Developmental Considerations on the Free-Piston Stirling Power Convertor for Use in Space

by

Jeffrey Schreiber
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Abstract

Free-piston Stirling power conversion has been considered a candidate for radioisotope power systems for space for more than a decade. Prior to the free-piston Stirling architecture, systems were designed with kinematic Stirling engines with rotary alternators to convert heat to electricity. These systems were proposed with lightly loaded linkages to achieve the necessary life. When the free-piston configuration was initially proposed, it was thought to be attractive due to the relatively high conversion efficiency, acceptable mass, and the potential for long life and high reliability. These features have consistently been recognized by teams that have studied technology options for radioisotope power systems. Since free-piston Stirling power conversion was first considered for space power applications, there have been major advances in three general areas of development: demonstration of life and reliability, the success achieved by Stirling cryocoolers in flight, and the overall developmental maturity of the technology for both flight and terrestrial applications. Based on these advances, free-piston Stirling convertors are currently being developed for a number of terrestrial applications. They commonly operate with the power, efficiency, life, and reliability as intended, and much of the development now centers on system integration. This paper will summarize the accomplishments of free-piston Stirling power conversion technology over the past decade, review the status, and discuss the challenges that remain.

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by
Jeff Schreiber
NASA Glenn Research Center
Cleveland, OH

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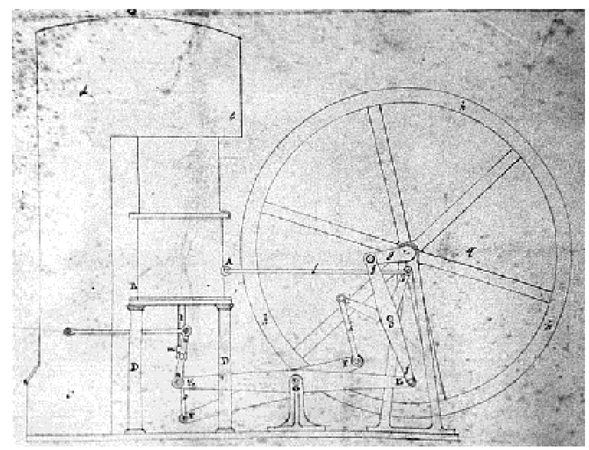
Development of Stirling

- Stirling technology development can be viewed as having gone through 3 general phases
  - Early air engines
  - Advanced kinematic engines
  - Free-piston Stirling
- The paper gives an overview of the past development, and then summarizes the current status
  - Particular emphasis is placed on the advances between 1999 and 2005, years of radioisotope generator development

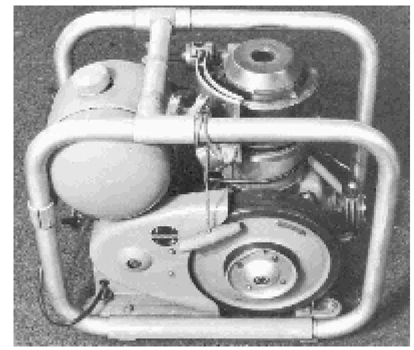
Development of Stirling

- Stirling air engines were popular from 1816 until about 1900
  - Operation was with one atmosphere with air as the working fluid
  - The competed well against other prime movers, primarily because of high efficiency, quiet operation, and safety
  - Efficiency was high because Robert Stirling’s original patent included the economizer, known today as a regenerator
- Development was eventually surpassed by steam engines, IC engines, and the electric motor,
- The first general phase of Stirling development came to an end

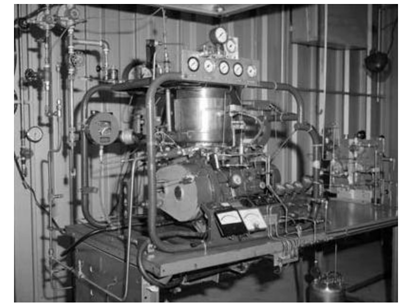


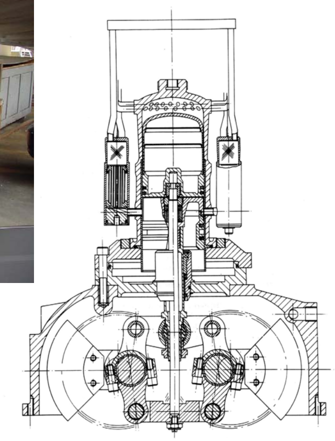
Development of Stirling

- Development was picked up by Philips Laboratories, Einhoven, the Netherlands starting in the 1930's
  - All configurations at that time were kinematic
  - They were initially air cycle machines, with a compressor to increase mean pressure
- As Philips tried to convert the heat engine into a cooler, the working fluid was changed to helium and hydrogen
  - Great improvement in performance resulted
  - Lower flow losses, higher heat transfer coefficient
  - Higher efficiency
- Philips developed an improved understanding of the thermodynamics
  - Regenerator research
  - Cycle modeling
- Applications were thought to be portable generators, marine generators, locomotive and automotive application

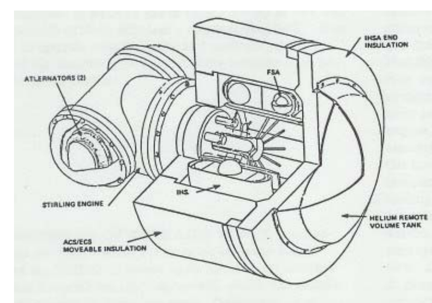


Development of Stirling



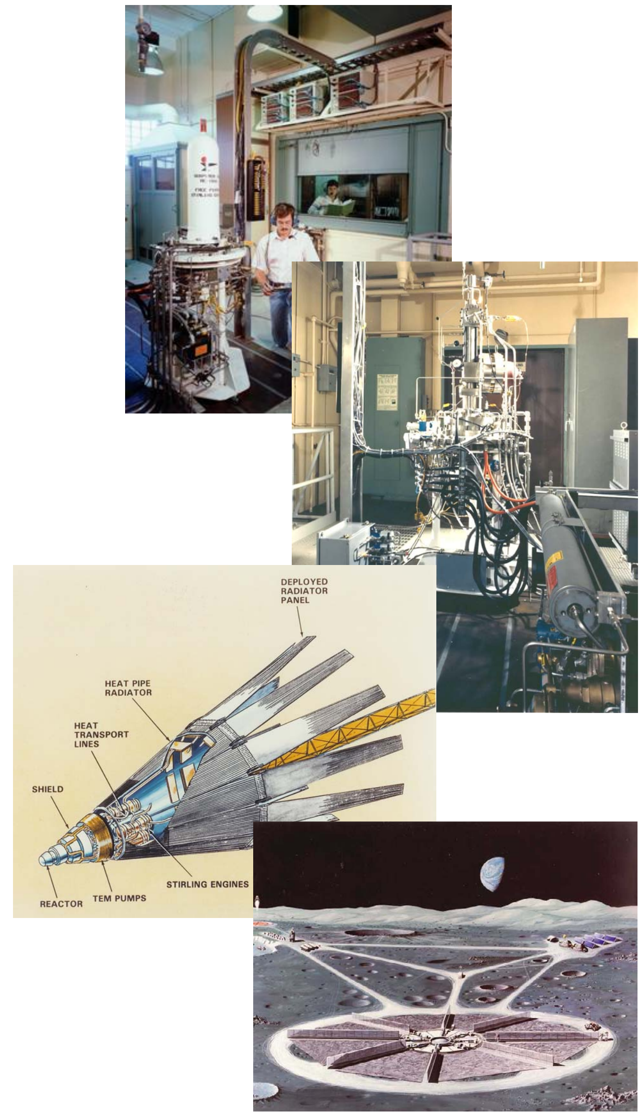


- Development for applications included
  - GPU-3 for military, quiet portable power
  - Ford/Philips 4-215 for automotive application
  - United Stirling of Sweden P-40 leading toward automotive
- Kinematic systems required many auxiliaries
  - Oil pump and filter
  - Coolant pump, radiator and fan
  - Compressor and high-pressure tank
  - Sliding seals
  - Mean pressure control system
  - Kinematic linkage system, such as the rhombic drive or crossheads to manage side loads
- For space power, it was generally viewed as too complex, heavy, and inherently life-limited
  - Stirling Isotope Power System (SIPS) was developed by DOE/General Electric
  - Based on rhombic drive with two rotary alternators
- Advanced versions of kinematic Stirling can be viewed as the second general phase of Stirling development



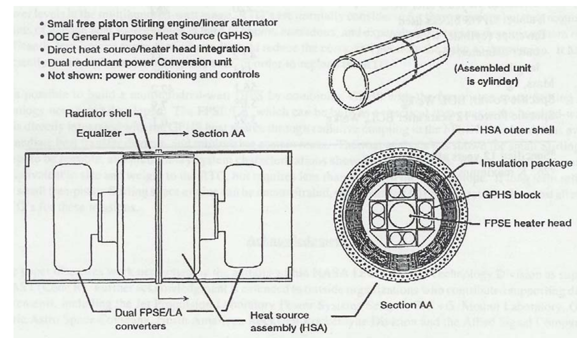
Development of Stirling

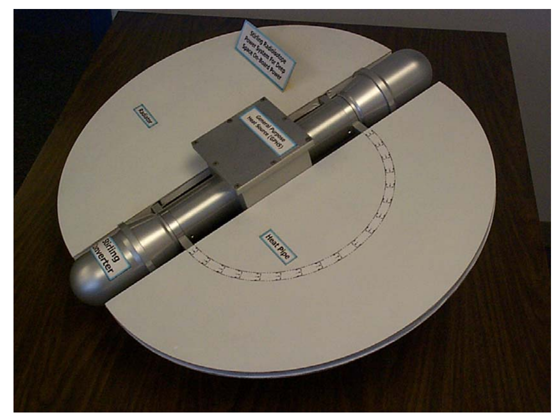
- The third phase of development began with the invention of the free-piston Stirling in the 1960's
- Eliminated:
  - Lubrication system
  - Gas compressor and gas management system
  - Life limiting wear of sliding seals
- Could be developed to have:
  - Hermetic containment of working fluid
  - Non-contacting operation
  - Control through the load of an external controller
  - Long life
- The technology matured and success was:
  - 1960's operation
  - 1970's reaching design performance following significant development
  - 1980's design performance following limited development
  - 1990's design performance following minimal development
- Still minimal consideration of system integration



Development of Stirling

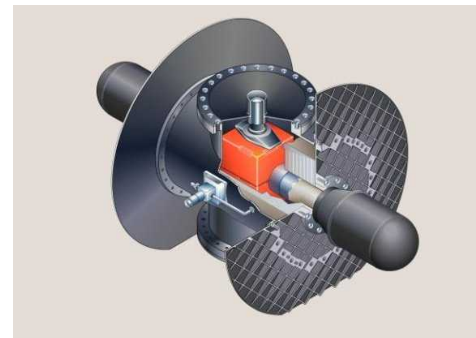
- Free-piston Stirling convertor technology for radioisotope applications was being developed by NASA & DOE at low levels during the 1990’s
- 1997 study led by DOE concluded that Stirling technology existed, and was available for flight development
- 1999 Technology Readiness Assessment was commissioned to determined if Stirling was sufficiently mature for transition to flight development
- Team members DOE, GRC, JPL, LM, OSC
- Readiness Assessment considered
  - Performance mapping
  - EMI/EMC characterization
  - Launch load vibration test
  - Fault tolerant generator configuration
  - Flight worthy controller design
  - Radiation tolerance
  - FMECA





Development of Stirling

- The 1999 study found that:
  - EMI measurement showed that a Stirling generator could meet the requirements of most science missions, but not the most demanding
  - Stirling convertor TDC #1 survived 12.3 grms random vibration test
  - Generator conceptual designs existed from LM, OSC, and GRC, with various degrees of detail and different concepts for fault tolerance
  - A flight controller conceptual design was developed, but not built or tested
  - There appeared to be no barriers for implementing a suite of organics that could survive the nominal radiation levels
  - The FMECA showed no show-stoppers
- 1999 Technology Readiness Assessment determined that Stirling was sufficiently mature for transition to flight development



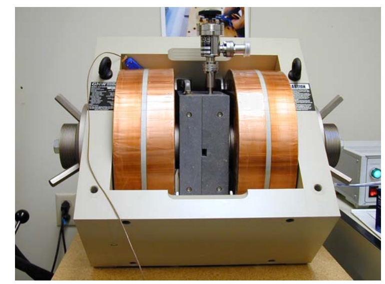
Development of Stirling

- LM was selected by DOE as the System Integration Contractor for the SRG110 generator
- Flight development continued at LM, Infinia, and GRC working in partnership through 2005
- GRC also conducted an advanced technology effort to increase efficiency, reduce mass, enhance robustness
- Highlights include:
  - Metallics
    - Optimized heater head materials for long life, characterized the materials
    - Developed techniques to represent the materials on a probabilistic basis, conduct life analysis in probabilistic terms
    - Validate heater head life analysis through benchmark tests
    - Optimize regenerator processing to enhance reliability

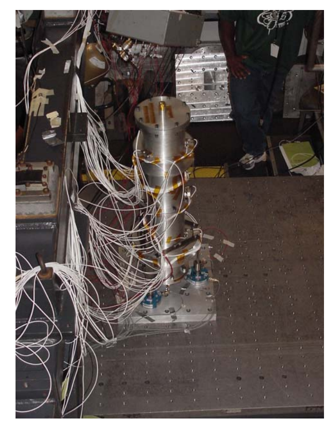
Development of Stirling

- Organics
  - Characterize cure kinetics of critical adhesives and optimize processing
  - Conduct aging tests of the organics
  - Initial assessment of radiation tolerance

- Magnets and linear alternators
  - Characterize candidate magnets
  - Develop short term and long term magnet aging tests
  - Develop technique to characterize curved magnets
  - Create technique for 3-D linear alternator magnetostatic analysis
  - Predict conditions for demagnetization in a linear alternator and validate with test data

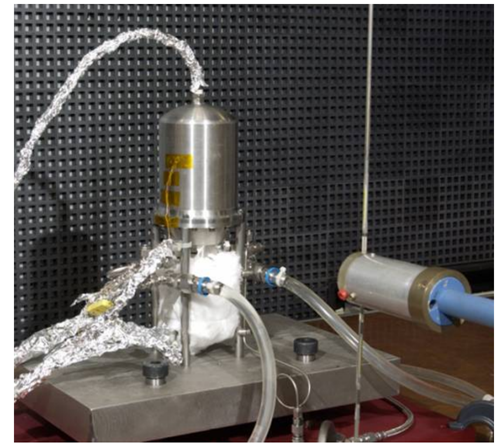


- Structural dynamics
  - Demonstrate full operation of convertor up to 12.3 grms, 0.2 g^2/Hz
  - Fully characterize modal response of the Stirling convertor
  - Develop concept for structural integration of Stirling convertors into the generator to reduce launch loads
  - Develop spacecraft adapter that could be used to reduce launch loads if needed
  - Validate structural model through generator simulator test
  - Show analytically that SRG-like generator could survive up to 15.1 grms, 0.3g^2/Hz



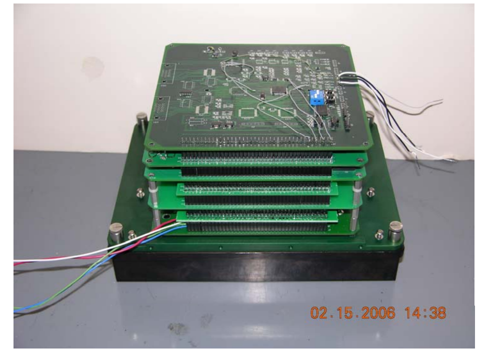
Development of Stirling

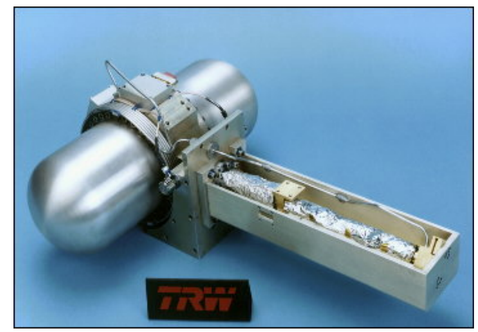
- EMI/EMC
  - Total of three tests conducted at GRC and JPL
  - It remains the finding that Stirling could meet general science requirements, but would need a mission kit for the more demanding missions
  - EMI remains a system level issue, requiring complete generator design
- Reliability
  - Techniques for probabilistic analysis have been applied to all critical components
    - Need to combine individual analyses into a single Stirling convertor analysis
  - Difficulty remains in verifying life and reliability of a device with no wear mechanism
    - Same problem faced by the cryocooler industry
  - Experience from long life Stirling convertors and cryocoolers is directly applicable
  - Much more operational data is now available
    - Over 80,000 hours at GRC



Development of Stirling

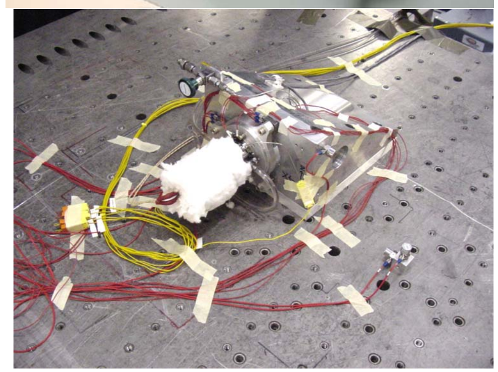
- Controller development
  - Flight controller has been partially designed
  - Hardware has not been tested, convertors remain on test with research controllers
  - New direction is being pursued in Active Power Factor Correction controllers
  - Controller remains unproven
- Stirling cryocoolers have been placed in flight
  - Data is being accumulated on life and reliability
  - Lessons learned are being applies where appropriate
  - Criterion for validation of life and reliability are being studied for possible use in power conversion
  - Terrestrial designs have been deployed, accumulated over 44 million hours, data is showing MTBF of over 500,000 hours
- System integration has advanced to a much higher level of detail





Development of Stirling

- Advanced technology
  - This effort has resulted in a 6-fold increase in specific power of the Stirling convertor
  - Two forerunners of the Advanced technology convertor were able to operate successfully at vibration levels up to 24 grms, 0.8 g^2/Hz
  - The advanced technology could increase generator specific power from ~4 W/kg to ~8 W/kg
  - APFC controllers could reduce controller mass and volume
    - Have been successfully used in laboratory, need to be made fully autonomous, flight worthy
  - Modeling now has tools to reduce time and risk of development
    - CFD to investigate details of operation, appears valid
    - SDM to investigate complete system dynamic interaction, including thermal condition, controller and end user load



Conclusion

- The status of Stirling development has changed fundamentally since 1999 with data at hand
  - Over 80,000 hours of operation of prototypical hardware
  - QA system understood including lessons learned from long life cyrocooler industry
  - Materials well characterized for long life and high reliability (metallics and organics)
  - Structural dynamics tests show successful operation at high levels of vibration
  - Critical component aging has been modeled and is being validated
  - Success of Stirling flight cryocoolers (and long-life terrestrial units) provides supporting data in power convertor transition to flight
  - Generator integration successful for launch loads
- Some areas remain to be completed, system integration, flight controller, extended operation of integrated generator, etc
- Third general phase will be concluded with successful system integration of free-piston Stirling into a system