# Modeling and Analysis of Stirling Power Convertors

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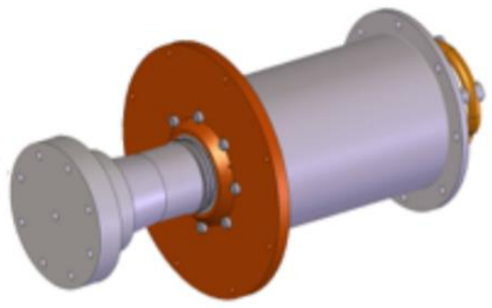
# Introduction

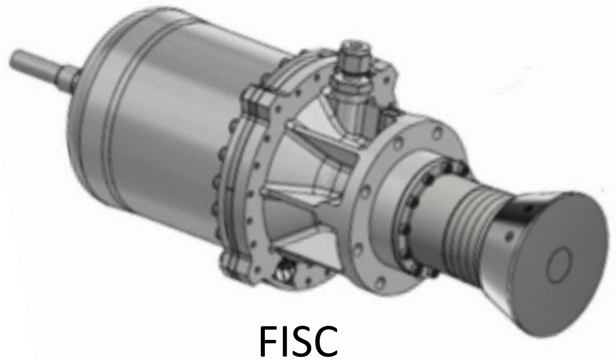
- NASA is developing Free-piston Stirling convertors as a steady source of electrical power for future space missions

- NASA Currently has contracts with Sunpower Inc. and American Superconductor (AMSC)
  - Sunpower Inc. is developing the Sunpower Robust Stirling Convertor (SRSC)
    - Both SRSC #1 and #2 delivered to GRC Oct 2020 and under test
  - AMSC is developing the Flexure Isotope Stirling Convertor (FISC)
    - Manufacturer completing testing on FISC pair, anticipate delivery summer 2021

- Both mechanisms used by convertor manufactures provide means of preventing contact in Stirling convertor operation
  - Mechanisms been well proven exceeding 10-14 years of operation at GRC



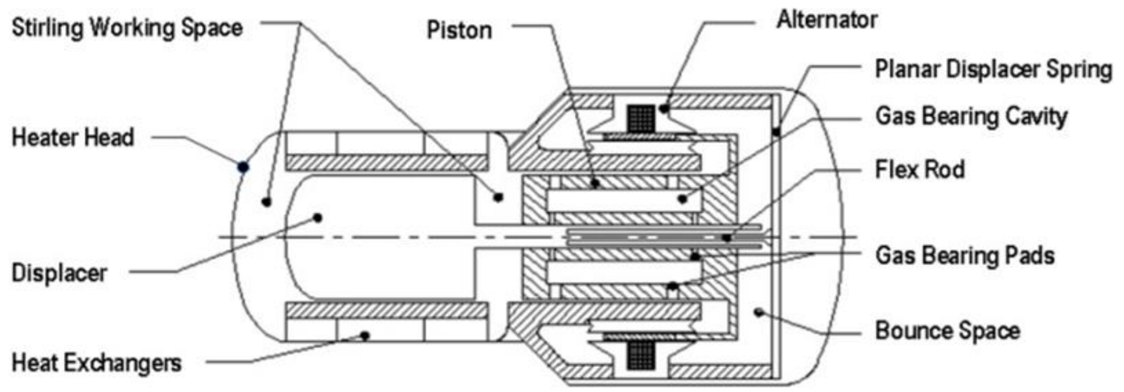
SRSC



FISC

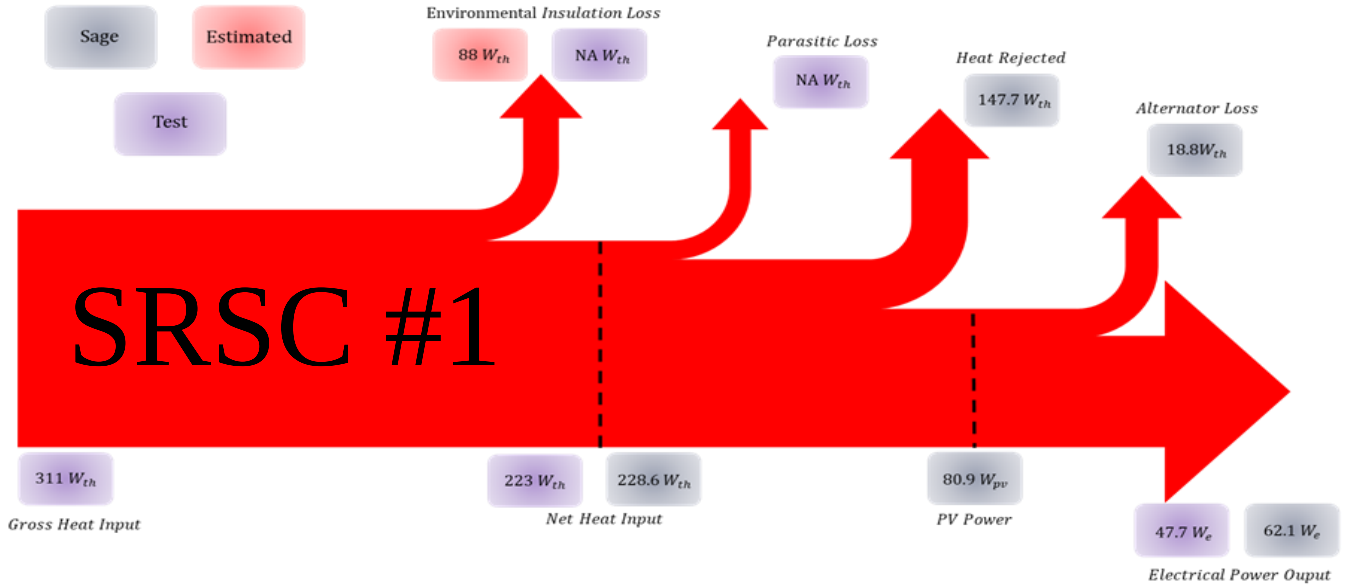
# Introduction

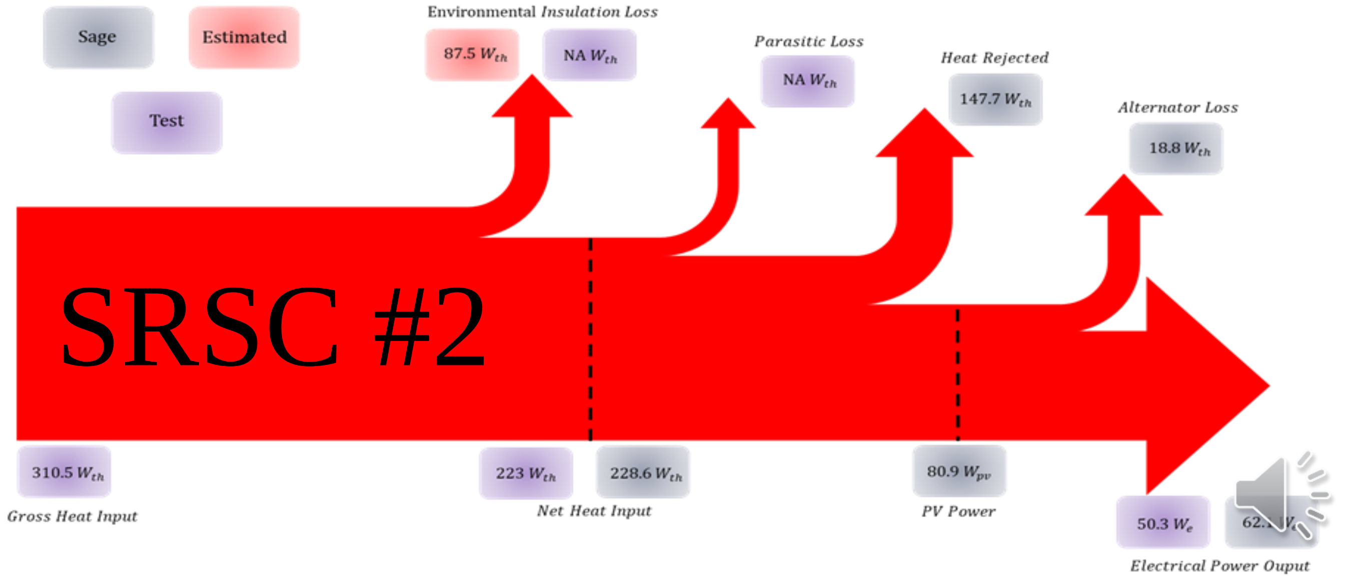
- **Sage** is a one-dimensional object-oriented software package used for modeling and optimizing Stirling convertors
- In this analysis, Sage models are compared against each convertors lab measured performance data and Sankey diagrams are used to illustrate the energy paths through the convertors
- **Ansys Fluent** used to build a 3-D CFD model to examine the Stirling Cycle losses and net heat input of the SRSC convertor
- **Ansys Maxwell** used to create a 3-D axisymmetric model for the SRSC and FISC alternators
- The alternator models calculate terminal voltage, current, electrical power, and efficiency



# Current SRSC Experimental and Sage Data

| Parameter | Definition | Sage Input Value | SRSC #1 Measured Values (08.31.20) | SRSC #2 Measured Values (05.21.20) | Unit |
|---|---|---|---|---|---|
| $X_p$ | Piston Amp. | 4.20 | 3.77 | 3.36 | mm |
| $f$ | Operating Frequency | 96 | 99.6 | 99.6 | Hz |
| $P_{charge}$ | Charge Pressure (abs.) | 3.8e6 (551.14) | 4.238e6 (614.7) | 4.238e6 (614.7) | Pa (psi) |
| $T_h$ | Hot End Temperature | 720 | 700.3 | 699.3 | ℃ |
| $T_k$ | Cold End Temperature | 100 | 100.3 | 99.6 | ℃ |
| **Parameter** | **Definition** | **Sage Output Value** | **SRSC #1 Measured Values (08.31.20)** | **SRSC #2 Measured Values (05.21.20)** | **Unit** |
| $X_d$ | Displacer Amp. | 3.15 | 3.01 | 2.97 | mm |
| $\phi_{diff}$ | Phase Difference | 53.92 | 55.7 | 58.4 | deg |
| $Q_{in}$ | Net Heat Input | 228.56 | 223 | 223 | Watt |
| $Q_{rej}$ | Net Heat Rejected | 147.68 | - | - | Watt |
| $W_{pv}$ | Piston PV Power | 80.88 | - | - | Watt |
| $W_{alt}$ | Electrical Power Out | 62.11 | 47.7 | 50.3 | Watt |
| $\eta_{conv}$ | Convertor Efficiency | 27.17 | 21.4 | 22.6 | % |

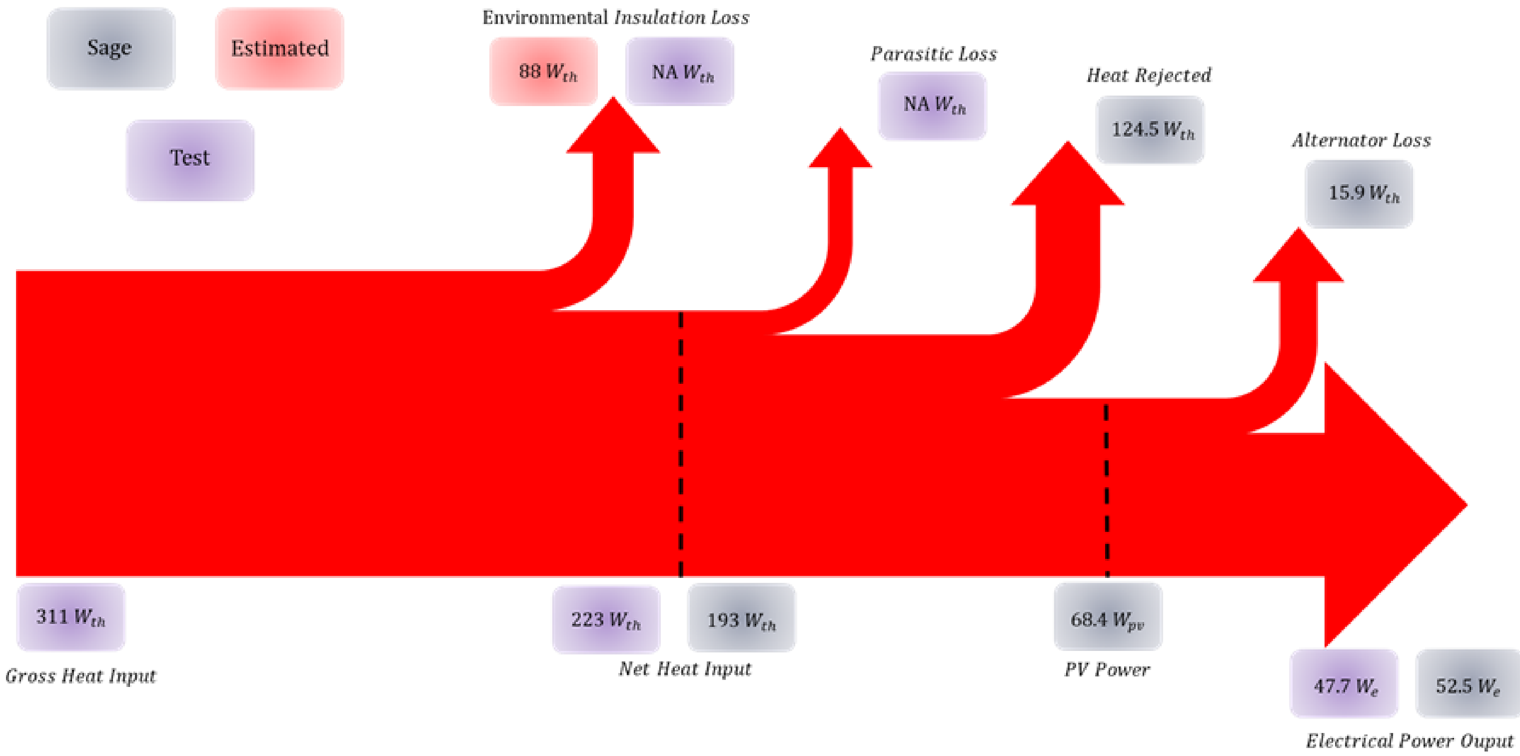


# SRSC #1 Calibrated Sage Model

| Parameter | Definition | Sage Input | SRSC #1 Measured Values (08.31.20) | Unit |
|---|---|---|---|---|
| $X_p$ | Piston Amp. | 3.77 | 3.77 | mm |
| $f$ | Operating Frequency | 99.6 | 99.6 | Hz |
| $P_{charge}$ | Charge Pressure (abs.) | 4.238e6 (614.7) | 4.238e6 (614.7) | Pa (psi) |
| $T_h$ | Hot End Temperature | 700 | 700.3 | ℃ |
| $T_k$ | Cold End Temperature | 100 | 100.3 | ℃ |

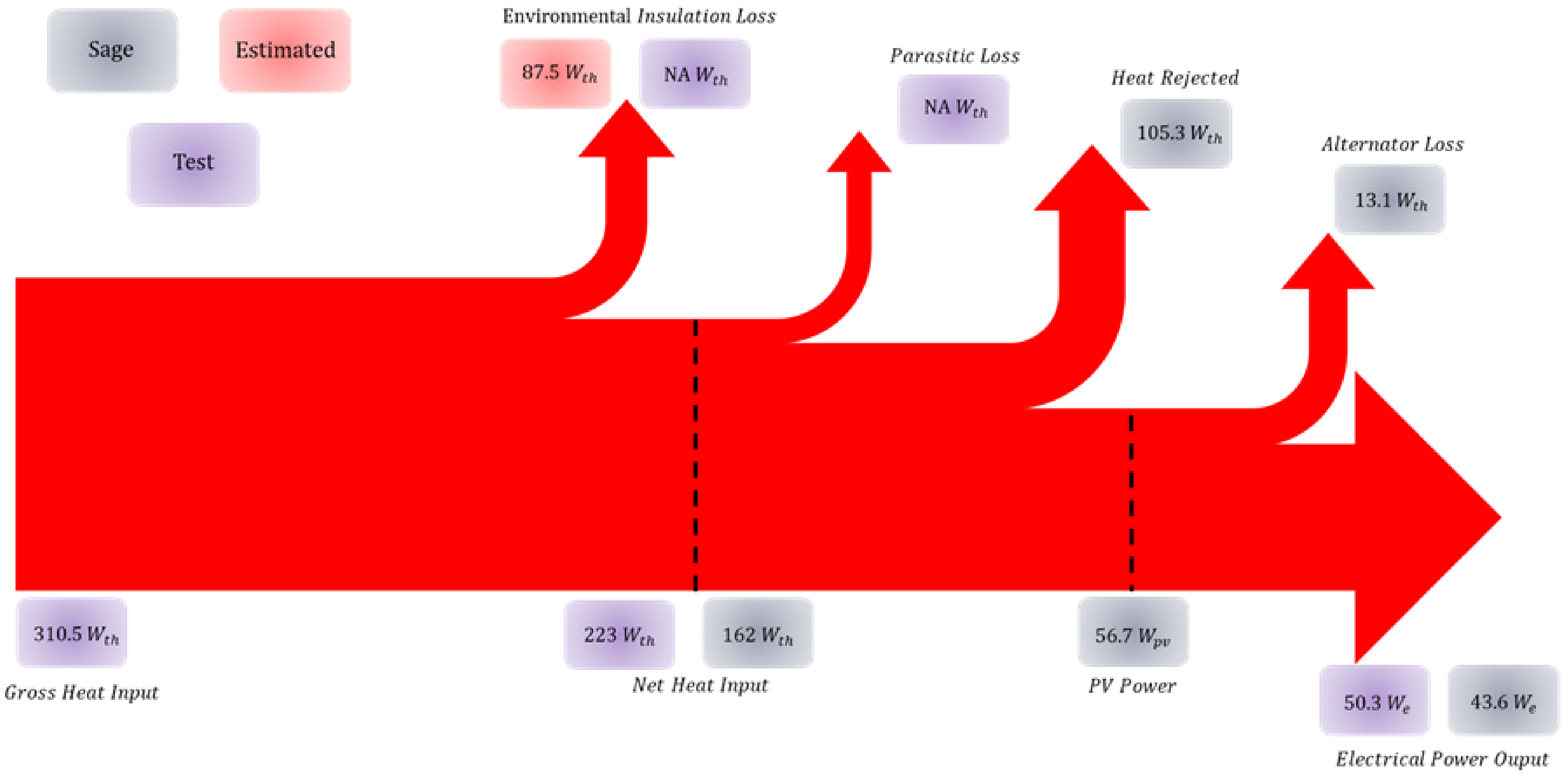
| Parameter | Definition | Sage Output | SRSC #1 Measured Values (08.31.20) | Unit | Error (%) |
|---|---|---|---|---|---|
| $X_d$ | Displacer Amp. | 2.97 | 3.01 | mm | 1.4 |
| $\phi_{diff}$ | Phase Difference | 43.6 | 55.7 | deg | 21.7 |
| $Q_{in}$ | Net Heat Input | 193.0 | 223 | Watt | 13.5 |
| $Q_{rej}$ | Net Heat Rejected | 124.5 | - | Watt | - |
| $W_{pv}$ | Piston PV Power | 68.4 | - | Watt | - |
| $W_{alt}$ | Electrical Power Out | 52.5 | 47.7 | Watt | 10.1 |
| $\eta_{conv}$ | Convertor Efficiency | 27.2 | 21.4 | % | 27.2 |



# SRSC #2 Calibrated Sage Model

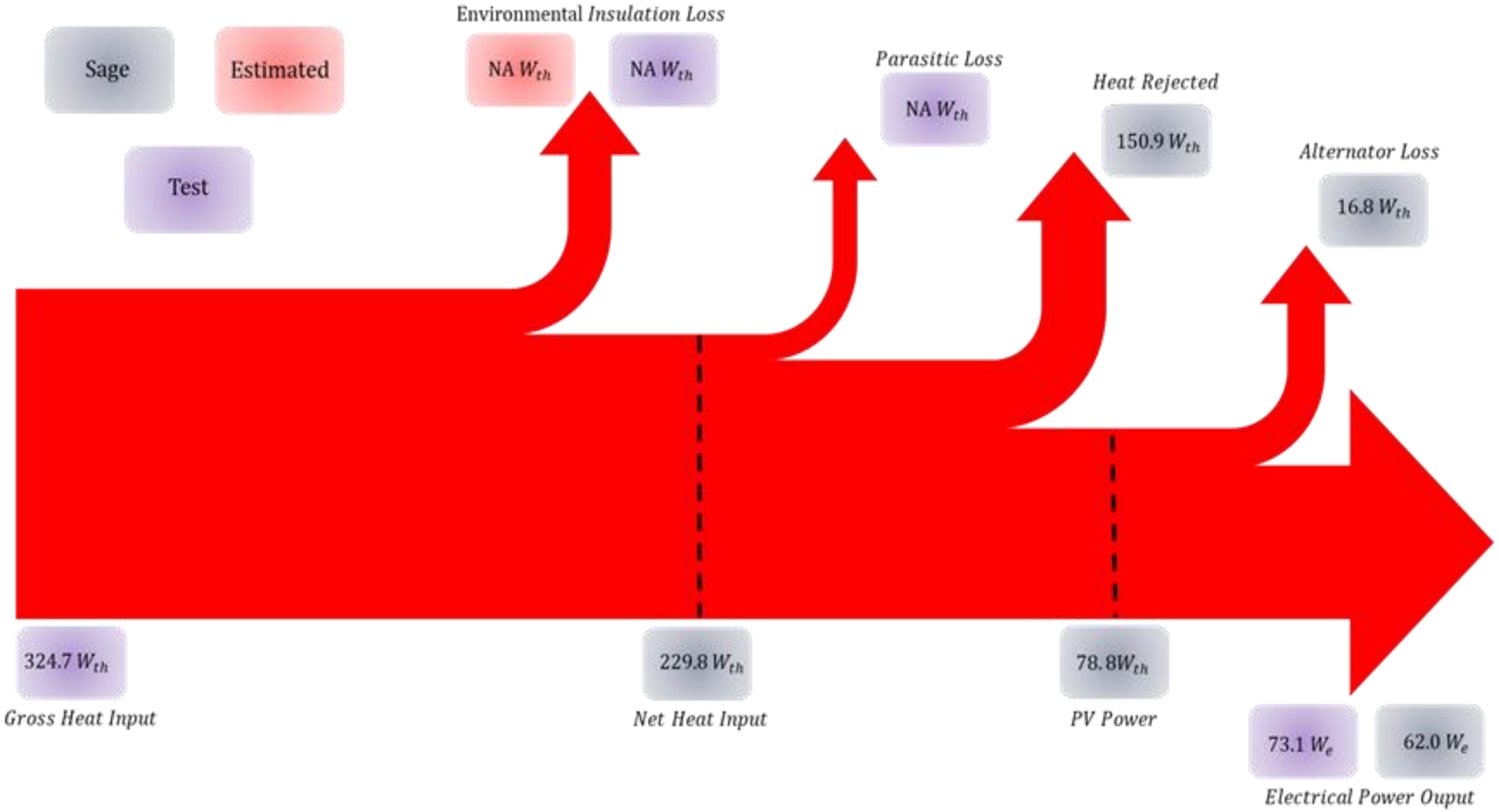
| Parameter | Definition | Sage Input | SRSC #2 Measured Values (05.21.20) | Unit |
|---|---|---|---|---|
| $X_p$ | Piston Amp. | 3.36 | 3.36 | mm |
| $f$ | Operating Frequency | 99.6 | 99.6 | Hz |
| $P_{charge}$ | Charge Pressure (abs.) | 4.238e6 (614.7) | 4.238e6 (614.7) | Pa (psi) |
| $T_h$ | Hot End Temperature | 700 | 699.3 | ℃ |
| $T_k$ | Cold End Temperature | 100 | 99.6 | ℃ |

| Parameter | Definition | Sage Output | SRSC #2 Measured Values (05.21.20) | Unit | Error (%) |
|---|---|---|---|---|---|
| $X_d$ | Displacer Amp. | 2.68 | 2.97 | mm | 9.8 |
| $\phi_{diff}$ | Phase Difference | 43.8 | 58.4 | deg | 24.9 |
| $Q_{in}$ | Net Heat Input | 162.0 | 223 | Watt | 27.4 |
| $Q_{rej}$ | Net Heat Rejected | 105.3 | - | Watt | - |
| $W_{pv}$ | Piston PV Power | 56.7 | - | Watt | - |
| $W_{alt}$ | Electrical Power Out | 43.6 | 50.3 | Watt | 13.4 |
| $\eta_{conv}$ | Convertor Efficiency | 26.9 | 22.6 | % | 19.0 |



# Current FISC Experimental and Sage Data

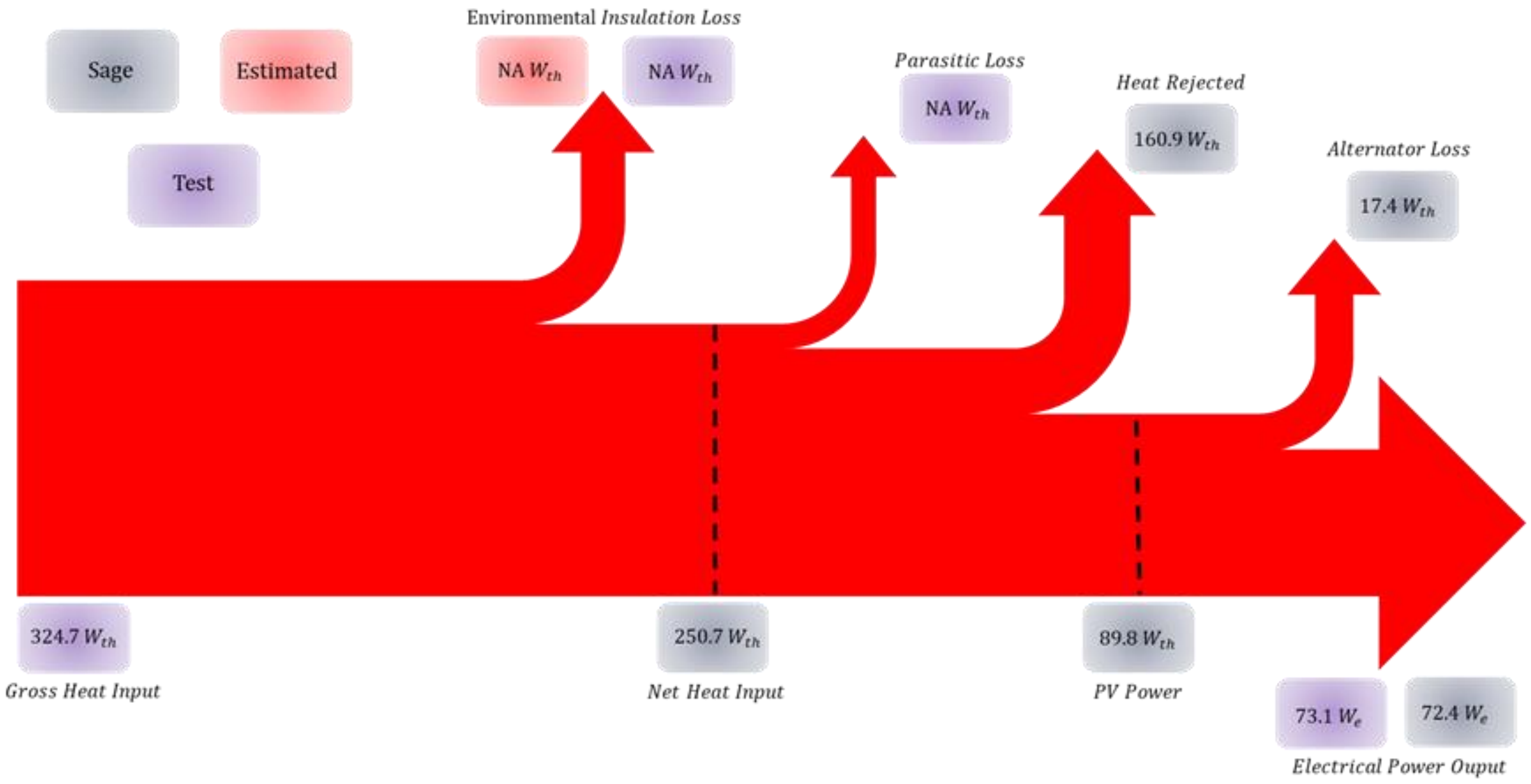
| Parameters | Definition | Sage Input | Measured Values (02.08.21 Results) | Unit |
|---|---|---|---|---|
| $X_p$ | Piston Amp. | 5.55 | 5.86 | mm |
| $f$ | Operating Frequency | 81 | 82.9 | Hz |
| $P_{charge}$ | Charge Pressure (abs.) | 2.5e6 (362.59) | 2.48e6 (359.74) | Pa (psi) |
| $T_h$ | Hot End Temperature | 613.8 | 652.4 | °C |
| $T_k$ | Cold End Temperature | 100.1 | 104.6 | °C |
| **Parameter** | **Definition** | **Sage Output** | **Measured Values (02.08.21)** | **Unit** |
| $X_d$ | Displacer Amp. | 2.64 | 2.87 | mm |
| $\phi_{diff}$ | Phase Difference | 74.7 | 72.4 | deg |
| $Q_{in}$ | Net Heat Input | 229.8 | - | Watt |
| $Q_{rej}$ | Net Heat Rejected | 150.9 | - | Watt |
| $W_{pv}$ | Piston PV Power | 78.8 | - | Watt |
| $W_{alt}$ | Electrical Power Out | 62.0 | 73.1 | Watt |
| $\eta_{conv}$ | Convertor Efficiency | 27.0 | 25.4 | % |



# FISC Calibrated Sage Model

| Parameters | Definition | Sage Input | Measured Values (02.08.21 Results) | Unit |
|---|---|---|---|---|
| $X_p$ | Piston Amp. | 5.86 | 5.86 | mm |
| $f$ | Operating Frequency | 82.9 | 82.9 | Hz |
| $P_{charge}$ | Charge Pressure (abs.) | 2.48e6 (359.74) | 2.48e6 (359.74) | Pa (psi) |
| $T_h$ | Hot End Temperature | 652.4 | 652.4 | °C |
| $T_k$ | Cold End Temperature | 104.6 | 104.6 | °C |

| Parameter | Definition | Sage Output | Measured Values (02.08.21 Results) | Unit | Error (%) |
|---|---|---|---|---|---|
| $X_d$ | Displacer Amp. | 2.84 | 2.87 | mm | 1.1 |
| $\phi_{diff}$ | Phase Difference | 64.0 | 72.4 | deg | 11.6 |
| $Q_{in}$ | Net Heat Input | 250.7 | - | Watt | - |
| $Q_{rej}$ | Net Heat Rejected | 160.9 | - | Watt | - |
| $W_{pv}$ | Piston PV Power | 89.8 | - | Watt | - |
| $W_{alt}$ | Electrical Power Out | 72.4 | 73.1 | Watt | 1.0 |
| $\eta_{conv}$ | Convertor Efficiency | 28.9 | 25.4 | % | 13.7 |

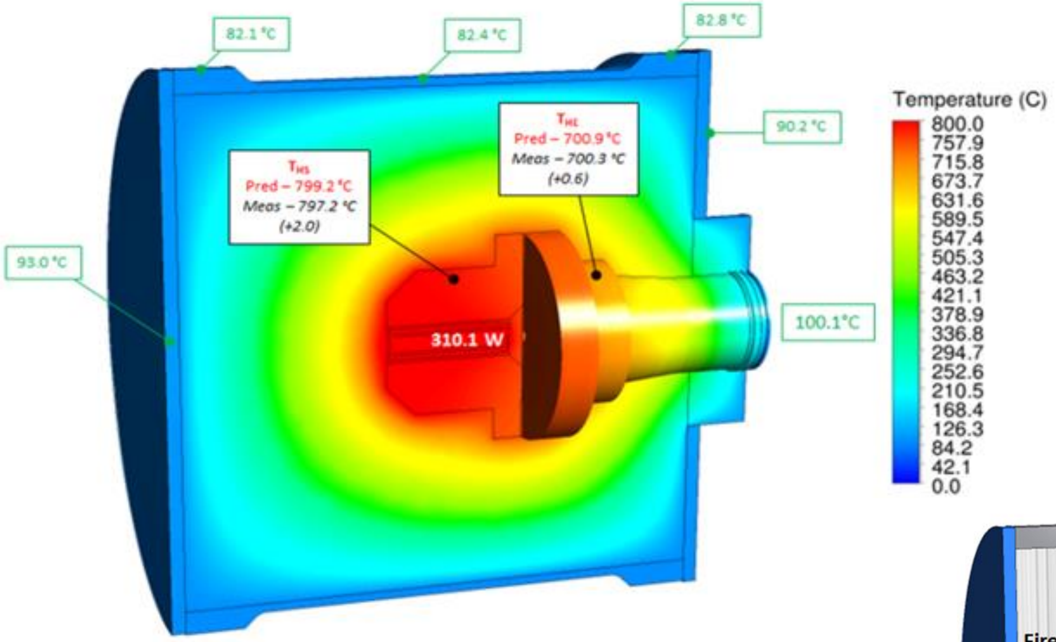


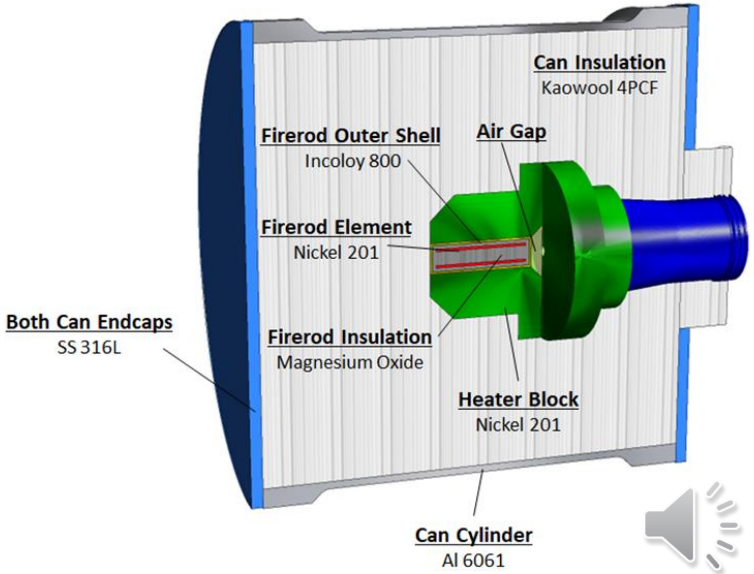
# SRSC-Stirling 3D CFD Model Analysis

- The Goal is to use ANSYs Fluent CFD to tools to understand what is going on inside the convertor
  - Since it is difficult to measure some parameters such as Qesd and parasitic losses

- Lab gathered temperature boundary conditions, geometry, heat inputs, and material properties are used to determine the net heat input, parasitic losses, and convertor efficiency

- Hence, after heat input and temperature data is collected, Fluent is run in a steady-state mode using a pressure-based solver with the ideal gas law applied to the working fluid



# Stirling 3D CFD Model Analysis

- When extracting variables from the converged solution, results indicated that the extracted heat, cold-end losses out of the CSAF, and environmental losses are $Q_{esd}$, $Q_{ce}$, and $Q_{env}$

- These losses can be used to predict parasitic losses and net heat input

**Units for values are Watts**

| Parameters | SRSC # 1 | SRSC #2 | ANSYS Fluent |
|---|---|---|---|
| $Q_{htr}$ | 311.0 | 310.5 | 310.1 |
| $Q_{ce}$ | - | - | 24.2 |
| $Q_{env}$ | 88 | 87.5 | 89.4 |
| $Q_{parasitic}$ | - | - | 113.6 |
| $Q_{in}$ | 223 | 223 | 220.7 |

$Q_{esd}$ = 196.5 W

$Q_{ce}$ = 24.2 W

$Q_{env}$ = 89.4 W

Parasitic Losses = $Q_{ce} + Q_{env}$ = 113.6 W

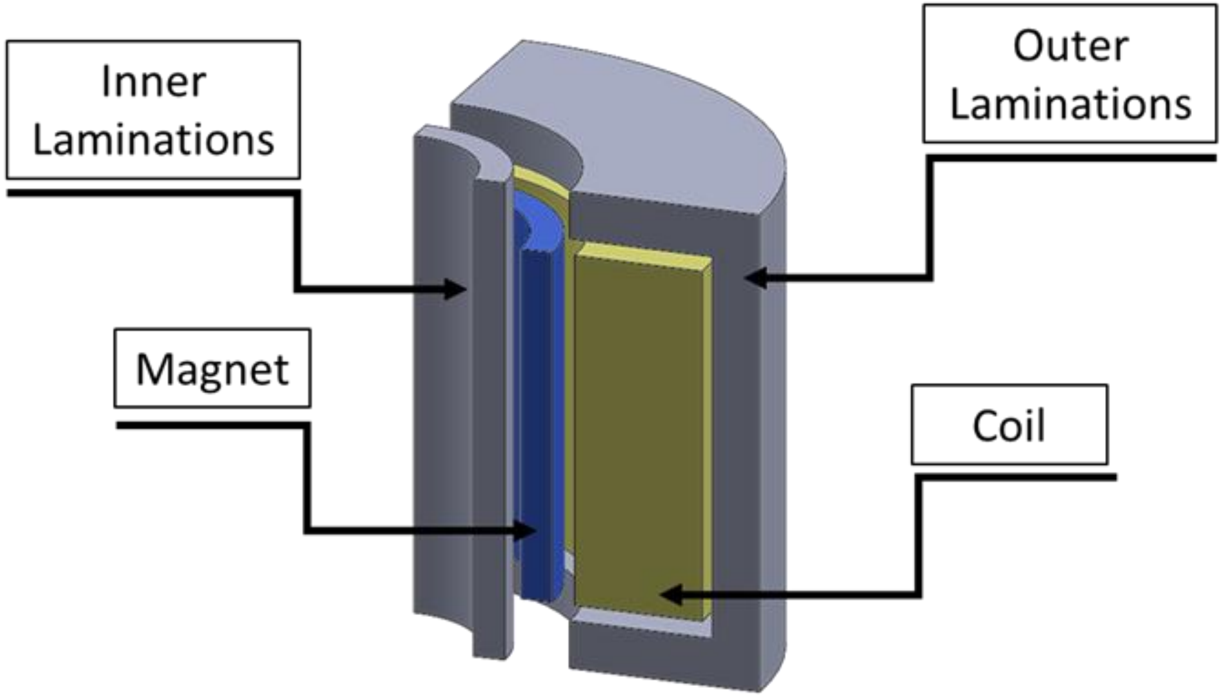
Net Heat Input = $Q_{ce} + Q_{esd}$ = 220.7 W

# Linear Alternator Modeling

- Transient three-dimensional (3D) axisymmetric Maxwell models were prepared for each of the SRSC and FISC linear alternators

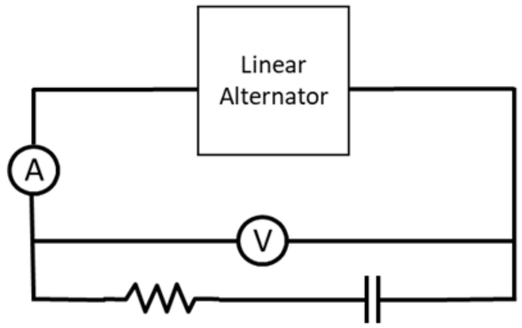
- The key alternator components included for each model are: 1) magnet(s), 2) magnet can (not shown), 3) inner laminations, 4) outer laminations, and 5) coil

- Both alternators are of the moving magnet type, and are made of similar materials

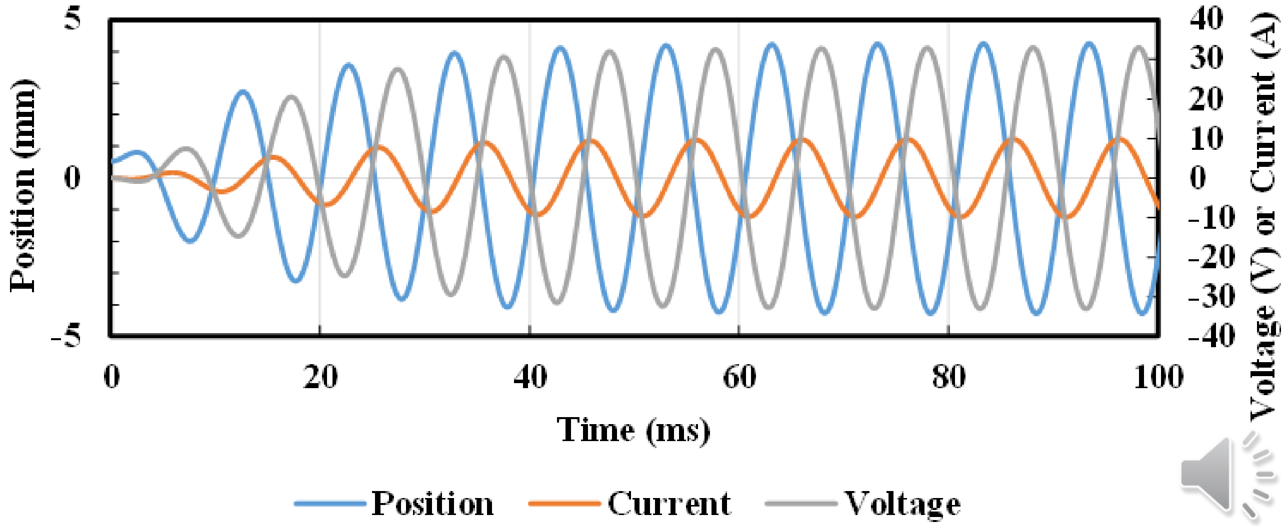


# SRSC : LA Performance Verification

- An external load circuit was added to the SRSC LA
  - The values for the load resistance and tuning capacitor were obtained from Sunpower, and reflect the actual load that was used during checkout testing
- In the transient model, the mover was gradually ramped-up to full stroke operation of 8.5 mm to maintain computational stability
  - The model obtained steady-state operation at about 10 cycles
  - The voltage and current values were calculated at the locations indicated as V and A respectively (In the SRSC Load circuit)




SRSC Load



# SRSC : LA Performance Verification

- Test data was acquired during the October 11, 2019 convertor checkout testing at Sunpower

- The test data indicated that the engine was operated at 3 Hz above the design frequency of 96 Hz
  - Model frequency was adjusted to match the test operating conditions

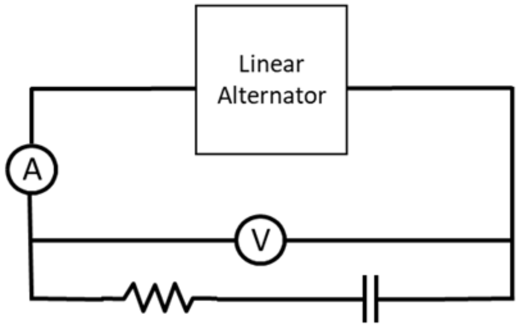
- The agreement between the predicted and measured data was good except for the terminal voltage
  - The model did not account for any voltage drops between the coil and convertor output terminals

| Parameter | GRC Prediction | Test Data | % Error |
|---|---|---|---|
| Piston Amplitude, mm | 4.25 | 4.25 | - |
| Frequency, Hz | 99 | 99 | - |
| Terminal Voltage, $V_{rms}$ | 23.3 | 16.8 | 38.7 % |
| Current, $A_{rms}$ | 6.98 | 6.5 | 7.4 % |
| Power, W | 64.3 | 63.4 | 1.4 % |
| Efficiency, % | 80.0 | - | - |
| Total Losses | 16.1 | - | - |

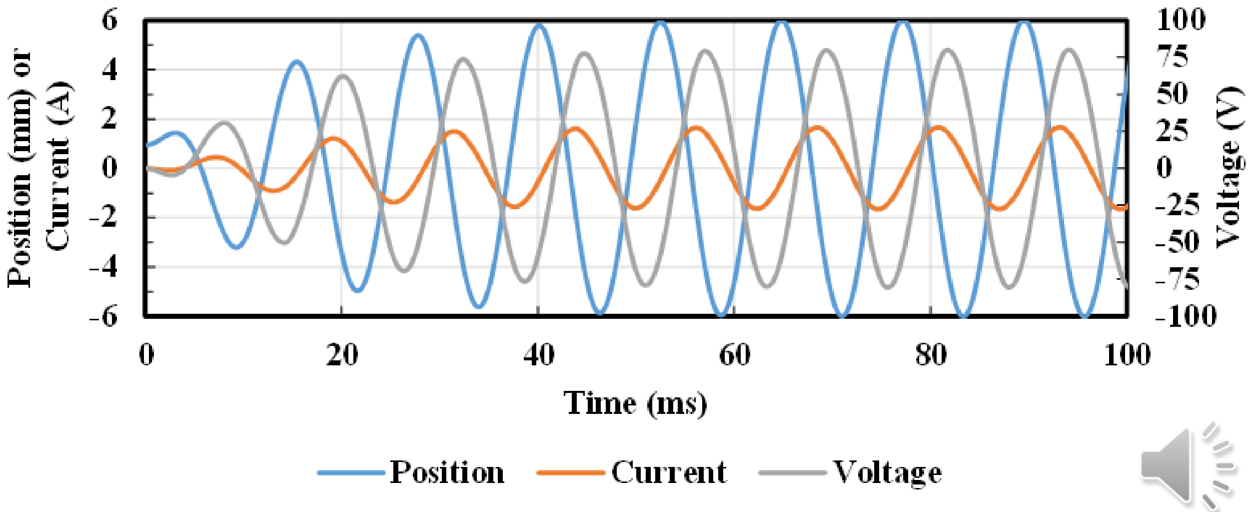
# FISC : LA Performance Verification

- A similar load circuit to that of the SRSC was used in the FISC
  - The values for the load resistance and tuning capacitor were obtained from AMSC, and reflect the actual load that was used during checkout testing

- In the transient model, the mover was gradually ramped-up to full stroke operation of 12 mm to maintain computational stability
  - The model obtained steady-state operation at about 10 cycles
  - The voltage and current values were calculated at the locations indicated as V and A respectively (In the FISC Load circuit)




FISC Load



# FISC : LA Performance Verification

- Test data was acquired during the October 3, 2019 convertor checkout testing at AMSC

- The test data indicated that the engine was operated at 4 Hz above the design frequency of 81 Hz
  - Model frequency was adjusted to match the test operating conditions

- The generated predictions for the FISC alternator resulted to be in good agreement with the experimental data

| **Parameter** | **GRC Prediction** | **AMSC Test Data (10/3/2019)** | **% Error** |
|---|---|---|---|
| Piston Amplitude, mm | 6.0 | 6.0 | - |
| Frequency, Hz | 77 | 77 | - |
| Terminal Voltage, $V_{rms}$ | 54.3 | - | - |
| Current, $A_{rms}$ | 1.56 | 1.54 | 1.3% |
| Power, W | 67.1 | 68.6 | 2.2% |
| Efficiency, % | 92.6 | 88 | 5.2% |
| Total Losses | 5.4 | - | - |

# Conclusion

- Sage models were received from both Sunpower and AMSC to interrogate and validate against nominal convertor performance data
  - A difference was noticed between the as received test data and the predictive models.
  - Due to this difference, models were calibrated respectively
  - As a result of errors between test data and the calibrated models further testing, model calibration, and model optimization will be performed

- ANSYS Fluent was used to collect useful data from, SRSC convertors, that is difficult to measure during performance testing
  - Lab temperatures measurements were collected from the cylinder can, CSAF, hot end of the convertor, and heater block surfaces and used in the CFD model
  - Results matched well with in-lab test (Such as : Net Heat Input, and $Q_{env}$)

- ANSYS Maxwell was used to model both SRSC and FISC
  - Model predictions were in good agreement with the test data for both convertor types
  - Except for the SRSC terminal voltage between the model and experimental value were not in good agreement
  - More parameters can be compared in the future as more test data becomes available.