Development Status and Plans of the Advanced Thermoelectric Converter (ATEC) Project

Space Technology and Applications International Forum

February 13, 2008
Albuquerque, NM

Richard Ewell & Thierry Caillat
Jet Propulsion Laboratory / Caltech

Copyright 2008 California Institute of Technology. Government sponsorship acknowledged.
Outline

- ATEC Project Description
- Phase I Results
- FY’08 Plans
ATEC Project Description
• Advances in thermoelectric materials with high ZT in mid-90’s, revived interest in advanced thermoelectric materials at DOE, DOD and NASA.

• JPL, in collaboration with Universities, identified promising high temperature thermoelectric materials for potential use in next generation RTGs under DOD and NASA funding (1995 to 2005)

• Based on these advances the ATEC project was initiated in January 2006 to develop an advanced converter by 2010 (10-12% couple efficiency)

• ATEC is a technology maturation project with an off-ramp to a proposed Advanced RTG (ARTG) providing 6-8 W/kg and 8-10 % system efficiency to support potential future SMD missions as early as 2017.

• In addition, work is continuing on advancing the TE materials technology to support development of an RTG with 12 -14 W/kg and 15 to 20% efficiency by 2020.
ATEC Project Overview

• Objectives
  – Develop and demonstrate an Advanced Thermoelectric Converter (ATEC) by 2010 - JPL
  – Develop a conceptual design for an advanced RTG (ARTG) for use in deep space missions by 2015 - DOE

• ARTG Performance Targets
  – Specific Power: 6 - 8 W/kg
  – System Efficiency: 8 - 10%
  – Life: 14 years with less than 22% degradation (Same as GPHS-RTG and MMRTG)

• ARTG Benefits
  – Would increase payload mass or reduce launch vehicle cost
  – Would reduce plutonium usage
  – Would be an all solid state device with long lifetime capability
  – No radiation shielding required: Multi Mrad
  – Would have high reliability due to series/parallel converters
  – Would utilize over forty years of RTG design heritage

• Potential Missions for ARTG
  – SMD Missions ~ 2017

• ATEC Team:
  – JPL, GRC, MSFC, DOE, Rocketdyne, Hi-Z, USC, Harvard
RTG Performance Comparison

- Technology Readiness Level
  - 1: Yellow
  - 2: Red
  - 3: Orange
  - 4: Pink
  - 5: Purple
  - 6: Blue
  - 9: Green

- System Conversion Efficiency (%)
- System Specific Power (We/kg)

- 125W MMRTG PbTe/TAGS Unicouple
- Equivalent Step-2 SiGe GPHS-RTG
- 285 W GPHS-RTG SiGe Unicouple
- 240W Proposed ARTG ATEC Unicouples
ATEC Organization

DOE

DOE Contractor(s)

Agreement to MOU

NASA

JPL

MSFC

Rocketdyne

GRC

Interface
The Project is divided into three Phases, each with a technology readiness gate:

- The Phase I objective was to: Develop and demonstrate the feasibility of a high efficiency thermoelectric couple and develop in conjunction with DOE an RTG conceptual design capable of 6 to 8 W/kg by August, 2007.
  - Development and demonstration of high temperature thermoelectric materials
  - Establish the leg feasibility relative to sublimation suppression and metallization to meet the required lifetime and performance
  - Have DOE subcontractors develop detailed ARTG conceptual designs to meet the performance requirements

- The Phase II objective is to: Develop and demonstrate the performance of a high efficiency thermoelectric couple November, 2008.
  - Development and demonstration for 1500 hours of metallized legs with sublimation barriers that meet the lifetime requirements
  - Development and demonstration of a high temperature couple providing 10% conversion efficiency while operating at typical RTG design temperatures

- The Phase III objective is to: Design and fabricate an Advanced Thermoelectric Electrical Performance Demonstrator (EPD) and demonstrate electrical performance and life goals (TRL 5) by June, 2010.
  - Demonstrate manufacturing feasibility of materials, couples, and converter
  - Design, fabricate and performance test an EPD demonstrating performance consistent with an updated RTG conceptual design capable of 6 to 8 W/kg
  - Demonstrate a minimum of 1 year of couple lifetime and using accelerated coupon testing predict 14 years of lifetime with no more than 22% degradation
# ATEC/ARTG Development Plan

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATEC Phase I</strong></td>
<td>Material &amp; Component Development</td>
<td>ATEC Phase II</td>
<td>ATEC Phase III</td>
<td>NASA/DOE ARTG Proposed Development *</td>
<td>ATEC Phase IV</td>
<td></td>
</tr>
<tr>
<td><strong>ATEC Phase II</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATEC Phase III</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATEC Phase IV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Design, Fabrication & Testing
- Qual and Flight Unit Fabrication and Testing

* Not included in baseline RPS plan

---

* R. Ewell
Key ATEC Milestones

FY’06  Select primary & back-up high temperature TE materials

FY’07  Demonstrate TE material feasibility and reduce couple options
       Demonstrate TE leg feasibility and select baseline RTG design

FY’08  Validate couple power output with 10% of predict

FY’09  Demonstrate 14 yr lifetime at coupon level with 1500 hr tests
       Validate 6 months of couple life with < 0.16% degradation

FY’10  Validate converter performance & predict 14 yr lifetime
Phase I Results
(1/06 to 8/07)
ATEC Phase I Accomplishments

• Developed couple materials and demonstrated the feasibility of a high efficiency thermoelectric couple and developed in conjunction with DOE an RTG design conceptual capable of 6 to 8 W/kg by August, 2007.
  – Development and demonstration of high temperature thermoelectric materials
    • Reproducibility, stability, and process scale-up for both Zintl and SiGe have been developed and demonstrated
  – Establish the leg feasibility relative to metallization and sublimation suppression to meet the required lifetime and performance
    • Demonstrated metallization with Zintl to have low electrical contact resistance and good stability, while SiGe would utilize metallization already demonstrated.
    • Initial Zintl sublimation suppression coating demonstrated for use with first couple build, multiple options being pursued to meet requirements for subsequent builds. Silicon-nitride coating would be used for SiGe
  – Develop detailed ARTG conceptual designs completed that meet the performance requirements
    • DOE contractors developed an ARTG conceptual design that would provide > 6W/kg and > 8% efficiency
• High-ZT, high-temperature (up to ~ 1300K) thermoelectric materials needed to achieve desired proposed ARTG performance goals
• High-temperature thermoelectric materials initially investigated under ATEC:
  – P-type
    • Yb₄MnSb₁₁ (Zintl)
    • HT- Skutterudite
    • Nanostructured SiGe
    • P-CeFe₃RuSb₁₂
  – N-type
    • LaTe₁.₄
    • Mechanically alloyed SiGe
    • HT- Skutterudite
    • N-CoSb₃
• TE materials requirements
  – Must be phase stable at maximum operating temperature
  – Can be produced by a synthesis process that is scalable
  – Must have repeatable thermoelectric properties
  – Can be metallized with bonds with electrical contact resistance ≤ 25 μΩ.cm²
  – Sublimation rate needs to be ≤ 10⁻² g/cm².hr for uncoated materials
ATEC Couple Option Reduction

- Preliminary ARTG conceptual system design and performance studies
  - Showed that several high-T material combinations could yield system efficiency > 8% and specific power > 6 W/kg
  - Segmenting high-T materials to low-temperature skutterudites materials does not provide substantial increase in efficiency (~0.5%) but adds development risk
  - Unicouple configuration selected as baseline
- High-T couple configurations selected as baseline for development after January 2007:
  - Primary
    - P-type \( \text{Yb}_{14}\text{MnSb}_{11} \) (Zintl)
    - N-type Mechanically alloyed SiGe
  - Back-ups
    - N-LaTe\(_{1.4}\)
    - P-type \( \text{Yb}_{14}\text{MnSb}_{11} \) (Zintl)
    - N-type Mechanically alloyed SiGe
    - P-nano SiGe
Established repeatability of ZT (within +/- 10% of average) for a minimum of four batches of Zintl and n-MA SiGe
## Thermoelectric Materials Comparison

<table>
<thead>
<tr>
<th></th>
<th>N-PbTe</th>
<th>P-TAGS</th>
<th>N-SiGe</th>
<th>P-SiGe</th>
<th>N-MA SiGe</th>
<th>P-Zintl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average ZT</strong></td>
<td>0.90</td>
<td>1.1</td>
<td>0.69</td>
<td>0.41</td>
<td>0.75</td>
<td>0.81</td>
</tr>
<tr>
<td><strong>Maximum Operating Temperature</strong></td>
<td>800 K</td>
<td>675 K</td>
<td>1275 K</td>
<td>1275 K</td>
<td>1275 K</td>
<td>1275 K</td>
</tr>
<tr>
<td><strong>Sublimation Suppression</strong></td>
<td>Argon</td>
<td>Argon</td>
<td>Silicon Nitride Coating</td>
<td>Silicon Nitride Coating</td>
<td>Silicon Nitride Coating</td>
<td>Coating in development</td>
</tr>
<tr>
<td><strong>Couple Efficiency</strong></td>
<td>7.0% [800 to 485K]</td>
<td>7.5% [1275 to 575 K]</td>
<td>10.0% [1275 to 550 K]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>MMRTG</td>
<td>GPHS-RTG</td>
<td>Conceptual ARTG</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: STAIF - 2008*
Leg Feasibility Demonstration

- Developed Zintl leg metallization
  - Demonstrated chemical stability over 2 weeks at 1273K
  - Demonstrated electrical contact resistance of less than 25 \( \mu \Omega \text{-cm} \)

- Initial Demonstration of Zintl Sublimation Suppression
  - Shows 100 times reduction in sublimation rate
  - Survived multiple thermal cycles

- Assumed heritage SiGe metallization and sublimation suppression based on GPHS-RTG
  - Replicated silicon-nitride sublimation suppression coating
Zintl metallization maintains stable interface with negligible contact resistance after 2 weeks at 1273 K
SiGe coupon coated with ~ 1μm of Si₃N₄

- The sublimation rate of SiGe coupon was ~ 3.9 × 10⁻⁷ g/cm²/hr after 2 weeks of testing, a ~ 200 times reduction compared to uncoated SiGe which is comparable to GPHS-SiGe

- Al₂O₃ paste coating with or without aerogel provides about x 100 time reduction in sublimation rate for Zintl
- Controlling thickness of Al₂O₃ contributes to minimize cracking of coating
ARTG conceptual design studies conducted by DOE contractors showed that several ATEC couple configurations could meet the goals of a specific power ≥ 6 W/kg and a system efficiency of ≥ 8%.

### System Conceptual Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Zintl and SiGe</td>
</tr>
<tr>
<td>Power per Unit (BOL), [W&lt;sub&gt;e&lt;/sub&gt;]</td>
<td>240</td>
</tr>
<tr>
<td>Power Degradation Rate, [%/yr]</td>
<td>~ 1.6</td>
</tr>
<tr>
<td>Mass per Unit, [kg]</td>
<td>~ 38</td>
</tr>
<tr>
<td>Dimensions, [mm]</td>
<td>Length: ~ 840 mm ; Cooling fin span: ~390 mm</td>
</tr>
<tr>
<td>Radiation Tolerance (RDF=1)</td>
<td>multi Mrad</td>
</tr>
<tr>
<td>Additional Shielding, [kg]</td>
<td>None</td>
</tr>
<tr>
<td>Number of GPHS Modules per Unit</td>
<td>12</td>
</tr>
<tr>
<td>Thermal Power (BOL), [W&lt;sub&gt;t&lt;/sub&gt;]</td>
<td>3000</td>
</tr>
<tr>
<td>Unit Specific Power (BOL), [W&lt;sub&gt;e/kg&lt;/sub&gt;]</td>
<td>6.3</td>
</tr>
<tr>
<td>Conversion Efficiency, [%]</td>
<td>8.3%</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Built-in (i.e., failure of a few thermocouples would not significantly impact operations)</td>
</tr>
<tr>
<td>Permissible Launch Vehicles</td>
<td>All</td>
</tr>
<tr>
<td>Operating Environment</td>
<td>Vacuum only</td>
</tr>
<tr>
<td>Lifetime requirement, [years]</td>
<td>14</td>
</tr>
<tr>
<td>Current Technology Readiness Level (TRL)</td>
<td>2 - 3</td>
</tr>
</tbody>
</table>
FY’08 Plans
FY 08 Specific Objectives / Approach

- **Develop and demonstrate ATEC couples**
  - Develop couple design consistent with ARTG conceptual design that meets NASA’s goals of at least 6 We/kg and 8% system efficiency
  - Fabricate and test 3 builds of ATEC couples
  - Validate that couple BOL power output is within 10% of prediction

- **Finalize Component Development**
  - Complete specifications for thermoelectric material synthesis and initiate qualification of outside vendors for production
  - Complete sublimation coating development

- **Initiate ATEC component and couple lifetime testing**
  - Complete 1500 hours thermoelectric property stability testing with materials produced using 100 gram processing methodology
  - Initiate 1500 hour component lifetime validation testing
  - Initiate 1500 hour ATEC couple lifetime testing
ATEC 1st Build Couple Design

- P-leg Heat Collector
- Transition Piece
- Sublimation Barrier
- P-leg (Zintl)
- P-leg Trilayer
- P-leg Cold Electrode
- N-leg Heat Collector
- Hot Electrode/Current Strap
- N-leg (MA-SiGe)
- N-leg Cold Electrode
- N-leg Trilayer
- Ti Nut Plate Assembly
- Heat Sink
Summary

• ATEC Project is developing the next generation thermoelectric converter for inclusion in an conceptual advanced RTG
• ATEC successfully completed Phase I
  • Development & demonstration of improved thermoelectric materials
  • Development of an Advanced RTG conceptual design using the demonstrated materials that meets the 6 to 8 W/kg and 8 to 10% system efficiency
  • Demonstration of Zintl leg feasibility
• Initiated Phase II of the ATEC project
  • Rocketdyne is on contract to develop and demonstrate advanced thermoelectric couples
  • Couple design has been established; in process of developing all of the associated interfaces