MMRTG-powered Mars Science Laboratory mission
Mars Science Laboratory is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the red planet. Mars Science Laboratory is a rover that will assess whether Mars ever was, or is still today, an environment able to support microbial life. In other words, its mission is to determine the planet’s "habitability."
Multi-Mission RTG Overview

- Ability to operate in vacuum and planetary atmospheres
  - 23-36 V DC capability, series-parallel circuitry
- 17 years lifetime requirement
  - Up to 3 years of storage and up to 14 years of operation
- Ability to withstand high mechanical loads
  - ~ 0.3 g²/Hz (random vibrations)
  - Up to 6000 g (pyrotechnic shock)

Beginning of Life Performance
~ 125 W
~ 2.8 W/kg

768 $\text{PbTe + TAGS/PbSnTe}$ couples
### RTG Technology - Missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>RTG</th>
<th>TE</th>
<th>Destination</th>
<th>Launch Year</th>
<th>Mission Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit 4A</td>
<td>SNAP-3B7(1)</td>
<td>PbTe</td>
<td>Earth Orbit</td>
<td>1961</td>
<td>15</td>
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<tr>
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<td>1962</td>
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<td>SNAP-27 RTG (1)</td>
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<td>Lunar Surface</td>
<td>1969</td>
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<tr>
<td>Pioneer 10</td>
<td>SNAP-19 RTG (4)</td>
<td>PbTe/TAGS</td>
<td>Outer Planets</td>
<td>1972</td>
<td>34</td>
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<td>Triad-01-1X</td>
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<td>PbTe</td>
<td>Earth Orbit</td>
<td>1972</td>
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<tr>
<td>Pioneer 11</td>
<td>SNAP-19 RTG (4)</td>
<td>PbTe/TAGS</td>
<td>Outer Planets</td>
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<td>35</td>
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<tr>
<td>Viking 1</td>
<td>SNAP-19 RTG (2)</td>
<td>PbTe/TAGS</td>
<td>Mars Surface</td>
<td>1975</td>
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<tr>
<td>Viking 2</td>
<td>SNAP-19 RTG (2)</td>
<td>PbTe/TAGS</td>
<td>Mars Surface</td>
<td>1975</td>
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<tr>
<td>LES 8</td>
<td>MHW-RTG (4)</td>
<td>Si-Ge</td>
<td>Earth Orbit</td>
<td>1976</td>
<td>15</td>
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<tr>
<td>LES 9</td>
<td>MHW-RTG (4)</td>
<td>Si-Ge</td>
<td>Earth Orbit</td>
<td>1976</td>
<td>15</td>
</tr>
<tr>
<td>Voyager 1</td>
<td>MHW-RTG (3)</td>
<td>Si-Ge</td>
<td>Outer Planets</td>
<td>1977</td>
<td>31</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>MHW-RTG (3)</td>
<td>Si-Ge</td>
<td>Outer Planets</td>
<td>1977</td>
<td>31</td>
</tr>
<tr>
<td>Galileo</td>
<td>GPHS-RTG (2) RHU(120)</td>
<td>Si-Ge</td>
<td>Outer Planets</td>
<td>1989</td>
<td>14</td>
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<tr>
<td>Ulysses</td>
<td>GPHS-RTG (1)</td>
<td>Si-Ge</td>
<td>Outer Planets/Sun</td>
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<td>Cassini</td>
<td>GPHS-RTG (3) RHU(117)</td>
<td>Si-Ge</td>
<td>Outer Planets</td>
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<td>11</td>
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<tr>
<td>New Horizons</td>
<td>GPHS-RTG (1)</td>
<td>Si-Ge</td>
<td>Outer Planets</td>
<td>2005</td>
<td>3 (17)</td>
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<tr>
<td>MSL</td>
<td>MMRTG (1)</td>
<td>PbTe/TAGS</td>
<td>Mars Surface</td>
<td>2011</td>
<td>3</td>
</tr>
</tbody>
</table>

**RTGs have been successfully used on a number of long-life missions**

- **PbTe-based**
  - 40 W<sub>e</sub>, 3 W/kg
  - 6.3% Efficiency
  - Deep space and planetary surface operation
  - > 30 Year life demonstrated

- **SiGe-based**
  - 158 W<sub>e</sub>, 4.2 W/kg
  - 6.3% Efficiency
  - Deep space operation
  - > 30 Year life demonstrated

- **MHW-RTG**
  - 285 W<sub>e</sub>, 5.1 W/kg
  - 6.5% Efficiency
  - Deep space operation
  - > 18 Year life demonstrated

- **MMRTG**
  - 120 W<sub>e</sub>, 2.8 W/kg
  - 6.3% Efficiency
  - Deep space and planetary surface operation
  - > 30 Year life demonstrated

- **GPHS-RTG**
  - 120 W<sub>e</sub>, 2.8 W/kg
  - 6.3% Efficiency
  - Deep space and planetary surface operation
  - > 30 Year life demonstrated
# TE Converter Configurations

<table>
<thead>
<tr>
<th>Couple Configuration</th>
<th>P-leg</th>
<th>N-leg</th>
<th>Heat Source Coupling</th>
<th>Program</th>
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<tbody>
<tr>
<td>Segmented Couple</td>
<td>Bi$_2$Te$_3$/TAGS/PbSnTe</td>
<td>Bi$_2$Te$_3$/PbTe</td>
<td>Conductive</td>
<td>Terrestrial RTGs</td>
</tr>
<tr>
<td>Segmented Couple</td>
<td>TAGS/PbSnTe</td>
<td>PbTe</td>
<td>Conductive</td>
<td>SNAP-19, MMRTG</td>
</tr>
<tr>
<td>Segmented Couple</td>
<td>Si$<em>{0.63}$Ge$</em>{0.37}$/Si$<em>{0.8}$Ge$</em>{0.2}$</td>
<td>Si$<em>{0.63}$Ge$</em>{0.37}$/Si$<em>{0.8}$Ge$</em>{0.2}$</td>
<td>Radiative</td>
<td>MHW-, GPHS-RTG</td>
</tr>
<tr>
<td>Multicouple</td>
<td>Si$<em>{0.8}$Ge$</em>{0.2}$</td>
<td>Si$<em>{0.8}$Ge$</em>{0.2}$</td>
<td>Conductive, Radiative</td>
<td>SP-100, MOD-RTG</td>
</tr>
<tr>
<td>Segmented Couple</td>
<td>Bi$_2$Te$_3$/SKD*</td>
<td>Bi$_2$Te$_3$/SKD</td>
<td>Conductive</td>
<td>Segmented TE Couple (2002)</td>
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<tr>
<td>Multicouple</td>
<td>SKD (Skutterudites)</td>
<td>SKD</td>
<td>Conductive</td>
<td>STMC (2005)</td>
</tr>
<tr>
<td>Unsegmented Couple</td>
<td>Zintl</td>
<td>Nano Si$<em>{0.8}$Ge$</em>{0.2}$</td>
<td>Radiative</td>
<td>2008</td>
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<tr>
<td>Unsegmented Couple</td>
<td>Zintl</td>
<td>La$_{3-x}$Te$_4$</td>
<td>Conductive or radiative</td>
<td>2009 ATEC</td>
</tr>
<tr>
<td>Segmented Couple</td>
<td>SKD/Zintl</td>
<td>SKD/La$_{3-x}$Te$_4$</td>
<td>Conductive or radiative</td>
<td>2011</td>
</tr>
<tr>
<td>Segmented Couple</td>
<td>Adv. PbTe/Zintl</td>
<td>Adv. PbTe/La$_{3-x}$Te$_4$</td>
<td>Conductive</td>
<td>2012</td>
</tr>
<tr>
<td>Segmented Multicouple</td>
<td>SKD/Zintl</td>
<td>SKD/La$_{3-x}$Te$_4$</td>
<td>Conductive or radiative</td>
<td>2012 Small FPS</td>
</tr>
</tbody>
</table>

**Multicouples developed for higher power systems (space reactor, terrestrial)**

**Arrays of discrete couples typically used for RTGs**

**DOE TEAW 03/21/2012**
# High Temperature TE Materials

## RTG Technology Development Timeline

### Mission

|----------|-------|-------|-------|-------|-----------|-----------|-----------|

### Generator

|----------|-------|-------|-------|-------|-----------|-----------|-----------|

### Technology

|----------|-------|-------|-------|-------|-----------|-----------|-----------|

*DOE TEAW 03/21/2012*
Lifetime Performance Validation
What controls RTGs Lifetime Performance?

1. **Fuel decay**
   - ~ 0.8%/year decrease in power output

2. **Decrease in hot-junction as a result of decreasing heat input**
   - ~ 0.5%/year decrease in power output

3. **Thermoelectric materials-related mechanisms**
   - Decrease in power output: ~ 0.3%/year
   - Decrease in power output: ~ 0.3%/year total

**GPHS RTG**

**MMRTG**

- ~ 0.8%/year decrease in power output
- ~ 0.8%/year decrease in power output
- ~ 0.5%/year decrease in power output
- ~ 0.5%/year decrease in power output

**TE-related degradation mechanisms can represent a significant fraction of the overall RTG degradation over time**

* Averaged to 14 years operation

** Rate estimation based on ~ 2 years MSL EU test data and averaged to 14 years operation
### Impact of key TE-related degradation mechanisms on RTG performance

<table>
<thead>
<tr>
<th>Degradation mechanism</th>
<th>Key potential impact(s)</th>
<th>Impact(s) on RTG performance</th>
</tr>
</thead>
</table>
| Sublimation of TE materials (A major concern for most TE materials…)                  | • Increase in electrical resistance  
• Electrical and thermal shorts  
• Promote the degradation of couple interfaces at the hot-junctions  
• Potentially impact all other mechanisms                                          | • Reduced power  
• Electrical isolation                                                              |
| Changes in TE properties (can be due to dopant precipitation, structural phase changes, phase segregation, electromigration, etc…) | • Can reduce thermoelectric efficiency if lower ZT  
• Lower temperature gradient across TE elements if increased thermal conductivity  | • Reduced power                                             |
| Increase in electrical & thermal contact resistances at interfaces (can be due to interdiffusion, microcrack propagation, etc…) | • Increase in electrical resistance  
• Lower temperature gradient across TE elements                                         | • Reduced power                                             |
| Increased conductance of thermal insulation (can be due to interactions between insulation packaging, TE materials and sublimation products, etc…) | • Increased heat losses  
• Reduced heat flux through the thermoelectric couples                             | • Reduced power  
• Thermal management                                                              |

Each TE-related degradation mechanism can have a significant impact on overall RTG degradation over time; must be tested for, quantified and modeled

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Life Testing & Performance Validation

- **Materials (TRL 1-3)**
  - Stable TE properties vs. time & temperature demonstrated over > 1 year of testing
  - Control of sublimation rates down to $10^{-6}$ to $10^{-7}$ g.cm$^2$/hr, verified over > 1 year of testing

- **Couples TRL (2-4)**
  - Stable electrical contact metallizations
  - Stable interfaces to hot and cold shoes, between TE segments
  - Maintain mechanical, thermal and electrical integrity
  - Greater than 5 years life predicted based on normal and accelerated testing

- **Couple Arrays (TRL 3-5)**
  - Use of prototypic couples
  - No interaction with thermal insulation, verification of mechanical integrity
  - Greater than 3 years of testing

- **Electrically heated Power Demonstrator (EPD, 18-couple) (TRL 4-5)**
  - Demonstration of thermal and electrical efficiencies at subscale system level

- **ETG (TRL 6)**
  - Validation of thermal and electrical efficiencies at full scale system level
  - Qualification testing

- **Life Performance Model**
  - Materials properties and test data used to predict long term performance
  - Provide Mission planners with performance profile during various scenarios and operation phases

*Well defined technology development roadmap to establish lifetime performance of RTGs*
Typically within 3% of experimental data after more than 15 years of operation (1997 launch)
High Temperature TE Couple Technology Development for Next Generation Space Power Systems
Impact of Higher Performance Materials on Thermoelectric Power Systems for Space Exploration

Ultimate goal: > 15% efficient, >10 W\textsubscript{e}/kg Advanced RTGs

\( T_{\text{hot}} = 1100 \text{ K} \) to 1275 K (higher is better!)

Lower System Mass and Higher Conversion Efficiency Needed (x2 to 4)

Advanced RTG Specific Power vs. System Conversion Efficiency (Based on radiatively coupled vacuum operation unicoouple based RTG concept)

\( T_{\text{hot}} = 1275 \text{ K} \)
\( T_{\text{cold}} = 500 \text{ K} \)

"MMRTG" PbTe/TAGS \( ZT_{\text{ave}} \approx 0.85 \)

"GPHS-RTG" Si-Ge \( ZT_{\text{ave}} \approx 0.55 \)

x 2 Improvement \( ZT_{\text{ave}} \approx 1.1 \)

x 4 Improvement \( ZT_{\text{ave}} \approx 2.2 \)
Advanced RTG Technology Development Path

**Advanced TE materials & Devices Task**

- **TRL 1-2**
  - High ZT TE materials

- **TRL 2**
  - Component Development

- **TRL 3**
  - Couple Dev. & Performance Validation
  - Initial life testing

- **TRL 4**
  - Advanced Thermoelectric Couple (ATEC) project
  - 4-couple/module development
  - Life testing, demo and modeling

- **TRL 5**
  - Converter (EPD) Development
  - Life & Performance Validation

- **TRL 6-8**
  - Engineering & Qualification
  - ARTG development & performance validation

**Advanced Thermoelectric Couple (ATEC) project**

DOE/Industry

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Baseline ATEC advanced TE Materials
Large performance gains over heritage Si-Ge alloys

Advanced Segmented Materials
ZT$_{ave}$ ~ 1.15 - 1.25
η ~ 14 - 15%

Heritage Si-Ge
ZT$_{ave}$ ~ 0.53
η ~ 8.5%
Couple Configurations in Development

Zintl (Yb$_{14}$MnSb$_{11}$) / NanoSiGe Couple (2007-2009)

Zintl (Yb$_{14}$MnSb$_{11}$) / La$_{3-x}$Te$_4$ Couple (2009-2010)

Zintl/ SKD // La$_{3-x}$Te$_4$/SKD Segmented Couple (2010 - )

Zintl/Adv.PbTe // La$_{3-x}$Te$_4$/Adv.PbTe Segmented Couple (2012 - )
Materials, Components & Couple Development Challenges

**Materials**
- TE materials
- Batch Synthesis Scale-up
- Reproducibility and stability of TE Properties

**Components**
- Leg segments
- Machining
- Stable metallization
- Sublimation control

**Couples**
- Design, Fabrication, Assembly & Testing
- Robust design
- Stable, low electrical contact resistance interfaces
- Couple Assembly
- Thermal Insulation
- Life demonstration

**Materials**
- p-type $\text{Ce}_x\text{Fe}_{3-x}\text{Co}_x\text{Sb}_2$
- n-type $(\text{Yb},\text{Ba})\text{CoSb}_3$
- p-type $\text{Yb}_{14}\text{MnSb}_{11}$ (Zintl)
- n-$\text{La}_{3-x}\text{Te}_4$

**Temperature Ranges**
- $T \leq 1273K$
- $T \approx 873K$
- $T \approx 473K$

**DOE TEAW 03/21/2012**
Segmented $\text{Yb}_{14}\text{MnSb}_{11}/\text{La}_{3-x}\text{Te}_4$

High Temperature TE Couple Technology Development

**Powder Metallurgy Synthesis Scale-up and Reproducible TE properties**

Reproducible BOL properties for $\text{Yb}_{14}\text{MnSb}_{11}$, $\text{La}_{3-x}\text{Te}_4$ and filled skutterudites produced in 100- to 200 g batches

12-month stability of Zintl at 1323 K

6-month stability of $\text{La}_{3-x}\text{Te}_4$ at 1323 K

Filled Skutterudites

Yb$_{14}$MnSb$_{11}$

La$_{3-x}$Te$_4$
Segmented $\text{Yb}_{14}\text{MnSb}_{11}/\text{La}_{3-x}\text{Te}_4$

High Temperature TE Couple Technology Development

**Sublimation Control for TE Materials and Thermally Stable Low Electrical Contact Resistance Metallizations**

12-month stability of SKD Sublimation Control at 873 K

18-month stability of Zintl Sublimation Barrier Coating at 1273 K

12-month stability of SKD Metallization at 873 K

2-month stability of Zintl Metallization at 1273 K

As-fabricated

After 5,000 hrs aging at 600°C
Segmented Yb₁₄MnSb₁₁/La₃₋ₓTe₄ High Temperature TE Couple Technology Development

Metallized TE Segment Fabrication

- Metallized Puck Dicing
- La₃₋ₓTe₄
- Yb₁₄MnSb₁₁ Zintl
- Filled Skutterudites

Couple Assembly and Test

- Stand-alone Segmented Legs
- Full couple assembly
- p-SKD
- n-SKD
- Zintl
- La₃₋ₓTe₄
- Sublimation Control and Thermal Insulation Packaging into Spring-loaded Test Fixture
- Hot Shoe

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Segmented $\text{Yb}_{14}\text{MnSb}_{11}/\text{La}_{3-x}\text{Te}_4$

High Temperature TE Couple Technology Development

Design of Robust HT Segmented Couples

- Detailed Finite Element Analysis (ANSYS, COMSOL)
- Supported by experimental data on temperature dependent mechanical and thermal properties on TE materials, electrical and thermal interfaces
- Coupon-level demonstrations
- Couple-level validations
- Extensive life testing

Spring-loaded couple design

Cantilevered couple design
1st iteration for 1st Gen Segmented Couple testing
– Demonstrated BOL efficiency –

- Demonstrated large increases in couple efficiency over MMRTG and GPHS couples. ~ 15% efficiency for 1273 - 463 K operating temperature range
Several couples have now been tested for up to 9,000 hours and at hot side operating temperatures ranging from 973 K up to 1273 K.

Long term performance degradation mechanisms have been identified; next iteration of couples will integrate small modifications to minimize degradation.

- Will be implemented later in FY12.

Changes in maximum Power output for n-leg of ATEC couples normalized to BOL performance.
Potential for Terrestrial High Grade Waste Heat Recovery Applications
Advanced high temperature TE technology being developed for space power systems could also be applied to terrestrial Waste Heat Recovery and auxiliary power systems.
Nuclear Electric Propulsion or Primary Power for Space Exploration and Science Missions

- Technology development was focused on arrays of thermoelectric couples grouped into power converter assemblies.
- Used liquid metal heat exchangers to interface with reactor heat source and radiator heat sinks.

Development of robust high temperature thermoelectric module technology is critical to all applications:

- Using low cost, practical fabrication techniques and relatively inexpensive materials (including thermoelectrics).
- Ability to integrate with various heat exchangers.
- Ability to reliably survive thermal/mechanical stresses.
Mechanically Compliant High Temperature TE Module Technologies at NASA/DOE/JPL

**SP-100 SiGe Multicouple (1990s)**
- Conductively coupled on hot side with built in compliant pads
- Tested for up to 25,000 hours

**MOD-RTG SiGe Multicouple Technology (1980s)**
- Graphite heat collector, bolted on radiator side

**Skutterudite Module Developed at JPL under NASA/SMD In-Space Propulsion Program (2004-2005)**
- Designed for integration with flat plate HXs, 873 K - 1273 K Steady State Hot Side operation

**Segmented Module under development for portable power system (2011-2012)**
- Designed for integration with high efficiency HXs, 400 K - 1223 K operation with multiple thermal cycles in vacuum or atmospheric environments
Summary

- Successfully completed the development of first generation Advanced High Temperature TE materials
  - Developed first generation TE materials with $x2 \text{ ZT}_{\text{ave}}$ improvement
  - Transitioned several first generation TE materials for engineering development of couples
- The majority of risks at the first generation TE materials and components levels have been retired
  - Demonstrated long term stability of first generation TE materials
  - Components-level life demonstrated through extended tests (up to 11,600 hours)
- Demonstrated up to 15% BOL efficiency with segmented TE couples
  - Work is in progress to demonstrate life performance capabilities
    - Without life, high ZT does not matter!
  - Fabricated and conducted up to 9,000 hrs of life assessment for 1st iteration ATEC couples
    - Still some work to be done to retire most significant degradation mechanisms but there are no “show stoppers” so far
- New technology could be applied to selected high temperature waste heat recovery applications
  - Availability of rugged TE couple & modular devices is a must to enable new applications
Acknowledgments

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