Appendix A

United States Space Nuclear Power Systems Launched into Space (as of January 2014)

Power Source[a]	Spacecraft	Mission Type	Launch Date	Status[b]	Initial Average RTG Power (We)[b]	Total Initial Spacecraft Power (We)[b]
RTGs						
SNAP-3(1)	TRANSIT-4A	Navigational	29-Jun-61	Succesfully operated for over 15 years. Currently in Earth orbit.	2.7	2.7
SNAP-3(1)	TRANSIT-4B	Navigational	15-Nov-61	Succesfully operated for over 9 years. Currently in Earth orbit.	2.7	2.7
SNAP-9(1)	TRANSIT-5BN-1	Navigational	28-Sep-63	RTG succesfully operated as planned. Non-electrical problems caused satelite to fail after 9 months. Currently in Earth orbit.	25.2	25.2
SNAP-9(1)	TRANSIT-5BN-2	Navigational	5-Dec-63	Sucessfully operated for over 6 years. Currently in Earth orbit.	26.8	26.8
SNAP-9(1)	TRANSIT-5BN-3	Navigational	21-Apr-64	Spacecraft failed to achieve orbit, RTG burned and dispered on re-ntry as designed.	25	25
SNAP-19(2)	NIMBUS-B-1	Meteorologocial	18-May-68	Mission aborted; power source retrieved intact and fuel source reused on later mission.	28	56
SNAP19-(2)	NIMBUS III	Meteorologocial	14-Apr-69	Sucessfully operated for over 2.5 years. Currently in Earth orbit.	28.2	56.4
SNAP-27(1)	APOLLO 12	Lunar/ALSEP	14-Nov-69	Succesfully operated for 8 years and currently on lunar surface.	73.6	73.6
SNAP-27(1)	APOLLO 13	Lunar/ALSEP	11-Apr-70	Mission aborted on way to moon. RTG re-entered Earth's atmosphere and landed in the South Pacific Ocean. No radiation release was detected.	73	73
SNAP-27(1)	APOLLO 14	Lunar/ALSEP	31-Jan-71	Succesfully operated for 6.5 years and currently on lunar surface.	72.5	72.5
SNAP-27(1)	APOLLO 15	Lunar/ALSEP	26-Jul-71	ALSEP sucessfully operated for 6 years and currently on lunar surface.	74.7	74.7
SNAP-19(4)	PIONEER 10	Planetary	2-Mar-72	Sucessfully operated to Jupiter and beyond; spacecraft operations terminated in 2003.	40.7	162.8
SNAP-27(1)	APOLLO 16	Lunar/ALSEP	16-Apr-72	ALSEP successfully operated for 5.5 years and currently on lunar surface.	70.9	70.9
TRANSIT-RTG(1)	TRAID-01-1X	Navigational	2-SEP-72	Currently in Earth orbit.	35.6	35.6
SNAP-27(1)	APOLLO 17	Lunar/ALSEP	7-Dec-72	Sucesssfully operated for 5 years and currently on lunar surface.	75.4	75.4
SNAP-19(4)	PIONEER 11	Planetary	5-Apr-73	Succesfully operated to Jupiter, Saturn, and beyond; spacecraft operations terminated in 1995.	39.9	159.6
SNAP-19(2)	VIKING 1	Planetary	20-Aug-75	Landed and succesfully operated for over 6 years on Mars. Operations ended in 1982.	42.3	84.6
SNAP-19(2)	VIKING 2	Planetary	9-Sep-75	Landed and succesfully operated for over 4 years on Mars. Operations ended in 1982.	43.1	86.2
MHW-RTG(2)	LES 8	Communications	14-Mar-76	Currently in Earth orbit.	153.7	307.4
MHW-RTG(2)	LES 9	Communications	14-Mar-76	Currently in Earth orbit.	154.2	308.4

Power Source[a]	Spacecraft	Mission Type	Launch Date	Status[b]	Initial Average RTG Power (We)[b]	Total Initial Spacecraft Power (We)[b]
MHW-RTG(3)	VOYAGER 2	Planetary	20-Aug-77	Successfully operated to Jupiter, Saturn, Uranus, Neptune and beyond. Extended mission ongoing; currently at heliopause.	159.2	477.6
MHW-RTG(3)	VOYAGER 1	Planetary	5-Sep-77	Successfully operated to Jupiter, Saturn, and beyond. Extended mission ongoing; currently in interstellar space.	156.7	470.1
GPHS-RTG (2)	Galileo	Planetary	18-Oct-89	Successfully explored Venus and then orbited Jupiter. Spacecraft deorbited into Jupiter in 2003.	288.4	576.8
GPHS-RTG (1)	Ulysses	Solar-Polar	6-Oct-90	Successfully explored Jupiter and entered solar polar orbit. Spacecraft operations ended in 2009.	283	283
GPHS-RTG (3)	Cassini	Planetary	15-Oct-97	Successfully explored Venus, Jupiter, and currently orbiting Saturn.	295.7	887
GPHS-RTG (1)	New Horizons	Planetary	19-Jan-06	Explored Jupiter; Pluto fly-by expected July 2015; additional exploration of Kuiper Belt and beyond will follow.	249.6	249.6
MMRTG (1)	Curiosity	Planetary	26-Nov-11	Succssfully landed on August 6, 2012 and currently exploring Martian surface.	113	113
Space Nuclear Reactors						
SNAP-10A (1)	SNAPSHOT	Experimental satellite	3-Apr-65	Reactor operated for 43 days after which it shut down due to non-nuclear electrical problem on the spacecraft. Currently in Earth orbit.	500	500

(a) The number in parenthesis is the number of power sources on the spacecraft.

(b) Personal communication with Ryan Bechtel (DOE), June 18, 2015.

Mission	RHUs (#)	Wt (BOM)
Radioisotope Heater Units		
Apollo 11	2	15 each
Pioneer 10	12	1 each
Pioneer 11	12	1 each
Voyager 1	9	1 each
Voyager 2	9	1 each
Light-Weight Radioisotope Heater Units		
Galileo	120	1 each
Mars Rover Pathfinder	3	1 each
Cassini	117	1 each
Mars Rover Spirit	8	1 each
Mars Rover Opportunity	8	1 each

B

Appendix B
Accidents Involving Spacecraft Carrying U.S. RTGs

Since 1961, the United States has launched 27 spacecraft with RTGs on board. Although three of the missions failed, none of the failures were due to problems with the RTGs.

1. **April 21, 1964: Transit satellite 5BN-3 with one SNAP-9A RTG**

   On April 21, 1964, a Transit satellite, 5BN-3, was launched from Vandenberg Air Force Base in California. When the satellite failed to achieve orbit, the SNAP-9A RTG re-entered the atmosphere in the Southern Hemisphere. Consistent with the burnup-dispersion safety philosophy in use at the time, the SNAP-9A unit and its metal plutonium fuel burned up and was dispersed into the atmosphere. Although there were no unacceptable health risks, with larger quantities of plutonium fuel planned for future RTGs, AEC changed its safety philosophy to one of intact re-entry.

2. **May 18, 1968: Nimbus B weather satellite with two SNAP-19 RTGs**

   On May 18, 1968, a NASA Nimbus B weather satellite with two SNAP-19 RTGs was launched from Vandenberg Air Force Base. Approximately two minutes after liftoff, the rocket went off course, prompting a mission abort command. The abort-induced explosion destroyed the launch vehicle, after which the two RTGs fell into the Santa Barbara Channel just north of San Miguel Island off the coast of California. Five months later, the SNAP-19 units were recovered – intact – from the ocean floor at a depth of approximately 300 feet. The capsules were returned to Mound Laboratory, where the fuel was recovered and reused in a new RTG.

3. **April 17, 1970: Apollo 13 lunar module with re-entry SNAP-27 RTG aboard**

   During the Apollo 13 mission, the lunar module and its SNAP-27 RTG were supposed to be left on the moon. Due to an explosion on the main craft, however, the lunar module was brought back to Earth, along with the command module, to provide life support for the astronauts. Prior to re-entry, the lunar module (with the SNAP-27 RTG onboard) was jettisoned from the command module. During re-entry, the lunar module disintegrated and the RTG fell into the Tonga Trench of the Pacific Ocean. Subsequent monitoring and sampling found no detectable radioactivity, indicating the RTG survived the crash intact.

Appendix C

Space Power Reactor Summary 1955 - 1973

(adapted from "Nuclear Reactors for Space Power," William R. Corliss, 1971)

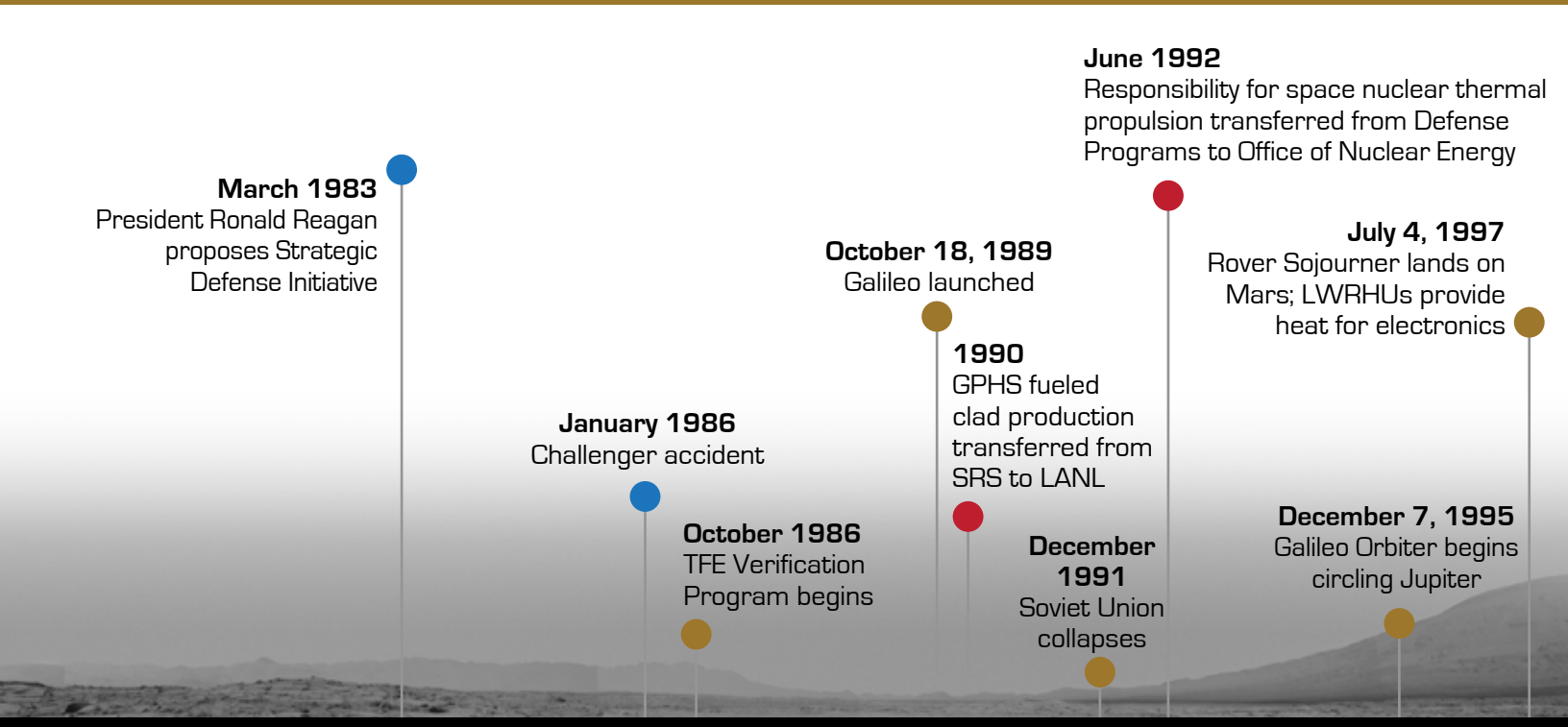
	Electrical Power Level, kW	Mass, kg (lbs)	Specific mass, kg/kw (lb/kw)	Overall efficiency, %	Core type	Core coolant	Energy conversion scheme (s)	Status
SNAP-2	3	668 (1,470)	223 (490)	5.4	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator	Discontinued space power plant
SNAP-8	35	4,450 (9,800)	127 (270)	7.8	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator, mercury working fluid	Component development competed, power plant concept discontinued in 1970
SNAP-10	0.3	–	–	–	Uranium zirconium hydride	None	Thermoelectric	Early design using conductive cooling of reactor; changed to SNAP-10A, convective heat-transfer design
SNAP-10A	0.6	427 (960)	908 (2,000)	1.6	Uranium zirconium hydride	NaK	Thermoelectric	Completed; in orbit April 1965
SNAP-50	100-1,000	At 300 kw, 2,700 (6,000) At 1,000 kw, 9,000 (20,000)	At 300 kw, 9 (20) (unshielded)	15	Fast, uranium nitride	Li	Rankine-cycle turbogenerator, potassium working fluid	Discontinued in 1965. Replaced by Advanced Liquid-Metal-Cooled Reactor
Advanced Hydride Reactors	10-100	–	–	Up to 20%	Uranium zirconium hydride	NaK	Thermoelectric and Brayton	SNAP-8 technology improvements
Advanced Liquid-Metal-Cooled Reactor	100-600 plus	–	–	15-25%	Fast, uranium nitride	Li	Brayton and potassium Rankine	Basic technology program only
In-Core Thermionic Reactor	100-1,000	8,500 (19,000) at 300 kw	28 (62)**	10-20%	Fast with thermal driver	–	Thermionic	Technology program with emphasis on thermionic fuel element

**Two other advanced reactor concepts were investigated in the basic technology programs: a gas-cooled reactor for use with the Brayton cycle and a boiling-potassium reactor for a Rankine-cycle power plant.*

***With shielding for an unmanned mission.*

D

Appendix D
Timeline (1983 - 2013)



March 1983
President Ronald Reagan proposes Strategic Defense Initiative

January 1986
Challenger accident

October 1986
TFE Verification Program begins

October 18, 1989
Galileo launched

1990
GPHS fueled clad production transferred from SRS to LANL

December 1991
Soviet Union collapses

June 1992
Responsibility for space nuclear thermal propulsion transferred from Defense Programs to Office of Nuclear Energy

July 4, 1997
Rover Sojourner lands on Mars; LWRHUs provide heat for electronics

December 7, 1995
Galileo Orbiter begins circling Jupiter

1980 1985 1990 1995

October 1983
SP-100 Program Phase I begins

October 1985
SP-100 Program Phase II begins

MMW program begins

April 1986
Chernobyl accident

Mid-1987
Timberwind begins (SDIO and DOE)

November 1988
George H.W. Bush elected President

October 4, 1989
Bush announces Space Exploration Initiative

October 6, 1990
Ulysses launched

MMW program terminated

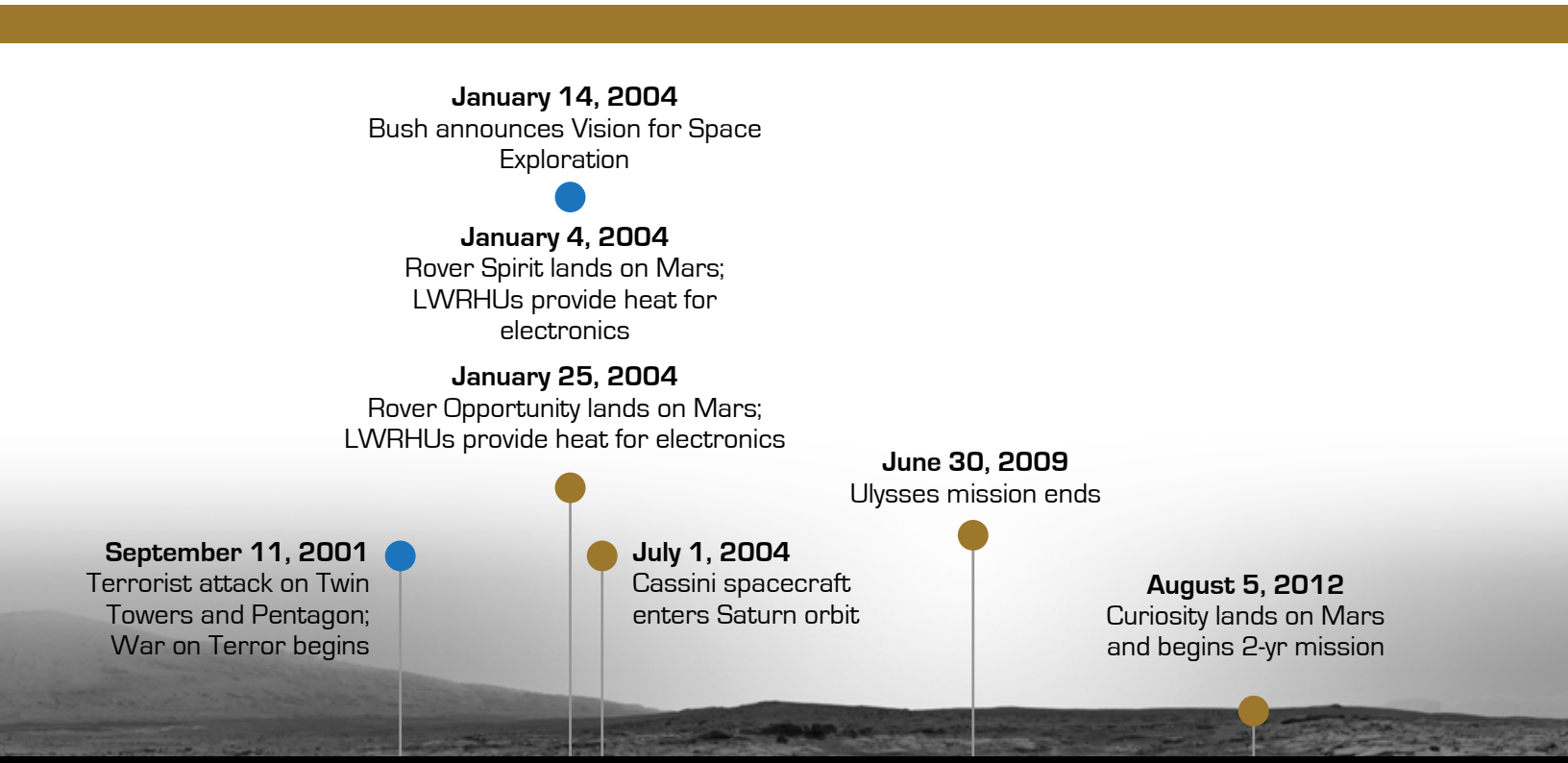
November 1992
William J. Clinton elected President

December 1993
SP-100 Program terminated

1994
TFE Verification Program ends

SNTP program terminated

- **Milieu-Defining Events**
- **Institutional Events**
- **Technical Events and Developments**



January 14, 2004
Bush announces Vision for Space Exploration

January 4, 2004
Rover Spirit lands on Mars; LWRHUs provide heat for electronics

January 25, 2004
Rover Opportunity lands on Mars; LWRHUs provide heat for electronics

June 30, 2009
Ulysses mission ends

September 11, 2001
Terrorist attack on Twin Towers and Pentagon; War on Terror begins

July 1, 2004
Cassini spacecraft enters Saturn orbit

August 5, 2012
Curiosity lands on Mars and begins 2-yr mission

2000 2005 2010

October 15, 1997
Cassini-Huygens launched

November 2000
George W. Bush elected President

2002
RTG assembly and testing operations transferred from Mound to ANL-W (INL)

Bush Nuclear Systems Initiative

March 2003
Prometheus project begins

September 21, 2003
Galileo mission ends

May 2005
Prometheus project terminated

January 19, 2006
New Horizons launched; begins 10-yr journey to Pluto

November 2008
Barack Obama elected President

November 26, 2011
MSL-Curiosity launched; first MMRTG launched

Appendix E
Rover/NERVA Reactor Test Summary[1]

Date	Test Article	Maximum Power	Time at Maximum Power*
July 1, 1959	Kiwi-A	70 MW	5 minutes
July 8, 1960	Kiwi-A'	85 MW	6 minutes
October 10, 1960	Kiwi-A3	100 MW	5 minutes
December 7, 1961	Kiwi-B1A	300 MW	30 seconds
September 1, 1962	Kiwi-B1B	900 MW	Several seconds
November 30, 1962	Kiwi-B4A	500 MW	Several seconds
May 13, 1964	Kiwi-B4D	1,000 MW	~40 seconds
August 28,1964	Kiwi-B4E	900 MW	8 minutes
September 10, 1964	Kiwi-B4E	900 MW	2.5 minutes - restart
September 24, 1964	NRX-A2	1,096 MW	40 seconds
October 15,1964	NRX-A2	Restart	Performance mapping
January 21, 1965	Kiwi-TNT	Safety test reactor - deliberately destroyed on power excursion	
April 23, 1965	NRX-A3	1,093 MW	3.5 minutes
May 20, 1965	NRX-A3	1,072 MW	13 minutes
May 28, 1965	NRX-A3	≤500 MW	46 minutes - performance maps
June 25,1965	Phoebus 1A	1,090 MW	10.5 minutes
March 3, 16, 25, 1965	NRX/EST	1,055 MW	1.25 minutes, 14.5 minutes, 13.7 minutes, respectively
June 8, 1966	NRX-A5	1,120 MW	15.5 minutes
June 23, 1966	NRX-A5	1,050 MW	14.5 minutes (restart)
February 10, 1967	Phoebus 1B	588 MW	2.5 minutes
February 23, 1967	Phoebus 1B	>1,250 MW	30 minutes - low power
December 15, 1967	NRX-A6	1,125 MW	62 minutes
June 8, 1968	Phoebus-2A	2,000 MW	~100 seconds
June 26, 1968	Phoebus-2A	4,100 MW	12 minutes
July 18, 1968	Phoebus-2A	1,280 MW – 3,430 MW	30 minutes of total operation
December 3-4, 1968	Pewee	514 MW	40 minutes
June 11, 1969	XE-Prime	1,140 MW	3.5 minutes
Note: XE-Prime had 28 experimental restarts from December 4, 1968 to September 11, 1969.			
June 29 - July 27, 1972	Nuclear furnace	44 MW	109 minutes (6 experiments)

*Note: in several cases the reactor was operated at lower powers for longer times.

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Acronyms

3M	Minnesota Mining and Manufacturing Company
AEC	Atomic Energy Commission
ANL-W	Argonne National Laboratory-West
ASC	advanced Stirling converter
ASRG	Advanced Stirling Radioisotope Generator
BIPS	Brayton Isotope Power System
BMDO	Ballistic Missile Defense Organization
DARPA	Defense Advanced Research Projects Agency
DIPS	dynamic isotope power system
DNA	Defense Nuclear Agency
DoD	Department of Defense
DOE	Department of Energy
DOE-ID	Department of Energy Idaho Operations Office
DOE-NE	Department of Energy Office of Nuclear Energy
DOE-NR	Department of Energy Office of Naval Reactors
EBR-II	Experimental Breeder Reactor-II
EIS	environmental impact statement
ERDA	Energy Research and Development Administration
ESA	European Space Agency
ETG	electrically-heated thermoelectric generator
FFTF	Fast Flux Test Facility
FMEF	Fuels and Materials Examination Facility
FWPF	fine-weave pierced fabric
GAO	U.S. General Accounting Office
GE	General Electric
GPHS	general purpose heat source
GPS	global positioning system
GRC	Glenn Research Center
HiPEP	High Power Electric Propulsion
INL	Idaho National Laboratory
INSRP	Interagency Nuclear Safety Review Panel
ISA	Italian Space Agency
ISPM	International Solar Polar Mission
IUS	inertial upper stage
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory

KIPS	Kilowatt Isotope Power System
KSC	Kennedy Space Center
kWe	kilowatts of electric power
LANL	Los Alamos National Laboratory
LASL	Los Alamos Scientific Laboratory (later the Los Alamos National Laboratory)
LRL	Lawrence Radiation Laboratory (later the Lawrence Livermore National Laboratory)
LWRHU	light-weight radioisotope heater unit
MHW	multi-hundred watt
MITG	modular isotopic thermoelectric generator
MMRTG	multi-mission radioisotope thermoelectric generator
MMW	multi-megawatt
MOD	modular
MSL	Mars Science Laboratory
MWe	megawatts of electric power
MWt	megawatts of thermal power
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NEPSTP	Nuclear Electric Propulsion Space Test Program
NERVA	Nuclear Engine for Rocket Vehicle Application
NEXIS	Nuclear Electric Xenon Ion System
NRC	National Research Council
NRX	nuclear rocket experimental
NSI	Nuclear Systems Initiative
NSTAR	NASA Solar Technology Application Readiness
ORNL	Oak Ridge National Laboratory
PBR	particle bed reactor
PIPET	PBR Integral Performance Element Tester
PRTR	Plutonium Recycle Test Reactor
psi	pounds per square inch
PuFF	Plutonium Fuel Form Facility
RCA	Radio Corporation of America
RFS	reference flight system
RHU	radioisotope heater unit
RPS	radioisotope power system

RTG	radioisotope thermoelectric generator
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SEI	Space Exploration Initiative
SIG	selenide isotope generator
SNAP	Systems for Nuclear Auxiliary Power
SNL	Sandia National Laboratories
SNPO	Space Nuclear Propulsion Office
SNTP	Space Nuclear Thermal Propulsion
SRG	Stirling radioisotope generator
SRS	Savannah River Site
SSPSF	Space and Security Power Systems Facility
STS	space transportation system
TDC	technology demonstration convertor
TES	Teledyne Energy Systems
TFE	thermionic fuel element
TFEVP	TFE Verification Program
TOPAZ	thermionic experiment with conversion in active zone
TRIGA	Training, Research, and Isotopes General Atomic
TSET	Thermionic System Evaluation Test
VEEGA	Venus-Earth-Earth Gravity Assist
We	watts of electric power
ZPPR	Zero Power Physics Reactor

Index

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Chapter 1

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