Stirling Convertor (Engine) Power Generation System: Control Electronics

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Sponsors:

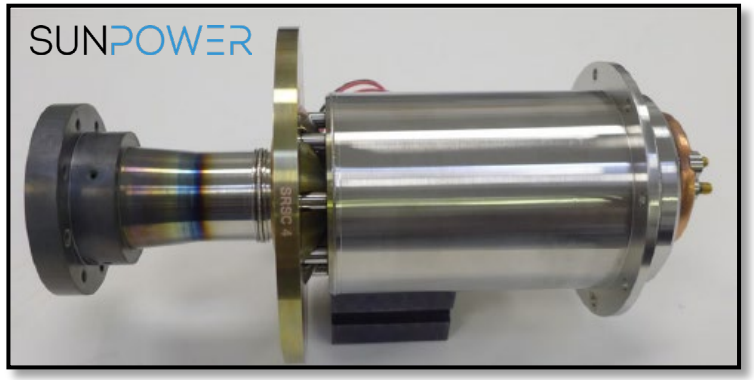
INTUITIVE MACHINES

AIR FORCE RESEARCH LABORATORY

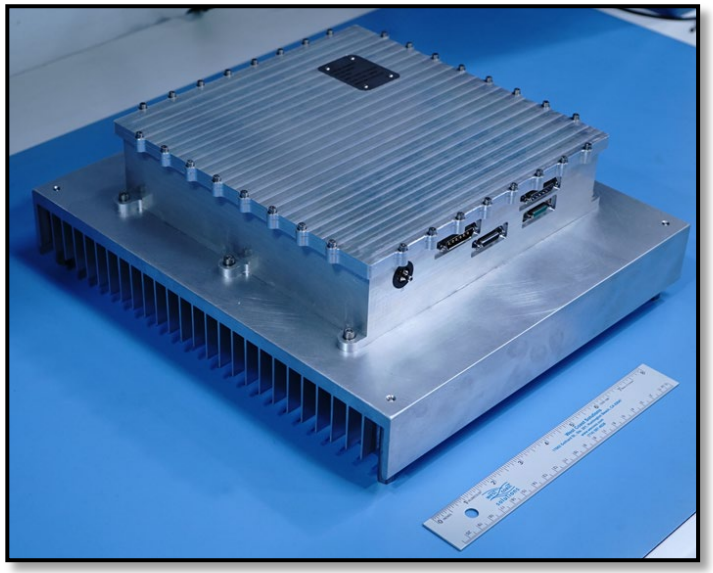
Background and Motivation

- Radioisotope Power Systems (RPS) consist of a heat-generating isotope power source in combination with a thermal / electrical power conversion system
  - Legacy RPS systems utilized thermoelectric conversion with efficiency **~6%**
  - Stirling power conversion efficiency currently approaches **30%** → *less isotope required for a given power level*
- High-efficiency, Stirling RPS are garnering interest for multiple applications, including Deep space probes, rovers and landers, and lunar Survive the Night applications
- Stirling Convertors themselves are approaching maturity, though they must be paired with a suitable space-compatible, radiation hardened controller system
  - **Controller / Convertor interactions are nontrivial, and demonstration of a path-to-flight controller with a Stirling Convertor provides substantial risk reduction for a variety of current and future programs**
- AFRL and Intuitive Machines are planning to fly a Sunpower Convertor and WCS Controller on the Space Operations via Nuclear Emerging Technologies (SONET) Program
- Initial demonstration flight has been dubbed Stirling Technology spAce Research experiment (START)

Intuitive Machines and AFRL sponsored a critical risk reduction test to prove the viability of the combined path-to-flight SRSC / SCSC power conversion system



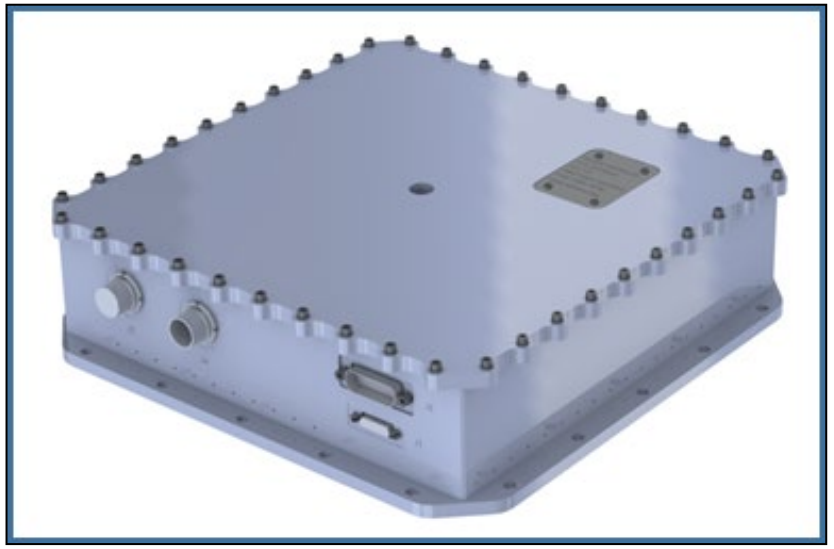
Sunpower Robust Stirling Convertor (SRSC)



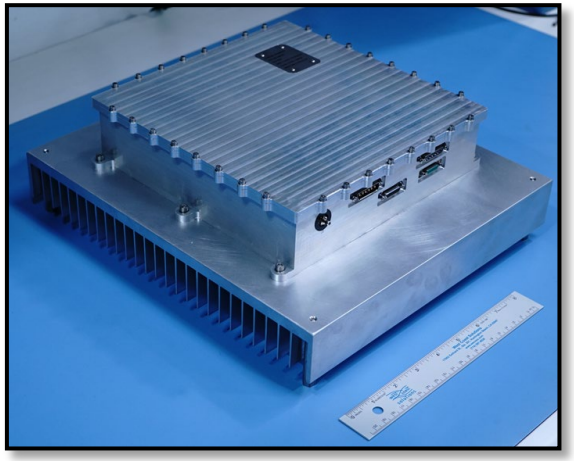
Stirling Convertor Space Controller (SCSC): High Fidelity Brassboard Unit

Stirling Convertor Space Controller(SCSC)

- WCS has developed a spaceflight, radiation hardened Stirling Convertor Space Controller (SCSC) through the NASA SBIR Program (Phase II and Phase III)
- Engineering Model Qualification Unit is in assembly with Qual Testing scheduled for June 2026
- Flight Model is at CDR level – final assembly pending successful EM Qual
- High fidelity Brassboard (BB) SCSC from the Phase I SBIR used for the Risk Reduction testing due to availability
- The BB SCSC contains all of the necessary functionality for the planned testing, and was designed with a straightforward path-to-flight
- BB SCSC circuit board integrated with a convective heatsink for the planned benchtop testing



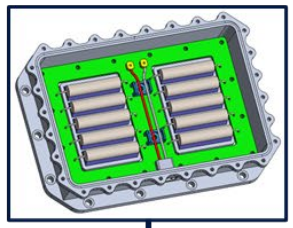
EM/FM SCSC. 10” x 10” x 2.8”; ~ 4kg



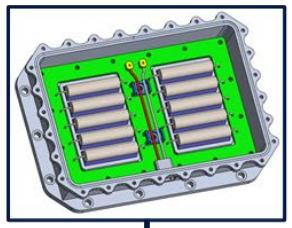
BB SCSC used for risk reduction testing in October 2025.

The BB SCSC is highly representative of the Flight Model SCSC

Flight SCSC Functional Block Diagram



30 W Shunt Array



30 W Shunt Array

BB version used for test essentially identical in architecture. Primary differences were COTS vs. Flight parts and reduced telemetry channels.

Shunt Regulator 2

Shunt Regulator 1

External Power Input

Startup Power
22 – 36 V

Sunpower AVC

Active Vibration Balancer H-Bridge

Midpoint Energy Storage (capacitance)

Bus Interface Converter

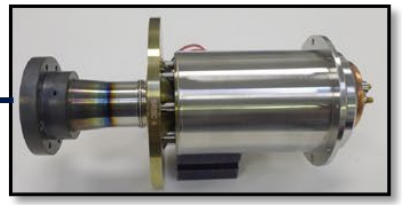
Downstream Loads
22 – 36 V

Accelerometer

Charge Amplifier

Microcontroller

Converter (Engine) Interface H-Bridge



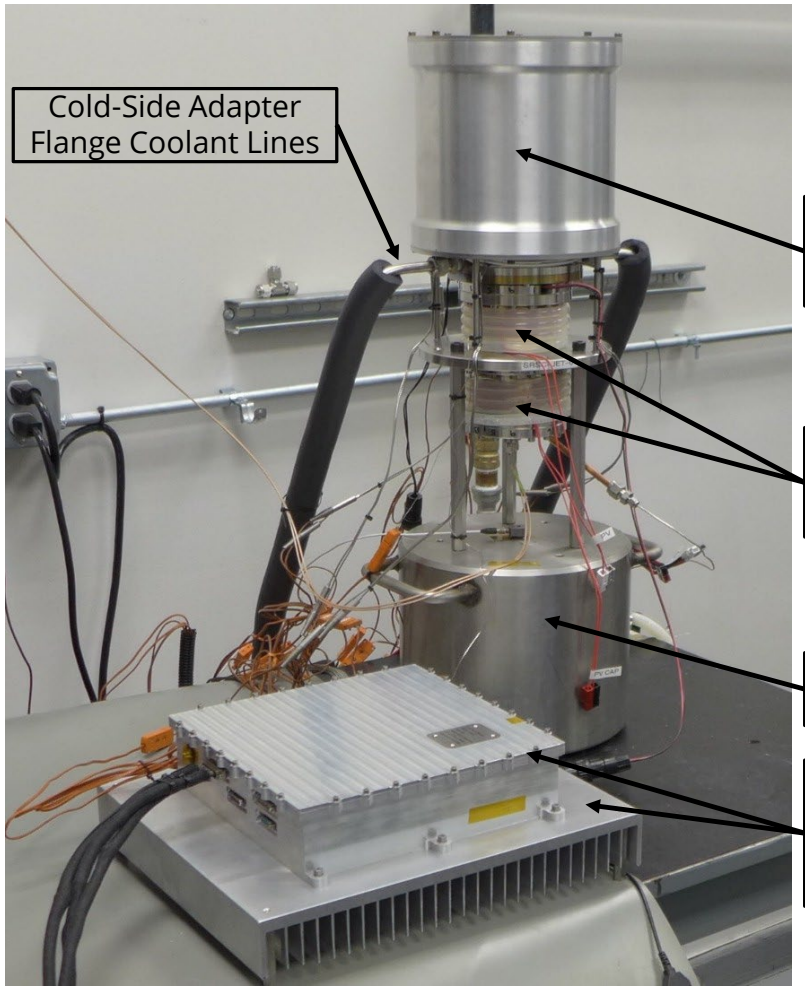
SRSC

Thermocouples

Telemetry
8x type K TCs
2x type-N TCs
2x FLDT interfaces

SCSC Controller Chassis

Sunpower Test Facility and Setup



Test Results: Steady-State Mapping

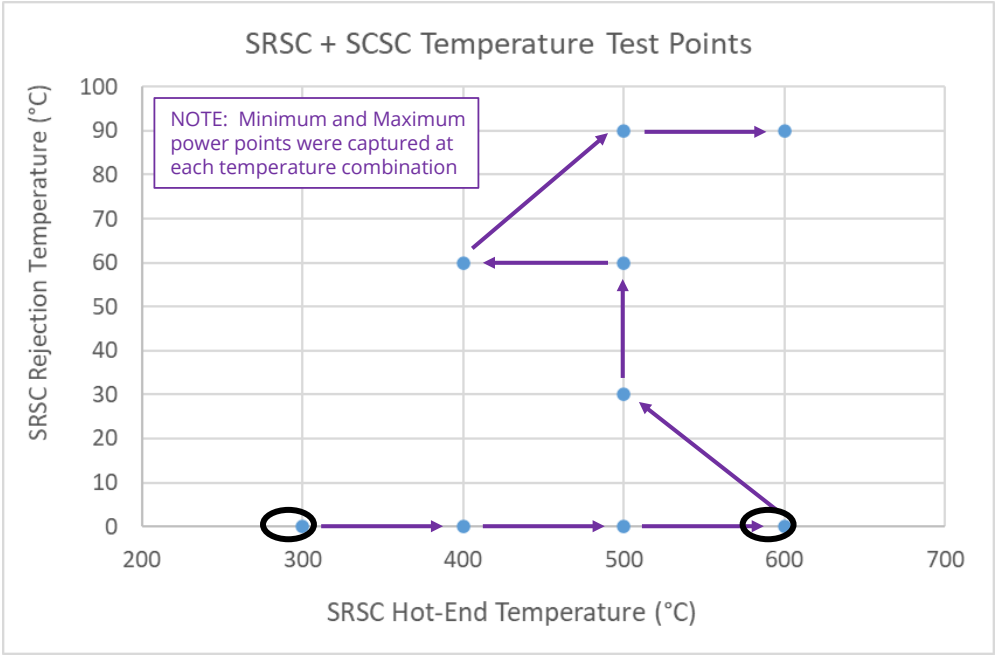
300 °C
0 °C reject

600 °C
5 °C reject

SRSC / SCSC Steady-State Testing	All points recorded on 10/29/2025																			
SRSC Hot-End Temp [C]	299.2	301.1	399.9	399.9	498.9	501.1	599.6	598	500.3	500.9	500.4	498.2	498.9	402.2	401	498.9	497.9	600.8	599.6
SRSC Rejection (CSAF) Temp [C]	0.2	2.1	2.6	0.8	1.9	4.4	5.1	2.4	29.9	30	30.2	60.3	59.7	59.8	60.5	90.9	89.3	90.8	89.7
CSAF Temp Control Cart Setting [C]	-10	-22	-22	-10	-10	-23	-24	-11	19.5	12.3	6	36.5	50.5	51	38	68	81	81.5	65.5
SRSC Alternator Stroke [normalized]	1.06	2.135	2.145	1.06	1.08	2.22	2.245	1.08	1.08	1.7	2.135	2.185	1.07	1.09	2.18	2.19	1.045	1.085	2.17
SRSC Displacer Stroke [normalized]	0.84	1.5	1.57	0.875	0.92	1.67	1.73	0.935	0.94	1.36	1.645	1.7	0.95	0.935	1.64	1.725	0.945	1.005	1.77
SCSC Chassis Temp [C]	23.5	24.4	24.9	24.5	24.1	24.6	25.2	24.9	24.2	24.5	24.9	25.2	24.9	24.7	24.7	25	25	24.8	25.2
SCSC PCBA Temp [C]	24.2	25.9	26.7	25.6	25.3	26.7	27.7	26.4	25.6	26.2	27	27	26.2	25.6	25.9	26.7	26.2	26.2	27.6
SCSC Terminal AC Power [W]	8.83	23.15	38.53	12.44	15.4	52.74	63.46	16.93	15.1	33.82	49.47	48.81	14.12	11.92	35.75	44.5	12.39	15.17	55.2
SCSC DC Bus Power Output [W]	2.65	15.38	30.08	5.95	8.5	43.25	52.94	9.67	8.26	25.73	40.56	40.25	7.38	5.6	28.36	36.3	5.75	7.92	45.3
SCSC DC Bus Voltage Output [V]	4.77	11.44	15.93	7.07	8.46	19.04	21.06	8.97	8.29	14.66	18.42	18.35	7.84	6.83	15.39	17.42	6.92	8.12	19.5
SCSC DC Bus Current Output [A]	0.56	1.34	1.89	0.84	1.01	2.27	2.51	1.08	0.99	1.75	2.2	2.19	0.94	0.82	1.84	2.08	0.83	0.97	2.33

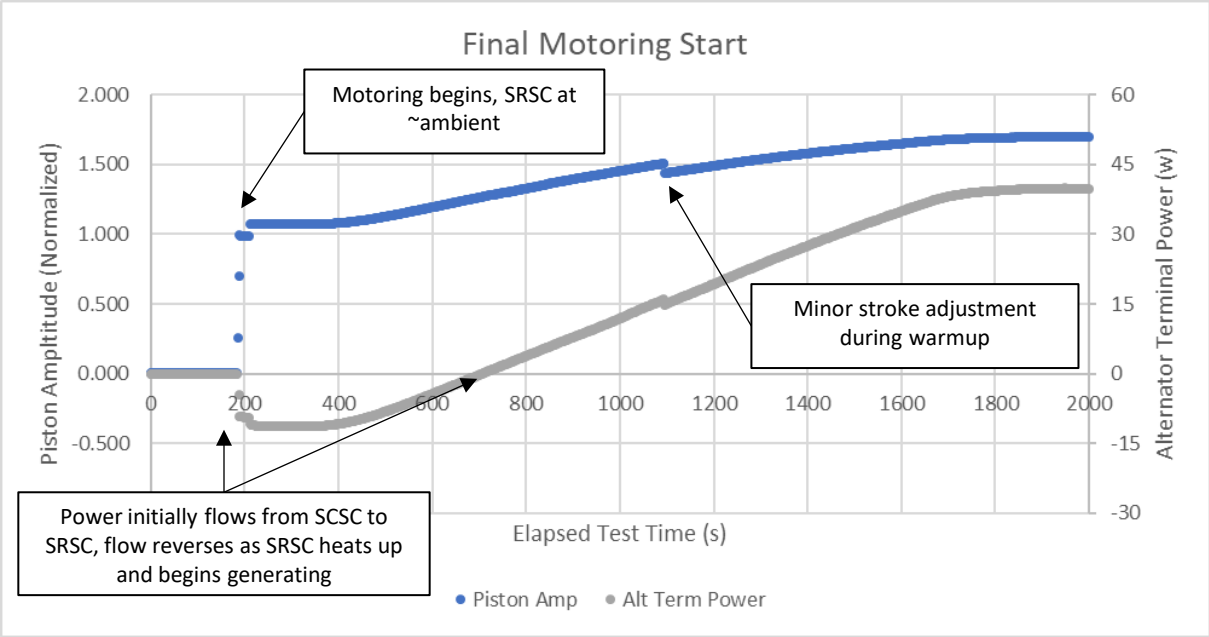
Lowest Power:
8.8 Wac

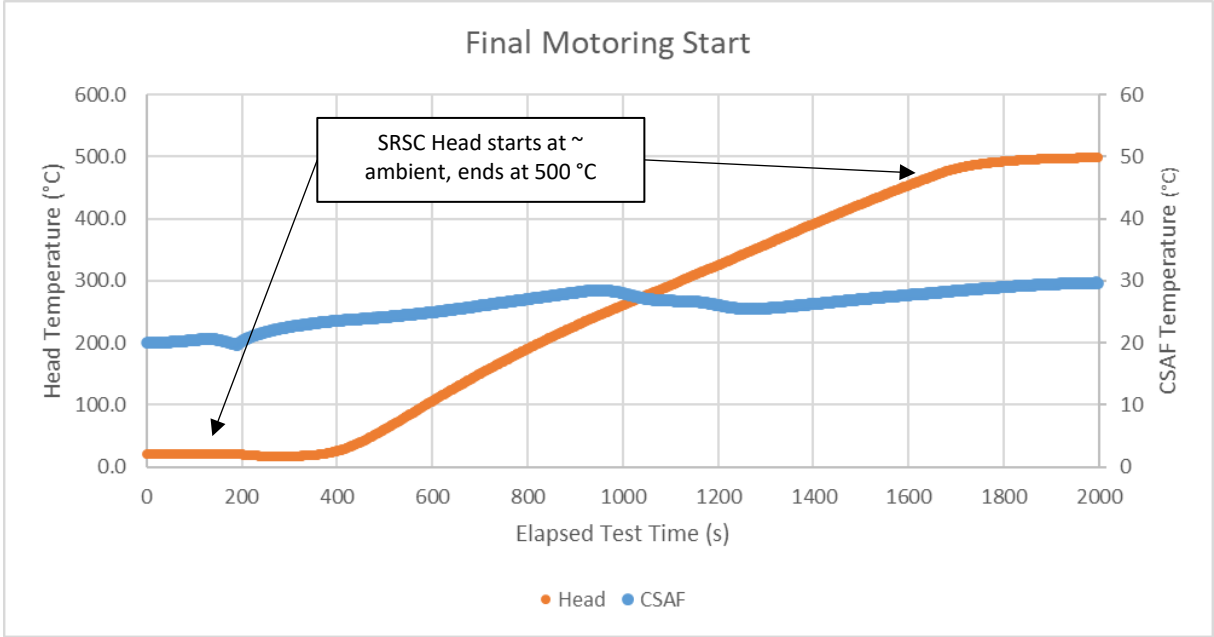
Highest Power:
63.5 Wac



Steady-State testing was performed across a wide range of source (hot end) and rejection temperatures.
SRSC AC power levels (input to the SCSC) range from ~9 W to ~63 W.

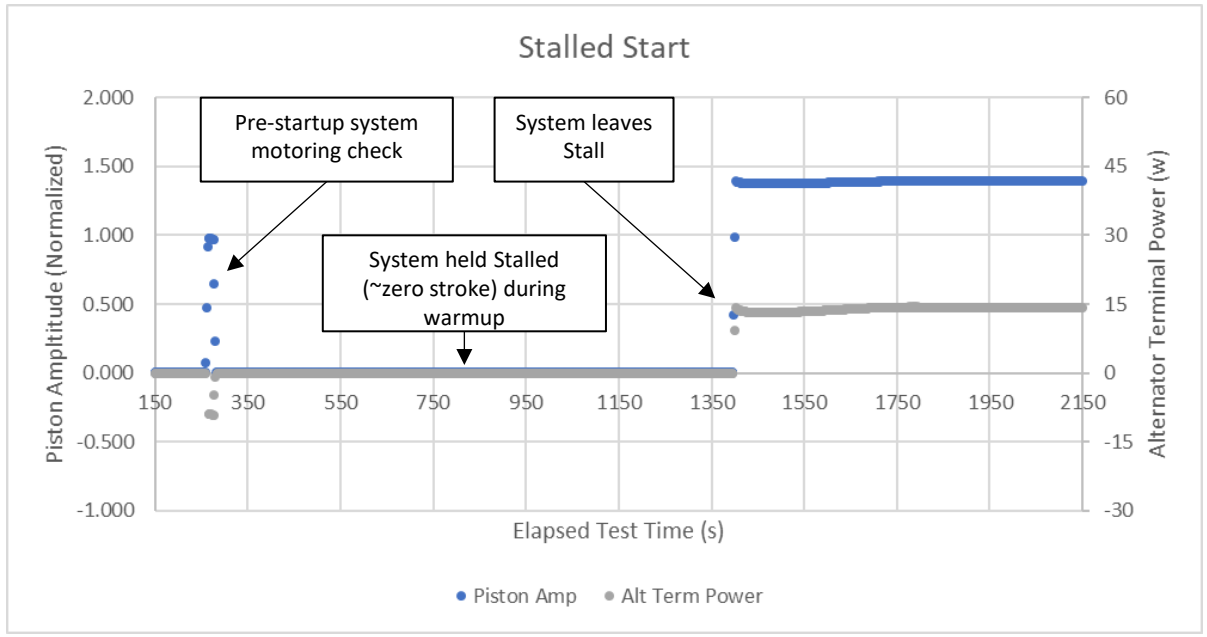
Test Results: Motor Startups

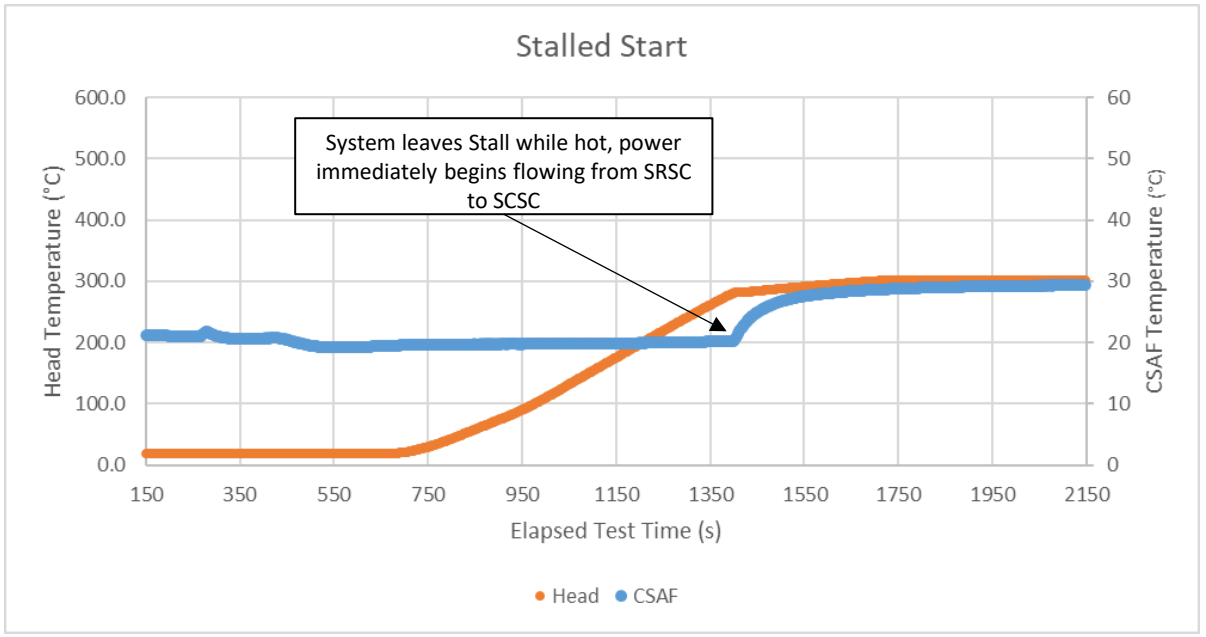




Motoring-type startup procedures were utilized twice in the testing, no issues in either case

Test Results: Stalled Startup

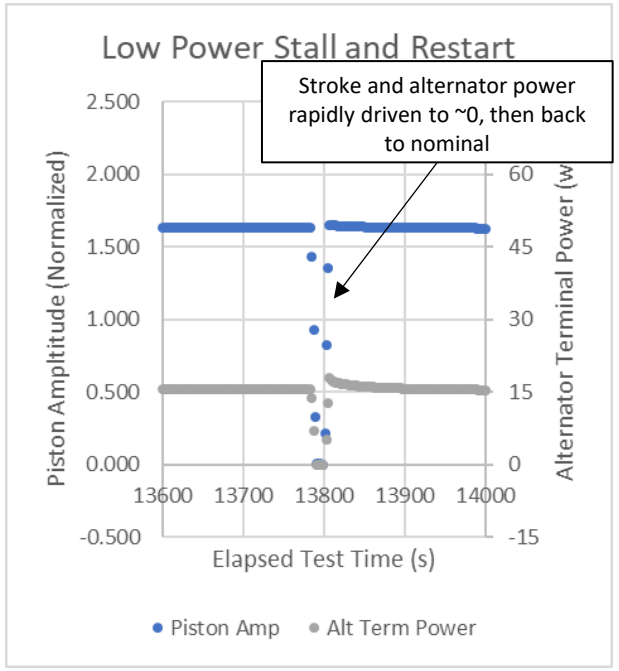


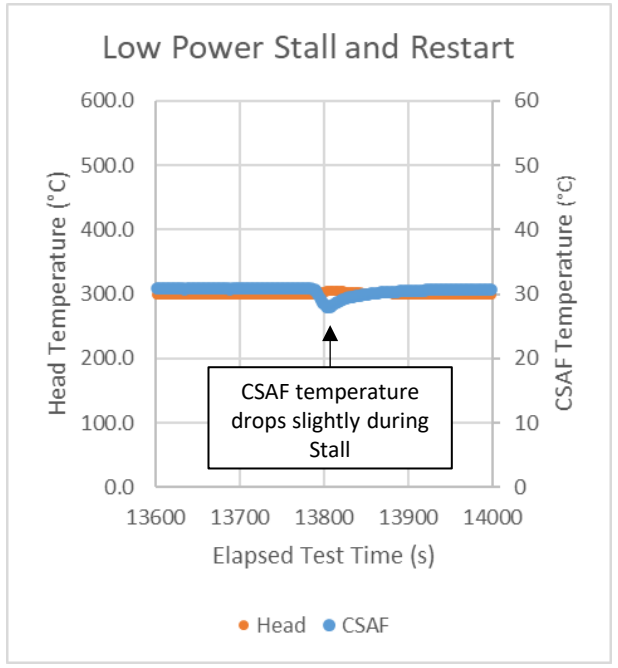


System was held in Stalled state during warmup, piston stroke ramped up at Head temperature of ~300 °C with power immediately being delivered by SRSC to SCSC

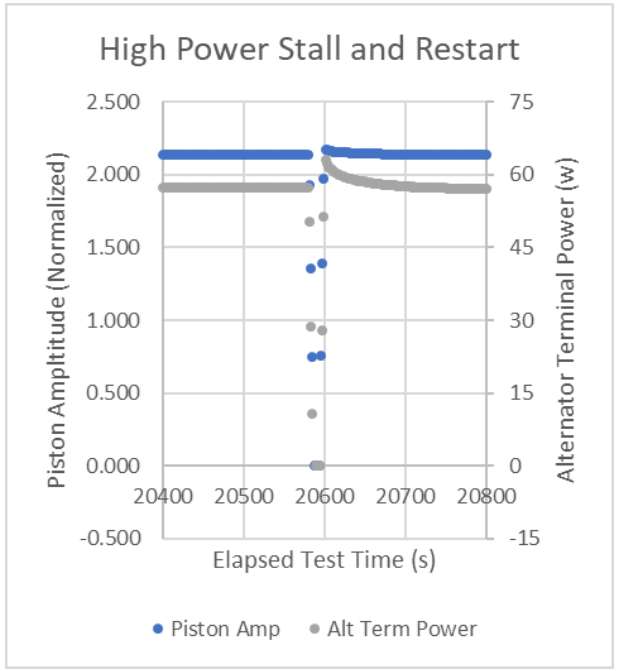
Test Results: Stall and Restart Demonstration

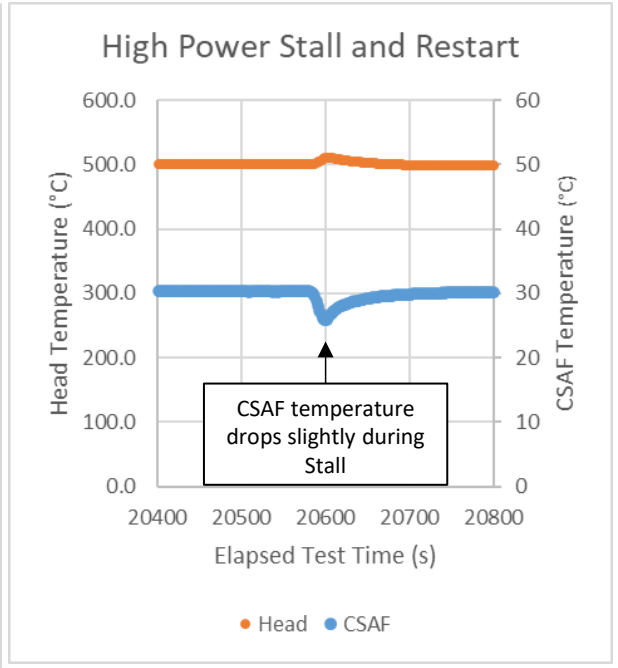
Low-Power demonstration at 300 °C and 15 Wac





High-Power demonstration at 500 °C and > 50 Wac

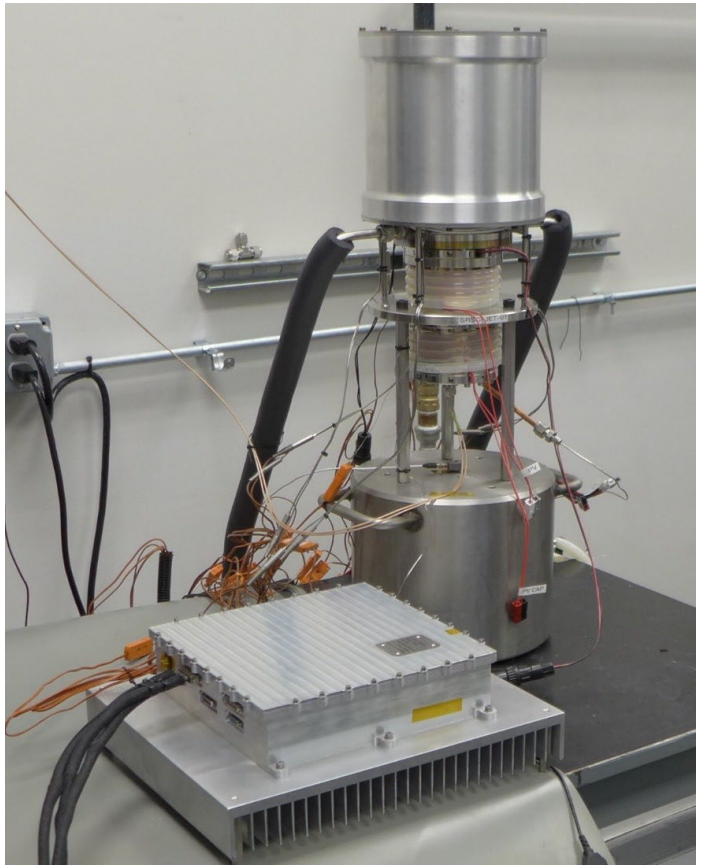




Stall / Restart procedure demonstrates SCSC ability to induce SRSC stall in a hot system, and subsequent controlled restart; stable control demonstrated

Conclusion

- This test marked the first time a *path-to-flight* controller has been used to drive an actual Stirling Convertor (to our knowledge)
- All test goals met with significant demonstrations achieved
  - Motoring and Stalled startup procedures
  - Hot stall-and-restart
  - System shutdown
  - Accumulated steady-state operation time
- SRSC / SCSC highly scalable to meet higher power demands
  - Sunpower had demonstrated up to 6 kW Convertors
  - WCS under contract to develop an 8-channel SCSC (>500 W)
  - Higher power single- and multi-channel Controllers on the WCS Road Map



Stirling Convertor / Convertor Controller Power Chain Successfully Demonstrated – Proving Viability for a Wide Range of Applications