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A Note on Information Sources

Various types of materials were used in preparing this history. At the outset, an extensive computer search of the Department of Energy (DOE) library, including the data base at the Oak Ridge Laboratory, revealed that the type of technical reports there would not be helpful in developing this history. Primarily, three other sources of information were relied upon: materials from DOE Archives, which were identified and assembled by Roger Anders of DOE's History Division; the data bases of the Library of Congress, which led to a review of newspapers, periodicals, technical journals, and books; and interviews.

Three classes of information were used: technical events and developments, institutional developments, and related events in the milieu. The five categories of materials used are discussed below.

Printed reports and government documents were used to identify particular facts about the RTGs and the program. Some of the materials provided relevant facts covering broad time periods; other sources pinpointed narrow time periods and revealed program status at a time, or presented important decisions or statements relevant to the program. A few of the materials focused on particular aspects of the program.

Books and pamphlets provided a breadth and depth of understanding. Several stand out for an understanding of the technology and the broad and changing issues of the time period covered: the historical documents about the AEC, ERDA, and the DOE, and the energy chronology produced by the history staff of DOE (Buck, Dean, and Holl) were invaluable in succinctly presenting relevant events in the institutional environment. The work on radioisotopic power generation by Corliss and Harvey was a valuable primer in the technology. For background on the times and glimpses of the views of top-level scientists and administrators, the cited books by Seaborg, Webb, Killian, Kistiakowsky, and Levine were profitable. The Newell book also proved helpful in tracing the history of NASA. Detailed information on specific space missions was found in several NASA documents on Apollo, Viking, and

Voyager; the books by Washburn added an emotional dimension. The books by Rolph and Ford aided in understanding the changing milieu at the time the AEC was disbanded.

Articles from newspapers, periodicals, and technical journals were used to obtain insights into the changing technical, political, and social milieu during the period covered by the history. The articles used in the text are presented in chronological order since the chronology of changing foci and issues was most significant to the history. All of the newspaper articles came from the DOE archives; "Other Articles" cited were uncovered in a topical search for specific facts.

Unpublished materials encompass a number of different types of items uncovered during the research, ranging from documents prepared by program participants, such as Mike Dix and Tom Kerr, to remarks of key functionaries on particular occasions. It is possible that some of this may have been published at a later date.

It should be noted that archives materials were extremely helpful throughout the research and writing of this history. "Letters", "memos", and "news releases" are not cited in the Bibliography although they are cited with full dates in the chapter notes; such materials were invaluable in obtaining insight into day-by-day issues discussed and acted upon by key administrators during particular time periods. They were most numerous in the archives for the AEC years but much less so for ERDA and DOE.

Interviews were emphasized throughout the research, to preserve an oral history of the program on tape. All interviewees were cooperative, helpful, and for the most part eager to share their recollections. Some are now retired but made themselves available for interviews; others took time from busy work schedules to be interviewed. The list of those interviewed represents coverage of differing but important perspectives on and involvements in the program.

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FOOTNOTES

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29. Personal interview with James E. Webb.

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1. Impressions of organizational atmosphere and relationships at AEC/ERDA from personal interview with Bob Carpenter.

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27. Personal interview with Harry Press.
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29. Personal interview with Mike Dix.
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31. "Second Nimbus-B," NASA news release, June 28, 1968. (From DOE archives.)
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13. Personal interview with John Dassoulas.
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15. "Apollo 17/SNAP-27 Status Report," December 13, 1972. (From DOE archives.)
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18. Information from *Aeronautics and Space Report of the President: 1980 Activities*, (Washington: National Aeronautics and Space Administration, 1980), pp. 95-97; Appendixes B-1, B-2, and B-3.

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25. Mark Washburn, *Mars At Last!* (New York: G.P. Putnam's Sons, 1977), p. 217.

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Division of Nuclear Research and Applications, January 27, 1977. (From DOE archives.)

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58. "NASA Moves to Salvage Planetary Program," *Aviation Week & Space Technology*, November 2, 1981, p. 16.

59. "Science Academy Asks Caution In Research, Development Cuts," *Aviation Week & Space Technology*, November 2, 1981, p. 16.

60. "Better Than Nothing" (by William H. Gregory), *Aviation Week & Space Techology*, July 12, 1982, p. 13. President Reagan quoted from *Public Papers of the Presidents of the United States: Ronald Reagan, 1982, Book II* (Washington: U.S. Government Printing Office, 1983), p. 892.

CHAPTER VIII

1. Personal interview with Jerry Soffen.
2. Personal interview with Rod Mills.
3. Personal interviews with Vincent Truscello and Gerald Stapfer.
4. Personal interview with Guy Linkous.
5. Personal interview with Bob Carpenter.
6. Holl, op. cit., pp. 9-10.
7. *Ibid.*, p. 10.
8. Personal interview with Bernard Rock.
9. *Program Plan: . . . 6/12/84*, op. cit., p. 3.
10. *Ibid.*, p. 6.
11. Personal interview with Bernard Rock.
12. See, for example, "Bean-Counting the Solar System" (by William H. Gregory), *Aviation Week & Space Technology*, December 14, 1981, p. 11.
13. Washburn, *Distant Encounters*, op. cit., p. 262; citation of project scientist, *ibid.*

APPENDIX A. CHRONOLOGY

Time Period	Milieu-Defining Events	Institutional Events	Technical Events & Developments
1896			H Becquerel discovers radioactivity
1913			H G J Moseley reports construction of first nuclear battery
1945			Nuclear battery (of Lebanov & Beliakov) generates 10^{9} amps device built by P H Miller using PO 210
July August 1945	First A bomb detonated at Alamogordo Hiroshima and Nagasaki bombs dropped Atomic Age begins		
June July 1946	Operation Crossroads conducted at Bikini		
August 1946		AEC established by Atomic Energy Act	
Jan 1947		AEC begins operations under David E Lilienthal	
Oct 1947		AEC appoints Industrial Advisory Group to investigate peaceful uses of atomic energy	
1948 1952	U S conducts numerous atomic tests in Pacific & Nevada Soviets detonate their first A bomb in 1949 first U S test of experimental thermonuclear device at Eniwetok in 1952		
July 1950		Gordon Dean becomes chairman of AEC	
1951			AEC lets series of contracts to study 1 kw electrical space power plant using reactors or isotopes
1952			RAND issues Project Feedback report discussing radioisotopic power for space Several companies recommend using isotopes for space power as result of AEC contracts
Nov 1952	Eisenhower elected President		
July 1953		Lewis Strauss becomes head of AEC	
Dec 1953	Eisenhower delivers Atoms for Peace speech before U N		
Aug 1954	Atomic Energy Act of 1954 gives added impetus to development of peacetime atomic uses & private development of reactors		
1954			K C Jordan & J H Birden build nuclear thermoelectric generator at Mound Laboratory

July 1955	Eisenhower proposes "Open Skies" policy for mutual aerial inspection during Geneva Summit		
Aug 1955		Space nuclear auxiliary power program begins in Joint AEC/DOD Aircraft Nuclear Propulsion Office	Upon DOD request AEC begins work on nuclear auxiliary power system (reactor and RTG) for USAF uses
Feb 1956	AEC makes available 20,000 kilograms of U-235 for use in power and research reactors abroad and 20 000 kilograms for power reactors in U S		
Mar 1956			AEC low-level effort undertaken by Martin Baltimore for isotope-fuel space power unit for military satellite
July 1956		AF advanced reconnaissance system designated WS-117L	AEC proceeds with development of heat source for WS-117L
Nov 1956	Eisenhower re-elected		
Oct 1957	Soviets launch Sputnik Name "Pied Piper' (AF code name for 117L) compromised by *Aviation Week* article		New unclassified title of 'SNAP" authorized to refer to AEC's work on Space Nuclear Auxiliary Power
Nov 1957		President's Science Advisory Committee created	
July 1958		John McCone becomes chairman of AEC NASA established	
Aug 1958	Eisenhower announces moratorium on weapons testing (to begin Oct 31)	T Keith Glennan appointed first administrator of NASA	
Nov 1958 Sept 1961	U S Great Britain, & U S S R agree to moratorium on atmospheric nuclear testing		
Jan 1959	Eisenhower reveals existence of plutonium fuel (by product of weapons development) for spacecraft		Martin Company and AEC demonstrate SNAP 3B to president
May 1960	Summit conference broken up by U-2 incident		
Oct 1960		Joint AEC/NASA Nuclear Propulsion Office created with Harold Finger as head	
Nov 1960	Kennedy elected President		
Feb 1961		James E Webb becomes head of NASA	
Mar 1961		Glenn Seaborg named AEC chairman atomic regulatory function placed under AEC Director of Regulations	
May 1961	Kennedy gives special message to Congress committing U S to reach the Moon "before decade is out"		

June 1961			SNAP 3 A orbits successfully on Navy TRANSIT 4A navigational satellite
Sept 1961	Soviets break nuclear test moratorium Kennedy orders resumption of underground testing		
Nov 1961			Second SNAP 3 A orbits successfully on Navy TRANSIT 4B navigational satellite
Feb 1962	John Glenn becomes first U S astronaut to orbit the earth		
April 1962	Kennedy authorizes resumption of atmospheric testing		
June 1962		Office of Science & Technology created in Executive Office of President	
July 1962 June 1963	Underground tests conducted in Nevada		
Oct 1962	Cuban Missile Crisis		
Aug 1963	Limited Nuclear Test Ban Treaty signing by U S Great Britain & U S S R		
Sept 1963			SNAP 9 A orbits successfully on Navy TRANSIT 5BN 1 navigational satellite
Nov 1963	Kennedy assassinated Lyndon Johnson becomes President		
Dec 1963			Second SNAP 9 A orbits successfully on Navy TRANSIT 5BN 2 navigational satellite
April 1964			Third SNAP 9 A launched on Navy TRANSIT 5BN 3 mission aborted (SNAP burned up on re entry)
Aug 1964	Gulf of Tonkin resolution begins heavy U S involvement in Vietnam Johnson signs Private Ownership of Special Nuclear Materials Act		
Nov 1964	Johnson elected President		
Dec 1964		AEC issues permit to construct Oyster Creek power plant—first civilian reactor built on competitive basis without government assistance	
1965 1970	U S involvement in Vietnam increases criticism of government and protests about nuclear safety begins to place stress on space budgets		

April 1965			SNAP 10 (reactor) successfully achieves orbit
June 1965		Harold Finger heads new Space Nuclear Systems Division of AEC	
Nov 1965		Finger decentralizes many space nuclear functions to laboratories	
Jan 1967	Fire on APOLLO at Cape Kennedy delays lunar program		
Mar 1967		Harold Finger receives new permanent assignment at NASA replaced in AEC and RTG program roles by Milton Klein	
Feb 1968	Tet offensive in Vietnam		
April 1968	M L King Jr assassinated		
May 1968			SNAP 19B2 launched on NIMBUS B 1 weather satellite mission aborted heat source retrieved
June 1968	Robert F Kennedy assassinated		
July 1968	Treaty for Non Proliferation of Nuclear Weapons signed		
Oct 1968		James Webb retires as administrator of NASA	
Nov 1968	Nixon elected President		Official decision made not to use SNAP device on first APOLLO lunar landing
Dec 1968	APOLLO 8 orbits Moon		
Jan 1969		Council on Environmental Quality established	
Mar 1969		Thomas O Paine becomes NASA administrator	
April 1969			SNAP 19B3 launched on NIMBUS III successfully achieves orbit
July 1969	APOLLO 11 lands on Moon		
Nov 1969			SNAP 27 device successfully placed on lunar surface on APOLLO 12 mission
Jan 1970		Russell Train appointed chairman of Council on Environmental Quality first report of Council submitted to Congress in August 1970	

Mar 1970	Treaty for Non Proliferation of Nuclear Weapons ratified by U S Great Britain U S S R & 45 other nations		
April 1970	Millions participate in first Earth Day anti pollution demonstrations APOLLO 13 mission aborted on way to Moon		SNAP 27 heat source returned to Tonga Trench in deep Pacific
May 1970	Campus unrest and Kent State killings follow president s announcement of Cambodian incursion		
July 1970		Environmental Protection Agency and National Oceanic & Atmospheric Administration created	
Jan 1971			SNAP 27 device successfully placed on lunar surface on APOLLO 14
June 1971		President proposes new Department of Natural Resources	
July 1971			SNAP 27 device successfully placed on lunar surface on APOLLO 15
Aug 1971		James R Schlesinger becomes chairman of AEC replacing Seaborg	
Nov 1971		David Gabriel replaces Milton Klein as director of Space Nuclear Systems Division	
Feb 1972	President Nixon visits China pledges normalization of relations		
Mar 1972			SNAP 19 device successfully launched on PIONEER 10 to Jupiter and beyond
April 1972			SNAP 27 device successfully placed on lunar surface on APOLLO 16
May 1972	President Nixon visits U S S R holds summit talks and signs SALT I		
Sept 1972			TRANSIT RTG device successfully orbits on Navy TRIAD 01 1X navigational satellite
Nov 1972	Nixon re elected President		
Dec 1972			SNAP 27 device successfully placed on lunar surface on APOLLO 17

Jan 1973	North and South Vietnam and U S sign peace treaty officially ending Vietnam conflict and U S involvement	Joint AEC NASA Space Nuclear Systems Office dissolved	Major cutbacks made in nuclear rocket propulsion & space reactor programs
Feb 1973		Dixy Lee Ray designated AEC chairman	
Mar 1973	Last GIs leave Vietnam		
April 1973		National Energy Office established in Executive Office of the President	SNAP 19 device successfully launched on PIONEER 11 to Jupiter Saturn and beyond
June 1973		President proposes to Congress a Department of Energy & Natural Resources & an independent Energy Research & Development Administration (ERDA)	
Summer 1973	Watergate hearings held in Washington		
Oct 1973	Yom Kippur War Arab OPEC countries embargo oil sales to U S	President establishes Energy Research and Development Advisory Council	
Nov 1973	President Nixon calls for Project Independence (re energy)		
Dec 1973	Gerald Ford sworn in as vice president following resignation of Spiro Agnew	Federal Energy Office established	SNAP 19 powers PIONEER 10 in its fly by of Jupiter
May 1974		Federal Energy Administration Act establishes Federal Energy Administration incorporating Federal Energy Office	
Aug 1974	President Nixon resigns Vice President Ford becomes President		
Oct 1974		Ford signs Energy Reorganization Act of 1974 abolishing AEC and establishing ERDA and Nuclear Regulatory Commission	
Dec 1974			SNAP 19 powers PIONEER 11 in its fly by of Jupiter
Jan 1975		ERDA activated Robert Seamans Jr named administrator RTG programs become part of new Division of Nuclear Research and Applications	
April 1975	South Vietnam falls to North Vietnamese		
Aug 1975			SNAP 19 device successfully launched on VIKING 1 mission to Mars
Sept 1975			SNAP 19 device successfully launched on VIKING 2 mission to Mars

Mar 1976			MHW devices successfully orbit on LES 8/9 DOD communication satellites
May 1976		ERDA assumes responsibility for managing Clinch River Breeder Reactor	
July Aug 1976			SNAP 19 devices successfully power VIKINGs 1 and 2 in Mars landings
Nov 1976	Carter elected President		
April 1977	President announces U S will defer reprocessing of spent reactor fuel indefinitely delays Clinch River development	President proposes a Cabinet level Department of Energy (DOE)	
Aug 1977		Energy Reorganization Act creates DOE abolishing ERDA Federal Energy Administration and Joint Committee on Atomic Energy	MHW device successfully launched on VOYAGER 2 mission to Jupiter Saturn and beyond
Sept 1977			MHW device successfully launched on VOYAGER 1 mission to Jupiter Saturn and beyond
Oct 1977		DOE activated James Schlesinger nominated as first Secretary of Energy	
Jan 1978	Soviet spy satellite containing nuclear reactor breaks up over northwest Canada		
Mar 1978	Nuclear Non Proliferation Act authorizes president to pursue international studies on proliferation of nuclear materials		
Jan 1979	Revolution forces Shah of Iran to flee		
Mar 1979	Three Mile Island accident		
July 1979			MHW successfully powers VOYAGER 1 fly through of Jovian system
Aug 1979		Charles Duncan Jr named Secretary of Department of Energy	MHW successfully powers VOYAGER 2 fly through of Jovian system
Sept 1979			SNAP 19 successfully powers PIONEER 10 in Saturn fly by
Nov 1979	U S embassy hostages seized in Iran		
Nov 1980	Ronald Reagan elected President		MHW successfully powers VOYAGER 1 in rendez vous with Saturnian system

Jan 1981		James B Edwards named Secretary of Department of Energy	
Feb 1981	Reagan presents "America's New Beginning A Program for Economic Recovery" to Congress	Edwards announces major reorganization of DOE creates Energy Policy Task Force	
Aug 1981			MHW successfully powers VOYAGER 2 in rendez vous with Saturnian system
Oct 1981	Reagan announces nuclear energy policy proposes accelerated deployment of methods for storing high-level radioactive waste lifts ban on commercial reprocessing of nuclear fuel		

TABLE B. TABLE OF ISOTOPE SYSTEMS IN SPACE

Power Source	*Sponsoring Agency and Spacecraft*	*Mission Type*	*Launch Date*	*Outcome*
SNAP-3A	Navy-Transit 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP-3A	Navy-Transit 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-3	Navigational	April 21, 1964	Mission aborted; burned up on re-entry
SNAP-19B2	NASA-Nimbus-B-1	Meteorological	May 18, 1968	Mission aborted; heat source retrieved
SNAP-19B3	NASA-Nimbus-III	Meteorological	April 14, 1969	Successfully achieved orbit
SNAP-27	NASA-Apollo 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP-27	NASA-Apollo 13	Lunar	April 11, 1970	Mission aborted on way to Moon; heat source returned to South Pacific Ocean
SNAP-27	NASA-Apollo 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP-27	NASA-Apollo 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP-19	NASA-Pioneer 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter and beyond
SNAP-27	NASA-Apollo 16	Lunar	April 16, 1972	Successfully placed on lunar surface
Transit-RTG	Navy-"Transit" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP-27	NASA-Apollo 17	Lunar	Dec. 7, 1972	Successfully placed on lunar surface
SNAP-19	NASA-Pioneer 11	Planetary	April 5, 1973	Successfully operated to Jupiter, Saturn, and beyond
SNAP-19	NASA-Viking 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP-19	NASA-Viking 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	AF-LES 8	Communications	Mar. 14, 1976	Successfully achieved orbit

MHW	AF-LES 9	Communi-cations	Mar. 14, 1976	Successfully achieved orbit
MHW	NASA-Voyager 2	Planetary	Aug. 20, 1977	Successfully operated to Jupiter, Saturn, and beyond
MHW	NASA-Voyager 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter, Saturn, and beyond

APPENDIX C. BUDGETS FOR THE RTG PROGRAM

TABLE C: BUDGETS FOR THE RTG PROGRAM*
(Figures in thousands of dollars)

1956	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*	*1963*	*1964*	*1965*
46	485	1,890	3,526	2,386	1,170	4,189	11,279	27,260	28,643
1966	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*
37,158	48,154	35,516	29,703	20,645	18,294	16,372	29,030	27,900	27,272
1976	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*
25,085	29,137	24,100	34,000	33,700	36,000	34,246	37,962	27,735	27,950

Explanation of Budget Figure Aggregations

The space RTG program existed under many organizational names and within many organizational configurations. Therefore, it is not readily identifiable as a single, separate entity through the years since 1956. In preparing the budget figures and plottings for APPENDIX C, the following procedures were followed to identify dollar amounts that could be said to represent allocations to the "Space RTG Program":

- for the years 1956-1972, subtotals were obtained from budgets for "Space Electric Power Development" at the AEC. The specific line items included to arrive at the program totals were: "Radioisotopes," "Power Conversion Technology," "Space Nuclear Safety," and "Isotope Fuel Development." "Isotope Fuel Development" did not appear as a budget item until 1962.
- for the years 1973-1974, two items were taken from the "Space electric Power Program" budgets: "Total Isotope Systems *Operating*" funds and "Total Radioisotope Systems Equipment" funds.
- for 1975, two items were taken from the "Space Nuclear Systems Program" budget: "Total Space Electric Power *Operating*" funds and "Total Space Electric Power Equipment" funds.
- for 1976 and 1977, three items were taken from the "Nuclear Research and Applications Program" budgets: "Total Space Applications *Operating*," "Space Applications *Capital Equipment*," and "Advanced Isotope Separation Technology *Capital Equipment*" funds.

- for 1978 and 1979, totals for "Space and Terrestrial Applications *Operating* Expenses" "Space and Terrestrial Applications *Capital* Equipment" were used, but from each of these totals, sub-items for "*Terrestrial* Isotope Applications" were subtracted. In 1978, the latter amount was substantial for "Operating," $4,400 thousand; but in 1979, the figure on this item was $4,300 thousand.
- for 1980-1982, subtotals under "Advanced Nuclear Systems" were taken for "Space and Terrestrial Applications *Operating* Expenses" and ". . . *Capital Equipment*," and the sub-item "*Terrestrial* Isotope Applications" was subtracted, amounting to $2,000 to $2,700 thousand in each of those years.
- for 1983-1985, subtotals under "Advanced Nuclear Systems" were taken for "Space and Special Applications *Operating* Expenses" and ". . . *Capital Equipment*," and the sub-item "*Special* Applications" (described as heavily terrestrially-oriented) was subtracted. This item amounted to -0- in 1983 and $1,000 thousand in 1984 and 1985.

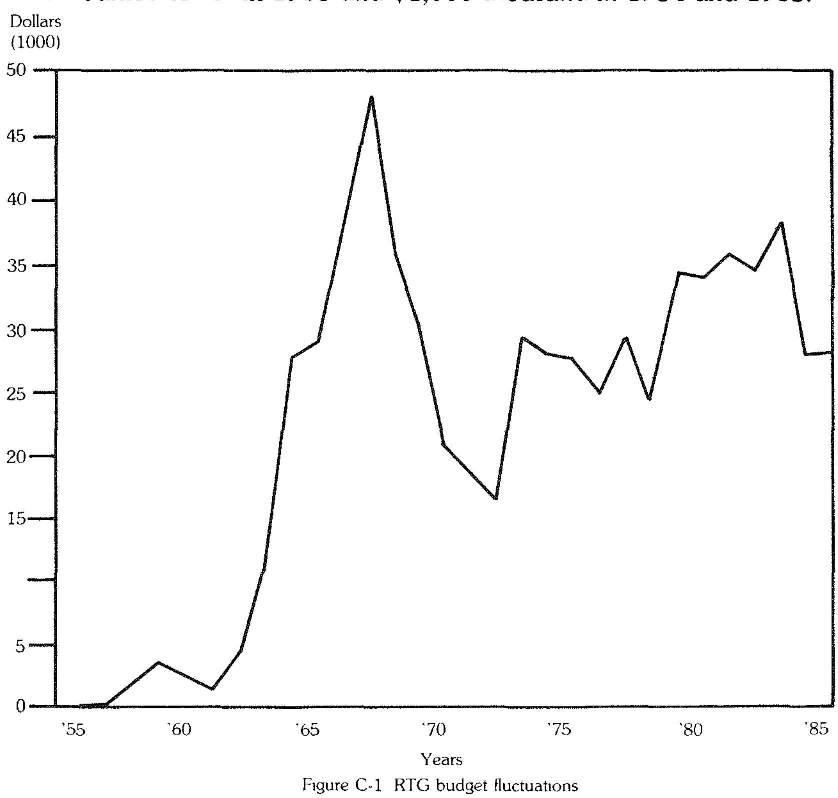

Figure C-1 RTG budget fluctuations

APPENDIX D. CHANGES IN ORGANIZATIONAL LOCATIONS OF THE RTG PROGRAM

During the years 1955-1982, the location of the RTG program within government agencies changed from time to time. (See organization charts in Figs. D-1 to D-7.

1955-1960

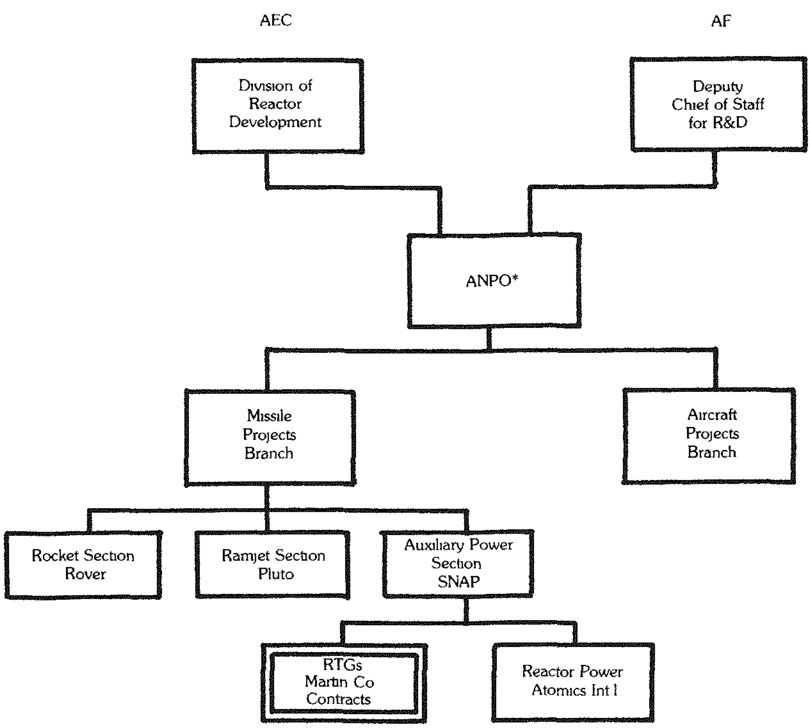

Figure D-1

*Aircraft Nuclear Propulsion Office (Joint AEC/AF).

1961-1965
(As of August 1960)

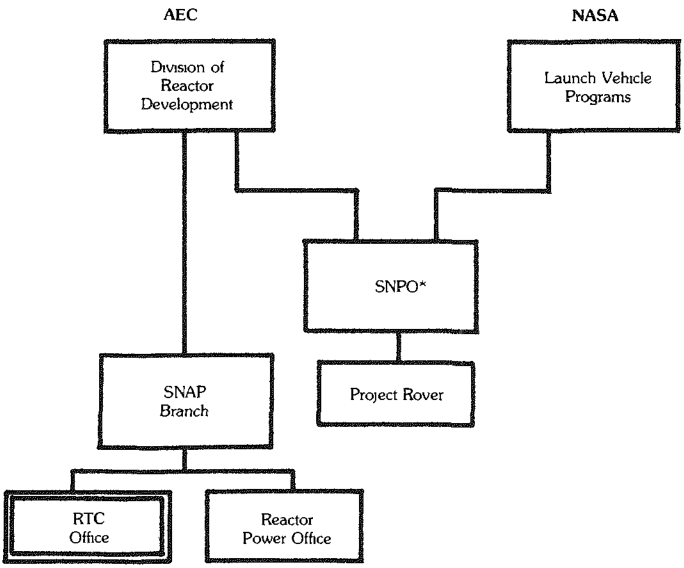

Figure D-2

*Space Nuclear Propulsion Office (Joint AEC/NASA).

1965-1972*

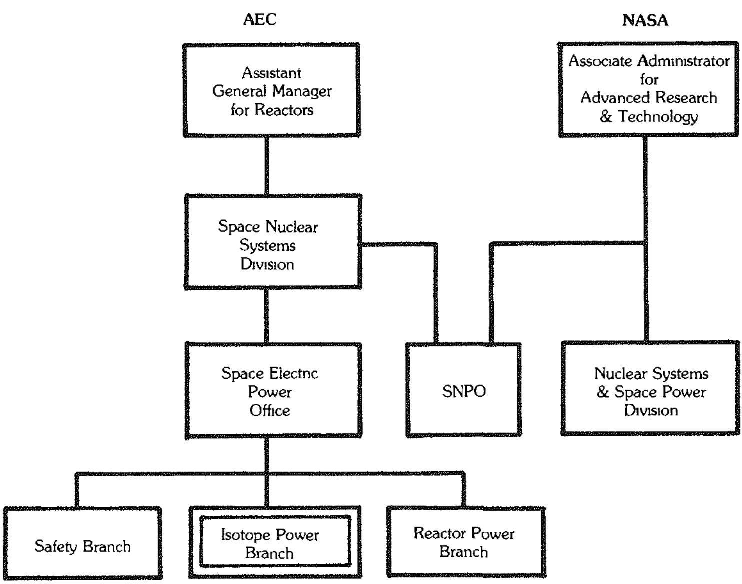

Figure D-3

*After creation of Space Nuclear Systems *Division* at AEC. There were 23 divisions at the Commission at this time.

1973-1974*
AEC

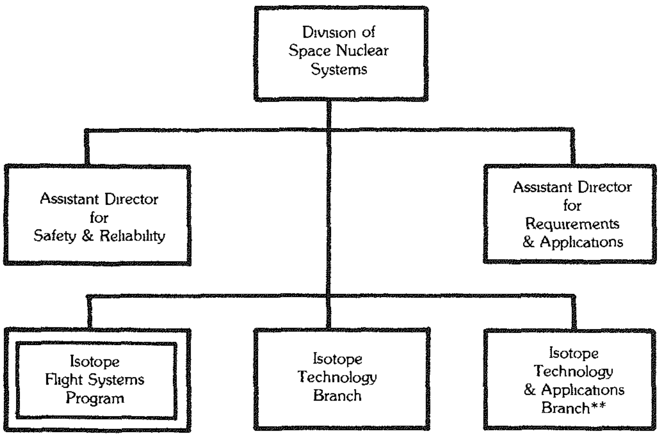

Figure D-4

*After dissolution of Joint AEC/NASA Space Nuclear Propulsion Office.
**Earlier divided into *Reactor Power Systems Branch & Power Conversion Branch.*

1975-1977
ERDA

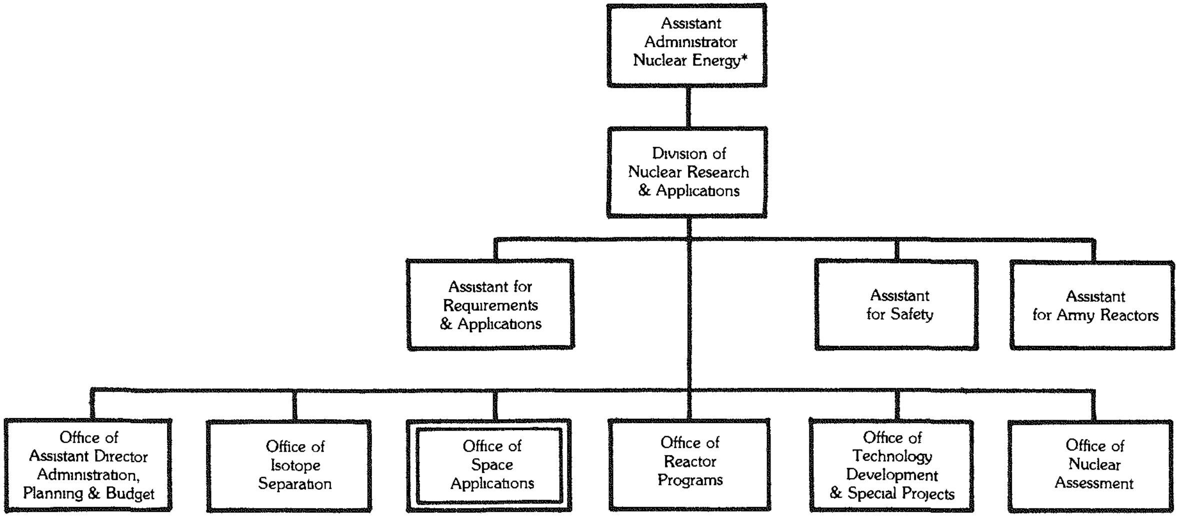

Figure D-5

*Other "Assistant Administrators" at ERDA were for. Administration, Conservation; Environment and Safety, Field Operations, Fossil Energy; International Affairs, National Security; Planning & Analysis, Geothermal & Advanced Energy Systems.

1978-1981
DOE

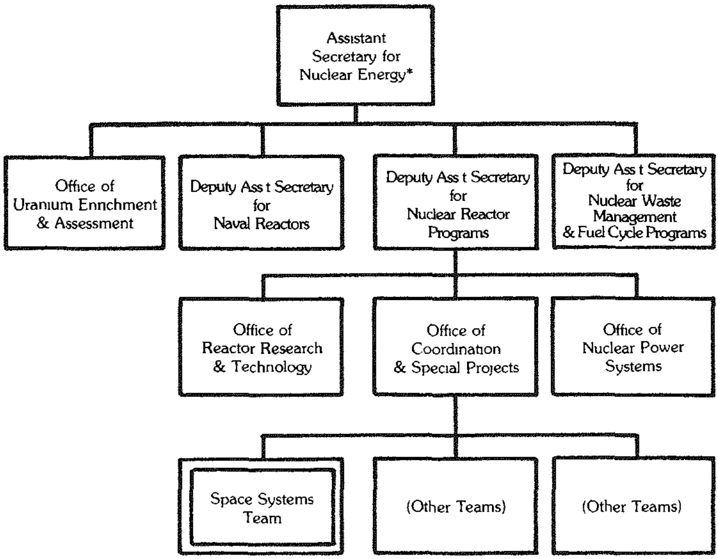

Figure D 6

*At first the term at this level was *Energy Technology*, later it became *Nuclear Energy* Other Assistant Secretaries at DOE were for Conservation & Solar Applications, Defense, Environment, Intergovernmental & Institutional Affairs, International Affairs, Policy & Evaluation Resource Application

1982*
DOE

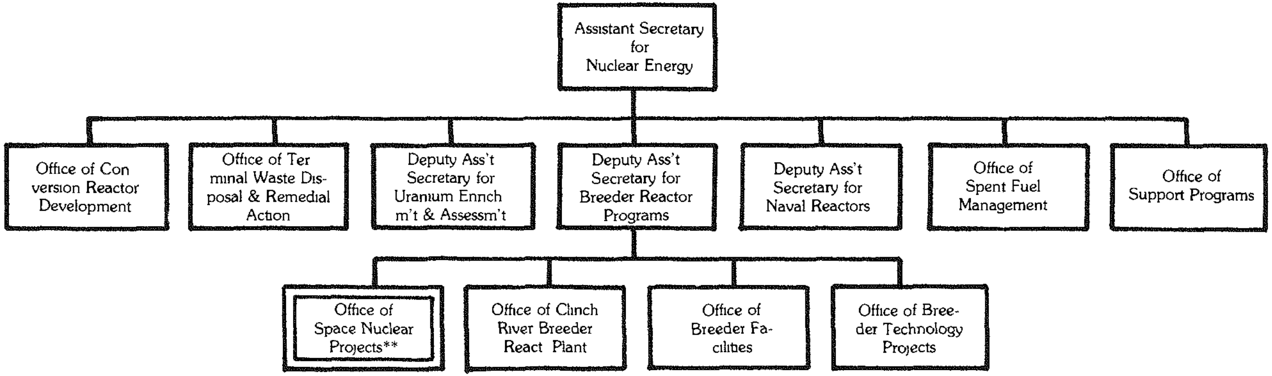

Figure D-7

*Although configurations varied somewhat under DOE/*Nuclear Energy*, just two are shown Before and after a reorganization which "flattened" the organization
**Later this was designated *Space & Terrestrial Applications Programs*, and then *Space & Special Applications Programs.*

TABLE E. DEVELOPMENTS IN RTG TECHNOLOGY

PARAMETERS	*SNAP-3B*	*SNAP-9A*	*SNAP-19*	*SNAP-27*	*TRANSIT-RTG*	*MHW-RTG*	*GPHS-RTG*
MISSION	TRANSIT 4	TRANSIT 5BN	PIONEER	APOLLO	TRIAD	VOYAGER	GALILEO
BOM POWER[a] PER RTG, W(E)	2.7	26.8	40.3	73.4	35.6	158.0	292.0
THERMOELECTRIC MATERIAL	PBTE 2N/2P	PBTE 2N/2P	PBTE 2N/ TAGS-8	PBTE 3N/3P	PBTE 2N/3P	SIGE	SIGE
PU-238 FUEL FORM	METAL	METAL	PMC[b]	OXIDE MICRO-SPHERES	PMC[b]	PRESSED OXIDE	PRESSED OXIDE
CONVERSION EFFICIENCY, %	5.1	5.1	6.2	5.0	4.2	6.6	6.6
SPECIFIC POWER W(E)/KG	1.29	2.2	3.0	2.3[c]	2.6	4.2	5.2

Source Gary Bennett, James J. Lombardo, and Bernard J. Rock, *U.S. Radioisotope Thermoelectric Generator Space Operating Experience (June 1961-December 1982)*, Paper presented before the 18th Intersociety Energy Conversion Engineering Conference, Orlando, Florida, August 21-26, 1983.
[a]Beginning-of-Mission.
[b]Plutonia Molybdenum Cermet. (Cermet: a heat-resistant alloy formed by compacting and sintering a metal and a ceramic substance.)
[c]The SNAP-27 Specific Power is calculated with the mass of the fuel cask included.

The table above indicates changes and improvements in the RTG technology from early SNAP-3 devices to the GPHS = RTG to be used on the GALILEO mission.

*Significance of Developments in RTG Technology**

Essentials of the Technology. An RTG basically consists of a radioisotopic heat source and a thermoelectric converter that transforms thermal energy into electrical energy through two conductors, made of different metals, which are at different temperatures at their point of juncture. The heat results from the radioactive decay of plutonium-238, a radioisotope which has a half-life of 87.8 years. Plutonium-238 fueled all RTGs that flew on U.S. space missions. The principal decay process of this radioisotope is by emission of alpha particles, which are easily absorbed in the heat source to produce heat and require no special shielding.

Design Type and Trends. The RTG's flown since 1961 can be grouped into six basic design concepts—SNAP-3, SNAP-9A, SNAP-19, SNAP-27, TRANSIT-RTG, MHW-RTG. The general trend was to improve generator performance, efficiency, and specific power (electric power per kg of weight).

Basic Improvements. Power requirements for missions rose from a few watts electric to the 292 W(e) required in the forthcoming Galileo mission. Conversion efficiency rose slightly but specific power improved greatly as lighter weight converter materials (Beryllum or aluminum) reduced mass, even as fuel loadings increased and high-temperature thermoelectric power-conversion materials were introduced.

Snap-3(B). Each generator in the SNAP-3(B) RTG, which was the first to fly, was designed to provide an initial power output of 2.7 W(e). Heat source was approximately 52.5 W(t) of encapsulated plutonium-238 metal. Design life was five years. The power-conversion subsystem consisted of 27 spring-loaded, series-connected pairs of PbTe 2N/2P thermoelectric elements operating at a hot-juncture temperature of about 783 K and a cold-juncture temperature of about 366 K. This subsystem had a power-conversion efficiency of 5 to 6 percent and specific power of 1.29.

SNAP 9A. RTGs were adopted for the DOD Transit 5BN-1 and 5BN-2 satellites because RTGs are inherently radiation-resistant, while solar cells on earlier Transits were adversely affected by the 1962 high-altitude nuclear explosion. Each SNAP-9A was designed to provide 25 W(e) at a nominal 6V for five years in space after one year of storage on Earth. Thermal inventory of approximately 525 W(t) was supplied by Pu-238 metal encapsulated in a heat

*Abstracted from Bennett et al, 1983 paper (op. cit.) and *Enhancing Technology Leadership: Space . . .* (op. cit.), by the same authors.
W(e) = Watts electric
W(t) = Watts thermal
K = Kelvin

source of six fuel capsules maintained in a segmented graphite heat-accumulator block. The main body of the sealed generator was a cylindrical magnesium-thorium shell containing six heat-dissipating magnesium fins and 36 threaded holes; 70 pairs of series-connected PbTe 2N/2P thermoelectric couples were assembled in 35 modules of two couples each. Hot-junction temperature was calculated at about 790 K at beginning of life. Some waste heat from the RTG was used to maintain electronic instruments in the satellite at a temperature near 293 K.

SNAP-19. This technology-improvement program built on the SNAP-9A developments. The SNAP-19B power system was designed specifically for NASA's Nimbus weather satellites—a first demonstration of RTG technology aboard NASA spacecraft. Modifications to SNAP-19B were required to power the Pioneer and Viking missions.

Nimbus/SNAP-19. Specifications required 50 W(e) deliverable after one year in orbit. Two SNAP-19B's, with higher fuel loadings than those of SNAP-9A, were used on Nimbus III. To meet safety requirements, the Pu-238 fuel was changed from a metal form to oxide microspheres. Thermoelectric elements were made of cold-pressed and sintered PbTe. Each RTG thermopile consisted of 90 PbTe 3P/2N couples distributed in six modules of three parallel rows of five couples each. Modules were connected in series and enclosed in a magnesium-thorium housing. Hot-junction temperature was 800K. The two RTG's produced 56 W(e) — 49.4 W(e) usable — at launch and 47 W(e) one year later. Unlike the sealed capsules used in SNAP-3B and SNAP-9As, the SNAP-19B fuel capsule was vented into the generator. Possible sources of power degradation were identified as: rate of argon leakage; replacement of argon with helium in fuel decay; oxygen released from the PuO fuel attacking the thermoelectric elements and bonds. Design of subsequent RTGs was changed to reduce these sources of degradation.

Pioneer/Snap-19. Improvements for powering the Jupiter fly-by were made in the 19B converter, heat source, and structural configuration. A TAGS-SnTe/2N* thermocouple was designed with modified electrical circuitry to limit the magnetic field from the RTG to very low levels. Fill gas was a 75:25 helium-argon mixture, with a zirconium getter added to eliminate oxygen in the RTG. End covers were bolted and seam-welded to the cylindrical housing to further reduce gas leakage. Mission requirement called for four RTGs to produce 120 W(e) total at the Jupiter fly-by. Power output at Jupiter encounter was 144 W(e) for Pioneer 10 and 142.6 W(e) for Pioneer 11. Estimated minimum power requirements for a Saturn fly-by were 90 W(e) and the RTG's on Pioneer 11 actually provided 119.3 W(e) at Saturn.

*TAGS: a solid solution of silver antimony telluride in germanium telluride.

Viking SNAP-19. Distinctive mission requirements for Viking included high-temperature (400 K) sterilization, storage during the long cruise to Mars, and ability to withstand the rapid, extreme temperature changes of the Martian day-night thermal cycle. Each Viking Lander used two Snap-19 RTG's modified to meet those requirements. Each RTG was to produce a minimum of 35 W(e) during a 90-day Mars surface mission following an 11 to 12-month cruise after launch. The two series-connected RTGs were the primary power sources on each Viking Lander, supplying the energy for scientific instruments and for recharging four nickel-cadmium batteries. The RTGs also supplied the Landers with thermal energy. All four RTGs more than met the 90-day requirement.

A modification from Pioneer SNAP-19 was the addition of a dome reservoir. Initial fill gas for the converter was a 90:10 helium-argon mixture; the reservoir was filled with a 95:5 argon-helium mixture. This configuration permitted a controlled interchange of gases in the two volumes to minimize heat-source operating temperatures up to launch while maximizing electrical output at the end of the mission. Although data-relay capability ended, the RTGs on the Viking Landers were still operating when last transmissions were received and those on Viking Lander-1 were capable of providing power through 1994.

In the development of the SNAP-19s, the principal contribution to power degradation was judged to come from gas effects. Changes made in SNAP-9A and Nimbus SNAP-19 designs significantly minimized the degradation effects in the SNAP-19s.

SNAP-27. The SNAP-27 RTG was developed to power the experiments of NASA's Apollo Lunar Surface Experiments Package (ALSEP). The RTG design requirement was to provide at least 63.5 W(e) at 16 V DC one year after lunar emplacement. The use of RTGs was a natural choice because of their light weight, reliability, and ability to produce full electrical power during the long lunar night-day cycle. Since the ALSEPs were to be positioned manually by the astronauts, the designers took advantage of this assembly capability: the converter and sealed-fuel-capsule were kept separate in the Lunar Module and assembled on the Moon.

SNAP-27 used 442 thermoelectric couples made of PbTe 3N/3P elements arranged in two series strings of 221 couples connected in parallel. Heat from the fuel capsule, which was loaded with Pu-238 oxide microspheres and had a nominal rating of 1,480 W(t), was transmitted to the hot frame of the RTG by radiation coupling. Design analysis and ground tests indicated that the hot-junction temperature was about 866 K and the cold-side thermoelectric temperature was maintained at about 547 K in the lunar environment. Both the cold frame and the outer case were made of beryllium. Eight cross-rolled beryllium fins were attached integrally to the outer case by brazing. The converter had a mass of 12.7 kg. The mass of the fuel-capsule assembly, without the graphite Lunar Module cask, was about 7 kg.

Five SNAP-27 powered ALSEPs were placed on the lunar surface. In each case, all of the RTGs exceeded their mission requirements in both power and life-cycle. All five ALSEPs, powered by RTGs, were operating when NASA shut down the stations on 30 September 1977.

Transit-RTG. The Transit-RTG was developed specifically as the primary power source for the DOD TRIAD navigational satellite. Auxiliary power was provided by four solar-cell panels and one 6 Ah nickel-cadmium battery. The objective of the Transit-RTG program was to produce an RTG capable of providing a minimum end-of-mission power of 30 W(e) after five years, at a minimum of 3 V. To do this, the 12-sided converter used light-weight PbTe thermoelectric panels (Isotec) that operated at a low hot-side temperature of 673 K in a vacuum, eliminating the need for hermetic sealing and a cover gas to inhibit the sublimation of thermoelectric material. The Transit-RTG was designed to be modular; each of the 12 Isotec panels contained 36 PbTe 2N/3P couples arranged in a series-parrallel matrix with four couples in a row in parallel and nine rows in series. The panels were supported structurally by 12 webbed, magnesium-thorium corner posts with teflon insulators. The masses of the converter and heat source were 5.98 and 4.2 kg respectively. Including a titanium heat-source cage and support structure, the Transit-RTG had a mass of about 13.6 kg. The short-term objectives of the TRIAD satellite were demonstrated, including a checkout of RTG performance; however, a telemetry-converter failure caused a loss of further telemetry data. The TRIAD satellite continues to operate normally and to provide magnetometer data using power from the RTG.

MHW-RTG. The MHW-RTG was designed to provide a major increase in the power output of a space RTG. The DOD Lincoln Experimental Satellites 8 and 9 required 125 W(e) per RTG, with an output voltage of 30 ($\pm$0.5) V at the end of mission — an operational life of at least five years after launch. The NASA VOYAGER mission required 128 W(e) per RTG, with an end-of-mission output of 30 ($\pm$0.5) V or an operational life of at least four years after launch. To achieve these requirements, the MHW-RTG was equipped with a new heat source of 24 pressed plutonium oxide fuel spheres, each producing about 100 W(t). Electrical conversion was achieved through 312 silicon-germanium (SiGe) thermoelectric couples—high temperature alloys. The converter consisted of a beryllium outer case; end-closure structures that physically held the heat source; thermoelectric elements; a multifoil (molybdenum-Astroquartz) insulation packet and a molybdenum internal frame; and a gas-management system. The gas-management system maintained an argon or xenon gas environment to allow partial power operation on the launch pad; full-power operation in space was effected by venting the gas through a pressure-relief device. The average RTG flight masses were 39.69 kg for LES 8/9 and 37.69 kg for Voyager 1/2. The 312 thermoelectric couples were arranged in 24 circumferential rows, each row containing 13 couples individually bolted to the outer case. The design hot-junction temperature was 1,273 K with a cold-junction temperature of 573 K. Design voltage was 30 V. The peak initial power was 159.6 W(e) for RTG Number 3 on Voyager 2. The MHW-RTGs allowed the LES 8/9 satellites to operate beyond the five-year operational life; enabled NASA to complete flights to Jupiter and Saturn; and will enable Voyager 2 to conduct an extended mission to Uranus in 1986.

GPHS-RTG. The successful performance of the MHW-RTG led to the use of SiGe technology for the high-power — 285 W(e) — General Purpose Heat Source RTG, which is to be launched in 1986 on the NASA Galileo Mission to Jupiter and the International Solar-Polar Mission around the sun.

Transition to High-Temperature Materials. The use of high-temperature SiGe alloys as thermoelectric power-conversion materials was a direct outgrowth of spacecraft requirements for higher RTG power levels and lower RTG masses. In general, higher hot-side operating temperature means a high efficiency, although the optimum temperature is dictated by the mission life, i.e., minimizing sublimation. The cold-side temperature is optimized to obtain the desired power-to-mass ratio. To a first approximation, PbTe can be used from room temperature to about 900 K before materials properties and the figure of merit become concerns. The SiGe alloy can be used from room temperature to about 1,300 K and offers the potential of higher power with improved efficiency.

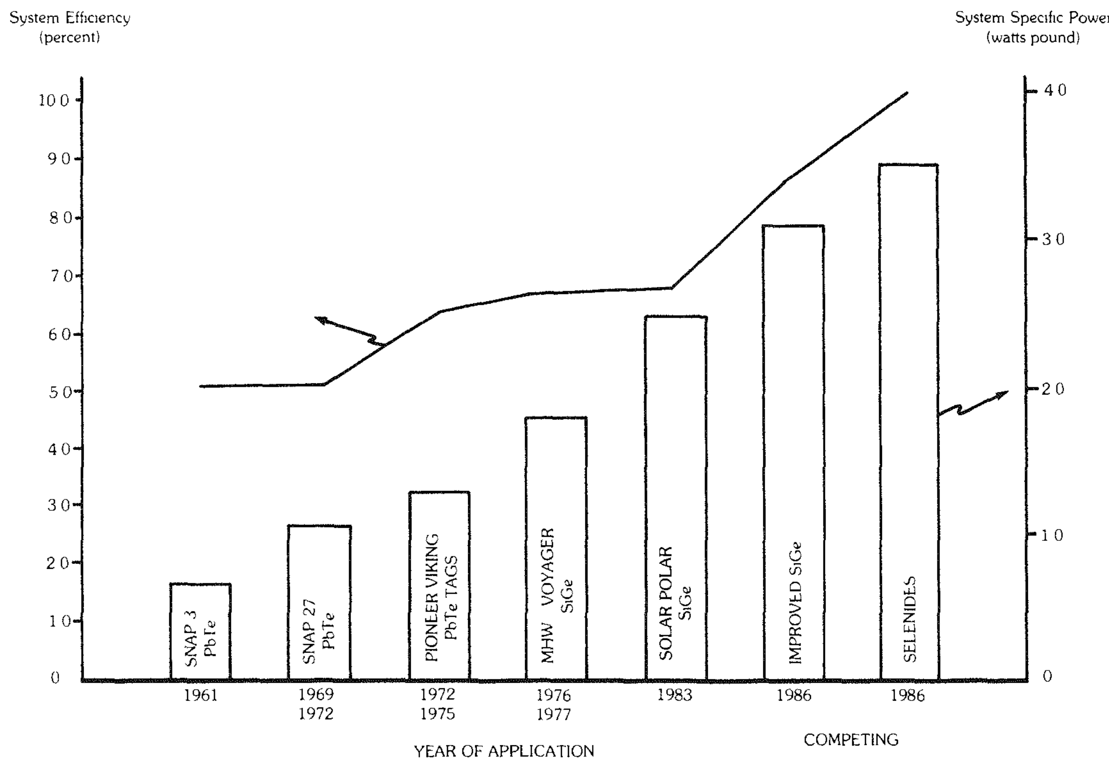

Figure E RTG performance demonstrated predicted

Source Gary L Bennett James J Lombardo and Bernard J Rock *Enhancing Technological Leadership Space Nuclear Electric Power Systems* Paper delivered at Annual Meeting of the American Astronautical Society October 20 23 1980 Boston MA

INDEX

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