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# Free-Piston Stirling Convertor Technology for Military and Space Applications

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Director

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# Examples of Expertise at the SRI

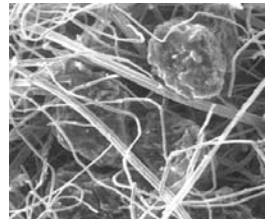
(A blatant marketing pitch)



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★ Generally we have an **applications/product focus**:

- » Radar power system – reformed diesel fuel to 5-9s H<sub>2</sub> for 1 kW PEM FC
  - ◆ Evaluated over 200 catalyst systems; used microfibrinous materials for support
  - ◆ Commercial fuel cell input filter – stops all hazards for PEM FCs (Intramicon)
  - ◆ Demonstrated ~5x reaction rate increase with microfibrinous materials
    - › CO<sub>2</sub> safety mask, biohazard removal and destruction
    - › Can independently vary pore size and porosity with polymer, metal and ceramic matrices
- » Supercapacitors and pseudocapacitors
  - ◆ Ni/C material with high volume, papermaking process
  - ◆ Hydrus RuO<sub>x</sub> pseudocapacitor made with screen printing technology
  - ◆ Hybrid battery/supercapacitor systems for cell phones, etc...
- » Hypervelocity impact facility for space (~10 km/sec, ~100 μm diameter particles)
- » Lightweight space solar array flight demonstration (~300+ W/kg, 8x concentration)
- » Hybrid robotic power systems
- » Space electric “direct drive” propulsion systems
- » High power short pulse emitters for IED destruction and lunar ISRU
- » Electronics packaging and assembly for harsh vehicle applications (reliability)
  - ◆ 1.2 M automatic electric transmission controllers in Chrysler vehicles
- » **Stirling power systems** for CERDEC and NASA





# Outline



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- ★ Why free-piston Stirling?
  - » Description of a free-piston Stirling convertor
  - » Rationale for Stirling power systems
- ★ Background
  - » Previous free-piston Stirling convertor technology developments
    - ◆ 25 kW Space Power Demonstrator Engine (NASA)
    - ◆ Intermediate size 1.1 kW battery charging system
    - ◆ Small 35W to 80 W convertors
- ★ 160 W CERDEC Battery Charging System
- ★ NASA 5 kW Stirling Convertor Assembly (SCA) effort
  - » Contract just issued
- ★ Summary

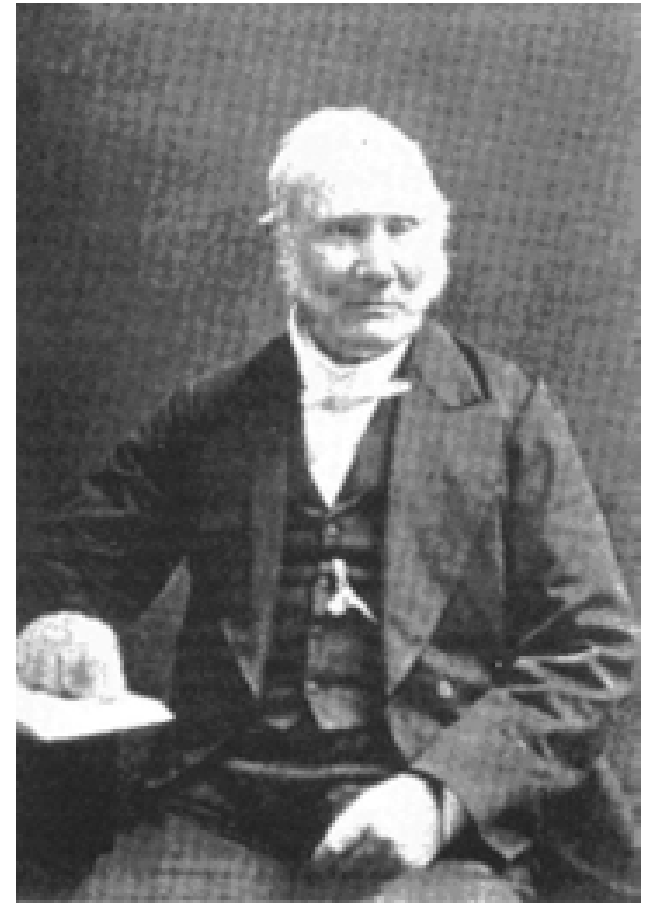


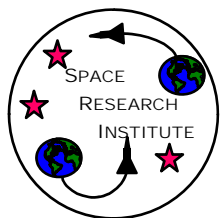
# The Rev. Dr. Robert Stirling



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- ★ Born near Methven, Perthshire, Scotland on Oct. 25, 1790. Died at Galston on June 6, 1878.
  - » Attended Edinburgh University, 1805 to 1808
  - » Enrolled as student of divinity in Glasgow University in 1809 – 1815, was an exemplary student
  - » Licensed as a minister by the Presbytery of Dumbarton on March 26, 1816
- ★ He was the co-inventor of a highly efficient heat engine now known as ***Stirling Engines***
- ★ He also invented a regenerator, which he called the ***Heat Economiser***, that improved engine efficiency.
  - » He obtained a patent for the **economiser**, and the **air engine** incorporating it in **1817**
- ★ In **1971**, William Beale of Sunpower, Inc. invents the free-piston Stirling engine (US Patent #3,552,120
  - » Radical advance over kinematic designs

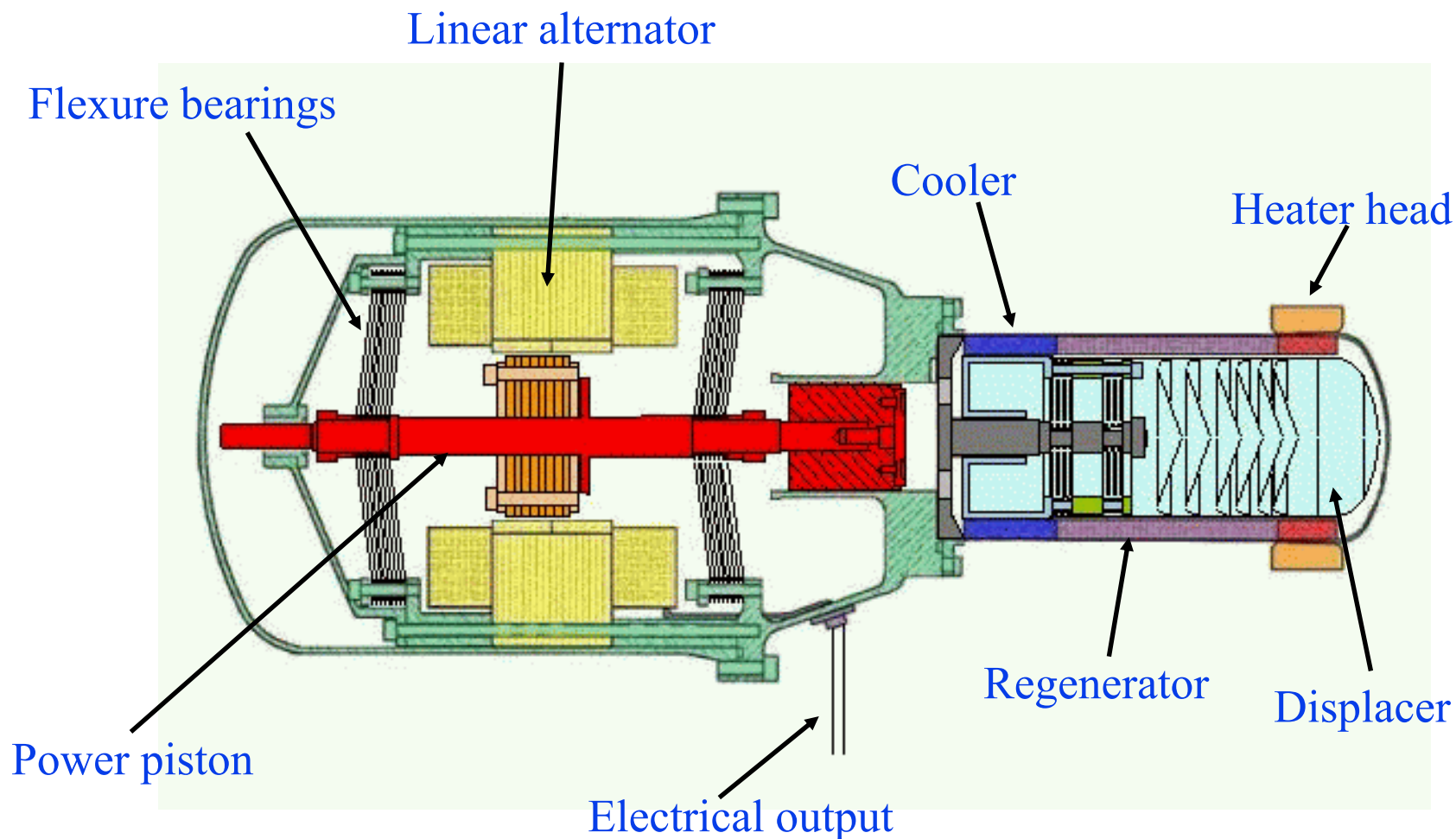


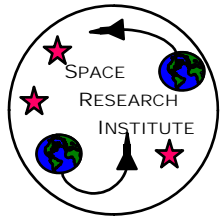


# What's a Free-Piston Stirling Converter?



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# Why Free-Piston Stirling Systems?



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- ★ Only two moving parts
  - » No contact with walls = no wear
    - ◆ Repair life determined by BOS
- ★ Efficiency independent of size
  - » 35 W and 25 kW ~same
    - ◆ Only dynamic system to do this
  - » Any Vac output – easy to convert
- ★ Takes any source of heat
  - » Radioisotopes, nuclear reactor
  - » Diesel, gasoline, propane, biofuels
  - » Sunlight, wood, ammonia, etc...
- ★ Continuous burning flame
  - » No explosions hence it's **quiet**
  - » Clean burning, low pollution



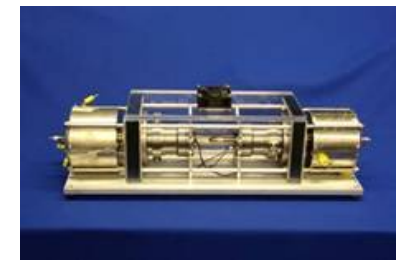
35 W & 80 W FPSC, ~7" and 11" tall, Sunpower, 2006



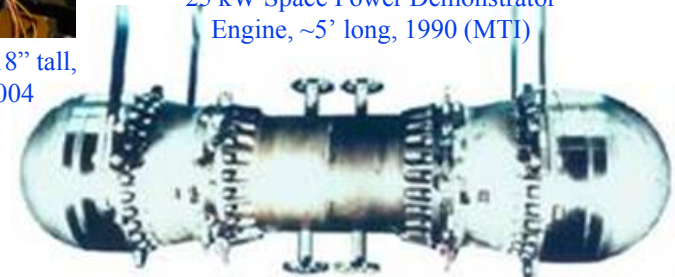
Dual 55 W FPSCs; 2' long, 2002 (STC, now Infinia)



1.1 kW FPSC, ~18" tall, Sunpower, 2004



Dual 80 W FPSCs, propane-fueled, SP 2006



25 kW Space Power Demonstrator Engine, ~5' long, 1990 (MTI)





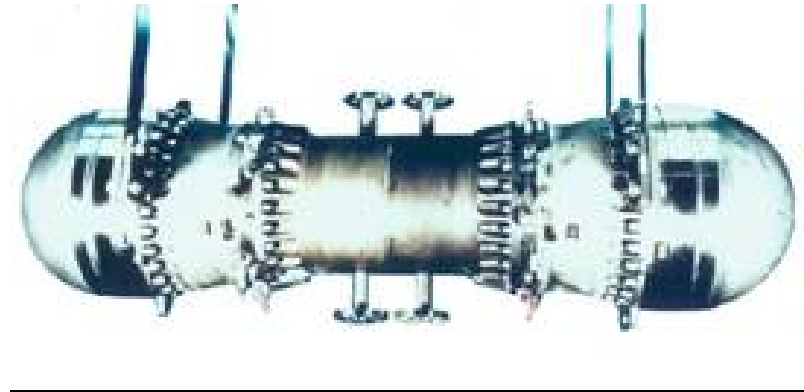
# Free-Piston Stirling Background

## (Large Convertors)



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- ★ SP-100 project, NASA ~1987-1992
  - » **25 kW** free-piston Stirling Space Power Demonstrator Engine (SPDE)
    - ◆ Two **12.5 kW** opposed-piston convertors
    - ◆  $T_h = \mathbf{650\ K}$ ;  $T_c = 325\ K$ ; 25% efficiency
    - ◆ Operated successfully for 1500 hrs
  - » **12.5 kW** Component Test Power Convertor (**Generation 2**)
    - ◆  $T_h = \mathbf{1050\ K}$ ,  $T_c = 525\ K$
    - ◆ One unit built, >20% efficiency
- ★  $T_h/T_c$  ratio of  $\sim 2$  provided the best system level performance in space
  - » Convertor efficiency rises with  $>T_h/T_c$





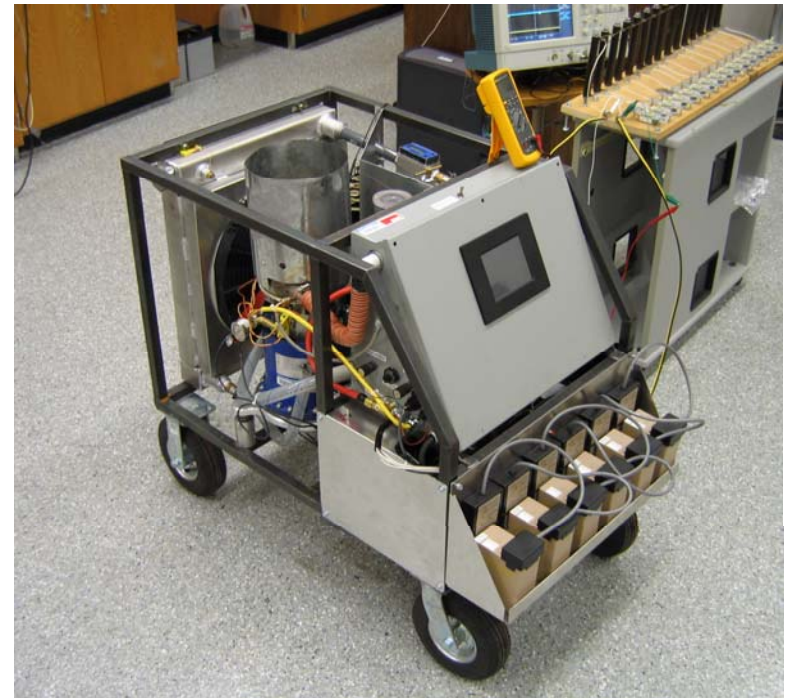
# Free-Piston Stirling Background

## (Intermediate Size Convertors)

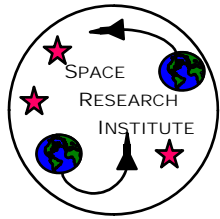


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- ★ ~1.1 kW battery charging system
  - » Auburn/Radiance team
    - ◆ US Army CERDEC supported
    - ◆ Propane-fired demonstrator
  - » Based on 1.1 kW Sunpower cogeneration convertor
    - ◆ Being repackaged to save mass
  - » Charges six BA-2590 Li-ion batteries
    - ◆ Six hours of continuous operation
    - ◆ ~800 total hours operation to date
    - ◆ Automatic system control, dumps excess power as batteries are charged







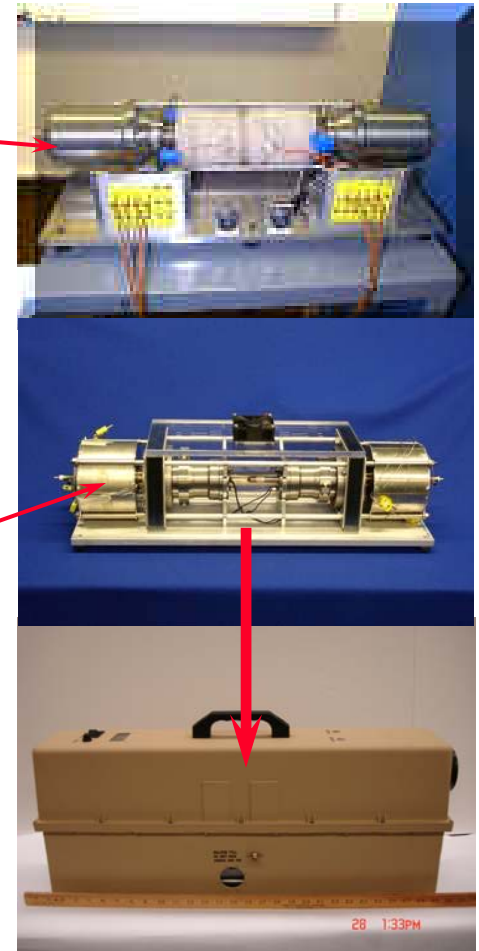
# Free-Piston Stirling Background

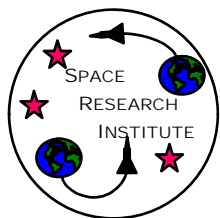
## (Small Convertors)



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- ★ Infinia Corp. Convertors (was STC)
  - » Dual 55 We units aimed at radioisotope systems
  - » Testing at NASA GRC >100,000 hrs total
    - ◆ >25,000 hrs on one pair (still running)
  - » 3 kW under development (low cost goal)
- ★ Sunpower, Inc. Convertors
  - » 80 W units for radioisotope applications
    - ◆ Hermetically sealed units demonstrated
  - » 160 W propane-fueled battery charging system demonstrated for US Army
  - » 35 W demonstrated in DARPA Palm Power program
    - ◆ Diesel-fueled for soldier power
    - ◆ Convertor also operating on H<sub>2</sub> at AU
- ★ There just aren't enough units for new systems





# CERDEC Motivation

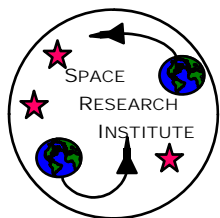


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$\approx 650$  AA batteries used every 5 days per platoon



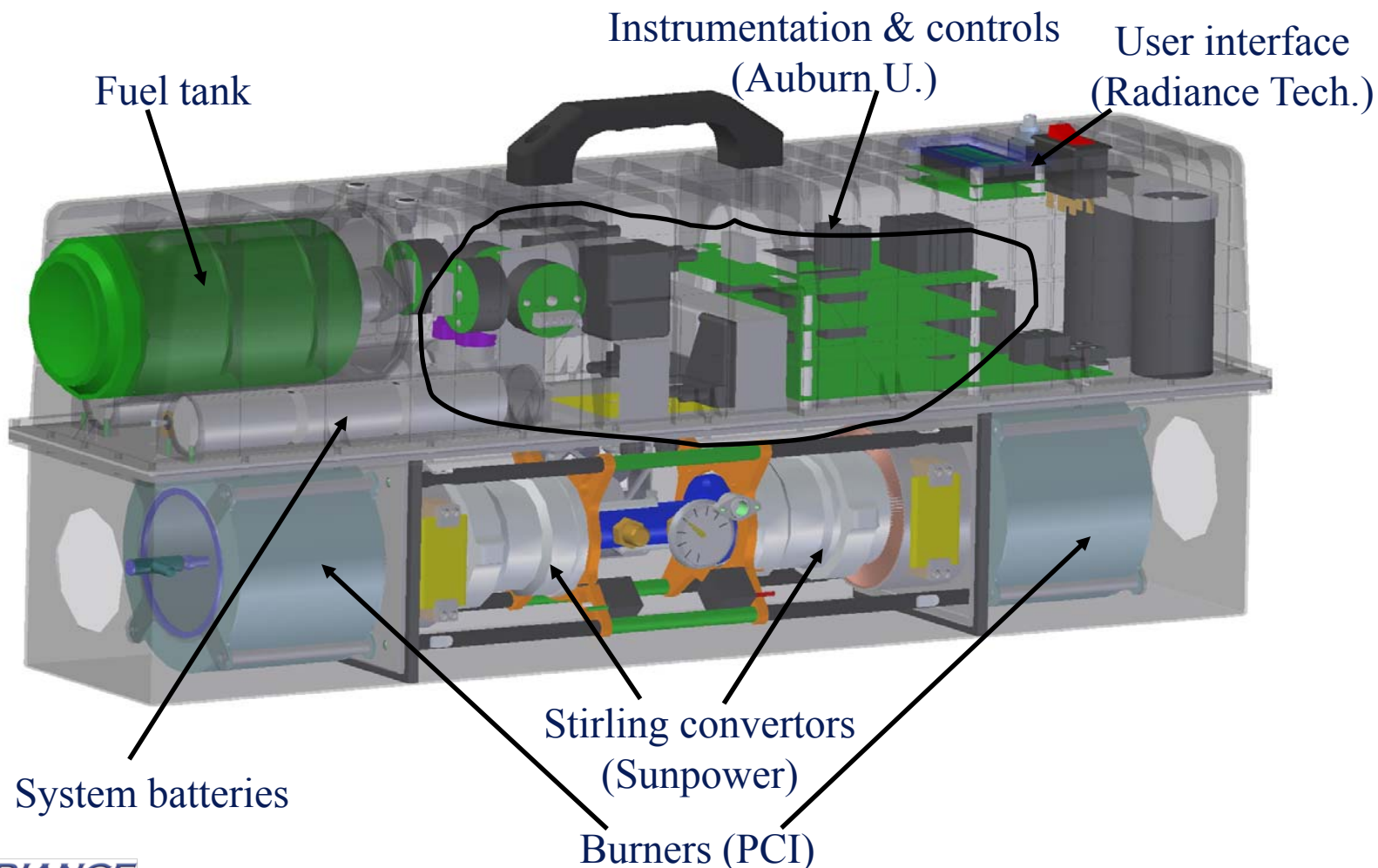
Thus the need for a quiet efficient charging source

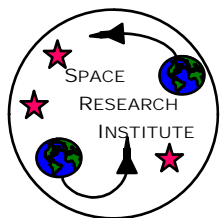


# System Overview with Team



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# Simple To Operate

(...even a cave man could do it)



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## ★ ON-OFF

- » Automatic start-up by pressing **ON**
- » Automatic shut-down procedure by pressing **OFF**

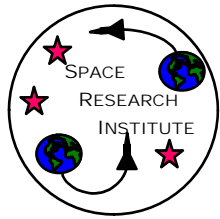
## ★ E-KILL

- » Stalls engines
- » Independent circuit

## ★ Display

- » Engine head temperatures
- » System DC voltage
- » Output load status
- » Error messages



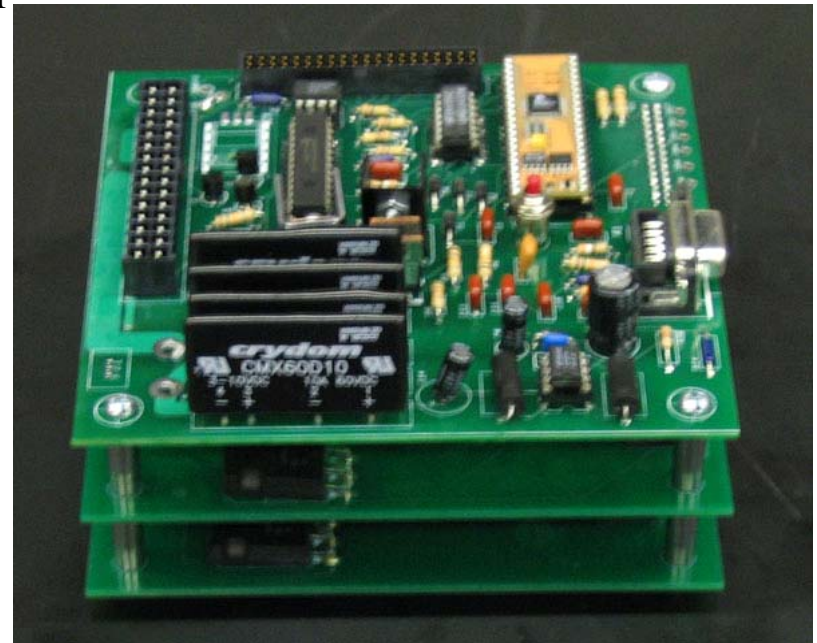


# 160 W Control System

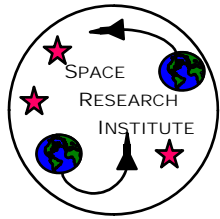


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- ★ FSPC is an inherently unstable system
  - » Uses closed loop, dissipative stroke control
  - » Engine controller limits stroke to 8 mm
- ★ Two independent burner controllers
  - » Start-up and temperature control
- ★ Master controller automatically starts engine and supervises system
- ★ First-ever demonstration of dual-converto, stand-alone, portable Stirling power system
  - » Charges up to six AA-sized Li-ion batteries, 102 W output
  - » Weight: 21.3 kg







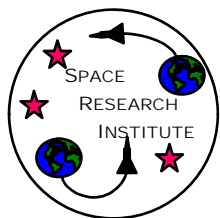
# Balance of Plant



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- ★ A system issue
  - » MTTR depends upon mechanical and electrical/electronic components in the system
  - » Components this size are scarce
- ★ Components
  - » Burner Support
    - ◆ Combustion air pump
    - ◆ Fuel system
    - ◆ Thermocouple interface
  - » Engine Support
    - ◆ Rejector cooling
    - ◆ Helium system
  - » Electrical Support
    - ◆ System battery
- ★ All impact packaged system mass

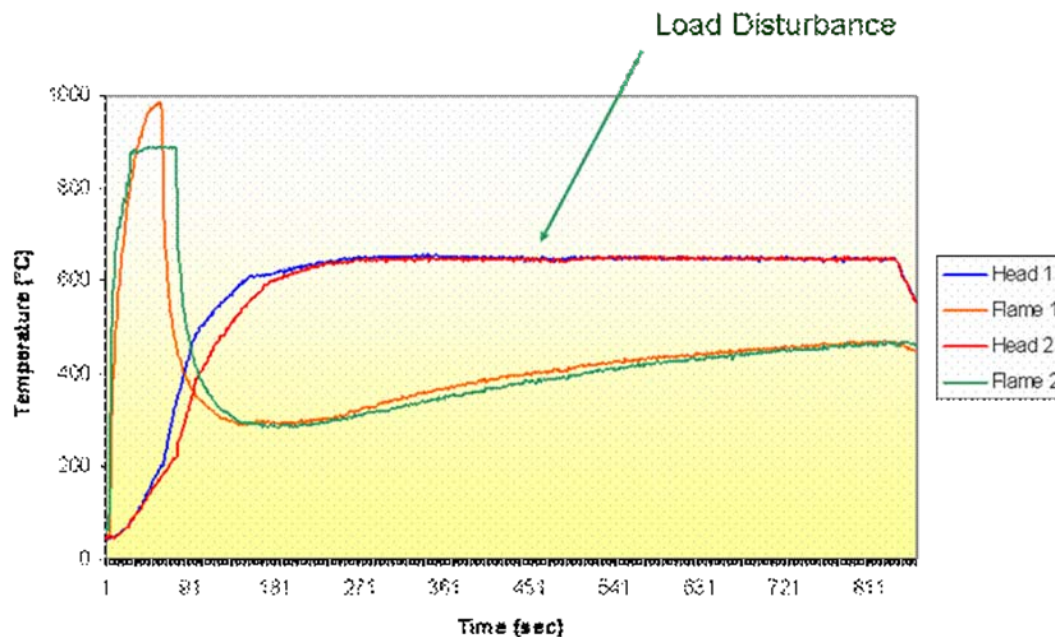




# 160 W System Performance



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58.1 dB(A) @ 1 M

56.6 dB(A) @ 1 M



56.7 dB(A) @ 1 M

55.1 dB(A) @ 1 M



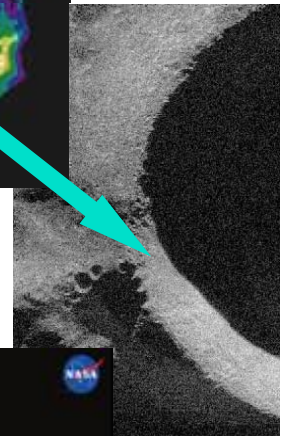
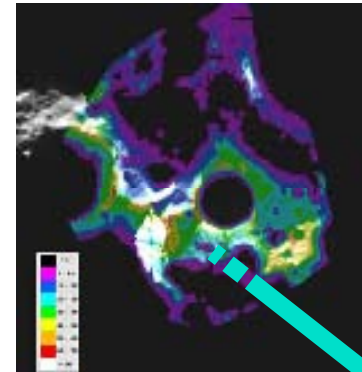
# NASA's Lunar Exploration Approach

(includes nuclear-Stirling power source requirements)



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- ★ Outpost at the South Pole
  - » Uses sunlight for PV (>60%/month)
  - » Can expand to a nuclear reactor power system
- ★ *Assumed* reference requirements
  - » Reactor power system: **~30 kW**
    - ◆ 5 kW/piston in balanced configurations
    - ◆ Minimum efficiency: 25% (heat in to AC out)
    - ◆ Th = **830 K** Tc = 415 K; NaK loop
    - ◆ 5 year life at full power, 2 Mrad radiation dose
- ★ Contractor: Foster-Miller, Inc., Albany, NY
  - » Will be built for Th = **650 K**
  - » Planned efficiency at Th/Tc = 2 is 28%





# Summary



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- ★ Significant free-piston Stirling convertor development is ongoing in the U.S.
  - » Convertor sizes range from 35 W to 5 kW
  - » Power systems range from 35 W to 1.1 kW
  - » Past demonstration of 25 kW FPSC shows potential for larger power
- ★ 160 W system development is progressing
  - » Propane-fueled version demonstrated feasibility
    - ◆ Extremely quiet
  - » Diesel-fueled version under development
    - ◆ Will undergo soldier testing
- ★ NASA 5 kW FPSC beginning development
  - » Can lead to military version as well
- ★ Stirling development for the military can lead to commercial systems
  - » Cost reduction is a major factor