



CLEAR VISION

SOUND STRATEGIES

SOLID PERFORMANCE



Sunpower Advanced Stirling Converter (ASC)

Stirling Technical Interchange Meeting
at Ohio Aerospace Institute
June 29, 2015

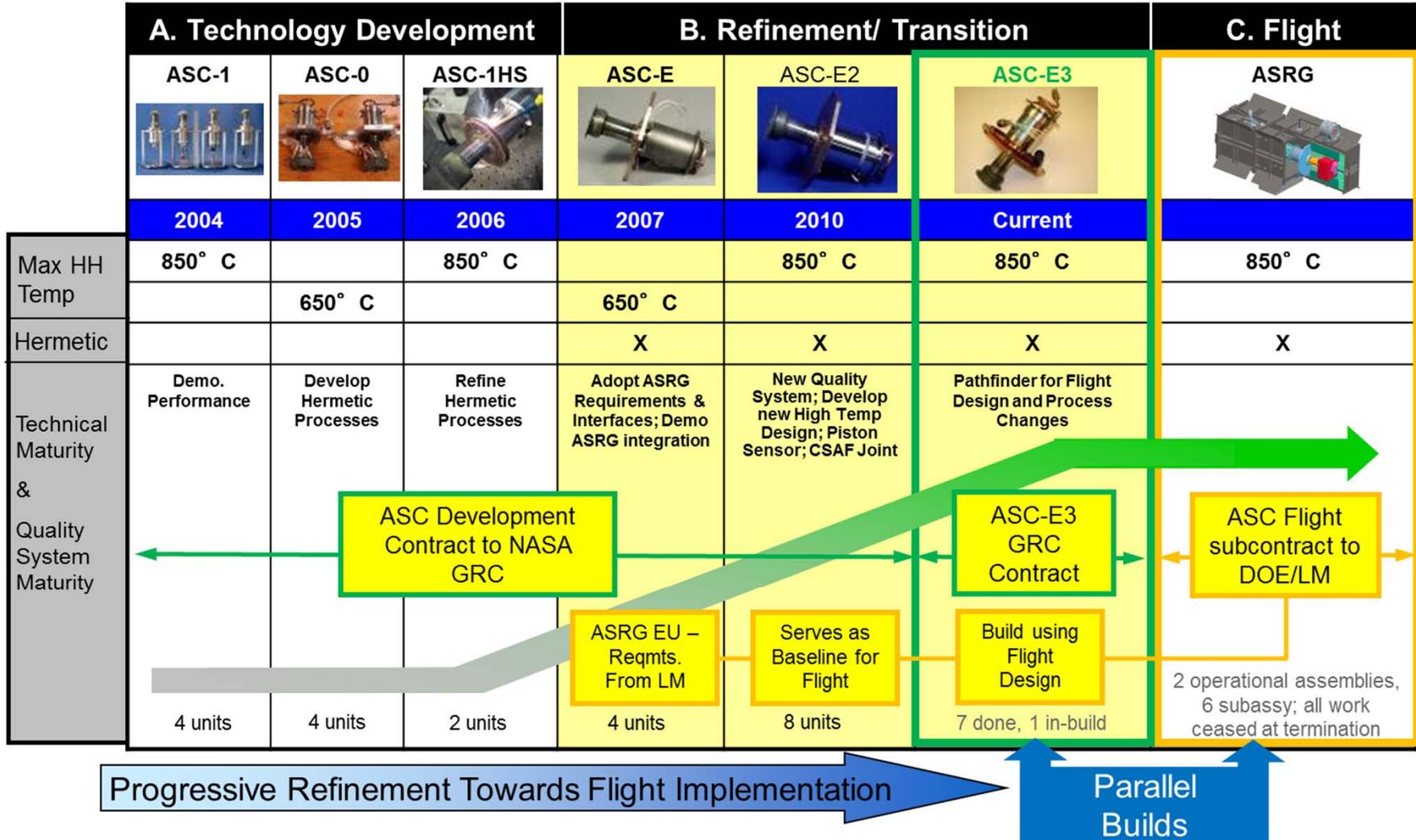
Advanced Stirling Converter History

- ASC technology development initiated in 2003 under NASA NRA contract
- Early successful demonstrations led to ASC adoption into DOE Advanced Stirling Radioisotope Generator (ASRG)
 - Five models of ASC (22 convertors) were built in technology development and transition-to-flight phases - prior to the ASC-E3 model
- Flight contract award necessitated parallel Sunpower ASC contracts due to compressed schedule to deliver flight hardware for potential selection for Discovery 12 mission
 - ASC-E3 Development Contract with NASA GRC
 - ASC-F Flight Sub-contract to DOE/Lockheed Martin

Advanced Stirling Converter History

- ASC-E3 Development Contract with NASA GRC
 - Reduce flight technical and schedule risk by early production and performance demonstration
 - ASC-E3 pathfinders - 8 converters with progression from flight design through clean room processes to fully flight-like converters
- ASC-F Flight Sub-contract to DOE/Lockheed Martin
 - ASC-F - 8 converters to fulfill qualification, flight and spares
 - Terminated for convenience November 2013

Sunpower ASC Technology Evolution

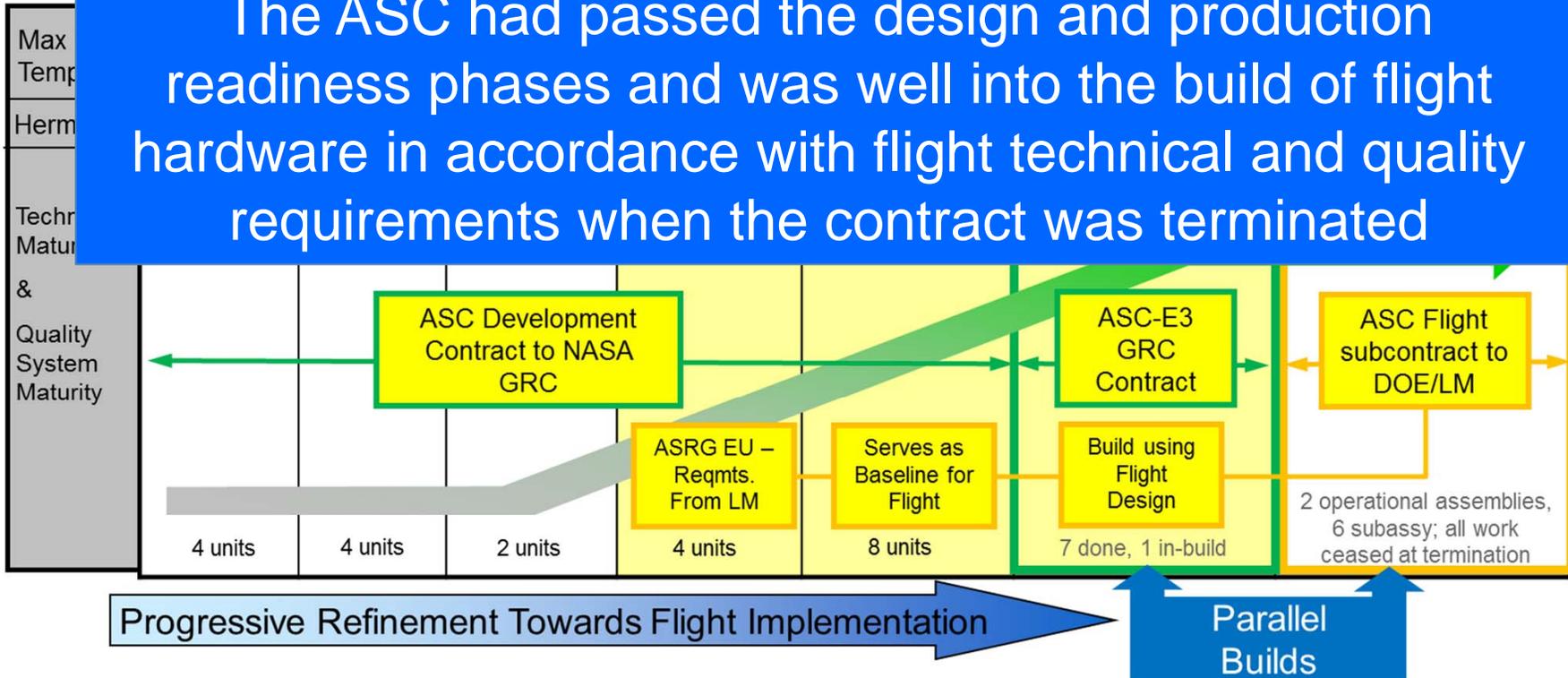


Credit Wayne Wong, NASA Glenn Research Center

Sunpower ASC Technology Evolution



The ASC had passed the design and production readiness phases and was well into the build of flight hardware in accordance with flight technical and quality requirements when the contract was terminated



Credit Wayne Wong, NASA Glenn Research Center

Engineering and Design – Flight Readiness

- Passed Flight Preliminary Design Review - Jan 2011
- Passed Flight Final Design Review - Feb 2012
- Passed Flight Manufacturing Readiness Review - Apr 2012
- Full GD&T implemented incorporating all previous lessons learned
- Full Flight requirements were successfully implemented such as M&P, NASA STD-5017, etc.
- Engineering documentation and production processes meet flight standards and were approved by the Flight Configuration Control Board
- Dedicated staff for Materials and Processing, Design, and Production

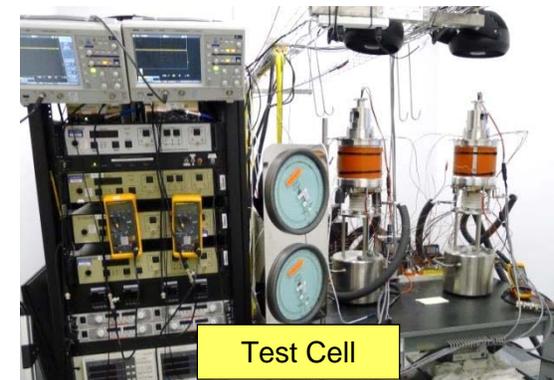
Quality Assurance – Flight Readiness

- Implemented configuration and nonconforming product control systems
- Implemented customer approved Quality Assurance Program, Configuration Management, Software Management, Contamination Control , QA Inspection, and Program Readiness Plans
- Successfully passed multiple customer quality system audits
- Quality system continues to be exercised on ASC-E3 production since termination of ASRG contract
- Sunpower continues to implement best practices from the flight quality system where appropriate throughout the company

Sunpower Production and Test Facilities

- Sunpower moved to new facility in 2011
- ASC lab for general component and subassembly processing
- 3 Test cells with capacity to operate 6 ASCs
- Clean room with capacity to process 8 ASCs
 - Class 8 clean room with Class 5 work spaces
 - Clean inspection capability
 - ASC-E3 #3 - #9 and ASC-F #1 & #2 processed in certified clean room facility
- Many in-house special process capabilities

Flight pedigree components and assemblies are on hand and available for use



ASC Hardware Accomplishments

Extended Operation Testing - conducted at GRC's Stirling Research Laboratory

Convertor(s)	Cumulative Operation
Tech. Demonstration Units (ASC-0, ASC-1, ASC-1HS)	137,433 hours (15.7 years)
Engineering Units (ASC-E & ASC-E2)	201,521 hours (23.0 years)
Flight pathfinders (ASC-E3)	44,979 hours (5.1 years)
Total ASC	383,933 hours



ASC-E3 Operations at GRC's SRL

Includes:

- Leader ASC-0 #3 with >52,700 hours (6 years)
- ASC-E #4 with >37,000 hours (4.2 years) and >26,500 hours (3 years) following launch vibe test

GRC Cumulative ASC operation >43 years and counting

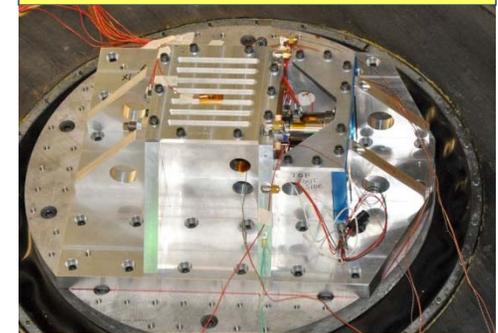
ASC Hardware Accomplishments

Environmental Testing

Test	ASC Units
Qual Level Vibration	ASC-E #1 ASC-E #2 & #3 (as part of ASRG EDU on controller) ASC-E2 #2 – multiple exposures ASC-E2 #8
Launch Level Vibration	ASC-E #4 ASC-E3 #4
EMI	ASC-E2 #1 & #2
Thermal Vacuum	ASC-1 #1 & #2
Durability Tests	
Centrifuge Acceleration (axial and lateral)	ASC-E2 #2
Start/Stop Cycling (accelerated tests)	ASC-E2 #8



Centrifuge Test Facility at CWRU



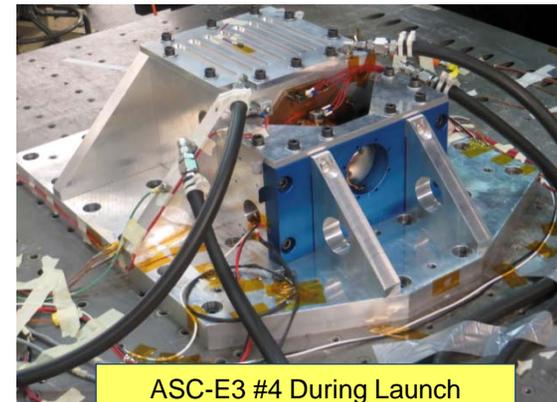
Vibe Testing at GRC SDL

ASC-E3 Highlights

- Five ASC-E3 convertors have successfully passed 2,000 hours of error-free operation as part of GRC independent performance verification testing
 - ASC-E3 #8 is currently in the middle of this testing and has passed 1,000 hours of error-free operation
- ASC-E3 #4 successfully completed flight acceptance and launch simulation vibration testing
 - Has accumulated >12,000 error-free hours of operation including >10,000 error-free hours since launch vibration test
- The average thermal efficiency of the delivered ASC-E3 units is 40% at Beginning Of Mission (BOM) Low Reject (LR) conditions (760C hot end and 38C reject)
 - 57% of Carnot efficiency



Completed Flight-Like ASC-E3 Pair 3



ASC-E3 #4 During Launch
Vibration Testing

Challenges to Date

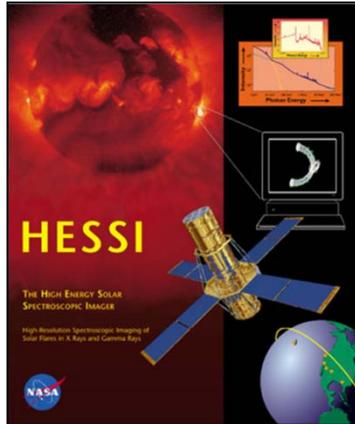
- Throughout building more than 30 ASC units over the last 12 years, there have been many lessons learned and corrective actions applied to the design, build and testing
- Each predecessor model influenced the subsequent build until the design and manufacturing process was frozen as of the ASC-E3 3rd pair and ASC-F 1st pair
- Several major investigations were conducted from the ASC-E2 build forward. Each investigation completed to date successfully resolved the issue via inter-agency and multi-disciplinary contributions and teamwork.

Path Forward

- The collective ASC team acknowledges that a significant lesson learned throughout design and development is that too much risk to reliability and robustness was accepted when tradeoffs were made in an effort to increase efficiency and specific power
- Sunpower has initiated activities targeted at improving the ASC robustness to off-nominal operating conditions which may reduce efficiency and specific power

Sunpower remains committed to NASA in the advancement of Stirling technology to enable future RPS missions

Sunpower Cryocooler Space Lineage



- Sunpower M77 cryocooler has been operating on RHESSI satellite for more than 13 years. A similar unit built at the same time has been operational in the Sunpower lab since the launch.
- Sunpower M223 Stirling freezer was flown on STS-60 Shuttle mission in 1994. The cooler was operational during launch. A similar unit built at the same time has been operational at Sunpower since 1995.
- There have been a total of 52 successful launches of 21 CryoTel CT-F units into space. The CT-F has been rated for 15 launches per unit based on customer testing. Some coolers are operational during launch and some are not.