

Advanced Stirling Convertor (ASC) - From Technology Development to Future Flight Product

Wayne A. Wong¹, J. Gary Wood², Kyle Wilson²

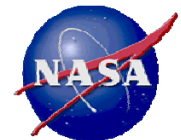
¹NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135

²Sunpower Inc., 182 Mill Street, Athens, OH 45701

Abstract. The Advanced Stirling Convertor (ASC) is being developed by Sunpower, Inc. under contract to NASA's Glenn Research Center (GRC) with critical technology support tasks lead by GRC. The ASC development, funded by NASA's Science Mission Directorate, started in 2003 as one of 10 competitively awarded contracts that were to address future Radioisotope Power System (RPS) advanced power conversion needs. The ASC technology has since evolved through progressive convertor builds and successful testing to demonstrate high conversion efficiency (38 %), low mass (1.3 kg), hermetic sealing, launch vibration simulation, EMI characterization, and is undergoing extended operation. The GRC and Sunpower team recently delivered three ASC-E machines to the Department of Energy (DOE) and Lockheed Martin Space Systems Company, two units for integration onto the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU) plus one spare. The design has recently been initiated for the ASC-E2, an evolution from the ASC-E that substitutes higher temperature materials enabling improved performance and higher reliability margins. This paper summarizes the history and status of the ASC project and discusses plans for this technology which enables RPS specific power of 8 W/kg for future NASA missions.

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Advanced Stirling Converter (ASC)

From Technology Development to Future Flight Product

Wayne A. Wong
RPT/ Thermal Energy Conversion Branch
NASA Glenn Research Center, Cleveland, OH

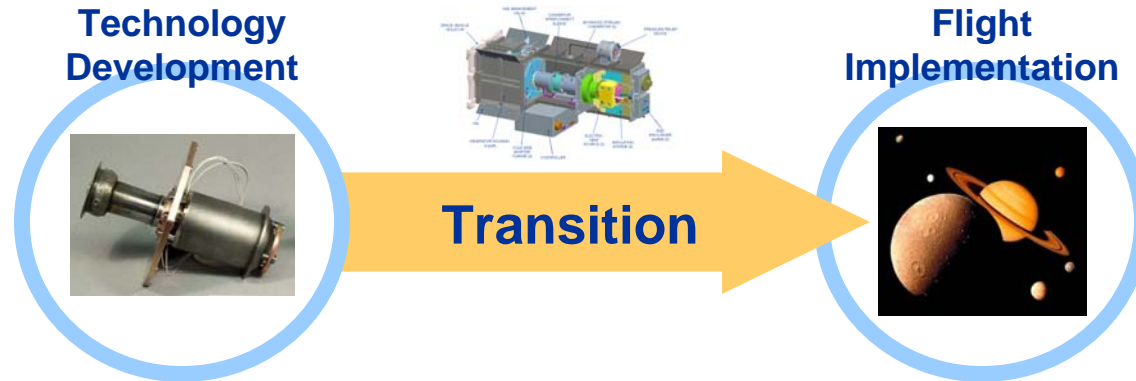
J. Gary Wood and Kyle Wilson
Sunpower Inc., Athens OH

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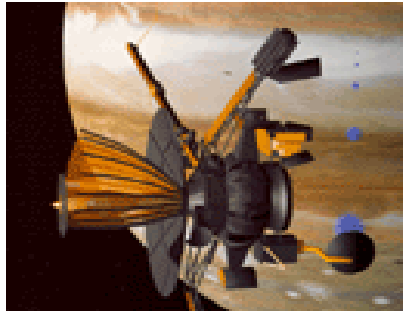


Agenda



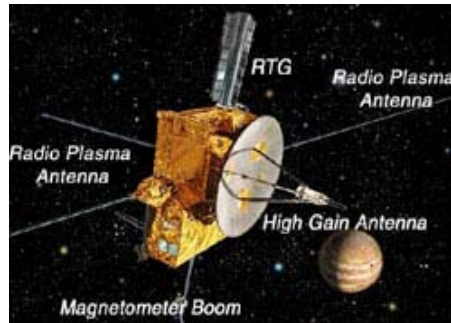
- Introduction and Background
- Baseline ASC Project (Phase I and II)
 - Accomplishments
- Re-planned ASC Project (Phase III)
 - Accelerated development
 - Advanced Stirling Radioisotope Generator (ASRG)
- Current Status to support potential Flight in 2013

Radioisotope Power Systems (RPS)



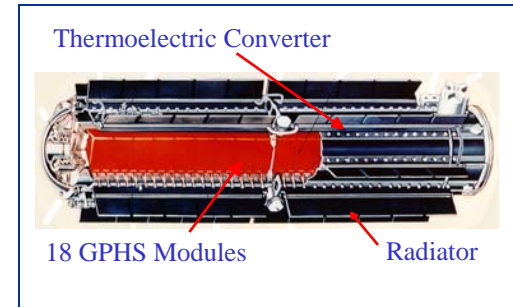
Galileo

Launch 1989
Interplanetary Cruise – 6 yrs
Jupiter Orbit – 8 years
Mission end 2003

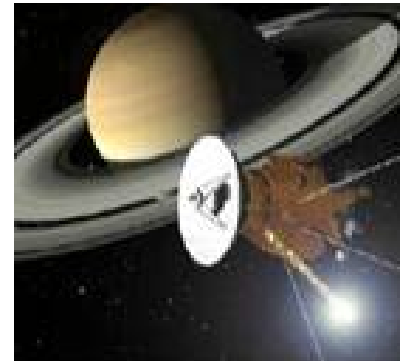


Ulysses

Launch 1990
Still operational
Sun-Heliosphere

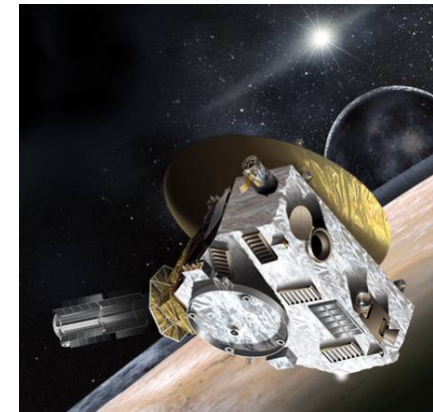


GPHE-RTG



Cassini-Huygens

Launch 1997
Arrive Saturn region July 2004
Huygens probe - Titan
landing Jan 2005



New Horizons

Launch 2006
Pluto-Charon encounter 2015
Kuiper-Belt Object encounters
2016-2020

RPS - Where solar
power is not effective

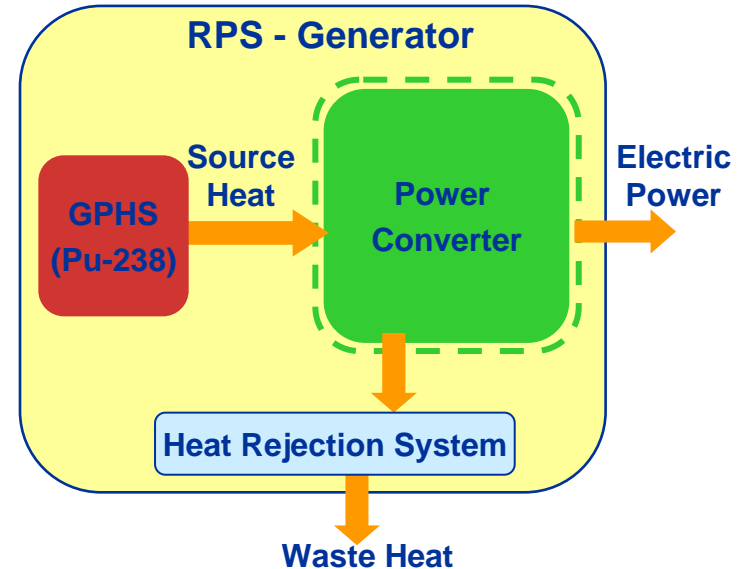
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RPCT Background and Sunpower ASC

- Sunpower and GRC Collaboration on small convertors started on a 2002 SBIR (35 W)
 - Based on Sunpower's cryocooler technology already demonstrated in flight (RHessi, >6 yr ongoing mission)
- ROSS 2002 NRA (02-OSS-01) – Radioisotope Power Conversion Technology (RPCT)
 - Develop power conversion technologies for future RPS systems
 - High Efficiency, reducing Pu-238 requirement
 - Enable high Specific Power
 - High Reliability (17 year life)
- 10 RPCT contracts awarded Fall 03 - 3 phases
 - Free-piston Stirling, Turbo-Brayton, Thermoelectrics, Thermophotovoltaics
- At conclusion of Phase I, an extensive 2 week review was held with each of the 10 RPCT contractors
 - Review committee included members from NASA HQ, GRC, JPL, DOE and Orbital Sciences



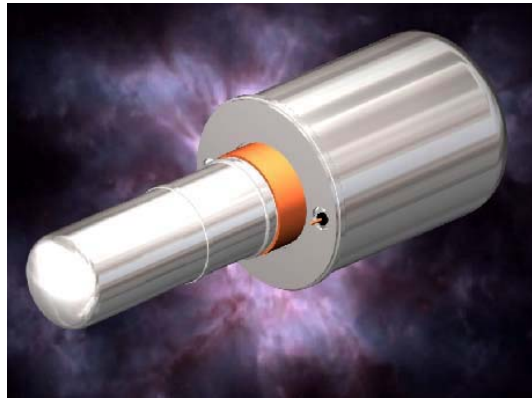
After Phase I, among 10 contracts, Sunpower's ASC was very highly ranked due to early hardware demonstrations of performance and continued relevance to NASA's goals.

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Sunpower ASC Baseline Technology Development



Early ASC Concept

Original Plan

Task/Milestone	Ph. I	Ph. II	Ph. III
1. FTB Design, Fab, & Test	— ▽		(Re-Planned)
2. ASC-1 Design Complete	— ▽		
3. ASC-1 Fab & Test		— ▽	
4. ASC-2 Design Complete		— ▽	
5. ASC-2 Fab & Test			— ▽
6. ASC-2 Qual. Test			— ▽

Proposal Goals

- Develop ASC with much higher efficiency than state-of-practice for next generation RPS
 - >80 We AC Output
 - >30% convertor efficiency (Reduce Pu238 by factor of 4)
 - ≥ 8 W/kg projected RPS system specific power (~2x improvement).
- Progressive convertor development:
 - FTB, ASC-1, ASC-2

Participants

- **GRC** - Management
- **Sunpower** - Prime, Stirling technology
- **Pratt & Whitney Rocketdyne** – HH materials & fabrication
- **Cleveland State University** – CFD modeling
- **University of Minnesota** – Large Scale Mock-up Regenerator testing
- **Stirling Consultants** – Penswick, Gedeon, Berchowicz, and Cairelli

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ASC Phase I Accomplishments

- **Frequency Test Bed (FTB) convertor demonstrated efficiency of 36% (AC power out/heat in)**
 - Design, built, and operational in 5 months, one month ahead of schedule
 - $T_{\text{hot}} = 650^{\circ}\text{C}$, $T_{\text{reject}} = 30^{\circ}\text{C}$, Temperature Ratio of 3.0
 - Quickly built FTB provided guidance on design of later ASC convertors
- **Selected MarM-247 for Heater Head and Udimet 720 for displacer to allow 850°C operation and improved performance**
 - Considered results of on-going material assessments at GRC
 - Performed many material coupon tests and various joining samples
- **Initiated reliability assessment**
 - Identify key elements that require further evaluation (i.e., high temperature alternator testing, regenerator durability evaluation)
- **Internal Displacer Losses – Studied both analytically, and experimentally**
 - Impact: ASC design with fewer displacer baffles, reducing part count (improving reliability), and easing manufacturability (reducing risk)

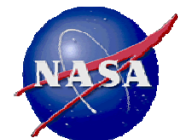


FTB Convertor

Early FTB demonstration of 36% efficiency retired risk, demonstrating potential of small machine performance and guiding ASC design

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ASC Phase II Accomplishments

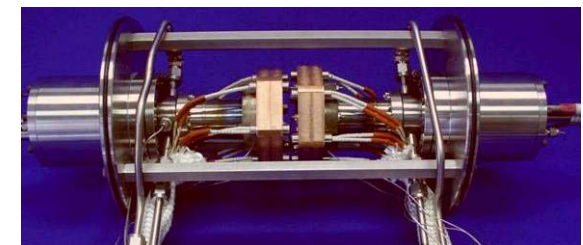
- **Completed and operated ASC-1 #1 on schedule**
 - Milestone 1st run on September 15, 2005
 - Non-hermetic high temperature developmental convertor
 - Four units completed
- **ASC-1 #1 full power high temperature achieved on Oct. 11, 2005**
 - 38% conversion efficiency, Power output = 88 W_{AC}
 - T_{hot} = 850°C, T_{reject} = 90°C
- **Max power capability = 114 W_{AC} with unlimited heat input**
- **Demonstrated Inertia Weld of MarM-247 to Inconel 718**
- **Hot Alternator Test Rig (HATR)**
 - High temperature characterization of alternator performance
 - Destructively Identify temperature limits & failure mechanisms
- **ASC-1 convertors operated in dual opposed configuration to investigate low vibration**
- **Large Scale Mock Up Regenerator Study – Providing data on near wall and jetting effects**



Phase II ASC-1 Convertors Completed



Hot Alternator Test Rig (HATR)

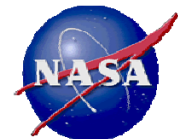


Dual Opposed ASC-1 Convertors

ASC-1 convertors demonstrated high temperature operation and breakthrough 38% performance

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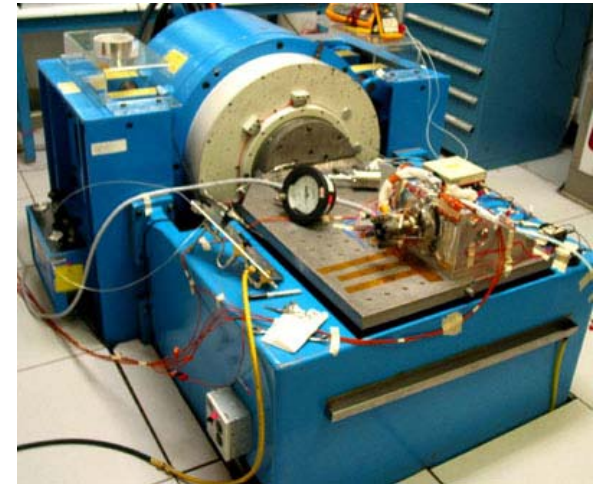


ASC Launch Vibration Test

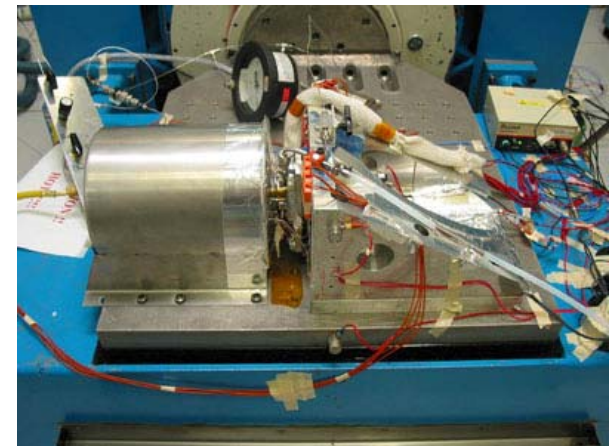
- ASC-1 #4 successfully passed vibration testing conducted April 2007 at P&W Rocketdyne facility
 - ASC was operational producing power during test sequence
 - Testing performed in axial and lateral directions
 - ASC-1 #4 modified to include internal FLDT
- Collaboration – PWR operated facility, Sunpower operated ASC, GRC provided test fixture, structural dynamics data acquisition system and analysis

	Level	Time (minutes)
Workmanship	6.8 g _{rms}	1
Flight	8.7 g _{rms}	1
Qualification	12.3 g _{rms}	3
Qualification + 3 dB	17.5 g _{rms}	1

Sunpower ASC convertor successfully passed vibration testing up to 17.5 g_{rms}



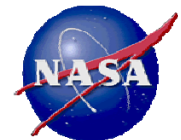
ASC-1 on PWR Shake Table



ASC-1 #4 Mounted in Test Fixture

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Phase III – ASC Project Re-planned

ASC Project re-planned to accelerate development toward flight implementation due to accomplishments of Phase I and Phase II

1. Additional Hermetic ASCs for GRC Extended Testing

- Freeze ASC-1 design and implement hermetic sealing and processing
- Identify and resolve developmental issues and provide extended operation data
- IN718 heater head ASC-0s (650°C); MarM-247 heater head ASC-1HS (850°C)

2. Integrated NASA GRC Technical Support

- NASA HQ re-directed GRC technical support from previous SRG110 to ASC (Fall `05)
- GRC technical support includes convertor, component, and materials testing and analysis to enhance reliability, reduce risk, and prepare for RPS flight development

3. DOE and Lockheed Martin Adopt Sunpower ASC for ASRG (May `06)

- Substituting ASC into SRG110 configuration increases specific power from 3.5 W/kg to about 7 W/kg
- GRC and Sunpower to provide ASC-Es to DOE and LM for ASRG EU integration
- After LM completes generator testing, ASRG EU delivered to GRC for extended operation in 2008

4. Preparing for Flight Implementation of ASC

- September 2007, NASA announces Discovery and Scout Mission Capabilities Expansion, seeking mission concepts that are enabled by up to a pair of ASRGs with potential launch as early as 2013
- ASC-E2 plans initiated to support this timetable
- ASC-E2 to increase reliability margin and offer higher temperature operation and improved performance while increasing design rigor and Quality system requirements
- ASC-E2s to be produced 2008-2009 for delivery to GRC for extended operation to help develop reliability database for operation up to 850°C

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Technology Evolution (ASC Project Phases)

Phase I



FTB #1 & #2

- Stainless Steel HH
- Non-Hermetic
- 650°C Thot
- 30°C Treject
- ASRG Controller Development (currently at LMSSC-Denver)

Phase II



ASC-1 #1 & #2

- All MarM-247 HH
- Non-Hermetic
- 850°C Thot
- 90°C Treject
- ASRG controller testing

ASC-1 #3 & #4

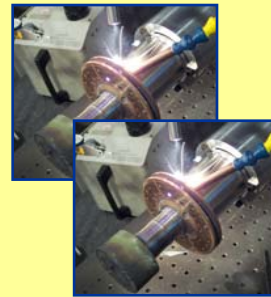
- Inertia Welded MarM-247 HH
- Non-Hermetic
- 850°C Thot
- 90°C Treject
- GRC extended testing

Phase III



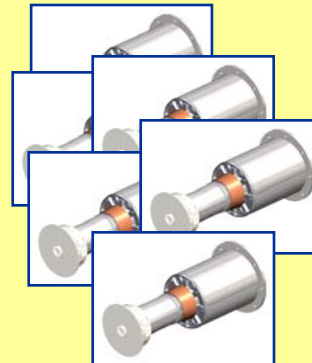
ASC-0 #1 & #2

- IN718 HH
- Hermetic
- 650°C/ 30°C Trej
- GRC Thermal-vac testing



ASC-1HS #1 & #2

- MarM-247 HH
- Hermetic
- 850°C/ 90°C Trej
- GRC Thermal-vac testing

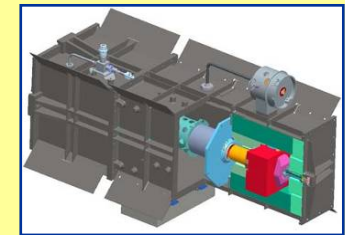
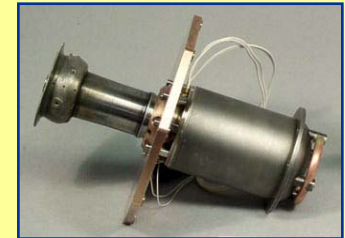


ASC-E2 #1-#6

- MarM-247 HH
- Hermetic
- Refinement of ASC-E

In Design

ASRG EU



ASC-E #1, #2, & #3

- IN718 HH
- Hermetic
- 650°C/ 60°C

ASRG Interface Dev.

Process Development

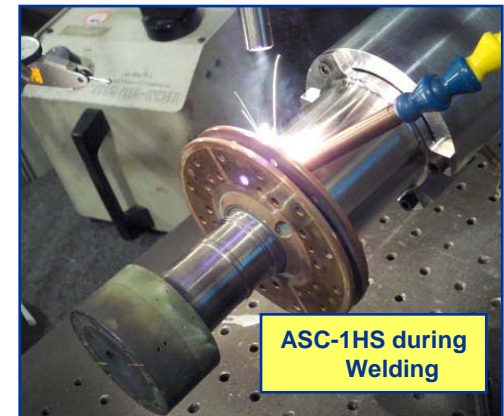
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Additional Hermetic ASCs for GRC Extended Testing

- Objective – Provide life and reliability data and evaluate performance by accumulating operational hours
- Hermetic convertors critical for extended operation testing, eliminating possibility of external trace contaminants and minute pressure changes
- Freeze design of ASC-1 and implement hermetic seal on developmental units
 - Pair of ASC-0 (IN718/ 650°C); Additional pair added to order
 - Pair of ASC-1HS (MarM-247/ 850°C)
- GRC testing in-air and in thermal vacuum conditions
- Benefits
 - Identify and address developmental issues
 - Provide extended operation data on hermetic ASCs
 - Processing, quality practices, and all lessons learned from these early developmental units can be applied to the later hermetic ASCs.
- ASC-0 #1 & #2 delivered Dec. 2006; ASC-0 #3 & #4 delivered July 2007; ASC-1HS #1 & #2 delivered Nov. 2007



Hermetic ASCs are now accumulating operating hours at GRC, adding to the reliability database

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Integrated NASA GRC Technical Support

- Highlights Below - Detailed overview in Schreiber and Thieme, STAIF 08
 - Continuous extended operation of convertors at Stirling Research Laboratory (in air and in thermal vacuum)
 - Total ASC operating time at GRC is over 25,000 hours
 - Total ASC operating time GRC + Sunpower is over 28,000 hours
 - ASC-0 #1 and #2 each have over 8,000 total hours (currently in T/V)
 - Verification of MarM-247 for unique ASC application
 - Uniaxial creep characterization including fine, medium, large grain sizes, database for life and reliability predictions
 - Braze joint for MarM-247 to IN718 (alternative to inertia weld)
 - Testing of MarM-247 heater heads – multi-axial creep and high temperature permeability
 - Development of high temperature regenerators and processes
 - Organic materials assessment – characterize properties and recommend processing techniques
 - CFD analysis including gas bearings assessment
 - Magnet aging tests – quantify time and temperature affects
 - Understand and Improve Reliability, support ASRG RWG
 - Guide Quality plan development and implementation



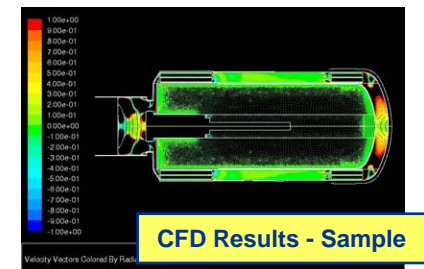
In-air Converter Test Stands



34 Creep Frames, 24/7



MarM Head Creep Test

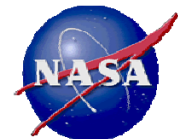


CFD Results - Sample

GRC expertise and capabilities focused on enhancing reliability and accelerating ASC development

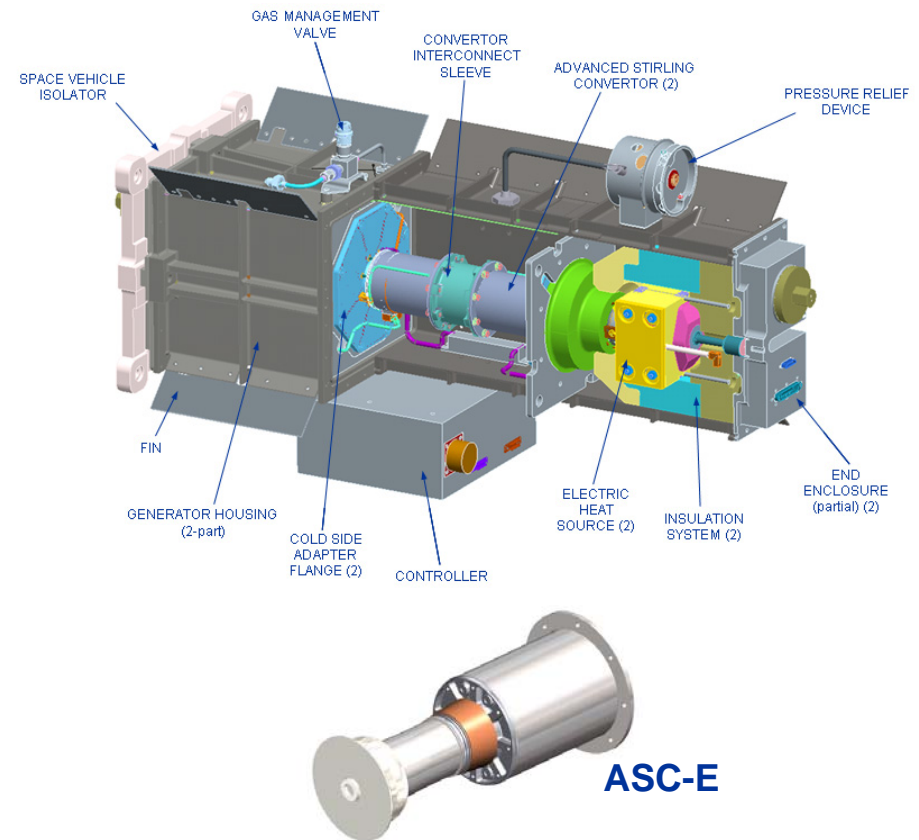
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DOE and Lockheed Martin Adopt ASC for ASRG

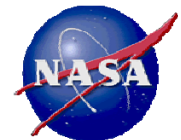
- Lockheed Martin, DOE's system integration contractor was developing SRG110 generator
- Agreement reached to substitute the Sunpower ASC into SRG110, renaming it Advanced Stirling Radioisotope Generator (ASRG)
- Initial ASRG Engineering Unit (EU) utilizes existing long lead and high value hardware from SRG110. Thus ASRG EU demonstrates the technology but is not optimized
- The ASC-E (for Engineering Unit) convertors utilizes IN718 hot end material and is limited to 650°C operation
- High efficiency and low mass of the ASC results in specific power increase from 3.5 W/kg for SRG110 to about 7 W/kg for ASRG
- ASRG Optimization could result in ≥ 8 W/kg
- ASC substitution also results in 25% reduction in generator length



NASA GRC and Sunpower to provide 2 ASC-Es plus a spare to DOE and LM for integration on to ASRG EU

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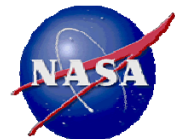
ASC-E Advancements as part of ASRG EU

- ASC-E significantly advances the technology
 - Previous ASCs were developmental convertors for lab testing. Generator interfaces not considered and out of scope of NRA contract
 - ASRG integration allows inclusion of integration interfaces and system requirements flowed-down from the generator design
- ASC-E product specification developed jointly by GRC, Lockheed Martin, and Sunpower
- Developed processes specific to integration (i.e. heat collector joints, CSAF attachment)
- More rigorous quality practices implemented including detailed documentation of process procedures, test plans, and test procedures
- ASC-E Configuration management exercised with oversight of Engineering Review Board (GRC, Lockheed Martin, Sunpower)
- Participation in ASRG Reliability Working Group

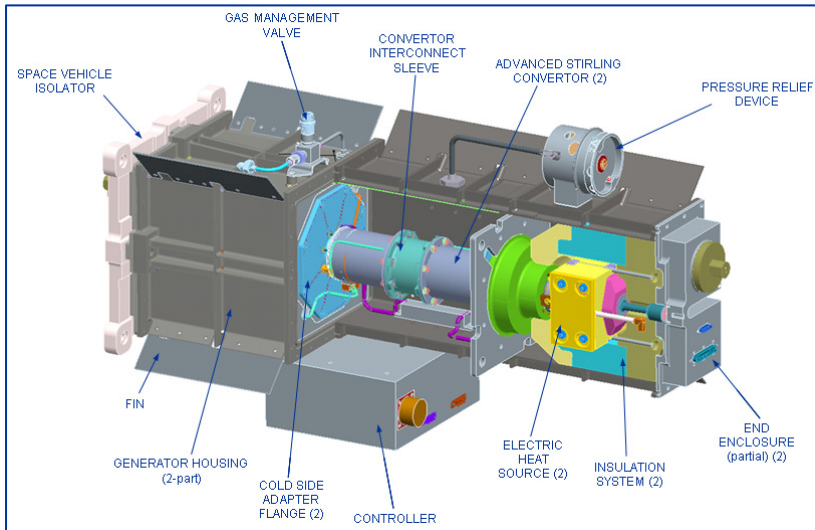
ASC-E and ASRG integration represents a major step from convertor technology development towards flight product

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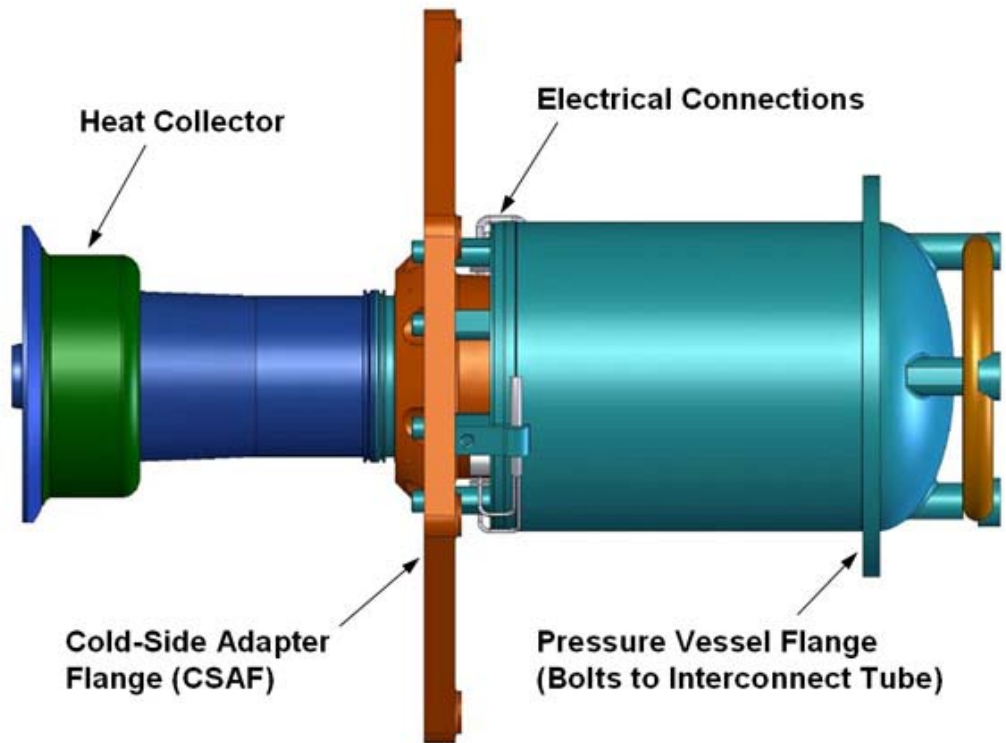


ASRG Integration Interfaces



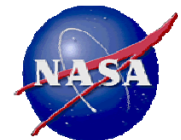
**Two ASCs (each with a GPHS)
in an ASRG**

**ASC-E and ASRG interfaces
defined by Interface Control
Document**



**Note: ASC-E2 shown. Interface types
are common for ASC-E and ASC-E2**

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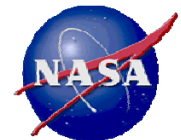
ASC-E/ASRG Integrated Team Effort



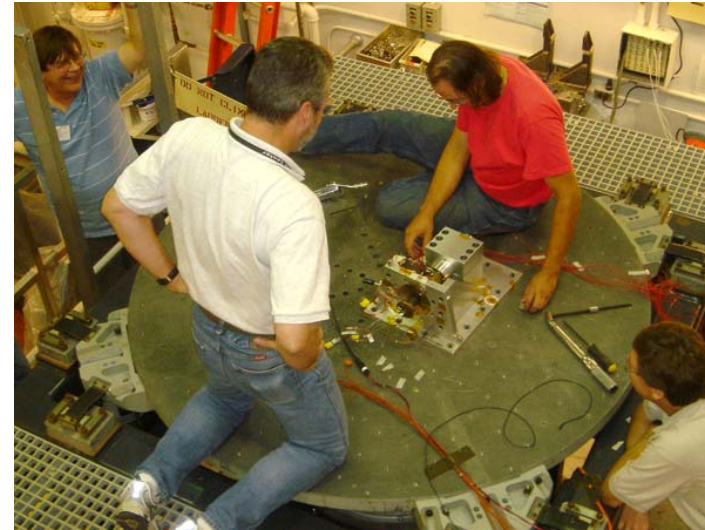
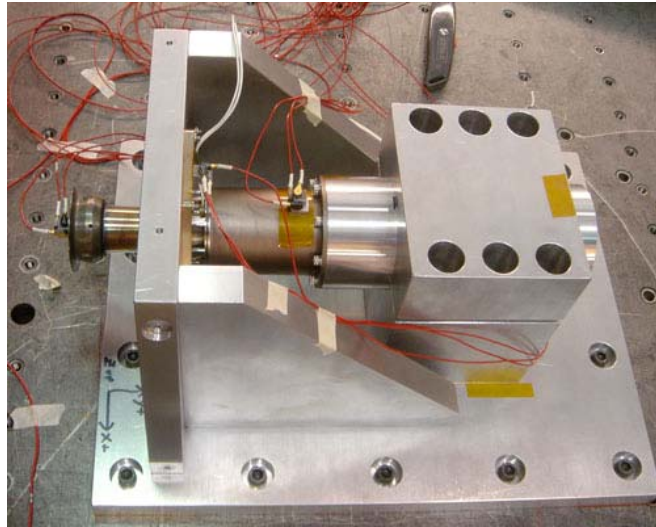
- The integrated hardware required an integrated team, from project inception to hardware delivery
 - Requirements definition
 - Trade studies
 - Process development
 - Component and Subassembly testing
 - Converter testing
 - Documentation and Review
 - Delivery
- Sunpower responsible for ASC-E production, but entire team contributed to hardware
- Lockheed Martin provide the nickel heat collectors and the copper-based CSAFs, and performed soldering and potting of external electrical feedthroughs
- GRC provided high temperature regenerators, performed soldering and wiring for internal electrical connections, assisted in various braze joint development and epoxy curing procedures, provided autonomous test station for burn-in testing, as well as coordination, inspection, and testing

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GRC ASC-E Workmanship Vibration Testing



- Workmanship testing conducted at GRC's Structural Dynamics Laboratory (SDL) with on-site support by Sunpower and Lockheed Martin personnel
- Convertors were motored during all vibration tests
- Structural integrity was confirmed by comparison of sine sweeps conducted prior to and after exposure to workmanship random vibration
- Integrity further confirmed by comparison of operational characteristics at Sunpower prior to and after vibration testing

All ASC-E convertors passed 6.8 grms workmanship vibration testing in all three axes (to NASA-STD-7001) per Product Specification

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ASC-E Accomplishments

- Trade Study Closure – July 2006
 - Trade studies performed to assess changes or features required to evolve the ASC design to one suitable for integration onto the ASRG EU
- ASC-E Design Review – November 2006
- ASRG Final Design Review – February 2007
- Delivery of early prototype convertors to Lockheed Martin to support controller development (2 pairs)
- Development of internal piston position sensor, heater head/heat collector joining process, and CSAF attachment
- ASC-E first test completed 7/16/07
 - 75 W_{AC} full power operation with first run, “Right out of the box.”
- Hermetic ASC-E first pair completed 9/21/07
 - After various tests (performance, checkout, and burn-in tests), and various processing steps (subassembly vacuum bakeout, welding, convertor bakeout, Helium final fill processing, fill tube closure)
- GRC Workmanship vibration testing complete on first pair 9/26/07
- Final performance testing complete 10/1/07
- GRC/Sunpower delivered first ASC-E pair to DOE/Lockheed Martin on-schedule 10/4/07
- Spare third ASC-E also delivered to DOE/LM on-schedule 10/29/07

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ASC-E Delivery Milestone Met!



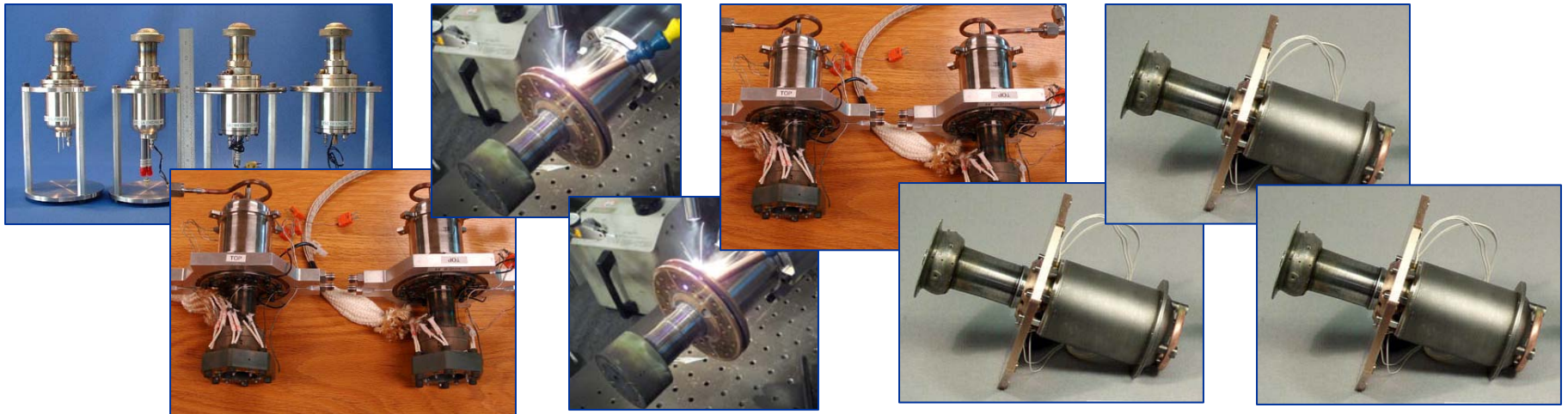
- ASC-E pair delivered on schedule October 4, 2007
- Power of $78 W_{AC}$ exceeded requirement of $75 W_{AC}$
- Spare ASC-E also delivered on schedule October 29, 2007

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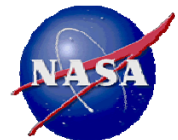
Productive Year for ASC

- Within a year between 12/06 and 11/07, Sunpower delivered 13 ASC convertors to GRC
 - 3 ASC-E and 2 ASC-1 provided to Lockheed Martin
 - 4 ASC-0, 2 ASC-1HS, and 2 ASC-1 remain at GRC for extended operation
- Anticipate continued accumulation of operational database with 8 ASCs currently at GRC



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ASC-E2 - Preparing for Flight Implementation

- Discovery and Scout Mission Capabilities Expansion (DSMCE) - Mission concepts that are enabled by ASRG with potential launch as early as 2013
- ASC-E2 Kicked-off in November 2007 to support this timetable
- ASC-E2s to be produced in 2008-2009 for delivery to GRC for extended operation to help develop reliability database for operation up to 850°C
- ASC-E2 based on heritage ASC-E with material substitutions for increased reliability margin, capable of higher temperature operation for improved performance (MarM-247 heater head, Udimet 720 displacer)
 - While ASC-E2 will not be implemented on ASRG, all ASC-E integration interfaces and current ASRG requirements will be adhered to (with updates)
 - ASC-E2 design, processing, testing, documentation and quality methods maintain relevance to the eventual ASRG flight application
- Emphasis to be placed on implementation of Quality system program based on DOE requirements for flight nuclear systems
- To enhance design and production, adding to Sunpower's infrastructure
 - Dedicated NASA ASC facility
 - Refinement in design practices
 - Upgrade to 3D design software project wide
 - Addition of dedicated equipment for welding
 - Increased inspection capability

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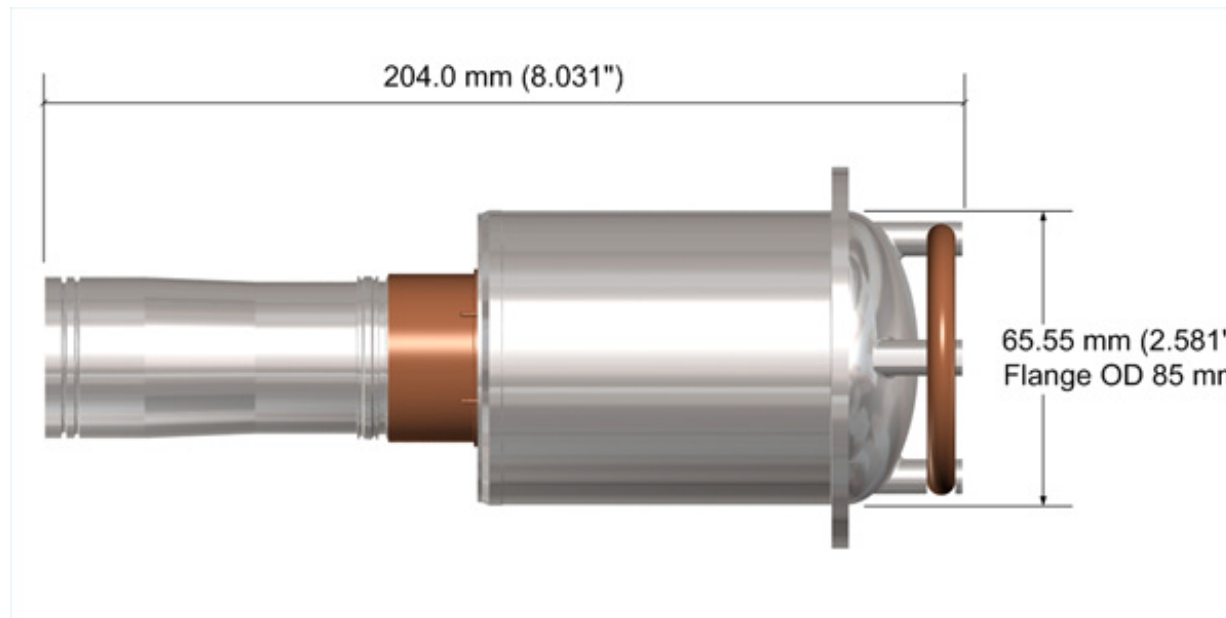


ASC-E2

Preliminary Estimates:

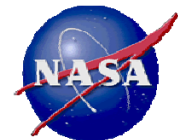
- 84.5 W_{AC} power output
- 37.7% Efficiency
- 850°C T_{hot} and 90°C T_{reject} reference operating temperatures
- 1.32 kg (not including ASRG interfaces – heat collector and CSAF)

ASC-E2 based on ASC-E and other previous convertors lending confidence in performance estimates





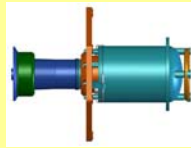
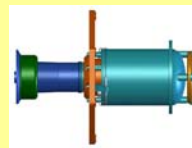
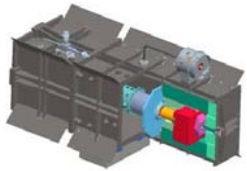


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Advanced Stirling Convertor Notional - Technology Development to Flight Evolution

	A. Tech. Development			B. Flight Transition			C. Flight
	ASC-1 	ASC-0 	ASC-1HS 	ASC-E 	ASC-E2 	ASC-E3 	ASRG 
Material	MarM-247		MarM-247		MarM-247	MarM-247	MarM-247
		IN718		IN718			
Hermetic		X	X	X	X	X	X
Progress	<ul style="list-style-type: none"> • Demo high efficiency and Low Mass • High temp components and joints demo. (HH, and Disp.) 	<ul style="list-style-type: none"> • Develop Hermetic Processes • Identify and resolve development al issues • Initiated QA/process documents • Extended Operation, in air 	<ul style="list-style-type: none"> • Demo Hermetic Processes on High temp units • Improve processing (brazes, gas bearings, etc.) • Extended Operation, in thermal-vac 	<ul style="list-style-type: none"> • ASRG Integration Interfaces • Major Improvement in quality & docs. • Improve processing (i.e. Closure weld, flow bench, etc.) • Configuration control (ERB) 	<ul style="list-style-type: none"> • Develop and Implement Quality Project Plan <ul style="list-style-type: none"> • Based on DOE Nuclear standard • Enhance interfaces • Refine high temp. processes & joints • Enhance reliability and manufacturability • Infrastructure <ul style="list-style-type: none"> • Dedicated Facility • Design Software • Laser Welder • Inspection (CMM) • Epoxy Mixer 	<ul style="list-style-type: none"> • Manufacture refinement as needed • Refinement to Include any new mission or generator derived requirements 	<ul style="list-style-type: none"> • NASA completes Sunpower ASC technology development and hands off to DOE for Flight implementation

Progressive Refinement Towards Flight Implementation

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Pre-decisional – For discussion only

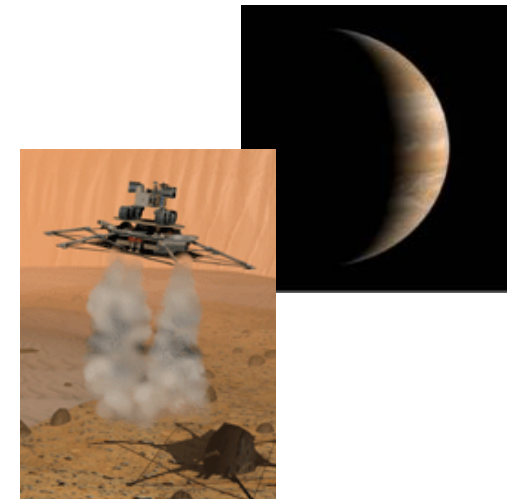
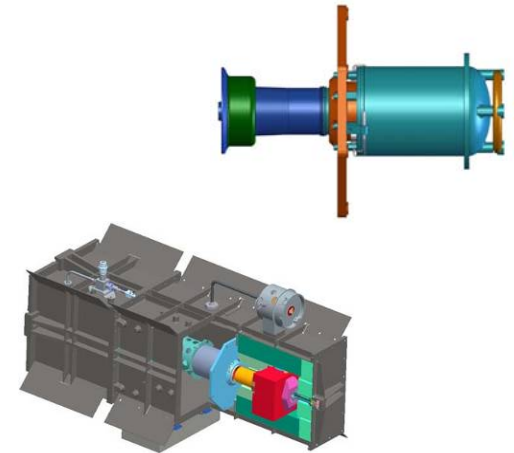
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Advanced Stirling Converter Summary

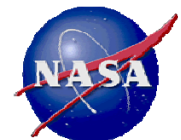
- ASC technology development began in 2003
- Demonstration of performance and hardware completion has led to project re-planning to accelerate development toward flight implementation
- 2008 represents mid-point in transitioning from technology development to potential flight as early as 2013
- Transition involves more than the hardware, but of the culture, processes, practices, and quality related to the hardware
- Successful earlier developmental convertors progressively advanced the technology
- ASC-E initiated the transition to potential flight application with ASRG integration
- ASC-E2 builds on the success of ASC-E

Integrated into the ASRG, the ASC could enable NASA missions as early as 2013 while minimizing the fuel requirements, and maximizing the specific power.



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