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Renovation of Thermal Vacuum Chambers at Idaho National Laboratory for Testing of Radioisotope Power Systems

Jaymon Birch, Brandon M. Horkley, Joe Giglio, Harmon D. Veselka

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Idaho National Laboratory

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RENOVATION OF THERMAL VACUUM CHAMBERS AT IDAHO NATIONAL LABORATORY FOR TESTING OF RADIOISOTOPE POWER SYSTEMS

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ABSTRACT

The Radioisotope Power Systems (RPS) program at Idaho National Laboratory (INL) fuels and performs environmental testing of RPS in support of National Aeronautics and Space Administration (NASA) missions. Recently the programs' thermal vacuum chambers, housed within INL's Space and Security Power Systems Facility (SSPSF), underwent successful renovations to improve functional capabilities and system control in support of customer missions. Thermal vacuum system renovations focused primarily on three core functions. The first focus area was integration of semi-automated Programmable Logic Controllers (PLC) to enhance operational feedback and process control. This included the use of numerically controlled vacuum valves and integration of real time feedback from process pressure transducers. Improvements to the system high vacuum pumping technology was the second priority focus. Legacy diffusion pumps were replaced with turbo-molecular and cryogenic pumps to help mitigate the possibility of back streaming diffusion pump oil onto the surface of the test article or radiative cooling surfaces located within the chambers. The third and final core function involved meeting emergent customer thermal requirements. This led to retro-fitting one of the vacuum chambers with a cryogenically cooled Thermal Conditioning Unit (TCU) and thermal shrouds. The TCU utilizes gaseous nitrogen to heat or cool a cylindrical shroud to maintain a set temperature with a programmable range of –185 to 100°C. With the successful completion of RPS acceptance testing, the newly renovated thermal vacuum chamber systems are operational and better equipped to support testing of Radioisotope Power Systems for space exploration missions.

INTRODUCTION

The RPS program is responsible for the fueling and testing of RPSs in SSPSF at the Material and Fuels Complex (MFC) located at Idaho National Laboratory (INL). This work was previously performed at the Mound laboratory in Miamisburg Ohio but was subsequently moved to INL in 2005 in support of the Pluto New Horizon's launch (2006). INL also fueled and delivered the Mars Science Laboratory power system for a 2012 launch. RPSs provide the power to operate spacecraft or rover systems such as battery chargers, scientific instruments, robotic arms, computers, radio, and drive systems. The energy from decay of Plutonium-238, a radioisotope material with an 88 year half-life generates usable heat. The RPS units convert this heat into reliable electricity for years or even decades in the case of the Voyager spacecraft. Although any heat to electricity conversion technology can be used, the only conversion technology used to date is thermoelectric thermocouples. Thermoelectric materials convert heat to electricity with no moving parts due to the voltage that is generated when a temperature gradient is present across the material (the Seebeck effect).

Following RPS assembly, a series of acceptance tests are performed to characterize the units' performance and to confirm flight requirements are met. Thermal vacuum testing is one of the acceptance tests performed. During power testing the RPS is placed in a thermal vacuum atmosphere chamber (TVAC) and subjected to simulated space atmospheric pressure and temperature conditions. Upon completion of service connections, the TVAC door is sealed and the RPS is exposed to simulated space conditions. Testing begins with evacuation of the TVAC. During testing, the TVAC can be backfilled with air, nitrogen, argon, helium or can be evacuated to a high vacuum. Once testing is complete, the chamber is returned to ambient conditions (temperature and pressure) and the RPS is transferred out of the chamber.

In an effort to revitalize legacy equipment and meet emergent customer needs, the TVAC systems underwent significant modernizations. The upgrades to the Rm-112 system were initiated in 2011 and the Rm-111 modifications began in 2015. Renovations to the TVAC systems were focused in three key areas: process control, high vacuum pumping technology and thermal conditioning capability.

PROCESS CONTROL UPGRADES

Legacy Controls

Legacy control systems used on the thermal vacuum chambers utilized solid state controls and relays to provide operator input to the process systems. While the control systems were robust and provided years of service, the basic manual functionality limited the usefulness and flexibility of the systems. Updated control components were selected with a significant focus on the ability to semi-automate the entire process from chamber pump down to backfill.

The updated control system was developed using a programmable logic controller, position controlled valves and updated chamber pressure sensors.

Programmable Logic Controller

The control system is comprised of a Programmable Logic Controller (PLC) with its associated Operator Interface Terminal (OIT) and an Operator Control Station (OCS) as well as an array of transducers, sensors, valves, Residual Gas Analyzers (RGAs), and actuators to support system operations. The TVAC control architecture is based on commercially available hardware and software suites. The platform has three banks of Input/Output (I/O) Modules with associated expansion cables. The control software is a combination of ladder logic, structured text, and function block diagrams which were developed using a commercially available development environment.

The PLC controller, shown in Figure 1, offers state-of-the-art control, communication, and I/O capability in a compact control package. The PLC provides a flexible control system by incorporating multiple control technologies in a single chassis and by allowing future system upgrades by simply adding control modules. An OIT provides basic operator interface to the controller (see Figure 1). Basic system functions are available from this touch screen which allows operation of system components at the PLC cabinet. The OIT is primarily used for system calibration, troubleshooting, and basic system configuration. Normal operation of the system is performed at the OCS shown in Figure 2. This remote interface allows for touch screen operation of sub-systems and components using a Windows based layout. The PLC software also enables enhanced user definable data logging and trending features.

Process Control Valves

In conjunction with the updates to the PLC, the systems were retrofitted with position controlled valves to improve process control. The original equipment configuration did not implement any means of isolating the high vacuum pumps from the chamber volume. Also, previous testing evolutions (evacuation and backfill) were performed by manually manipulating various ball valves to provide flow control. In both of these cases, significant improvements were obtained by reconfiguring the sub-systems with contemporary valve technology.

Vacuum rated isolation valves were installed for both the turbo-molecular pump as well as the cryopump. For the turbo-molecular pump, a 200 mm (8 in.) high through put gate valve was installed to maximize the effective opening to the chamber atmosphere thus improving pumping speed. The gate valve is a high vacuum rated valve with a double acting pneumatic actuator.

A 508 mm (20 in.) pendulum valve acts as the isolation valve for the cryopump. This valve provides a compact profile when mounting while ensuring maximum through put to the cryopump cold head. A 3-position double acting pneumatic actuator also enables limited process control during pump down of the chamber. In both cases, the valves incorporate position sensors which enable automation using the PLC interface.

Butterfly valves with a sealing function were selected to replace legacy manual ball valves for pump down and backfill flow control. These valves afford downstream pressure and flow control as well as isolation functionality. The butterfly valves are fast acting and provide a local digital display that gives the valve status and position as well as integration into the PLC software by means of an RS-485 interface. Through this interface, it is possible to position the valve at the discretion of the operator or enable the PLC automation features to quickly and accurately control the chamber pressure and flow rate based on user defined pump down/backfill parameters.

Chamber Pressure Sensors

Given the age of the equipment transferred from the Mound facility, significant advances in pressure gauge technology could be reasonably integrated into the control systems. Thermocouple (TC) style and nude Bayard-Alpert (B-A) ionization gauges accounted for the majority of vacuum sensors on the legacy equipment. Following thorough discussion and performance testing of various sensors, a combination of sensors were selected to provide accurate pressure feedback from the system over the full gamut of TVAC pressures while communicating real time process variables to the PLC.

Due to the wide range of working pressures (atmosphere to 1×10^{-8} Torr) within the chamber, two separate "dual" technology transducers provide atmospheric to high vacuum monitoring. The first transducer uses a combination of MicroPirani sensor element and Absolute Piezo sensor. The MicroPirani consists of a silicon chip with a heated resistive element, while the Piezo sensor is based on measurement of the mechanical deflection of a silicon membrane relative to an integrated reference vacuum thus resulting in a true absolute pressure independent of gas composition. The second sensor utilizes a crystal sensor, which is a tuning-fork shaped quartz oscillator, at atmospheric pressures to roughly 1×10^{-4} Torr. For higher vacuum measurements, the sensor employs a double inverted magnetron cold cathode sensor. This sensor ionizes the residual gases in a magnetron discharge. The body of the sensor serves as the cathode and is maintained at ground potential. While this sensor is sensitive to gas species, there is no element to burn out which allows for operation at higher pressures.

A hot cathode sensor of the B-A style is used for high vacuum measurements. This sensor utilizes a fine wire collector with two yttria-coated iridium filaments for extended service life. The sensor is capable of measurements over a wide range, 10^{-2} to 10^{-10} Torr. For normal TVAC operations, the sensor is selected when chamber pressures are in the 10^{-5} Torr range. Digital communication (RS-485) allows for all adjustments and real-time monitoring to be accomplished via the PLC. To ensure accurate pressure measurement, the sensor also incorporates a degas function that operates without interrupting pressure measurement.

HIGH VACUUM PUMP TECHNOLOGY

Chamber Volume

The thermal vacuum chambers housed in SSPSF are cylindrical chambers approximately 1.8 m (6 ft) in diameter and 2.7 m (9 ft) in length. In addition to the cylindrical portion of the chamber, there is a large elbow that allows for evacuation equipment mounting. Given the cylindrical chamber and elbow layout described above, the total system volume is estimated at 9,279 L (328 ft^3). A photograph of the Rm-111 chamber is shown in Figure 3.

Emissive Coatings

Each RPS unit is painted with a special emissive coating which minimizes the heat rejection temperature of the RPS. In addition to the paint applied to the RPS unit, the internal surfaces of the chambers are painted with an emissive coating as well to improve the radiative heat transfer between the RPS unit and the chamber wall during testing operations. Both of these surfaces are highly susceptible to contamination which would limit their effectiveness. Concern for the back streaming of diffusion pump oil to these surfaces was a key driver for implementing the use of turbo-molecular and cryopump technologies.

Legacy Pump Technology

The original pumping equipment installed on the thermal vacuum chambers included various pumping technologies. Dual rotary piston pumps provided the basic pumping capacity for the chambers. One dual stage rotary piston pump was used as a roughing pump for the initial pump down of the chamber from atmospheric conditions. To establish a high vacuum atmosphere, the systems utilized dual diffusion pumps. The first diffusion pump was a 500 mm (20 in.) pump that was mounted to the elbow of the chamber. An additional 152 mm (6 in.) booster pump attached to the outlet of the main chamber diffusion pump to increase capacity. The second rotary piston pump was a single stage unit that provided the backing pump function for the diffusion pumps.

This combination of pumps provided a robust solution for evacuation of the chambers but due to the nature of the diffusion pumps, there was substantial concern of back streaming diffusion pump oil into the chamber. Ultimately, the diffusion pumps were replaced with new pumps which would integrate into the new control system and reduce the probability of oil back streaming into the chamber atmosphere.

Cryopump

A large diameter cryopump system was installed on the chamber elbow in place of the diffusion pumps. The cryopump has a 525 mm (20.7 in.) diameter body and a pumping speed of 10,000 L/s (2641 gal/s) Air. This unit provides equivalent pumping capacity to the diffusion pumps with the added benefit of pump isolation from the chamber volume by means of the pendulum valve as well as no possibility of back streaming pump oil. Modifications to auxiliary equipment associated with the TVAC systems enable cryopump regeneration during normal operations to minimize transition periods.

Turbo-molecular Pump

A 254 mm (10 in.) turbo-molecular pump is mounted to an instrumentation flange on the top of the chamber. The turbo-molecular pump provides a pumping speed of 1250 L/s (330 gal/s) gaseous nitrogen; while significantly minimizing the possibility of back streaming pump oil into the chamber atmosphere. While the turbo-molecular pump is capable of evacuating the chamber volume, its main purpose is to support the cryopump by evacuating gas species that are difficult to condense with the cryopump. During cryopump regeneration, the turbo-molecular pump is also capable of maintaining an acceptable vacuum level for testing. The backing pump for the turbo-molecular pump is a multi-stage roots vacuum pump. This pump is a near frictionless pumping module which is optimized for operation without internal lubricant thus ensuring a clean atmosphere in the turbo-molecular pump foreline.

CHAMBER THERMAL SHROUD

The legacy method of cooling the TVAC's and providing a thermal sink for radiative heat transfer was by means of chill pads mounted to the external surfaces of the chamber. This method limits the minimum sink temperature to approximately 7 °C (45 °F) due to the operating temperatures of the SSPSF facility chill water system. Historically, RPS units could be tested at the chill water heat rejection temperature and then analytically corrected reliably since static RPS units power output is material property dependent. However, emergent customer needs necessitated thermal sink temperatures between -185 to 110 °C (-300 to 230 °F). Given this significant change in operating temperature requirements (including heating), a thermal shroud system was designed and installed in the Rm-112 TVAC. This shroud system also enables dynamic RPS units to fully realize their power potential where the Carnot efficiency is absolute temperature dependent.

Thermal System Layout

The main TVAC shroud is a cylindrical shroud with a louvered end plate which rests on the internal surface of the TVAC. This cylindrical shroud is shown during the installation process in Figure 4 and installed in Figure 5. In conjunction with the cylindrical shroud, there is a circular shroud that is mounted to the door of the TVAC which results in a thermal envelope that is cylindrical with end caps. Each of the shroud components is connected to the cooling/heating system by means of vacuum jacketed flex lines which allow for operation of the TVAC door and also alleviate seismic concerns regarding the piping system. Each of the shrouds has multiple Resistance Temperature Detectors (RTDs) to provide temperature feedback to the PLC.

Thermal Conditioning Unit

To ensure the necessary shroud operating temperatures, a Thermal Conditioning Unit (TCU) is used to both cool and heat the system (see Figure 6). The working media for the thermal system is gaseous nitrogen (N_2). During the cooling process, liquid nitrogen (LN_2) is injected into the N_2 flow that is recirculated through the shrouds and their associated piping by means of a blower. The TCU will continue to inject LN_2 based on pressure, density and temperature feedback until the temperature set point is obtained. TCU functionality ensures that the flow remains gaseous so that LN_2 does not build up within the shroud lines. When an operating temperature above ambient is required, a 21 kW heater located within the N_2 flow path is used to heat the gas stream. TCU operation is based on operator input at the OIT where they have the ability to select a thermal sink set point as well as the blower speed to help minimize LN_2 consumption.

SUMMARY

Renovations performed on the thermal vacuum atmosphere chambers in SSPSF have resulted in improved system control through the use of a PLC while mitigating potential risk to mission objectives by using a turbo-molecular and cryopump to minimize oil back streaming. The addition of thermal shrouds and a thermal conditioning unit to the Rm-112 TVAC will ensure the RPS program is prepared to meet thermal testing requirements associated with evolving RPS designs. Ultimately, the modifications to the TVAC systems maintain and enhance the RPS programs unique ability to fuel and test RPS units at Idaho National Laboratory in support of NASA missions.

ABBREVIATIONS

B-A	Bayard-Alpert ionization gauge
°C	degrees Celsius
°F	degrees Fahrenheit
ft	feet
ft^3	cubic foot
gal	gallon
INL	Idaho National Laboratory
in.	inch
I/O	Input/Output
kW	kilowatt
L	liter
LN_2	Liquid Nitrogen
m	meter
mm	millimeter
MFC	Materials and Fuels Complex
N_2	Nitrogen gas
NASA	National Aeronautics and Space Administration
OCS	Operator Control Station
OIT	Operator Interface Terminal
PLC	Programmable Logic Controller
RGA	Residual Gas Analyzer
RPS	Radioisotope Power Systems
RTD	Resistance Temperature Detector
s	second
SSPSF	Space and Security Power Systems Facility
TC	Thermocouple
TCU	Thermal Conditioning Unit
Torr	torr
TVAC	Thermal Vacuum Atmosphere Chamber

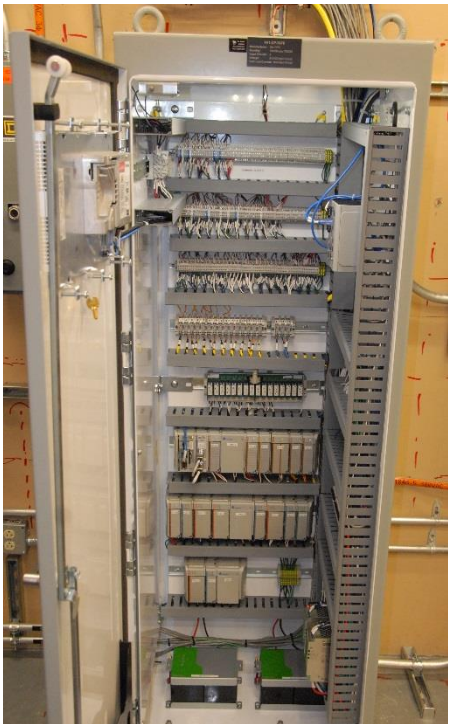


Figure 1, TVAC System PLC/OIT

Figure 2, TVAC System OCS

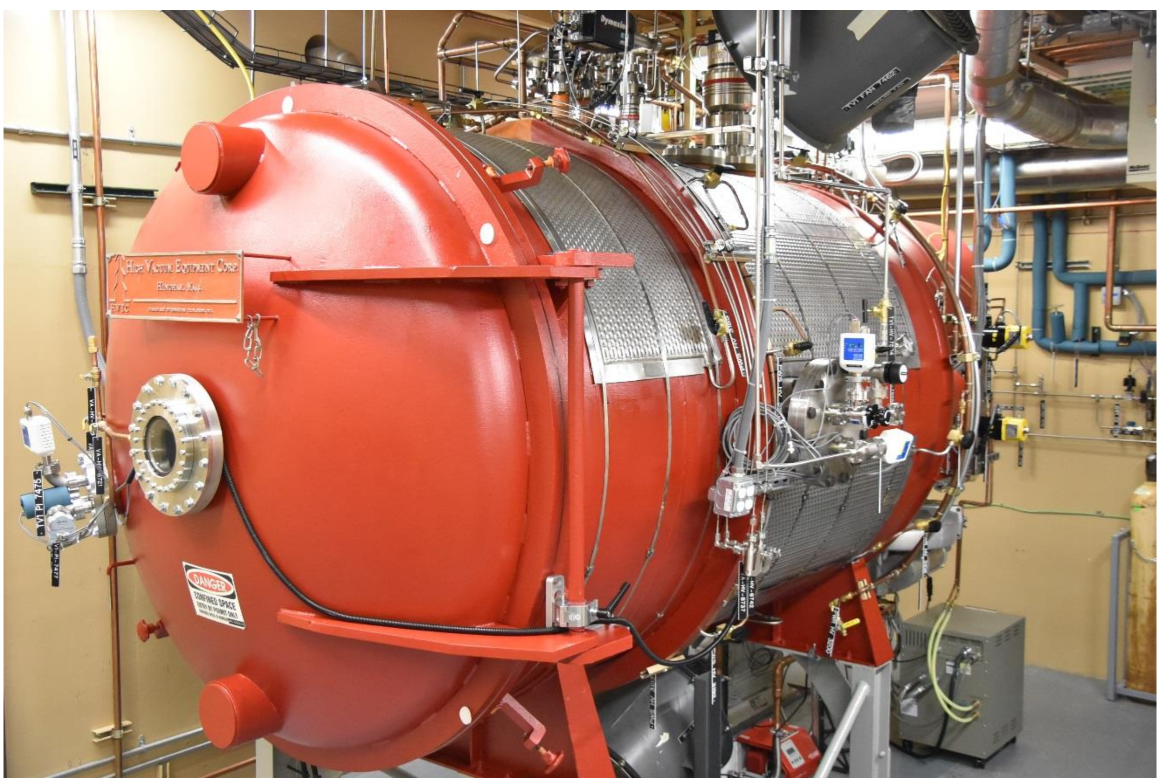


Figure 3, Rm-111 TVAC System

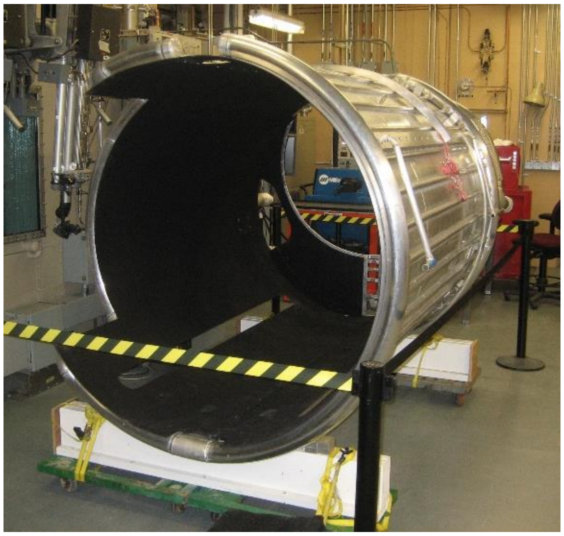


Figure 4, Rm-112 TVAC Thermal Shroud

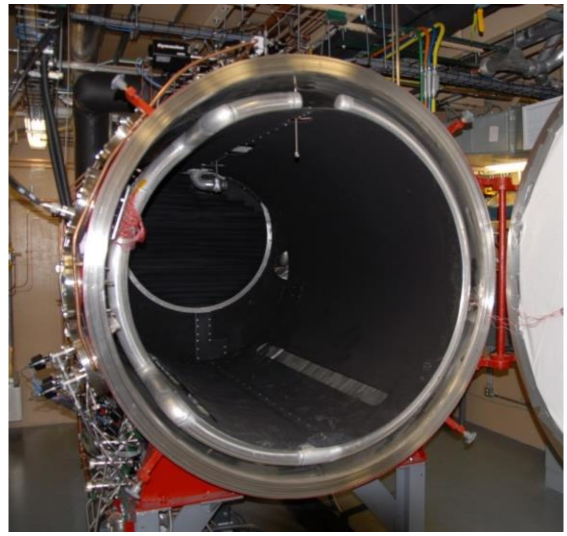
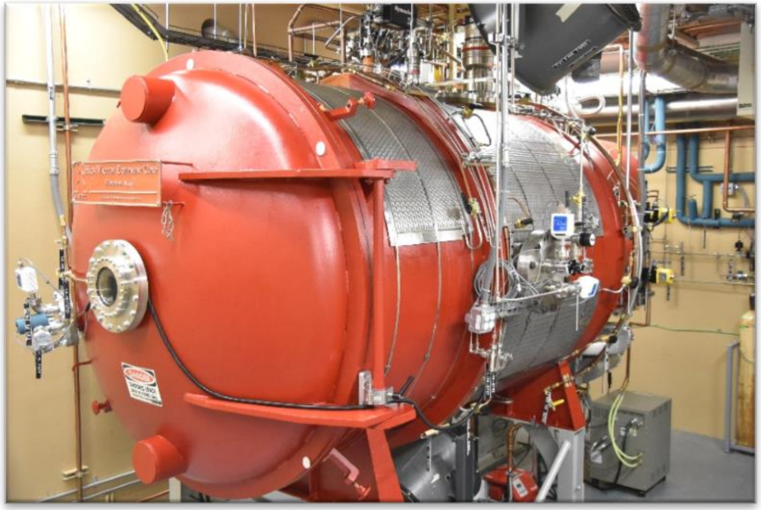


Figure 5, Thermal Shroud Installed

Figure 6, Thermal Conditioning Unit (TCU)

Renovation of Thermal Vacuum Chambers at Idaho National Laboratory for Testing of Radioisotope Power Systems

Jaymon Birch
INL RPS Thermal Vacuum
Subject Matter Expert



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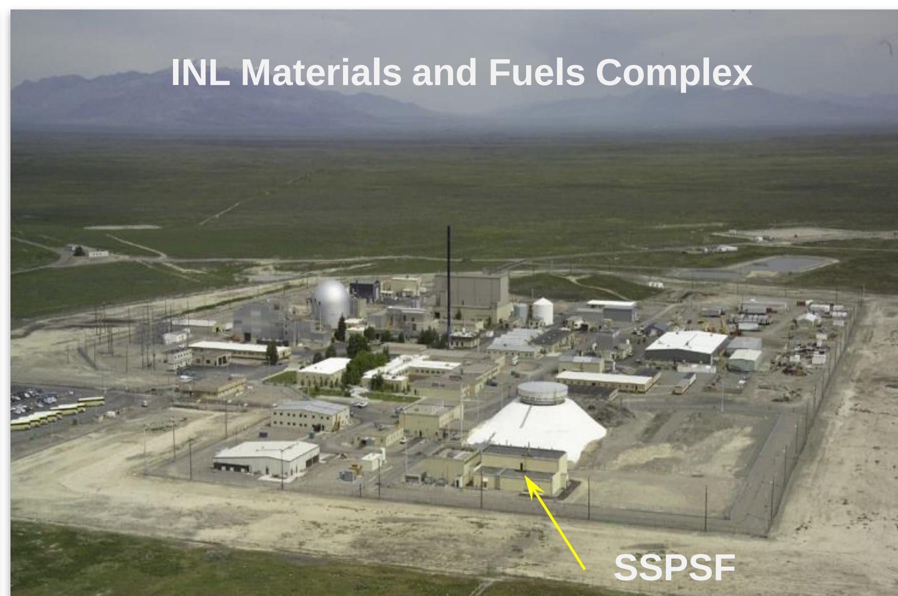
INL RPS Mission

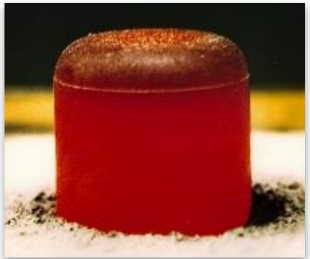
The Radioisotope Power Systems (RPS) Program is responsible for the fueling and testing of RPSs in the Space and Security Power System Facility (SSPSF) at the Material and Fuels Complex (MFC) at Idaho National Laboratory (INL).

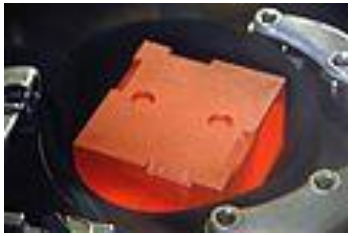
- One of a network of 17 DOE national labs
- INL is DOE’s lead lab for nuclear energy

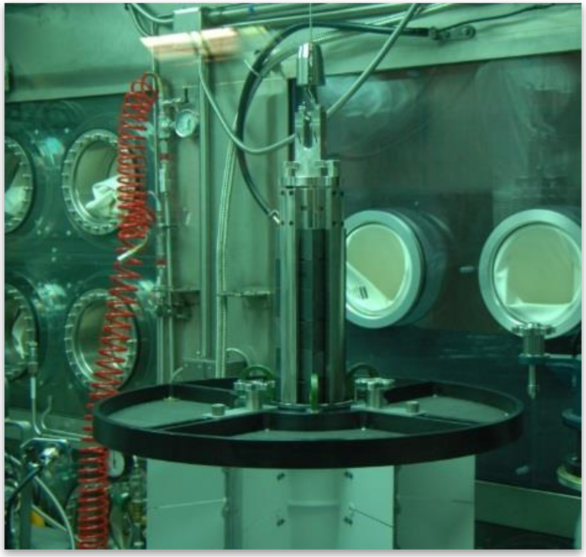


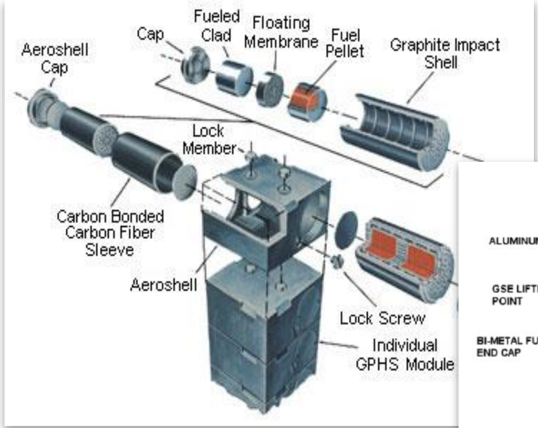
INL RPS Fueling

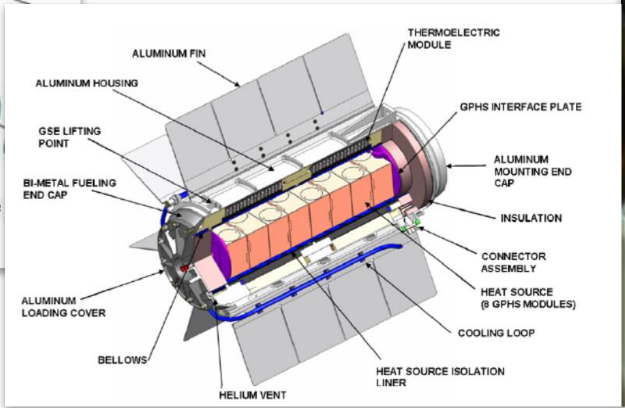
- Plutonium-238 is the material of choice for fueling RPS units.
- Through natural radioactive decay Pu-238 emits steady heat .
- The heat generated by Pu-238 has produced electrical power for over two-dozen U.S. space missions that have been powered by radioisotope power systems (RPS).





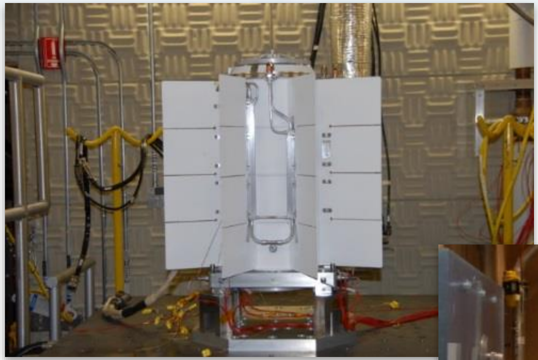


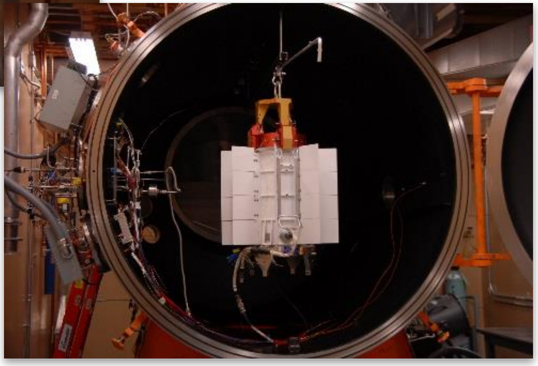




INL RPS Testing

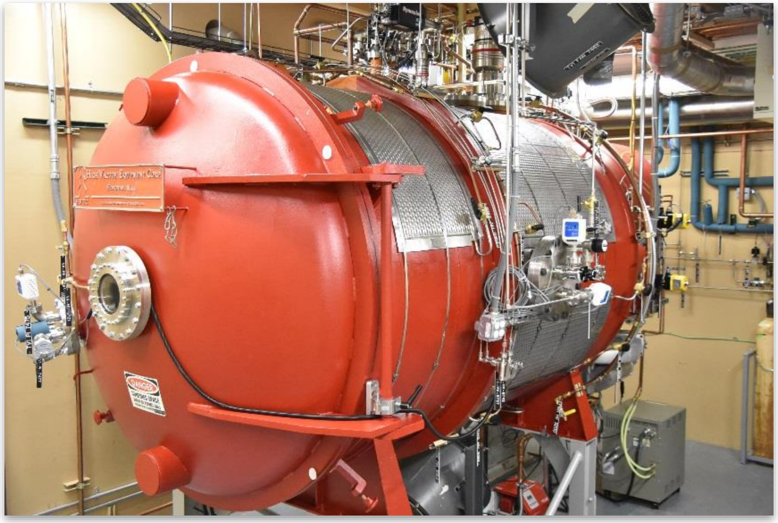
- RPS testing quantifies various unit characteristics to ensure successful integration to the spacecraft.
- RPS Testing Stations:
  - Vibration
    - Dynamic testing of a fueled RPS for launch and landing conditions
  - Magnetics
    - Establish magnetic characteristics to determine impact on spacecraft components and signals
  - Mass Properties
    - Determine overall mass, CG and moment of inertia
  - Thermal Vacuum
    - Test the RPS power output performance in a simulated space environment



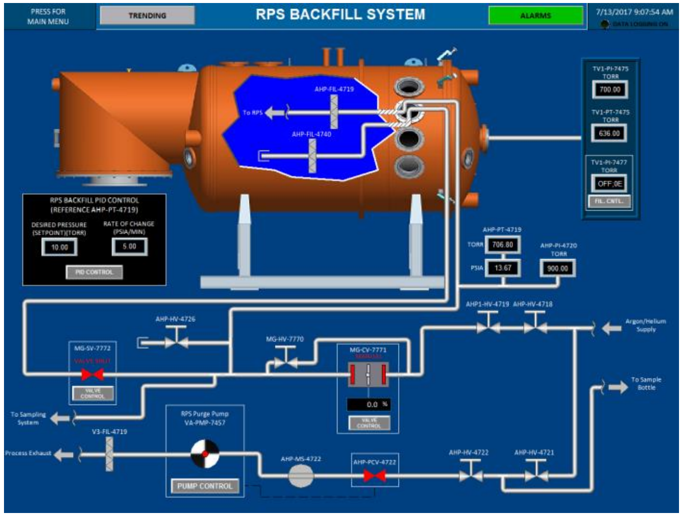
TVAC System Renovations

- RPS program maintains two TVAC systems in SSPSF (Rm-111 and Rm-112)
  - TVAC testing pressures $< 1x10^{-5}$ Torr
  - Enables radiative heat transfer
- Renovations to the RPS program TVAC's began in 2011 and were completed in 2017
- <u>Key Areas of Renovation</u>:
  1. Process Control
  2. High Vacuum Pump Technology
  3. Thermal Conditioning Capability



Process Control Upgrades

- Legacy Equipment
  - Solid state controls and relays
  - Basic manual operation
- Installed New Programmable Logic Controller
  - I/O Modules housed in an Operator Interface Terminal (OIT)
  - Operator Control Station (OCS)
  - Provides the ability to semi-automate evacuation and backfill processes
  - Both the OIT and OCS are touch screen enabled



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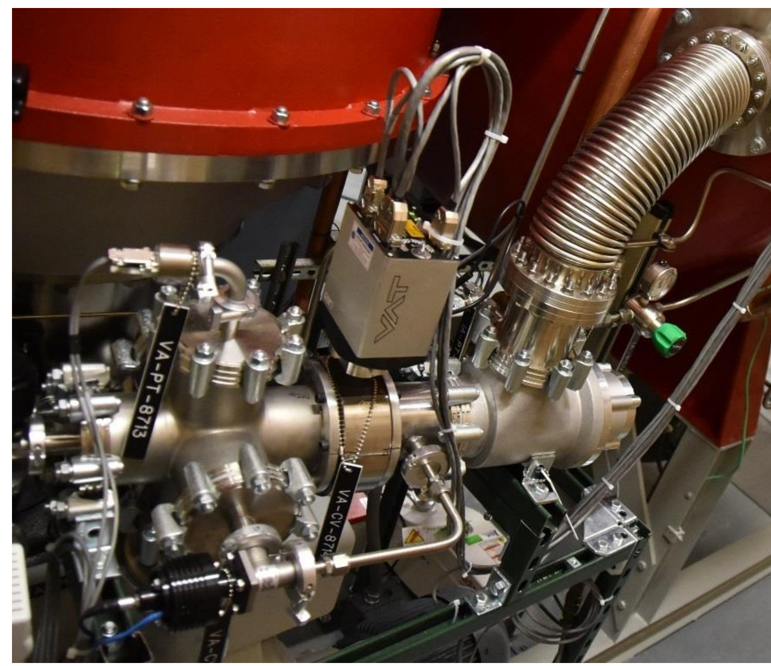
Process Control Upgrades

- <u>Process Control Valves</u>
  - Gate Valve
    - Isolation for the turbo-molecular pump
  - Pendulum Valve
    - Isolation for the cryo-pump
  - Butterfly Valves
    - Evacuation and backfill flow control

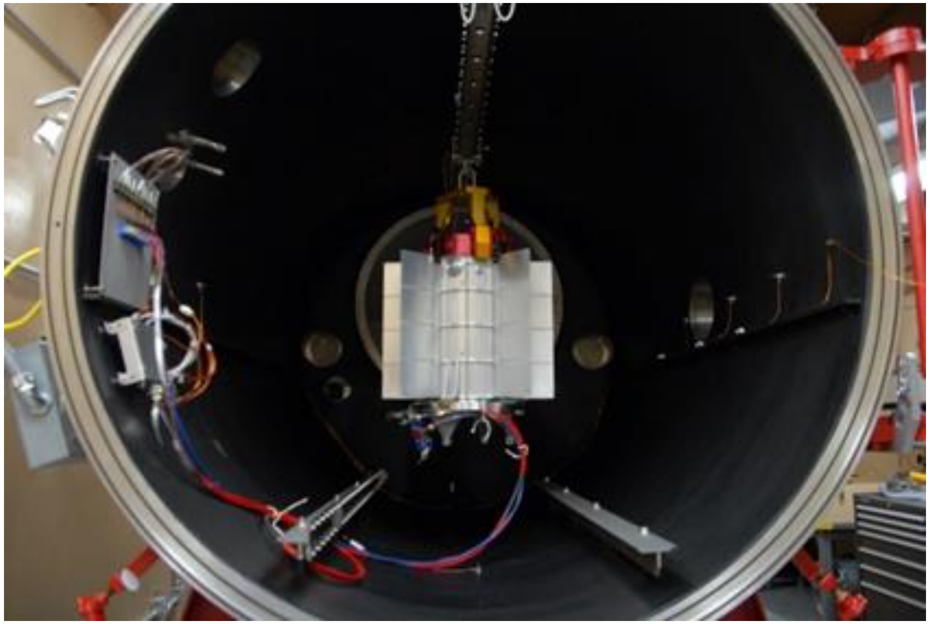


Process Control Upgrades

- Chamber Pressure Sensors
  - MicroPirani/Piezo Sensor
    - Range: Atmosphere to 10^{-4} Torr
  - Wide Range Sensor
    - Crystal Sensor/Cold Cathode
    - Range: Atmosphere to 10^{-7} Torr
  - Hot Cathode Sensor
    - Nude Bayard-Alpert ion gauge
    - Range: 10^{-2} to 10^{-9} Torr

High Vacuum Pump Technology

- Emissive Coating Concerns:
  - RPS unit painted with emissive coating to minimize the heat rejection temperature
  - Chamber coated to aid in radiative heat transfer. Emissivity approx. 0.8
  - Surfaces are sensitive to contamination
  - Updated pumping technology reduce risk



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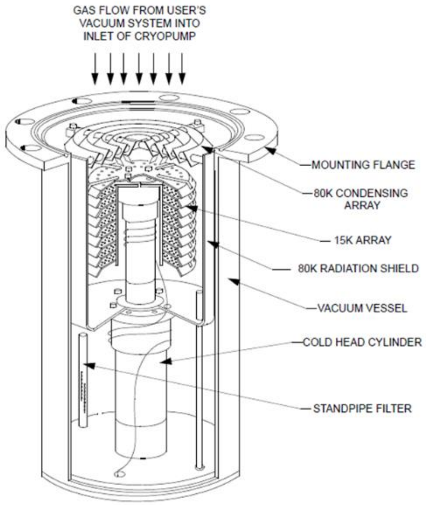
High Vacuum Pump Technology

- Legacy Pump Technology
  - Diffusion Pumps
    - 500mm and 150mm booster
  - No chamber isolation device
    - Possible oil back streaming

High Vacuum Pump Technology

- Cryopump
  - 525mm body
    - 10,000 L/s Air pumping speed
  - Chamber isolation provided by large pendulum valve
  - No moving parts
  - 80 K and 15 K condensing arrays
  - Regeneration system

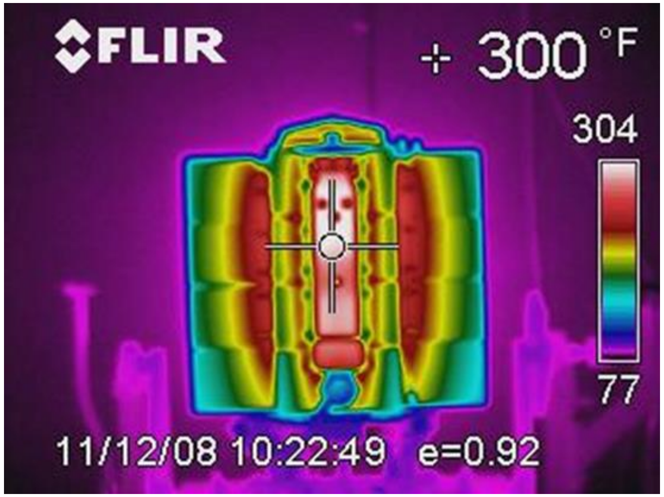


High Vacuum Pump Technology

- Turbo-molecular Pump
  - 250mm diameter body
    - 1250 L/s pumping speed (Nitrogen)
  - Maintains vacuum during cryo-pump regeneration
    - Evacuates non-condensable gases with reduced pumping speed
  - Multi-stage roots pump acts as backing pump
    - No lubricant to backstream

Chamber Thermal Shroud

- Legacy Cooling Method
  - Chill pads with convective cooling fans
    - Limited to approximately 7 ºC due to the operating temperature of the process chill water system in SSPSF
  - Historically, RPS unit power output was analytically corrected for specific temperatures since the power output was material property dependent

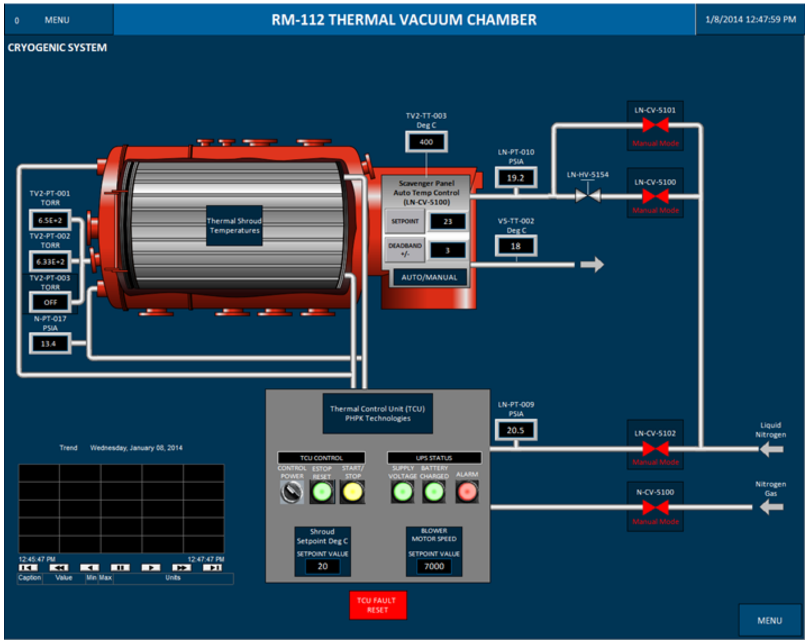


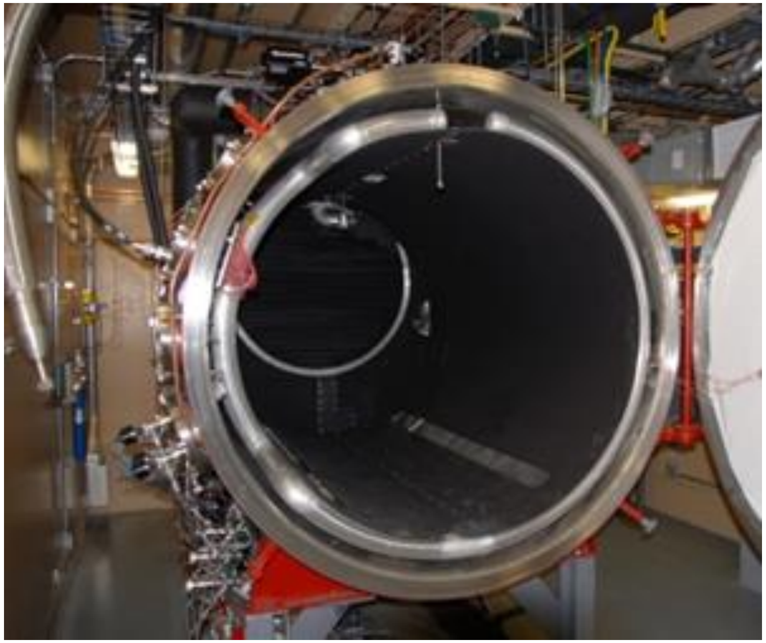
Chamber Thermal Shroud

- Rm-112 Cooling System
  - Thermal Conditioning Unit (TCU)
  - Thermal sink temperature range: -185 to 110 ºC
  - Gaseous nitrogen flow
    - Cooling accomplished with LN_2
    - 21 kW heater for shroud temperatures above ambient
  - TCU controls fully integrated into TVAC control system

Chamber Thermal Shroud

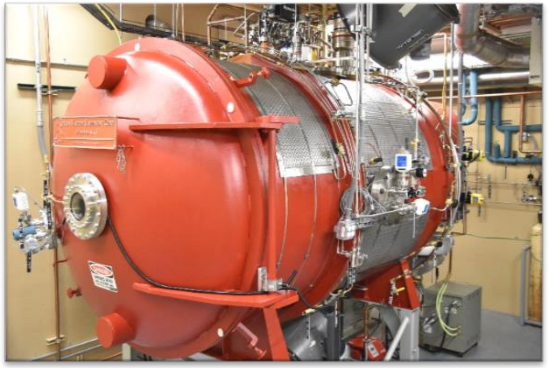
- Rm-112 thermal shrouds
  - Cylindrical main shroud with a circular door disk shroud
  - An optically dark louvered end plate enables radiative heat transfer while retaining high conductance to the cryo-pump
  - Emissive coating for improved heat transfer
  - RTD temperature sensors provide shroud temperature feedback to the control system

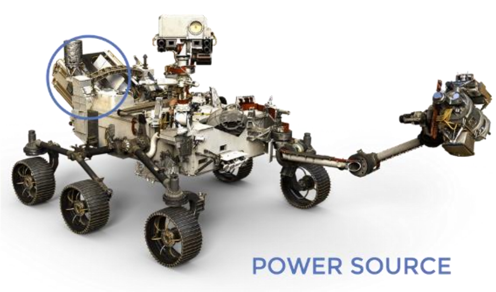


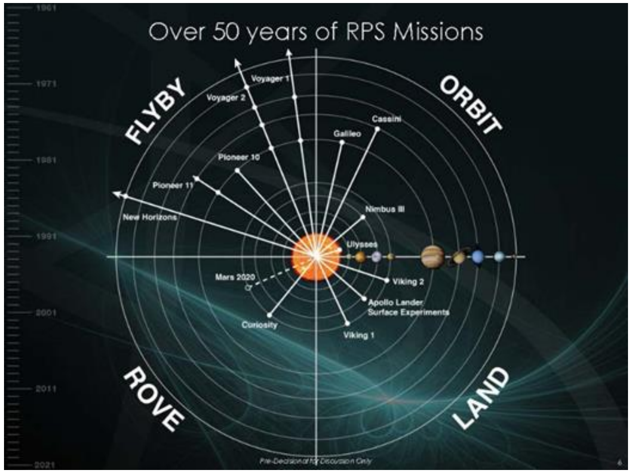


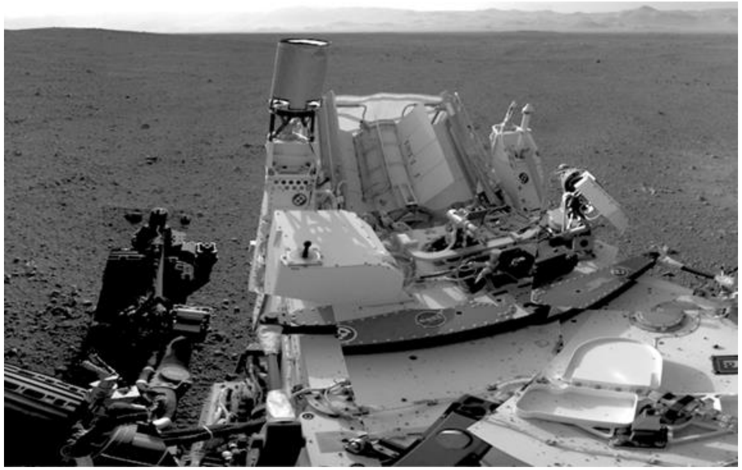
Summary

- The renovations to the TVAC systems maintain and enhance the RPS programs unique ability to fuel and test RPS units at Idaho National Laboratory in support of NASA missions.









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