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LWRHU User's Guide

July 2022

Changing the World's Energy Future

Andrew John Zillmer, Amanda E Gates

Idaho National Laboratory

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Revision 2

Light Weight Radioisotope Heater Unit User's Guide

July 2022

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SUMMARY

The production of radioisotope heater units has been an ongoing endeavor for the U.S. Department of Energy (DOE) and its predecessor agencies for the past six decades. The overall mission of the Radioisotope Power System (RPS) program is to develop, demonstrate, and deliver compact, safe nuclear power systems and related technologies for use in remote, harsh environments (e.g., space) where more conventional electrical power sources aren't sufficient.

This user's guide provides an overview of Light Weight Radioisotope Heater Units (LWRHU), including aspects of its physical design and performance under normal operations. This guide also identifies the planning and execution involved in launching a nuclear payload. Physical characteristics, interfaces, and environmental characteristics of the LWRHU are discussed in detail. Information relating to project management interfaces and effort are also addressed

This document:

- Provides a general description of the physical characteristics, system interfaces, and performance characteristics of the LWRHU.
- Provides to the mission proposer sufficient detail on the LWRHU and an understanding of the interfaces and support needed to utilize in a NASA RHU enabled mission.

The information in this user's guide should help organizations proposing the use of a LWRHU to prepare a sound handling, costing, and integration narrative.

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ACRONYMS

AO	Announcement of Opportunity
ARC	Ames Research Center
BOM	Beginning of Mission
CAD	Computer Aided Design
CatEx	Categorical Exclusion
CDR	Critical Design Review
DOE	Department of Energy
DOPAA	Description of Proposed Actions and Alternatives
EA	Environmental Assessment
EIS	Environmental Impact Statement
ELV	Expendable Launch Vehicle
EMD	Environmental Management Division (NASA)
FONSI	Finding of No Significant Impact
FSAR	Final Safety Analysis Report
FWPF	Fine-Weave Pierced Fabric
GRC	Glenn Research Center
HNBK	Handbook
INL	Idaho National Laboratory
INSRB	Interagency Nuclear Safety Review Board
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LV	Launch Vehicle
LWRHU	Light Weight Radioisotope Heater Unit
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NPR	NASA Procedural Requirements
NSPM	National Security Presidential Memorandum
ORNL	Oak Ridge National Laboratory
PDR	Preliminary Design Review
PE	Program Executive

PG	Pyrolytic Graphite
RHU	Radioisotope Heater Unit
ROD	Record of Decision
RPS	Radioisotope Power System
SAR	Safety Analysis Report
SDS	Safety Design Strategy
SER	Safety Evaluation Report
SNS	Space Nuclear System
TED	Total Effective Dose

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Light Weight Radioisotope Heater Unit User's Guide

1. SCOPE

The purpose of this document is to establish a user's guide to:

- Provide a general description of the physical characteristics and system interfaces of the Light Weight Radioisotope Heater Unit (LWRHU)
- Describe the physical and analytical models available to a mission design team
- Identify the planning and execution involved in launching a nuclear payload, including National Environmental Policy Act (NEPA) activities.

This guide is a reference document for organizations preparing responses to the National Aeronautics and Space Administration's (NASA's) mission Announcement of Opportunity (AO) and the mission developer selected by that AO.

This guide provides the mission proposer sufficient detail on the LWRHU and an understanding of the interfaces and support needed to successfully launch a nuclear payload. The information in this user's guide should help the proposing organization prepare a sound handling, costing, and integration narrative. Additionally, the guide supports preliminary designs for hardware, processes, and procedures.

2. LWRHU OVERVIEW

The basic characteristics of an LWRHU, including the basic performance, weight, and dimension specifications, are listed in Table 1.

The LWRHU is designed to operate in planetary atmospheres and vacuum environments. While it is anticipated that performance in other atmospheres is enveloped by past mission use success on Mars and the vacuum of space, performance and material compatibility may need to be tested and understood for specific environments.

Table 1 LWRHU basic characteristics and requirements.

Parameter	LWRHU Value
Thermal output (BOM)	1.1 ± 0.03 watts
Mass (max)	42.00 grams
Plutonium oxide mass	2.66 ± 0.030 grams
Neutron emission	<7000 n/s-g Pu238
Surface temperature in free air	45C
Aeroshell ablation recession	50% (max)
Impact resistance on reentry (intact capsule)	49 m/s
Maximum dynamic loading	425G
Length	31.95 ± 0.05 mm
Diameter	25.95 ± 0.05 mm
Key: BOM = Beginning of Mission (at launch)	

2.1 RHU History

RHU(s) have been used on NASA missions since the initial lunar landing. The purpose of their design was to provide heat to keep spacecraft components and systems warm in harsh cold environments throughout space without moving parts or disrupting electronic components. RHU's can be allocated where needed on spacecrafts.

Since their initial use, the RHU has been modified several times. The first RHU produced 15 Watts of thermal power and was used on Apollo 11 in 1969. That further developed into a one-watt version used on the Pioneer and Voyager programs in the 1970s. This one-watt RHU was improved to produce the same wattage but at a smaller size than its predecessor thus becoming the LWRHU (first used for the Galileo orbiter and probe in 1989).

The missions to have used RHUs are:

- Apollo 11 – contained two 15 Watt RHUs
- Pioneer 10 – 12 RHUs
- Pioneer 11 – 12 RHUs
- Voyager 1 – 9 RHUs
- Voyager 2 – 9 RHUs
- Galileo – 120 LWRHUs (103 on orbiter, 17 on atmospheric probe)
- Mars Rover Sojourner Pathfinder – 3 LWRHUs
- Cassini – 117 LWRHUs (82 on orbiter, 35 on Huygens Titan probe)
- Mars Rover Spirit – 8 LWRHUs
- Mars Rover Opportunity – 8 LWRHUs

2.2 LWRHU Description and Major Components

The heat source of the LWRHU is one fuel pellet containing ≥ 80% 238PuO2 fuel pellet encapsulated in platinum-30 rhodium (Pt-30 Rh) alloy cladding. The cladding serves as the primary fuel containment. The clad contains a frit vent made up of a pressed and sintered disk of platinum powder. The frit vent is designed to allow for the escape of helium that is released over time from the natural decay of the plutonium dioxide fuel, thus avoiding clad distortion from excessive pressure build-up.

The fueled capsule is placed into an assembly of three concentric, cylindrical, pyrolytic graphite insulator (PG) sleeves of increasing diameter and capped at both ends. The insulators provide protection to the fueled capsule during a re-entry by diverting the flow of heat generated at the aeroshell surface around the fueled capsule and delay the flow of this heat directly into the capsule. Thus, the temperature of the platinum-rhodium alloy cladding is maintained safely below its melting temperature. The fueled capsule and pyrolytic graphite insulator bodies are contained within a cylindrical Fine-Weave Pierced Fabric (FWPF) aeroshell and secured in place with a FWPF threaded cap. The aeroshell is the primary structural component and provides protection for the fueled capsule during re-entry and launch accident events. The FWPF aeroshell cap is screwed into the body and locked in place with a two-component, carbonaceous, bonding cement. The LWRHU has an overall diameter of 25.95 ± 0.05-mm and a length of 31.95 ±

0.05-mm. A cross-section of the LWRHU is shown in Figure 1 and Figure 2 provides the expanded view.

Table 2 LWRHU Materials

ITEM	QTY REQ'D	Drawing Number
Fueled Capsule Assembly	1	Los Alamos National Laboratory 26Y-318191
PG Insulator, Inner	1	818914
PG Insulator, Middle	1	818913
PG Insulator, Outer	1	818912
PG Insulator, Cap	2	818911
FWPF Aeroshell, Body	1	818504
FWPF Aeroshell, Cap	1	818505

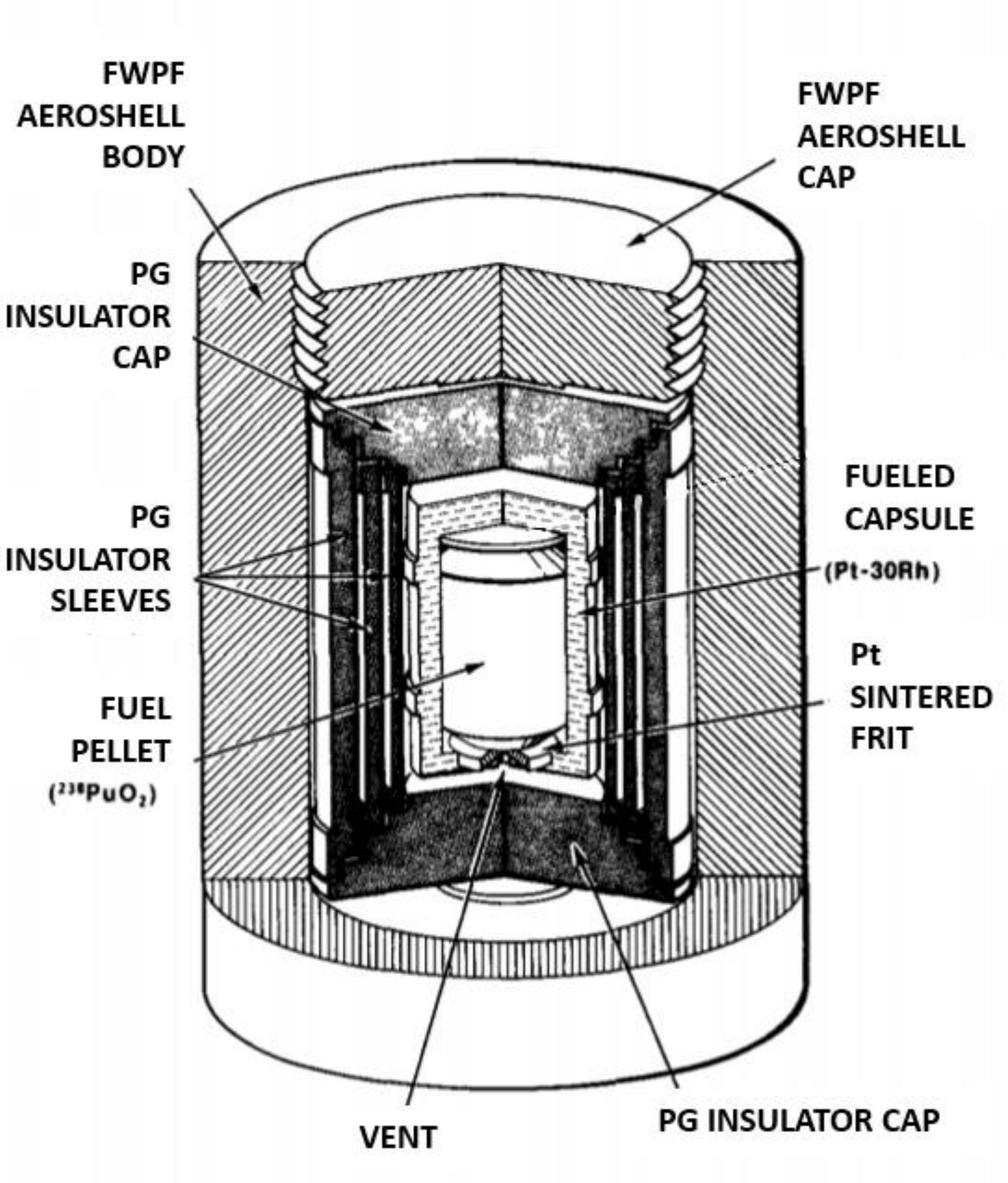


Figure 1. Cross Section Cut of LWRHU

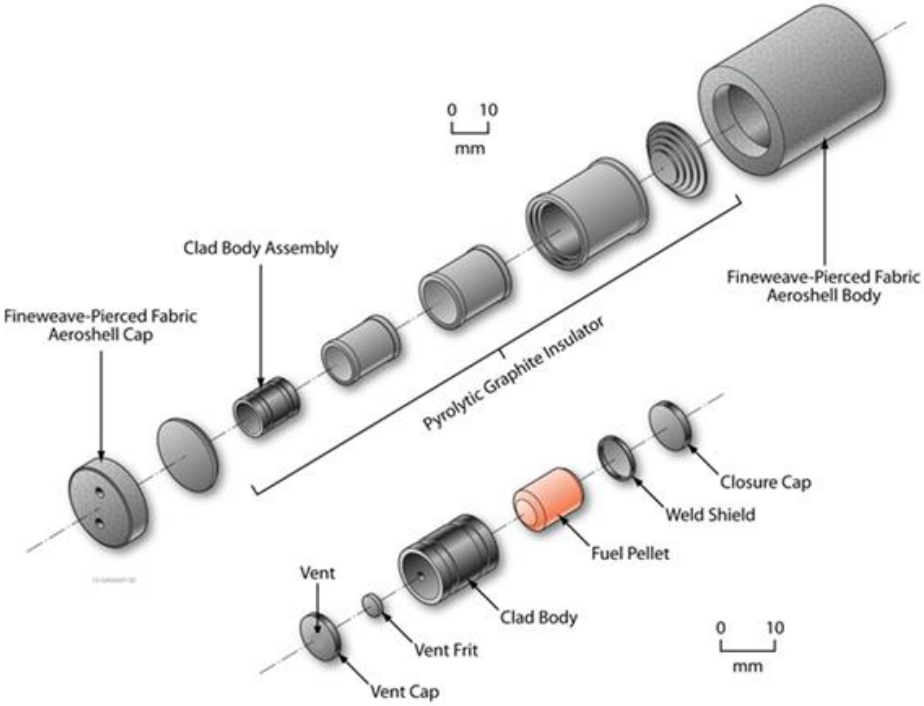


Figure 2. Expanded view of LWRHU.

2.3 System Considerations – Nominal Operations

There are operational considerations with the LWRHU. Once the LWRHU is fueled, it is thermally hot.

Integration occurs at Kennedy Space Center (KSC) to accommodate mission needs with the notion that security restrictions and oversight would be in place and must be considered once the LWRHUs are integrated to the spacecraft. The LWRHU was designed to operate either in a vacuum or an atmosphere of a planet. Testing completed and/or operation in air and Mars atmosphere have demonstrated combability with many known atmospheres in our solar system. However, some specific material compatibility testing may be needed depending on the mission environment.

The design of a spacecraft using an LWRHU must accommodate integration of the LWRHU(s). Integration configuration varies depending on mission. Additional information found in Section 3.2 “Interfaces”.

2.4 LWRHU Management

The detailed roles and responsibilities of individual agencies and groups will be delineated in an interfaceworking agreement prepared early in each project.

The nuclear launch process is established and has been successfully implemented on previous nuclear-enabled missions. Nuclear missions have added complexity that do not exist for typical NASA space-launch activities. Mission personnel should be aware of these additional activities when developing their overall plan (see Section 5.4 "Generic Notional Nuclear Launch Authorization Schedule").

2.5 Shipping the LWRHU

Upon completion of the fueling and testing sequence, the LWRHU is shipped to Kennedy Space Center (KSC) where there are two cask options: 9975 or 9516 shipping casks. The 9975 can hold up to 19 watts and is bolted for easy use. The 9516 can hold up to 500 watts and is a welded canister. The casks are transferred using a commercial dedicated transport. Typical pre-launch arrival times vary, but a period of 4 to 6 months prior to launch allows adequate time for testing and other pre-launch activities. Once the LWRHU arrives at KSC,the cask is unloaded.

2.6 Integration with Spacecraft

The LWRHU(s) are delivered and are stored either in a safe or at the Payload Hazardous Servicing Facility (PHSF) where spacecraft personnel integrate the fueled LWRHU(s) onto the spacecraft prior to encapsulation. LWRHU(s) are handled with terry cloth gloves.

Final checks will be made to ensure successful integration with the spacecraft and all systems are functioning as required. INL personnel will be responsible for nuclear material safety and security oversight at this point.

3. LWRHU CHARACTERISTICS

3.1 Physical Characteristics

The LWRHU has an overall diameter of 25.95 ± 0.05-mm and a length of 31.95 ± 0.05-mm.

3.1.1 Mass Properties from LWRHU

Table 3 below lists the mass properties of LWRHU.

Table 3. Mass properties of LWRHU.

Parameter		
Mass[a]	Max 42.00 grams	
Moments of inertia	Ixx	3.77 kg m^2
	Iyy	5.65 kg m^2
	Izz	5.65 kg m^2

3.1.2 Temperature of LWRHU

The anticipated surface temperature of a LWRHU in free air is 45°C.

3.2 Interfaces

The LWRHU has multiple interfaces that will be mission specific. These include:

- *Spacecraft interface*. Includes the mechanical and thermal interfaces with the unit (see Figure 3).
- *Space-environment interface*. Includes the space vacuum environment, radiation environment,thermal environment, and mission load environment.
- *Planetary-environment interface*. Includes the atmosphere, atmospheric pressure, radiation environment, thermal environment, and mission load environment.
- *Launch-vehicle interface*. Includes the atmosphere, atmospheric pressure, random vibration and quasi-static launch load environments, acoustic load environment, and thermal environment.
- *Ground Support Equipment*.

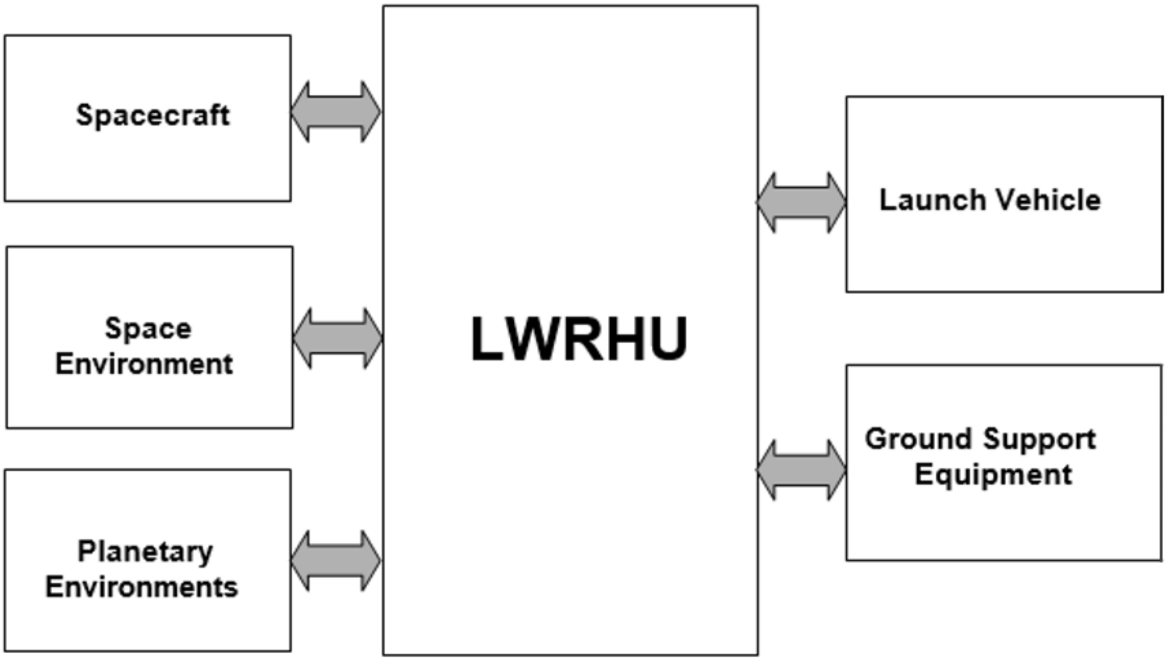


Figure 3. Spacecraft Interface.

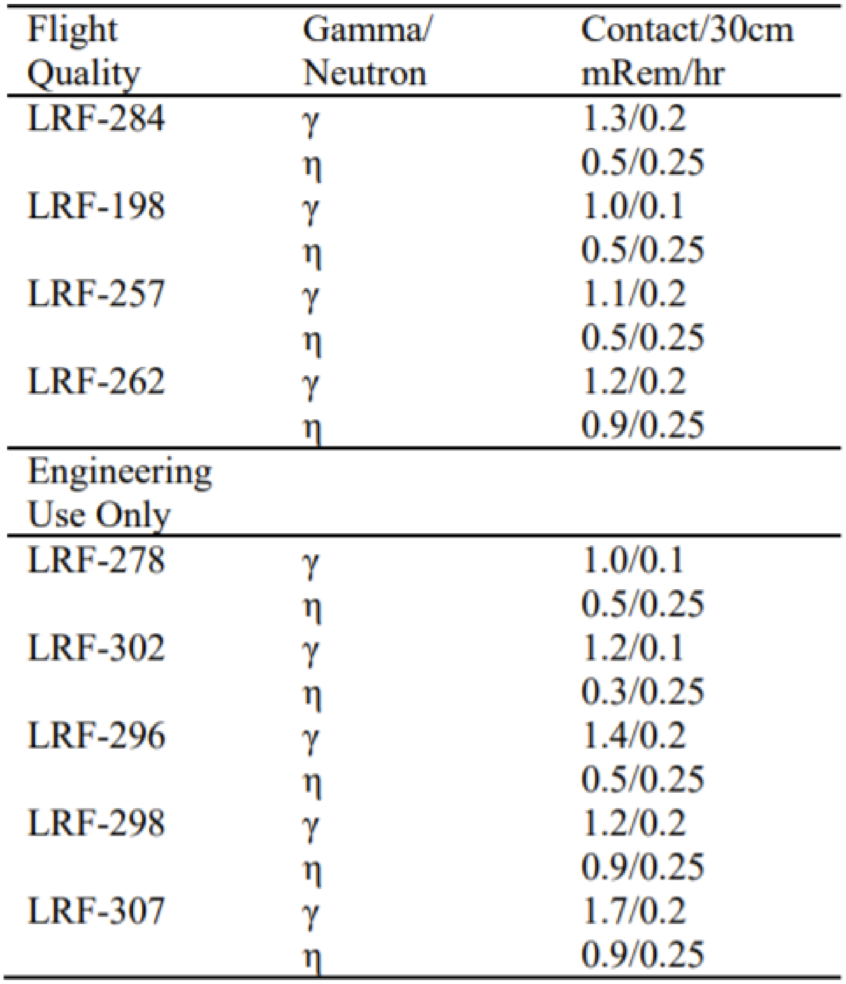
3.2.1 Mechanical Interfaces

Mounting of LWRHU on the spacecraft will be mission specific. DOE will be involved in approval of interface to ensure proper compliance.

3.2.2 Radiation Interfaces – Emission from the LWRHU

Contact dose readings for LWRHUs were measured from 24-year-old LWRHU's (shown in Table 4) and support engineering design activities. The ratio of gamma/neutron will vary based on the age of the Pu-238 and date of the last purification cycle. Gamma radiation emission peaks for Pu-238 about 17 years after fueling. The gamma values below are considered bounding. Neutron radiation emissions reduce with time and are considered bounding when the LWRHU is fueled. Neutron radiation emissions will be about 20% less 24 years after fueling.

Table 4. Dose readings of the LWRHUs.



Flight Quality	Gamma/ Neutron	Contact/30cm mRem/hr
LRF-284	γ	1.3/0.2
	η	0.5/0.25
LRF-198	γ	1.0/0.1
	η	0.5/0.25
LRF-257	γ	1.1/0.2
	η	0.5/0.25
LRF-262	γ	1.2/0.2
	η	0.9/0.25
Engineering Use Only		
LRF-278	γ	1.0/0.1
	η	0.5/0.25
LRF-302	γ	1.2/0.1
	η	0.3/0.25
LRF-296	γ	1.4/0.2
	η	0.5/0.25
LRF-298	γ	1.2/0.2
	η	0.9/0.25
LRF-307	γ	1.7/0.2
	η	0.9/0.25

3.2.3 Ground Support Equipment Interfaces

3.2.3.1 Orientation

The LWRHU can be orientated in any way to accommodate the measurement fixtures,transportation container, and vehicle requirements.

3.3 Environmental Characteristics

The foundational basis for the LWRHU was the Galileo mission where the LWRHU was designed to withstand the loading given in the requirements of that mission. All other missions have been based off Galileo, including Cassini.

3.3.1 Mission Environments

3.3.1.1 Vibration Requirements and Analysis

Two LWRHUs (fueled with depleted uranium oxide) were subjected to vibration testing, followed by impact testing at progressively higher impact velocities. Vibration testing (random and sinusoidal) was performed at Mound – the results did not indicate apparent degradation of the graphite components or the capsule cladding.

The enveloped specification for the Galileo Orbiter (Jet Propulsion Laboratory [JPL]) and the Galileo Probe (Ames Research Center [ARC]) are illustrated in two accompanying figures: Figure 4 shows a plot of the acceleration spectral density vs frequency (random mode), and Figure 5 shows a plot of the peak acceleration vs frequency (sinusoidal mode). In both cases, two levels are shown, a flight acceptance level, which is the vibration level anticipated in actual use, and the type acceptance level, which is a 50% over test to qualify the design.

3.3.1.2 Impact Testing

Information on impact testing is provided in table 6.

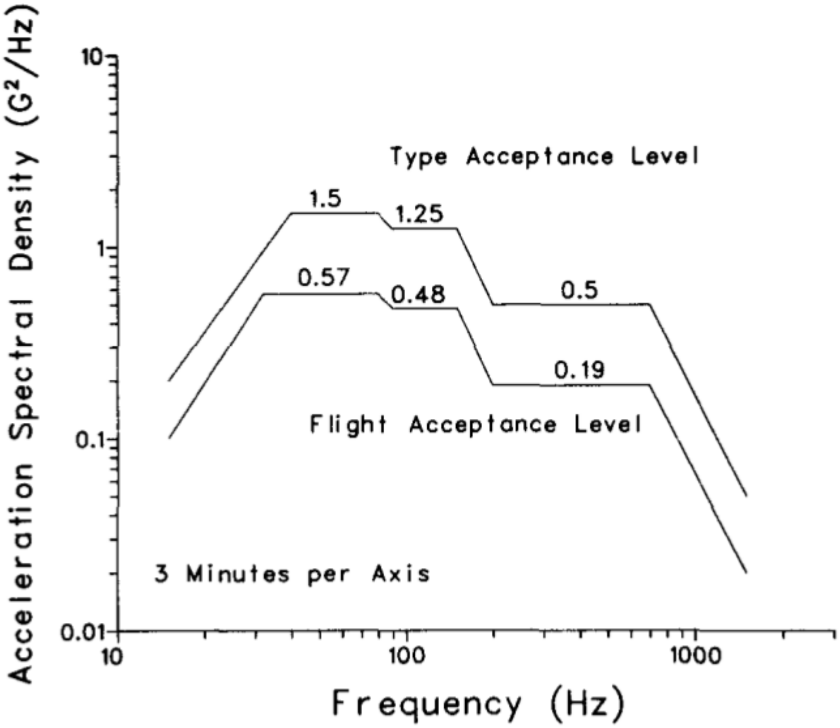


Figure 4. Random mode vibration environment for the LWRHU.

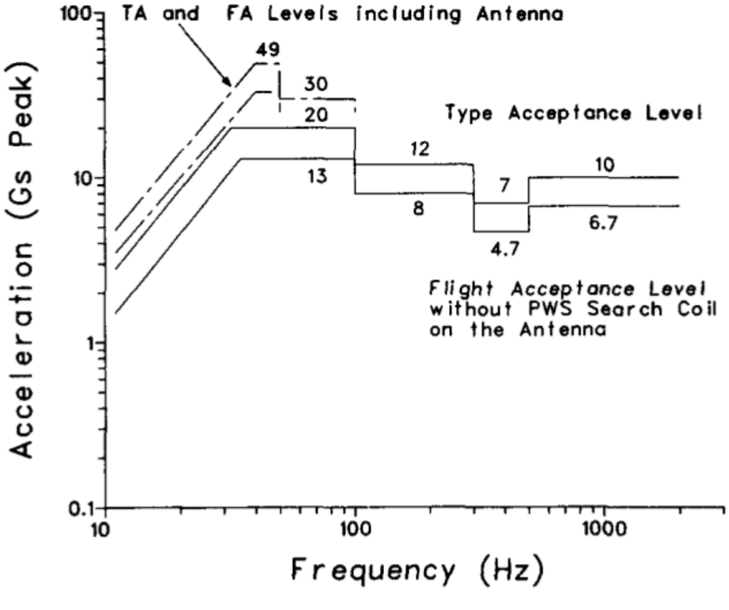


Figure 5. Sinusoidal Mode Vibration Environment for the LWRHU.

Table 5 below shows the individual part weights and weight losses from vibration testing. The stand-off rings were still quite visible and functional after exposure to the higher-level vibration environment.

Table 5. Pyrolytic graphite insulator weight losses in vibration tests

	Flight Acceptance Level		Type Acceptance Level	
	Part Weight (g)	Loss (mg)	Part Weight (g)	Loss (mg)
Rings Four Step Cap				
Top cap	1.2904	1.2	1.2862	1.7
Outer body	3.1008	0.4	3.0058	1.2
Middle body	1.4301	0.2	1.4142	0.7
Inner body	0.5783	0.8	0.6028	1.6
Bottom cap	1.2868	0.8	1.2983	1.9
Total Loss		3.4		7.1
Tubes With Rings Three Step Cap				
Top cap	1.2091	1.0	1.2044	0.7
Outer body	3.2588	0.3	3.2353	0.8
Middle body	1.5766	0.8	1.5689	0.4
Inner body	0.6337	0.6	0.6459	0.9
Bottom cap	1.2004	0.3	1.2048	1.2
Total Loss		3.0		4.0
Tubes With Rings Four Step Cap				
Top cap	1.2716	1.0	1.278	2.2
Outer body	3.1257	0.7	3.1762	1.4
Middle body	1.4652	0.6	1.5082	0.6
Inner body	0.6287	0.7	0.6326	1.4
Bottom cap	1.2813	0.6	1.2854	4.0
Total Loss		3.0		9.0

3.4 Planetary Protection

The LWRHU does not reach a temperature of 110°C (surface temp in free air is 45°C) and, therefore, is not self-sterilizing. If planetary protection is required for the mission, then the LWRHUs have to undergo sterilization treatment. Some methods for this treatment include: acceptance via a cement curing process (150°C for 16 hours), packaging and sealing LWRHUs inside sterile containers and shipping to KSC to be unpackaged and integrated into the spacecraft in a Clean Room, or sterilizing LWRHUs at KSC via heat sterilization process.

4. HARDWARE MODELING AND ANALYSIS

4.1 LWRHU Development Testing

The basis for the design of the LWRHU fuel pellets and cladding was determined primarily to meet stringent mission requirements. The LWRHU design project was supported by extensive research and development testing. Materials selection for the LWRHU was based, in part, on fundamental studies of fuel-form processing, fuel/container thermodynamics, platinum-alloy/carbon eutectic temperature determinations, and the high strain rate response of platinum-alloy. The analytical effort was supported by thermal diffusivity measurements on pyrolytic graphite and by measurements of the permeability of FWPF to gas. Engineering tests were conducted for vibration, helium release, impact, and G-loading to verify the capability of the materials and configurations of the LWRHU in the environments anticipated for its use. UO_2 simulant was used for some type of tests.

Since the design of the LWRHU assembly and its components are robust to withstand these conditions, they also function to prevent, or minimize, the release of significant quantities of respirable PuO2 in the event of an accident. The LWRHUs achieve this because they are designed and tested so that the PuO2 fuel elements have mechanical strength and will fracture into large pieces upon severe impact, but not produce significant fines. Further, the cladding of the LWRHU contains the PuO2 by resisting penetration under severe accident conditions. A summary of historical LWRHU developmental and safety testing is provided in Table 6.

Table 6. LWRHU Development Testing.

Test Type	Results	Reference(s)
Overpressure Testing (Depleted UO_2 fuel)	Conclusion: Fuel containment capability of the LWRHU fuel capsule (clad fuel pellet) is not impaired by the overpressure environment at the level tested (upto a static overpressure of 1,850 psi). Test conditions: • Static overpressure: 1,850 ± 100 psi (12.76MPa) • Static impulse: 5.6 ± 0.5. psi (38.6 MPa) Test Summary (two tests conducted): • Test 1 (LRF-007) – Graphite stripped from capsule – Flash x-ray indicated probable capsule integrity (while capsule was in-flight; estimated capsule velocity was 1,310 m/s) – Capsule was never recovered (likely propelled through an opening in the catchbox following the blast) • Test 2 (LRF-004, LRF-006, LRF-016) – somewhat different test setup based on results of Test 1 – LRF-004 • Graphite components stripped • Capsule deformed and breached in area of closure weld (report notes incompleteweld closure weld penetration observed during post-test met exam – lack of weld penetration was observed early in fabrication	LA-10352-MS, "Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit," R. E. Tate, C. C. Land, May 1985 Results: Test 1 (1 RHU): Graphitics stripped, clad velocity 1,310 m/s,not recovered Test 2 (3 RHUs): Graphiticsstripped 1 clad breached due to poorweld 1 clad intact but deformed 1 clad not recovered

Test Type	Results	Reference(s)
	development, corrected, and not observed in flight-qualified capsules)	
	– LRF-006 • Graphite components stripped • Capsule deformed by not breached – LRF-016 • Capsule not recovered.	
Fragment Impact (bullet) tests (Depleted UO_2 fuel)	Conclusion: LWRHU assemblies mounted on a magnetometer ring can survive impact by an 18-g aluminum bullet (simulated fuel-tank fragment) at velocities greater than 750 m/s (2,450 ft/s) but less than 900 m/s (2,950 ft/s) Test configuration: • 18-g Al bullet (2,219-878 alloy, used in shuttle external tank); 2-in. long; 0.5-in. diameter • Target: LWRHU assembly Tests – 7 total: – 289 m/s – 757 m/s (no capsule breach) – 908 m/s and 940 m/s (no physical remnants of target capsules were recovered; U not detected in post-test debris) Solid Rocket Booster Fragment impact tests • 212 m/s (LFT-2) – 1.42-m x 1.42-m x 12-mm D-6 ac steel – 90° (side-on)	LA-10352-MS, "Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit," R. E. Tate, C. C. Land, May 1985. Results: 3 tests (289 to 757 m/s): clads deformed but not breached 1 test (773 m/s): graphitics destroyed, struck off-center, clad not struck 2 tests (908 and 940 m/s): No physical remnants of RHUs found; significant uranium detected in recovered graphite debris Galileo FSAR, MLM-3540, October 1988 Results:

Test Type	Results	Reference(s)
	• 117 m/s (LFT-ENG-2) – 1.42-m x 1.42-m x 13-mm D-6 ac steel – 90° (side-on); 45□	212 m/s: Aeroshell failure; no clad breach 117 m/s: Aeroshell deformation and breakup but FWPF remained around clad; clads were deformed but not breached.
Solid Rocket Propellant Test (Depleted UO_2 fuel)	Conclusion: Capsule breach but graphitic components remain intact, thereby providing confinement of nuclear material and reducing release. Test configuration • 0.9-m x 0.9-m x 0.9-m (~ 3-ft x 3-ft x 3-ft) solid propellant cube in test assembly (uninhibited on 5 sides) • LWRHU placed 5 mm (0.2 in.) from the solid propellant, oriented horizontally and parallel to cube • 10.5-minute burn • Temp in flame zone (about 6 ft above the uninhibited portion of test box) was measured ~ 2,060°C • Inner insulator body (three nested insulator cylinders) had reacted with the Pt-Rh capsule, presumably forming a Pt/Rh eutectic – Pt-C eutectic forms at 1,705°C – Pt-Rh eutectic forms at 1,694°C – Pt frit vent was gone	LA-10352-MS, "Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit," R. E. Tate, C. C. Land, May 1985 Results: Pt frit vent melted Clad wall thickness reduced to 40% of original thickness

Test Type	Results	Reference(s)
	• Capsule wall thickness reduced in places to 0.41 mm (40% of original thickness) • Indication of reaction between the UO2 fuel and the inner surface of the capsule • Aeroshell surface was somewhat eroded and encrusted with propellant fire products • No alpha activity was detected on the exterior of the LWRHU following test	
Post-Reentry Impact (PuO2 fuel)	• Safety Tests - 6 LWRHUs tested (each fueled capsule was heated in a furnace to simulate reentry thermal pulse, then reassembled into LWRHU) – Temp range: 450℃ – 1,450℃ – Peak temp: ~ 1,450℃ – 1,475℃ – Heat pulse: 200s – 4 tested shortly after reassembly – 2 aged for 2.5 years prior to test • Engineering Development Tests – Bare capsules impacted @ 48 m/s (0, 45, and 90 orientation) – 90 orientation (48, 68, 88, 105, and 128 m/s) – Results showed deformation but no failure Respirable fines in the aged capsules was 3- 4X greater than the as-built LWRHUs – attributed to the buildup and storage of helium	LA-10352-MS, "Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit," R. E. Tate, C. C. Land, May 1985 Results (Safety Tests): Significantly damaged graphitics No clad breaches One small non-penetrating crack on interior of the weld closure zone on one LWRHU

Test Type	Results	Reference(s)
	during the aging period…was released to the grain boundaries during the reentry heating pulse which weakened the fuel.	
Environmental Test	Two LWRHUs with open vents placed in seawater for 1.75 yr, one at a depth of 0.25-m, and the second in a simulated ocean depth with pressure of 68.9 MPa (10,000 psi) corresponding to 6,000-m depth.	LA-10352-MS, "Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit," R. E. Tate, C. C. Land, May 1985. Results: No evidence of reaction between the seawater and Pt-30Rh fuel capsules or between the seawater and PuO2 fuel. Met the requirement that radioactivity in the water did not exceed 0.05 microcurie.
Fragment Impact Tests	High velocity bare clad impact tests (3 clads): • 3.5-mm-thick, 3-g Al flyer plate impacted on bare clad with subsequent bare clad impact on 12-mm-thick Al impact plate • Clads were of early developmental test configuration; contained UO2 fuel (simulant) • No heat treatment prior to impact testing • Impact of 3.5-mm-thick Al flyer plate at 1,100 m/s onto bare clad: – No clad breaches/failures. • Clads were subsequently impacted at 330 m/s against 12-mm-thick Al impact plate: – Significant clad deformation, but no breaches.	MLM-3303, "Cryogenic Explosion Environment Modeling and Testing of Space Shuttle and Light-Weight Radioisotope Heater Unit Interactions," October 1985, E. W. Johnson. Conclusions: Clad impact on essentially unyielding surfaces will remain intact up to impact velocities of 330 m/s. Clad failure can be expected with fuel release at 50% if the clad

Test Type	Results	Reference(s)
	High velocity bare clad impact tests (2 clads) • Bare clads were impacted onto 12-mm-thick steel plate • Impact of bare clad onto 12-mm-thick steel impact plate: – Failed at 607 m/s (end on). – Total release at 593 m/s at 45° impact angle.	velocity exceeds 330 m/s and impact involves an unyielding surface.
Sequential Impact Tests	Two LWRHUs (depleted Urania simulant fueled) were subjected to vibration testing followed by impact testing at progressively higher impact velocities • Vibration testing (random and sinusoidal) was performed at Mound – no apparent degradation of the graphite components or the capsule cladding • Impact testing conducted at LANL (same capsules from vibration testing, but placed in new graphite components): – LWRHUs placed in Al-6061 cans – Impact velocities increased incrementally (nominally 20, 30, 40, 50 m/s) – No evidence of contamination release – Damage was comparable to that incurred by a single LWRHU used in qualification testing (see below). • Conclusions: – Sequential testing results in slightly greater damage than single impact testing at the final velocity of 50 m/s	LA-13339-MS, "Light-Weight Radioisotope Heater Unit (LWRHU) Sequential Impact Tests," M. A. H. Reimus, G. H. Rinehart, August 1997.

Test Type	Results	Reference(s)
	– Deformation and fuel containment of the sequentially impacted LWRHUs were comparable to those of LWRHUs produced for and tested in support of the Galileo and Cassini missions. – Minimal deformation of the aeroshell and the fuel was entirely contained by the units.	
LWRHU Production Qualification Impact Test	Post-reentry impact test was performed on one of the 180 flight-quality units produced for the Cassini mission: • Qual LWRHU was subjected to a thermal pulse to simulate reentry (~200 s; max temp ~1,500°C) • Impact velocity: 53.5 m/s (ambient temperature) • Hardened steel target • Side-on orientation Results • Minimal deformation on the aeroshell and fueled capsule, and the fuel was entirely contained by the units. • Fuel fragmentation response of the Cassini LWRHU was much better than that of Galileo qual unit.	LA-13311-MS, "Light-Weight Radioisotope Heater Unit (LWRHU) Production Qualification Impact Test," M. A. H. Reimus, G. H. Rinehart, May 1997.
Helium Release Test	Each frit is flow rate tested at 10 to 30 cc^3/sec of helium at 7 kPa.	AIP Conference Proceedings 361, 1043 (1996) "Fabrication of Light Weight Radioisotope Heater Unit Hardware Components," Dennis C. McNeil.

Test Type	Results	Reference(s)
Weld	Sigma jig tested for weldability prior to cladding shell fabrication. Throughout production of the Cassini.	
G-Loading	Conclusion: The loading was quickly brought to 425 G where it remained for 15 s. The loading was above 300 G for 30 s. The LWRHU and mounting hardware survived the 425-G-loading without incident. After the test, the graphite components were disassembled and inspected visually with care. Absolutely no evidence of change was observed.	LA-9078-MS "The Light Weight Radioisotope Heater Unit (LWRHU): A Technical Description of the Reference Design," R. E. Tate January 1982.

4.2 Acceptance Testing

Acceptance testing for a LWRHU verifies:

1. Mass
2. Power (i.e., heat output of fueled capsule that would be measured via calorimetry at Los Alamos National Laboratory [LANL])
3. Radiation (neutron emission rate that would be measured by LANL)
4. Geometry.

Testing requirements are subject to change based on the mission.

5. LAUNCH SAFETY REQUIREMENTS

NASA missions planning to use a LWRHU must follow NASA Procedural Requirements (NPRs):

- NPR 8580.1, "Implementing the National Environmental Policy Act and Executive Order 12114,"describes requirements for compliance with NEPA. The level of NEPA documentation needed depends on the scope of the mission and its potential environmental impact.
- NPR 8715.3, "NASA General Safety Program Requirements," Chapter 6, describes requirements for compliance with nuclear safety and launch authorization. Depending on the use, type, and amount of nuclear material, the range of analyses varies, as does the level of approval.

NOTE: *NPR 8715.3 is undergoing revision. A new NPR specifically addressing nuclear launch authorization will be issued. In the meantime, NPR 8715.3 will be followed, with exceptions where provisions have been superseded by the National Security Presidential Memorandum 20 (NSPM-20). See NPI 8715.93 Impacts of NSPM-20 on NASA Nuclear Flight Safety Requirements and Practices.*

- NPR 8715.2, "NASA Emergency Preparedness Plan Procedural Requirements—Revalidated," describes requirements for developing radiological contingency plans when launching radioactive material. The extent of planning and documentation varies depending on the use, type, and amount of nuclear material being launched.
- NPR 7120.5E, "NASA Space Flight Program and Project Management Requirements," the mission shall prepare a nuclear safety launch authorization plan for any U.S. space mission involving the use of radioactive materials. Procedures and levels of review and analysis required for nuclear safety and launch authorization vary with the quantity of

radioactive material planned for use and potential risk to thegeneral public and the environment.

These processes require coordination across many organizations to be completed effectively and in a timely manner. The mission must plan early and throughout the mission life cycle to execute this work. The RPS Program, acting on behalf of the Mission PE, manages both NEPA compliance and nuclear launch authorization efforts for the specific mission to reduce NEPA and nuclear launch authorization mission schedule risk and to ensure that the activities are carried out consistently for agency missions and in an efficient and cost-effective manner for missions flying RPS or LWRHUs.

5.1 National Environmental Policy Act

NEPA requires all federal agencies, including NASA, to consider the environmental impacts of their proposed actions and any reasonable alternatives to those actions. NEPA compliance is required for all NASA activities that may result in an environmental impact.

NEPA requires federal agencies to integrate environmental values into their planning and decision- making processes, analyze the environmental impacts of major actions and reasonable alternatives, and present those impacts to the public before the action is undertaken. This analysis is documented in a categorical exclusion (CatEx), and an environmental assessment (EA) or an environmental impact statement(EIS).

As a federal agency, NASA is subject to NEPA for major actions and activities; therefore, a decision to undertake a nuclear-enabled mission should be made only after consider impacts that are reasonably foreseeable and have a reasonable causal relationship of potential environmental impacts associated with the mission and other reasonable alternatives (i.e., solar or battery). It is important for the level of environmental analysis to be proportionate to the potential environmental impact (that is, preparation of an EA/Finding of No Significant Impact versus preparation of an EIS). The agency must analyze the potential impacts that are reasonably foreseeable and have a reasonable casual relationship of the proposed action on affected environmental resource areas, and, when applicable, use scoping to identify the range of actions, alternatives, and impacts that consider and respond to the comments generated from a public review period in the environmental impact analysis.

It may be possible to adopt or tier information from existing NEPA documentation that may cover the proposed action and determine if the potential impacts are covered in previous analysis. DOE has worked with NASA to do an EA that covers 115 RHU's and is a starting point for NEPA analysis.

NASA published the Programmatic Environmental Assessment of Launches Involving Radioisotope Heater Units (RHUs) and Finding of No significant Impact (FONSI) in 2020. The programmatic document maybe applied each time a RHU is used in a space mission, as long as the parameters listed below are met:

- Only RHUs are included in this PEA. Other space nuclear power systems, such as radioisotope thermoelectric generators, are not included.

- This PEA covers missions using up to 130 RHUs for a maximum combined 351 grams of Plutonium-238 oxide (Pu-238) per launch. A RHU's standard configuration contains approximately 3 grams of Pu-238.

- This PEA only covers launches from the KSC and CCAFS launch complexes.

- Only launch vehicles that have been fully analyzed through the NASA NEPA process and have undergone the NASA launch approval process per NASA Policy Directives 8610.7D, 8610.23C, and 8610.24C and NASA Procedural Requirement 8705.4 are included in this analysis.

- Future launch vehicles that have been evaluated under NEPA and meet launch approval requirements are covered by this analysis.

- All potential NASA near-Earth, crewed, and deep space missions meeting the preceding requirements are included in this PEA.

The NASA NEPA Manager and the RPS NEPA and Launch Approval Manager will conduct the review for determination on if the missions are within the bounding conditions of the existing programmatic documentation.

If a mission proposing use of an LWRHU is found to be out of scope of the bounding conditions of the programmatic or existing environmental NEPA documentation, the RPS NEPA and Launch Approval Manager, along with the HQ NASA NEPA Manager, should determine if further analysis is warranted. If further analysisis warranted, NEPA regulations encourage federal agencies to conduct an environmental analysis (EA) to determine the potential for a significant impact. If the potential environmental impacts are found to be significant, then a mission specific EIS is required. NEPA requires public scoping as part of the preparation of a draft EIS. The draft EA and draft EIS must also be made available for comment to the public, regulators, and officials. Any comments received during the comment period must be considered in developing the final EA and final EIS. The DOE, as the provider of the nuclear material, and the U.S. Air Force, Cape Canaveral Air Force Station, as the traditional launch site, should serve as cooperating agencies in the NEPA process.

The NEPA process and timeline are depicted in the following chart.

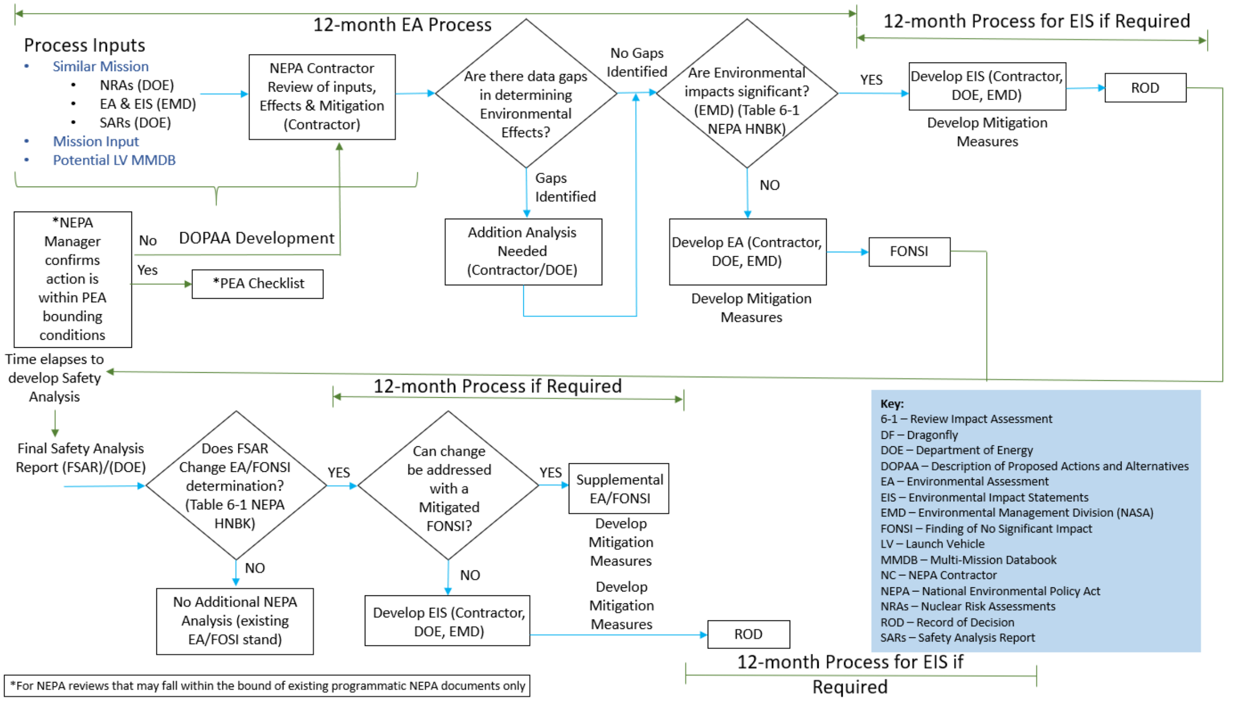


Figure 6. NEPA process for RPS missions.

5.2 Nuclear Launch Authorization

The NSPM-20 establishes three tiers for the launch authorization process, based on the quantity space nuclear system (SNS) of material being launched and the mission risk. The three tiers are defined as:

- Tier 1
    - Launches of spacecraft containing radioactive sources of total quantities up to and including 100,000 times the A2 value listed in Table 2 of the International Atomic Energy Agency's Specific Safety Requirements No. SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition (80 or fewer LWRHU's).
- Tier 2
    - Launches of spacecraft containing radioactive sources in excess of 100,000 times the A2 value referenced above (81 to 130 LWRHU's).
    - Any Tier 1 launches where the associated safety analyses determine that the probability of an accident during launch or subsequent operation resulting in

an exposure in the range of 5 rem to 25 rem total effective dose (TED) to any member of the public is equal to or greater than 1 in 1,000,000.

    – Any launches of spacecraft containing nuclear fission systems and other devices with a potential for criticality (defined as the condition in which a nuclear fission chain reaction becomes self- sustaining) when such systems utilize low-enriched uranium (less than 20% U-235 enrichment).

- Tier 3
    - Launches of any spacecraft containing a space nuclear system for which the associated safety analyses determine that the probability of an accident during launch or subsequent operation resulting in an exposure in excess of 25 rem TED to any member of the public is equal to or greater than 1 in 1,000,000.
    - Due to potential national security considerations associated with nuclear nonproliferation, Tier 3 shall also apply to launches of spacecraft containing nuclear fission systems and other devices with apotential for criticality when such systems utilize any nuclear fuel other than low-enriched uranium.

Launches involving only a LWHRU (no other SNS) have a Tier determining process based on the quantity of the LWRHUs used for its mission but will likely fall into either Tier 1 or Tier 2 in this process. All Tiers require the preparation of a SAR. A Tier 2 launch requires preparation of a SAR, review by the Interagency Nuclear Safety Review Board (INSRB), and approval by the NASA Administrator.

5.3 Radiological Contingency Planning

NPR 8715.2, NASA Emergency Management Program Procedural Requirements, addresses the NASA emergency preparedness policy and program requirements for missions utilizing radiological materials. The Office of Protective Services ensures that radiological emergency and recovery plans are developed, coordinated, and implemented where NASA is the Primary Authority as defined by the National Response Framework and the Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plans, to ensure familiarity with and alignment with NASA HQ and launch or landing site radiological contingency response plans. Planning for out-of-launch area accidents,such as inadvertent reentry or other spacecraft failures resulting in reentry from Earth orbit, requires additional coordination and documentation from the flight project for coordination with other federal agencies such as DOE and the U.S. Department of Defense. In cases of sample return missions using nuclear material, radiological contingency plans are also required for ground and emergency response operations at the sample landing/recovery site (NPR 8715.Y).

5.4 Generic Notional Nuclear Launch Authorization Schedule

An example of a generic NSPM-20 schedule for a competed mission planning to use an LWRHU is provided in the figures below. This timeline can be tailored, which will result in a shorter schedule.

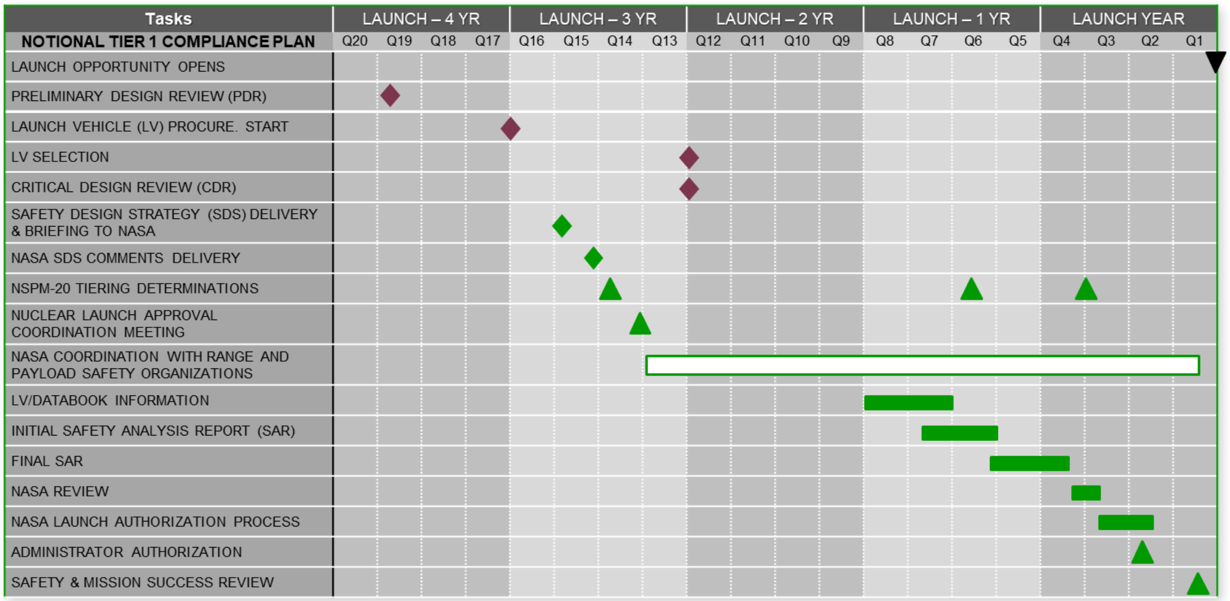


Figure 7. NSPM-20 notional schedule tier 1

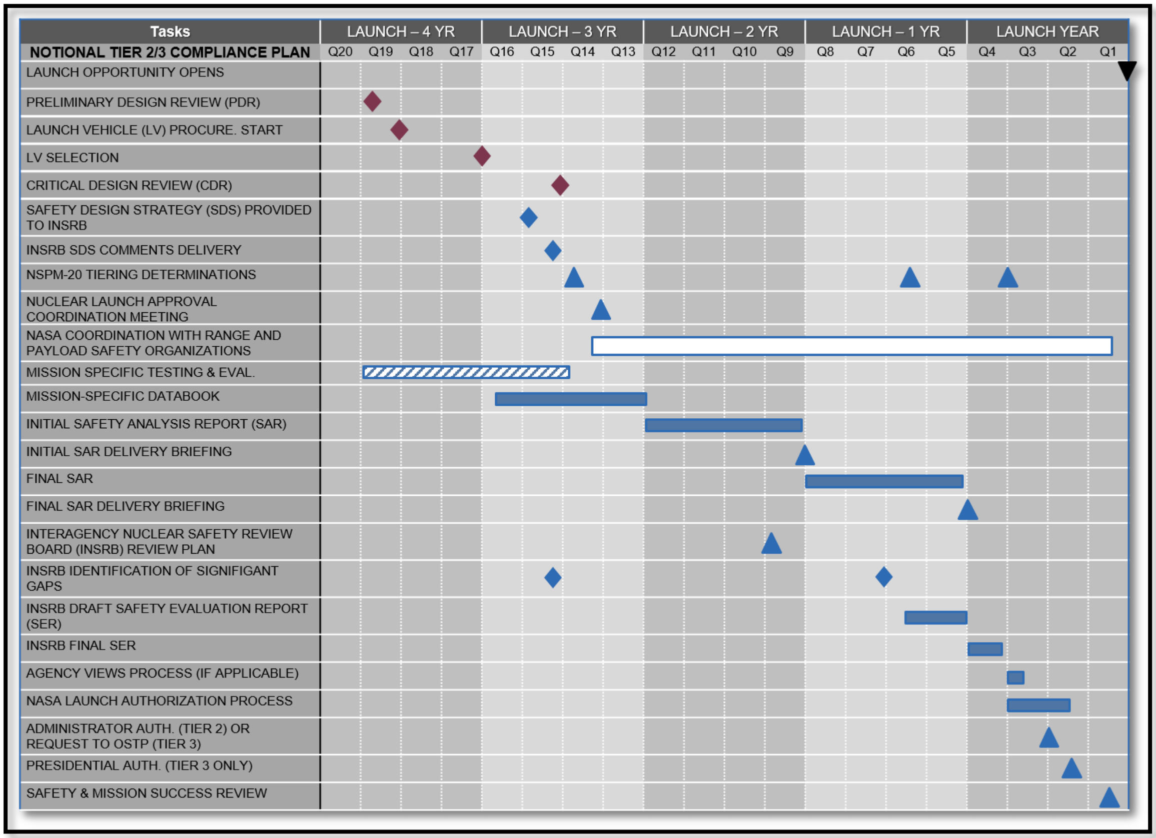


Figure 8. NSPM-20 notional schedule tier 2/3.

5.5 Expected Project Inputs in Support of Environmental and Nuclear Safety Processes

Mission inputs that are normally required when supporting NEPA compliance for a LWRHU mission include mission baseline design descriptions and participation in reviews, public meetings, and response to government/public comments. Sometimes additional special studies are required (e.g., missions utilizing gravity-assist trajectories).

Mission inputs normally required when supporting the NSPM-20 compliance process include detailed spacecraft/mission design information, trade studies, and implementations supporting the development of a SAR.

Mission inputs that are normally required when supporting radiological contingency planning requirements include developing out-of-orbit contingency plans (which can impact spacecraft and mission design), supporting the accident response team, and participating in reviews.

Missions that may use RHUs may require additional communication materials related to RHUs.

5.6 Required Databook Inputs

Missions are typically launched on an Expendable Launch Vehicle (ELV) that is procured by the mission or provided by the sponsoring program office. The KSC, through LSP, is the lead center for the acquisition and management of ELV launch services. LSP leads the preparation of multi-mission and mission-specific databooks for nuclear launches. The databooks describe the launch vehicle, launch complex, spacecraft, and the RHU; define potential accidents and their probabilities; and determine and characterize potential accident environments. The LSP also leads launch vehicle accommodations needed for the use of an RHU. The RPS program funds multi-mission databook development and receives the databook from LSP and includes LSP in its coordination activities for all aspects of nuclear launches.

Multi-mission databooks are used to expedite the development of mission-specific databooks and therefore reduce the mission risk, as well as aiding in identification of launch vehicle specific safety concerns for RHU missions earlier in the process.

Databooks are used by the DOE in the development of the DOE SAR, which supports the NSPM-20 launch authorization process (SAR databook). The SAR databook is developed following the mission preliminary design requirement and NASA selection of a launch service for the mission, so that databook is specific for both launch vehicle and spacecraft in content. Some, to all of the information included in databooks has historically been considered, at a minimum, proprietary and, in many cases, export controlled.The typical content of a databook is described below.

- **Chapter 1 - Introduction – Requires Mission Input**

The Introduction chapter should provide a brief summary of the SAR databook contents and a general overview of the major mission parameters. The following items are typically included in the Introduction chapter:

- Purpose of databook development (NSPM-20 and NPR 8715.x and nuclear risk assessment requirements)
- Mission objectives
- Launch information (site, vehicle, timeframe)

- SAR databook organization
- Analytical ground rules and assumptions.

This chapter is typically drafted by NASA/KSC Launch Services Program or its contractors with the mission providing information on the mission objectives.

- **Chapter 2 - Mission Overview – Requires Mission Input**

The Mission Overview chapter should provide a high-level summary of the mission, including but not limited to the following:

- Purpose
- Phases
- Critical events
- Communications
- Instrumentation.

This chapter is typically drafted by NASA/KSC Launch Services Program or its contractors with support from the mission.

- **Chapter 3 - Launch Vehicle Description**

The Launch Vehicle Description chapter should describe major characteristics of the launch vehicle,including but not limited to the following:

- General configuration (major structural elements, dimensions, etc.)
- Mass properties and vehicle coordinate system
- Tank capacities and pressures
- Fuel characteristics
- Avionics system
- Payload interface
- Stage interface
- Propulsion system
- Pneumatic system
- Telemetry system

- Ordnance components
- Flight termination system.

The launch service provider and launch vehicle manufacturer author this chapter.

- **Chapter 4 - Spacecraft Description – Requires Mission Input**

The Spacecraft Description chapter should describe the major characteristics of the spacecraft, includingbut not limited to the following:

- General configuration (major structural elements, dimensions, etc.)
- Spacecraft stage descriptions (if applicable, such as cruise stage, entry stage, surface rover)
- Mass properties and spacecraft coordinate system
- Instrumentation (to include radioisotope types and activities, if applicable)
- Ordnance components
- Tank quantities and pressures
- RPS/RHU installation details.

In order to provide sufficient detail to support impact modeling and other elements of the safety analysis,spacecraft design files should also be included as an appendix to this chapter.

The mission authors this chapter.

- **Chapter 5 - Launch Complex Description**

The Launch Complex Description chapter should address the major characteristics of the launch complex,including but not limited to the following:

- Overall site layout depiction
- Site functional description
- Propellant storage tank locations, capacities, and pressures
- Surface material composition data for launch site
- Structural material composition data for all structures on launch site

- GSE description and locations
- Propellant quantity data for nominal launch operations.

In order to provide sufficient detail to support impact modeling and other elements of the safety analysis,launch complex design files should also be included as an appendix to this chapter.

The launch service provider authors this chapter.

- **Chapter 6 - Flight Safety System**

The Flight Safety System chapter should address the procedures and facilities utilized by the flight safety organization for the particular range used for launch operations. Information includes, but is not limited to, the following:

- Impact limit line data and description of derivation
- Destruct limit line (both fixed and dynamic) data and description of derivation
- Vertical plane destruct line data and description of derivation
- General and mission-specific flight termination criteria
- Description of mitigations that would prevent an inadvertent flight termination event
- Types of flight termination
- Flight termination process
- Range safety system equipment descriptions.

The launch service provider and launch vehicle manufacturer authors this chapter.

- **Chapter 7 - Mission Timeline and Trajectory Data**

The Mission Timeline and Trajectory chapter should address all of the required steps for launch vehicle/spacecraft integration and processing, along with the trajectory design and performance information for the particular mission. Timeline data typically include, but are not limited to, the following activities:

- Vehicle/spacecraft receipt and inspection
- Spacecraft encapsulation
- Launch vehicle integration
- Launch vehicle readiness testing
- Spacecraft mate

- Integrated systems testing
- Final closeout/RPS/RHU installation (historically, RHUs are integrated in a clean room prior to spacecraft reaching the launch site).
- Movement to pad
- Contingencies that would result in delays
- Launch day events
- Launch day recycle timelines.

It is important to include detailed descriptions of each prelaunch processing activity in order to support the identification of potential prelaunch accident scenarios in the safety analysis.

Trajectory data pertaining to the mission typically includes, but is not limited to, the following information:

- Trajectory design and performance analysis data
- Launch vehicle performance definitions and assumptions
- Simulation data used to support propellant margin
- Parking orbit parameters
- Trajectory ground rules
- Post-engine ignition through Target Interface Point timeline.

Graphical depictions of the following mission parameters should also be included:

- Altitude versus mission time
- Range versus mission time
- Relative velocity versus mission time
- Acceleration versus mission time
- Instantaneous Impact Prediction trace from launch through park orbit injection
- Sub-vehicle trace through spacecraft separation.

The launch service provider and launch vehicle manufacturer authors this chapter.

- **Chapter 8 - Accident Probabilities**

This Accident Probabilities chapter typically defines and probabilistically quantifies the accidents that may be initiated by the launch vehicle. An overview of the framework and techniques used to define accident scenarios and derive the associated probability of failure for all mission phases of interest from the nuclear safety point of view is provided. This chapter also includes a discussion of sensitivity and uncertainty associated with the failure probabilities.

The NASA/KSC Launch Services Program or its contractors' authors this chapter.

- **Chapter 9 - Accident Environment**

This Accident Environment chapter quantifies the accident environments that are a consequence of the accident scenarios defined in Chapter 8. This chapter is organized to address the blast and/or blast-drivenfragments resulting from liquid propellant explosions (Section 9.1) and solid propellant explosions (Section 9.2); the thermal environment from liquid and solid propellant fires (Section 9.3); the fragment debris produced as a consequence of the nominal destruct of the launch vehicle , as well as launch pad debris (note that the launch *vehicle* debris is typically provided by the launch provider) (Section 9.4); and finally, the response of the spacecraft to aerodynamic-induced loads and heating during an accidental Earth reentry (Section 9.5).

The NASA/KSC Launch Services Program or its contractors' authors this chapter.

5.7 Mission Trajectories Utilizing Gravity Assist Maneuvers

Missions planning to use gravity assists to get to the final destination may require additional studies and supporting analyses as inputs to NEPA and NSPM-20 compliance activities. The extent of required mission design constraints and analyses would be determined in the development of the overall compliance approach, with inputs from NASA, DOE, and the mission.

6. PROGRAMMATICS

The DOE Office of Space and Defense Power Systems manages the development and delivery of the LWRHU. The NASA Science Mission Directorate funds the fueling and delivery of LWRHU projects. The NASA Science Mission Directorate has assigned the NASA GRC the role of implementing a Radioisotope Power Systems Program office, with responsibility for NASA approval of mission requirements, monitoring the progress of the mission, ensuring compliance with required review processes, and ensuring availability of required funding or other required NASA resources to support the mission.

In addition to the activities that form the scope of this mission, the use of a LWRHU on a mission requires supporting services that INL provides on behalf of DOE. These services include preparation of a SAR to support the launch authorization process, support of the NEPA process, support of launch site operations, and planning of emergency responses. These activities are managed and budgeted together with the project and are performed under the same agreements.

DOE will retain title to the LWRHU at all times, as provided in Article III of the MOU 2016.10.31. DOE is responsible for managing the following activities associated with a nuclear-enabled launch:

- Designing, developing, fabricating, evaluating, testing, and delivering the LWRHU, as agreed to by NASA and DOE, to meet the overall system requirements, specifications, schedules, and interface requirements.
- Retaining custody of the fueled LWRHU at all times, except when the devices are in NASA's custody pursuant to the MOU 2016.10.31, which provides that NASA is responsible for: accepting custody of the fueled LWRHU when turned over to NASA by DOE or a DOE contractor and retaining custody, for the purpose of carrying out the requirements of MOU 2016.10.31, at all times except when transferring custody to DOE or a DOE-designated recipient;
- Providing (with the assistance of NASA and any other appropriate agencies) a documented analysis of potential accidents and their associated risks (e.g. Safety Analysis Report);
- Specifying, in consultation with NASA, the minimum radiological, occupational/public health, safety procedures/criteria, and providing guidance with respect to safeguards and security requirements related to NASA facilities and services associated with the fueled LWRHU;
- Providing such information concerning the LWRHU as may be required for use in: (1) NASA operational plans and other documents required as part of the mission definition, environmental analysis, and launch authorization process; (2) advising the Department of State and the Office of Science and Technology Policy, National Space Council, and United Nations (as appropriate); and (3) operational planning and safety analysis concerning DoD controlled range facilities, including radiological safety in the event of a launch accident;
- Cooperating with NASA concerning the LWRHU with respect to international, national, state, or other governmental bodies as may be necessary or advisable;
- Preparing, with NASA, joint public information plans for applications involving LWRHU;
- Providing technical observation, advice, and assistance to NASA during various operations involving the RHU including, but not limited to: (1) prelaunch storage, monitoring, handling, transportation, and preparations for launch; (2) installation on the space vehicle; (3) prelaunch acceptance testing aboard the space vehicle; and (4) launch and mission operations;
- Affirming to NASA the operational use and flight readiness of the LWRHU with respect to nuclear safety, and participating in the nuclear safety and launch authorization process;
- Advising NASA (in the event of a ground or mission accident or flight termination) of DOE's determination of whether a nuclear incident has occurred and determining the extent of any off-site radiological releases. In the event of a nuclear incident, providing technical guidance to NASA and, if applicable, DoD range forces and others, as may be required, for the recovery of the LWRHU and necessary decontamination and disposal operations;
- Assuming, as between DOE and NASA and to the extent consistent with applicable law, legal responsibility for damages to life and property resulting from a nuclear incident in accordance with Article V, "Nuclear Hazards Indemnity" of MOU 2016.10.31; and
- Jointly investigating and reporting (with NASA) nuclear incidents.

DOE national laboratories involved with the LWRHU project are LANL (which processes plutonium oxide, fabricates fueled capsules, and performs some safety tests) and INL (which fuels, tests, qualifies, and accepts LWRHUs for flight and provides shipping and launch support services). Oak Ridge National Laboratory (ORNL) fabricates cladding and produces Pu-238 for the heat source.

INL coordinates with both NASA and DOE managerial and technical staffs to implement government oversight of the project. The project is managed by INL staff; however, additional NASA and DOE management personnel help to ensure that end-user requirements are appropriately factored into project decision-making and ensure the availability of NASA and DOE technical staff and resources necessary to successfully complete the project.

7. PROJECT INTERFACES

An LWRHU project has a number of organizational and technical interfaces. The project interfaces and organizational relationships are described briefly in Table 7.

The cost to build and support a launch can vary depending on mission environments, and the number of new fueled capsules and radioisotope heater units that need to be fabricated. The sponsoring NASA mission directorate funds both NASA and DOE activities for the entire effort and pays for the special nuclear material used in the LWRHU.

Table 7. Project Interfaces and Organizational Relationships

Project Interface	Associated Roles/Dependencies	Key Governing Documents/Processes
NASA Science Mission Directorate Planetary Science Division	Signatory to agreements with DOE to initiate LWRHU development and flight projects. Key document with DOE regarding overall scope, cost, and constraints for LWRHU projects.	*Memorandum of Understanding between the National Aeronautics and Space Administration and the Department of Energy Concerning Radioisotope Power Systems*, dated October 31, 2016.
Radioisotope Power Systems Program Office at NASA GRC	Delegated implementation lead for NASA LWRHU project responsibilities, NASA requirements management, budget coordination, and coordination of interfaces withmissions.	LWRHU performance specification.
Mission	The LWRHU project must perform the science mission reviews and participate in technical exchanges to ensure the mission understands LWRHU requirements, interfaces, and capabilities. DOE will also provide	LWRHU user interface document AO. for the science mission. Specific working agreements and mission-specific requirements documents will be negotiated as needed.

Project Interface	Associated Roles/Dependencies	Key Governing Documents/Processes
	mission/launch support services standards for nuclear missions.	

8. SUPPLIED USER MODELS OVERVIEW

8.1 Simplified Power Prediction Tool

Equation 1. Watt Output Decay Over Time

$$W = W_I * e^{(-\ln(2)*(\frac{Decay\ Period}{Pu^{238}\ Half\ Life}))}$$

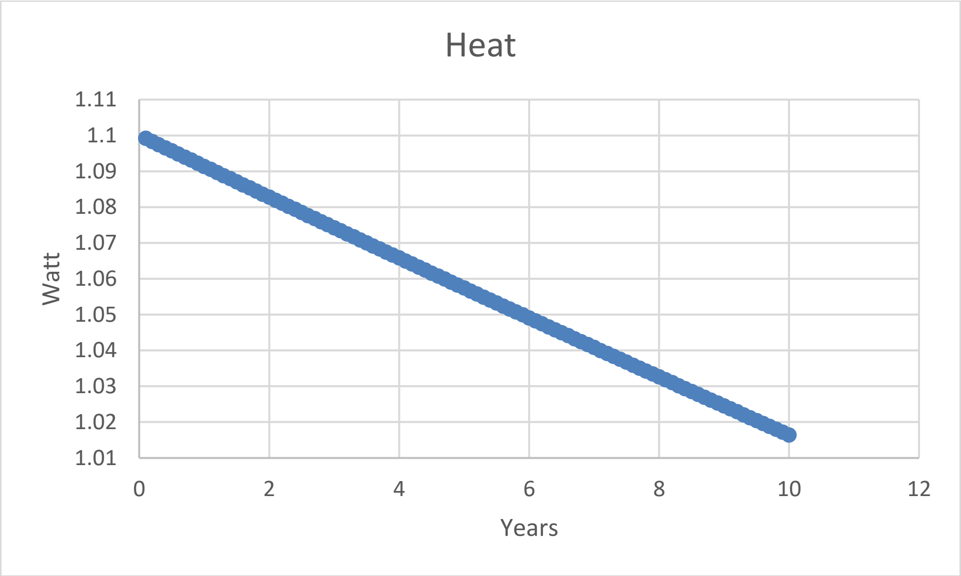


Figure 9. Watt Output Decay Over Time (10 Years)

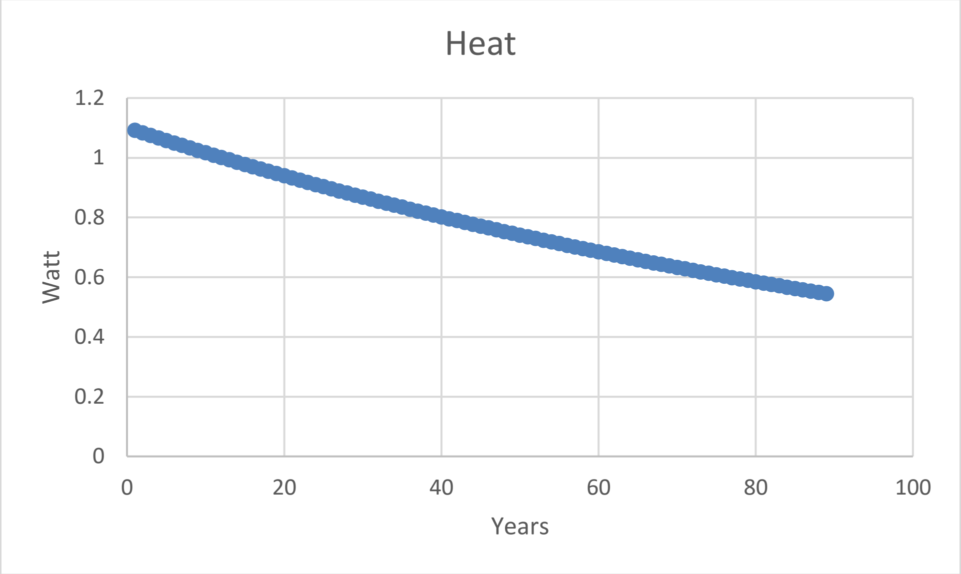


Figure 10. Watt Output Decay Over Time (100 Years)

8.2 Computer-Aided Design Shell Model

A CAD shell model (STEP format) of the LWRHU is available for use by the spacecraft developer in the LWRHU User's Guide Mission Planner Data Package. The CAD model is a full-fidelity model of the external surfaces and features of the LWRHU.

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