Free Piston Stirling Engine Based 1kW Generator

Year 1 Program Review

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Sunpower, Aerojet Rocketdyne,
Precision Combustion Incorporated
PI: Gary Wood, Sunpower Technical Leader

Project Team

- Sunpower, Inc. (SP)
  - Team lead, FPSE lead, controls lead, prototype system integrator
  - Free Piston Stirling machine design, prototype, and low-volume production expertise
  - Free Piston Stirling controls design and prototype expertise
  - Prototype system and FPSE/combustor integration experience
  - Successful licensing of technology and technology transfer
- Precision Combustion, Inc. (PCI)
  - Combustor lead
  - Combustor and recuperator design and prototype development expertise
  - Combustor/FPSE integration experience
- Aerojet Rocketdyne (AR)
  - High temperature materials lead
  - Expertise in High Temperature (HT) materials selection, and testing
  - Expertise in HT materials processing, joining, and fabrication
  - Potential HT materials manufacturing capability

Technology

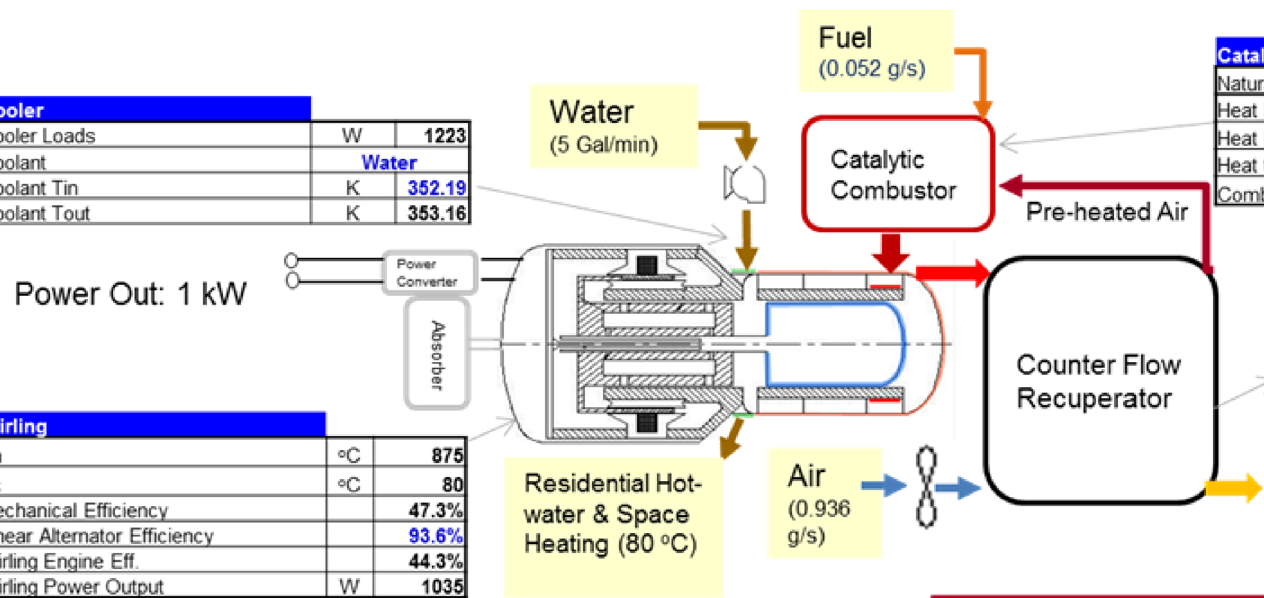
Objective – Deliver for 3rd party testing prototype GENSETS system meeting program performance and emissions requirements

Key system components

- Free piston Stirling engine
  - High heater head temperature and high efficiency linear alternator enable high efficiency target (~45%)
  - High temperature material heater head and displacer assemblies and hot cylinder
  - Advanced, compact design
- Recuperative burner
  - Novel, porous media heat acceptor serves as flame holder and fuel/air mixer
  - Highly recuperated burner (target efficiency of ~94%)
- Controls
  - Engine controller based on existing SP IP and designs
  - Burner and BOP controls to be developed based on previous program experience

Technology

Cooler		
Cooler Loads	W	1223
Coolant	Water	
Coolant Tin	K	352.19
Coolant Tout	K	353.16



Catalytic Combustor		
Natural Gas Fuel LHV	W	2530
Heat Leak to Env.	W	40
Heat Leak from Hot side to Cold side	W	103
Heat to Stirling Heater Head	W	2336
Combustor Efficiency		92.3%

Recuperator		
Air Inlet Temp	K	295
Combustor Outlet Temp	K	1198
Recuperator Leak to Env.	W	60
Effluent Exit Temp	K	379
Effectiveness	%	87.8%

Stirling		
Th	°C	875
Tc	°C	80
Mechanical Efficiency		47.3%
Linear Alternator Efficiency		93.6%
Stirling Engine Eff.		44.3%
Stirling Power Output	W	1035

$$\eta_{sys} = \eta_{comb} * \eta_{FPSE} * \eta_{alt} * \eta_{BOP}$$

$$40\% = 92.3\% * 47.3\% * 93.6\% * 96.6\%$$

GENSETS System		
Stirling Power Output	W	1035
Parasitic Power	W	35
Net Power	W	1000
System Efficiency	%	40%

Technical Progress (HT Materials)

- Two POC test articles were fabricated to demonstrating the ability to join to the metal foam and addressing diffusion concerns
- Two subscale burner test bar assemblies joined and delivered
- Full scale burner
  - Two full-scale test bars joined and delivered
  - One set of recuperator components were fabricated and delivered
- A PCA was developed, based on the prototype full-scale deliverables. High temperature components exceeded desired cost, but PCA can be used as a starting point for a DFM study

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GENSETS

Technical Progress (Burner)

- POC and Sub-scale Burner
  - Completed proof of concept testing of combustor concept
  - Sub-scale burner setup and tested
    - Exceeded required heat flux into acceptor to meet full scale requirements
    - Met required thermal input into Stirling acceptor
    - Demonstrated stable and complete combustion at target temperature
    - Achieved uniform temperature distribution in acceptor
- Full Scale Burner
  - Design for full scale combustor completed
  - Fabrication of burner components nearly complete
  - Next Step: Start burner assembly in mid December

Technical Progress (FPSE)

- Prototype FPSE
  - Prototype engine completed and assembled with an electric heat test head
  - First run of the engine occurred on Nov 16
  - Current maximum power achieved is 750W at a reduced heater head and reject temperatures
  - Testing is underway to work up to the design point
- Design
  - Completion of operating frequency, sizing and other trade studies
  - Completion of design review

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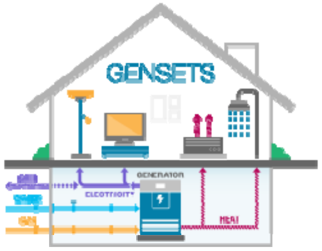
Challenges And Lessons Learned

Novel burner design

- Concerns - suitability of porous media as acceptor, joining to heater head, joint integrity, heat transfer, temperature uniformity, auto-ignition, burner efficiency
- Mitigation
  - POC burner sample demonstrated fuel/air mixing and stable operation
  - Subscale burner demonstrated: fuel combustion with no auto-ignition, joining integrity, heat transfer and temperature uniformity
  - Subscale and full-scale burners used to study performance and efficiency tweaks
  - Full-scale burner will be used to demonstrate target performance and metrics

High temperature material development and availability

- Concerns –
  - High temperature materials lead time is prohibitive
  - Joining method and bond integrity is uncertain
- Mitigation
  - All high temperature materials for prototypes were prioritized in order to minimize schedule effect
  - Seeking alternate materials and vendors as backup plans for future efforts
  - Diffusion sample demonstrated joining capability and joint integrity



Challenges And Lessons Learned

Meeting project cost targets

- Concerns –
  - High temperature components' PCA indicate they are cost-prohibitive
  - Burner and BOP components costs remain to be finalized
- Mitigation
  - Engine components can be produced economically in volume
  - Design trades have been made to reduce engine cost and system complexity
  - Material trades and design options continue to be considered as part of DFM
  - Volume pricing information is included and refined in TEA

Technology to Market considerations

- Concerns –
  - Team reach/understanding into the US CHP market is limited
  - Team has limited experience with Technology to Market efforts
- Mitigation
  - Significant effort put into market analysis and identifying alternate markets
  - Efforts turning to next stage funding and early adoption markets
  - Considering bringing in external expertise

Meeting program performance targets with prototype system

Next Steps (2017 Milestones)

Task/Deliverable	Completion
High temperature material deliveries for Beta burner and FPSE	Feb
Programmatic plan submission/revision (T2M, TEA, NSFP, etc.)	Feb
Alpha burner delivery	Mar
FPSE characterization testing (electrically heated)	Apr
Controller design and fabrication	May
Beta burner delivery	Jul
Engine/controller integration	Jul
Engine burner integration	Sep
FPSE characterization testing (burner heated)	Nov
Burner and BOP controller integration	Dec