MEMO **October 31, 2018**

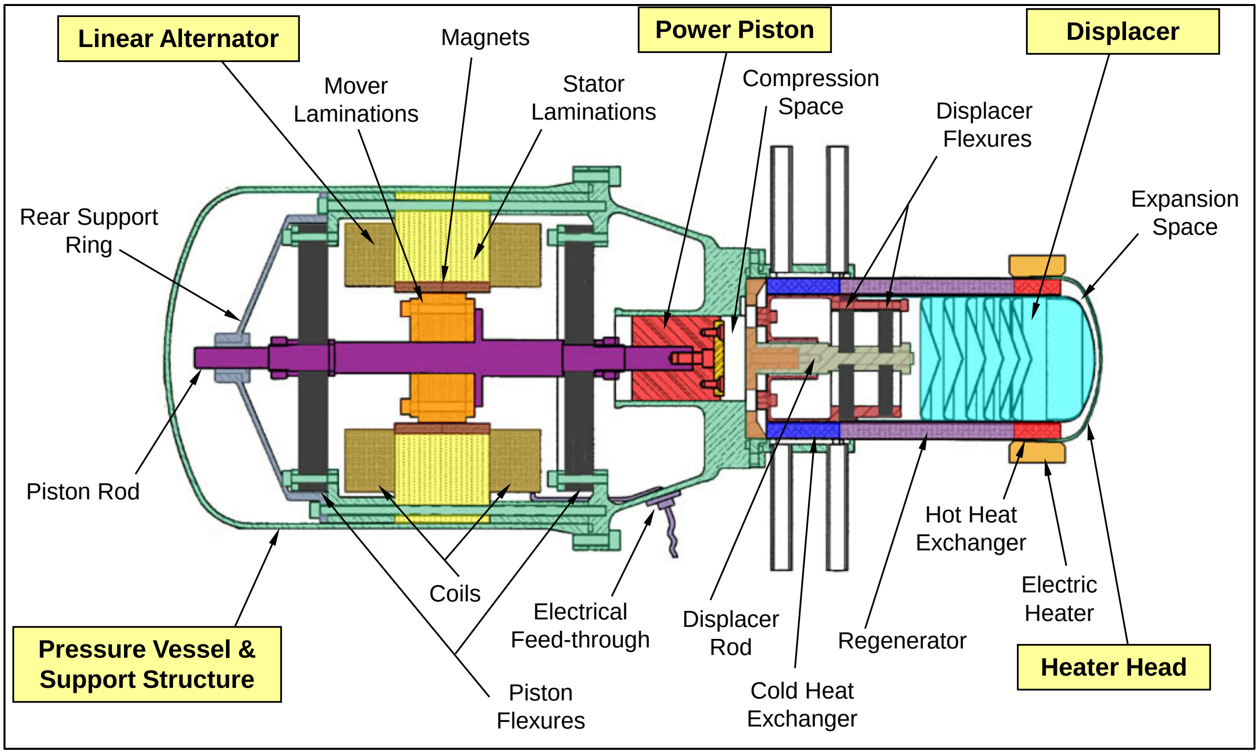
To : Glenn Turner, Stirling Engine Society
From : Sal Oriti, NASA Glenn Research Center, Cleveland, OH
Subject : New runtime record set for free-piston Stirling machine

Mr. Turner,

Greetings from the NASA Glenn Research Center in Cleveland Ohio! Thank you for your query about our pursuit of Stirling-cycle power conversion for NASA's missions. I am writing you today to describe the recent progress we've made in the arena of long-life heat engines for power conversion.

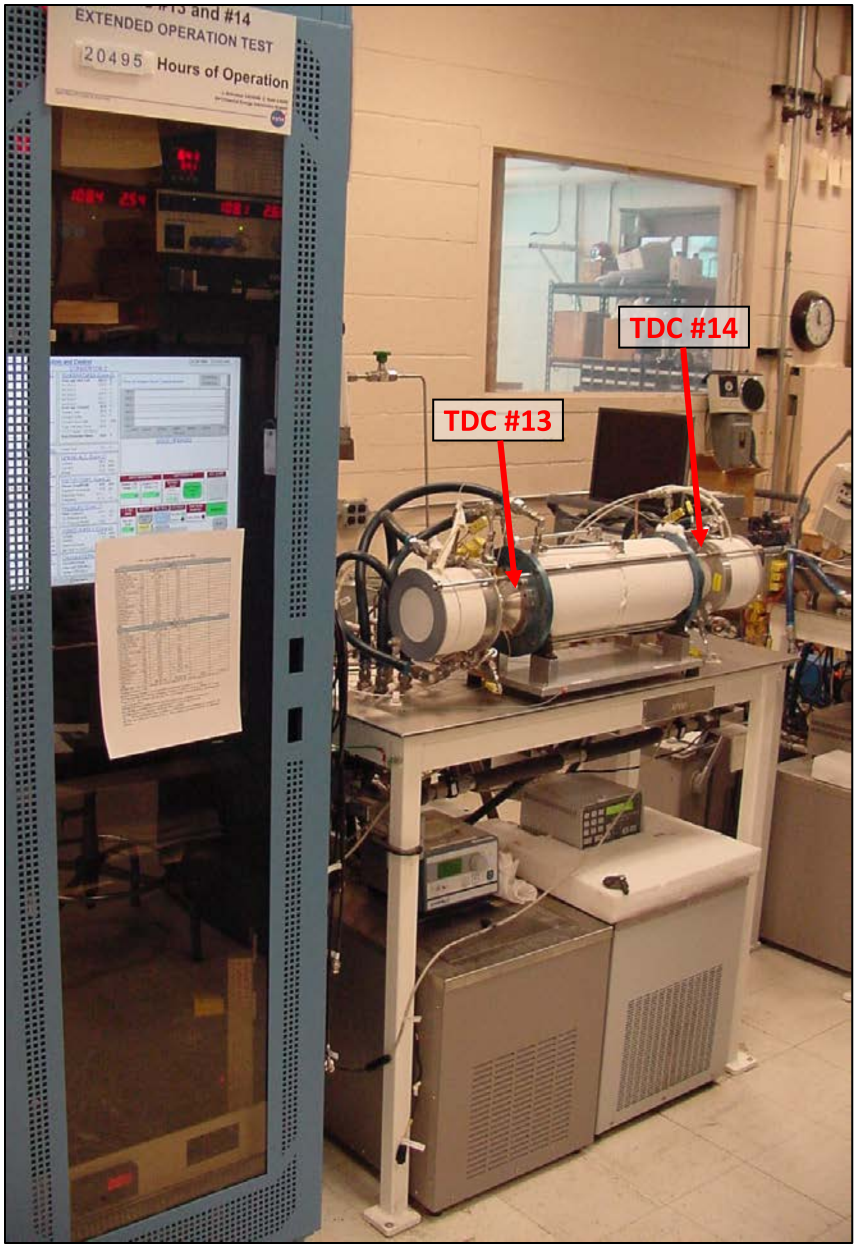
NASA has been developing Stirling-cycle machines for power conversion since the 1970s. At that time, it was recognized that such a device could be designed to achieve long-life continuous operation with high reliability, by leveraging the free-piston configuration in favor of a kinematic engine. The free-piston variant eliminates the wear mechanisms associated with rolling-element bearings, piston rings, and connecting rods, typically found in kinematic Stirling engine designs. By restricting the moving components to linear motion only, there is no need to convert linear piston movement to rotating motion. With this, the moving components can be suspended within their cylinders by non-contacting bearings and seals can be effected with close clearances, also non-contacting. The use of a linear alternator attached directly to the piston enables direct conversion of heat, to mechanical, then to electrical energy, all in one hermetically sealed vessel. The electrical output requires only simple feedthroughs, and the complexity of sealing a rotating crankshaft is eliminated. In the free-piston variant, the displacer-to-piston phase is not implemented by a connection to a common rotating shaft. Instead, the pressure wave itself is used to drive the displacer. The displacer is designed to have a higher natural frequency of motion than the piston, which achieves a leading phase angle required for power production. The free-piston Stirling behaves like a spring-mass-damper system, with a forcing function created by the alternate heater and cooling of the working gas, and damping provided by the current flowing through the linear alternator. Two types of non-contacting bearings are available to designers: flexure and gas bearings. Flexure bearings can be constructed from a spiral-cut disc of metal that has high radial stiffness but a deliberately engineered stiffness in the axial direction, to permit piston and displacer resonant motion. Gas bearings can be implemented with a pressure source and precisely machined flow channels to provide a radial stiffness around the moving component. The pressure source can be supplied by the engine's pressure wave itself.

In the late 1990's, the US government invested in the development of small free-piston Stirling technology for radioisotope-heated electrical power sources. A research contract was awarded to a company named Stirling Technology Company (STC), which has since been acquired and is now known as American SuperConductor (AMSC). This contract was focused on developing a free-piston Stirling convertor (engine with linear alternator) prototype. This design was deemed the Technology Demonstration Convertor (TDC). The TDC was sized to accept heat from one of the DOE's General Purpose Heat Source (GPHS) modules, which produces 250 W_{th}. The GPHS has been the Pu-238 radioisotope heat source used for many NASA missions that required nuclear power. Not all of the module heat can be directed into the conversion device. From a thermal input of 220 W_{th}, (a reasonable estimate of how much of the 250 W_{th} can be captured) the TDC produces 65 W_e, for a conversion efficiency of 29%. In 2001, the TDC was adopted as the conversion device by a project to develop flight radioisotope-heated generator, which was deemed SRG-110. Several convertor prototypes were produced throughout this timeframe. The TDC design is illustrated below:

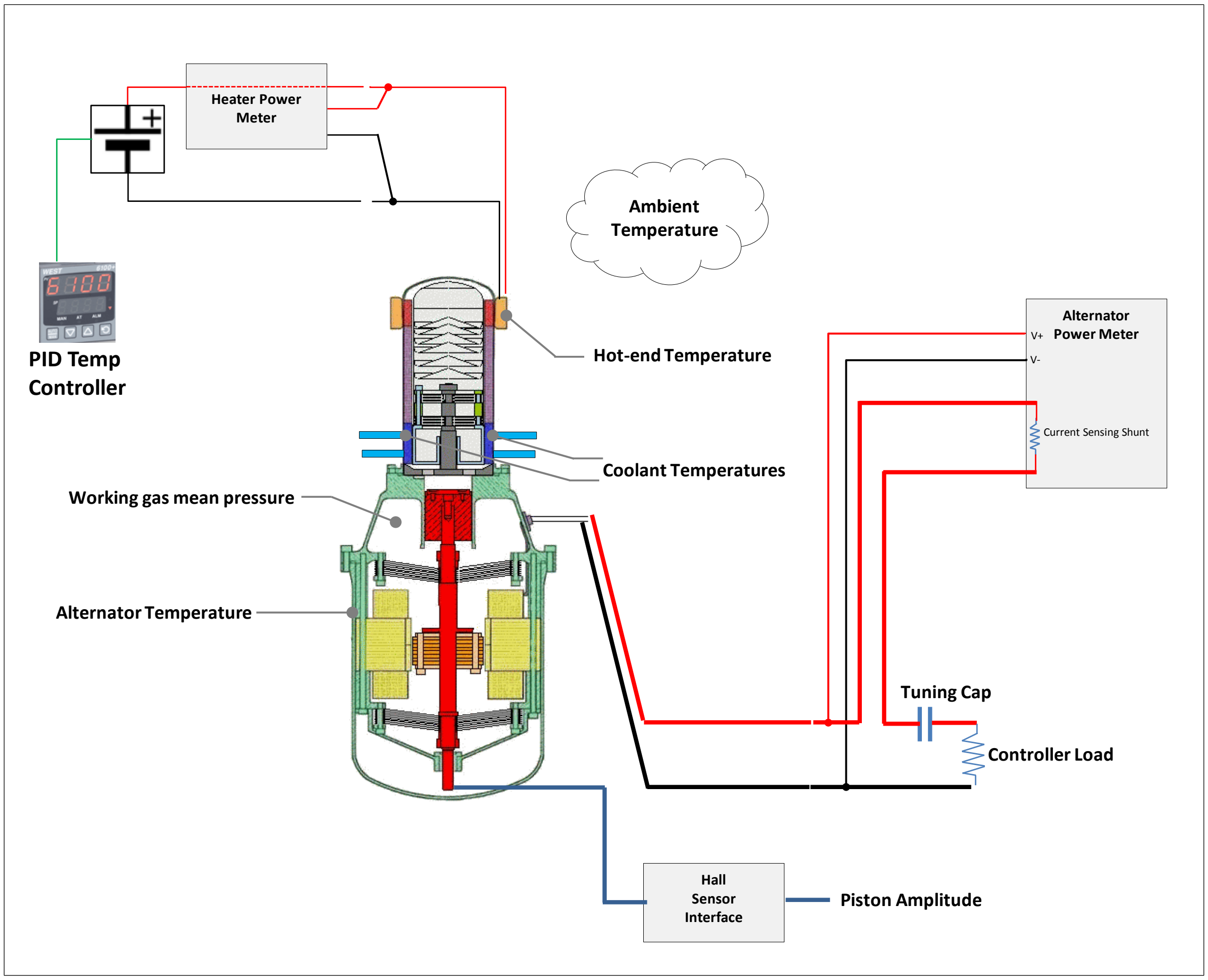


It consists of a flexure-supported displacer with an internal rod and gas volume. The piston and its associated rod are supported by larger flexures, and the moving iron lamination portion of the linear alternator is directly attached to the piston rod. Close clearance seals exist between the piston and its cylinder, the displacer and the cold-end exchanger, and between the displacer and its rod. The seal between the displacer rod and the displacer itself is necessary to provide a constant-pressure space inside the displacer. With this, the pressure wave from the alternate heating and cooling, and the displacer rod area, creates an excitation force to drive the displacer. The dynamics of all components are designed so that the displacer motion leads the piston motion.

NASA Glenn has performed a significant amount of research on these pieces of hardware to support its use as a critical element in NASA missions. The longest running units are TDC serial no. 13 and 14. These units were placed on continuous operation in July of 2003. NASA developed specialized test stations for this purpose. The test stations are capable of autonomously monitoring the test article parameters and safely shutting down operation if a fault condition occurs. The stations are powered by battery-backup supplies and can continue operation through a short grid power outage. The data system was tailored to automatically record and organize all the sensor data. We currently record all data at a rate of 0.5 Hz. An image of the test station is shown here:



The two TDCs were arranged in the dual-opposed, horizontal configuration, with their hot ends facing outwards. In the image, the convertors are obscured by the insulation and supporting items such as fluid hoses. Standard laboratory fluid circulators were implemented to effect cold-end temperature control. Electric heaters were arranged on the hot end of the convertor to provide thermal power input, which are temperature-controlled by a PID loop. Operation with this test station is not uninterrupted, as annual test equipment calibration requires a manual shutdown of the convertors. However, cumulative operation is still an effective metric for demonstrating long life. Also, one could say that the far more numerous thermal cycles than a spaceflight application demonstrate an element of robustness in the design. A spaceflight convertor would operate non-stop after fueling with Pu-238, as there is no way to turn off the heat source power in that case. An illustration of the instrumentation used to monitor convertor performance is shown below. The test setup provides us the ability to track performance very accurately, and examine for any signs of degradation:



TDC 14 was taken offline for disassembly and inspection after 12 yrs (105,620 hrs) of cumulative operation. It operated without issue during time, and was only taken offline for the valuable inspection. TDC 13 continued operation thereafter. On April 29, 2018, TDC 13 runtime reached 12.55 yrs (110,000 hrs), surpassing the previous record set in 1987 by Ted Cooke-Yarborough's Thermo-Mechanical Generator. TDC 13 has continued to operate and as of October 31, 2018 has reached a runtime of 113,200 hours. Performance of the machine over this length of time has been encouraging. After correcting disturbances due to facility equipment, there have been no signs of degradation, either in power output nor efficiency. Throughout this time, no maintenance or part replacement was necessary. Only small replenishments of the helium working gas were necessary, as TDC 13 has imperfect weld seal joints. A hermetically sealed flight unit would exhibit no working gas loss. The surpassing of the previous record makes TDC 13 the longest running zero-maintenance heat engine in the history of human civilization that we know of. This is a bold statement as it captures all engines ever built for automotive, terrestrial power generation, and aircraft. By way of engineering comparison, an automotive engine typically requires an overhaul after 10,000 hours of operation. Terrestrial and aircraft gas turbine engines also have regular maintenance schedules. NASA Glenn is also operating several other free-piston Stirling machines, and a few are close to this runtime as well. TDC serial no 15 and 16 have reached 12.0 yrs (105,300 hrs) of operation. A gas-bearing unit, called the Advanced Stirling Convertor (ASC), has operated for 8.7 yrs (76,400 hrs). Since 2000, testing of several dozen free-piston Stirling convertors of both bearing technologies have accumulated over 1 million convertor-hours of operation, demonstrating long-life reliability of this technology.