National Aeronautics and Space Administration

Status of Dynamic Power Convertor Development for RPS at NASA GRC

Sal Oriti and Scott Wilson
NASA Glenn Research Center, Cleveland, OH

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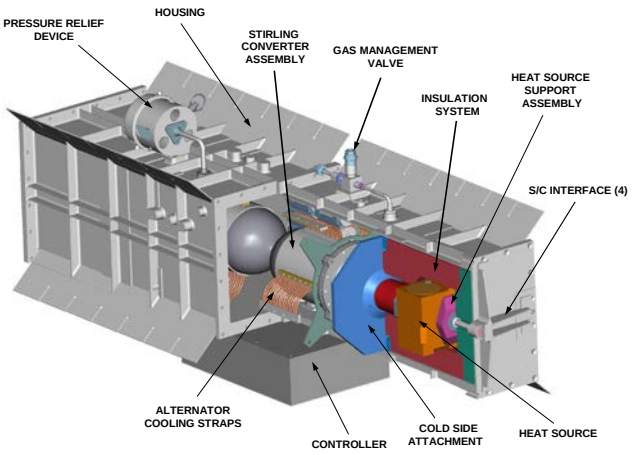
IAPG Mechanical Working Group Meeting

Dynamic Conversion Power System Background

Advantages:

- Higher efficiency, less waste heat for spacecraft
- Low generator power decline (fuel decay only)
- Large multi-mission generator design space
- Extensible to high power levels



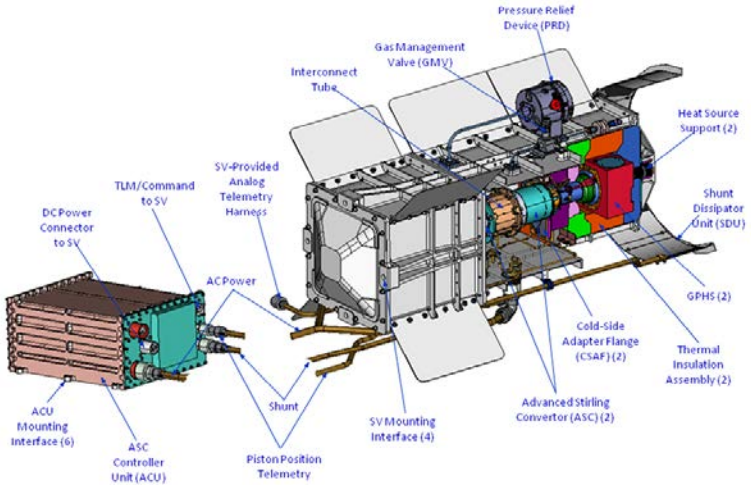
SRG110 (Lockheed Martin)

SRG-110

- **~114 W_e output**
- **Infinia's Technology Demonstration Convertor (TDC)**
- **2 GPHS modules**
- **Overall efficiency = 23%**
- **4.2 W_e/kg (before engineering unit build)**
- **Developed during 2001 to 2006 timeframe**

ASRG

- **~140 W_e output**
- **Sunpower's Advanced Stirling Convertor (ASC)**
- **2 GPHS modules**
- **Overall efficiency = 28%**
- **4.4 W_e/kg**
- **Developed during 2006 to 2013 timeframe**



ASRG (Lockheed Martin)

Key Convertor Performance Goals

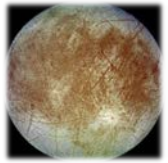
Item	Description
Life	20 years
Efficiency	≥ 24% at T_{cold} > 100 °C
Specific Power	20 W_e/kg (convertor only)
Partial power	Can be throttled down to 50%
Degradation	< 0.5% / year
Hot-End Temp	< 1000 °C
Cold-End Temp	20 to 175 °C
Random Vibe	Launch qual
Static Accel	20g for 1 minute, 5g for 5 days
Radiation	300 krad
Size	Enables generator that can fit in DOE shipping container

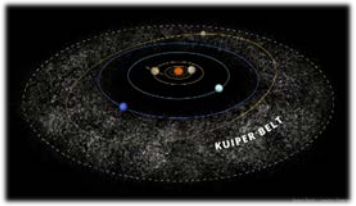
Multi-Mission Capable:

Mars 

Titan 

Moon 

Europa 

Deep Space 

Robustness goals also defined:

- Design has margin to tolerate events outside expected environments
- Fewer single-point-failures is more robust
- Tolerant of loss of electrical load
- Tolerant of operational error
- Manufacturability not dependent on specialized workmanship

Convertor Development Timeline

- RFP via Research Opportunities in Space and Earth Sciences (ROSES-2016), August 2016
- Received 14 proposals, encompassing multiple dynamic conversion methods
- 4 contracts awarded in FY2017:

Contractor	Convertor Name
American Super Conductor	Flexure Isotope Stirling Convertor (FISC)
Creare, LLC	Turbo-Brayton Convertor (TBC)
Northrop Grumman Aerospace Systems	Thermo-Acoustic Power Convertor (TAPC)
Sunpower, Inc.	Sunpower Robust Stirling Convertor (SRSC)

- Contracts consist of up to 3 Phases:

Phase	Duration	Work Focus
1	6 months	Design
Decision Gate 1		
2	18 months	Prototype Fabrication Performance Demonstration
3	12 months	IV&V Test Support
Decision Gate 2		

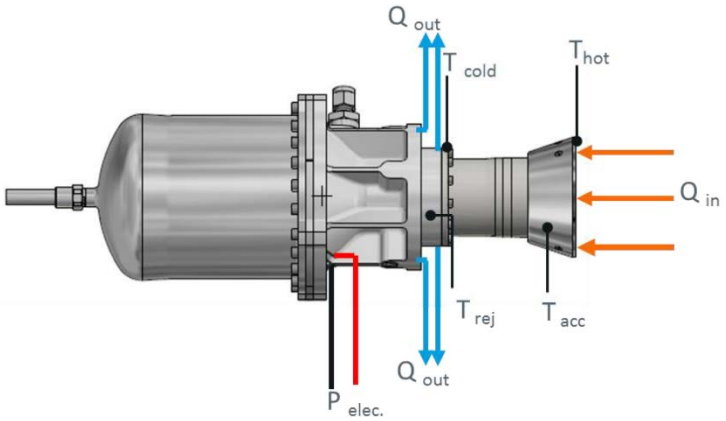
NASA Contracts

Flight Development New Frontiers 5 AO

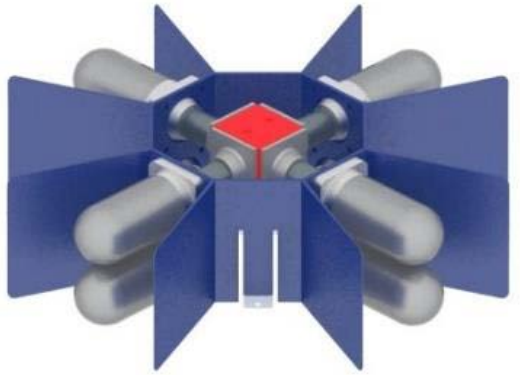
DOE Contract + NASA Partnership

Flexure Isotope Stirling Convertor (FISC)

American SuperConductor (AMSC), formerly Infinia Tech Corp.



70 W Flexure Isotope Stirling Convertor (FISC)



Notional 240 W generator concept with 100% convertor redundancy

Convertor Performance

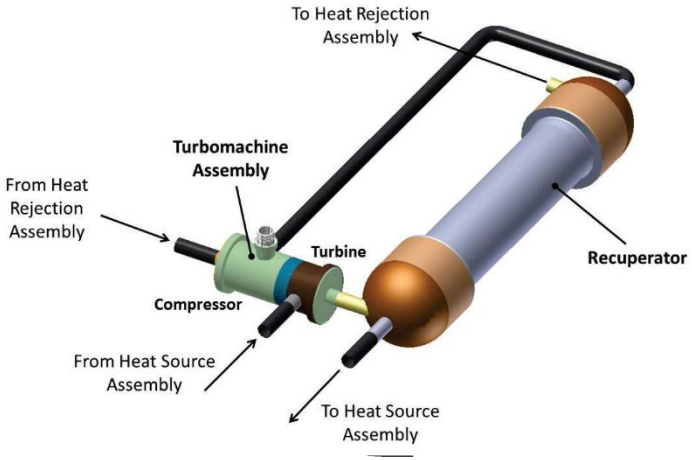
Hot-end Temp	650 °C
Cold-end Temp	20 to 175 °C
Efficiency	31% @ T_{COLD}=100°C
Power Output	70 W_{ac}
Mass	3.3 kg (>20W_e/kg)

- **Flexure-bearings, beta arrangement free-piston Stirling conv.**
- **Derivative of Technology Demonstration Convertor (TDC) from a 1990's SBIR and SRG-110 project**
- **Design deltas relative to TDC to improve the following:**
  1. Higher radial stiffness flexures, overstroke tolerance, hot-end temperature margin
  2. Independently verifiable subassemblies
  3. Higher efficiency alternator, higher cold-end temp capability
  4. System integration : Tailored interfaces

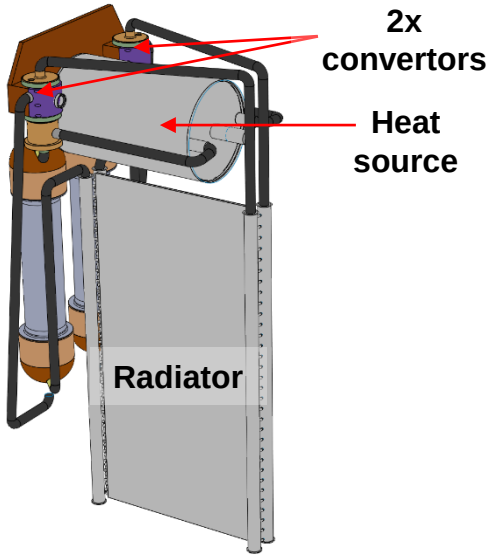
Status:
Decision Gate 1 successfully passed
Phase 2 awarded, April 2018

Turbo-Brayton Convertor (TBC)

Creare, LLC



355 W_e Turbo-Brayton Convertor (TBC)



Notional 355 W_e generator concept with 100% convertor redundancy

TBC Performance

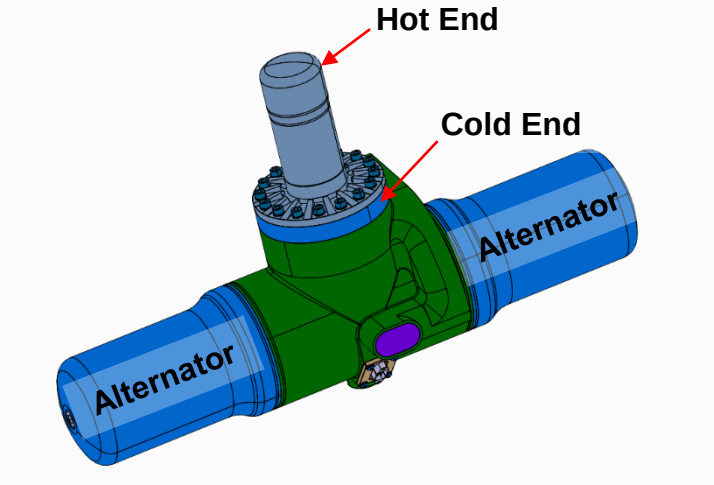
Turbine Inlet Temp (Hot End)	730 °C
Compressor Inlet Temp (Cold End)	20 to 175 °C
Efficiency	26% @ T_{COLD}=100°C
Power Output	355 W_{ac}
Mass	15.5 kg (>20W_e/kg)

- **Closed Brayton continuous flow cycle with recuperation**
- **Scaled-down from previous designs**
- **Leverages heritage from Creare's HST NICMOS cooler**
- **Two counter-rotating units permits redundancy, and nullifies angular momentum**

Status:
Decision Gate 1 successfully passed
Phase 2 awarded, April 2018

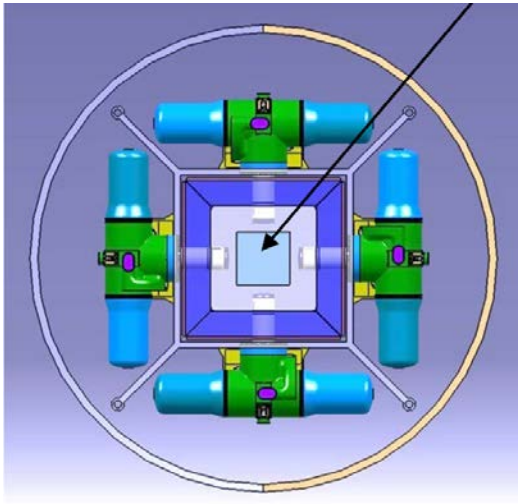
Thermo-Acoustic Power Convertor (TAPC)

Northrop Grumman Aerospace Systems



110 W_e Thermo-Acoustic Power Convertor (TAPC)

GPHS modules



Notional 220 W_e generator concept with 100% convertor redundancy

TAPC Performance

Hot-end Temp	700°C
Cold-end Temp	20 to 175 °C
Efficiency	26% @ T_{COLD}=100°C
Power Output	110 W_{ac}
Mass	6.4 kg (< 20 W_e/kg)*

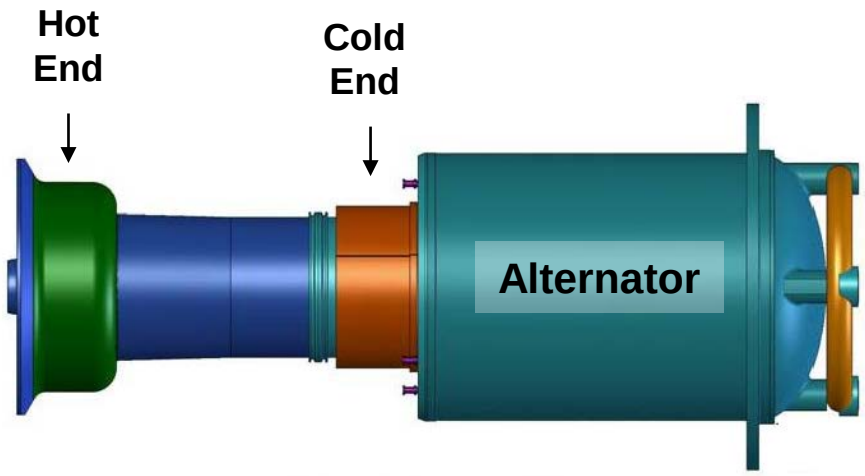
***Options being explored to reduce convertor mass to meet W/kg target**

- **Thermoacoustic Stirling cycle**
- **Eliminates physical displacer (no moving parts in hot end)**
- **Natively balanced, dual-opposed alternator building block**
- **Alternators driven by shared compression space**
- **Based on previous development efforts:**
  2003 NRA, IRAD-developed device

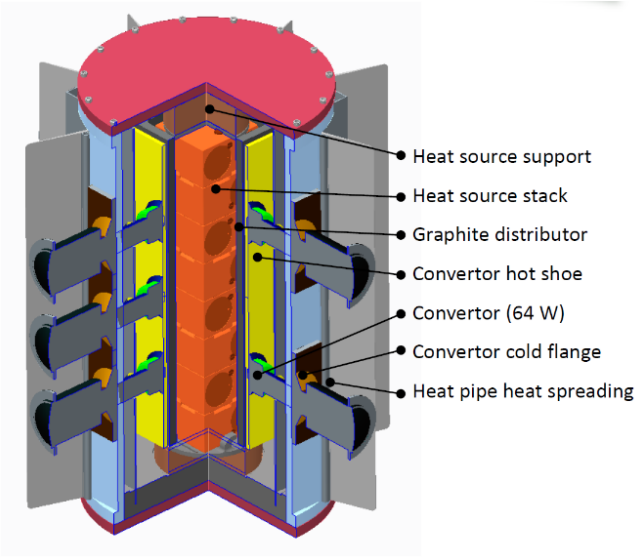
Status:
Phase 1 Design Review Completed, April 2018
Phase 2 award pending gov't decision

Sunpower Robust Stirling Convertor (SRSC)

Sunpower, Inc.



65 W_e Sunpower Robust Stirling Convertor (SRSC)



Notional 500 W_e generator concept with 25% convertor redundancy

SRSC Performance

Hot-end Temp	720°C
Cold-end Temp	20 to 175 °C
Efficiency	29% @ T_{COLD}=100°C
Power Output	65 W_{ac}
Mass	2.0 kg (> 20 W_e/kg)

- **Gas-bearing based, beta arrangement free-piston Stirling**
- **Derivative of Advanced Stirling Convertor (ASC) from ASRG Project**
- **Enables wide generator design space**
- **Design deltas relative to ASC to improve the following:**

1. Higher radial gas bearing stiffness, overstroke tolerance, regenerator robustness, debris tolerance
2. Higher cold-end temp capability, static acceleration

Status:
Phase 1 Design Review Completed, April 2018
Phase 2 award pending gov't decision

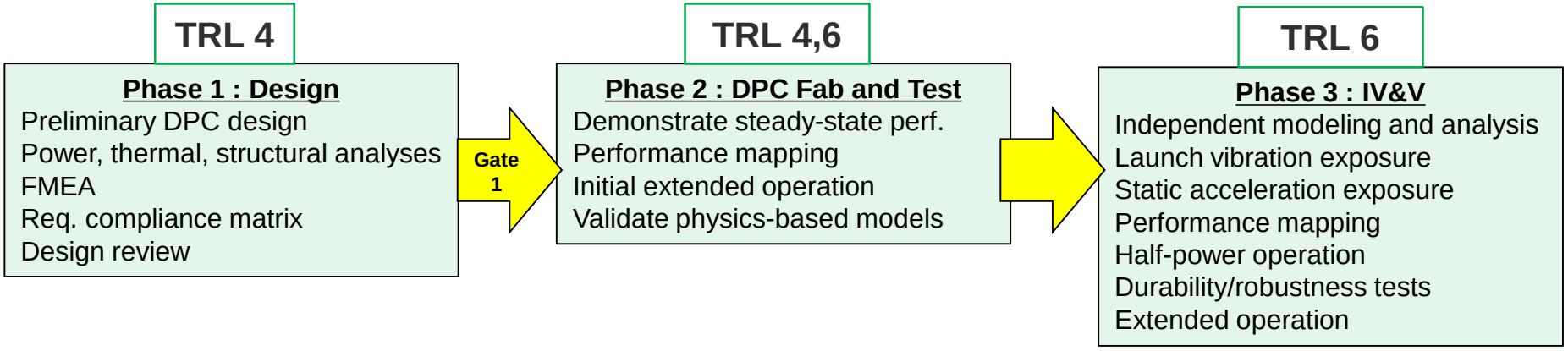
Path to Flight

Goal:
Achieve convertor TRL 6, then initiate generator flight development

NASA definition of TRL 6: “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”

Surrogate Mission Team (SMT), chartered by RPS Program

- NASA, DOE, JPL, APL, GSFC
- Formulated requirements to provide mission pull
- Integrated with DPC contract progress monitoring
- Formulated a TRL evaluation method
- Providing failure mode and probability of success analysis
- Work phases and deliverables tied to TRL advancement



Stirling Convertor Extended Operation

Many convertors from SRG110 and ASRG projects are still undergoing continuous operation today

Project & Provider	Test Article	Years of Operation
SRG 110 Infinia, Corp.	TDC #13	12.6[1]
	TDC #15	11.6
	TDC #16	11.6
	SES #2	0.3
ASRG Sunpower, Inc.	ASC-0 #3[2]	8.3
	ASC-E3 #4[2]	3.1
	ASC-E3 #6[2]	2.4
	ASC-E3 #9	1.6
	ASC-E3 #8	1.9
	ASC-L[2]	4.0

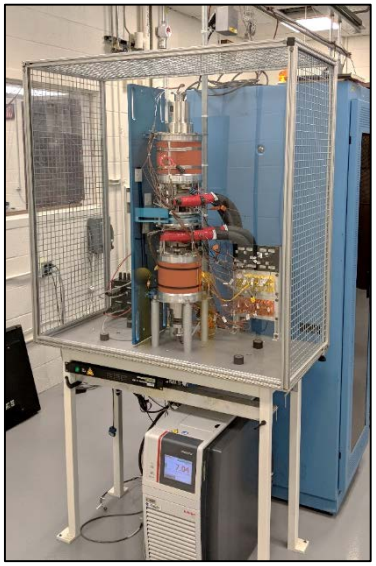
Cumulative Per-Convertor Runtime as of May 2018

[1]Current record-holder for maintenance-free heat engine

[2]Have undergone random vibe portion of life certification

Date	Nov 20, 2010	Aug 30, 2016
TDC #13	65.4 W	65.4 W
TDC #14	64.5 W	64.5 W

TDC #13 and #14 performance data over six year period

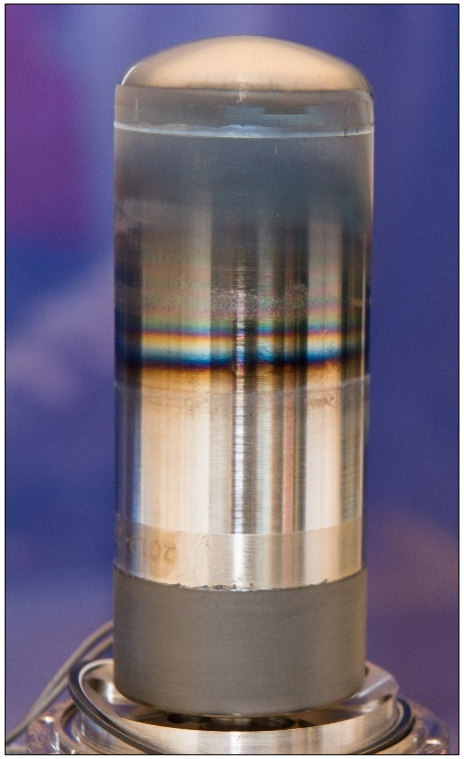


ASC-E3 Pair Extended Operation Test Article

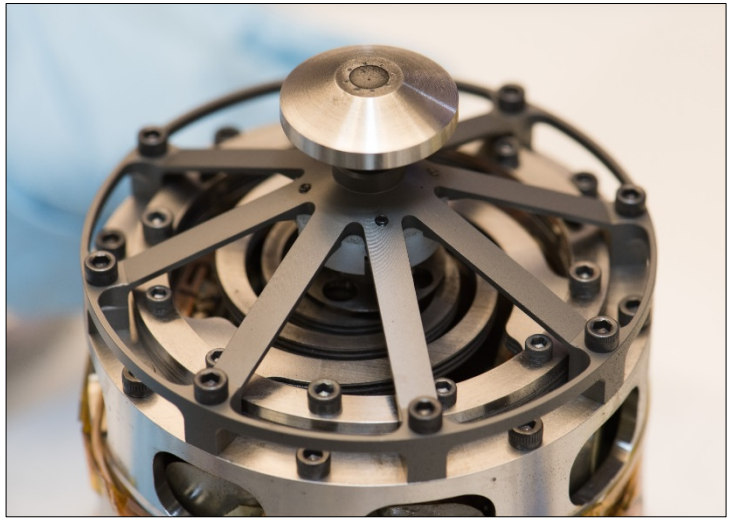
TDC #14 Disassembly and Inspection

Encouraging results from TDC #14 inspection
105,620 hrs of operation = 12 years, 31 billion cycles
Further disassembly is planned

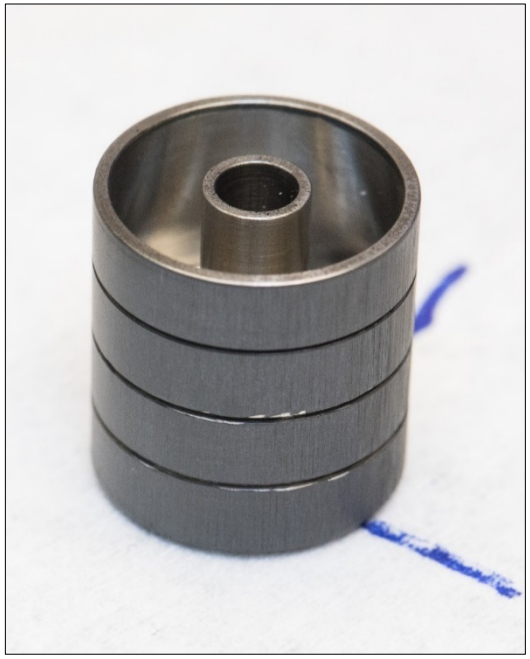
- **No sign of flexure degradation**
- **Signs of oxidation on expected surfaces – likely from early non-hermetic operation**
- **Geometric stability verified via Coordinate Measuring Machine (CMM)**
- **Evidence of oxide residue/dust in various areas – did not degrade operation**



TDC #14 displacer after 12 years of operation



TDC #14 aft flexure stack after 12 years of operation

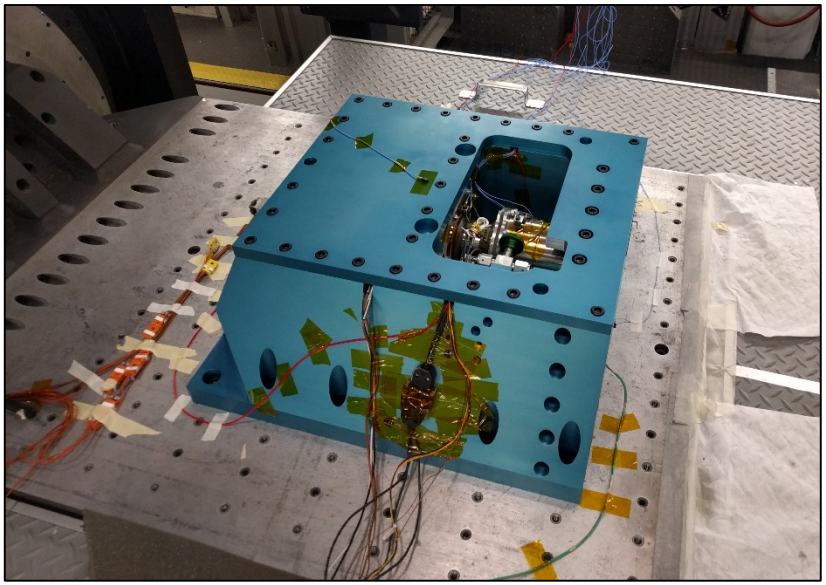


TDC #14 piston after 12 years of operation

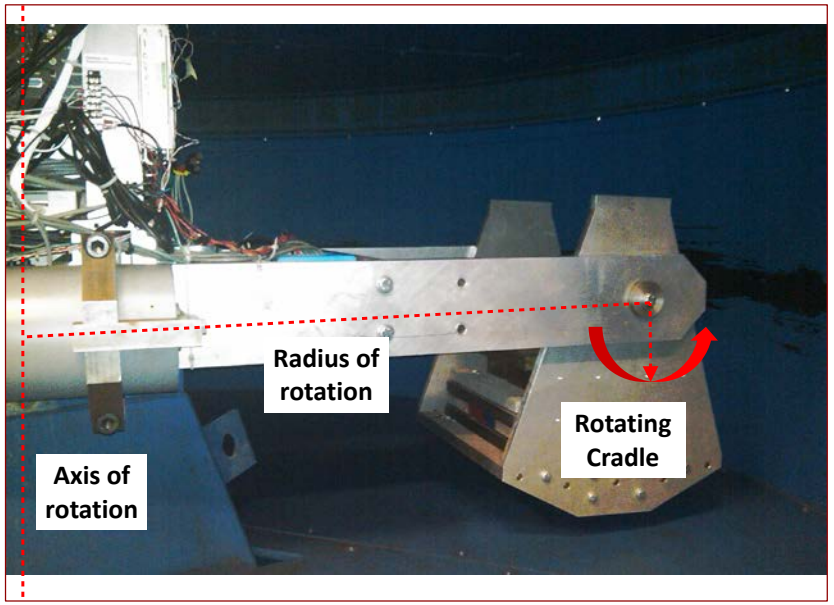
Launch Vibration Exposure on SES #2

Engineering Unit convertor from SRG-110 project successfully passed launch simulation while operating

- **10.35 g_{rms} profile formulated by SMT, encompasses wide span of launch vehicles**
- **2 min duration at full random vibe level**
- **Temporary reduction in power output during lateral axes exposures (expected)**
- **SES #2 now operating continuously at full power, 2900 hrs accumulated**
- **Static acceleration exposure test up to 20g recently performed**



SES #2 undergoing launch vibration exposure



Centrifuge facility for static acceleration tests (Case Western Reserve University)

Conclusions

NASA's dynamic power convertor development in support of high-efficiency RPS is progressing as planned, and shows promise

- **2 DPC contracts have passed Decision Gate 1, and have been awarded Phase 2 (convertor prototype fabrication and test)**
- **2 DPC contracts have completed Phase 1 reviews**
- **NASA GRC is preparing for DPC prototype IV&V, ~2020**
- **Ongoing research utilizing existing hardware supports viability of dynamic power conversion for RPS**