2014 Workshop on Thermionic Energy Conversion for Space and Earth

October 14-15, 2014
NASA Johnson Space Center
Houston, TX

Organizers:

Jeffrey A. George
EP/Propulsion and Power Division
NASA Johnson Space Center

Prof. David B. Go
Aerospace and Mechanical Engineering
University of Notre Dame
Getting Started

• Welcome
• Introductions
• Purpose, Goals, Objectives
• Logistics
• Discussion Guidelines
• Agenda
• Breakout Sessions
• Reporting, Next Steps
## Attendees

**NASA/JSC (not traveling)**

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**US Institutions (Academic & Commercial)**

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Workshop Announcement

2014 Workshop on Thermionic Energy Conversion for Space and Earth

October 14-15, 2014
NASA Johnson Space Center
Houston, TX

The Propulsion and Power Division of NASA Johnson Space Center is hosting a workshop on the research and development of thermionic energy conversion to power future space missions and terrestrial applications. Currently, NASA has a vision to send manned missions to Mars in the 2030's. However to do so, new power and propulsion technologies must emerge that have the capability of greatly reducing round trip time and initial launch mass. Thermionic energy conversion has the potential for high efficiency, "solid-state" operation with no moving parts, and could form the foundation of future power systems with high specific power, high reliability, and greatly reduced complexity and cost. Building upon the lessons, art, flight experience and discovered challenges of the 1960's-1990's, modern advances in nanotechnology, materials, and microfabrication may now enable thermionic converters to achieve their potential for space and terrestrial power.

The purpose of this workshop is to bring together intellectual leaders and others interested from academia, the U.S. military, U.S. government labs, and industry to restart the conversation on using thermionic energy conversion for space applications. The goals of the workshop are:

- To foster an intellectual and research community in thermionic emission and thermionic energy conversion focused on the development of thermionic energy conversion devices for space applications;
- To identify rationale that could lead to a larger sponsored research program, potentially in conjunction with other U.S. research agencies.

This two-day workshop will consist of both invited and contributed talks and brainstorming sessions centered around four themes:

1. Applications, need, requirements, and historical development
2. New and emerging cathode and anode materials for high current density thermionic energy conversion (doped diamond, carbon nanotubes, barium oxide, etc.)
3. New and emerging form factors and designs for thermionic energy conversion devices (microwafered structures, diode/triode configurations, photo-enhanced thermionic emission, etc.)
4. Testing and characterization apparatus and standards for material characterization, device performance and efficiency, and lifetime and robustness tests

There is no registration fee, but attendees are required to cover their own travel and lodging expenses. There are a limited number of open slots for the workshop, and registration will be granted on a first come basis. To register or request application title/abstract, please contact the organizers:

Jeffrey George (jeffrey.a.george@nasa.gov) Prof. David B. Go (dgo@nd.edu)
EB Propulsion and Power Division Aerospace and Mechanical Engineering
NASA Johnson Space Center, Houston, TX 77058 University of Notre Dame, Notre Dame, IN 46556

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Workshop Purpose & Goals

**Purpose:** In light of recent advances in materials, nanotechnology, and microfabrication, to bring together interested parties from government, academia, and industry to “restart the conversation” on using thermionic energy conversion for Space and Earth applications.

**Major Goals:**
- To foster a collaborative intellectual and research community in thermionic emission and energy conversion
- To identify and describe promising applications and “need”
- To identify rationale and recommendations for focused research
- To communicate recommendations to stakeholders and policymakers
- To have effected and advanced the realization and implementation of practical thermionic converters

**Workshop Topical Areas:**
- Applications, need, requirements, and historical development
- New and emerging cathode and anode materials for high current density thermionic energy conversion (doped diamond, carbon nanotubes, barium oxide, etc.)
- New and emerging form factors and designs for thermionic energy conversion devices (microfabricated structures, diode/triode configurations, photo-enhanced thermionic emission, etc.)
- Testing and characterization apparatus and standards for material characterization, device performance and efficiency, and lifetime and robustness tests
Logistics

- ISS Facility Badging, Rules
  - Visitors badge
  - Core hours 8:00am-5:00pm
- Wireless
- Emergencies
- Break room
- Restrooms
- Lunch
- Tuesday Dinner
  - Landry’s, Kemah Boardwalk
- Saturn V?
- Wednesday Dinner?
- Space Center Houston?
Discussion Guidelines

- Public meeting, information, discussion
- International attendance
- Export Control rules apply for US attendees
  - Limit discussions to cleared or publicly available info
- Mind the clock (so we can cover as much ground as possible)
  - 30 min slots
  - ~20 min presentation
  - ~10 min Q&A, discussion
Rom Primary Focus

Thermionic Energy Conversion for Space Missions
Jeff George, NASA
Michael Houts, NASA
Jean-Pierre Fleurial, JPL

Emerging Thermionic Emission Materials
Tim Fisher, Purdue University
Nicholas Melosh, Stanford University
Terrence Musho, West Virginia University
Steven Fairchild, AFRL

Emerging Thermionic Energy Conversion Devices
*Jochen Mannhart, Max Planck Institute
*Alireza Nojef, University of British Columbia
Joshua Smith, Army Research Lab
Tony Pan, Invention Science Fund
David Go, University of Notre Dame

Diamond-Based Thermionic Energy Conversion
Neil Fox, University of Bristol
Hank Paxton, IOP Technologies
*Robert Nemanich, Arizona State University
Amit Tiwari, Newcastle University

Commercial
Academia
Government
*Breakout Session Leader

2014 Thermionic Workshop
2014 Workshop on Thermionic Energy Conversion for Space and Earth

October 14-15, 2014
NASA Johnson Space Center
Houston, TX

Tuesday, October 14, 2014

8:00 – 8:30 a.m. Continental breakfast
8:30 – 8:45 a.m. Welcome, Overview, and Anticipated Outcomes of Workshop
Jeffrey George, NASA and David Go, University of Notre Dame

Session II: Thermionic Energy Conversion for Space Missions
9:45– 10:15 a.m. Jean-Pierre Fleurat, NASA Jet Propulsion Laboratory: “RTG’s, Thermoelectrics, and Thermionics”
10:15 – 10:30 a.m. Coffee Break

Session III: Emerging Thermionic Emission Materials I
10:30 – 11:00 a.m. Timothy Fisher, Purdue University: “Thermionic and Photo-excited Electron Emission from 2D Materials”
11:00 – 11:30 a.m. Nicholas Melosh, Stanford University: “Heterostructures for Improved Photon Enhanced Emission (PETE) for Solar Thermal Energy Conversion”
11:30 – 12:00 p.m. Terrence Muzio, West Virginia University: “Understanding the Role of Confined Carriers in Nanotipped Thermionic Emitters”
12:00 – 1:15 p.m. Lunch

Session IV: Emerging Thermionic Energy Conversion Devices I
1:15 – 1:45 p.m. Johann Mannhart, Max Planck Institute: “Gates: A Solution to the Space Charge Problem”
1:45 – 2:15 p.m. Arabian Najar, University of British Columbia: “Dimensionality, Feedback and Heat Trap for Nanostructured-Based Thermionic Emission”
2:15 – 2:45 p.m. Joshua Smith, Army Research Laboratory: “Achieving 20% Absolute Efficiency with a Thermoelectron Engine using a Negative Electron Affinity Collector”
2:45 – 3:00 p.m. Coffee Break

Session V: Diamond-Based Thermionic Energy Conversion Devices II
3:00 – 3:30 p.m. Alan Hoffman, Technion Israeli Institute of Technology: “Surface Conditioning for the Enhancement of Thermionic Emission of Diamond Surfaces”
3:30 – 4:00 p.m. Neil Fox, University of Bristol: “An Overview of the Beta-Enhanced Thermionic Diamond Energy Converter”
4:00 – 4:30 p.m. Day 1 Wrap Up and Summary
Jeffrey George, NASA and David Go, University of Notre Dame
6:00 p.m. Group Dinner

Wednesday, October 14, 2014

8:30 – 9:00 a.m. Continental breakfast
9:00 – 9:15 a.m. Day 2 Overview and Agenda
Jeffrey George, NASA and David Go, University of Notre Dame

Session VI: Emerging Thermionic Energy Conversion Devices II
9:15 – 9:45 a.m. Tony Pan, Invention Science Fund: “Inverse Tunneling in Field Emission Heat Engines”
9:45 – 10:15 a.m. David Go, University of Notre Dame: “Microplasmas for Enhanced Thermionic Emission”
10:15 – 10:30 a.m. Coffee Break

Session VII: Diamond-Based Thermionic Energy Conversion Devices II
10:30 – 11:00 a.m. William (Hank) Paxton, IOP Technologies/Vanderbilt University: “The Future of Diamond-Based Thermionic Energy Conversion Devices: Promise and Challenges”
11:00 – 11:30 a.m. Robert Nemanich, Arizona State University: “Thermionic and Photon-enhanced Emission from CVD Diamond and New Approaches for Energy Conversion”
11:30 – 12:00 p.m. Amit "Anil", Newcastle University: “Diamond-based Thermotunnel Devices for Hostile Environment Energy Conversion”
12:00 – 1:15 p.m. Lunch
1:15 – 2:30 p.m. Breakout Sessions [Will we Have Rooms?]
The objective of the breakout sessions is to outline the key elements that will go into the Workshop Technical Report that will be published and archived as a NASA Technical Memo. The intent is for the Workshop Technical Report to cover the state-of-the-art (Jan 2014), listing avenues for the future, and areas where resources should be focused to advance development. We will normally divide into 4 teams to outline the following topics:
- Applications and requirements for modern and future TEC devices;
- Form factors and device structures for modern and future TEC devices;
- Material requirements for modern and future TEC devices;
- Testing and characterization apparatus and standards for TEC devices
2:30 – 2:45 p.m. Coffee Break
2:45 – 3:45 p.m. Reconvene to Discuss Breakout Sessions and Assign Writing Tasks
3:45 – 4:00 p.m. Day 2 Wrap Up and Meeting Adjourned
Jeffrey George, NASA and David Go, University of Notre Dame

Note: All talks are 20 min. Gordon Conference Style with 10 min. of Q&A
Getting Started

• Welcome
• Introductions
• Purpose, Goals, Objectives
• Logistics
• Discussion Guidelines
• Agenda
• Breakout Sessions
• Reporting, Next Steps
Why Explore Mars?

• Most similar planet to Earth. (though still different)
• Compare Geography, Geology, Development History
• Once had a warm, wet Climate. (What happened?)
• Did Life once exist? (Or still exist?)
• Humans Can Explore Mars.
  – Not too far or hot or cold, sunlight, gravity, resources
• Humanity could Live there. (a second home to Earth)
• Our Next Big Challenge!
• What will we Learn?
• What will we Invent?
Increased Mission Duration →
Increased Risk, Health Concerns, Consumables, Spares

- Radiation
  - SPE
  - GCR
  - (Reactor)
- Depressed Immune System
- Bone Loss
- Muscle Loss
- Away from Family, Friends, Joys of Life
- Mental Well Being / Morale
- Catastrophic Environmental Events
- System Failures (&/or massive redundancies/spares to mitigate)
- Increased Food & Consumables load
- *<Good Thing → Power-rich can enable 3D printers to make spares, better/lighter ECLSS S/S’s, etc.>*

If we can’t find a way to break the 3.5 year Mars mission paradigm, we may never get to Mars.
Six Month Mars Mission: Case 1 Q-thruster

- 2 month outbound leg (Earth SOI → Mars SOI)
- 2 month Mars stay (orbital maneuver, EDL, Surface)
- 2 month return leg (Mars SOI → Earth SOI)
- 6 month Round Trip (Earth SOI → SOI)

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Copernicus runs by EG / Tim Dawn
Mars Vehicle Concepts
“Converter X” Design Ref. & Performance Goals

~ Initial Working Concept for Thermionic Converter:

- “Reasonable” unit scale, system quantity
- 25mm x 25mm area
- 20% system efficiency, 25% converter efficiency
- 20 We / cm^2
- 125 We converter
- Voltage = 1-2 V
- Current = 10-20 amps / cm^2
- Thot = 1600-1800 K
- Tcold = 900-1100 K
- Gap = TBD 5-10, or 100 micro-m (0.01-0.1 mm vacuum vs. mag. assist)
- Emitter Material/Surface = Nanostructured Tungsten w/ adsorbed BaO
- Emitter Work Function = 2 eV
- Collector Material/Surface = Doped diamond nano crystals
- Collector Work Function = 1 eV
- Other structural, insulating materials = Alumina
- Space Charge Mitigation = Small vacuum gap, Magnetic assist, Cesium plasma
- Design Approach, Morphology = tbd
- Microfabrication Approach / Techniques = tbd

2014 Thermionic Workshop
“21st Century” Pathways for Improvement

- New Emitter and Collector Materials with Lower Work Functions
- Nano-fabricated Surface Topologies to Lower Work Functions
- Microfabrication
- New Converter Design / Topography Approaches to Reduce or Eliminate Space Charge Effects
- Photon Enhanced Thermionic Emission (PETE)
- Others?
Thermionic Conversion Applications

**SPACE POWER:**
- Nuclear thermal sources
- Solar thermal sources
- Others?

**TERRESTRIAL POWER:**
- “Topping” of fossil fuel plants
- Energy harvesting / scavenging
- Others?