ANS®

NUCLEAR and EMERGING TECHNOLOGIES for SPACE

Powering the Next Era of Space Exploration

Development of Stirling Convertors for Radioisotope and Fission Power Systems

Scott Wilson

NASA Glenn Research Center

Thermal Energy Conversion Branch

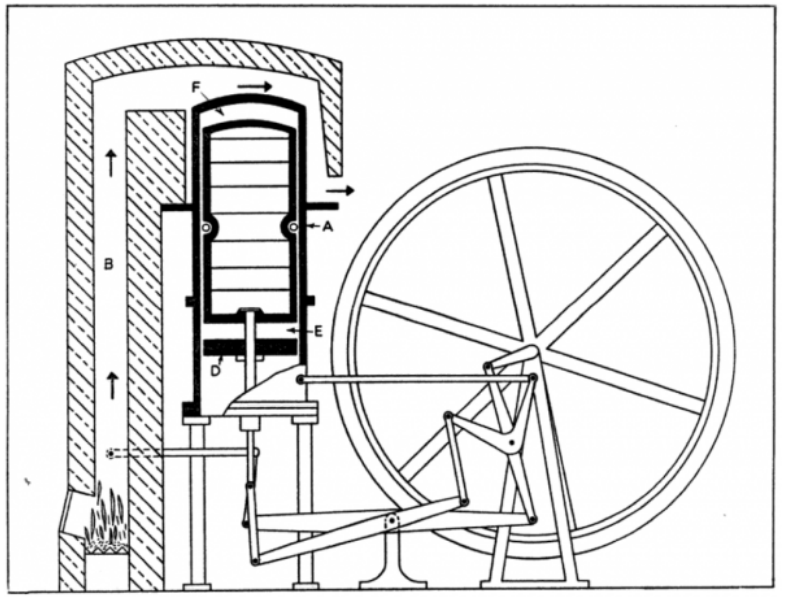
Dynamic Conversion Technical Lead

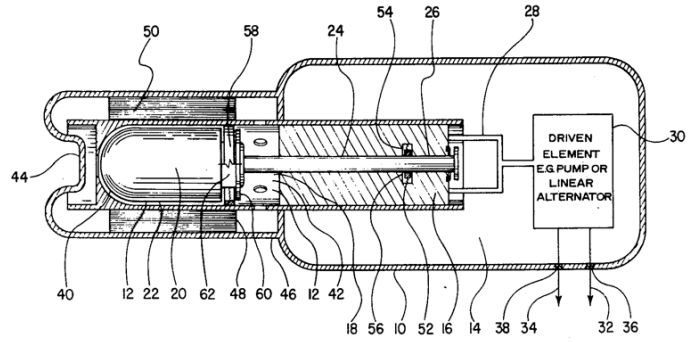
NASA

Stirling cycle machine development

Stirling cycle machines have been developed for terrestrial and space applications since 1800s

- **1816** – Robert Stirling patented the first Stirling cycle engine which he called “The Economiser”. Kinematic engines contain linkage arms and contact bearings.
- **1964** – Mr. Beale developed a working prototype of what he would call the “Free-Piston Stirling Engine” in his patent. Free-piston engines contain close running or non-contacting clearance seals to enable long life.
- **1970s-1990s** – Development of terrestrial Stirling cycle machines focused on predictable operation and life limiting aspects **(TRL 2-3)**
- **2000s** – Development of terrestrial and space designs focused on deployment into systems and demonstrating life and reliability **(TRL 4-5)**
- **2020s** – Development has focused on robustness **(TRL 5-6)**





Stirling power conversion development for terrestrial and space applications (flexure and gas bearings)

SRSC (DRPS)
STC/Infinia 55 We
Bolted/hermetic
26 % Efficiency
(20x) units built
(radioisotope)

P2A
Sunpower 1 kWe
Bolted
4x units built
(CHP)

DOE GENESTS
Sunpower 1 kWe
Hermetic
Gas burner
38 % Efficiency
(3x) units built
(CHP)

SRSC (DRPS)
Qnergy 7.5 kWe
Hermetic
26 % Efficiency
(4x) units built
(CHP)

EE-35 (SBIR/PalmPower)
Sunpower 40 We
32 % Efficiency
Bolted joints
(6x) units built
(defense/space)

ASC (ASRG)
Sunpower 80 We
Hermetic
39 % Efficiency
(30x) units built
(radioisotope)

DOE GENSETS
AMSC 1 kWe
Bolted joints
26 % Efficiency
(1x) unit built
(CHP)

(PowerDish)
Qnergy 3.5 kWe
Hermetic
26 % Efficiency
(4x) units built
(solar)

PCU (Fission TDM)
Sunpower 12 kWe
Bolted joints
Combined expansion space
26% Efficiency
(1x) 12 kW unit built
(fission)

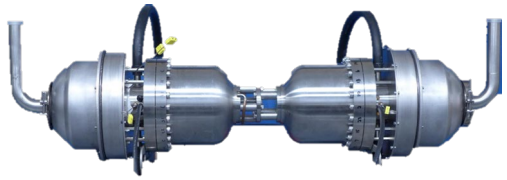
10W | 100 W | 1 kW | 10 kW | 100 kW

SRSC (DRPS)
STC 10 We
Hermetic
Isotope heat
29 % Efficiency
(4x) units built
(defense)

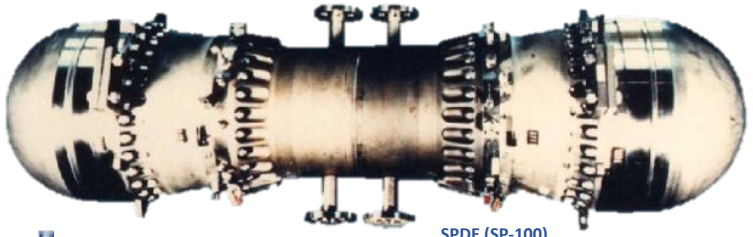
SRSC (DRPS)
Sunpower 60 We
Hermetic
26 % Efficiency
(4x) units built
(radioisotope)

SRSC (DRPS)
AMSC 70 We
Bolted joints
26 % Efficiency
(4x) units built
(radioisotope)

PM 1.0/1.5
(Sunpower license)
Microgen 1 kWe
15,000 units built
>250,000,000 hours
Accumulated
(CHP)



ARL GENSETS
Sunpower 1.8 kWe
Bolted joints
Gas burner
38 % Efficiency
2x units built
(defense)



SPDE (SP-100)
MTI 25 kWe
Bolted joint demo
Combined expansion space
20 % Efficiency
(2x) 12.5 kW units built
(1x) 25 kW unit built
(fission)

Flexure bearings
Gas bearings

Life and reliability testing has demonstrated long life capability in NASA's Stirling Research Laboratory

- NASA and it's DOE partners started maturing Stirling cycle machines for potential use in space in 1999
- Flexure and gas bearing machines tested
- Conversion efficiency ranges between 25-39%
- Convertors run 24/7 unattended with autonomous response systems and performance data archiving in NASA Glenn's Stirling Research Laboratory
- Long duration testing ensures design of life limiting mechanisms, geometric stability of non-contact running clearances, and materials compatibility
- Stirling convertors have operated at full power longer than needed to support a 14-year mission
- **Engineering methods needed to make a reliable long-life Stirling convertor have been established**

Unit	Years	Vibe	Spin	Note
TDC #13	**16.1**			*World Record*
TDC #15	**16.1**			*World Record*
TDC #16	**16.1**			*World Record*
ASC-0 #3	**12.7**	FA		*World Record*
ASC-L	**8.1**	FA		*World Record*
ASC-E3 #4	6.8	FA		
ASC-E3 #9	5.2			
SRSC #1	1.3			
SRSC #2	1.2	Qual		
SRSC #3	0.6	Qual	Qual	
SRSC #4	0.1			

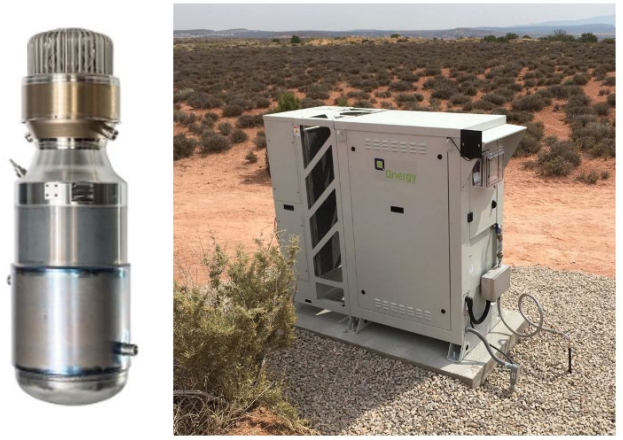
Extended Operation Data as of 4/2323, FA: Flight Acceptance, Qual: Qualification

Commercial applications have demonstrated the ability to produce large quantifies of free-piston Stirling units

- Microgen, Netherlands (Gas Bearings)
  - Application: Combined heat and power
  - Design based on licensing agreement with Sunpower, built in China
  - Power output: 1,000 W_e to 1,700 W_e
  - Units: Over 15,000 units produced
  - Hours: Over 250 million hours of operation accumulated
  - Temperatures: Hot side: 180-560 ^oC, Cold side: 6-70 ^oC
  - Fixed operating frequency

Microgen's PM 1.0 convertor in OkoFen generator

- Qnergy, US (Flexure Bearing)
  - Application: Solar and remote power
  - Power output: 1,200 W_e to 5,600 W_e
  - Units: Over 1,000 units produced
  - Hours: Over 10 million hours of operation accumulated
  - Temperatures: Hot side: 550-650 ^oC, Cold side: -40-100 ^oC
  - Floating operating frequency



Qnergy's QB80 convertor in PowerGen generator

Department of Defense has explored the use of Stirling conversion for deployment applications

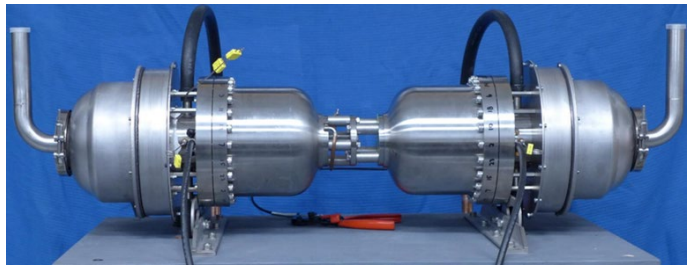
- RG-10
  - Stirling Technology Company
  - Application: Unknown
  - Power output: 10 W_e
  - Integrated isotope fuel tested >76k hrs (likely higher)

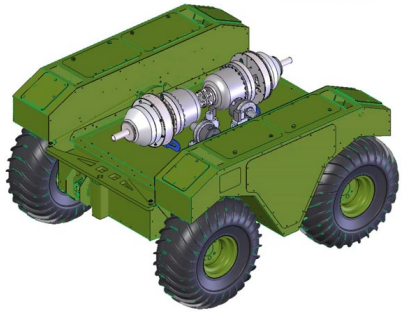
10 W_e for Terrestrial Power

- DARPA Palm Power
  - Sunpower Inc.
  - Application: Wearable soldier power
  - Power output: 35 W_e
  - Gas burner assembly and JP-8 used to deliver heat to engine

35 W_e for Wearable Power

- Warthog
  - Sunpower Inc.
  - Application: Deployable power
  - Power output: 1,800 W_e utilizing two individual 1 kW_e convertors
  - Gas burner assembly used to deliver heat to engines





1.8 kW_e for ARL Warthog Project

Maturation of Stirling Technology for Radioisotope Power Systems

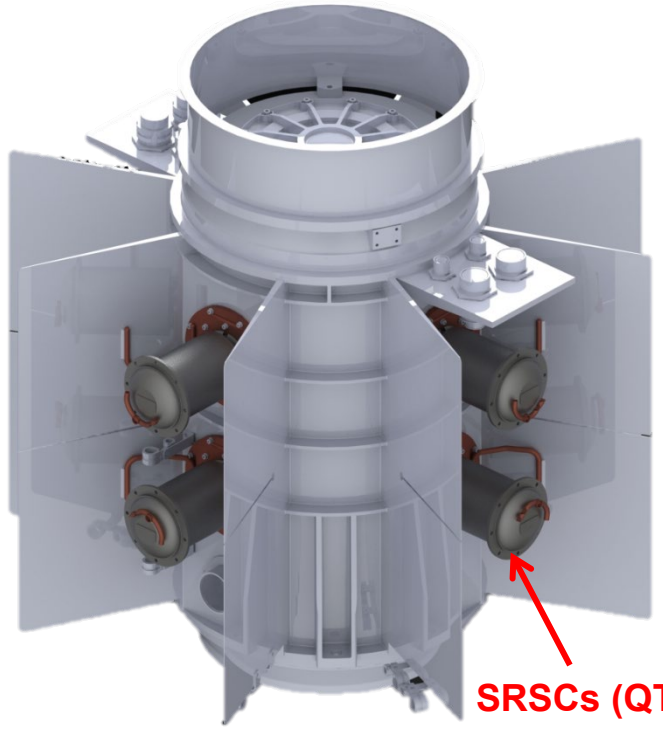
An update on recent achievements

Aerojet Rocketdyne's generator uses Sunpower Robust Stirling Convertors (SRSC)

- One-year design phase completed in January 2023
- Conservative performance models predict high efficiency (19.5%)
- Design is multi-mission capable, includes near Lunar equator
- Design contains 8 SRSC for power conversion redundancy
- Provides a compelling generator design for space missions

AR's Multi-Mission Performance Parameters

Parameter	Requirement	Performance Model Prediction
Design Life	17 Years	>17 Years
Power Output (BOL)	300 W_e	**293 W_e**
Power Output (EODL)	241 W_e	242 W_e
Conversion Efficiency	20 %	**19.5 %**
BOL Specific Power	> 2 W_e/kg	**2.6 W_e/kg**
Mass	< 150 kg	112 kg



Aerojet Rocketdyne's Generator Design with Sunpower Convertor

Controller not shown

Sunpower Robust Stirling Convertor (SRSC) Verification and Validation (V&V) Plan

- Measure performance under harsh conditions while operating at full power
- Demonstrate robustness to requirements
- Accumulate 20,000 hrs of extended operation, Tracks 1-4 account for ~30% of the total

Hermetic SRSC

Sequence	Focus	Primary Objective	Secondary Objective
Track 1	Performance	Acceptance and performance verification	Baseline data (steady state at single point)
Track 2	Dynamic loading	Qual-level random vibration	Steady operation comparison to baseline
Track 3	Static loading	Constant acceleration	Steady operation comparison to baseline
Track 4	Robustness	Thermal cycling and loss of load testing	Measure residual jitter from synchronized pair

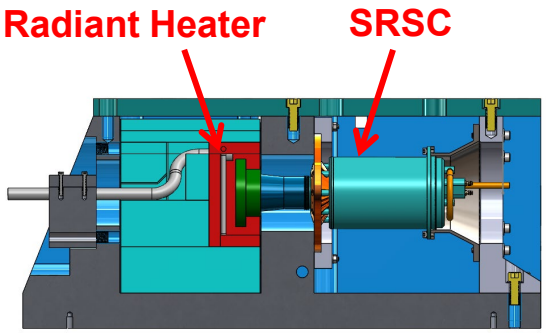
Stirling Convertors Passed Qualification-Level Random Vibration Testing

Exposure

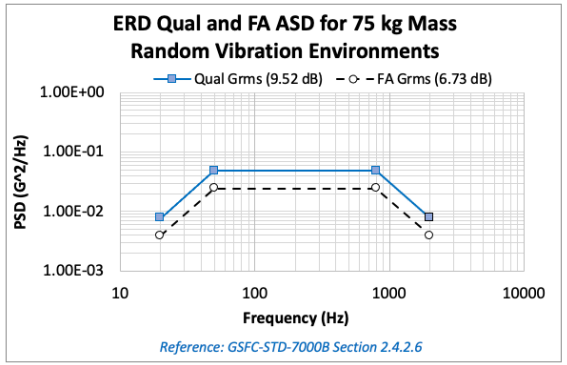
- Fixture mounted in centrifuge facility
- Test conducted while operating at full power
- 7.7 g_{rms} in 3 orthogonal orientations
- 2-minute duration each orientation

Performance

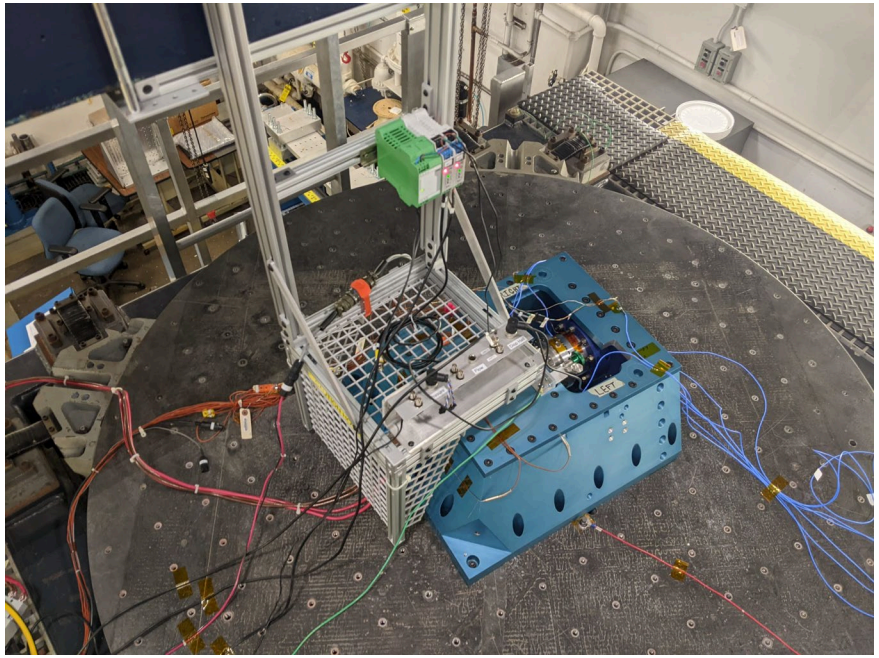
- Power dropped off during lateral orientation and recovered after exposure
- Pre-test baseline values = 55.2 W_e
- Post-test performance = 55.8 W_e
- No significant change in performance due to qualification level random vibration environment
- **Demonstrates robustness to dynamic loading anticipated during launch during PSD missions**



Environmental Test Fixture



Vibe Profile



Qual-level random vibration test

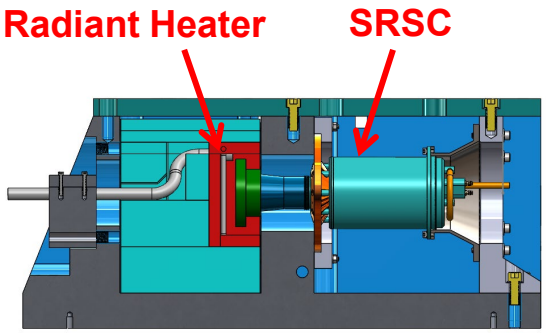
Stirling Convertors Passed Qualification-Level Static Acceleration Testing

Exposure

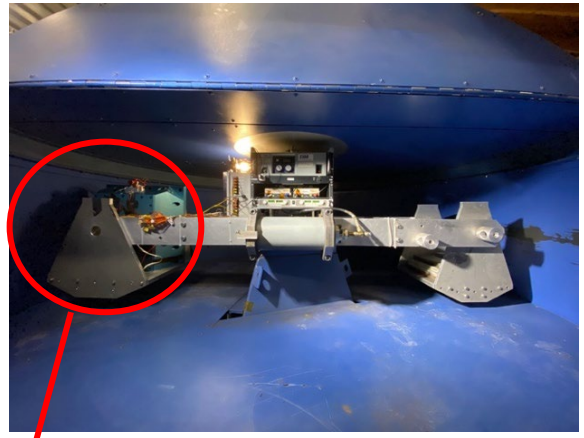
- Fixture mounted in centrifuge facility
- Test conducted while operating at full power
- 6.5g in 4 lateral orientations
- 22.5g in 2 lateral, 2 axial orientations

Performance

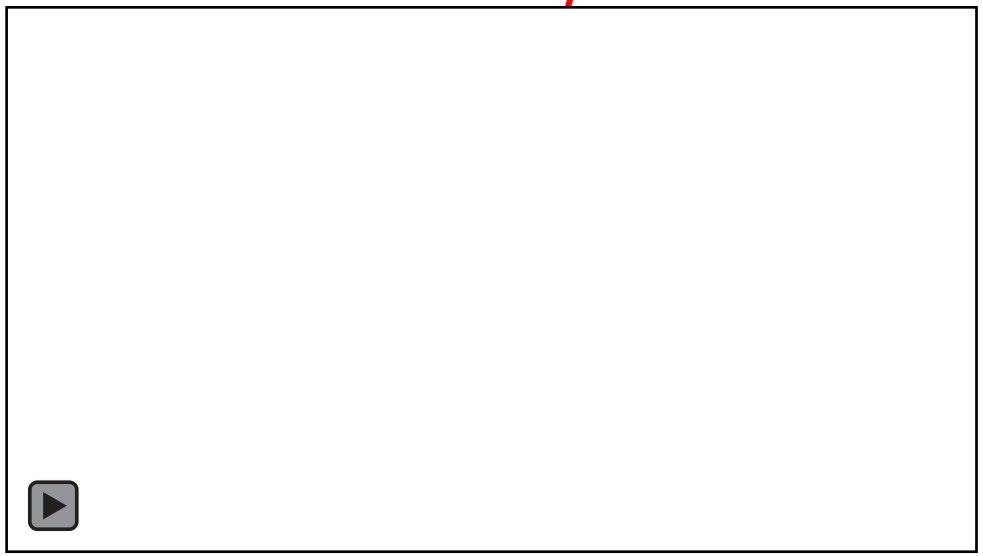
- Power dropped off during lateral orientation and recovered after exposure
- Pre-test baseline values = 55.5 W_e
- Post-test performance = 55.7 W_e
- No significant change in performance due to qualification level static acceleration environment
- **Demonstrates robustness to static loading anticipated during launch, spin stabilization, or EDL used by PSD missions**



Environmental Test Fixture



Centrifuge Facility at CWRU



Qual-level static acceleration test

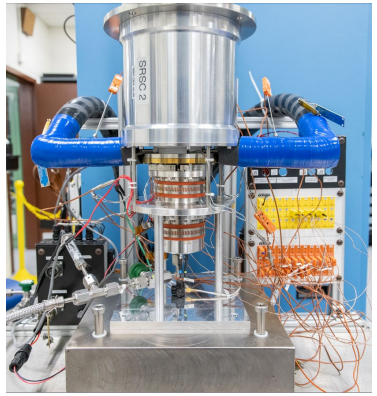
Stirling Convertors Passed Qualification-Level Thermal Cycling Testing

Exposure

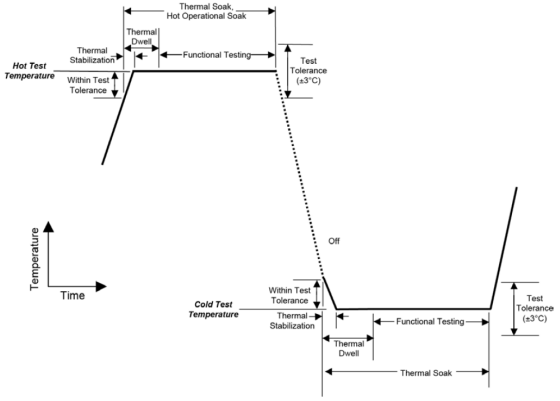
- Simulates thermal cycles accumulated during an estimated 13 on/off cycles anticipated during generator processing (prior to fueling)
- ON conditions
  - Full power operation
  - Accept temp = 720 °C
  - Reject temp = 120 °C
  - Alternator temp = 130 °C
- OFF conditions
  - No piston motion
  - Accept temp = 10-20 °C
  - Reject temp = 10 °C
  - Alternator temp = 10 °C

Performance

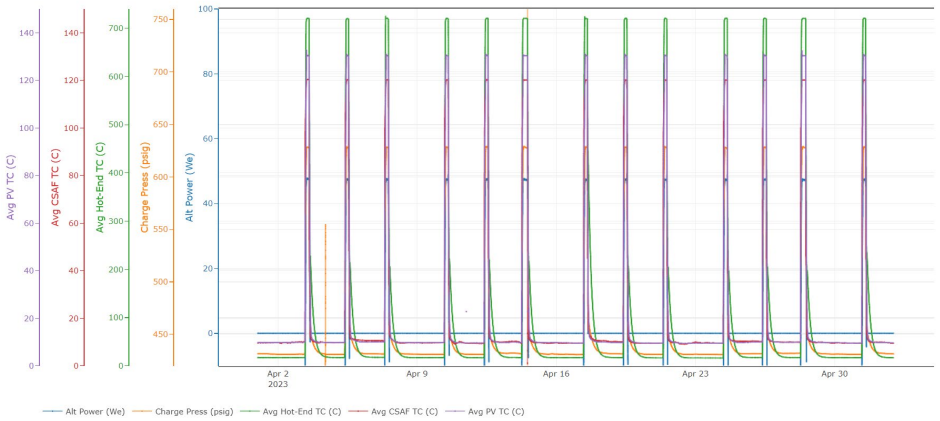
- Pre-test baseline values = 47.4 W_e
- Post-test performance = 46.4 W_e
- No significant change in performance due to qualification level static acceleration environment
- **Demonstrates robustness to thermal cycling anticipated during generator processing prior to fueling**



SRSC #2 Test Stand



Thermal Cycling Profile



Test Data for 13 Thermal Cycles

Summary of SRSC V&V Effort

- Passed environmental tests that include margin to simulate Qual-levels
- Working on 20,000 hr target and component/material testing
- **SRSC design is at TRL 5-6**

Hermetic SRSC

Test	Requirement	Status
Performance	Conversion efficiency	**Passed**
Random vibe	Dynamic loading	**Passed**
Centrifuge	Static loading	**Passed**
Loss of Load	10 sec	**Passed**
Thermal cycling	13 on/off cycles	**Passed**
Extended operation	10,300 hrs of 20,000-hr target	**Ongoing**
Creep test	Temperature, time	**Ongoing**
High-cycle fatigue	Piston spring endurance limit	**Ongoing**
Magnet aging	12,000-hr target	**Ongoing**
Radiation test	Organics & magnets	Delayed

Maturation of Stirling Technology for Fission Power Systems

Technology Demonstration for Fission Surface Power

Technology Demonstration Unit (TDU)

- Electrically heated system test in 2016
- Single 12 kW_e gas bearing Stirling convertor used to demonstrate full scale ¼ power output
- Demonstrated maximum system net power of 9.6 kW and system efficiency of 18.7%

Kilopower Reactor Using Stirling TechnologY (KRUSTY)

- Nuclear reactor test 2018 using HEU core
- Two 80 W_e gas bearing Stirling convertors used to demonstrate full scale ¼ power output
- Tested full power and various fault conditions
- Demonstrated maximum system net power of 183 W_e and conversion efficiency of 30-34%

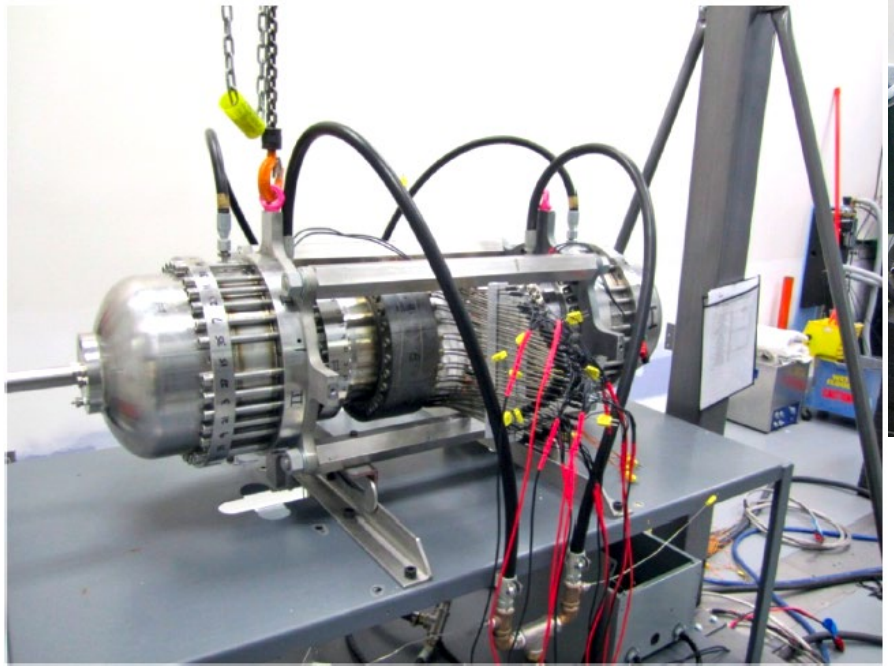
FSP TDU installed in Vacuum Facility 6 at GRC

KRUSTY installed at the Nevada National Security Site

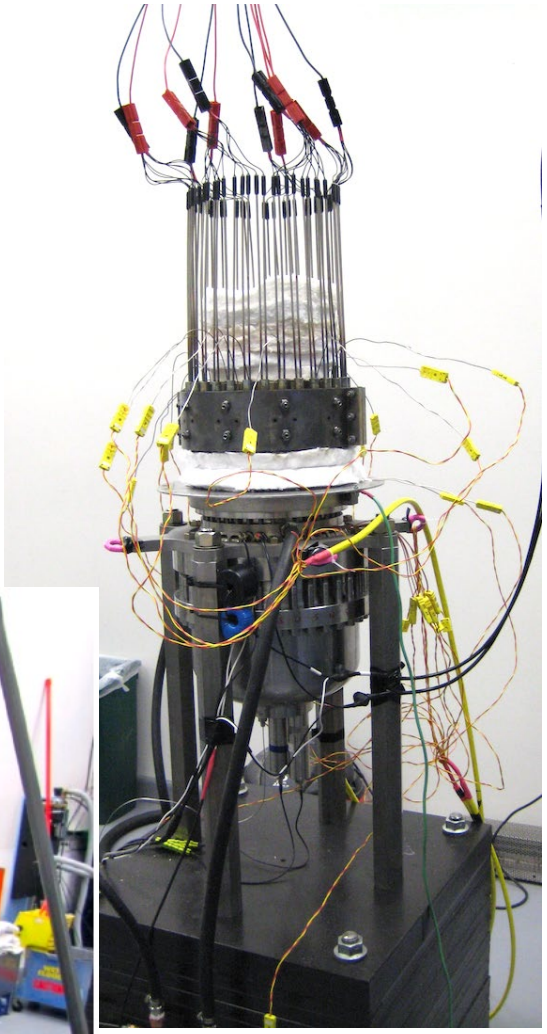
Power Conversion Unit (PCU) for TDU

- Single engine testing used to verify performance prior to joining in dual-opposed configuration (4,000 lb mass was used to mitigate the exported force from a single unit)
- Dual-opposed configuration utilizes a common expansion space to balance convertor forces, simple spring mount was used in TDU

  - Temperature limits for delivered hardware
    - Acceptor temp: 600 °C (650 °C target)
    - Rejector temp: 127 °C (177 °C target)
  - Power output achieved target power levels
    - 6.1 kW_e (Engine 1)
    - 6.05 kW_e (Engine 2)
    - > 12 kW_e in dual-opposed configuration
  - Efficiency
    - 26.5 % (Engine 1) at 23.0 kW_{th} heat input
    - 24.4 % (Engine 2) at 24.8 kW_{th} heat input
  - Mass
    - 219 kg (hermetic convertor design)
  - Specific power
    - 27.3 W/kg (single 6 kW hermetic design)
    - 23.7 W/kg (12 kW convertor + controller)



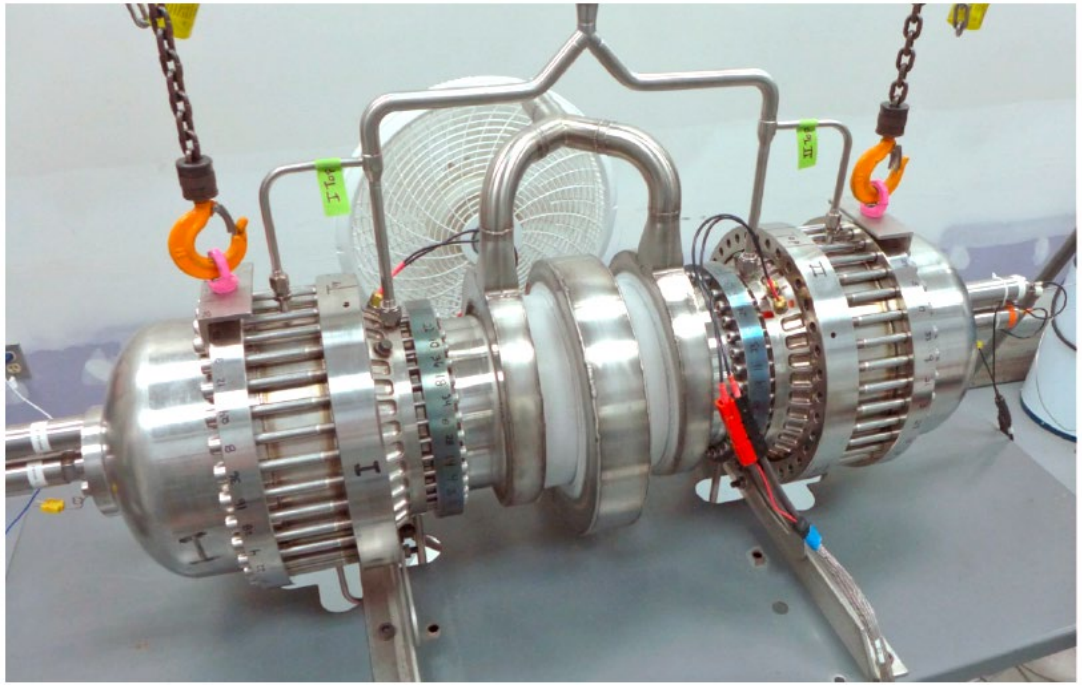
12 kW PCU *(electrically heated head)*



6 kW PCU shown in single configuration

Power Conversion Unit (PCU) for TDU

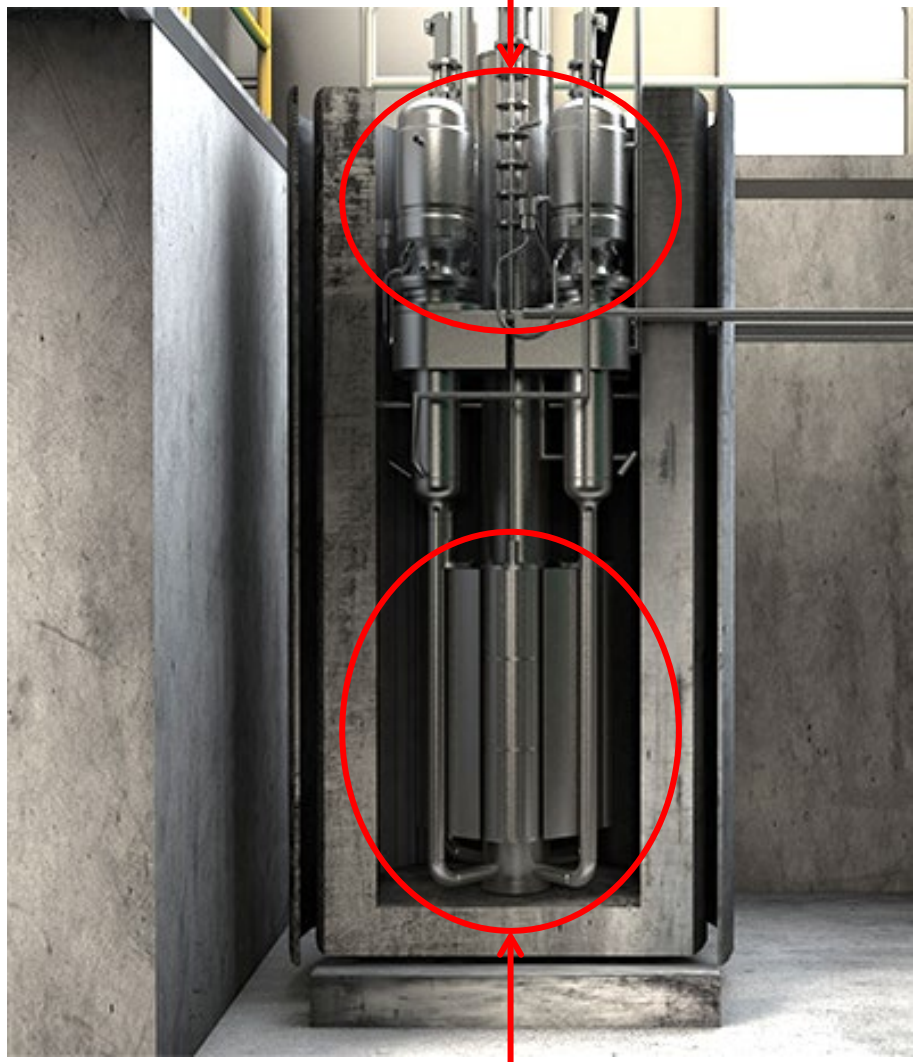
- 12 kW PCU was delivered in 2015
- Motored checkout test completed prior to delivery but unable to operate with newly integrated head
- Delivered unit met performance requirements
  - Potential lower than desired thermal contact between the NaK heat exchanger and the internal acceptor (not verified)
- Life requirement not fully met
  - Braze weld failure on heat rejection interface resulted in a helium leak that limited testing (proposed solutions not explored)
- **PCU design is at TRL 4-5**



12 kW PCU *(NaK loop heater head)*

MARVEL for Clean Terrestrial Power

- Microreactor Applications Research Validation and EvaLuation (MARVEL)
- Microreactor designs are currently under development in the United States as part of an aggressive government plan to combat climate change and reach net-zero emissions by 2050
- DOE is developing MARVEL
  - Liquid-metal cooled microreactor
  - Four (4) free-piston Stirling engines
  - 100 kilowatts system power output
  - High-assay, low-enriched uranium (HALEU) fuel
  - Built using off-the-shelf components allowing for faster construction
  - Located in the Transient REActor Test (TREAT) facility at Idaho National Laboratory
- **Looking forward to learning more!**



Conclusions

- **Stirling power conversion reduces fuel consumption of a limited supply, system waste heat and emitted radiation**
- Free-piston Stirling convertors have been developed for terrestrial and space applications since the 1960s
- Commercial units have operated >250M hrs on 15,000 units, demonstrating mature production capability for terrestrial applications
- Space designs have been demonstrated from 55 W_e to 25,000 W_e
- Reliable long-life Stirling convertors continue to operate beyond 16 years
- Aerojet Rocketdyne's generator design estimated 293 W_e at BOM, 19.5% efficiency, and a specific power of 2.6 W/kg with power conversion redundancy
- **Stirling convertors have been matured to TRL 5-6 for RPS applications and to TRL 4-5 for Fission reactor applications**

ANS®