THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

Thermoacoustic Power Convertor (TAPC)

8 May 2018

Michael Petach

Manny Tward

TIM for Industry

Contract #: 80GRC017C0049

Approve for Public Release by NASA, 5/3/18; NG18-1012

Northrop Grumman Today

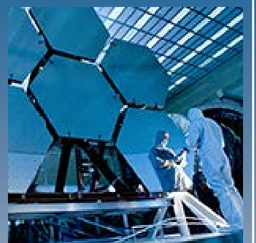
- Leading global security company
- $25.8 billion sales in 2017
  - 87% U.S. / 13% International
- $42.9 billion total backlog
  (as of Dec. 31, 2017)
- Leading capabilities in:
  - Autonomous Systems
  - Cyber
  - C4ISR
  - Strike
  - Logistics and Modernization

Focus on Performance

Three Operating Sectors at a Glance

NORTHROP GRUMMAN

Aerospace Systems



Autonomous Systems

Strike Operations

Military and Civil Space Systems

Aircraft and Spacecraft Design, Integration and Manufacturing

Intelligence, Surveillance and Reconnaissance

Protected Communications

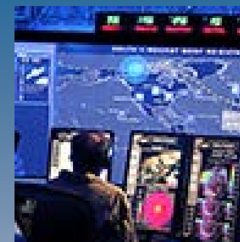
Battle Management

Missile Defense

Space Exploration

Advanced Technologies

Mission Systems



Airborne C4ISR Systems

Cyber and Intelligence Mission Solutions

Land and Avionics C4ISR Mission Solutions

Missile Defense and Protective Systems

Navigation and Maritime Systems

Space ISR Systems

Advanced Concepts and Technologies

Technology Services

Technology-Differentiated, Mission Services and Training Systems

Logistics and Modernization of Military Equipment

Global Sustainment Engineering and Support

New Innovative Logistics Products

Health IT

Civil Security and Public Safety Systems

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Northrop Grumman Products

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Aerospace Systems

UNMANNED SYSTEMS

- $10 Billion Sales 2014
- Systems Prime
  - Unmanned Autonomous Systems
  - Manned Weapon Systems
  - Space (National, Military, Civil)
- 6 Design Centers Of Excellence

- Strong Focus On Values and Performance
  - Leadership and Ethics
  - Program Performance and Customer Satisfaction
  - Affordable Cost Structure and Innovation
  - Engaged Work Force

MANNED SYSTEMS

SPACE SYSTEMS

A Snapshot of Space Systems

NORTHROP GRUMMAN

- A leader in high-reliability satellites and electronic systems
- Differentiated by technology and system engineering
- Large, long duration development programs with flight proven production processes
- Delivery of multiple systems and technologies for the United States
- World-class workforce

Space Park Named an AIAA Historical Site

Taking on the Toughest Missions for Over 50 Years

Space Systems: A Brief History

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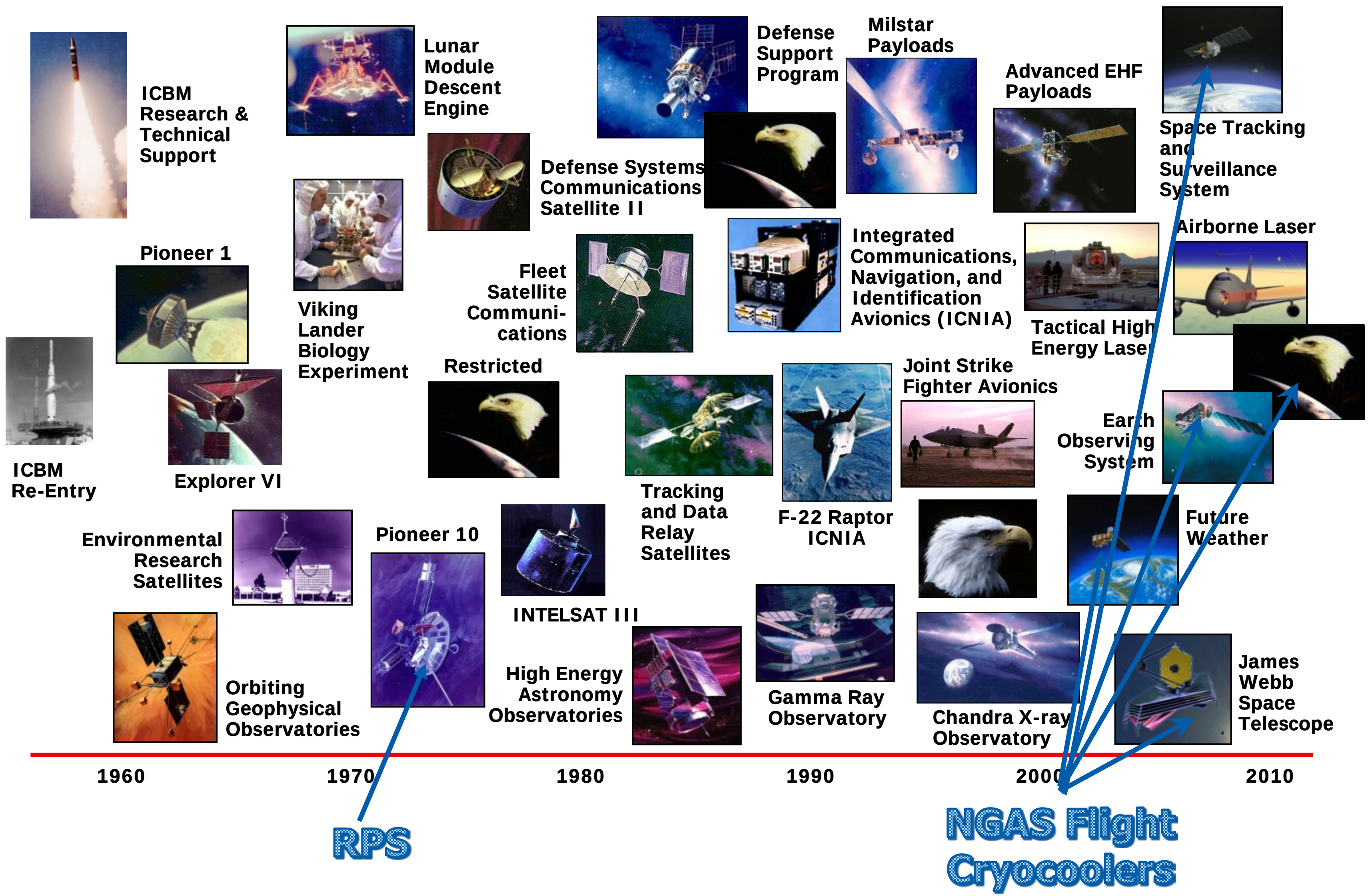
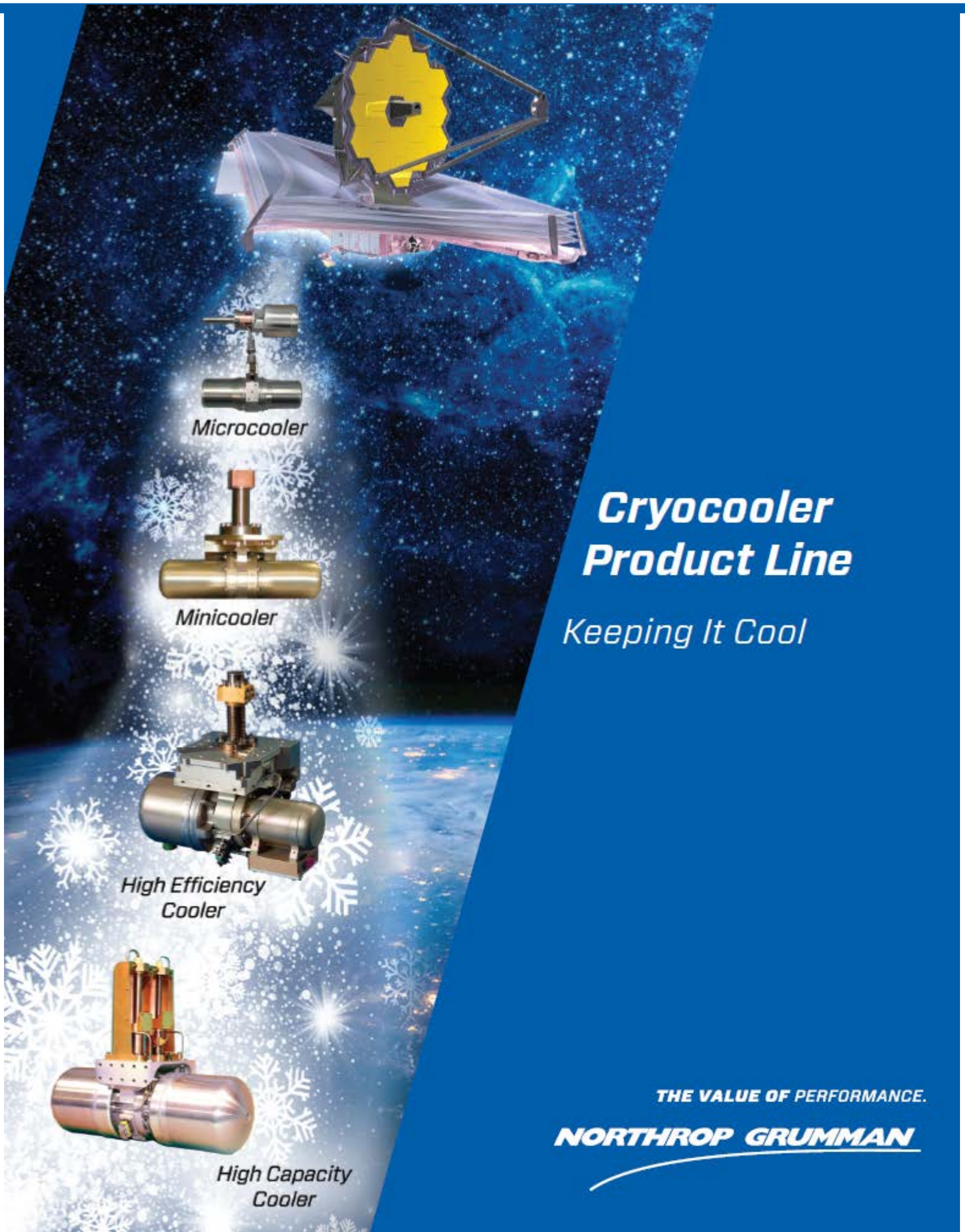


Scaled Cryocooler Products are Technology Basis of TAPC



www.northropgrumman.com/cryocoolers

TRL 9 HEC Cryocooler Compressor is Basis of TAPC Alternator

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High Efficiency Coolers (HEC): delivered to multiple customers for over 200 years of on orbit operation with no failures or change of performance.

Cryocooler Performance	
Refrigeration Capacity (in 25°C ambient)	2W @ 45 K 10W @ 77 K 23W @ 150K
Compressor Input Power	Up to 180 W
Life	> 87,600 Hours (10yrs)
Environment	- 40°C to +70°C
Exported Vibration	< 50 mN Drive Axis
Exported Vibration	< 200 mN Pulse tube Axis
Mass (Single Stage)	< 4.5 kg
Mass (Electronics)	< 3.8 kg

- Northrop Grumman's TRL 9 HEC cooler—unmatched legacy of success in space cryocoolers
- Space cryocooler system includes flight electronics and cold heads- all TRL 9
- Available in one and two stage cooling configurations, enabling thermal control of multiple sites
- Pulse tube architecture provides very low output vibration
- Electronics provides active vibration dampening, as well as temperature control
- High efficiency over a wide range of operating temperatures
- Low mass reduces system level cost
- Cold head optimized for different operating temperature

www.northropgrumman.com/cryocoolers


Linear configuration provides high thermal performance (shown in two stage configuration)


Proven electronics provides active dampening temperature control


Coaxial configuration provides small form factor, ease of integration

Flight Heritage

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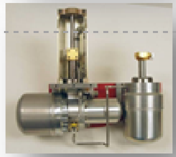
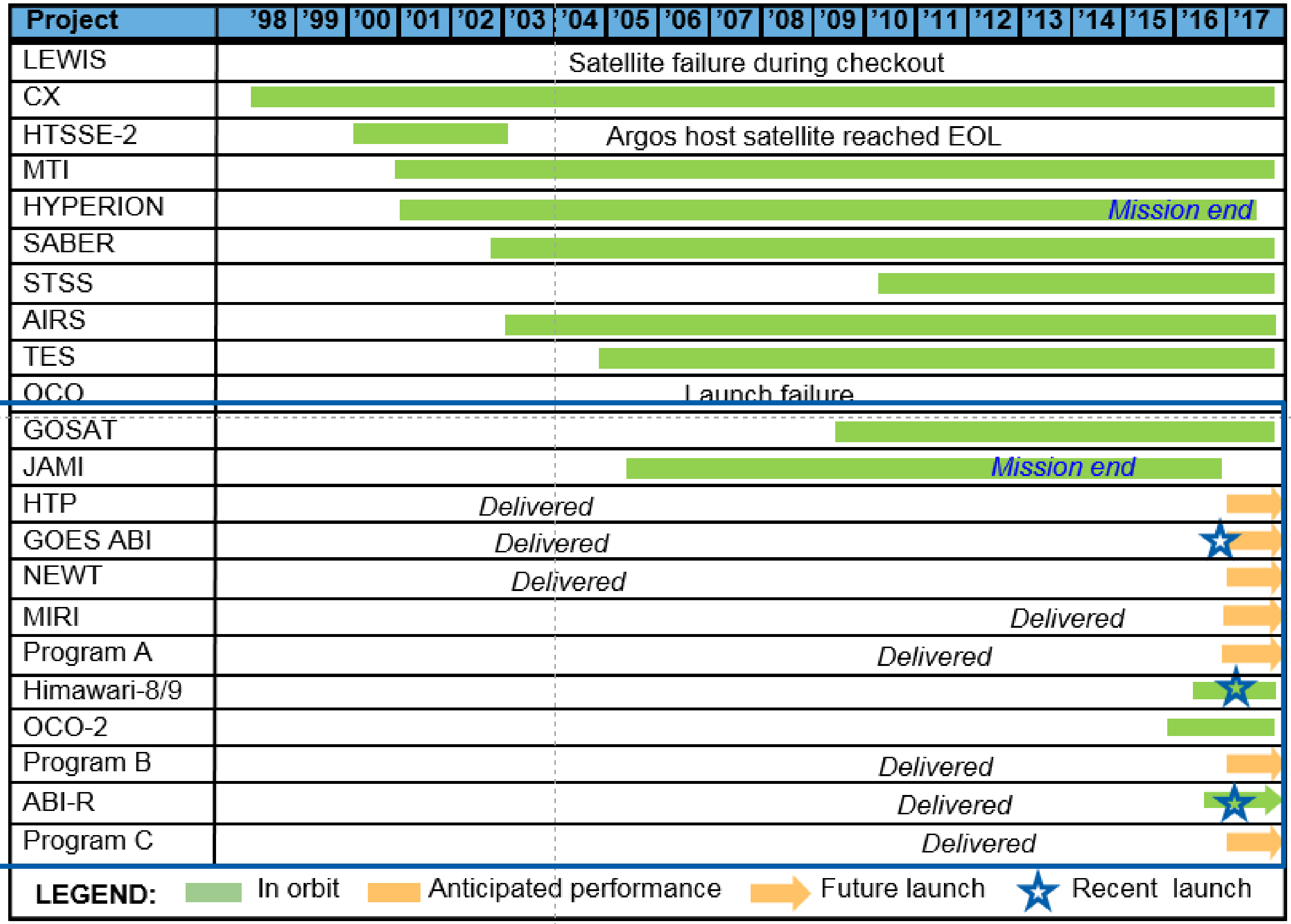


NGAS has produced more space flight coolers than the rest of US industry combined



100% Successful On-Orbit Performance –
No NG cryocooler has failed or even changed performance in orbit – All performing nominally

History of Space Cryocoolers – Chart Developed by Ron Ross of JPL

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Turbo- Brayton

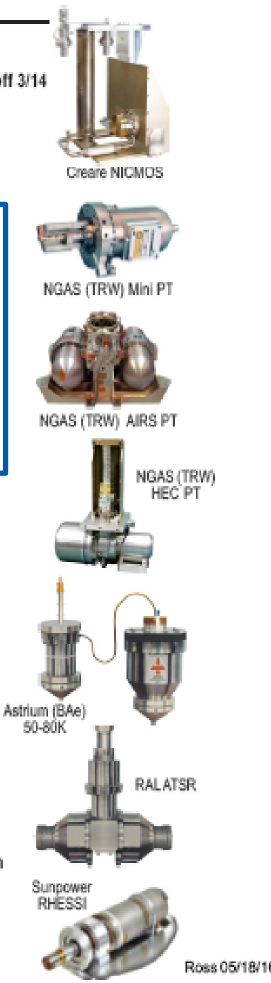
Flexure Bearing Compressors

Gas Bearing Compressor (ASRG basis)

Recent Long-Life Space Cryocooler Flight Operating Experience as of May 2016

NASA JPL

Cooler / Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	85,600	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling		
HIRDLS (60K 1-stage Stirling)	83,800	8/04 thru 3/14, Instr. failed 2008; Data turned off 3/14
TIRS cooler (35K two-stage Stirling)	27,900	Turn on 3/6/13, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system)	141,700	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
Mitsubishi Stirling (ASTER 77K SWIR system)	137,500	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	161,600	Turn on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degrad.
MTI (60K 6020 10cc PT)	141,600	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	133,600	Turn on 12/00, Ongoing, No degradation
SABER on TIMED (75K Mini PT)	129,600	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	121,600	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	102,600	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	91,000	4/05 to 12/15, Mission End, No degrad.
GOSAT/IBUKI (60K HEC PT)	63,300	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	52,800	Turn on 4/10, Ongoing, No degradation
OCO-2 (HEC PT)	14,900	Turn on 8/14, Ongoing, No degradation
Himawari-8 (65K HEC PT (2 units))	12,800	Turn on 12/14, Ongoing, No degradation
Oxford/BAe/MMS/Astrium/Airbus Stirling		
ISAMS (80 K Oxford/RAL)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degrad.
MOPITT (50-80K BAe (2 units))	138,600	Turn on 3/00, lost one disp. at 10,300 h
ODIN (50-80K Astrium (1 unit))	132,600	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
MIPAS on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
INTEGRAL (50-80K Astrium (4 units))	118,700	Turn on 10/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	96,600	Turn on 4/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	58,800	Turn on 4/10, Ongoing, No degradation
SLSTR (50-80K Airbus (2 units))	1,400	Turn on 3/16, Ongoing, No degradation
Planck (4K JT using 2 Astrium Comp.)	38,500	5/09 thru 10/13, Mission End, No Degrad.
Raytheon ISSC Stirling (STSS (2 units))	52,800	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL)		
ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
Kaguya GRS (70K 1-stg)	14,600	10/07 thru 6/09, Mission End, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling		
RHESSI (75K Cryotel)	124,600	Turn on 2/02, Ongoing, Modest degradation
CHIRP (CryoTel CT-F)	19,700	9/11 to 12/13, Mission End, No degradation



Ross 05/18/16

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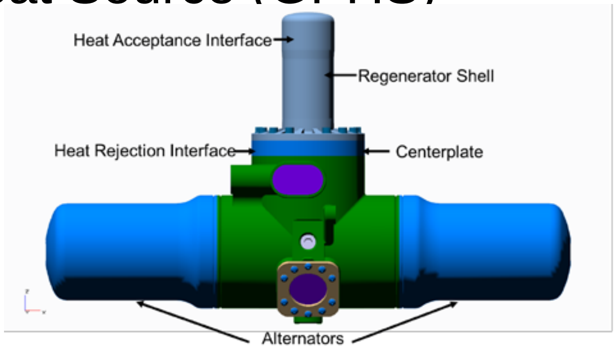
Technical Description of Convertor Operation

Background

- In this presentation we will describe the Thermoacoustic Power convertor (TAPC), its performance as a space power convertor when powered by the radioisotope General Purpose Heat Source (GPHS) and its integration onto a spacecraft.
- Operates on the Stirling thermodynamic cycle
- High reliability and efficiency
- Reliability results from their mechanical simplicity
  - No moving part thermoacoustic (Stirling) heat engine coupled to
  - balanced linear alternator derived from the non-wearing and proven TRL 9 NGAS thermoacoustic pulse tube cryocooler compressors
  - Low complexity electronic control



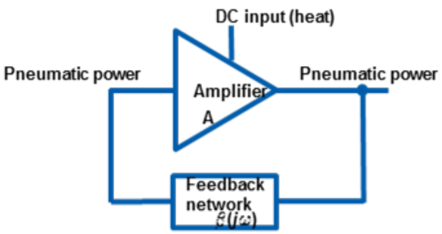
- Ease of integration of TAPC onto spacecraft results from the mechanical and thermal interfaces incorporated into the device
- Low exported vibration to the spacecraft and sensitive science payloads has been flight proven with the NGAS pulse tube cryocoolers in use with very sensitive space telescopes.

Why TAPC

Background on Stirling Cycle Heat Engine Classes

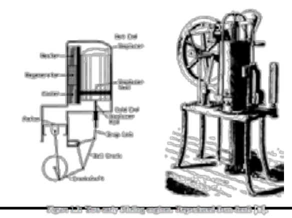
Stirling (or ThermoAcoustic) Cycle Heat Engines

- Pneumatic power is amplified by application of heat
- Some of the amplified power is utilized for useful work, and some is fed back to be used in the next cycle



Kinematic Stirling Engines use mechanical components for energy storage and feed back

- Flywheel for energy storage from one part of the cycle to the next
- ***Mechanical linkages for feedback of power***



Free-Piston Stirling Engines

- The **moving alternator and hot displacer pistons** bounce against gas springs in resonance producing pneumatic feedback
- ***Eliminates other moving parts such as connecting rods and crankshafts.***

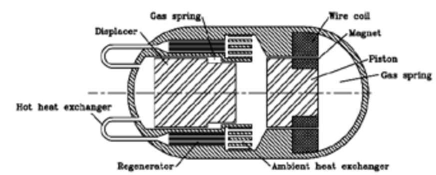


Figure 1.2: Schematic of a typical free-piston Stirling engine. Gas-spring spaces change volume and exert force when the piston and displacer move.

ThermoAcoustic Heat Engine - RELIABILITY

- Phasing between pressure and velocity in the thermodynamic elements of Stirling machines is the same as in a traveling acoustic wave
- Acoustics and tuned lumped acoustic elements (pipes) provide feedback and all the control of the gas motion and gas pressure.
- ***Eliminates moving hot displacer – avoids moving parts***

Figures from G. Swift *Thermoacoustics*

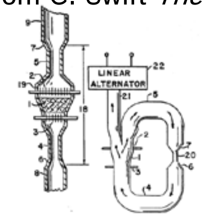


Figure 1.4: The traveling-wave engine concept. Tag lines 2 and 3 are heat exchangers; 1 is a regenerator. The complicated shape of the enclosure ensures the correct relative amplitudes and phasing of the oscillating pressure and gas motion. Reproduced from one of Ceperley's patents [32, 33].

The ThermoAcoustic Power convertor operates on the Stirling cycle with the highest reliability because of its low complexity relative to other Stirling heat engines

Replacing Stirling Heat Engine with Thermoacoustic Heat Engine Makes TAPC Reliable and Producible

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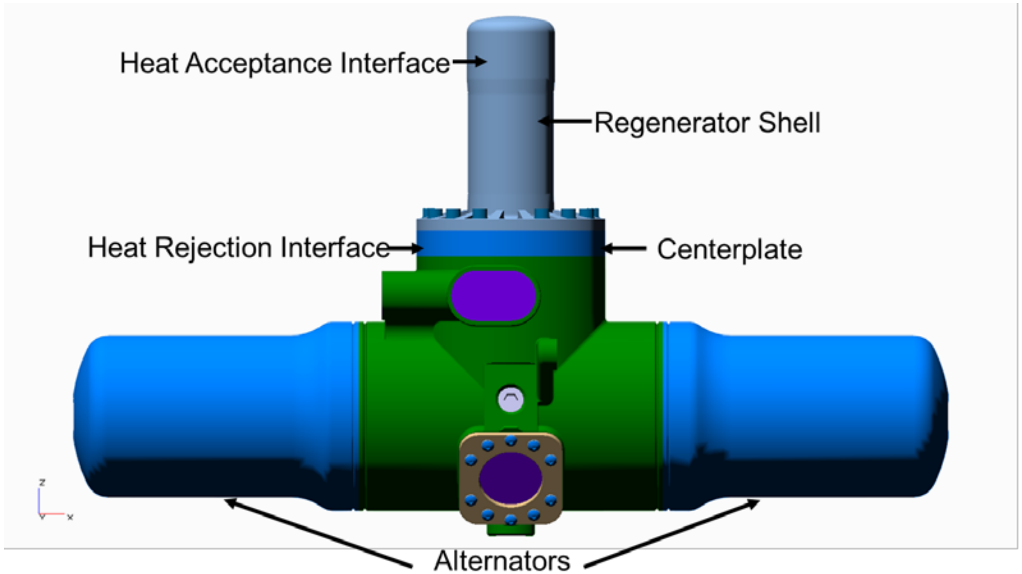
Free Piston Stirling Engines Versus Thermoacoustic Heat Engines

- In the **free piston Stirling** convertor oscillating gas is heated at the hot heat exchanger and cooled at the cold heat exchanger.
- **Regenerator** gas motion is amplified to oscillate ~1/3 the regenerator length by the resonant moving displacer (a big piston with a large axial temperature gradient and close piston/cylinder tolerances)
- The displacer motion and the alternator piston motions are both powered by the “thermo-acoustic” oscillation produced in the regenerator
- In the **Thermo acoustic heat engine (TASHE),** resonant (**no moving parts)** lumped element components replace the displacer

Alternator for Stirling and TA Engines

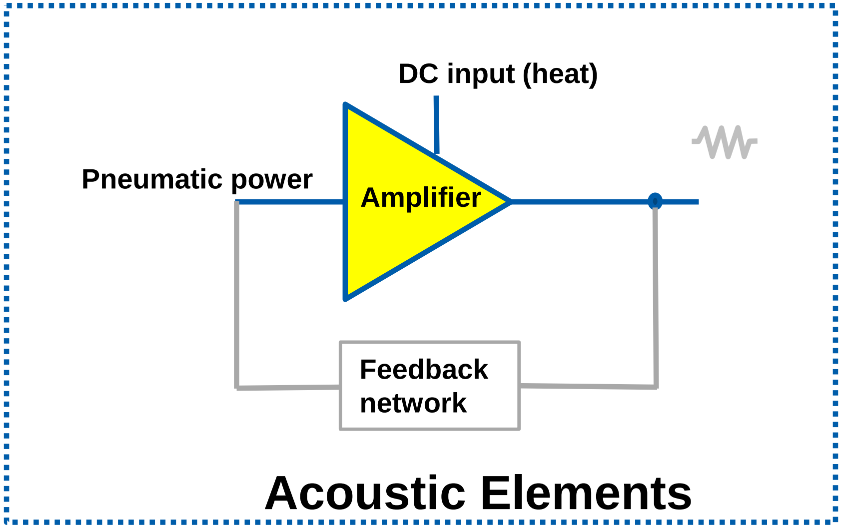
- In both convertors, the coupled oscillating pressure drives the resonant alternator piston to produce the electrical output
- The alternators differ chiefly in the piston size because the extra volume of the TAHE results in a lower Δp than in the Stirling unit

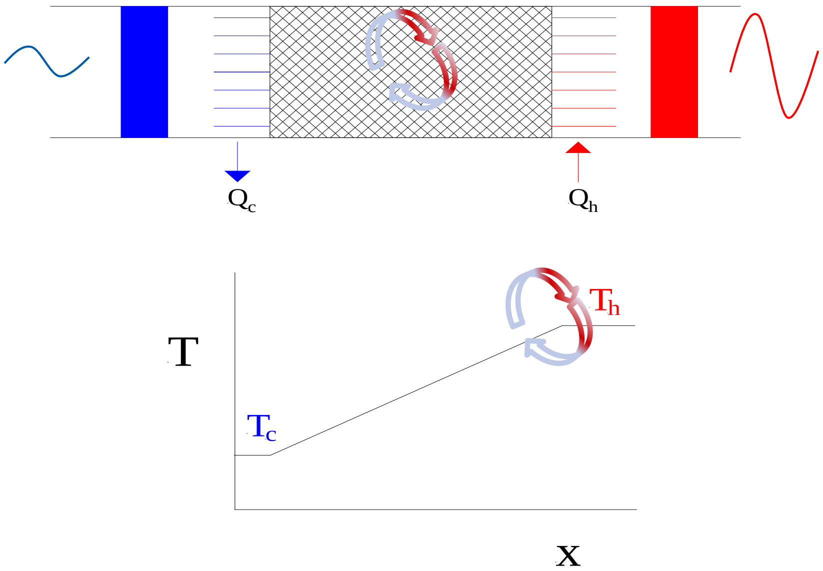


Characteristic of a traveling wave device, the pressure and the particle velocity are temporally in phase in the regenerator for both Stirling and TASHE - same thermodynamic process

The Regenerator as an Acoustic Amplifier

- Over 100 years ago, Rayleigh understood that heating and cooling could amplify acoustic power *"if heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction."*
- Sound wave traveling up a thermal gradient is amplified
  - As a gas parcel moves back and forth in the regenerator, the heat transfer and pressure are phased such that the gas parcel expands via heating at high pressure and contracts via cooling at low pressure



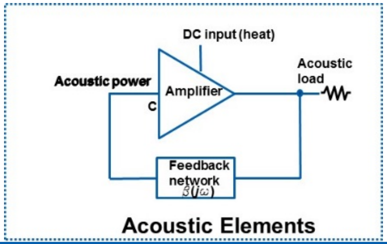


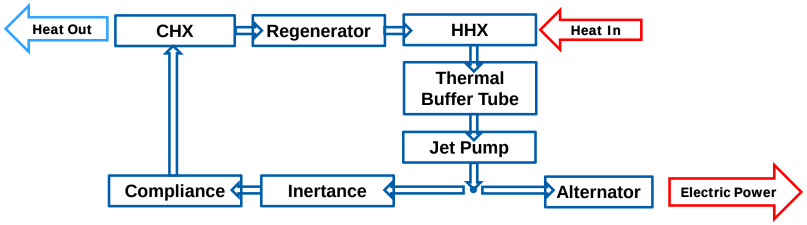
TAPC uses heat to amplify acoustic pressure

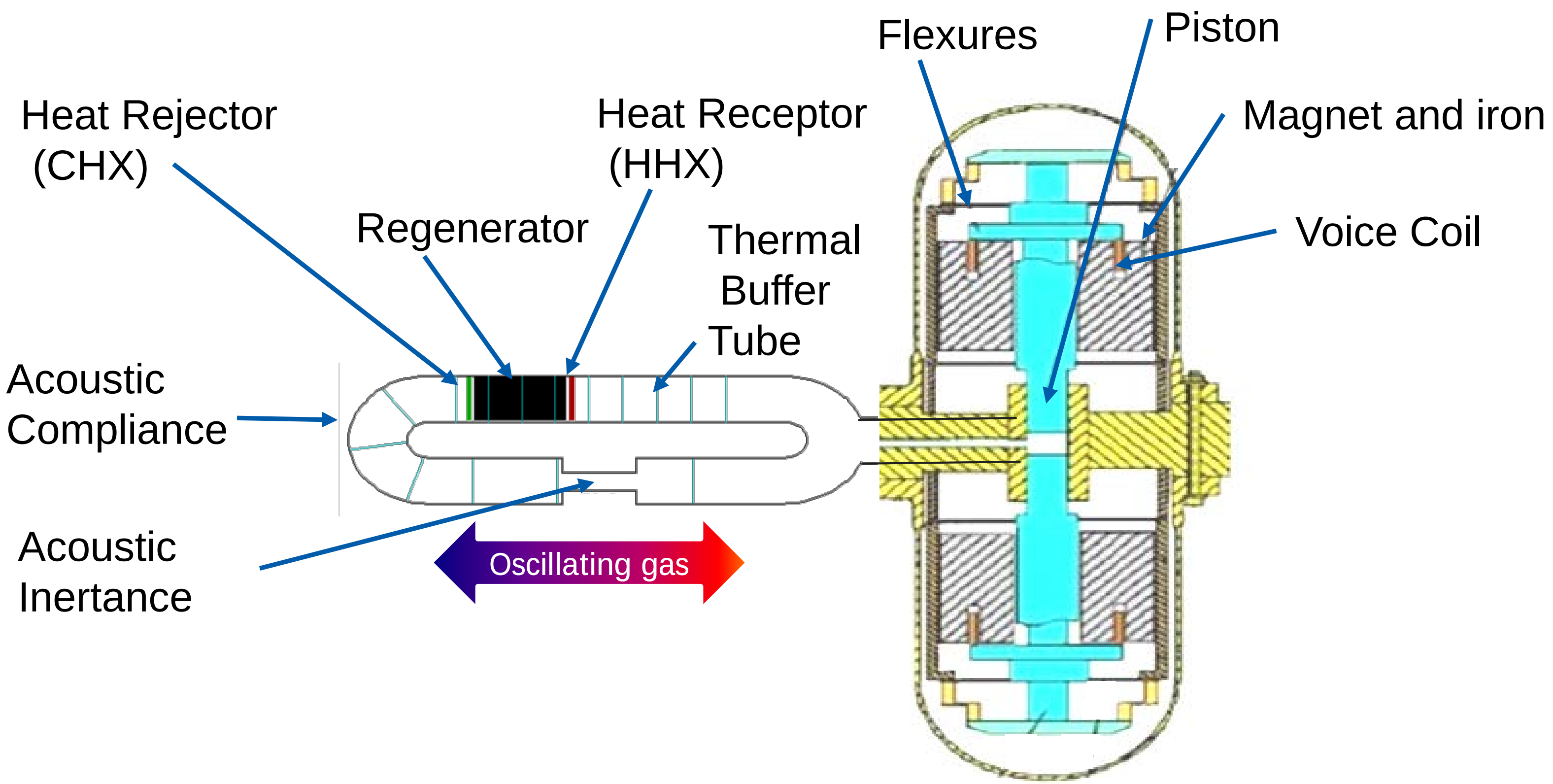
Technical Description of Convertor Operation: Summary

- Heat provided by GPHS (General Purpose Heat Source – ^{238}Pu)
- Using no moving parts, thermoacoustic heat engine converts heat to acoustic travelling wave
  - No moving parts in the hot end
  - No close tolerance fits or volume sensitivity in the hot end
  - Single piece metal shell has not hot joints (no welds or brazes)
- Acoustic travelling wave drives an oscillating pair of resonant opposed pistons in an alternator similar to NGAS flight cryocooler compressor
  - Inherently self balanced
- Pistons are supported on flexures same as NGAS flight Cryocoolers
  - Infinite life, no wearing parts
- Pistons are connected to voice coils that produce alternating current (AC) power when oscillating in magnetic circuit
  - Voice coil produces no side loads
  - Voice coil more robust than moving magnet in over stroke
- Power extracted by passing the current through a controlled impedance

Thermo Acoustic Power Convertor (TAPC)







Coaxial Configuration of TAPC

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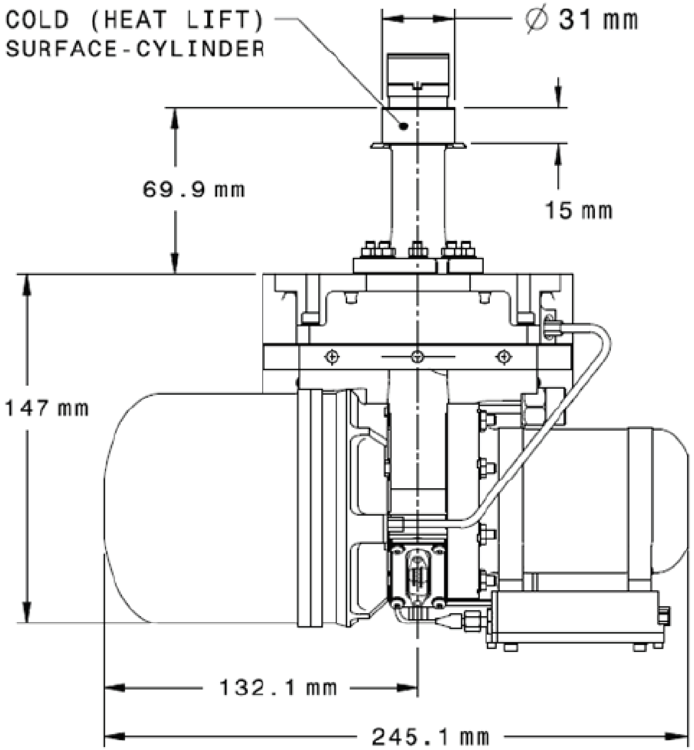
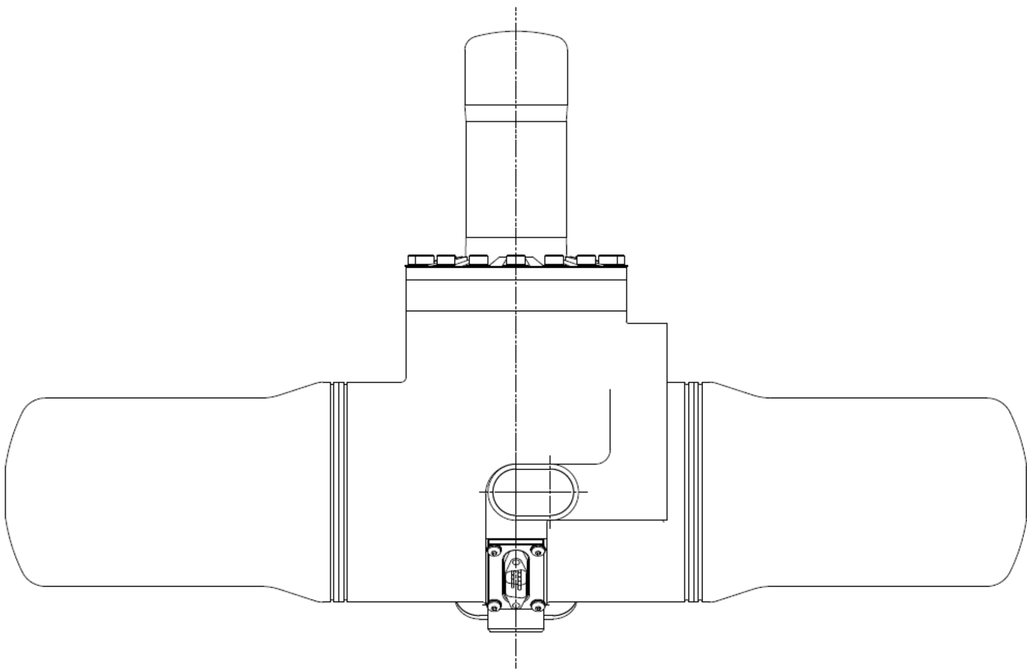
Envelope for CoaxialCrycooler

(Coaxial High Efficiency Cryocooler)



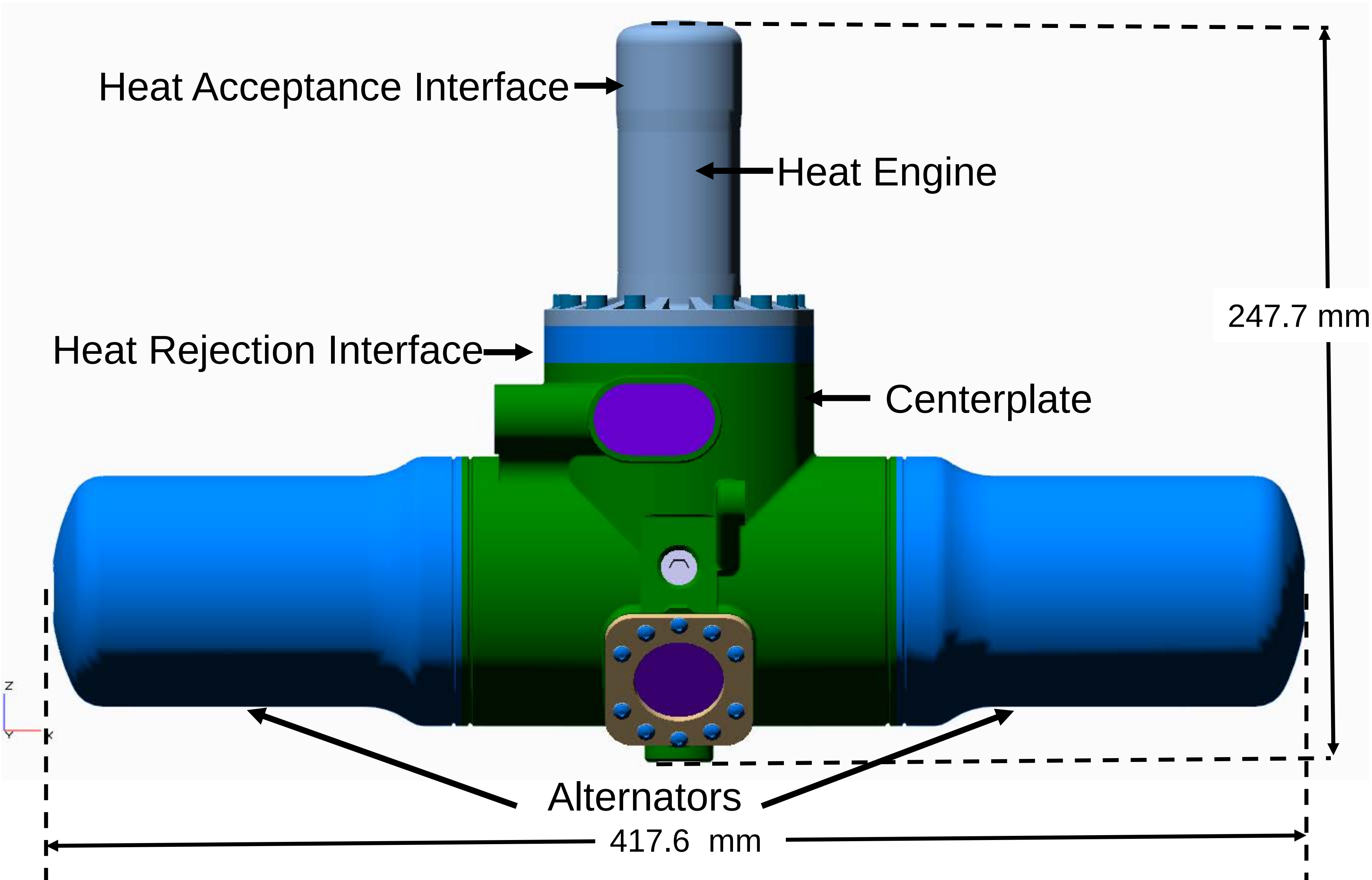
Envelope for Coaxial TAPC

(based on motors in High Efficiency Cryocooler)



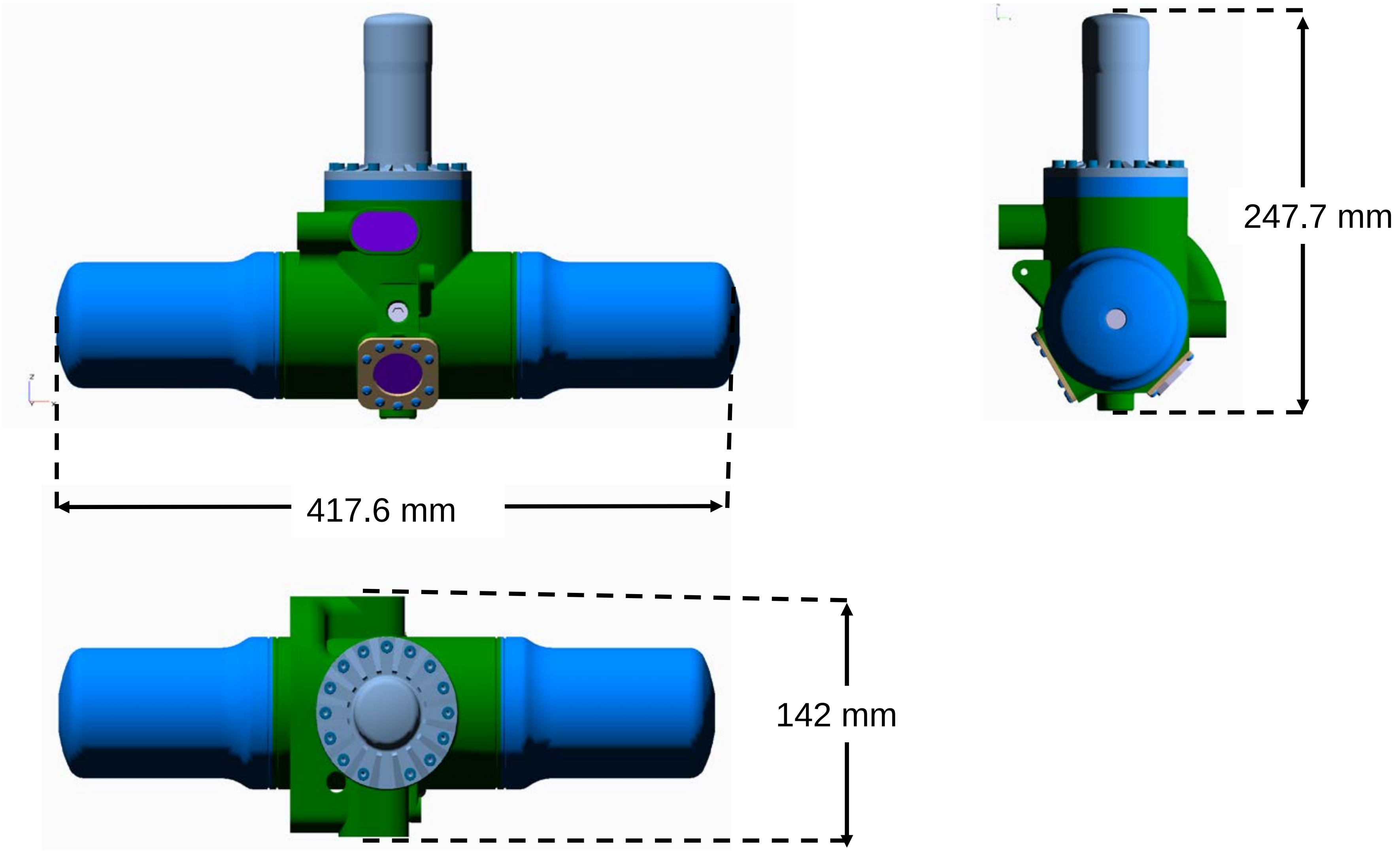
For more information about High Efficiency Cryocoolers, please visit on the web:
www.northropgrumman.com/cryocoolers

TAPC Design



Heat Acceptance Interface
Heat Engine
247.7 mm
Heat Rejection Interface
Centerplate
Z
Y
X
Alternators
417.6 mm

Envelope



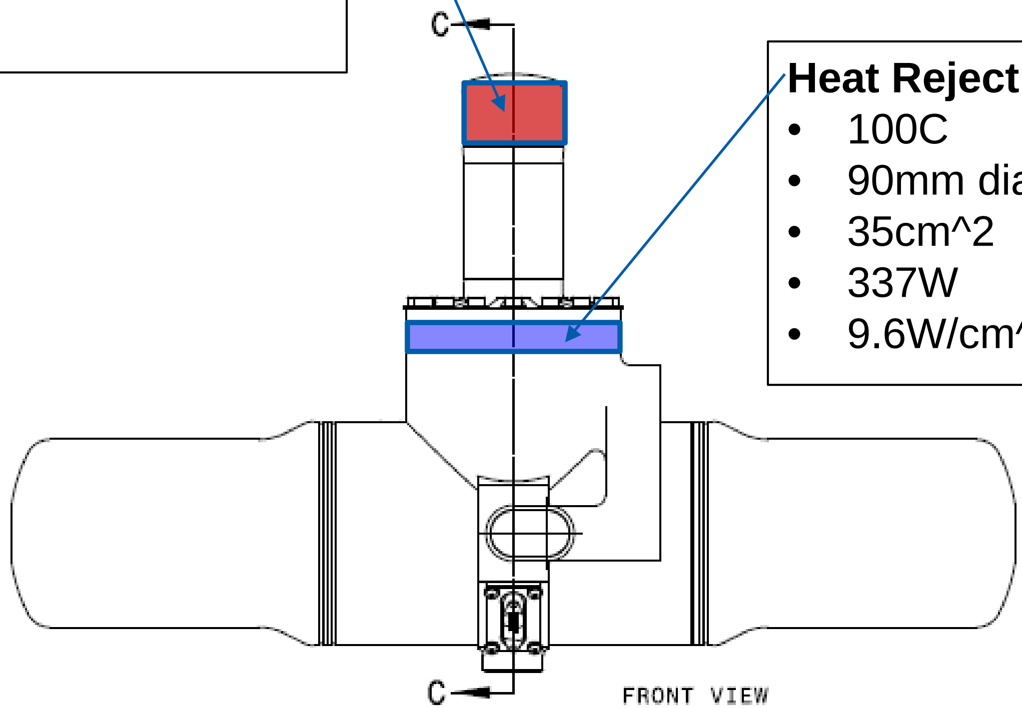
Thermal Interfaces

Heat Source Interface

- 700C
- 42mm diam x 25mm long
- 33cm^2
- 450W (500Wth-10%)
- 13.6W/cm^2 average

Heat Rejection Interface

- 100C
- 90mm diam x 12.5mm long
- 35cm^2
- 337W
- 9.6W/cm^2



TAPC:
Thermoacoustic (Stirling) Power Convertor

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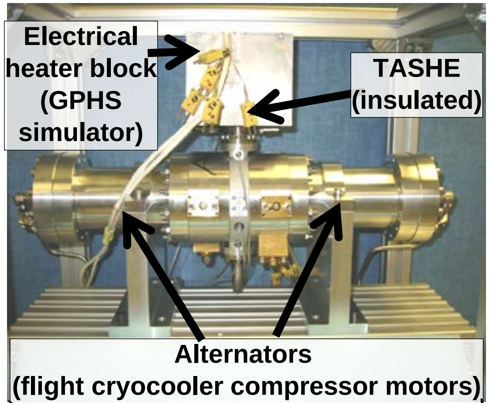
1st Unit demonstrated in 2003

- No moving parts thermal to acoustic power conversion in the hot heat engine component
- TA heat engine technology was scaled down by an order of magnitude from previous demonstrations to 100W power range
- Demonstrated 18% efficiency on first try
- Demonstrated a simple and efficient heat exchanger interface directly to GPHS units
- Demonstrated the use of a highly reliable alternator using a modified TRL 9 cryocooler compressor
- Demonstrated self-starting
- Demonstrated the simplicity of the electronic control system



NGAS designed, built and tested the first ever Thermoacoustic Power convertor that converted heat to electricity in 2003

Spacecraft Systems Design and Integration Example: Earlier Version TAPC

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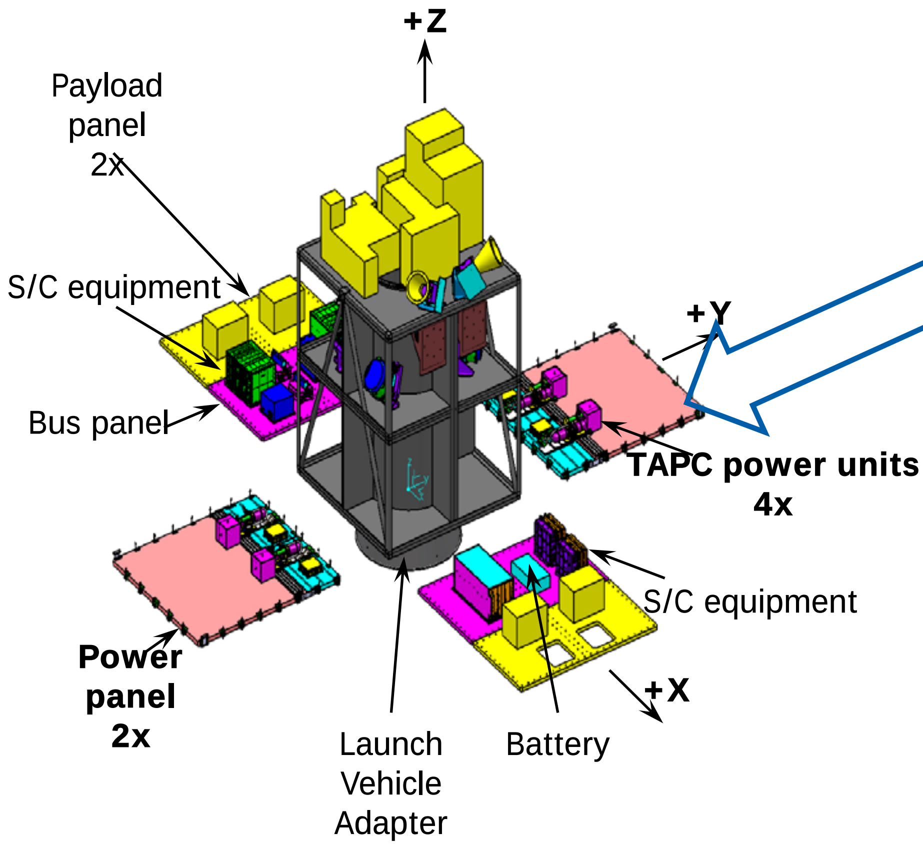
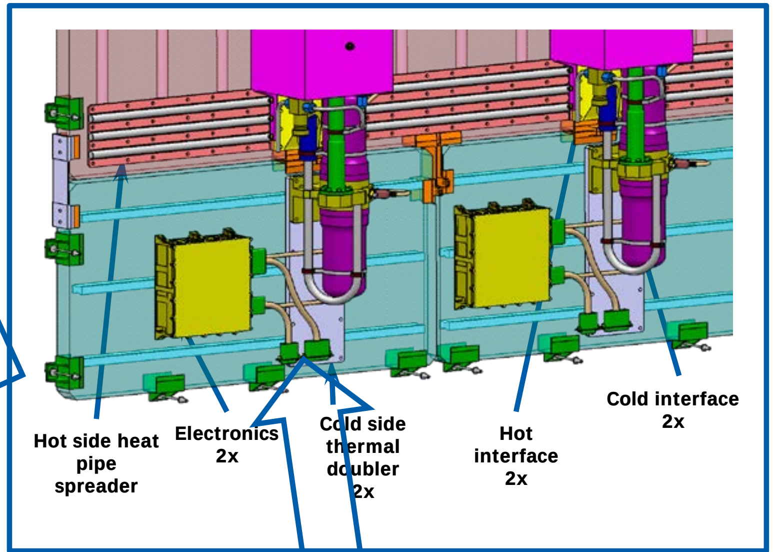
System: Level 2

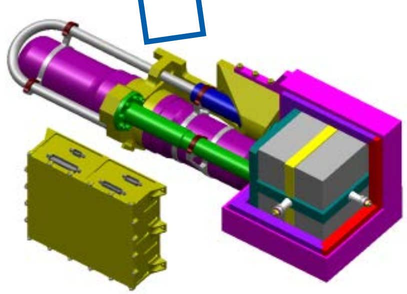
Redundancy example



Subsystem: Level 3

Integration on split radiator shown





Unit: Level 4

TAPC

NGAS understands TAPC's spacecraft thermal, mechanical and electrical interfaces

Prior TAPC Performance Predictions for Flight: System Comparison to Alternative RPS Devices

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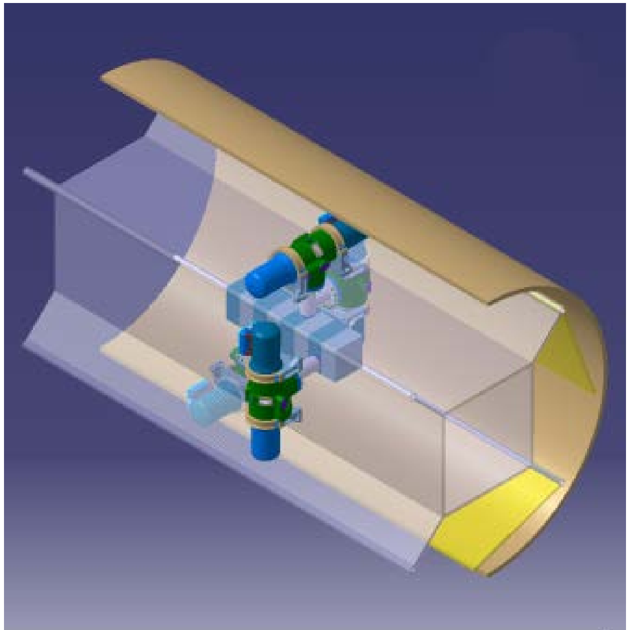
	MMRTG[1]	eMMRTG[1]	ASRG[2]	TAPS
Technology	PbTe/TAGS	SKD	Stirling	TA Stirling
Pu^{238} mass (Kg)	4.8	4.8	1.2	1.2
# GPHS Modules	8	8	2	2
Hot Temperature (°C)	530	600	850	650
BOL Power (W)	110	145	130	129
EOL (17 yrs) Power (W)	60	90	102	101
Mass (Kg)	43	43	32	15
BOL Specific Power (We/kg)	2.6	3.4	4.1	8.6
EOL Specific Power (We/kg)	1.4	2.1	3.2	6.7
Exported Vibration (N)	0	0	~2	<0.2

[1] http://solarsystem.nasa.gov/rps/docs/eMMRTG_onepager_LPSC20140317.pdf
[2] http://solarsystem.nasa.gov/rps/docs/APP ASRG Fact Sheet v3 9-3-13.pdf

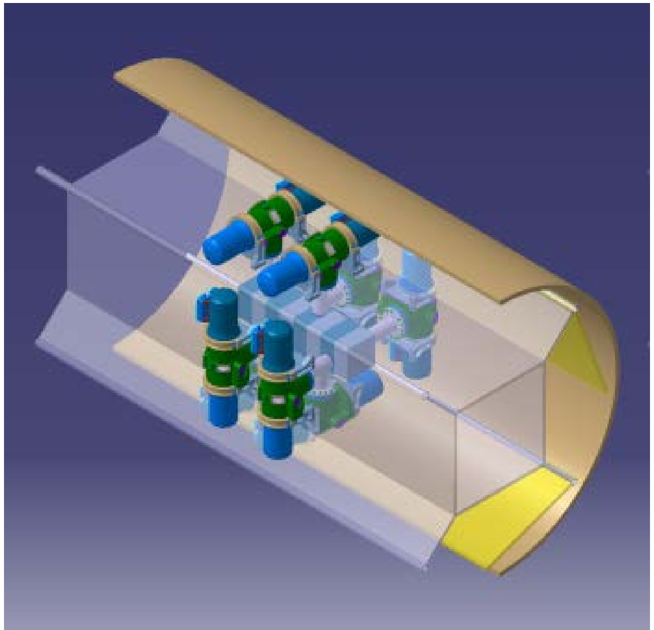
TAPC provides high reliability, high specific power, low mass, low vibration

Notional 456We Generator with Full Redundancy

- The “corkscrew” arrangement shown in left hand image is what was presented at the TIM#1, which showed the non redundant form.
- The right hand image shows the same “corkscrew” arrangement with redundant convertors
- Each redundant convertor is placed 180 degrees away from each primary convertor, such that each primary-redundant pair share the same pair of GPHS’s.



Non redundant



Redundant

Requirements Compliance

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	REQUIREMENT	Compliance	
#	Category	Requirement	Goal
1	Design life	Y	NA
2	convertor power output	Y	NA
3	Start-stop cycles	Y	NA
4	Launch vibration	Y	NA
5	Static acceleration	Y	*20g
6	Performance degradation	Y	NA
7	Thermal-to-electric conversion efficiency	Y	NA
8	Partial power operation	Y	NA
9	Hot-end operating temperature	Y	NA
10	Cold-end operating temperature	Y	Y
11	Thermal energy input	Y	NA
12	Atmospheric environment	Y	NA
13	Radiation	Y	NA
14	EMI	Y	NA
15	Autonomy	Y	*20g
16	Tolerance of loss of electrical load	Y	NA
17	Transmitted forces	Y	NA
18	Specific power (W/kg)	Y	NA
19	Size	Y	NA
20	Manufacturability	NA	Y
21	Instrumentation necessary for flight convertor operation	Y	NA
22	Performance measurement	Y	NA

Requirement: Design Life

#	Category	Requirement	Goal
1	Design life	20 years of continuous operation at full power	-

- Baseline design meets this requirement based on
  - flexure bearing alternator with no wearing parts
  - Conservative, flight proven flexure design.
  - Conservative hot material creep design
- Design approach is component level reliability of at least .99 at 20 years

Requirement: Convertor Power Output

#	Category	Requirement	Goal
2	convertor power output	Enables a 200 to 500 W_e generator	-

This is treated as input to all trades and designs, with simple generator constraint assumptions

- e.g. radiators fit in shipping container, radiators have view to space etc.

- Baseline unit convertor size of 129Wac (500Wth and 100C reject) allows 200We (2x) to 500 W (5x) generators

- Assuming 10% insulation loss(i.e. 450Wth and 100C reject) unit convertor output is 116Wac

Requirement: Start Stop Cycles

#	Category	Requirement	Goal
3	Start-stop cycles	Capable of 150 start-stop cycles without any permanent effect on performance	-

- Baseline design meets this requirement based on;
  - Hot end temperature is controlled during start stop cycles by generator.
  - Flexure bearing, clearance seal alternator with no contact between piston and cylinder, including during start up or shut down is insensitive to the number of start-stop cycles
  - No moving parts in heat engine
  - CTE matched materials in locations with large temperature swings in start stop

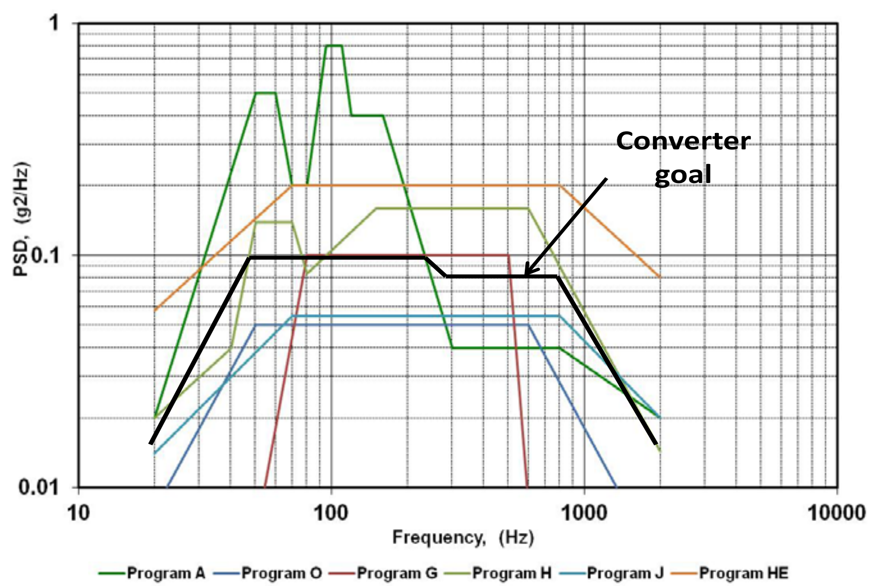
Requirement: Launch Vibration

#	Category	Requirement	Goal
4	Launch vibration	No permanent loss of power or long-term effect after exposure to launch acceptance vibration testing, defined as: • Duration of 1 min in each axis • convertor operating at full power at onset of random vibration • Random vibration of magnitude 10.35 g_{rms} in all axes with following spectral distribution:	

Frequency (Hz)	Acceleration Spectral Density (g^2/Hz)
20	0.015
50	0.100
250	0.100
300	0.080
800	0.080
2000	0.015

The baseline design meets this requirement, based on;

- Analysis of convertor
- Heritage TRL 9 compressor



Requirement: Static Acceleration

#	Category	Requirement	Goal
5	Static acceleration	Capable of exposure to the following static and quasi-static acceleration with no permanent effect on performance, while operating at *less than* full design piston amplitude: • 20 g for 1 minute in all axes Capable of exposure to the following static and quasi-static acceleration with no permanent effect on performance, while operating at full design piston amplitude: • 5 g for 5 days in all axes	Capable of exposure to the following static and quasi-static acceleration with no permanent effect on performance, while operating at full design piston amplitude: • 20 g for 1 minute in all axes

- Meet 5g requirement
- 20g goal will require intervention by controller.
    - Very small generator impact because 1 minute is short enough that thermal effects at GPHS are small.

Requirement: Performance Degradation

#	Category	Requirement	Goal
6	Performance degradation	Output power decreases by less than 0.5 % per year for the case of constant thermal input (Does not include generator-level sources of degradation, such as Pu-238 fuel decay, or insulation degradation)	-

The proposed baseline design meets this requirement, based on:

- No known degradation mechanisms in heat engine or alternator over lifetime
- No observed degradation in multiple cryocooler compressors in orbit (some for 18 years and counting)
- Alternator is very similar mechanically to current generation TRL 9 compressor

Requirement: Thermal to Electric Conversion Efficiency

#	Category	Requirement	Goal
7	Thermal-to-electric conversion efficiency	≥ 24% when cycle rejection temperature is ≥100 C (Defined as electrical power out from the convertor divided by heat input to the convertor)	≥28% when cycle rejection temperature is ≥100 C (Defined as electrical power out from the convertor divided by heat input to the convertor)

The proposed baseline design meets this requirement based on

- Reject at 100 C
- Rejection temperature is defined on convertor side of the interface

Requirement: Partial Power Operation

#	Category	Requirement	Goal
8	Partial power operation	Maintains ≥ 20 % thermal-to-electric conversion efficiency when input thermal power is 50% of designed maximum	-

The proposed baseline design meets this requirement, based on

- SAGE model anchored by prior test measurements

Requirement: Hot-end Operating Temperature

#	Category	Requirement	Goal
9	Hot-end operating temperature	< 1000 °C	-

- The proposed baseline design meets this requirement, based on heater head at 700^{o}C

Requirement: Cold-end Operating Temperature

#	Category	Requirement	Goal
10	Cold-end operating temperature	Requires no less than 100 °C to meet efficiency goal	Capable of operation between 20 and 175 °C without any permanent effect on performance

The proposed baseline design meets the goal based on

- Model and test measurements on IRAD convertor

Requirement: Thermal Energy Input

#	Category	Requirement	Goal
11	Thermal Energy Input	Designed to accept heat from an integer number of GPHS-Step 2 modules (250 ± 6 Wth each)	

- convertor design was done for an integer number of GPHS modules

Requirement: Atmospheric Environment

#	Category	Requirement	Goal
12	Atmospheric Environment	Capable of operation in the following environments without any permanent effect on performance: • Earth : 1 atm of air • 2 atm of argon • Deep space : vacuum • Mars : 5 torr CO_2 • Titan : 1.5 atm 94-99% N_2, 1-6% CH_4, and 0.2% H_2	

The proposed baseline design meets this requirement with no material compatibility issues with either the alternator or the heat engine.

- We note that by definition within this program there is no effect of atmospheres on required convertor performance due to reduction of heat into the convertor since the insulation is part of the generator

Requirement: Radiation

#	Category	Requirement	Goal
13	Radiation	No loss of performance after exposure to 300 krad	

The proposed baseline design meets this requirement based on:

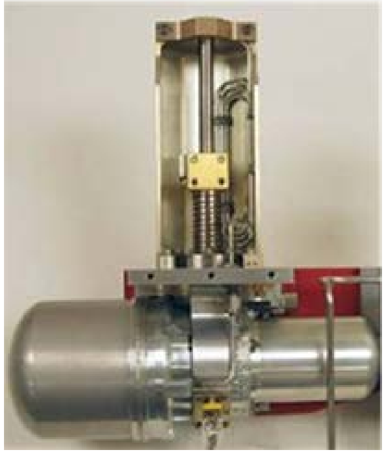
- Similarity- cryocooler heritage is consistent with these levels

Requirement: EMI

#	Category	Requirement	Goal
14	EMI	DC magnetic field : less than 100 nT at 1 m while operating at maximum power (Also, no element of the design precludes characterization of the AC magnetic field)	

The proposed baseline design meets this requirement based on

- Similarity – heritage cryocooler with same motor is consistent with these levels
- Scaling the maximum cryocooler measured dc fields of 350 nT at 62 cm by the distance cubed results in a dc maximum field of 85 nT at 1 meter which is less than the 100nT requirement



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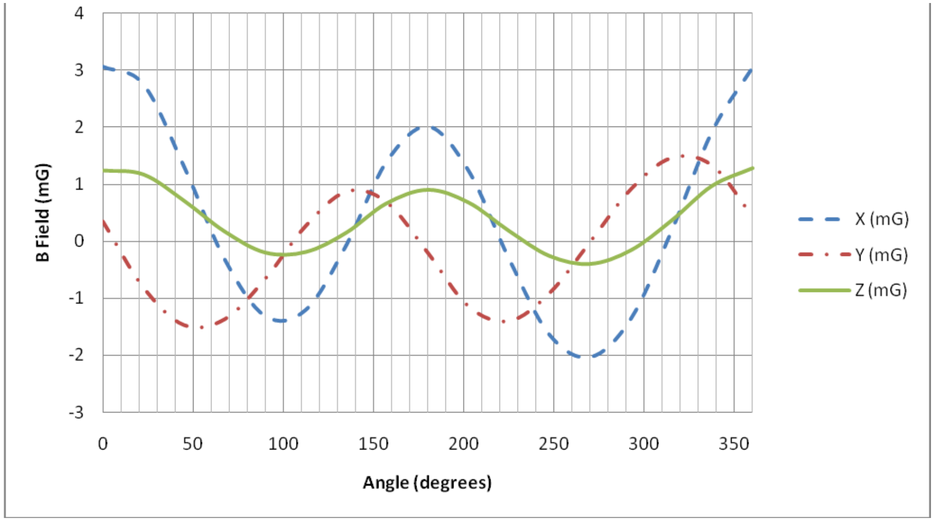


Approve for Public Release by NASA, 5/3/18; NG18-1012

Requirement: Autonomy

#	Category	Requirement	Goal
15	Autonomy	No operational adjustments needed during launch	No adjustments needed during static acceleration

The baseline design meets this requirement based on:

- Stroke and radial displacement margin analyses

Requirement: Tolerance of Loss of Electrical Load

#	Category	Requirement	Goal
16	Tolerance of Loss of Electrical Load	Capable of loss of electrical load at the alternator terminals for 10 seconds while operating at full power, without any permanent effect on performance	

The proposed baseline design meets this requirement based on:

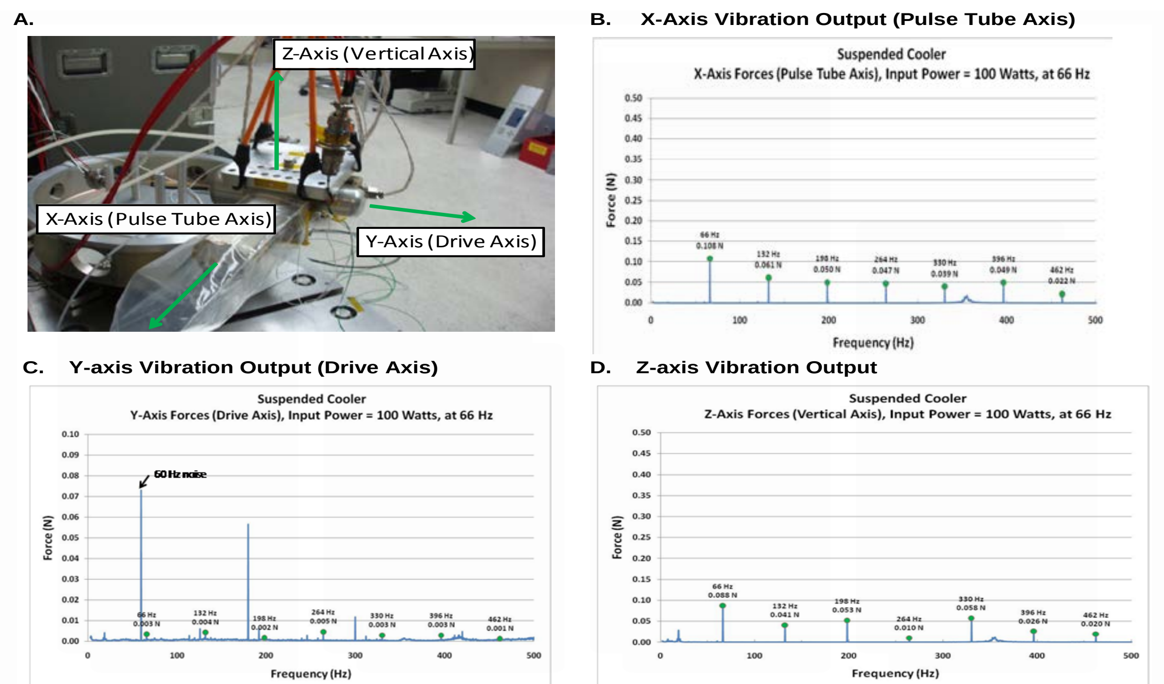
- Analysis of passive energy absorbing damper soft stop

Requirement: Transmitted Forces

#	Category	Requirement	Goal
17	Transmitted Forces	Low force transmission to structure is desirable	

The proposed baseline design meets this requirement based on:

- Similarity to multiple flight cryocoolers.
- Scaling of the cooler compressor by moving mass and frequency yields <650mN in all axes at the fundamental frequency of ~120Hz



Requirement: Specific Power

#	Category	Requirement	Goal
18	Specific Power	> 20 W/kg (convertor only)	

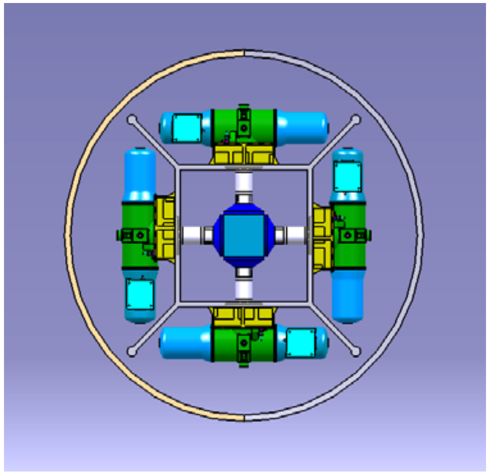
The proposed baseline design meets this requirement based on:

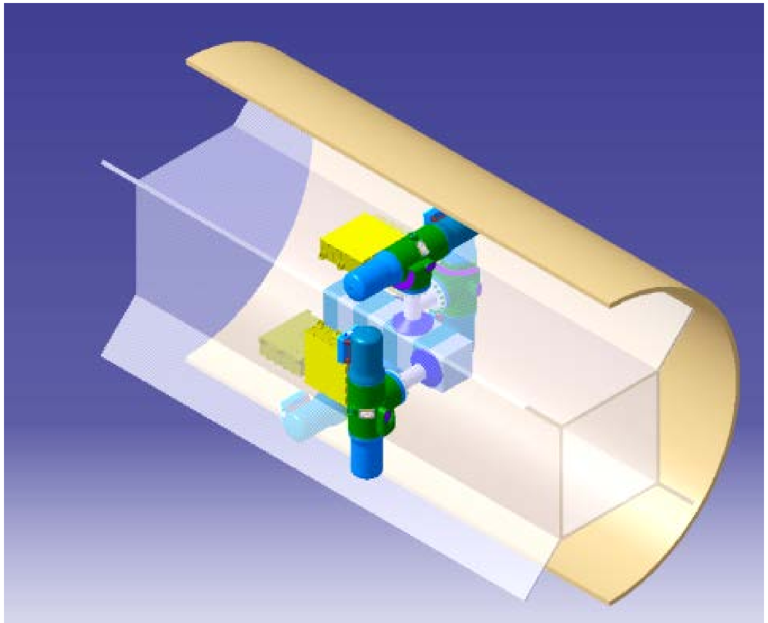
- Modeled performance and geometry yields >20kg/W

Requirement: Size

#	Category	Requirement	Goal
19	Size	Enables a generator design that will fit in the DOE shipping container of the following dimensions: • 86cm diameter • 144 cm height	

- The baseline design meets this requirement based on CAD layout of current baseline design convertors with GPHS and notional candidate generator in shipping container





Requirement: Manufacturability

#	Category	Requirement	Goal
20	Manufacturability		Utilizes proven and effective manufacturing approaches

The proposed baseline design meets this goal based on:

- The 700^{o}C used in the design was chosen for the hot end specifically to eliminate exotic materials
- The heat engine design was chosen to use a heritage manufacturing approach
- The alternator uses the heritage manufacturing approach

Requirement: Instrumentation Necessary for Flight Convertor Operation

#	Category	Requirement	Goal
21	Instrumentation necessary for flight convertor operation	Enables a generator that performs long-life science missions without the need for long-life sensors on the convertor(s)	

This is interpreted as referring to the flight design. The proposed baseline design meets this requirement without sensors on or inside the convertor.

Requirement: Performance Measurement

#	Category	Requirement	Goal
22	Performance Measurement	The convertor design shall enable direct measurement of the following items for performance testing: 1) Temperature of the interface to the generator’s heat source 2) Temperature of the interface to the generator’s heat rejection system 3) Alternator output (voltage, current, power, frequency) 4) Disassembly for internal inspection	

- This is interpreted as pertaining to the prototype convertor only, not the flight design, in which case the design complies

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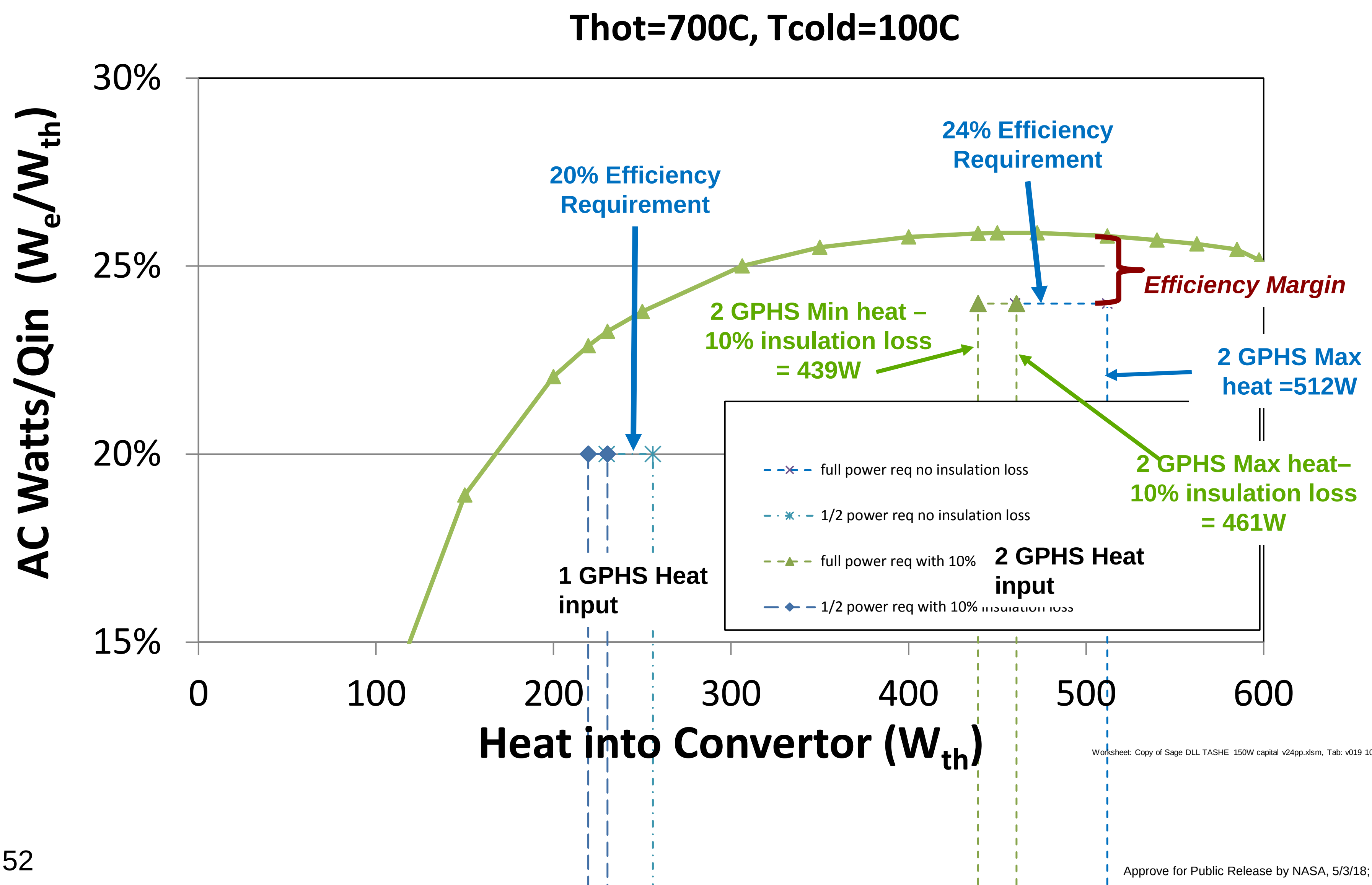
Performance Predictions

Key Performance Parameters – Baseline Convertor Unit at BOL, at Nominal Operating Points

Parameter	Nominal	Design Point	1/2 Heat	High Reject Temp	Low Reject Temp
Thermal Source	2 GPHS	2 GPHS	1 GPHS	2 GPHS	2 GPHS
Alternator basis	MAK 105	MAK 105	MAK 105	MAK 105	MAK 105
Input Heat (W_{th})	500	439.2	219.6	439.2	439.2
Output Power (W_{ac})	129.2	113.6	50.2	79.3	122.1
Efficiency %	25.83%	25.87%	22.9%	18.6%	27.8%
Hot Temperature (°C)	700	700	700	700	700
Cold Temperature (°C)	100	100	100	175	25
Output Voltage (V_{rms})	~ 86.9	~ 80.0	~ 50.1	~ 82.0	~ 79.7
Output Current (A_{rms})	~ 1.81	~ 1.71	~ 1.15	~ 1.18	~ 1.7
Mass (Kg)	6.42	6.42	6.42	6.42	6.42
Specific Power (W_e/Kg)	20.1				

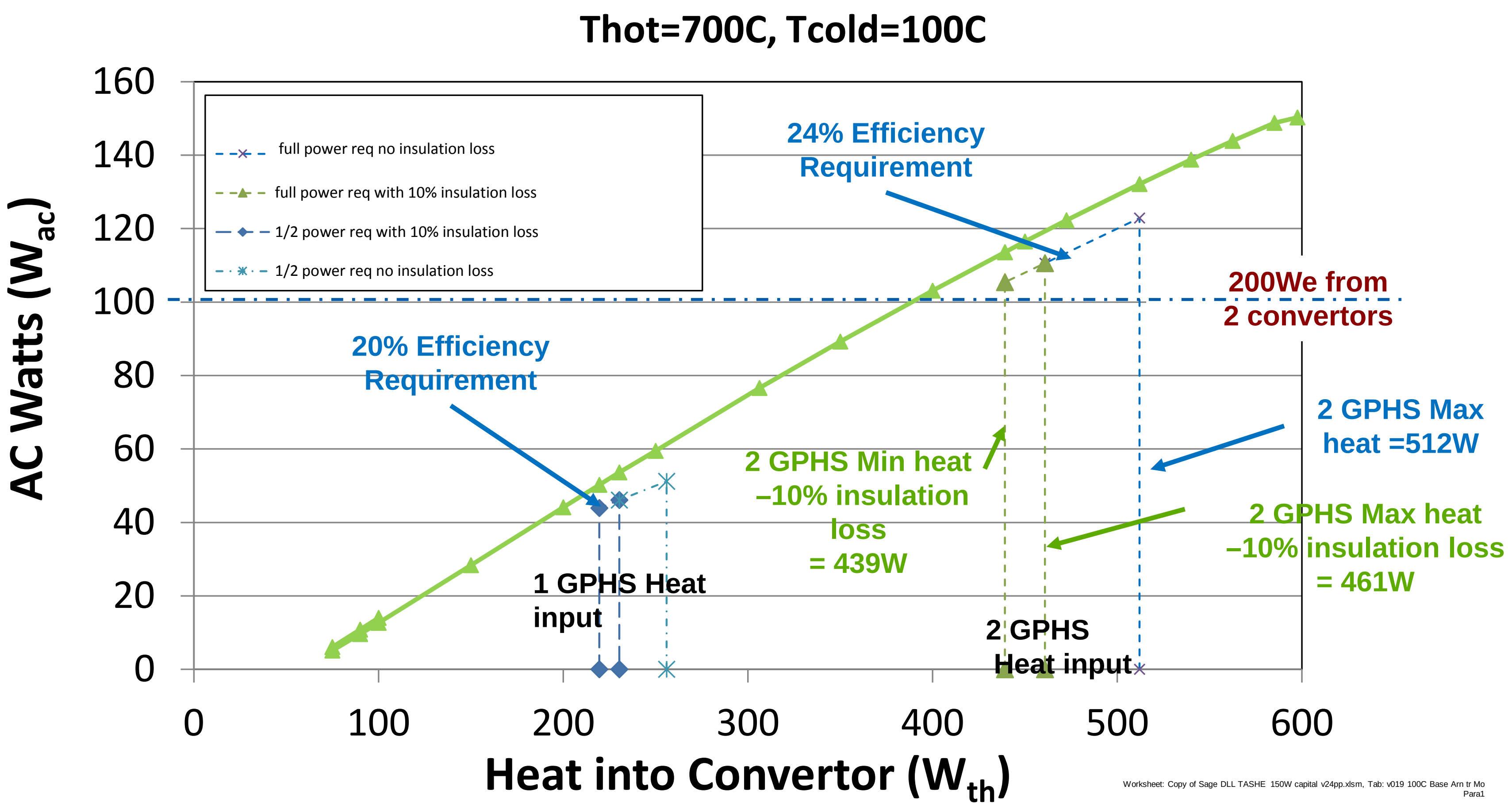
AC Efficiency vs Heat into Convertor



Worksheet: Copy of Sage DLL TASHE 150W capital v24pp.xlsm, Tab: v019 100C Base Arn tr Mo Para1

Operational Capability Prediction

AC Power vs Heat into Convertor



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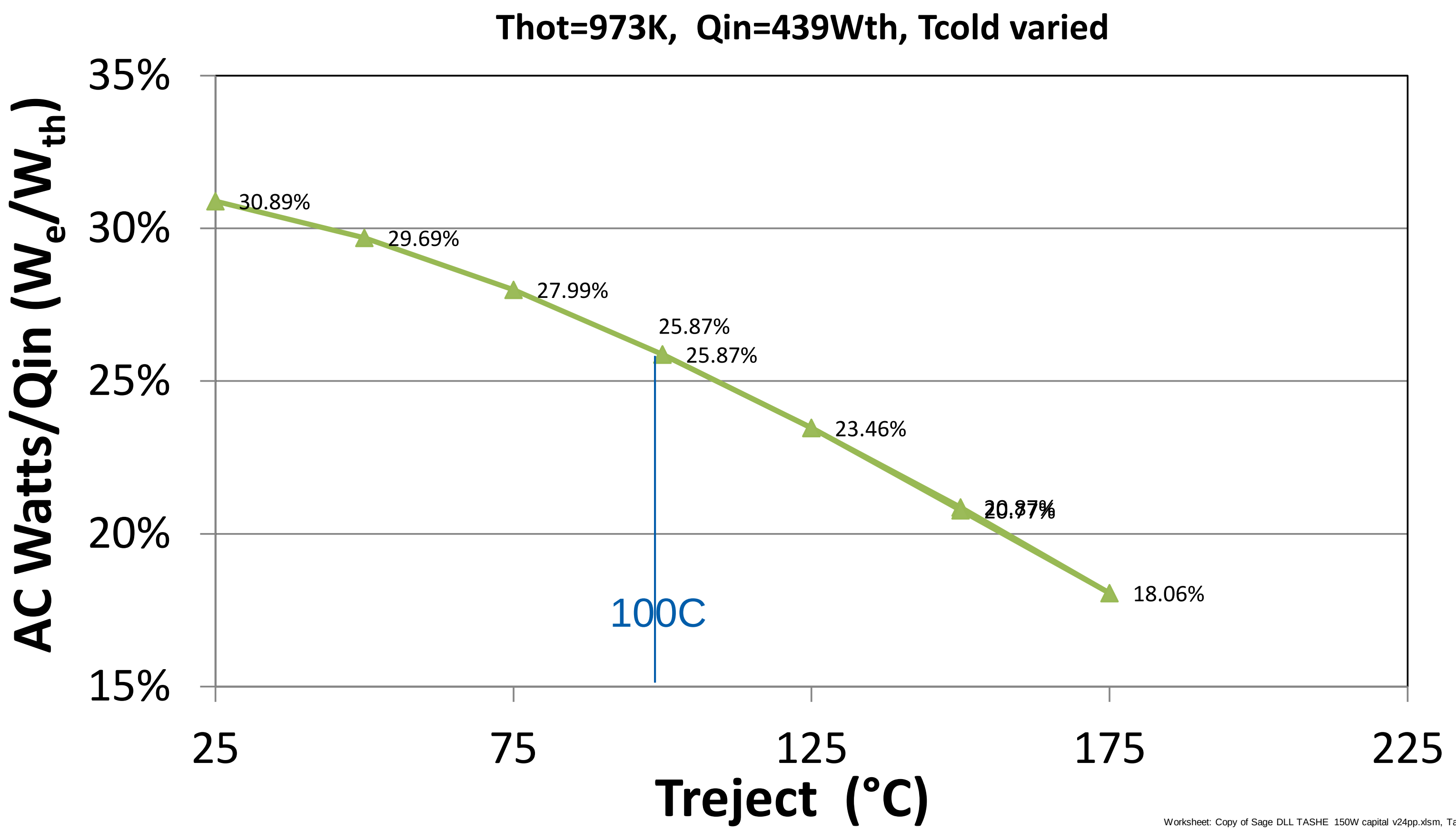
Operational Capability Prediction

AC Power and Efficiency vs Reject Temperature



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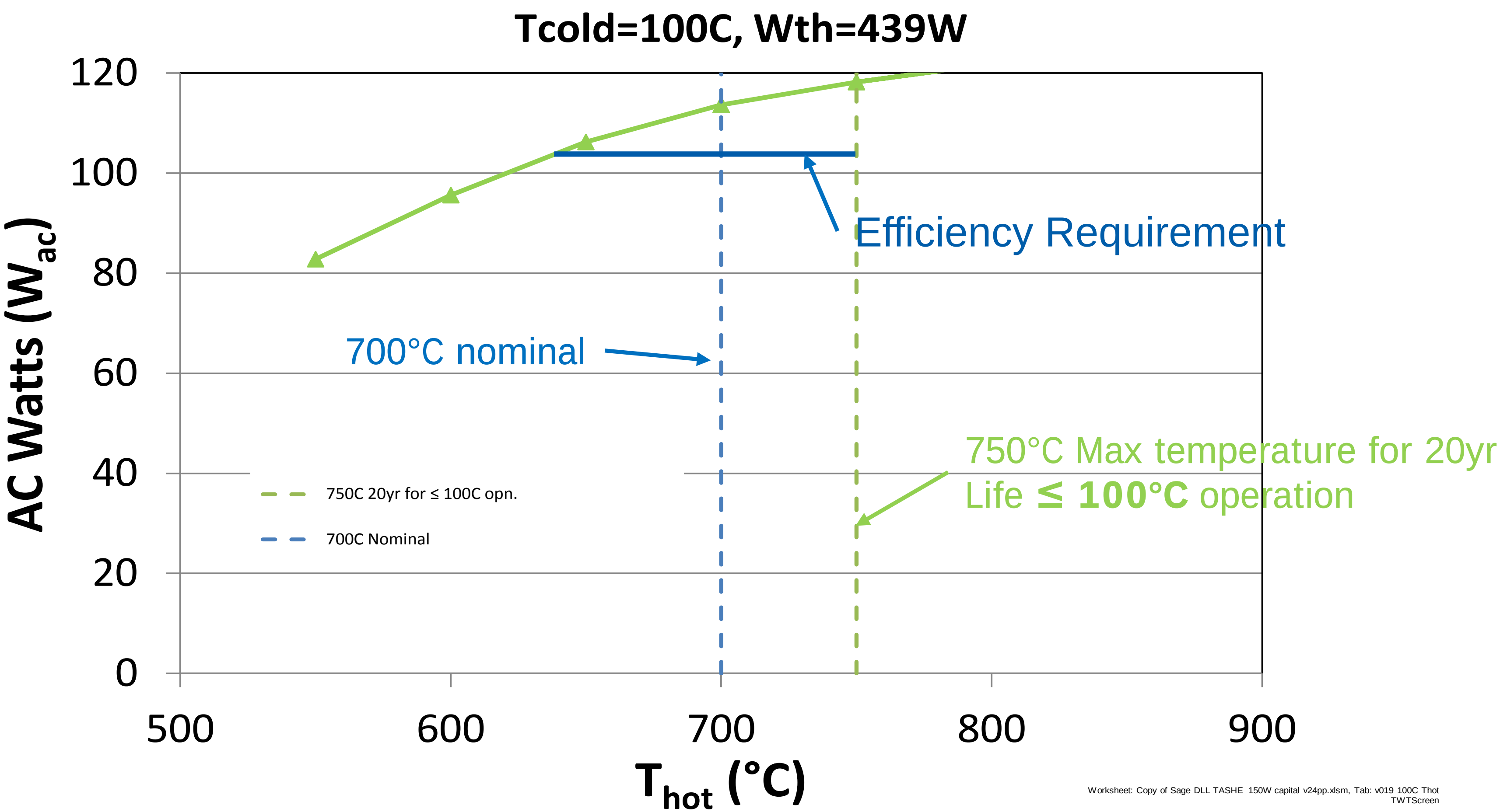
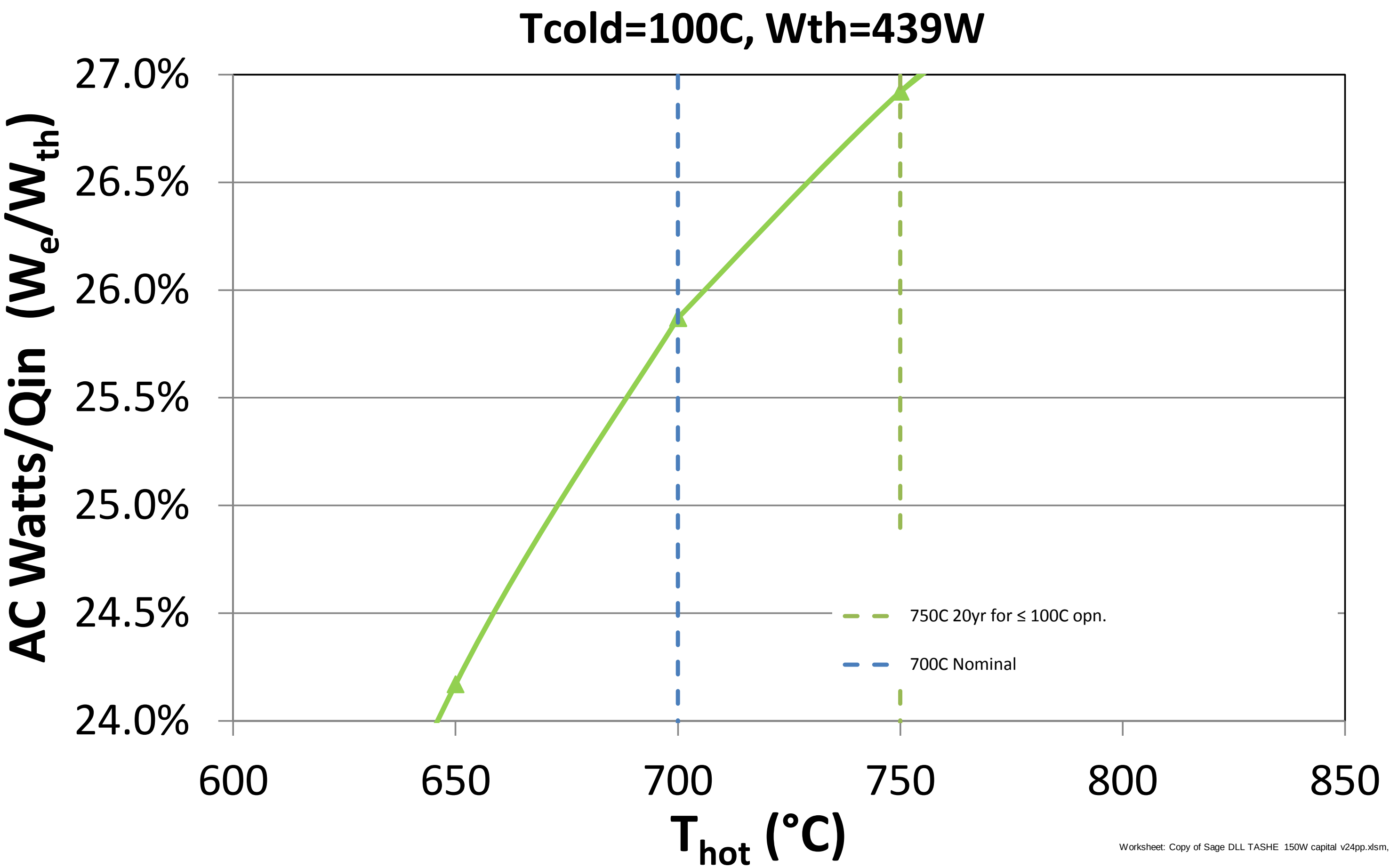
Operational Capability Prediction

AC Power vs Thot



AC Efficiency vs Thot



Worksheet: Copy of Sage DLL TASHE 150W capital v24pp.xlsm, Tab: v019 100C Thot TWTScreen

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Summary

Summary

- Northrop Grumman is developing thermoacoustic power convertors for use in radioisotope power systems for space applications
- Efficiencies appear comparable to conventional Stirling systems
- Less complexity promises higher reliability and manufacturability
- Conceptual design of 2 GPHS back-back system is complete
- Detailed analyses of components and materials demonstrate feasibility to meet key requirements and goals

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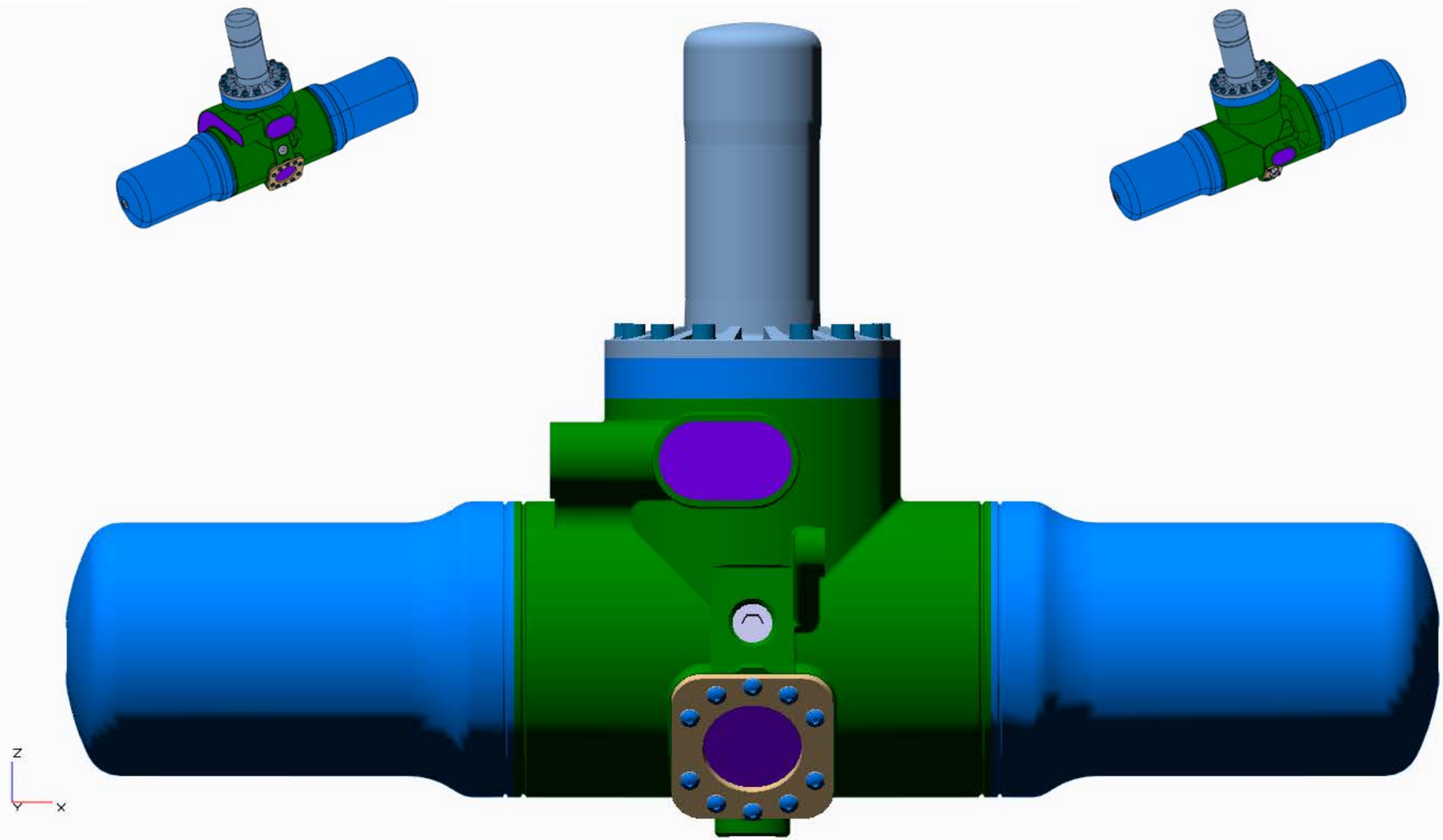
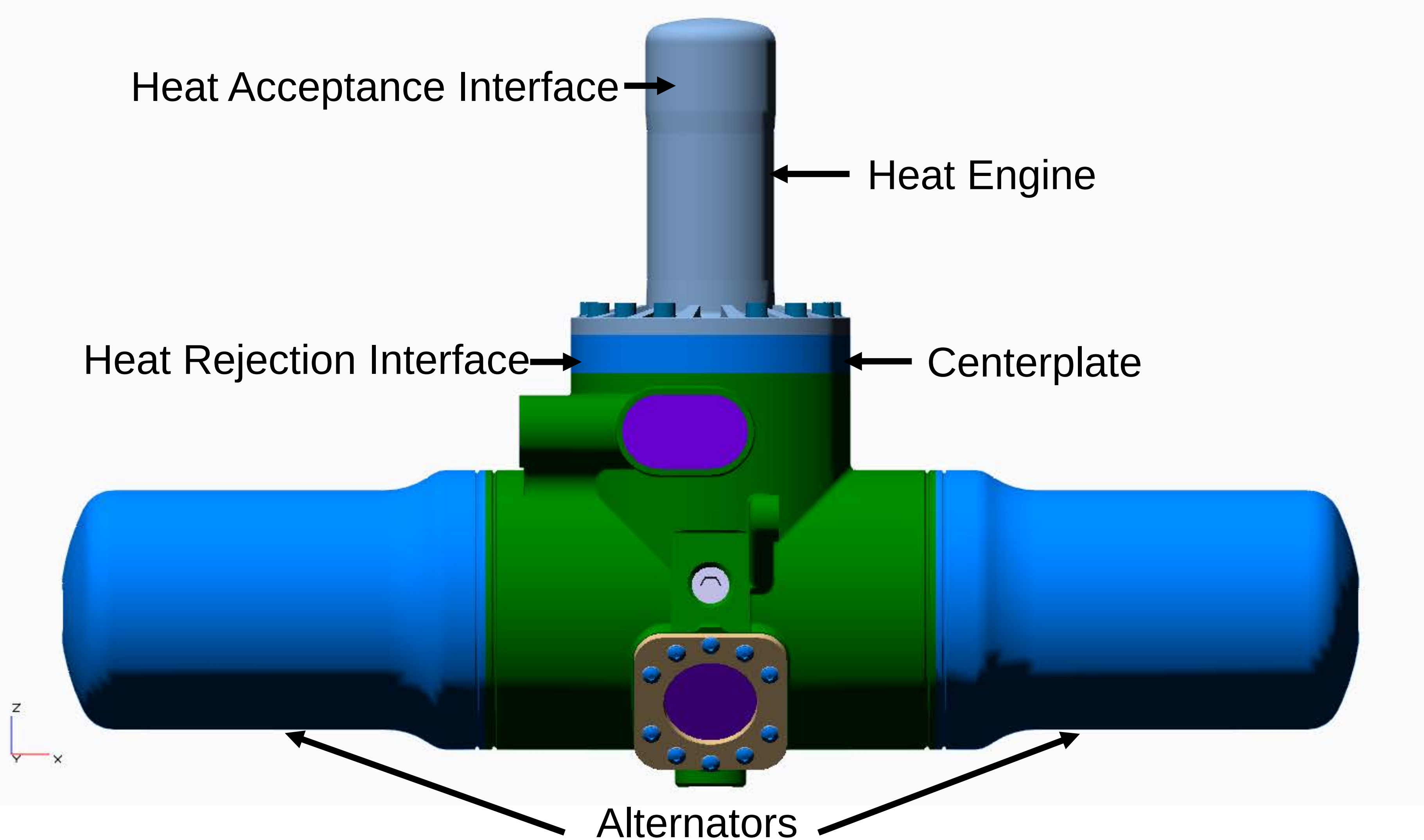
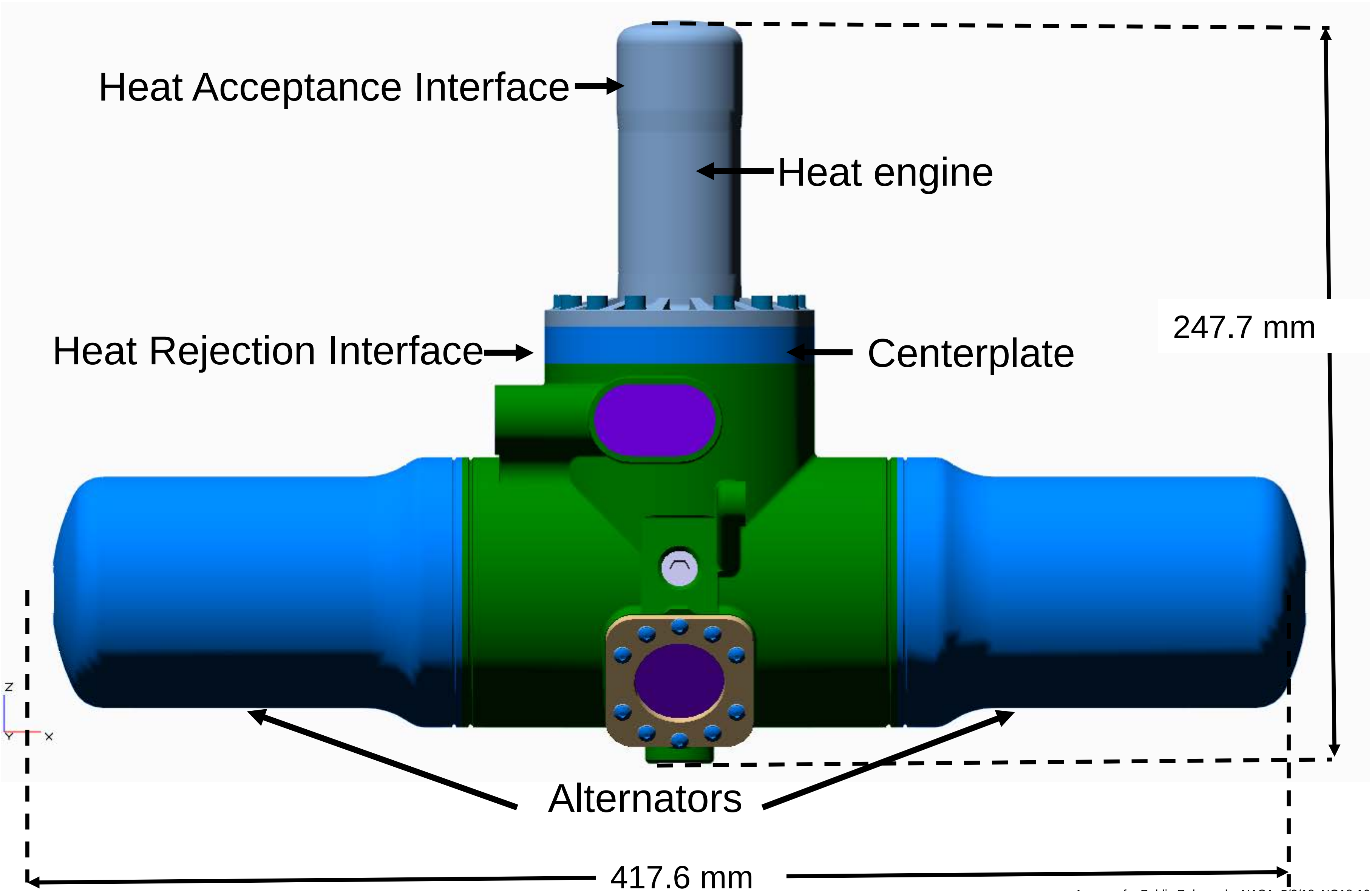
BACKUP

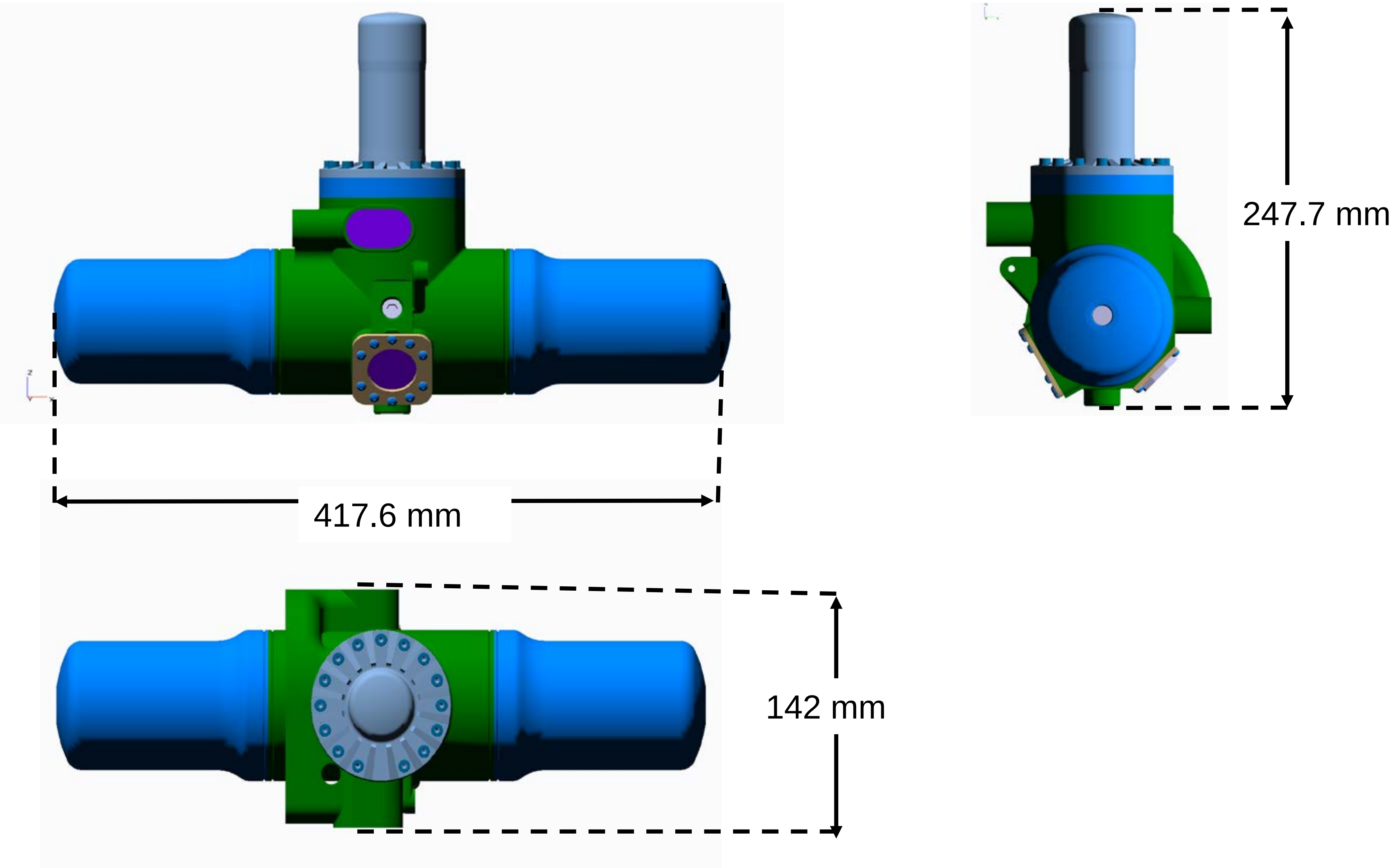
Solid Model Views

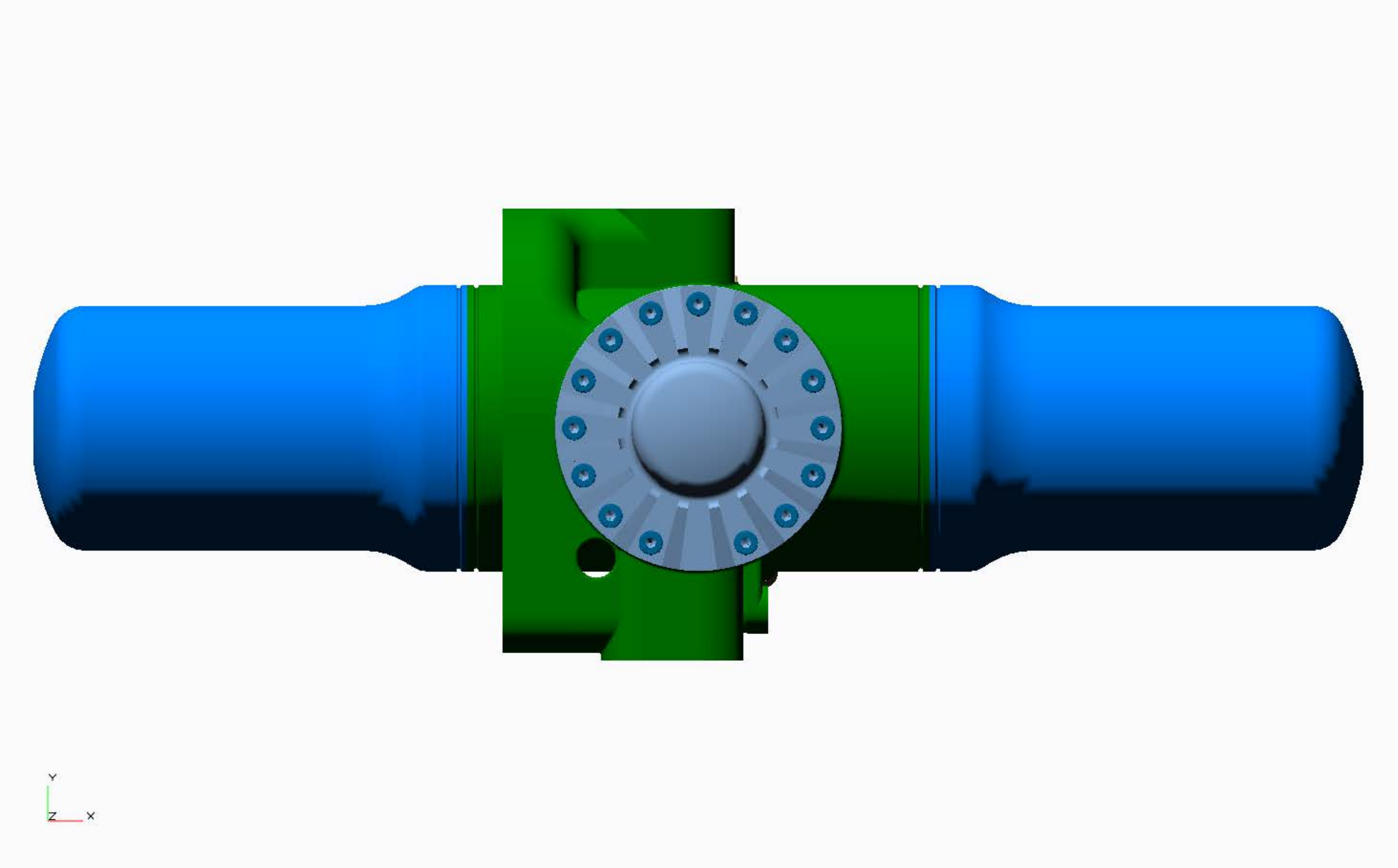


Solid Model Views




Heat Acceptance Interface
Heat engine
Heat Rejection Interface
Centerplate
247.7 mm
Alternators
417.6 mm


247.7 mm
417.6 mm
142 mm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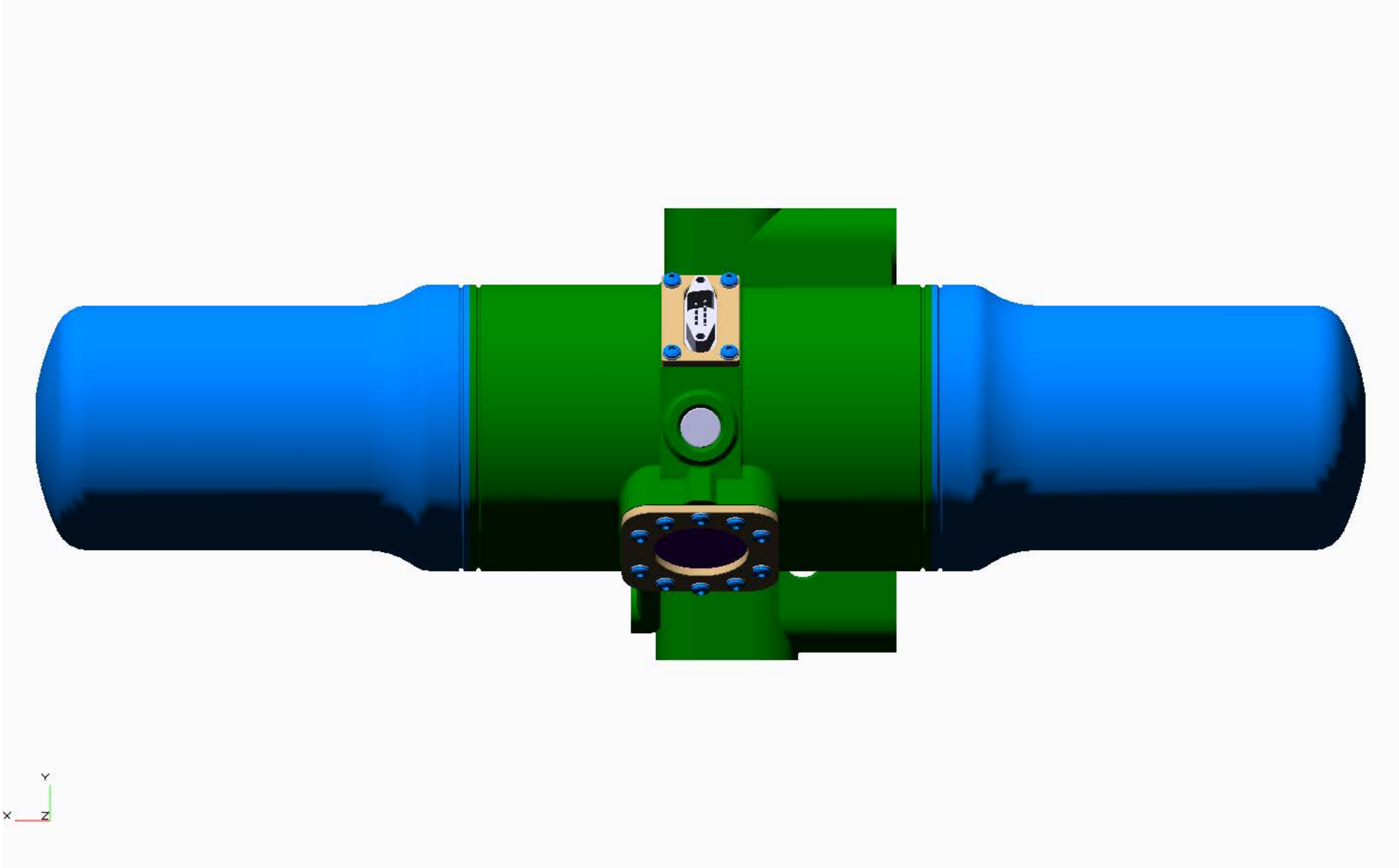
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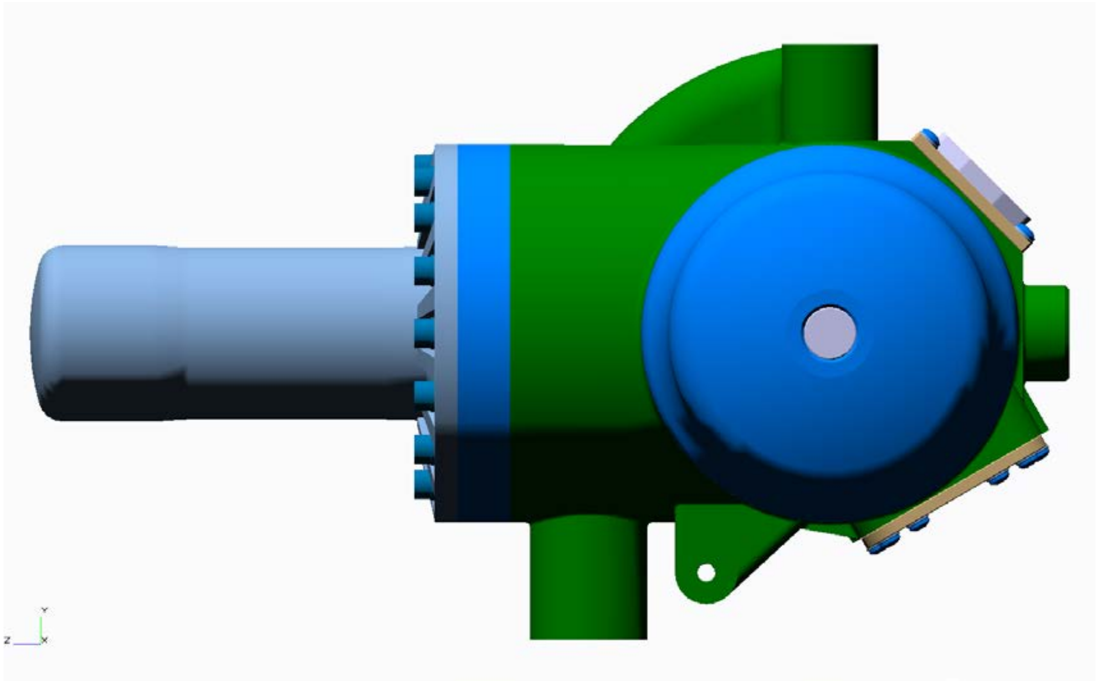
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