



Highly Efficient Stirling Power Conversion for Robotic Space Exploration

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STIRLING POWER CONVERSION DESIGNS HAVE DEMONSTRATED HIGH TRL

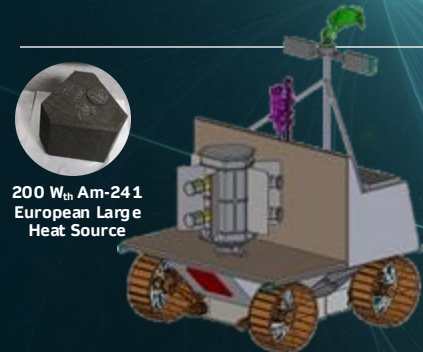
- NASA GRC is developing Convertors, Controllers, and Generators for potential use in space applications
- Sunpower Robust Stirling Converter (SRSC) has passed key environmental tests demonstrating performance/robustness at TRL 5
 - Margin to survive temperature extremes of Moon and Mars
 - Demonstrated non-contacting bearings survive external loading from harsh environments
 - Survival of electrical load loss verified during production testing
- Multiple Stirling convertor designs have demonstrated over 30% efficiency
- Multiple convertors have operated over 17 years, controller engineering model operated over 14 years
- Reliability of convertors has been demonstrated by analysis and testing

FLIGHT DEMONSTRATION NEEDED FOR TRL ADVANCEMENT FOR STIRLING TECHNOLOGIES

HIGH EFFICIENCY STIRLING GENERATORS OFFER NEW FUEL ECONOMY

- High efficiency reduces required amount of fuel and corresponding emitted radiation
- System efficiency demonstrated at 28% on ASRG, new multi-convertor designs exceed 20% efficiency
- High reliability by design using redundant convertors and controllers
- NASA's Stirling Generator Testbed allows demonstration of critical interfaces and fault tolerance
 - Demonstrated 17% eff. using radiantly-coupled Stirlings to central heat source stack
 - Demonstrated four convertors with heat rejected to environment using fins
 - Demonstrated stable operation of housing with four convertors operating
 - Convertor fault tolerance demonstration and controller testing

STIRLING GENERATOR DESIGNS CAN BE ADAPTED TO VARIETY OF MISSIONS



200 W_{th} Am-241
European Large
Heat Source

Viper-class rover concept powered by
Americium-based dynamic RPS

Ref: <https://hdl.handle.net/2381/23708967.v1>

STIRLING CONVERTORS SELECTED FOR COMMERCIAL RPS DEVELOPMENT

- Commercial development of Stirling RPS designs in progress on NASA's Harmonia and AFRL's JETSON
- Stirling power conversion and high efficiency applicable for RPS with commercial isotope heat sources
- NASA's Tipping Point selected Zeno Power Systems to develop an americium-241 (Am-241) radioisotope Stirling generator (RSG) for lunar surface missions
- COMPASS study completed for Viper-class rover concept powered by Americium-based Stirling RPS
- University of Leicester (UK) developing 200 W_{th} European Large Heat Source using Am-241 and radioisotope generator designs for European Space Agency (ESA) missions

STIRLING RPS ENABLING SURVIVE & THRIVE THE LUNAR NIGHT



Zeno Power's Rover Concept Powered by
a Radioisotope Stirling Generator

Ref: <https://www.zenopower.com>

SUNPOWER STIRLING CONVERTORS FOCUSED ON SURFACE POWER

- 100 W_e Stirling convertors used in 2016 KRUSTY demonstration
- 1 kW_e Stirling convertors (38% eff. @ 23 kg) demonstrated pumped sodium (NaK) loop in vacuum, tech dev for 40 kW_e Technology Dem. Unit (TDU)
- 12 kW_e Stirling used in 40 kW_e Technology Dem. Unit (TDU)
 - Stirling convertors were 26% efficient, 110 kg (hermetic design)
 - Full scale dual-opposed Stirling convertor pair
 - Electrically-heated demonstration of UO₂ fast-spectrum reactor design cooled by a primary pumped liquid metal loop
- 1 kW convertors delivered to DOE's ARPA-E GENSETS project for CH&P
- 2 kW assembly delivered to Army Research Lab UMV project called WARTHOG

STIRLING TECHNOLOGY AVAILABLE NOW FOR FLIGHT DEVELOPMENT



12 kW_e Stirling Converter Assembly

Ref: NASA/CR—2016-219088

2 kW_e Stirling Converter Assembly from Sunpower, Inc.

Ref: https://www.army.mil/article/235022/army_converts_heat_into_electricity_to_power_autonomous_robots_for_months



Concept art of FSP on Mars

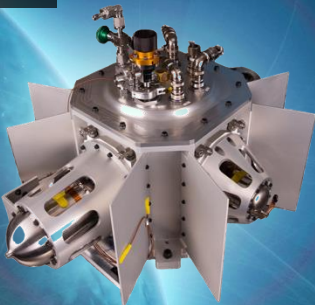
Ref: <https://www.nasa.gov/tdm/fission-surface-power/>

Convertor Parameters	Value
Convertor Power Output	Demonstrated 88 W _e
Design Life (includes 3 yrs of storage)	17 years
Convertor Efficiency	Demonstrated 31%
Convertor Mass (SRSC)	3.6 kg
Robustness	Loss of Electrical Load Tolerant



Sunpower Robust Stirling
Converter (SRSC)

Generator Parameters	Value
Generator Power Output	100 - 500 W _e
Design Life (includes 3 yrs of storage)	17 years
Generator Efficiency	> 20%
Target Specific Power	3 W _e /kg
Robustness	Single fault tolerant



Stirling Generator Testbed
NASA Glenn Research Center