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POSSIBLE STRONTIUM - 90
DEMANDS AND AVAILABILITIES

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POSSIBLE SR-90
DEMANDS AND AVAILABILITIES

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September 30, 1971

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by Union Carbide Corporation, Nuclear Division

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I. INTRODUCTION

This study was made at the request of the USAEC Division of Isotopes Development (DID). It is intended to (1) assist DID in assessing the market potential, including anticipated requirements for naval applications, for Sr-90 from the Richland Waste Encapsulation and Storage Facility (WESF) and (2) provide a critical review of the technical feasibility of using the Hanford Waste Containers (HWC) directly as Sr-90 heat sources for naval applications. A supplementary purpose of the study is a discussion of long-term Sr-90 markets that could be met only by recovery of the material from commercial spent fuel reprocessing plants.

Encapsulated Sr-90 is useful primarily as a heat source for radioisotope power generators (RPGs). Strontium-90 is most useful for those RPG applications in which a long-lived (5 to 10 year) source of power is needed in the range of a few watts to a few kilowatts and a fairly heavy power source can be tolerated. Strontium-90, which emits a 0.54 Mev beta particle and has a 28.8-year half-life, requires moderately heavy shielding because of bremsstrahlung from the 2.26 Mev beta particle emitted by its daughter yttrium-90. Its relatively long half-life of 28.8 years gives Sr-90 an advantage over shorter-lived isotopes, such as Co-60, for missions of 5 years or longer. Strontium-90 is also considerably cheaper than other long-lived heat source isotopes, such as Pu-238 and Cm-244. For short missions of 1 to 3 years, Co-60 is an important competitor.

The Navy is, and has been, the major customer for Sr-90 fueled RPGs. The major naval use of Sr-90 is to fuel devices used in deep-sea applications. Projections of naval requirements have been obtained from the Naval Facilities Engineering Command (NAVFAC) and are discussed in this report. In addition to naval requirements, there may be large near-term requirements within the AEC for R&D purposes in support of the naval program.

In the course of this study, members of the staffs of DID, NAVFAC, Pacific Northwest Laboratories (PNL), Oak Ridge National Laboratory (ORNL), Brookhaven National Laboratory (BNL), and manufacturers of RPGs were contacted to discuss (1) the feasibility and potential of various Sr-90 applications and (2) competition from other energy sources. Literature¹⁻²⁰ on Sr-90 and other isotope heat sources was reviewed.

II. SUMMARY AND CONCLUSIONS

The only appreciable market for Sr-90 during the next few years is as energy sources for naval applications. It is the practice of the Department of Navy to procure all RPGs through NAVFAC. Since the deployment of systems using large numbers of RPGs is, in general, classified as far as quantitative requirements, there is no good way of making an independent forecast of Sr-90 requirements for naval applications.

A June 1971 NAVFAC forecast²¹ of their projected Sr-90 requirements through FY 1980 appears reasonable as it is based primarily on small (<1 kwe) RPGs, using thermoelectric generators. Thermoelectric generators of a few hundred watts electric are reasonable extrapolations of present technology. Although none of the requirements in the NAVFAC projection can be considered firm until an official request for the Sr-90 is received, it is probable that a large fraction of these requirements will materialize.

Through 1978, the June 1971 NAVFAC requirements are about 45 megacuries of Sr-90. There is probably sufficient, high specific activity strontium scheduled to be reprocessed at the Richland WESF to meet the projected naval requirements through 1978. An additional 7 megacuries of Sr-90 will be produced by the N reactor if it continues to operate at 4 billion kwhr/year for 3 years. An earlier (July 1970) NAVFAC forecast²² of Navy Sr-90 requirements projects needs to the year 1990.

To meet the requirements of these projections after 1978, it would be necessary to find another Sr-90 supply other than Richland. A quantity of Sr-90 comparable to the Richland supply could be recovered from the waste tanks at the AEC's Savannah River Plant, but at present there are no plans to recover this material. However, by the late 1970s, the commercial power reactors will be producing sufficient quantities of Sr-90 in spent fuel to meet all conceivable requirements.²³ At present, no commercial fuel reprocessor has announced plans to recover Sr-90 waste streams. Mr. R. W. McKee of PNL is currently making a study of the economic feasibility of a co-product Sr-90 Cs-134/137 recovery plant.

Present plans at the Richland WESF are to produce SrF_2 , which will be encapsulated in Hastelloy C-276 or Hastelloy C for waste disposal. The possibility of using these capsules directly as heat sources has been considered; however, compatibility studies of the container materials with radioactive strontium fluoride²⁴ are inconclusive and additional testing is needed. In the previous tests there was undoubtedly some water in the test capsules. Also, the test materials were contained in stainless steel capsules, giving rise to possible galvanic corrosion. The effect of trace elements in the radioactive samples is not understood because of the masking by effects mentioned above. To be relevant, single-metal tests using capsules of the encapsulation material to be tested and encapsulation with provisions to preclude moisture would be required. Based on experience at ORNL, it is highly probable that corrosion rates with completely dry radioactive strontium fluoride encapsulated in single-metal capsules would be satisfactory at a reasonable operating temperature of 800°C.

If it is not possible to demonstrate that the Richland WESF SrF_2 can be satisfactorily encapsulated for heat source applications, then some alternative steps will be necessary if the material is to be made available to meet naval requirements. Possibilities are (1) an additional purification step to remove impurities, (2) conversion to another usable compound such as the oxide titanate at Richland, and (3) conversion to the carbonate at Richland with the conversion to the titanate and encapsulation done elsewhere. Once the material is precipitated as the insoluble fluoride, it would be difficult to convert it to another compound.

Some design modifications in the WESF capsule design may be needed as the present capsule design is probably not acceptable for deep-sea applications. A wall thickness in the range of 0.30 in., instead of the present 0.120-in. wall thickness, would be required, depending on the length and diameter of the capsule.

The development of large markets for Sr-90 other than naval applications does not look hopeful in the next 5 to 10 years. There has been some experimentation with the use of Sr-90 fueled RPGs to power undersea oil well blowout control valves and well marking devices. Concern over public acceptance may stifle these latter applications until the successful experience of large deployment of RPGs for a few years by the Navy is accomplished. A near-term market for up to 10 megacuries of Sr-90 could develop in support of AEC-sponsored R&D on the ORNL Isotopes Kilowatt Program.

III. DISCUSSION

A. NAVFAC PROJECTION OF NAVY Sr-90 FUEL REQUIREMENTS

A projection of Navy requirements for Sr-90 to fuel RPGs through FY 1980 was recently furnished to DID by the Department of Navy.²¹ The annual projection in terms of curies of Sr-90 is shown in Table 1 and Fig. 1. The cumulative requirements are shown in Fig. 2. Table 2 presents the efficiencies and initial power outputs used in making the conversion from RPG requirements to curies of Sr-90.

The basis for the projection as stated in Commander Cope's memorandum²¹ is as follows: "The figures shown in the enclosure represent the best determination that can be derived from information communications concerning Navy plans and will be significantly affected by continuing Navy action in various oceanography programs. The forecast is considered, however, realistic and conservative at this time."

A projection of the Navy's Sr-90 requirements out to 1990 was obtained by analyzing a forecast²² made by Messrs. Fleming and Starr of NAVFAC in July 1970. This projection, which assumes that only thermoelectric generators are used, has been converted into megacuries of Sr-90 and is shown in Table 3. The cumulative data of Table 3 were used as the basis to calculate annual requirements, which are plotted in Fig. 3 as two curves:

- (1) Curve A assumes that all RPG requirements are met by thermoelectric generators, and
- (2) Curve B assumes that generators in the 1- to 10-kwe range are actually 5-kwe generators and use a Rankine cycle conversion system, which is several times more efficient than a thermoelectric conversion system. Generators <1 kwe are assumed to be thermoelectric devices.

To meet the requirements of either of these projections after 1978, it would be necessary to find another Sr-90 supply other than Richland. A quantity of Sr-90 comparable to the Richland supply could be recovered from the waste tanks at the AEC's Savannah River Plant, but at present there are no plans to recover this material. By the late 1970s, the commercial power reactors will be producing sufficient quantities of Sr-90 in spent fuel to meet all conceivable requirements. Projections of commercial power reactor Sr-90 production made by PNL²³ are shown in Fig. 4.

To date, the use of RPGs by the Navy has been largely experimental. The Navy inventory of radioisotope power devices published⁸ in October 1970 is given in Table 4. The total inventory comprises about 300 w(e) or about 1.3 megacuries of Sr-90. According to the Sr-90 sales data presented in Section III.B. (Table 5), cumulative sales to domestic and AEC project customers totaled 2.5 megacuries at the end of FY 1970. The 1.2 megacuries that were not in the active Navy inventory were either in use for research purposes or in the pipeline to supply future naval demands. In FY 1971, domestic sales were more than 0.72 megacurie and scheduled shipments in FY 1972 are about 1.0 megacurie.

Table 1

JUNE 1971 NAVFAC FORECAST OF Sr-90 FUEL REQUIREMENTS,
FY 1972 - FY 1980

Fiscal Year	Power, Watts (e)	Number of Sources	Megacuries/Unit	Total Megacuries	Cumulative Megacuries
72	8	2	0.037	0.075	
	100	1	0.368	<u>0.368</u>	
				0.443	0.443
73	10	4	0.032	0.128	
	25	1	0.108	0.108	
	100	1	0.368	<u>0.368</u>	
				0.604	1.047
74	1	1	0.007	0.007	
	5	1	0.027	0.027	
	10	1	0.032	0.032	
	25	3	0.108	0.325	
	300	1	1.103	<u>1.103</u>	
				1.495	2.54
75	1	6	0.007	0.043	
	5	1	0.027	0.027	
	25	3	0.108	0.325	
	100	3	0.368	1.103	
	300	1	1.103	<u>1.103</u>	
				2.602	5.14
76	1	11	0.007	0.079	
	5	3	0.027	0.082	
	25	4	0.108	0.433	
	100	2	0.368	0.433	
	300	1	1.103	1.103	
	750	1	2.757	<u>2.757</u>	
				5.191	10.33
77	1	5	0.007	0.036	
	5	1	0.027	0.027	
	10	5	0.032	0.160	
	25	3	0.108	0.325	
	100	4	0.368	1.471	
	300	4	1.103	<u>4.412</u>	
				6.431	16.76

(NOTE: Columns may not add due to rounding.)

Table 1 (Continued)

JUNE 1971 NAVFAC FORECAST OF Sr-90 FUEL REQUIREMENTS,
FY 1972 - FY 1980

Fiscal Year	Power, Watts (e)	Number of Sources	Megacuries/Unit	Total Megacuries	Cumulative Megacuries
78	50	100	0.201	20.11	45.10
	100	6	0.368	2.22	
	300	3	1.103	3.32	
	750	1	2.757	2.76	
				28.38*	
79	1	5	0.007	0.036	56.10
	5	10	0.027	0.276	
	10	5	0.032	0.160	
	25	5	0.108	0.542	
	50	4	0.201	0.802	
	100	2	0.368	0.735	
	300	1	1.103	1.103	
	2000	1	7.353	7.353	
				11.007	
80	1	5	0.007	0.036	68.21
	5	10	0.027	0.276	
	10	5	0.032	0.160	
	25	5	0.108	0.542	
	50	4	0.201	0.802	
	100	2	0.368	0.735	
	300	2	1.103	2.205	
	2000	1	7.353	7.353	
				12.110	

*Without one hundred, 50-watt sources, the 1978 total would be 8.27 megacuries.

(NOTE: Columns may not add due to rounding.)

Figure 1

NAVFAC FORECAST OF NAVY
ANNUAL Sr-90 FUEL REQUIREMENTS

*Possible single procurement of 100, 50-watt RPGs.

Figure 2

NAVFAC FORECAST OF NAVY
CUMULATIVE Sr-90 FUEL REQUIREMENTS

Table 2
Sr-90 UNIT FUEL REQUIREMENTS
FOR THERMOELECTRIC RPG UNITS

Power Level Watts (e)	Beginning Of Life, Watts (e)	Overall Assumed Efficiency, % ^a	Thermal Watts	Megacuries/RPG ^b
1	1.5	3.06	49	0.007
5	7.5	4.0	188	0.027
8	12	4.71	255	0.038
10	15	6.88	218	0.032
25	38	5.16	736	0.108
50	75	5.5	1,364	0.201
100	150	6.0	2,500	0.368
300	450	6.0	7,500	1.103
750	1125	6.0	18,750	2.76
2000	3000	6.0	50,000	7.35

^aThe overall assumed efficiencies for 1-w(e) to 25-w(e) generators is based upon empirical data. The efficiencies for the 50-w(e) to 2-kw(e) generators are conservative and could theoretically, with new thermoelectric materials, reach ~7 to 8.5%. These new thermoelectric materials are presently in the R&D stages.

^bBased upon 6.8 w(t)/kilocurie of Sr-90.

Table 3

NAVFAC JULY 1970 FORECAST OF Sr-90 REQUIREMENTS

FISCAL YEAR*

(Units of Megacuries)

Units Size, w(e)	1970	1971	1972	1973	1974	1975	1980	1990
0-1	0.035	0.035	0.035	0.035	0.10	0.15	0.50	2.00
1-5	0.04	0.06	0.05	0.05	0.30	0.50	0.20	8.00
5-10	0.105	0.175	0.245	0.385	0.70	1.050	3.50	7.0
10-25	1.40	1.70	2.10	2.30	3.0	3.50	10.0	50.0
25-100	0.30	0.30	0.60	0.60	1.20	3.0	9.0	30.0
100-1000	0	0	0	0	2.50	5.0	5.0	250.0
1000-10,000	0	0	0	0	0	0	40.0	200.0
Total	1.88	2.27	3.04	3.38	7.80	13.20	70.0	547.0

*Accumulative totals at year end.

Figure 3

NAVFAC JULY 1, 1970 FORECAST
OF ANNUAL NAVY Sr-90 REQUIREMENTS

Figure 4

ANNUAL Sr-90 POTENTIALLY
AVAILABLE FROM POWER REACTORS*

*Reference 24, page 46, Case 4.

Table 4

CURRENT NAVY INVENTORY OF RPGs

RPG Name	No. of Units	Design Power (Watts)	Function	Date Acquired	Location 12/31/69
LCG-25A	1	25	Instruments & Telemetry	8/66	Fairway Rock, Alaska
MW-3000	1	2.5	Ocean Engineering Program	2/67	Port Hueneme, California
URIPS P1-1002	1	1	Ocean Engineering Test Program	9/67	Port Mugu, California
URIPS P1-1001A	1	1	Temporary Storage	2/68	San Diego, California
LCG-25C1	1	25	Acoustic Range Program	11/67	Pacific Ocean
TRACS-25A	1	25	Temporary Storage	1/69	Miami, Florida
Sentinel-25D	3	25	Weather Station	10/69	Washington, D.C.
Sentinel-25E	3	25	Temporary Storage	3/69	Port Hueneme, California
SNAP-7D*	1	60	Weather Station	1/64	Galveston, Texas
SNAP-7E*	1	6.5	Ocean Bottom Beacon	7/64	Atlantic Ocean
RIPPLE III**	1	0.7	Ocean Engineering Test Program	2/67	Port Hueneme, California

*AEC owned and loaned for testing.

**Loaned to the Navy for testing.

There is evidence that some of the applications under development may be approaching large-scale deployment. Plans for procurement of one hundred 50-watt RPGs in 1978 seem relatively definite. Manufacturers already have the capability of furnishing 100-watt units and are developing 300-watt units. At least one manufacturer feels a 2-kwe unit is feasible. The long life times (5 to 10 years) required by the Navy give Sr-90, with its 28.8 year half-life, a technological advantage over competing isotopes with shorter half-lives such as Co-60. In RPGs of sizes of ≤ 2 -kwe, Sr-90 probably will remain the preferred isotope.

Even though the development of naval systems using the RPGs has been largely unclassified, the quantitative plans for deployment of these systems are classified. Hence, it is impossible to make an independent quantitative assessment of potential requirements. NAVFAC is undoubtedly in the best position to make a projection. The RPG technology to meet the requirements of the NAVFAC projection looks feasible, and there is no apparent alternate to fulfill the requirements for power under the sea than with isotope power generators.

B. PAST SALES OF Sr-90

At the present time, the only U. S. source of Sr-90 has been the AEC through the ORNL Isotopes Division. The material is recovered from the Richland waste tanks and shipped as the carbonate to ORNL. At ORNL it is purified, converted to the titanate, and encapsulated. Some strontium sources have also been produced.

Sales data from FY 1946 through the first 10 months of FY 1971 are shown in Table 5. Also shown are current orders, which will probably be shipped in 1972. It is of interest to note that sales were negligible except to AEC project uses until after the price was lowered in October 1965. Since 1968, sales have been 0.75 to 1 megacurie/year. Most of the material (excluding foreign shipments) has gone into power generating devices for use by the Navy, AEC, or other government agencies.

There is no statistical trend in the data of Table 5 to lead one to expect the rapid expansion of requirements forecast by NAVFAC (Fig. 1). The continued sales of a megacurie/year does, however, indicate a continued R&D effort.

C. INTERVIEWS WITH Sr-90 USERS, RADIOISOTOPE GENERATOR SUPPLIERS, AND OTHER KNOWLEDGEABLE INDIVIDUALS

The names of organizations and individuals contacted during the study are listed in Table 6.

At the beginning of the study, a number of individuals on the DID staff were interviewed for background information. Visits were made to NAVFAC, Arlington, Va., Isotopes-Teledyne, and the ORNL Isotopes Division. Most other interviews were made by telephone.

The discussions did not lead to a firm basis for making a market projection for Sr-90 fueled RPGs. Some pertinent opinions from the interviews include:

Table 5

SR-90 SALES BY ORNL

Fiscal Year	Foreign		Domestic		AEC Projects		Total	
	Curies	Shipments	Curies	Shipments	Curies	Shipments	Curies	Shipments
1946-55	4	16	260	228	22	98	286	342
1956	1	1	63	55	2	31	66	87
1957	1	2	21	53	1	26	23	81
1958	1	4	10	44	5	23	16	71
1959	3	5	97	66	5	35	105	106
1960	21	12	217	75	24	31	262	118
1961	3	5	253	88	17,545	26	17,801	119
1962*	1,030	12	252	54	335,521	31	336,803	97
1963**	53	11	913	62	315	14	1,281	87
1964	3,261	10	735	82	4,723	36	8,719	128
1965	826	4	107	57	82	31	1,015	92
1966	43,435	15	65,820	114	7	21	109,262	150
1967	15,380	7	29,891	33	351,011	15	396,282	55
1968	366,939	9	534,853	45	275,641	14	1,177,433	68
1969	154,402	8	671,186	49	128,028	16	953,616	73
1970	300,406	9	33,605	31	35,084	10	369,095	50
1971 (10 mos.)	11,225	5	725,352	29	-	4	736,577	38
TOTAL	896,988	135	2,063,637	1,160	1,148,018	468	4,108,643	1,763

Table 5 (Continued)

SR-90 SALES BY ORNL

Current Orders for Sr-90 (As of March 1971)		
Customer	Amount-Curies	Estimated Shipping Date
U. S. Navy	208,000	July 1971
U. S. Navy	424,000	July 1971
U. S. Navy	29,000	June 1971
Gulf Energy & Environmental Systems	14,500	June 1971
Teledyne-Isotopes, Inc.	20,000	To Be Scheduled
U. S. Navy (Potential)	300,000	Est. Nov. 1971
TOTAL	995,500	

NOTES: March 1, 1947 (Sr.89-90) - \$1.35/mc (\$1,350/ci). "Old Price" - \$500/ci.

April 1958 price reduced to \$10.00/ci per annual order less than 50 ci. (Press Release A-79, 4/11/58) 7.50/ci - order \$500 - 5,000 ci; \$5.00/ci - orders greater than 5,000 ci. 5/31/61 - P.R. #D-139 re increase availability of fission products. 3/20/62 - P.R. #E-86 re prices reduced - \$2.00/ci or fraction - orders 0.5000 ci; 1.00/ci - 5000 - 30,000 ci - 0.75/ci - over 30,000 ci. Effective 11/10/65 prices reduced - \$0.50 - orders 0-5,000 ci; 0.30 - 5,000-50,000 ci; 0.25 - 50,001 - 150,000 ci; (10/11/65 - P.R. #222) 0.20 - over 150,000.

Sept. 6, 1968 press release #L-209 - AEC decided to retain for time being its present prices - AEC 994/59 approved 8/28/68.

* FY 1962	** FY 1963
17,500 - W/S	32,000 - SNAP-7E
40,000 - SNAP-7C	225,000 - SNAP-7B
40,000 - SNAP-7A	
225,000 - SNAP-7D	257,000 curies
322,500 curies	

Table 6

ORGANIZATIONS AND INDIVIDUALS CONTACTED DURING THE STUDY

AEC-Division of Isotopes Development

F. D. Haines
J. E. Machurek
J. N. Maddox
R. W. Shivers

AEC-Division of Materials Licensing

R. B. Chitwood

AEC-Division of Reactor Development & Technology

W. D. Holloman, LCdr.

Brookhaven National Laboratory

J. H. Cusack

Oak Ridge National Laboratory

E. G. Bohlmann
J. H. Gillette
E. Lamb
C. L. Ottinger
R. A. Robinson

Naval Facilities Engineering Command

T. P. Flemming
Cmdr. M. D. Starr

Sanders Nuclear Corporation

D. G. Harvey

Isotopes - Teledyne

J. S. Cochran
John Morrison

Minnesota Mining & Manufacturing Co.

R. N. Walz

Pacific Northwest Laboratories

H. T. Fullam

Atlantic Richfield, Richland

T. R. McKenzie
A. E. Smith

Douglas United Nuclear, Richland

J. P. Hamric

1. Manufacturers of RPGs feel that eventually the Navy will be a sizeable customer for large RPGs, although they do not expect this market to develop for a few years. Their primary source of marketing information is NAVFAC. Companies in the business are relying on other activities to stay in business. For example, Isotopes-Teledyne's major product using thermoelectrics is natural-gas-fueled generators for pipeline valve control. To date, the volume of orders for RPGs has been so small that mass production techniques have not been used. If orders should reach the 100/year level, substantial cost reductions would result.
2. Projections of Navy requirements by NAVFAC are by no means firm. They are based on the best information available but are always subject to budget approval in future years. Most requests from other parts of the Navy to NAVFAC are in the form of possible requirements and requests for development. Firm quantitative orders for generators are not made until implementation of a system is underway and money budgeted.
3. The current design of the Richland HWC may not be applicable for deep-sea applications. Most generator manufacturers would prefer a shorter-length larger-diameter capsule. Specifics on this subject are discussed in Section III. E.
4. From the standpoint of the generator manufacturers, compounds with a high strontium density, such as SrO or SrF_2 , are more desirable than the titanate or meta-titanate because they give a higher specific power. In licensing the only SrO source used in a deep-sea application, the AEC-DML required that it be recoverable. Whether this same criteria will be required of SrF_2 sources is not known. Although SrF_2 is very insoluble, it is not as insoluble as the titanates.
5. Opinions are mixed on the feasibility of radioisotope generators using a dynamic energy conversion cycle. The main concern is the reliability of moving parts, such as turbines, to last 5 to 10 years without maintenance. Developments in this area are discussed in Section III. F.
6. There is general agreement that there is little or no market for Sr-90 as a beta source for chemical processing.
7. The market potential of Sr-90 during the 1970s looks bleak except for naval applications and R&D programs directed at these applications.

D. COMPETITIVE RADIOISOTOPES AND Sr-90 APPLICATIONS

1. Competitive Radioisotopes

Strontium-90 is a particularly useful heat source when a long lifetime is required for the power source and when relatively heavy shielding can be tolerated. The primary competitor in this area is Co-60. Cobalt-60 has the advantage that much higher specific powers are possible. With 300 curies/g Co-60, power densities of 40 watts/cm³ are obtained. With fission product Sr-90, power densities are limited to the 1.0 to 1.5 watt/cm³ range.

The major disadvantage of Co-60 is its relatively short 5.3-year half-life. It may be possible to develop methods of dumping heat initially to flatten the power output of a Co-60 generator over a 5-year life. A 10-year life would not be feasible. In small-size generators, the heavy shielding required for Co-60 with its energetic 1.2 Mev gammas is a serious disadvantage. In large sizes (somewhere between 2 and 6 kwe), the higher power density of Co-60 becomes important and the shielding weights for Sr-90 and Co-60 become comparable. In larger sizes Co-60 has the advantage.

Other isotopes that could compete with Sr-90 on a technical basis are plutonium-238 with an 89-year half-life and curium-244 with an 18-year half-life. At present, both of these isotopes are too expensive to compete with Sr-90. It is doubtful that Pu-238 (even with high Pu-236 contamination) will ever be competitive because of high cost of shielding. Manufacture of Pu-238 requires recovery of Np-237 and subsequent irradiation in a neutron flux. The cost per unit heat output from Pu-238 will remain on the order of 5 times the cost of Sr-90.

Whether Cm-244 will be a serious competitor for Sr-90 will depend on how cheaply it can be recovered from spent reactor fuel reprocessing plants. In order to compete with 20¢/curie Sr-90, the cost of Cm-244 would need to be \$10/g. By 1980, the availability²⁴ of Cm-244 in domestic commercial reactor spent fuel will be about 200 kg/year.

Short half-life isotopes such as promethium-147, cesium-144, polonium-210, and thulium-170 are too short lived to be useful in long-lived power generator applications such as the Navy is considering. In general for short-lived applications of a year or less, it is more economical to use batteries.

2. Sr-90 Applications

a. Energy Sources

Aside from the Navy applications presented in Table 4, the other potential applications that have been considered are (1) energy sources for off-shore oil well applications, (2) communication relay devices, and (3) terrestrial marker beacons.

In the past, Sr-90 fueled RPGs have been used experimentally by Humble Oil in the Santa Barbara Channel (California) and by Sinclair Oil Co. (now Atlantic Richfield Co.) in the Gulf of Mexico. As a result of the bad publicity for oil companies caused by the blowout of a Union Oil Company well in the Santa Barbara Channel, Humble Oil removed its Sr-90 RPG. A similar incident caused Sinclair to remove their generators from the Gulf. Perhaps after a few years of use by the Navy, oil companies will again consider RPGs for oil well applications. In the development of a field, several hundred wells may be drilled. If each well used an average of 50 watts of electricity for blowout valve control, well marking, etc., this would represent a market for Sr-90 of 20 megacuries for each 100 wells.

American Telephone and Telegraph Company considered using RPGs to power remote microwave relay stations. They decided there was little advantage since the electronic equipment needed servicing every 6 months and it was more economical to use batteries.

Consideration has been given to using RPGs as marker beacons for navigation over remote regions (for example, the RIPPLE program in Saudi Arabia). There are undoubtedly a few locations that are sufficiently remote so that long-lived Sr-90 RPGs would be more economical than batteries. If this market were on the order of 20 generators/year of 15 watts each, the Sr-90 requirement would be about 1 megacurie/year.

Another application for Sr-90 that has been discussed is as a direct heat source for underwater environmental control. Use of Sr-90 sources as heaters for diving suits does not appear feasible because of shielding requirements. Use as a heat source in underwater living quarters would be technically feasible. At present, this type of application is only in the speculative stage. The fact that the energy is used directly would be an advantage, and the main disadvantage would be cost. At 20¢/curie and a 10-year device life, the cost of heat would be 11,213¢/million BTU.

b. Chemical Processing

There has been some consideration of using the beta radiation from Sr-90 and its daughter Y-90 for chemical processing, and studies were made by Radiation Applications Inc.,⁴ and Western New York Research Center, Inc.¹⁴ Dr. Cusack of BNL is currently planning some experiments in this area.

In the past, applications of this type have failed with Sr-90. In order to use the beta energy effectively, it must be in very close proximity to the material irradiated. If the barrier between the Sr-90 and the target is sufficiently thin for this purpose, the likelihood of contaminating the product with Sr-90 is high. Electron accelerators can do the job more efficiently without risk of contamination. Thus at present no commercial market for Sr-90 in chemical processing is foreseen.

E. RICHLAND WASTE MANAGEMENT CONTAINERS AS HEAT SOURCES FOR NAVAL APPLICATIONS

In order to be used for deep-sea naval applications, the outer capsule of a Sr-90 source must be made of a material that is corrosion resistant to sea water and sufficiently strong to withstand the collapsing pressure from the sea at the depth to which it is exposed. In addition, the inner container must be compatible with the strontium compound (or mixture) used so that penetration of the capsule does not occur over very long (> 300 years) periods.

1. Corrosion Resistance to Sea Water

The Navy specifications⁸ state that Hastelloy C, Hastelloy C-276, or Uniloy-HC shall be used for the fuel capsule. The design allowance for corrosion of these materials, including welds, shall be not <0.0001 in./year. Thus, a 100-year design life would require a 10-mill corrosion allowance on the wall thickness. A nonrecoverable source should probably be designed for at least 10 half-lives or 300 years. Hence, a 30- to 50-mill external corrosion allowance should be made to the wall thickness shown in Fig. 5.

2. Resistance to Collapse

The ORNL safety criteria¹² for capsule resistance to collapse from external pressure are that the capsule should be designed so that the yield strength is not exceeded at 10,000 psi and the capsule should withstand 14,505 psi without collapsing (some yielding allowed) with no credit for internal support. The Navy specifications⁸ state that the capsule shall be designed for 10,000 psi and allowable membrane stresses shall be limited to 0.9 of the yield strength. ORNL safety data show a yield strength of 60,000 psi and an ultimate strength of 105,000 psi for Hastelloy C aged at 900°C and 50,000 psi and 93,000 psi for yield and ultimate strengths, respectively, of material aged at 1100°C.

Considering that the capsules would probably be operated at about 800°C and taking in the 0.90 factor, a design stress of 50,000 psi at 10,000 psi external pressure should be reasonable. At 14,505 psi, the corresponding stress would be 72,500 psi, which is well below the ultimate strength of the material.

In analyzing the ORNL Isotopes Kilowatt Program capsules, which were 40.28 in. long, Haff¹² found that the maximum stress was the circumferential stress in the wall midway between the ends. The circumferential stress^{12,25} at a point midway between the ends is

$$S = -P \left[\frac{b^2 (a^2 + r_c^2)}{r_c^2 (b^2 - a^2)} \right]$$

where a = inner radius,
b = outer radius,
 $r_c = [(b - a)/2] + a$, and
P = external pressure.

Figure 5

REQUIRED CAPSULE WALL THICKNESS VS
CAPSULE INSIDE DIAMETER FOR TWO DESIGN STRESSES

This would remain the controlling stress in sources with a smaller length to diameter (L/D) ratio and this would be the case with the Richland sources.

In Fig. 5, the wall thickness required as a function of capsule inner diameter (I.D.) is shown for the 10,000 psi external pressure for 50,000 and 60,000 psi allowable stresses. Note that the wall thickness shown in Fig. 5 does not include a corrosion allowance, which will probably be 0.03 to 0.05 in.

The current Richland Waste Management container design with a 2.385-in.-I.D. outer capsule would require a 0.273-in.-thick wall. Adding 30 mills for corrosion allowance brings this to 0.303 in.

In the final design of the source capsule, it would, of course, be necessary to carry out a detailed stress analysis to ensure that the end caps and weldments are properly designed.

3. Inner Capsule Compatibility

The only compatibility studies that have been made with radioactive strontium fluoride were carried out at PNL.²⁴ The results of these tests are inconclusive. Tests were carried out using a nonradioactive mixture of SrF_2 and other salts to simulate the material expected from the waste recovery process. In these tests, the calcined mixture of salts was encapsulated in a single metal to be tested and an electron beam welded in a vacuum chamber. Welding in a vacuum probably removed any moisture from the sample.

These nonradioactive samples showed good compatibility with Haynes alloy No. 25, Hastelloy C, and Hastelloy X at both 400°C and 800°C.

For reasons of economy, the tests with radioactive SrF_2 mixture were carried out in a different manner. Wafers of the test metals were embedded in layers of salt and encapsulated in a stainless steel capsule. Wafers of several different metals were used in each capsule. The capsules were welded in a hot cell in air with no special humidity control. The salt undoubtedly picked up some moisture. The radioactive salt showed poor compatibility with all of the metals tested at 400°C. No tests were run at 800°C.

The presence of moisture in these tests would undoubtedly cause trouble. The water would be disassociated into hydrogen and oxygen by the intense radiation field. At 400°C the hydrogen would diffuse out through the wall leaving free oxygen behind.

Another difficulty with the tests is the use of composite samples where dissimilar metals were used in the same capsule. Stainless steel and Hastelloy have electromotive potentials that differ by about 0.1 volt. If the radioactive salt is ionized by the radiation field and is electrically conductive, then the possibility of galvanic corrosion exists. This could not occur in a capsule with a single metal.

Another difference between the radioactive and nonradioactive tests was the trace impurities in the samples. While the radioactive samples contained traces of copper (.01%) and lead (.01%), there were no trace impurities in the nonradioactive samples. It is not obvious that this should have made any difference, since both copper and lead fluorides are stable.

The tests were discussed with chemists on the Molten-Salt Reactor Program at ORNL. They could see no reason why, even with the trace impurities, the fluoride salt mixture should not be compatible with the Hastelloy alloys at temperatures in excess of 800°C, provided no water was present.

F. ISOTOPES KILOWATT PROGRAMS

A large fraction of the projected Navy requirements for Sr-90 in the 1980s (shown in Fig. 3) is for large, kilowatt-size generators. At the request of the Department of Navy, the AEC is carrying out programs to develop RPGs in the kilowatt electrical range. The two major programs that are underway are the Co-60 Heat Source Demonstration Program¹⁵ by Westinghouse Electrical Company and the Isotopes Kilowatt Program¹¹ at ORNL.

1. Westinghouse Cobalt-60 Heat Source Demonstration Program

The Co-60 generator has been designed and manufactured by the Westinghouse Astronuclear Laboratory at Large, Pennsylvania. The unit has been loaded with 2 megacuries of Co-60 from Savannah River and is undergoing tests. At present, it has no energy-conversion system. The AEC intends to solicit proposals for a conversion system, either an organic Rankine cycle or a Brayton cycle using nitrogen. It is probable that one will be funded in FY 1973. The initial power output should be in the range of 5 kwe.

2. ORNL Isotopes Kilowatt Program

A detail design study of the many alternatives that might be used in large-scale generators has been made¹¹ by ORNL. The study is continuing in a second phase where a more detailed design is being made. Early implementation of the hardware phase of this program could require up to 10 megacuries of Sr-90 before 1975.

Two major development problems are apparent:

- (1) A turbine or other energy-conversion device that can operate for long periods of time without maintenance is needed. Past development work in this area is discussed in detail by Robinson (ref. 11, p. 175); total development funds expended in this area as of 1968 was in excess of \$40 million.

The device with the best performance record is a turbine operated with either Dowtherm E or monochlorobenzene manufactured by Ormat Turbine, Ltd., in Yavne, Israel. A 400-watt Ormat turbine has operated unattended up to 15,000 hr. Experience on other dynamic conversion devices has in general been limited to 1,000-hr tests.

- (2) The second critical development problem is a means of safely dissipating the heat, if the primary cooling system fails. Two types of systems — active or passive — are possible.

An active system requires some mechanical action to remove insulation, provide a heat path, or move sources in order to establish a heat removal mechanism. Extensive demonstration of reliability and effectiveness would be required.

In a passive system, enough heat flow area and leakage is allowed so that even though the primary coolant system fails, the source capsules do not reach intolerable temperatures. This type of system would, in general, be less efficient and heavier than one with an active system. In large sizes, it may be necessary to disperse the heat-producing isotope within a large heat block. This would negate some of the advantages of high power density Co-60 in favor of Sr-90.

It would appear that the development work underway should lead to a successful 5 to 10 kwe generator for long-term unattended duty by 1980, provided funding by the Government is continued. One would not expect the commercial industry to make the financial expenditure required for hardware development without large-scale firm contracts for devices.

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