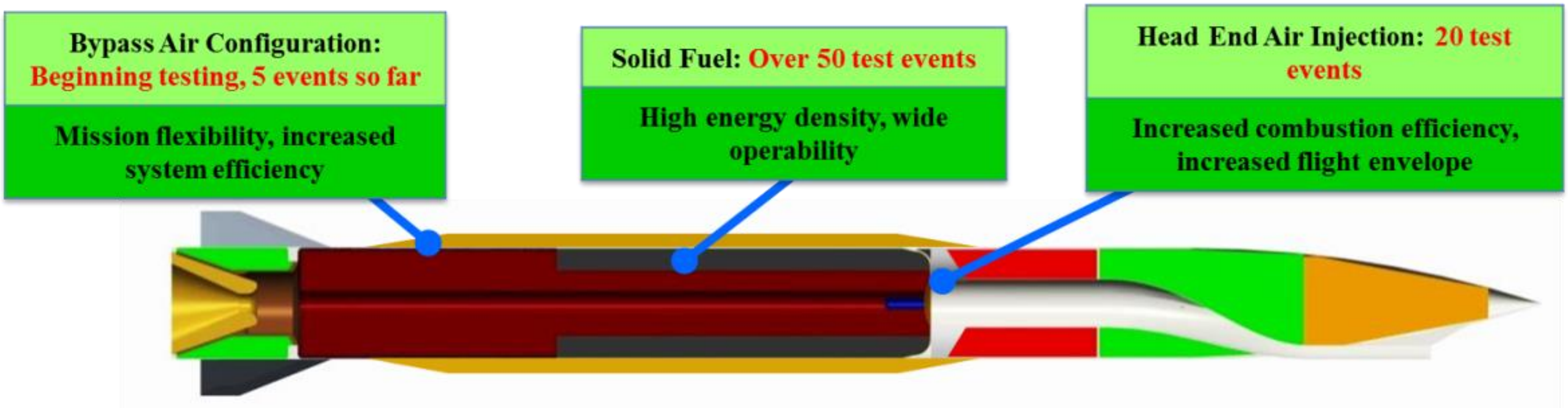
Strategic Partners

Goal:

US Navy/Norway project to develop a high-performance Advanced Solid Fuel Ramjet (ASFRJ) demonstrator which enables a 2-4x increase in range over current Solid Rocket Motor (SRM) systems

SFRJ System Design

- Design is 10” diameter propulsion unit featuring
  - Advanced air injection techniques
  - Next generation, high energy-density solid fuels
  - Bypass air configuration
- The project will culminate in mission trials of the SFRJ combustor at NAWCWD T-Range (full size, long duration tests)



Solid Ramjet Fuel Heritage

Soviet Union
White phosphorous

German
Crushed coal
& oxidizer

NACA (NASA) & NOTS
Mg with $NaNO_3$

US Navy and Army
Mg-Al alloy with
oxidizer

NAWC
CROW
boron & oxidizer

US ARMY
No oxidizer,
all HTPB/CLPS

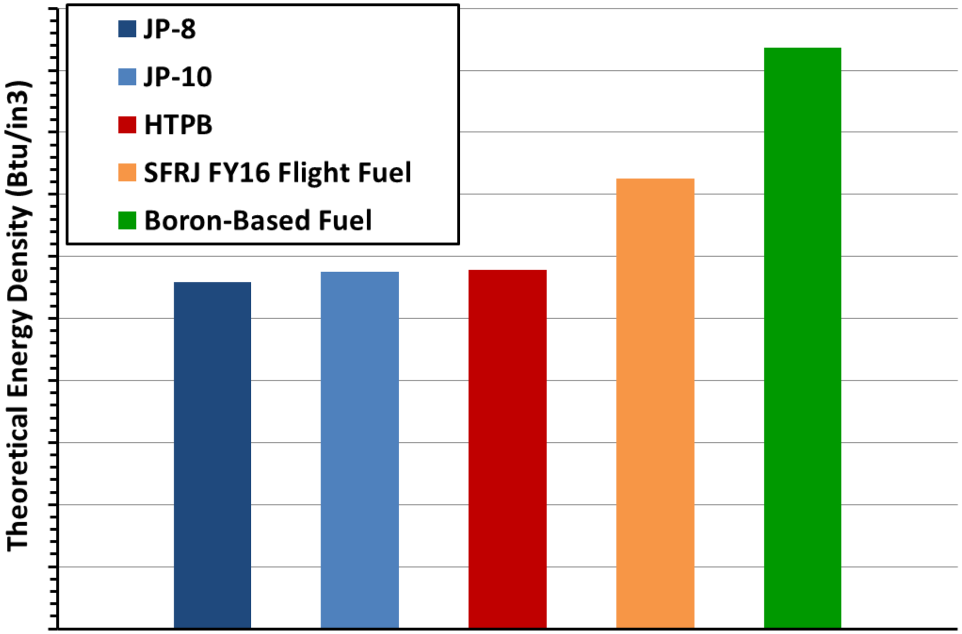
NAWCWD
Boron-based

1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

CWP SFRJ Fuel Development

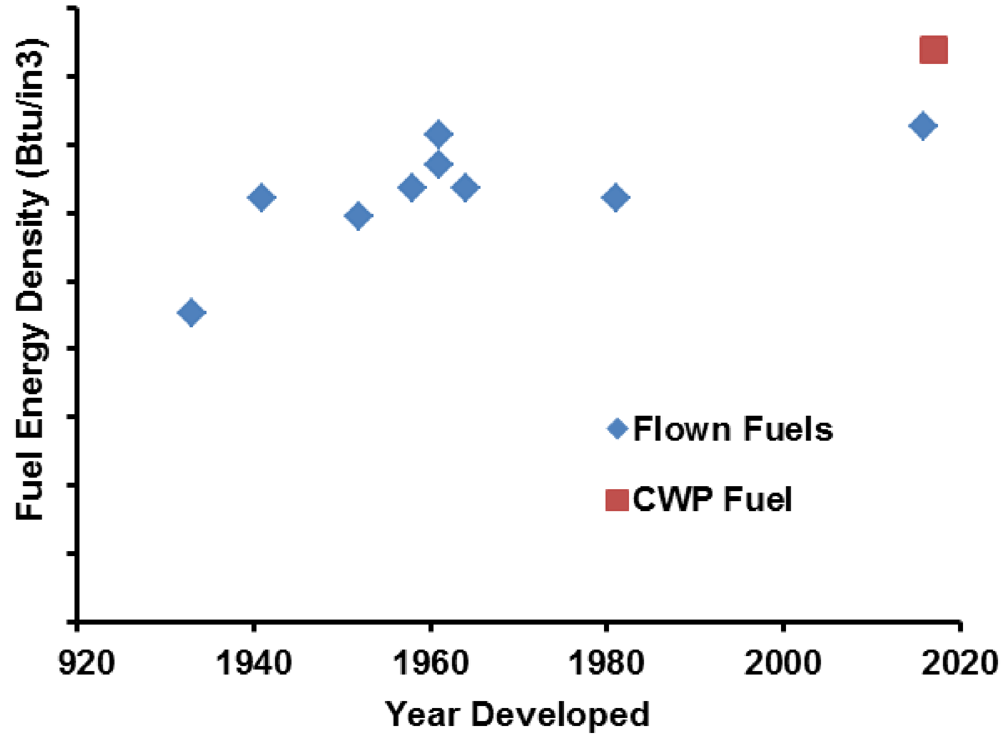
- Goal: Develop solid fuels for ramjet application that have the potential to greatly enhance the range capability of tactical missiles for the Navy
- Boron is attractive ingredient for SFRJ application due to its energy density
  - Only beryllium comes close, boron still is 10% higher volumetric energy density
  - 64% higher than aluminum, 83% higher than silicon
  - ≈4x the volumetric energy density of gasoline, Jet-A, kerosene based fuels

Boron is domestically sourced, has wide commercial applications, and is a trace element of our diet.



Where we stand: SFRJ Flight Tested Fuels

Boron-containing flights



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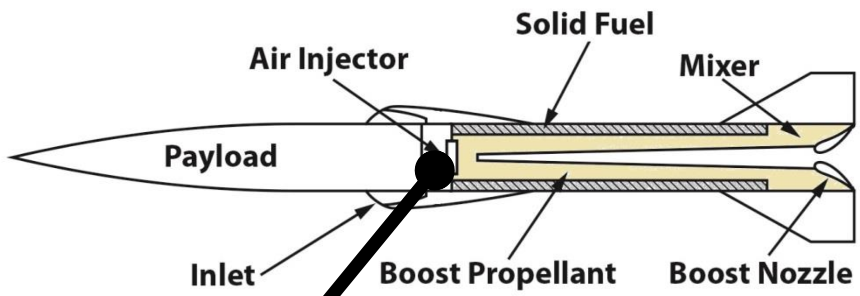
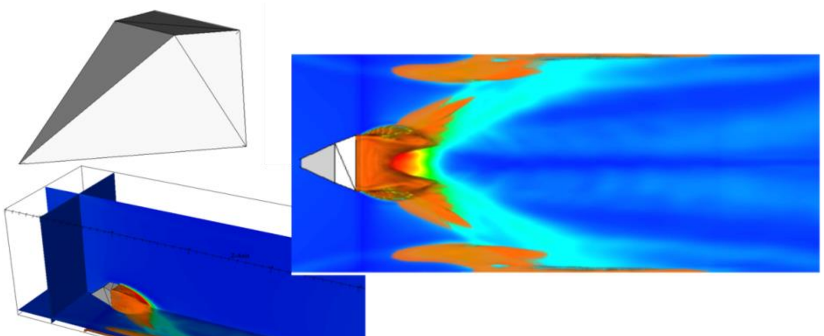
Head-End Air Injection Techniques

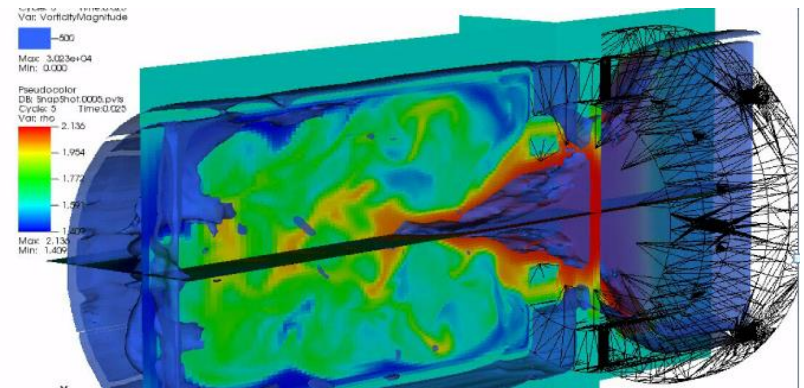
- Over 21 various geometries have been investigated
  - These unique shapes increase mission flexibility by expanding flammability limits and flame holding
  - Design for increased mixing increases SFRJ performance

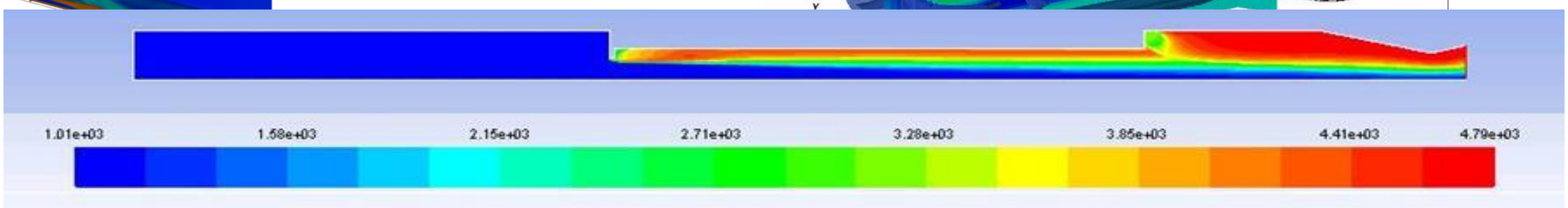


Head-End Air Injection

- Both modeling and ground testing have confirmed increased flame holding
  - Enables more solid fuel loading in the combustor (more range)
  - Using computational fluid dynamics and ground test data, we have developed and 3D printed air injectors that enable both wide ramjet operability envelope as well as a higher solid fuel loading in the combustor

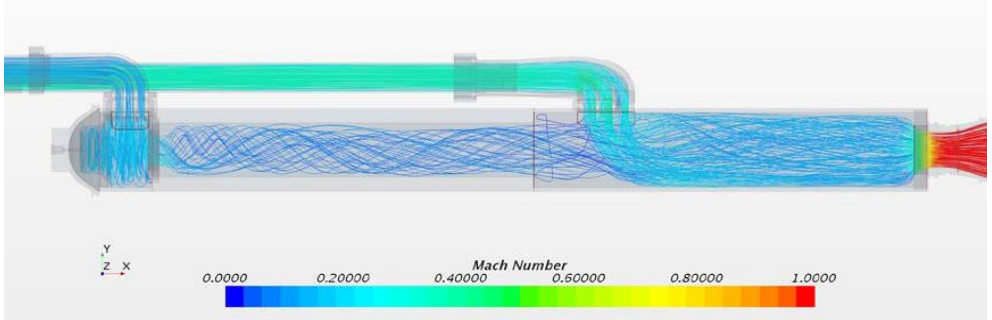






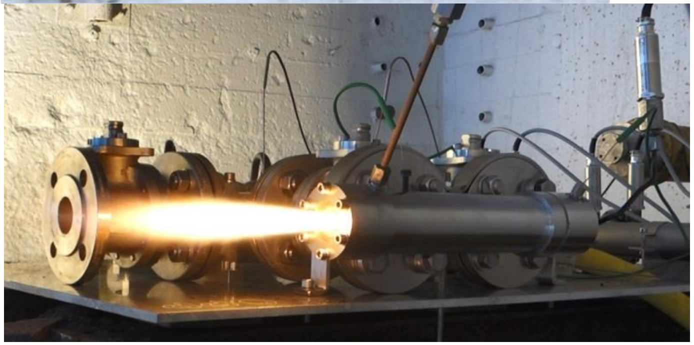
Bypass Air Injection

- We are developing a throttle-able SFRJ using bypass air injection
- More by-pass:
  - Higher thrust, accelerate/climb conditions
- Less by-pass:
  - Lower thrust to conserve fuel, supersonic cruise conditions

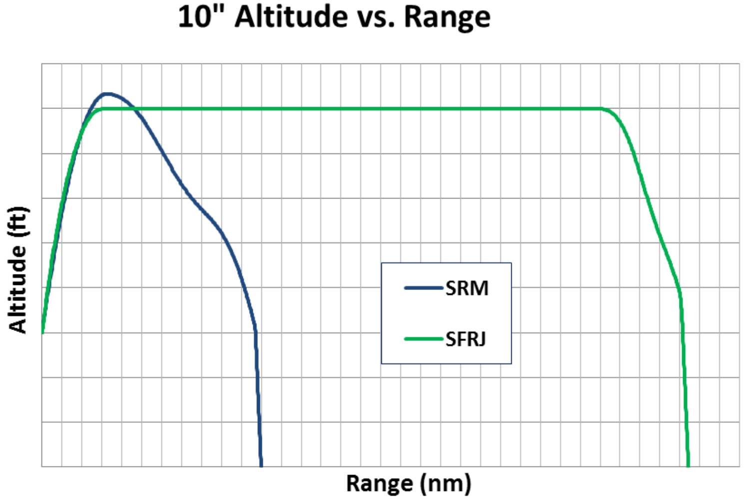


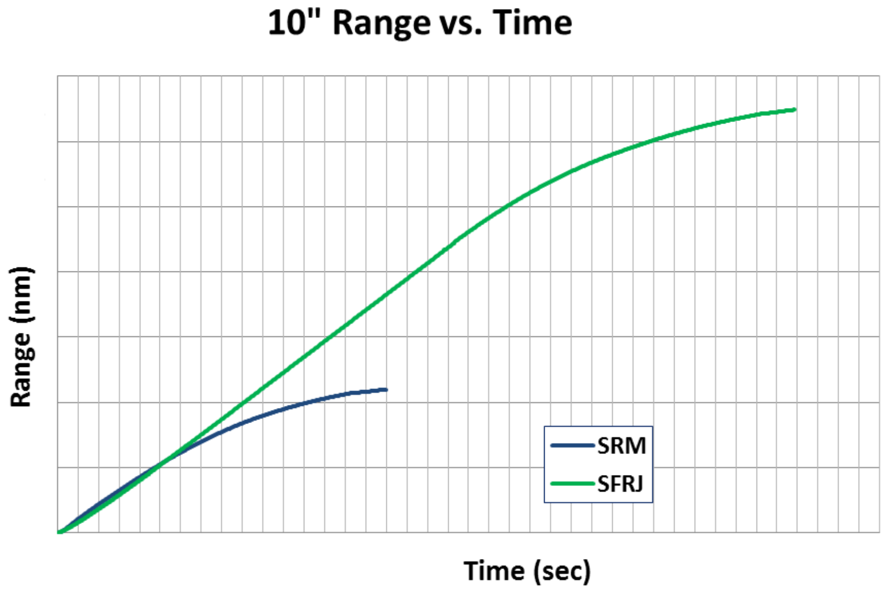
Ground Testing → Flight Predictions

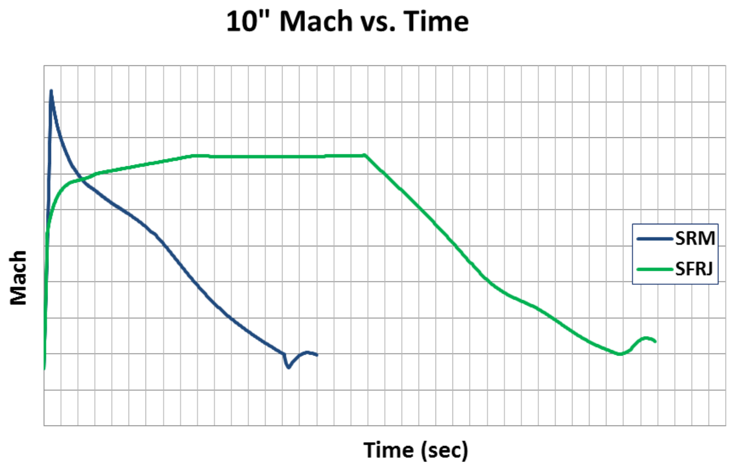
- We are developing trajectory analysis tools based on over 100 ground test events at NAWCWD and a similar number in Norway



Air-Launched Comparison (SRM vs. SFRJ)



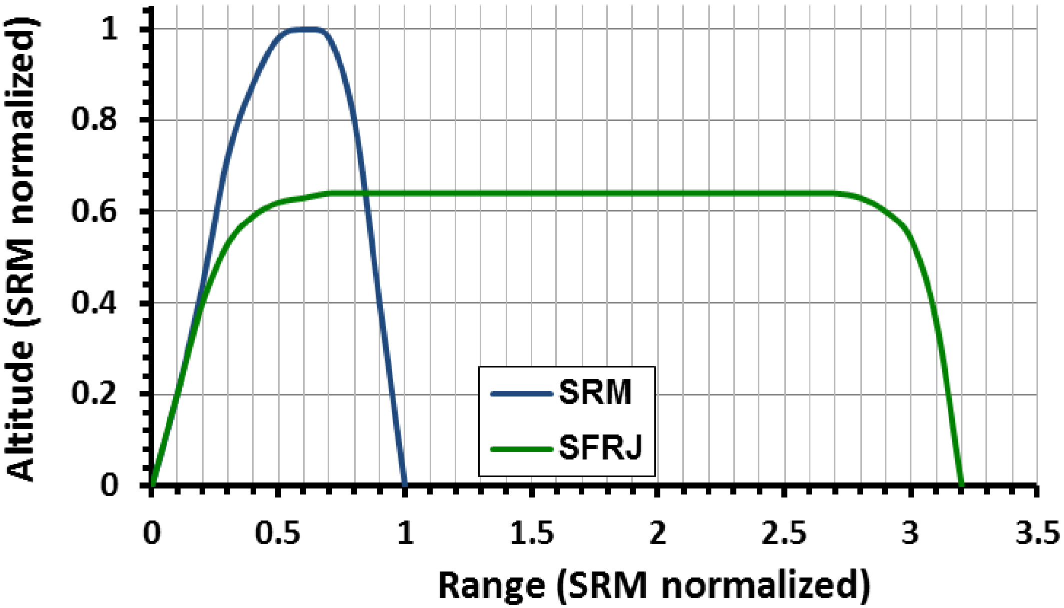




We consistently predict 3-4x range over SRMs based on our ground testing results.

SFRJ Progress: Mission Definition and Fly-outs

- Our predictive capability improves as we gather test data
  - ~500 engine firings at NAWCWD have been completed over the last two years
  - Eight flight tests
- SFRJ technology offers >3x range over comparably sized SRM



Recent fly-out for 10-inch SRM vs. SFRJ for surface launched application.

Questions?