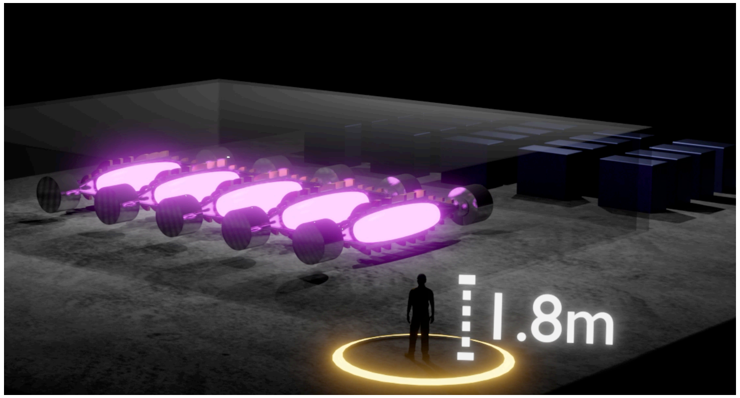
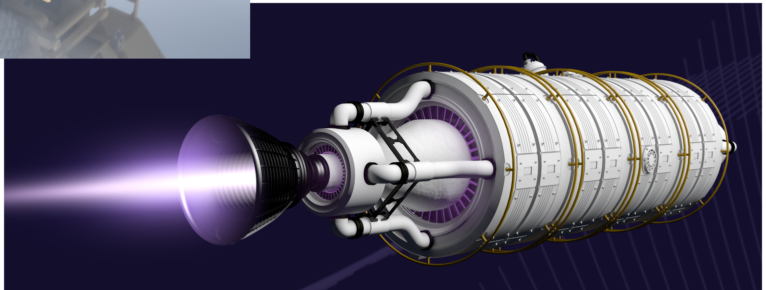
Fusion Forward Power

Portable Fusion Microreactors

PFRC on a HEMTT



5-unit PFRC power plant



PFRC fusion rocket

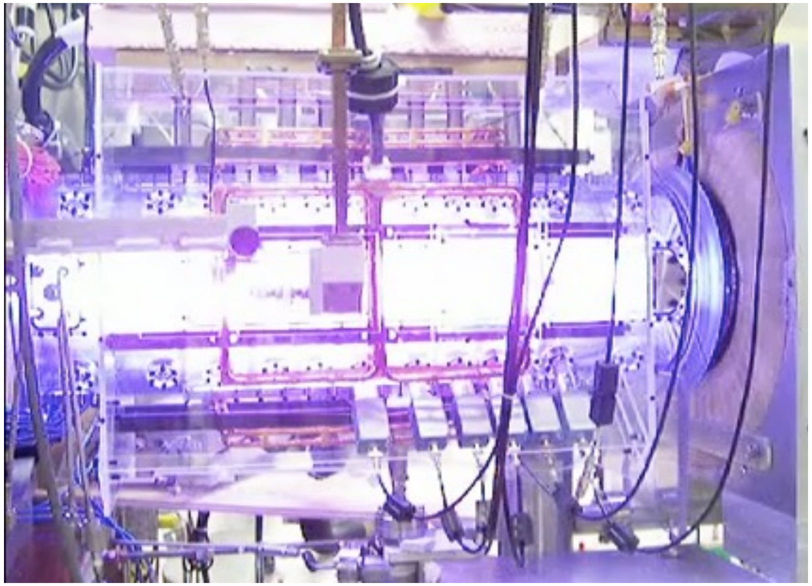
There is a critical military need for forward and deployable power in the 1 MWe range

Princeton Field-Reversed Configuration (PFRC)

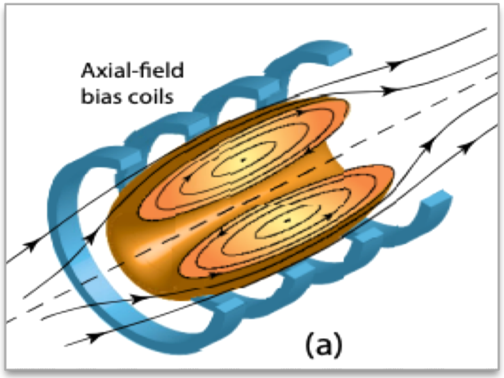
SIMPLE, SMALL, CLEAN FUSION MICROREACTOR

Patented RF heating method for the lowest possible radioactivity reactors.

- **1-10 MW microreactors**
- High-β FRC for **clean operation**
  - High-β means high temperatures with modest magnet size
  - Use of **D-^{3}He** (clean fuel)
  - No tritium breeding
- Experiment at Princeton Plasma Physics Laboratory
  - DOE, ARPA-E support > 10 years



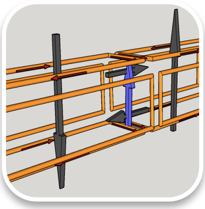
PFRC-2 in operation at PPPL



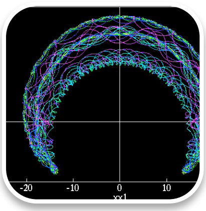
FRC plasma& magnet configuration

PFRC Key Innovations: RMF_o and Shell Flow

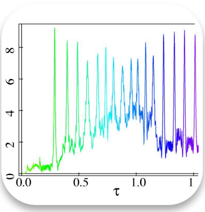
RMF_o: heating *and* confinement



Current forms FRC: closed field lines



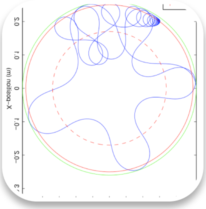
Push/pull cycles



Explosive heating

Single steady-state heating method with no moving parts performs both heating and confinement

Shell flow: remove ash



Cool and capture ash < 10 ms

~~D + T~~

Prevent T fusion

~~n (14.1 MeV)~~

Prevent neutrons

Shell flow captures fusion energy efficiently and reduces radiation production

Why the PFRC Fusion Reactor for the Battlefield?

VALUE PROPOSITION

- **Low cost – Under $10M/reactor**
  - SMRs will be more expensive to develop
- **Clean & Safe - No highly radioactive materials**
  - PFRC is not a radioactivity hazard
    - A destroyed PFRC has some mildly activated material
  - No uranium or plutonium – No potential to be made into a dirty bomb
  - No nuclear proliferation
- **Fast - Time to a production machine 10-12 years**
  - Similar to realistic time frames for SMRs
- **Reduce Casualties from Fuel Resupply**
  - Currently 0.042 casualty factor for fuel resupply convoys
  - Annual or less fuel supply/maintenance for PFRC
- **Scalability risks (heating) retired with PFRC-3**

Soviet SMR technology abandoned

Much like the author's Dad's heavy artillery battery in Korea – SMRs will be prime targets

Hummer military EV

Many Markets for Fusion Microreactors

*PFRC will produce **1-10 MWe** per mini-van size reactor, with almost no radiation.*

Military Terrestrial

- Forward deployment
- Remote locations
- Submarines
- Upper atmosphere cruise vehicles
- Large UAVs
- Distributed power on surface ships

Civil

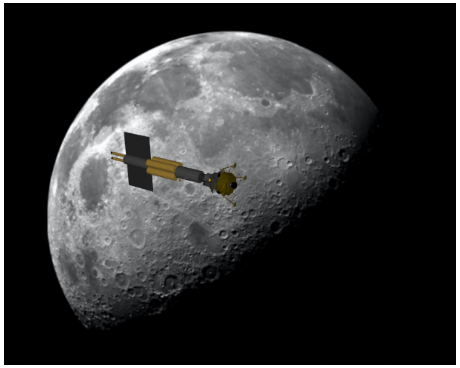
- Distributed and remote power
  - Manufacturing, mining
  - Off-grid towns
- Mobile and emergency power
  - Hurricanes: Puerto Rico
- Modular power
  - Low capital cost power plants

Space

- Deep space missions
- Lunar/Mars bases
- Asteroid/comet intervention
- Space platform power
- High power satellites
  - Earth observation
  - Communications

PFRC on an HEMTT for Forward Power

Off-Grid Power



Lunar Transport

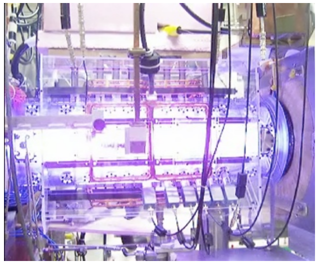
Path to PFRC Fusion Plant

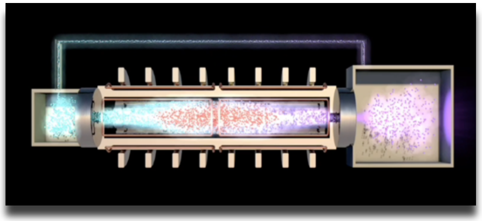
COMPLETED:
Heated electrons with RMF_o in PFRC-1
Met: 0.2 keV
$2M non-diluted funded

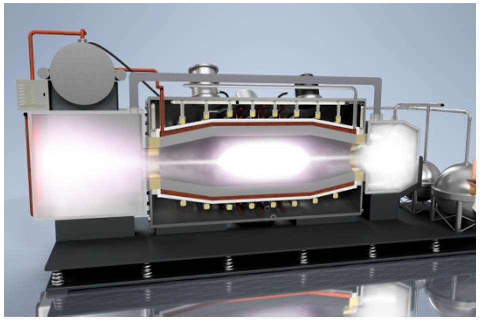
IN PROGRESS:
Heat ions in PFRC-2
Goal: 1 keV
$8M non-diluted funded

DESIGN UNDERWAY for PFRC-3:
Achieve fusion temps [10 keV] via superconducting magnets
Triple product ~10^{18} s-keV/m^3
Requires $40M

PLAN for 2030:
Goal ~1 MW D-^{3}He fusion, net electric power [80 keV]
Requires $60M







Proof of concept merits private investment

Value inflection from proof of principle

Low-cost, low-radioactivity fusion reactors

$10M funding to date from DOE, NASA, IR&D

$150M est. total to net energy

Power Generation Projections - ^{3}He Supply

Near Term

- Terrestrial ^{3}He
  - CANDU, weapons
  - Li rods
- ~50 MW/year

Mid Term

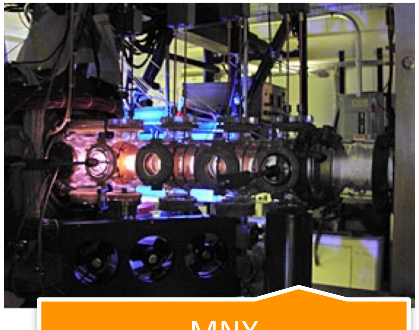
- ^{3}He from natural gas
- ~1.5 GW/year

All military needs can be met with domestic production

Far Term

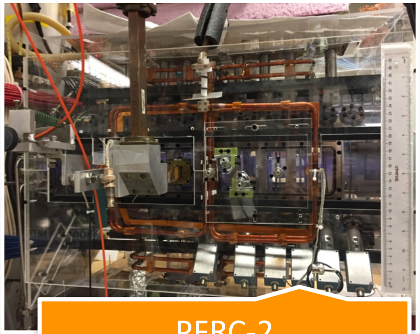
- D-D breeding reactors, or
- Moon/Gas Giant mining
- > TW

PFRC Prior Contractual Support with PPPL

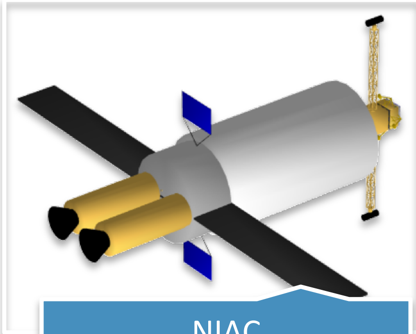


MNX
DOE 1998-2015

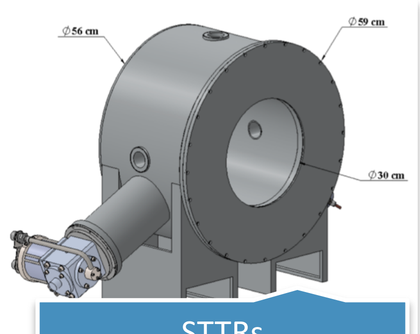
PFRC-1
DOE FES 2002-2009



PFRC-2
DOE FES 2010-2016

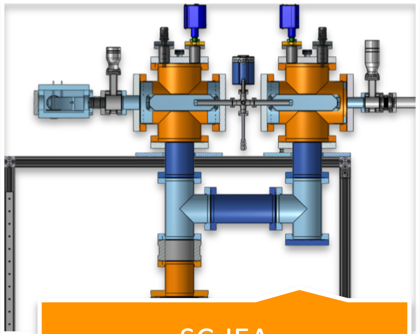


NIAC
NASA 2016-2019



STTRs
NASA 2017-2020

ARPA-E OPEN
2019-2021



SC-IEA
DOE 2019-2021

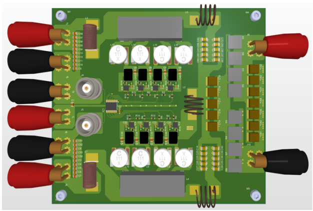
GAMOW
ARPA-E 2020-2023

PPPL-led projects

PSS-led projects

Current Status Development Needs

- PFRC-2 currently operating at PPPL
  - Bulk T_e ~ 200 eV, target T_i ~ 500 eV, maximum field 0.1 T
- PFRC-3 program estimate: **$40M over 5 years**
  - Maintain PFRC-2 as a training facility until PFRC-3 is operational
  - Retire risk in RMF_o heating method
  - Achieve fusion-temperatures plasmas with lowest cost
    - 10x higher magnetic field than PFRC-2 via superconducting magnets
    - Use H fuel
    - Compute D-T equivalent gain
- PFRC-4 program estimate: **$60M over 5 years**
  - Total program cost to net energy ~ $150M
- Early revenue from power electronics product line supported by ARPA-E contract



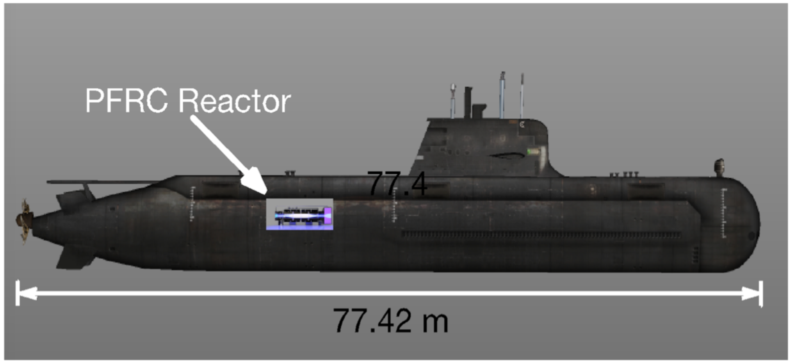
Military Applications Examples

- **Small, portable microreactors can be installed anywhere**
- **PFRC would support long-duration missions requiring reliable, portable power over weeks or months**

Defense Applications: Naval and Space

Submarines

- PFRC would enable a new class of small, extremely long-duration submarines
- Applications are small (smaller than diesel) attack submarines
  - Autonomous underwater vehicles



Diesel submarine example

Extreme Altitude Hypersonic Cruise Vehicle

- For reconnaissance or strike
- Fly lower than satellites
- Unpredictable trajectory

Extreme Altitude Hypersonic Cruise Vehicle powered by PFRC
Image courtesy Captain Ryan Weed, USAF

Defense Applications: Ground and Air

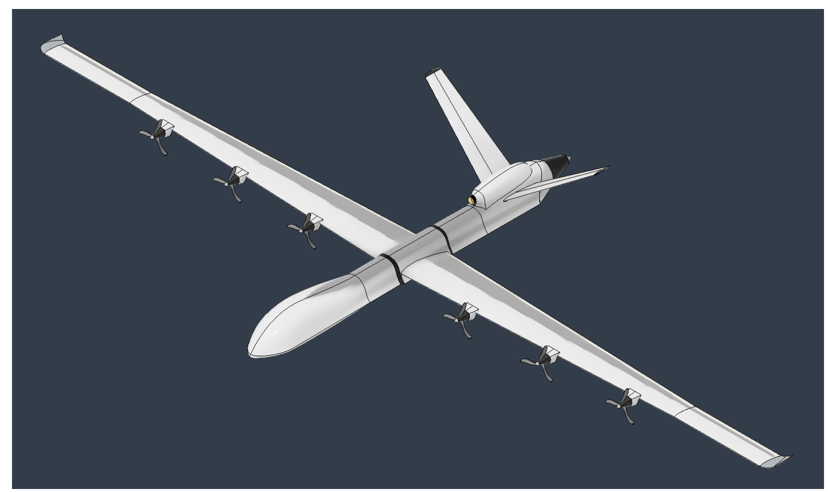
Ground Forces

- PFRC supports the all-electric battlefield
- Forward power for Army brigade combat teams
- Reduce casualties from fuel-related convoys

Hummer military EV

Long-Duration Aircraft Missions

- 1 MW PFRC for the Reaper
- Long-duration missions of 1 month
- Power for laser-armed drones



Conceptual 6-Propeller MQ-9 REAPER

Defense Applications: Marines and SOCOM

Marine Expeditionary Units

- Forward power for Marines
- 1 MW for Landing Craft Utility
- Amphibious Combat Vehicles deployed farther from shore (> 12 miles)

Electric amphibious armored vehicle

Special Operations Command

- Long-duration missions
- Can get into submersibles 100 miles from shore
- Small submersibles for special forces

SEAL Delivery Vehicle on an attack submarine

Letter of Support from DIU

PFRC proposal for DIU evaluated positively for their Area of Interest, Nuclear Advanced Propulsion and Power

DEFENSE INNOVATION UNIT

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https://www.diu.mil/

Letter of Support – Princeton Field Reversed Configuration (PFRC) Fusion Reactor

To whom it may concern,

I am writing a letter of support for funding of the Princeton Field Reversed Configuration (PFRC) fusion reactor under development by Princeton Fusion Systems (PFS). PFRC was recently evaluated by the Defense Innovation Unit (DIU) for their Area of Interest, Nuclear Advanced Propulsion and Power (NAPP). PFS' proposal received high marks from all reviewers. Due to the development time frame of ten to fifteen years, it was not within DIU's charter to deliver technology to the warfighter in three to five years.

As a Program Manager, Physicist, and active duty USAF officer I can attest to the military utility of the PFRC powered spacecraft concept under consideration. Advanced propulsion technology is essential to expanding the capabilities of spacecraft, allowing for orbital changes, methods to control or facilitate de-orbit, transfer of materials between orbits, and other missions. Current state-of-the-art in-space propulsion systems based on chemical or solar power fail to meet requirements of 21st century DoD space missions. The DoD needs a propulsion and power system that can scale to medium sized spacecraft, and enables high delta-V and electrical power to payloads. Such a system could provide quicker tactical results, allow for more capable on-board instruments, and allow for persistent and mobile coverage of any region of interest.

DIU was impressed by how compact and powerful the PFRC can be without requiring any exotic technology or materials due to its low radioactivity. It uses superconducting coils for confinement and MRI type coils are adequate for a production machine. The heat engine, used to produce electric power, is similar in size and design to a gas turbine on a small helicopter. The heating system uses only radio-frequency heating and is similar to the stator on an induction motor. The power electronics for the machine are under development as part of the ARPA-E GAMOW program.

The first great power to exploit fusion propulsion effectively for maneuver could have a significant advantage in sustaining space superiority if not supremacy. A Fusion propulsion system would far out-compete nuclear thermal and nuclear electric propulsion on a power density and delta-V capability basis, while offering restart and significant payload electrical power capability. Research and development efforts like PFRC are critical to raising the TRL of promising space technologies.

Warm Regards,

Ryan Weed
Program Manager
DIU Space Portfolio

Accelerating Commercial Technology for National Security

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