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# Enabling Extended Utilization of Cryogens in Space: Plans and Status of the Cryo Fluid Technologies Project under NASA's Game Changing Development Program


Michael P. Doherty[1]
Wesley L. Johnson[2]
Jonathan R. Stephens[3]
Jason W. Hartwig[4]
Benjamin T. Nugent[5]
Angela G. Krenn[6]

[1] Aerospace Engineer, NASA Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH, 44135, Mail Stop 162-4, Associate Fellow AIAA.
[2] Aerospace Engineer, NASA Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH, 44135, Mail Stop 86-12, AIAA Senior Member.
[3] Aerospace Engineer, NASA Marshall Space Flight Center, Huntsville, AL 35812.
[4] Research Aerospace Engineer, NASA Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH, 44135, Mail Stop 86-12, Associate Fellow AIAA.
[5] Aerospace Engineer, NASA Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH, 44135, Mail Stop 86-12.
[6] Senior Cryogenics R&D Engineer, NASA Kennedy Space Center, FL 32899.




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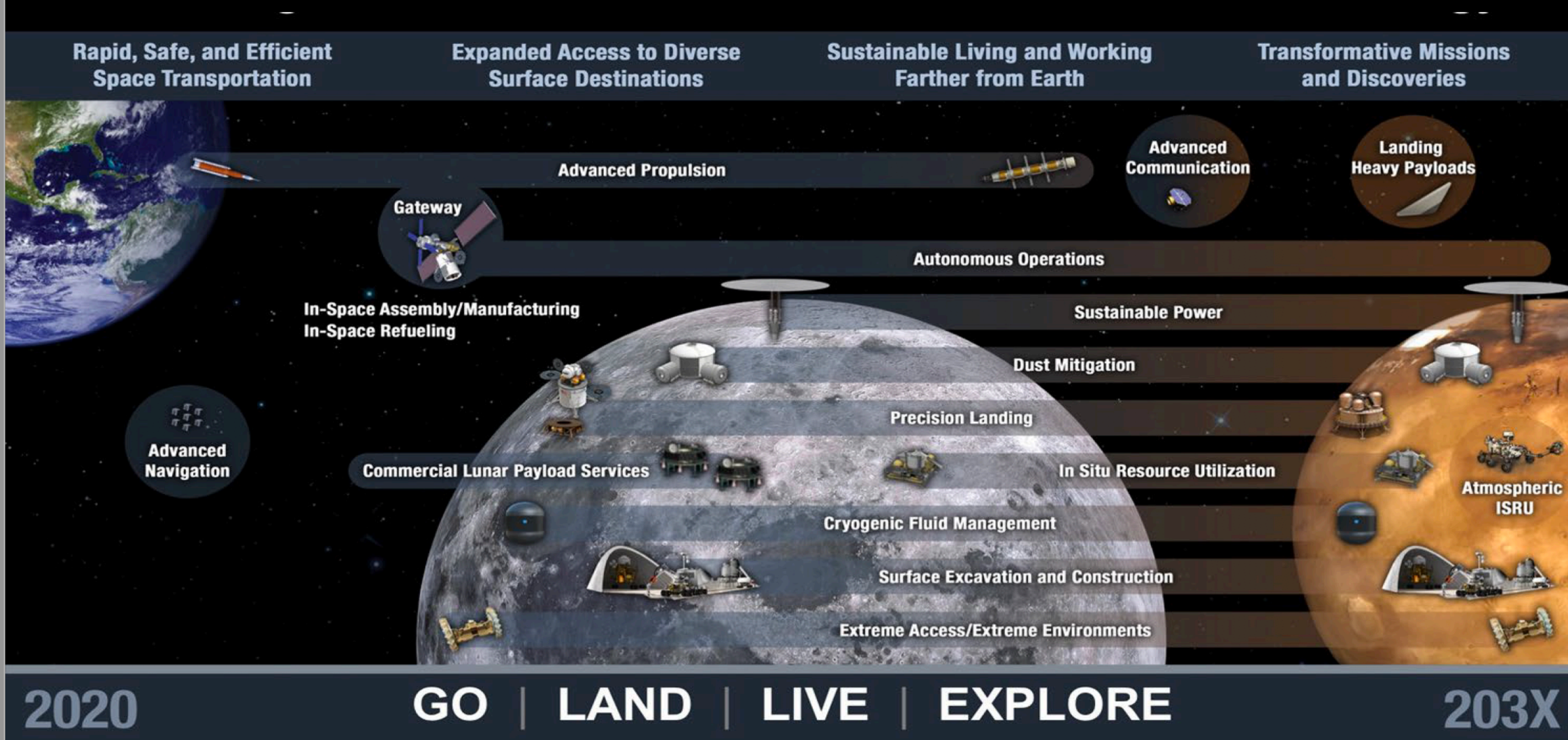
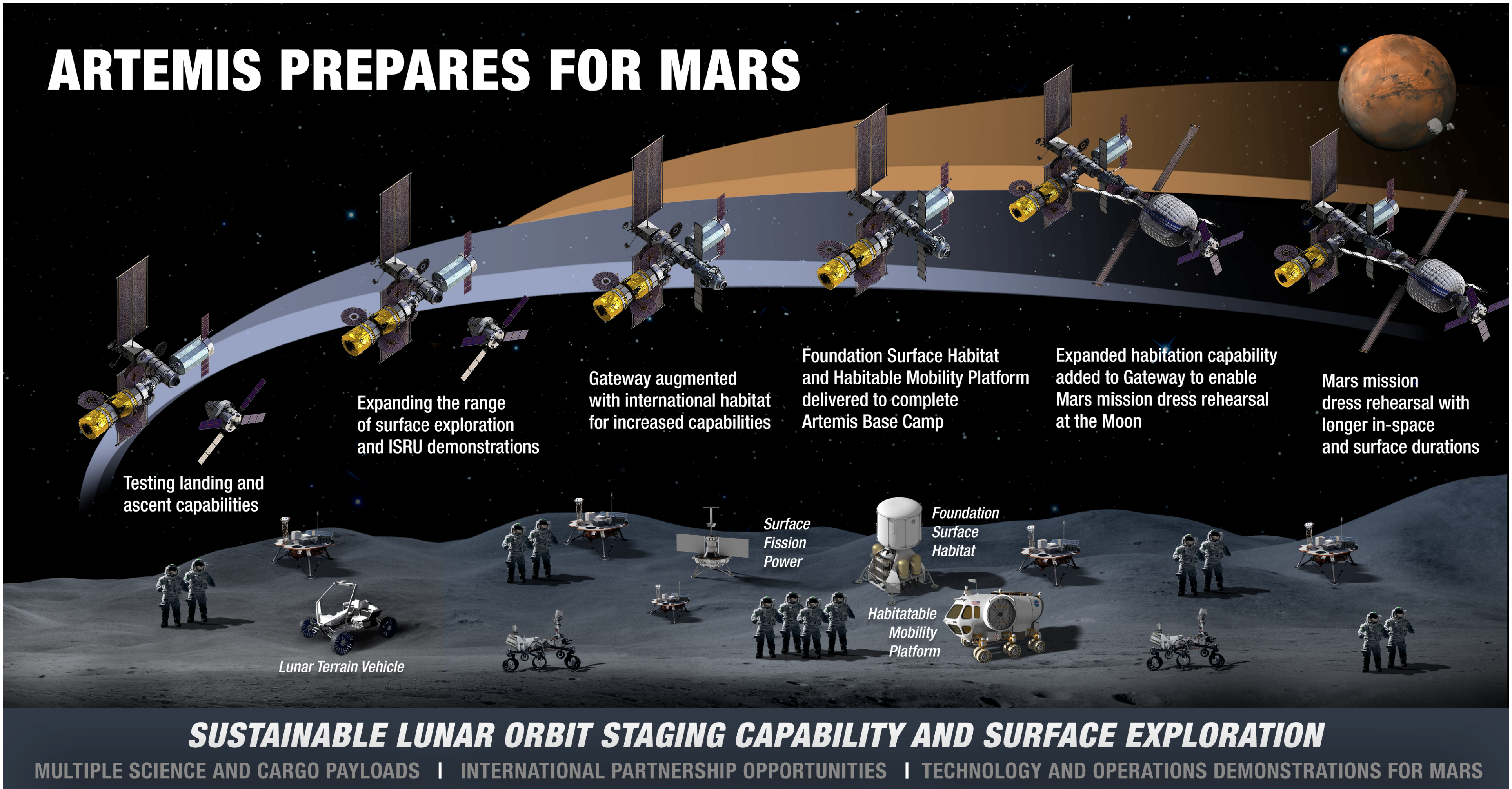
**Cryogenic propellants provide high-energy propulsion solutions critical to future, long-term human exploration missions beyond Low-Earth Orbit (LEO). Challenges include transferring cryogenic propellants in space and storing them for long-duration missions.**

# Reaching the Moon and Mars Faster With NASA Technology




Reference 1: STMD FY 2021 NASA Advisory Council TI&E Briefing, James Reuter, March 2020




Reference 2: Artemis Plan, NASA's Lunar Exploration Program Overview, Sept 2020

# Cryogenic Fluid Management (CFM) Technologies

Demonstrate technologies enabling autonomous transfer and storage of cryogenic hydrogen, capable of scaling to tens of metric tons, with negligible losses for long duration in space and on the lunar surface.

**Technology Gaps**

- LOX/Methane CFM - Zero Boil Off and Liquefaction at Low Power (100's Watts @ 90K)
- Zero-g Cryo Storage & Transfer (LOX, LCH4, LH2)
- Advanced Cryocoolers
- Improved Vacuum Insulation Systems
- Transfer Operations
- Zero-g Fluid Modeling

Technologies Addressed by CFT

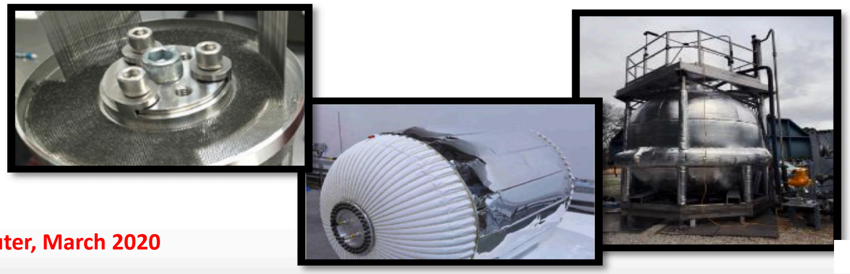
**Current CFM component development work:**

- HLS BAA Refueling Studies
- Cryogenic thermal coatings
- Automatic Cryo-couplers
- Low Conductivity Structures (SHIIVER tank)
- Propellant Densification
- High Vacuum MLI (IFUSI and CELSUIS)
- Vapor Cooling (eCryo)
- Unsettled liquid mass gauging (RRM-3)
- Low Leak Valves
- High Capacity Cryocooler (20K 20W)
- 90K Cryocooler development

**Future Mission Planning:**

Demonstrate enabling technology for a propellant refueling and storage needed for both lunar sustainability and Mars Transit Integrated demo, including, but not limited to the following technologies:

- Autogenous pressurization
- Multilayer Insulation
- 90 K Cryocoolers
- Tube-on-tank heat transfer
- Unsettled Mass Gauge
- Thermodynamic Vent
- Transfer Operations
- Line-chilldown & 2 phase flow meter
- Automated Cryo-coupler

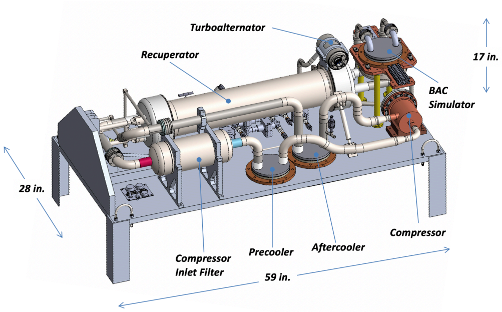


Reference 1: STMD FY 2021 NASA Advisory Council TI&E Briefing, James Reuter, March 2020

# CFT Technology Overview

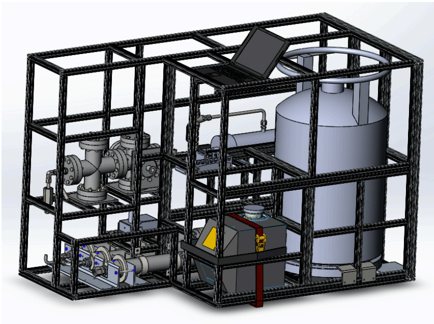
The Cryogenic Fluid Technologies (CFT) Project is focused on the maturation of several cryogenic fluid management (CFM) technologies essential to NASA's future missions in science and exploration which utilize both chemical and nuclear thermal (NTP) in-space propulsion, surface landers, and in situ resource utilization, addressing liquefaction, storage, and transfer of liquid hydrogen, methane, and oxygen in space.

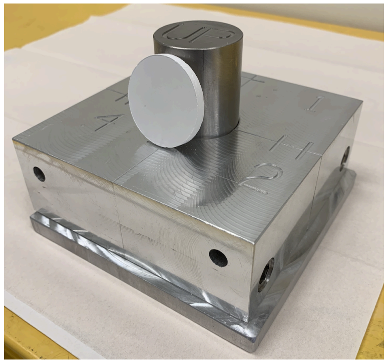
- CFT, under NASA Space Technology Mission Directorate's Game Changing Development Program, is one of a number of projects addressing the NASA's cryogenic fluid management technology gaps. Another recent publication describing progress in CFM technology advancement is *Cryogenic Fluid Management Technologies Enabling for the Artemis Program and Beyond*.[3]



**150W/ 90K Cryocooler Conceptual Design**


**20W 20K Cryocooler in Cleanroom**


**RGCT Transfer Line Chilldown Test**


**One Inch Diameter Yttrium Oxide (Y2O3) Rigid Tile Sample Sitting on Sample Mold**

# 150W/ 90K Cryocooler

**Rationale for Development:**

- High Capacity Cryocoolers are deemed to be an enabling technology for the long duration storage of cryogens in large-scale propellant tanks, and the liquefaction of in-situ produced propellants on the lunar and Martian surfaces.
  - The 150W/ 90K Cryocooler was proposed to Game Changing Development during the Spring of 2018
- The Reverse Turbo-Brayton (RTB) cycle cryocooler was recognized as having significant maturity as well as the ability to meet performance demands

**Team:**

- Glenn Research Center (Lead) and Marshall Space Flight Center
- Industry Partners: Creare (RTB Cryocoolers), Lockheed Martin and Northrop Grumman (Pulse Tube Cryocoolers)

**Maturity Timeframe:**

- Mature 150W/90K RTB Cryocooler to TRL-6 by early 2022

**Goals (G) and Objectives (O):**

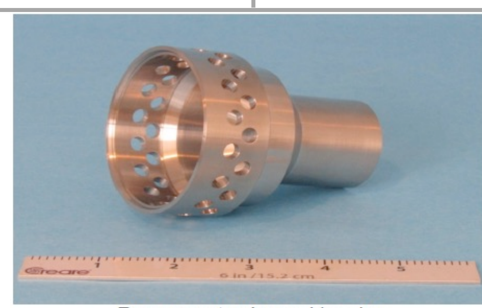
- (G) Design, build, demonstrate a 150W/ 90 K RTB cryocooler having a specific mass of 0.4 kg/W and a specific power requirement of 8.0 W/W.
- (O) Design and build the recuperator and turbo-alternator
  - (O) Perform brassboard testing along with the previously built compressor
- (O) Complete the build of a prototype cryocooler; conduct system performance and vibration testing

**Applicability/ Infusion Focus**

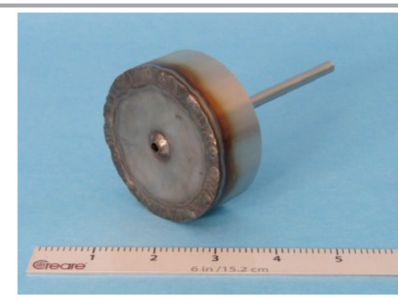
- Deliver the prototype cryocooler directly to the Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL) Project for the liquefaction and storage prototype testing at GRC
- Provide knowledge for technology infusion to the Human Landing System
- Nuclear Thermal Propulsion liquid hydrogen storage (first stage 90K heat intercept assist to 20K second stage)

TA Bellows

TA Stator



Recuperator Inner Header



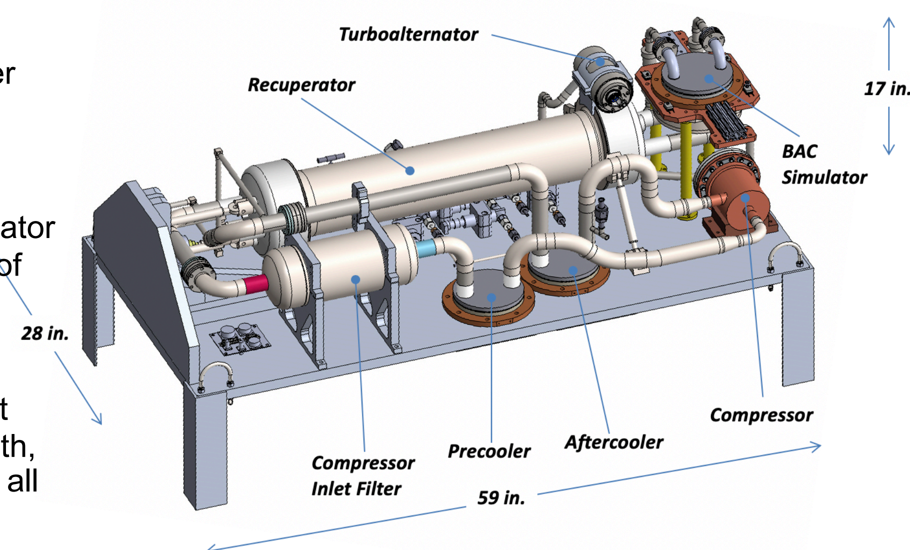
Recuperator Header Weld Trial

**Images courtesy of Creare**

# 150W/ 90K Cryocooler (cont.)

**<u>Technical Status – Work Performed at Creare</u>**

- Components
  - Recuperator (status to date): Completing fabrication of outer shell and inner tube components and finalizing design of recuperator supports, in support of fab, assembly, and workmanship testing.
  - Turboalternator (status to date): Completing fabrication of stator laminations and housing, and assembling stator, in support of fab, assembly, and mechanical verification testing
- Brassboard cryocooler test (status to date):
  - Determined cryocooler component layout inside existing test facility, and completed specification of harnesses (size, length, heat leak) and pass-thru assignments and specifications for all signals and fluid interfaces, in support of brassboard testing
- Cryocooler Prototype (status to date):
  - Held successful Initial Design Review in June 2020.
  - Planning for integration into CryoFILL oxygen liquefaction demonstrations




**150W/ 90K Cryocooler Preliminary Design**

**Cryocooler rendition courtesy of Creare**

# 20W 20K Cryocooler

## Rationale for Development:

- The 20W 20K Cryocooler Project was stood up to address the need for zero boil off storage of Liquid Hydrogen (LH2), critical to Nuclear Thermal Propulsion as well as LH2-based architectures for exploration.
  - The Reverse Turbo-Brayton (RTB) cycle cryocooler was recognized as having the ability to meet performance demands. The effort was initially planned as a two-year task, but a number of technical challenges extended the timespan of the work original lifecycle.

## Team:

- Glenn Research Center (Lead) and Marshall Space Flight Center
- Industry Partners: Creare

## Maturity Timeframe:

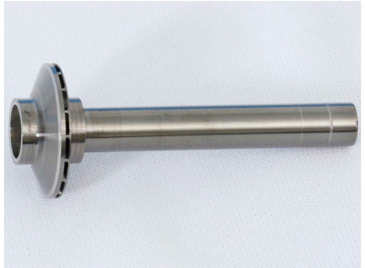
- Mature 20W 20K Cryocooler to TRL-5/6 by late 2022

## Goals (G) and Objectives (O):

- (G) Design, build, and demonstrate a 20W 20K RTB cryocooler with a specific mass of 4.4 kg/W and a specific power requirement of 60 W/W.
- (O) Complete the build of the 20W 20K RTB Cryocooler and conduct acceptance testing to validate system performance in an operational environment
  - (O) Conduct characterization testing over a broader range of expected operating conditions (cooling temperatures, heat rejection temps, cryo tank sizes)

## Applicability/ Infusion Focus

- Provide knowledge for technology infusion to the Human Landing System
- Provide for zero boil off LH2 storage for Nuclear Thermal Propulsion as well as LH2-based architectures for exploration



Compressor Rotor

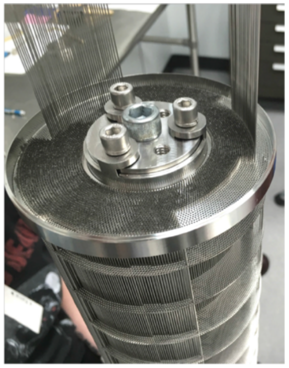
20W 20K Cryocooler in Creare's Clean Room

**Images courtesy of Creare**

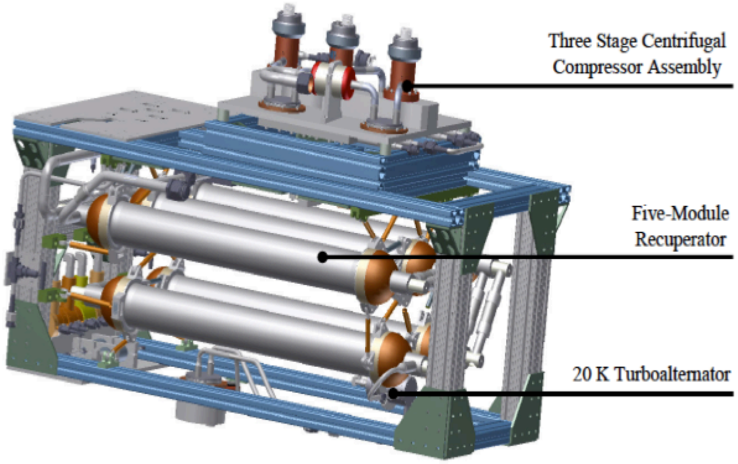
# 20W 20K Cryocooler (cont.)

**Technical Status – Work Performed at Creare**

- Creare has designed, fabricated and thermal performance tested a high effectiveness, micro-tube shell-and-tube heat exchanger, recuperator.
  - This design utilizes over 6600 tubes that are 0.56 mm in diameter in each of five recuperator modules in the cryocooler assembly.
- After installing compressors in the Warm Module, Creare will connect the cryocooler, perform leak testing and bakeout, and prepare for thermodynamic testing
- Thermodynamic testing will evaluate the performance of the cryocooler at a range of thermal loads (3-20W) at a 20K cooling temperature
- Extended testing will evaluate cryocooler performance at additional cooling temperatures, heat rejection temps, cryo tank sizes



In-process assembly of core for first recuperator




Three-dimensional model of the 20-W, 20-K cryocooler, showing its main components.

Image and rendition courtesy of Creare

# Reduced Gravity Cryogenic Transfer

**Rationale for Development:**

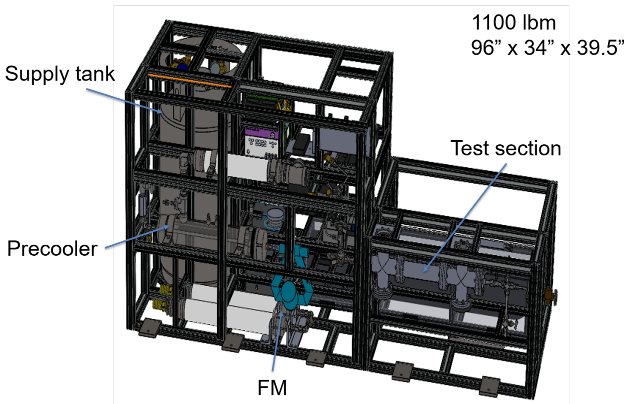
- It was recognized that future flight missions will require transfers of cryogens in low or zero gravity environments which can lead to losses through boil off.
  - The Reduced Gravity Cryogenic Transfer effort was proposed to Game Changing Development during the Spring of 2018

**Team:**

- Glenn Research Center (Lead) and Marshall Space Flight Center
- Industry Partners: University of Florida and Aerospace Corporation

**Maturity Timeframe:**

- Mature line and tank chilldown technologies to TRL-5 by mid to late 2023




**Line Chilldown parabolic flight hardware**

**Goals (G) and Objectives (O):**

- (G) Develop methods and approaches to reduce cryogen propellant mass loss due to line and receiver tank chilldown during transfer operations and validate them through analysis and testing.
- (O) Line Chilldown: Modify an existing flightworthy cryogenic testbed for experimentation of reduced gravity transfer line chilldown; Demonstrate, in low gravity, reduction of propellant mass consumed through application of pulse flow technique, as well as chilldown improvements due to application of thermal coating on inside diameter of transfer lines
- (O) Tank Chilldown: Design, build, and verify a versatile flightworthy cryogenic testbed for experimentation of reduced gravity cryogenic tank to tank transfer experiments; Demonstrate, in low gravity, the feasibility of tank to tank transfer
- (O) Develop, verify, and validate numerical models

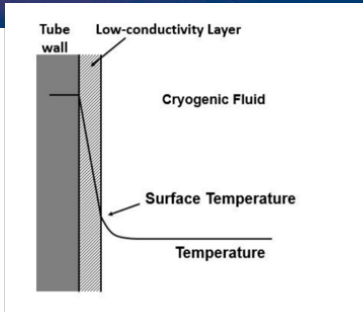
**Applicability/ Infusion Focus**

- Provide knowledge for technology infusion to the Human Landing System

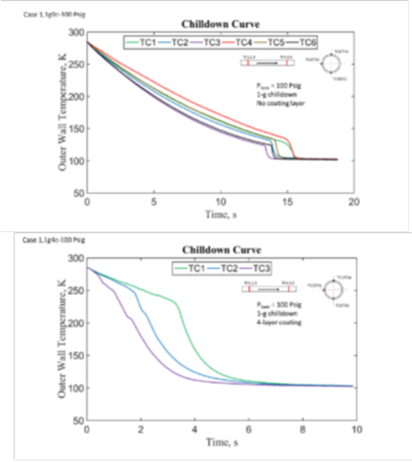
# Reduced Gravity Cryogenic Transfer (cont.)

**Technical Status**

- **Line Chilldown – Work Performed by University of Florida and Aerospace Corporation**
  - Demonstrated 1-g performance gain, reduction in chilldown time, of Teflon coatings on the transfer line (see figures)
  - Developed analytical model for optimizing thermal coating material and coating type on transfer line.
  - Modified and flight qualified a test rig to obtain low-g line chilldown data
  - Plan was to conduct parabolic flight tests on-board the Zero-G aircraft in March 2020
    - Flights, delayed due to COVID, are rescheduled for November.
- **Modeling and Analysis – Work Performed at GRC and MSFC**
  - Performed CFD and lumped node code validation against two historical data sets
  - Completed Thermal Desktop model validation against K-site tank chilldown data
  - Developed an analytical tool to design and size optimal tank chilldown and fill injectors




Temperature profile of coated transfer line

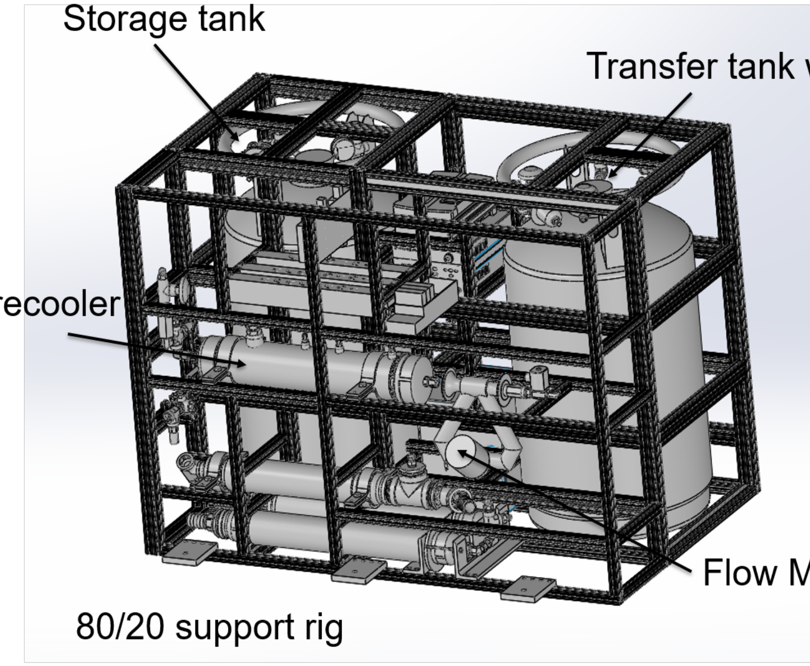



Effect of thermal coatings on chilldown time

# Reduced Gravity Cryogenic Transfer (cont.)

**Technical Status**

- **Tank-to-Tank Parabolic Flight Rig – Work Performed at GRC**
  - Successful System Requirements Review for NASA flight rig
  - Developed injector concept designs
    - 24 concepts paired down to 8 concepts for Concept Validation Review (scheduled in 10/2020) using the Analytical Hierarchy Process
    - Developed multiple concept of operations for different chilldown methods
    - Developed Qty=3 Tank chilldown concepts, and made final selection of concept




Tank-to-Tank Parabolic Flight Rig

# Cryo Thermal Coating

**Rationale for Development:**

- Solar reflectors can serve a critical role in the passive maintenance of cryogens such as liquid oxygen or liquid methane in deep space storage when properly integrated into a flight system
  - Subsequent to one year (and moderate level) funding as a seedling project, Cryo Thermal Coating was stood up as a two year effort by Game Changing Development at the beginning of FY20.

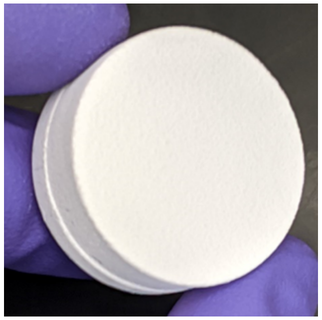
**Team:**

- Kennedy Space Center (Technical Lead) and Glenn Research Center

**Maturity Timeframe:**

- Mature Spray-on coating and Rigid tile technologies to TRL-5 by early to mid 2022

Rigid tile coating with holes for suspension in test chamber



Spray on coating on 7075 Al achieved 2.8% solar absorptivity!

**Goals (G) and Objectives (O):**

- (G) Develop technology to manufacture solar reflector tile of Yttrium Oxide (Y2O3) with solar absorption levels between 1% and 0.3% capable performing in deep space environments on future space vehicles.
- (G) Develop technology to use Y2O3 as a spray-on solar reflector coating that can be readily applied to large structures with solar absorption levels between 6% and 3%.
- (O) Develop the optimal process to manufacture Y2O3 tiles that meet the desired performance standards; Develop a high performance spray-on coating based on Y2O3 with uniformity, minimal thickness and flake generation, while maximizing solar reflectance.
  - (O) Test to quantify tile and spray-on-coating performance in deep-space environmental chambers and spectrophotometers.
  - (O) Test to quantify tile degradation due to interactions with atomic oxygen.

**Applicability/ Infusion Focus**

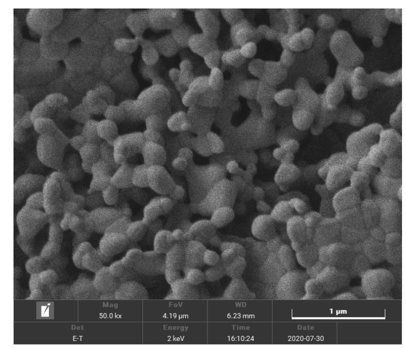
- Spray-on coating was included in a Tipping Point proposal by a US company. If awarded, Y2O3 coating will be sprayed onto a flight cryogenic tank to reduce heat load during space flight.
- Collaboration occurring with launch providers and aerospace companies interested in multiple applications of both spray-on coating and rigid tiles to reduce heat loads while in space flight.

# Cryo Thermal Coating (cont.)

**Technical Status – Work Performed at KSC and GRC**

- Completed installation of new Spectral Reflectometer and acquisition of NIST traceable reflectance standards
- Collaborated with several industries on the development and evaluation of material samples
- Completed a systematic Study of High Reflection Yttrium Oxide ($Y_2O_3$)-Based Spray on Coating. Three different formulations were applied to aluminum, steel, silver, and multilayer insulation. Achieved the project goal of 3% solar absorptivity by spraying on a smooth surface of 7075 aluminum.
- Progressed on Rigid Tile development with the receipt of a new oven (see photo) and better fabrication procedures. The new tiles are much stronger (see the SEM photo of a tile showing the welded particles) yet still exhibit good solar absorptivity (better than the NIST standard compared against).
- GRC is developing/ refining a deep space simulator to measure solar absorptivity of coatings and tiles. COVID issues have delayed final checkouts.
  - Atomic oxygen and ultraviolet exposure of coatings and tiles, along with before and after evaluation within the deep space solar simulator, will be performed.

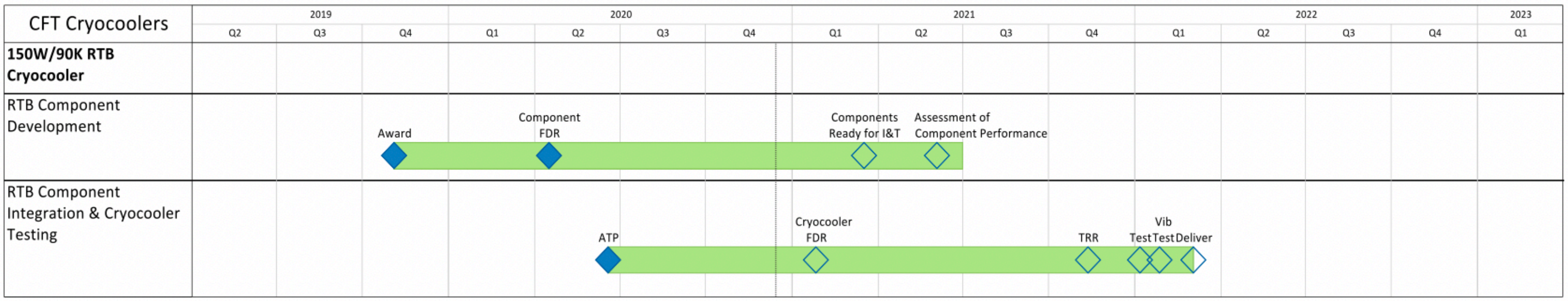
The inside of the new oven, allowing higher sintering temperatures. A ceramic mold containing pressed powder is shown.



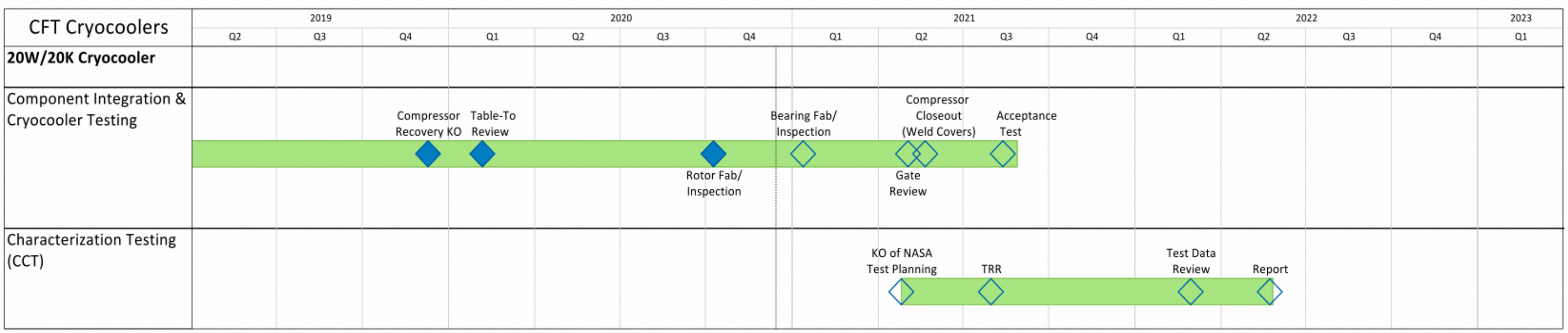
An SEM image of high temp. sintered $Y_2O_3$ powder showing fusing, resulting in a strong, rigid, highly reflective material. The white bar is 1 micron long.

# Outlook (Schedule Going Forward)

**The 150W/90K Cryocooler is on schedule for delivery to Glenn Research Center in the 1QFY22 for integration into LOX liquefaction testing**

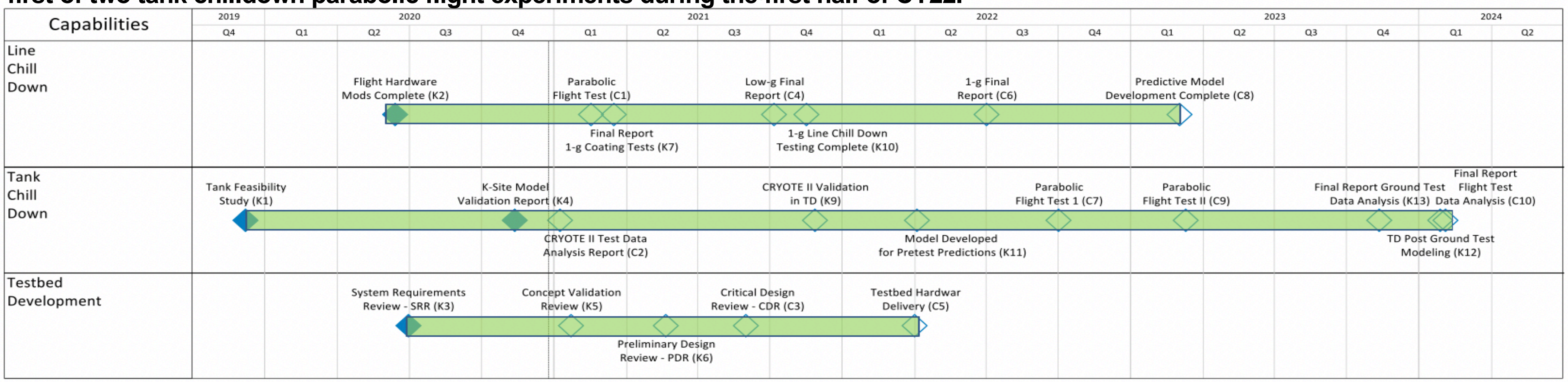



**The 20W 20K Cryocooler is on schedule for acceptance testing during the 3QFY21, and testing over a broader range of expected operating conditions (cooling temperatures, heat rejection temps, cryo tank sizes) by 1QFY22**

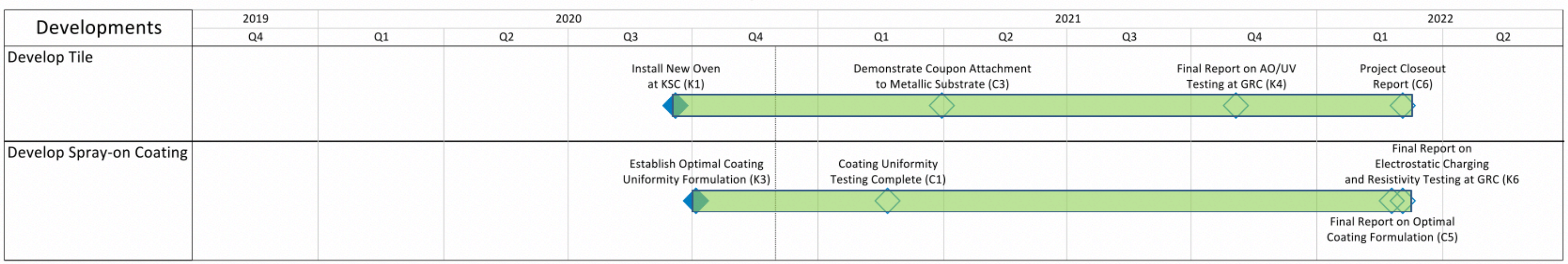


# Outlook (Schedule Going Forward)

**The Reduced Gravity Cryogenic Transfer effort is on schedule to fly the line chilldown parabolic flight experiment during 1QFY21 and the first of two tank chilldown parabolic flight experiments during the first half of CY22.**




**The Cryo Thermal Coating effort is on schedule to mature both rigid tile and Spray-on coatings to TRL-5 by 1QFY22.**



# Summary

The Cryo Fluid Technologies project, under the Space Technology Mission Directorate's Game Changing Development Program, is:

- Maturing both cryogenic storage and cryogenic transfer technologies for NASA's future missions in science and exploration to a TRL 5/6 maturity:
  - Essential for chemical and nuclear thermal (NTP) in-space propulsion, in situ resource utilization, and relevant for surface landers

The Project is positioned to produce data, modeling tools, and hardware as follows (on-going, planned, or potential impacts):

- Deliver prototype High Capacity 90K Cryocooler hardware directly to ISRU Liquefaction (CryoFILL) prototype testing at GRC (planned)
- Provide (and make available) prototype 20W 20K Cryocooler hardware for integration into possible future zero boil off demonstration for LH2 storage (potential)
- Inform trade studies and conceptual designs for Nuclear Thermal Propulsion, as well as LH2-based architectures, for exploration (on-going)
- Deliver data and validated numerical models to inform the design of cryo transfer systems and operations in reduced gravity (planned)
- Provide and characterize Yttrium Oxide (Y2O3) rigid tile and spray-on solar reflector coating technology for U.S. Industry use (potential)
- Provide knowledge for technology infusion to the Human Landing System (on-going)
- Provide wide dissemination of results from this technology development effort to a larger audience through conferences, technical publications, and industry workshops (on-going)

# Acknowledgements

*The author and co-authors are deeply appreciative of the Cryo Fluid Technologies project team located at GRC, KSC, and MSFC, along our industry and university partners, who have worked, and continue to work, diligently to stand up and execute a multi-faceted portfolio of cryogenic fluid technologies critical to future, long-term human exploration missions beyond Low-Earth Orbit.*

# References


1) STMD FY 2021 Briefing to the NASA Advisory Council Technology, Innovation & Engineering Committee, James Reuter, Associate Administrator for NASA STMD (March 19, 2020)
2) Artemis Plan, NASA's Lunar Exploration Program Overview, September 2020
3) Hansen, H., Johnson, W., Meyer, M., Werkheiser, A., and Stephens, J., *Cryogenic Fluid Management Technologies Enabling for the Artemis Program and Beyond*, to be presented at AIAA Accelerating Space Commerce, Exploration, and New Discovery (ASCEND) Conference, November 2020

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