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AN EVALUATION OF THE PROSPECTS
FOR LARGE-SCALE
PRODUCTION OF PROMETHIUM-147

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

R. W. McKee

August, 1966

BATTELLE-NORTHWEST

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by

R. W. McKee

Chemical Development
Chemistry Department

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AN EVALUATION OF THE PROSPECTS
FOR LARGE-SCALE PRODUCTION OF PROMETHIUM-147

ABSTRACT

This report reviews the potential requirements for Pm-147 as a heat source isotope and compares these requirements with estimated availability of Pm-147 as a recovered fission-product both from the proposed Isochem Inc FPCE Plant and from future power reactor spent fuel processing. The economic feasibility of producing additional Pm-147 by irradiation of Nd-146 is also evaluated and found to be unattractive if Pm-147 pricing must be competitive with Pu-238 pricing.

TABLE OF CONTENTS

1.0	INTRODUCTION	1
2.0	SUMMARY AND CONCLUSIONS	1
3.0	POTENTIAL DEMAND	4
4.0	AVAILABILITY OF FISSION-PRODUCT PROMETHIUM	5
4.1	Sources of Fission-Product Promethium	5
4.2	Promethium from Hanford Wastes	5
4.3	Promethium from Civilian Power Reactor Wastes	6
5.0	PROMETHIUM PRODUCTION BY IRRADIATION OF NEODYMIUM	14
5.1	Description of Production Cycle	14
5.2	Economic Considerations	25
5.2.1	Natural Neodymium Costs	26
5.2.2	Isotope Separation Costs	28
5.2.3	Target Encapsulation Costs	29
5.2.4	Irradiation Costs	31
5.2.5	Target Reprocessing Costs	32
5.2.6	Target Inventory Costs	32
5.2.7	Pm-aging Inventory Costs	36
5.2.8	Total Production Costs	36
5.2.9	Optimum Irradiation Period	39
5.3	Irradiation in a Recirculating Loop	39
5.4	General Competitive Considerations	41
6.0	APPENDIX - Calculations for ND-146 Irradiation Process Costs	43
7.0	REFERENCES	46

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page No.</u>
SUMMARY TABLE	Pm-147 Production Rates and Costs for the Nd-146 Irradiation Process	3
I	Refueling Schedule for Each 1000 MW(e) of New Installed Reactor Capacity	6
II	Natural Neodymium Composition	15
III	Promethium-147 Production with a One-Year Target Irradiation of Neodymium-146	23
IV	Neodymium-Oxide Prices	27
V	Effect of Natural Nd Cost on Pm-147 Cost (Nd-146 Irradiation Process)	28
VI	Effect of Isotope Separations Cost on Pm-147 Cost (Nd-146 Irradiation Process)	29
VII	Effect of Target Encapsulation Cost on Pm-147 Cost (Nd-146 Irradiation Process)	30
VIII	Effect of Irradiation Cost on Pm-147 Cost (Nd-146 Irradiation Process)	32
IX	Gross Inventory Charges (Nd-146 Irradiation Process)	35
X	Effect of Target Inventory Charges on Pm-147 Cost (Nd-146 Irradiation Process)	36
XI	Total Pm-147 Production Cost (Nd-146 Irradiation Process)	37
XII	Summary of Total Pm-147 Production Costs (Nd-146 Irradiation Process)	38

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
1	U. S. Electrical Generating Capacity Growth Estimates	7
2	Spent Fuel Availability from U. S. Power Reactors	9
3	Estimated Average Exposure of Fuel Discharged from U. S. Reactors	10
4	Pm-147 Yields from Reactor Fuels	11
5	Aged Pm-147 Availability from U. S. Power Reactors (Arithmetic Plot)	12
6	Aged Pm-147 Availability from U. S. Power Reactors (Semi-log Plot)	13
7	Neodymium-146 Irradiation for Promethium-147 Production (Schematic Flow Diagram)	16
8	Promethium-147 Production by Irradiation of Neodymium-146 ($\phi = 1 \times 10^{13}$ n/cm ² /sec, $r = 0.2$)	18
9	Promethium-147 Production by Irradiation of Neodymium-146 ($\phi = 3 \times 10^{13}$ n/cm ² /sec, $r = 0.2$)	19
10	Promethium-147 Production by Irradiation of Neodymium-146 ($\phi = 6 \times 10^{13}$ n/cm ² /sec, $r = 0.2$)	20
11	Promethium-147 Production by Irradiation of Neodymium-146 ($\phi = 6 \times 10^{13}$ n/cm ² /sec, $r = 0.05$)	21
12	Promethium-147 Production by Irradiation of Neodymium-146 ($\phi = 1 \times 10^{14}$ n/cm ² /sec, $r = 0.05$)	22
13	Effect of Irradiation Time Cycle on Promethium-147 Production Costs (Nd-146 Irradiation Process)	40

AN EVALUATION OF THE PROSPECTS
FOR LARGE-SCALE PRODUCTION OF PROMETHIUM-147

1.0 INTRODUCTION

The prospects for large-scale production of promethium-147 both as a recovered fission product and as a product of neodymium target irradiation have been evaluated in this study.

Interest in radioisotopes as heat sources for power generation in remote applications has grown rapidly in the last few years. Space exploration missions are a primary interest. Since weight is a critical factor in any space mission, desirable characteristics for heat source radioisotopes include high specific power (watts/gram) and a low level of penetrating gamma radiation to minimize shielding requirements. To provide capability for relatively long missions, a further desirable characteristic is a reasonably long half-life.

Promethium-147 produced as a fission product in the Hanford production reactors and in civilian nuclear power reactors appears to meet these requirements very well. It has a specific power of 0.33 W/g which compares favorably with Pu-238 at 0.56 W/g, it is almost a pure beta emitter, and has a half-life of 2.6 years. However, apparently because of concern that Pm-147 might not be available in sufficient quantity to meet more than a small fraction of the total potential demand, customer interest in promethium has not developed as rapidly as expected. For this reason this study was undertaken to provide a basis for a more complete understanding of the Pm-147 production prospects and the economic factors that are involved. This is not an exhaustive survey and some aspects are explored somewhat superficially. However, the important facets of the question have been considered and some broadly stated conclusions are possible.

2.0 SUMMARY AND CONCLUSIONS

Potential requirements for heat-source isotopes were first reviewed for applications where Pm-147 might be uniquely suited. It was concluded

that demand could reach 50 to 100 thermal kilowatts per year in the 1970's and increase to possibly hundreds of thermal kilowatts per year in the 1980's.

The potential availability of Pm-147 fission product sources was then explored. The principal sources of Pm-147 up through about 1975 will be Hanford waste streams and possibly Savannah River waste streams. Isochem Inc has announced plans for recovery of some of the Hanford fission product isotopes and plans Pm-147 production at about 10 to possibly 20 kW/yr. After 1975 Pm-147 supplied from power reactor fuel processing will become a significant source of supply and after 1980 power reactor sources will overshadow Hanford sources. Availability from power reactor fuel processing is projected at 30 ± 8 kW/yr in 1980 and 150 ± 50 kW/yr in 1990. It was concluded that Pm-147 availability from fission product sources will probably be significantly below potential demand in the 1970 and 1980 period. After 1980, however, availability will be increasing rapidly and should be capable of supplying an increasingly significant share of the market at that time.

The feasibility of producing Pm-147 by irradiation of Nd-146 in the neutron flux of a reactor was also explored. This approach turns out to be an expensive process as the result of several factors.

- An isotope separation process to obtain relatively pure Nd-146 is necessary because this isotope is only one of seven naturally-occurring neodymium isotopes and has a low cross section relative to the others.
- The combination of low cross section for Nd-146 (2 barns) and a relatively large cross section of the Pm-147 (235 barns thermal) indicates that the Pm-147 will saturate at very low concentration and the conversion per cycle will be small.
- Target encapsulation and reprocessing charges are large because so little Pm-147 is produced each cycle.
- Small processing losses accumulating over many cycles will result in low ultimate yields of Pm-147.
- A large in-reactor inventory of Nd-146 which is of high value relative to the Pm-147 produced per unit time results

in very large inventory carrying charges and large reactor space requirements. These are the most significant production costs.

Pm-147 production rates and yields were calculated for five irradiation conditions. Production costs were then estimated assuming 1% process losses and one-year irradiation cycles. The cost estimates were developed as a range of probable costs and the results are summarized below:

Pm-147 PRODUCTION RATES AND COSTS FOR THE Nd-146 IRRADIATION PROCESS

Neutron Flux $n/cm^2/sec$	Spectral Index	Production Rate, g Aged Pm-147/yr per MF Nd-146 in Reactor	Total Pm-147 Production Cost, \$/W of aged Pm-147	
			5%/yr Inventory Charge	12.5%/yr Inventory Charge
1×10^{13}	0.2	237	1,600 - 19,000	3,000 - 32,000
3×10^{13}	0.2	580	670 - 8,000	1,200 - 13,000
6×10^{13}	0.2	865	460 - 5,400	820 - 8,800
6×10^{13}	0.05	1,150	340 - 4,100	620 - 6,600
1×10^{14}	0.05	1,573	250 - 3,000	460 - 4,900

The 12.5% inventory charge is representative of private business financing while the 5%/yr rate is representative of government financing.

Brief consideration was given to the possibility of irradiation in a recirculating solution loop. This did not appear attractive because of a sixfold increase in reactor target space required.

A high degree of uncertainty in the cost estimates is indicated by the spread between the low and high estimates. Nevertheless, comparing the estimated costs with the current price for Pm-147 (\$560/W) and projected Pu-238 prices (\$500 to \$900/W), it was concluded that the prospects are not attractive for production of Pm-147 by Nd-146 irradiation and pricing it competitively with either Pu-238 or fission product Pm-147. If Pm-147 is wanted for its own unique properties in quantities over and above those available from fission product sources and if sales prices above current levels can be considered, then this irradiation process may prove feasible. However, further consideration of this irradiation process does not appear warranted if the price of Pm-147 must be competitive with Pu-238.

3.0 POTENTIAL DEMAND

A clear picture of potential demand for Pm-147 or for heat-source isotopes in general has not yet developed. Some concept of the possible magnitude of this demand can be gained by reviewing some of the comments that have been made regarding isotopic power requirements just for space exploration. Pu-238 has been favored in most public comments regarding NASA's needs for isotopic power sources. However Pm-147 can be considered a substitute for Pu-238 for missions up to two or three years duration assuming satisfactory availability and a competitive cost.

In March 1963, NASA estimates of annual Pu-238 requirements were reported⁽¹⁾ to reach 2000 electrical watts [20 to 40 kW(t)] in 1970 and 3000 electrical watts in 1972. In September 1963 another report⁽²⁾ on NASA annual requirements indicated a 3500 electrical watts [35 to 70 kW(t)] requirement in 1970 and 4500 electrical watts in 1972. In April 1965 the AEC Division of Isotope Development estimated⁽³⁾ NASA requirements in 1970 at 25 kW(t) for Pu-238 and 10 kW(t) for Pm-147--in general agreement with the earlier projections assuming Pu-238 and Pm-147 are somewhat interchangeable.

Other sources indicate rapid expansion of heat source isotope demand during the 1970's. For example one source⁽⁴⁾ mentioned a NASA request for 1000 kg of Pu-238 at \$270/g by 1980. This is understood to be a cumulative total and amounts to 560 kW(t) at \$480/W(t).

Harold B. Finger, Manager of the joint AEC-NASA Space Nuclear Propulsion Office, testifying before the Senate Aeronautical and Space Sciences Committee in August 1965, commented⁽⁵⁾ in part, "In considering the Apollo extension missions..., it is apparent that isotope power systems will find extensive use. ...The power levels that will be required are well above the 25 to 50 watt levels that are being developed for currently approved missions. Power levels of 250 watts up to a few kilowatts will be needed for these intermediate missions." Thus based on a thermal to electric conversion efficiency of 10%,

individual devices requiring 2.5 to over 10 thermal kilowatts will be required. Current thermoelectric device conversion efficiencies are only around 5% but Mr. Finger indicated a factor of "two or more" improvement in conversion efficiency would be necessary before isotopic power systems could be used at the higher power levels.

Although the uncertainties are large, it appears that the demand for heat source isotopes of a type for which Pm-147 would have unique qualifications could reach 50 to 100 thermal kilowatts per year in the early 1970's and increase to possibly hundreds of thermal kilowatts per year in the 1980's.

4.0 AVAILABILITY OF FISSION-PRODUCT PROMETHIUM

4.1 Sources of Fission-Product Promethium

Promethium-147 is produced as a by-product in the fissioning of U-235 or Pu-239 with a fission yield of about 2.5%. There are potentially two sources of supply for recovered fission-product promethium--the AEC separations plant wastes (Hanford and Savannah River) and civilian-power reactor fuel processing wastes.

4.2 Promethium from Hanford Wastes

Promethium is available now in the Hanford wastes and Isochem Inc has announced plans for an \$8 million fission product conversion and encapsulation (FPCE) plant. Plans include recovery of Pm-147 as well as Sr-90, Cs-137 and possibly Ce-144. According to the program justification data submitted⁽⁶⁾ to the Joint Committee on Atomic Energy by the AEC, the plant will have capacity to process 53 megacuries per year (20 kW/yr) of Pm-147. However, the anticipated processing and fabrication schedule⁽⁷⁾ indicates only 24 megacuries per year (8.6 kW/yr) of promethium planned for delivery by the AEC to the Isochem fission product conversion and encapsulation plant. Presumably, if demand is sufficient, additional capability could be realized through a program to process Savannah River wastes for promethium.

4.3 Promethium from Civilian Power Reactor Wastes

To project promethium availability from civilian power reactors it is first necessary to develop projections on the growth rate of the power reactor industry and its characteristics. The AEC and the Federal Power Commission as well as the General Electric and Westinghouse Corporations have published estimates^(8,9,10) of the future growth rates of the nuclear power industry. The information on these estimates, available as of December 1965, is summarized in Figure 1. The median estimate, assumed to be the best estimate for the purpose of this survey, coincides with the Federal Power Commission's 1964 projection of 70,000 MWe of nuclear capacity in 1980. The disagreement in the 1980 projections appear to be about $\pm 20,000$ MWe or $\pm 30\%$.*

From the estimates of generating capacity a spent fuel discharge pattern for yearly increments of added nuclear power capacity was developed assuming new capacity to be 50% boiling water reactors and 50% pressurized water reactors and fuel management schemes published⁽¹¹⁾ for General Electric and Westinghouse advance design BWR and PWR reactors shown in Table I. The resulting projection of

TABLE I
REFUELING SCHEDULE FOR EACH 1000 MW(e)
OF NEW INSTALLED REACTOR CAPACITY⁽¹¹⁾

<u>Reactor</u>	<u>Discharge Batch</u>	<u>Initial Enrichment, %U-235</u>	<u>Discharge Enrichment, %U-235</u>	<u>Fuel Exposure, MWd/MTU</u>	<u>Fuel Residence Time @ 80% C. F., years</u>
BWR [500 MW(e), 1600 MW(t), UO ₂ , 105 MTU inventory, refueling 1/5 replacement batch, scatter pattern]					
First Core	1	2.05	1.14	10,900	2.2
	2	2.05	1.02	13,100	2.8
	3	2.05	.87	15,900	3.4
	4	2.05	.71	19,300	4.2
	5	2.05	.56	23,500	5.3
	Equil.	2.42	.84	22,000	4.8
PWR [500 MW(e), 1600 MW(t), UO ₂ , 63 MTU inventory, refueling 1/3 replacement batch, out in]					
First Core	1	2.50	0.90	15,800	1.6
	2	2.80	0.85	22,800	2.7
	3	3.10	1.05	25,400	3.7
	Equil.	3.00	1.20	24,000	3.2

*More recent estimates now indicate 90,000 to 100,000 MW(e) installed capacity in 1980 as probable.

FIGURE 1

U.S. Electrical Generating Capacity Growth Estimates

spent fuel discharge rate is shown in Figure 2. Spent fuel discharge rates are indicated to increase from 175 $\pm$ 25 MT/yr in 1970 to 2200 $\pm$ 600 MT/yr in 1980.

The average exposure of the fuel available for processing each year was calculated using the same assumptions and these results are presented in Figure 3. The average exposure of the discharged fuel is shown to increase gradually to 20,000 MWd/MTU in 1980 where it then levels out. Even though goal exposures of 22,000 and 24,000 MWd/MTU were assumed, the lower exposure achieved with the first fuel loads for the new reactors added each year holds the average exposure down.

Another factor affecting Pm-147 availability was an assumed 2-1/2 year (one half-life) cooling requirement after reactor discharge to allow for decay of 41-day Pm-148. This cooling requirement affects availability in two ways (1) the amount of Pm-147 is reduced by a factor of two and, (2) the effect of any increased spent-fuel discharge rate on Pm-147 availability is delayed by 2-1/2 years.

Promethium yields, as a function of fuel exposure, were obtained from data developed by Rohrman and Merrill⁽¹²⁾ and are shown in Figure 4.

The estimated potential Pm-147 availability from U. S. power reactors up through 1985 is shown in Figures 5 and 6. Figure 5, an arithmetic plot, shows how slowly Pm-147 availability increases up through about 1975 when availability begins to increase rapidly. Figure 6, a semi-log plot, is included to illustrate more clearly the availability trend in the 1980's and beyond. Availability of aged Pm-147 from power reactor fuels will not reach 5 kW(t)/yr until 1974. However by 1980, availability from this source will reach 30 $\pm$ 8 kW(t)/yr and will double about every 4 or 5 years for some time thereafter reaching possibly 150 $\pm$ 50 kW/yr in 1990.

Thus it appears that the Hanford waste streams will be the

FIGURE 2

Spent Fuel Availability from U.S. Power Reactors

FIGURE 3

Estimated Average Exposure of Fuel Discharged from U.S. Reactors

FIGURE 4

Pm-147 Yields from Reactor Fuels

FIGURE 5

Aged Pm-147 Availability from U.S. Power Reactors

FIGURE 6

Aged Pm-147 Availability from U.S. Power Reactors

principal source of Pm-147 up through about 1975 with production planned at about 10 to possibly 20 kW/yr. After 1975 Pm-147 supplies from power reactor fuel processing will become a significant source of supply and after 1980 will overshadow Hanford sources.

Comparing Pm-147 availability against the potential demand discussed previously, it appears that availability could fall significantly behind demand in the 1970 to 1980 period. After 1980, fission product Pm-147 availability will be increasing rapidly and should be capable of supplying an increasingly significant share of the market at that time.

5.0 PROMETHIUM PRODUCTION BY IRRADIATION OF NEODYMIUM

5.1 Description of Production Cycle

Production of Pm-147 by irradiation of Nd-146 has been proposed as a means of supplementing the amount available as a fission product in fuel processing wastes. The following reaction would be utilized.

Two facts of nature make it difficult to utilize this process. First, Nd-146 is only one of seven naturally occurring neodymium isotopes (17.2% Nd-146 in the natural neodymium mixture). Second, Nd-146 has a very low thermal neutron absorption cross section, 2 barns, and five of the six other neodymium isotopes all have higher cross sections. The abundance and thermal cross sections of the individual neodymium isotopes are shown in Table II. If the natural neodymium mixture were placed in a neutron flux, less than 1% of the absorbed neutrons would be absorbed in the Nd-146. It thus becomes apparent that an isotope separation process would be required for a reasonable neutron utilization.

Some of the principal economic factors involved in producing Pm-147 by Nd-146 irradiation were examined to determine if the economic incentives were large enough to justify a more detailed exploration. The production cycle is discussed first and specific

cost factors are discussed in more detail in the next section. It was assumed that the isotope separation process was technically feasible.

TABLE II
NATURAL NEODYMIUM COMPOSITION

<u>Isotope</u>	<u>% Abundance</u>	<u>Cross Section, barns</u>
142	27.11	17.0
143	12.17	330.0
144	23.85	5.0
145	8.30	50.0
146	17.22	2.0
148	5.73	4.0
150	5.62	1.5
Composite	100.00	50.0

The target irradiation cycle is illustrated schematically in Figure 7. Because of the small cross section for Nd-146 and a much larger cross section for Pm-147 (235 barns thermal and a 3220 barn resonance integral)⁽¹³⁾ only a relatively small amount of the Nd-146 can be converted to Pm-147 during one irradiation cycle. This is true even for long periods of irradiation because the Pm-147 content tends to level off as it approaches saturation after a year or two depending on the neutron flux.

The small Nd-146 conversion per cycle affects the economics of Pm-147 production in three ways: (1) a relatively large in-reactor inventory of valuable Nd-146 target must be maintained for a given Pm-147 production rate, resulting in turn in large inventory charges and large reactor space charges per unit of product, (2) small processing losses per cycle accumulate over many cycles and result in very low ultimate yields of Pm-147 from the expensive Nd-146 target material and, (3) target encapsulation and reprocessing costs are large because so little Pm-147 is produced in each process cycle.

FIGURE 7

Neodymium-146 Irradiation for Promethium-147 Production

To provide a quantitative basis for evaluation of this Pm-147 production scheme, production rates and yields were calculated for five irradiation conditions as follows:

- (1) A neutron flux of 1×10^{13} n/cm²/sec and a spectral index of 0.2 representative of average conditions in a water moderated power reactor.⁽¹⁴⁾ A flux of 2 or 3×10^{13} n/cm²/sec is claimed for some reactors but with successive plutonium recycle, the flux might be as low as 2×10^{12} n/cm²/sec.
- (2) A neutron flux of 3×10^{13} n/cm²/sec and a spectral index of 0.2 representative of about the best that could be expected from water moderated power reactors⁽¹⁵⁾ without special target irradiation design features.
- (3) A neutron flux of 6×10^{13} n/cm²/sec and a spectral index of 0.2 representative of target irradiation in select central core locations possibly requiring special core and fuel design features.
- (4) A neutron flux of 6×10^{13} n/cm²/sec as in (3) but a more thermalized flux with a spectral index of 0.05 (softer spectrum resulting in lower Pm-147 cross section) such as might be realized in reactors like the Canadian natural uranium reactors. This softer spectrum has the effect of reducing the rate of Pm-147 disappearance by neutron capture and increases the ultimate yield of Pm-147.
- (5) A neutron flux of 1×10^{14} n/cm²/sec and a spectral index of 0.05. This represents a probable upper limit for thermal neutron flux that would perhaps be available only in small research reactors.

A standard loss of 1% for both encapsulation and chemical separation was assumed. In addition a variation of case 4 was calculated with an 0.25% loss to illustrate the effect of process losses. A 1% loss was considered a reasonable assumption for the type of processing required. Losses less than 1% could probably be achieved but might well require increased processing costs that would offset any advantage in improved yields. Results of the calculations are presented in Figures 8 through 12 and are summarized for a one-year irradiation cycle in Table III.

The data in Table III show that Pm-147 yield and production rate increase markedly with the flux. The ultimate yield from Nd-146 is inversely proportional to the process losses but these losses have only

FIGURE 8

Promethium-147 Production by Irradiation of Neodymium-146

FIGURE 9

Promethium-147 Production by Irradiation of Neodymium-146

FIGURE 10

Promethium-147 Production by Irradiation of Neodymium-146

FIGURE 11

Promethium-147 Production by Irradiation of Neodymium-146

FIGURE 12

Promethium-147 Production by Irradiation of Neodymium-146

TABLE III

PROMETHIUM-147 PRODUCTION WITH A ONE-YEAR TARGET IRRADIATION OF NEODYMIUM-146

Case	Neutron Flux, n/cm ² /sec	(r) Spectral Index ^(a)	(L ₁ and L ₂) Process Losses ^(b) %	(Y) Cycle Yield, g Pm-147/MT Nd-146 (no loss basis)	(P) Production Rate, g aged Pm-147/yr per MT Nd-146 in reactor	(Y*) Ultimate Yield, kg aged Pm-147 per MT Nd-146
1	1 x 10 ¹³	0.2	1.0	480	237	11.5
2	3 x 10 ¹³	0.2	1.0	1150	580	26.0
3	6 x 10 ¹³	0.2	1.0	1748	865	36.3
4	6 x 10 ¹³	0.05	1.0	2330	1150	48.0
4a	6 x 10 ¹³	0.05	0.25	2330	1162	206.0
5	1 x 10 ¹⁴	0.05	1.0	3178	1573	59.7

(a) The value of r is determined by the ratio of epithermal to thermal neutrons in the reactor spectrum. A lower value for r represents a more thermalized flux.

(b) Losses are incurred both for reprocessing and for encapsulation. Thus the total loss of target material per cycle is twice the value shown.

a minor effect on the production rate. It is important to recognize how small the production rate is relative to the reactor inventory. For example, even for the high flux case, less than 0.2%/yr of the Nd-146 in the reactor is converted to Pm-147 product. It is also important to recognize how small the ultimate recovery of Pm-147 is from the valuable Nd-146 target. The value of utilizing the softest possible neutron spectrum for this irradiation is illustrated by comparing yields and production rates for the two 6×10^{13} n/cm²/sec cases.

The data plotted on Figures 8 through 12 show that the Pm-147 production rate increases very rapidly as the irradiation cycle time increases and reaches a maximum at around a 100- to 200-day irradiation cycle depending on the neutron flux. The production rate (the product of yield/cycle x cycles/yr) then drops off as cycle time increases due to fewer cycles/yr and a decline in the rate that the cycle yield is increasing. The yield of Pm-147 from the neodymium increases sharply as the irradiation cycle lengthens up to a year or so and then increases more slowly as saturation is approached.

It would be desirable to utilize an irradiation cycle that maximized production rate since this would minimize inventory charges and charges for target space in the reactor. However, it would also be desirable to obtain maximum yields of Pm-147 to minimize the cost of feed material and isotope separations as well as processing costs. Obviously both conditions can not be realized, at least not for the cases considered here. A one-year irradiation cycle was selected as the basis for the economics calculations since it appeared, judging from the relationships shown in Figures 8 through 12, that the optimum cycle would likely be on the order of one year. This assumption was subsequently confirmed by the results of calculations that are presented later in this report.

Promethium 147 recovered from fission product wastes is always contaminated with small quantities of 710-day Pm-146 and 41-day Pm-148. These are both gamma-emitting isotopes and increase shielding

requirements for the Pm-147. The Pm-146 results from an $n,2n$ reaction on Pm-147 and the Pm-148 from an n,γ reaction on Pm-147. There may be no practical means of reducing the Pm-146 content although studies are in progress on selective burning out of this isotope by irradiation with thermal neutrons. The Pm-148 content can be reduced to a negligible amount by aging the Pm-147 for about one half-life or about 2-1/2 years.

Qualitative considerations indicated that Pm-147 produced by target irradiation of Nd-146 would have amounts of Pm-148 associated with it comparable to the fission product promethium. The same one half-life aging requirement was therefore assumed for the target irradiation product. The degree of uncertainty did not appear to warrant detailed calculations for this study.

Since an $n,2n$ reaction requires fast neutrons and since target elements would be exposed to a more thermalized flux than fission product promethium which is exposed to fission neutrons, Pm-147 produced by target irradiations should have a lower Pm-146 content. This would mean a higher quality product but would not affect the production cost in any way.

As far as is known, there is no resonance absorption of epithermal neutrons by Nd-146. The calculations here are all based on an Nd-146 cross section at 2200 m/sec of 2 barns. If there is, in reality, a resonance it might have an appreciable effect on the prospects for economic production of Pm-147 discussed in the next section.

5.2 Economic Considerations

Determination of whether or not Pm-147 should be produced by irradiation of Nd-146 will be governed in the final analysis by economic considerations. An initial economic analysis of this question has been carried out in this study. The principal cost factors have been evaluated in a preliminary manner to provide a basis for evaluating the desirability of more extensive investigations.

The cost factors involved in Pm-147 production by Nd-146 irradiation can be outlined as follows:

- (1) Cost of natural neodymium consumed
- (2) Cost of isotopic separations processing to produce the Nd-146 target material
- (3) Target encapsulation costs
- (4) Irradiation costs including
 - a. Increase in reactor operating costs such as:
 1. Increased enrichment cost (if any)
 2. Handling costs for target elements
 3. Capitalization of any reactor modifications required
 - b. Loss of revenue as a result of displaced fuel and consequently
 1. Reduction in power production and power sales revenue or
 2. Reduction in plutonium production if a production reactor were used
- (5) Processing costs for separation of Pm-147 from the unburned Nd-146 target material
- (6) Inventory charges for the valuable Nd-146 in the production cycle
- (7) Inventory charges on the Pm-147 during aging

These cost factors were each analyzed separately. A high and low cost estimate, based on probable maximum and probable minimum cost considerations, were developed for each factor. Results of the cost analysis for three selected cases from Table III are discussed in detail in the following paragraphs. The total production costs for all of the cases in Table III are then summarized.

5.2.1 Natural Neodymium Costs. Natural neodymium is fairly expensive, consequently the starting material will represent a significant cost because of the low yield of Pm-147 (see Table III). However, as will be seen later, it turns out to be the least significant of all the cost factors.

Neodymium oxide is available in several purity grades with substantial variations in the cost depending on the

purity. The principal rare earth impurities and prices for several grades of neodymium as published in a 1965 Lindsay Catalog and Price List are shown in Table IV.

TABLE IV

NEODYMIUM-OXIDE PRICES

<u>Purity</u>	<u>Principal Rare Earth Impurities</u>	<u>\$/lb (up to 99 lb lots)</u>
65-70%	12-16% Pr_6O_{11} 10-13% Sm_2O_3 3-5 % Gd_2O_3 1-6 % other RE	4.10
85%	10-12% Pr_6O_{11} 0.1-0.5% Sm_2O_3 0.2% Gd_2O_3 2-4 % other RE	4.50
99%	0.1-0.4% Pr_6O_{11} 0.1-0.4% Sm_2O_3 0.5% other RE	32.50
99.9%	0.1% Max any RE	37.50
99.999%		285.00

Considering the difficulties involved in any isotope separations process, it is reasonable to assume that at least a 99% neodymium purity would be desirable as a starting material. This would mean a current cost of \$32.50/lb Nd_2O_3 or \$37.90/lb Nd. A lower price for quantity purchases could be expected and a minimum cost of \$10/lb Nd was assumed. The raw material (natural Nd) portion of the Pm-147 cost for these two price levels and for three irradiation conditions is shown in Table V. An 80% recovery of Nd-146 from the isotope separations process was assumed. Even with a \$10/lb charge for natural neodymium, a flux of 6×10^{13} and an r of 0.05, the raw material cost still amounts to \$10/W.

Some of the neodymium tailings from the isotope separations process could probably be marketed and would thus reduce

the raw material costs. Whether the tonnage quantities that would be available from large-scale Pm-147 production could be sold at a significant price, however, is debatable. A Pm-147 production rate of 10 kW/yr would produce 4 to 16 MT/yr of neodymium tailings.

The question of neodymium availability was not explored in depth. However, neodymium is the third most abundant rare earth in monazite ore (11% Nd₂O₃) and there is no indication any difficulty would arise on that score.

TABLE V

EFFECT OF NATURAL Nd COST ON Pm-147 COST
(Nd-146 Irradiation Process)

Neutron Flux, n/cm ² /sec	3 x 10 ¹³	6 x 10 ¹³	6 x 10 ¹³
Spectral Index, r	0.2	0.2	0.05
Kg Natural Nd/W of aged Pm-147(a)	0.85	0.61	0.46
<u>Natural Nd Cost Increment, \$/W of aged Pm-147</u>			
Natural Nd @ \$10/lb	19	13	10
Natural Nd @ \$37.90/lb	71	51	38

(a) Based on a one-year irradiation, 80% recovery of Nd-146 in isotope separation, 1% process losses and 0.33 W/g Pm-147 (pure).

5.2.2 Isotope Separation Costs. No attempt was made to estimate actual isotope separations costs. Some generalizations can, however, help to shed some light on this aspect of the production cycle.

R. T. Alleman⁽¹⁶⁾ briefly investigated the feasibility of an isotope separation process for Nd-146 production. He concluded that the separation by an ion exchange process appeared possible, "...based on calculations made with extrapolated theory". Based on his calculations, approximately 350 one-foot diameter by 35-foot ion exchange columns would

be required to separate 1 MT of 99% pure Nd-146/yr. Unquestionably this would be a costly process.

A cost of \$285/lb (\$628/kg) is indicated for 99.999% pure neodymium in Table IV. Isotope separation of Nd-146 would certainly be at least as difficult as producing 99.999% pure neodymium and it's not difficult to visualize an order of magnitude higher cost. The effect of isotope separation costs on Pm-147 cost for an assumed separation cost of \$600 and \$6000/kg Nd-146 is shown in Table VI.

TABLE VI

EFFECT OF ISOTOPE SEPARATIONS COST ON Pm-147 COST

(Nd-146 Irradiation Process)

Neutron Flux, n/cm ² /sec	3 x 10 ¹³	6 x 10 ¹³	6 x 10 ¹³
Spectral Index, r	0.2	0.2	0.05
kg Nd-146/W of aged Pm-147 ^(a)	0.117	0.083	0.063
Separation Cost Increment, <u>\$/W of aged Pm-147</u>			
Separation Cost @ \$600/kg Nd-146	70	50	38
Separation Cost @ \$6000/kg Nd-146	700	500	380

(a) Based on a one-year irradiation, 1% process losses and 0.33 W/g Pm-147 (pure).

The cost of isotope separation appears to be more significant than the raw material cost and certain to have a major effect on the cost of Pm-147 produced by this method. The effect of an isotope separations cost of \$600/kg Nd-146 is almost identical with a raw material cost (Table V) at \$37.90/lb Nd.

5.2.3 Target Encapsulation Costs. Based on some estimates published in previous studies^(15,17) of target irradiation costs for other materials, encapsulation or canning costs could be

expected to range from around \$10/kg up to possibly \$300/kg of Nd-146 as a maximum. This assumes the target material to be Nd_2O_3 and that encapsulation would be no more difficult than Tm_2O_3 encapsulation.

The effect of target encapsulation costs on Pm-147 costs is shown in Table VII. Although the encapsulation costs are much less per kilogram of Nd-146 than the isotope separation costs assumed for Table VI, their effect on the Pm-147 cost is just as significant, or possibly more so. The encapsulation cost is incurred each time the Nd-146 is recycled whereas the isotope separations cost is incurred only once on each unit of Nd-146. Another consideration that increases the importance of encapsulation costs is that processing losses do not have a cumulative effect on this cost as in the case of raw material or isotope separations costs, thus the effect of encapsulation costs cannot be reduced significantly by reducing processing losses. Simplified and inexpensive encapsulation procedures would be essential to the feasibility of Pm-147 production by Nd-146 irradiation.

TABLE VII

EFFECT OF TARGET ENCAPSULATION COST ON Pm-147 COST

(Nd-146 Irradiation Process)

Neutron Flux, $\text{n/cm}^2/\text{sec}$	3×10^{13}	6×10^{13}	6×10^{13}
Spectral Index, r	0.2	0.2	0.05
kg Nd-146 Encapsulated/W of aged Pm-147 ^(a)	5.21	3.50	2.64
<u>Encapsulation Cost Increment,</u> <u>\$/W of aged Pm-147</u>			
Encapsulation @ \$10/kg Nd-146	52	35	26
Encapsulation @ \$300/kg Nd-146	1560	1050	790

(a) Based on a one-year irradiation, 1% process losses and 0.33 W/g Pm-147 (pure).

5.2.4 Irradiation Costs. It is difficult to define the probable limits of direct irradiation costs. They will be strongly dependent on the specific reactor being utilized and the extent a target irradiation program would disrupt normal operations. It is conceivable that both a reactor and its fuel design might be modified to provide more favorable conditions for target irradiations. It is also conceivable that in some instances limited target space could be provided without displacing fuel or disrupting normal operations. On the other hand, a large scale target irradiation program such as would be required for significant Pm-147 production would most likely have a significant effect on normal operations. Because of the small cross section of Nd-146 target however, it is reasonable to assume that relatively little cost would be incurred for increased enrichment requirements.

Irradiation costs for target irradiations were developed for the Malibu and Oyster Creek reactors in ORNL-3792.⁽¹⁵⁾ A minimum cost of \$0.20/cc-yr for target space was indicated if no enrichment costs or loss of revenue costs due to displaced fuel are incurred. A maximum cost of \$2.00/cc-yr was indicated if revenue is lost because of reduced power production but no enrichment costs are incurred, or \$3.00/cc-yr if both enrichment and loss of revenue costs are incurred. Another estimate of target space costs in a Hanford study⁽¹⁷⁾ for a natural uranium reactor indicated \$2.50/cc-yr excluding any incremental enrichment cost.

Assuming a range of target space costs from \$0.20 to \$2.50/cc-yr, the effect of irradiation costs on Pm-147 cost is shown in Table VIII. Irradiation costs are indicated to be the most significant cost factor of those discussed so far. Even with target space costing only \$0.20/cc-yr the effect on Pm-147 costs is substantial.

TABLE VIII

EFFECT OF IRRADIATION COST ON Pm-147 COST
(Nd-146 Irradiation Process)

Neutron Flux, $n/cm^2/sec$	3×10^{13}	6×10^{13}	6×10^{13}
Spectral Index, r	0.2	0.2	0.05
Reactor Space Required, cc/W of aged Pm-147/yr ^(a)	879	595	448
Irradiation Cost Increment, <u>\$/W of aged Pm-147</u>			
@ \$0.20/cc-yr	178	119	90
@ \$2.50/cc-yr	2220	1490	1120

(a) Based on a one-year irradiation, 1% process losses and 0.33 W/g Pm-147 (pure). Target assumed to be Nd_2O_3 at 95% theoretical density. If neodymium metal targets could be utilized, space requirements would be reduced about 15%.

5.2.5 Target Reprocessing Costs. The target reprocessing costs to to separate Pm-147 from the Nd-146 target. should not exceed \$100/kg Nd and probably would not be less than \$10/kg Nd. The reprocessing cost, like encapsulation cost, is incurred each time the Nd-146 is recycled so its effect on Pm-147 costs should be similar to, but possibly less than, encapsulation costs.

5.2.6 Target Inventory Costs. One of the most significant cost factors is the carrying charge on the required large inventory of target material. In the case of private industry this charge would be based on a minimum attractive return on investment. A rate of 12.5%/yr before taxes is representative of the chemical industry. In the case of a government program, the charge can be related to the cost of borrowed capital to the government or about 5%/yr. For example, the use charge on enriched uranium which is supposed to represent full cost recovery to the government is set at 4-3/4%/yr.

The inventory charge is not generally considered as a cost in accounting but is a device used in engineering economy studies to insure minimum attractive rates of return. It is easier to visualize the necessity for this inventory charge in private business situations than in government financing situations where it is sometimes neglected. However, it cannot be ignored in a case like this in which the value of the inventory is very large in comparison to the value of the end product. It is a method for relating the cost of the initial investment in inventory to the unit cost of the final product. Grant and Ireson⁽¹⁸⁾ in their "Principles of Engineering Economy" state their view regarding interest rates for inventory charges in economic studies for government enterprises as follows, "Just as in private enterprise, the question of interest rate to be used in an economy study is essentially the question of what is the minimum attractive return under the circumstances. Although the cost of borrowed money is one appropriate element in determining the minimum attractive return, it is not the sole element to be considered. In most instances the appropriate minimum attractive return should be somewhat higher than the cost of borrowed money."

The target inventory would include not only the amount of target material being irradiated in a reactor, but also the amount of target material in other parts of cycle required to maintain full utilization of target space in the reactor. Most power reactors are opened up for refueling on 6- to 18-month cycles with preference in the newer designs for one-year refueling cycles. A one-year irradiation cycle would require a total of two tons of target material for each ton in the reactor to insure full utilization of target space. When one batch of target elements was discharged a new batch should be ready to charge--there wouldn't be time

to reprocess the discharged targets during the reactor turn-around period. If reactors with a more frequent discharge schedule could be utilized or if shutdown for target replacement were feasible, a partial target discharge schedule could be developed and a target inventory on the order of 1.2 tons/ton in the reactor might be possible as a minimum requirement.

The value of the Nd-146 target inventory would include the investment in natural neodymium, isotope separations and encapsulation costs. The encapsulation inventory cost would not be carried by that portion of the recycling inventory between reactor discharge and reencapsulation. A breakdown of the gross inventory charges per metric ton of target material being irradiated is shown in Table IX. The grouping into high and low estimates in Table IX indicates the inventory costs on isotope separation charges overshadow the other inventory costs. This wouldn't necessarily be true in some intermediate situations and none of the charges can be neglected.

The effect of the inventory charges on Pm-147 costs is shown in Table X for just the most favorable inventory requirement of 1.2 MT/MT in the reactor. These data indicate inventory costs to be easily the most important cost of any of those considered at the 12.5%/yr rate and about the same magnitude as the irradiation cost if the 5%/yr rate is applied. The inventory costs on investments in raw material and isotope separation are of larger magnitude than the material and isotope separations costs themselves. This is because of the very small conversion of target material per cycle, that is, the very large in-reactor target inventory relative to the production rate of Pm-147. For example, more than 40 tons of Nd-146 must be irradiated in one cycle to obtain the amount of Pm-147 that can ultimately, after many recycles, be produced from one ton of Nd-146.

TABLE IX

GROSS INVENTORY CHARGES
(Nd-146 Irradiation Process)

Nd-146 Inventory, MT/MT in Reactor ^(a)	1.2	2.0
Inventory Charges, \$/yr/MT in Reactor @ 12.5%/yr rate		
On Raw Mat'l. @ \$10/lb Nat'l Nd	24,000	40,000
On Isotope Sep'n @ \$600/kg Nd-146	90,000	150,000
On Encapsulation @ \$10/kg Nd-146	<u>1,400</u>	<u>1,900</u>
Low Estimate Total	115,400	191,900
On Raw Mat'l @ \$37.90/lb Nat'l Nd	91,000	152,000
On Isotope Sep'n @ \$6000/kg Nd-146	900,000	1,500,000
On Encapsulation @ \$300/kg Nd-146	<u>41,000</u>	<u>56,000</u>
High Estimate Total	1,032,000	1,708,000
Inventory Charges, \$/yr/MT in Reactor @ 5%/yr rate		
On Raw Mat'l @ \$10/lb Nat'l. Nd	9,600	16,000
On Isotope Sep'n @ \$600/kg Nd-146	36,000	60,000
On Encapsulation @ \$10/kg Nd-146	<u>600</u>	<u>800</u>
Low Estimate Total	46,200	76,800
On Raw Mat'l @ \$37.90/lb Nat'l. Nd	36,400	60,700
On Isotope Sep'n @ \$6000/kg Nd-146	360,000	600,000
On Encapsulation @ \$300/kg Nd-146	<u>16,500</u>	<u>22,500</u>
High Estimate Total	412,900	683,200

(a) The encapsulation inventory charges are based on an encapsulated inventory of 1.1 and 1.5 MT/MT where the total inventory is 1.2 and 2.0 MT/MT respectively.

TABLE X

EFFECT OF TARGET INVENTORY CHARGES ON Pm-147 COST
(Nd-146 Irradiation Process)

Neutron Flux, n/cm ² /sec	3×10^{13}	6×10^{13}	6×10^{13}
Spectral Index, r	0.2	0.2	0.05
Inventory Ratio, MT/MT in Reactor	1.2	1.2	1.2
Production Rate, W/yr/MT in Reactor ^(a)	191	286	380

Inventory Charges, \$/W of aged Pm-147

@ 12.5%/yr

Low Estimate	603	403	304
High Estimate	5410	3610	2710

@ 5%/yr

Low Estimate	242	162	122
High Estimate	2160	1440	1090

(a) Based on a one-year irradiation, 1% process losses and 0.33 W/g Pm-147 (pure).

5.2.7 Pm-aging Inventory Costs. Because of the requirement for storing Pm-147 for about one half-life to allow for the 41-day Pm-148 to die out, another inventory charge is required for the Pm-147 during this aging period. This charge will be a function of the value of the promethium ultimately recovered. Depending on the type of financing (government or private) it would amount to from 10 to 25% of the final promethium value.

5.2.8 Total Production Costs. All of the production costs as they have been developed in the preceding discussion are tabulated and totaled in Table XI. The low and high estimated costs are shown for each item to indicate the probable range of \$/W costs.

TABLE XI

TOTAL Pm-147 PRODUCTION COST
(Nd-146 Irradiation Process)

Neutron Flux, n/cm ² /sec	3 x 10 ¹³	6 x 10 ¹³	6 x 10 ¹³
Spectral Index	0.2	0.2	0.05
<u>Production Costs,</u> <u>\$/W of aged Pm-147(a)</u>			
Natural Nd Cost	19- 71	13- 51	10- 38
Isotope Separation Cost	70- 700	50- 500	38- 380
Encapsulation Cost	52- 1,560	35-1,050	26- 790
Irradiation Cost	178- 2,220	119-1,490	90-1,120
Reprocessing Cost	52- 521	35- 350	26- 264
Target Inventory Cost @ 5%/yr	242- 2,160	162-1,440	122-1,090
Pm-147 Inventory Cost @ 5%/yr	<u>61- 723</u>	<u>41- 488</u>	<u>31- 368</u>
Rounded Total	670- 8,000	460-5,400	340-4,100
Rounded Total if 12.5% per year inventory charge used	1,200-13,000	820-8,800	620-6,600

(a) Based on one-year irradiation, 1% process losses and 0.33 W/g Pm-147 (pure).

A high degree of uncertainty in the estimates is indicated by the factor of 10 difference between the low and high estimate. Nevertheless, the estimates, as a range of costs, are believed realistic. It would be a mistake to put too much emphasis on either the low or the high estimate. The probable true cost lies somewhere in between.

The range of calculated total production costs for all cases in Table III are presented in Table XII. These data show a spectacular 2-1/2 fold increase in production costs

TABLE XII
SUMMARY OF TOTAL Pm-147 PRODUCTION COSTS
 (Nd-146 Irradiation Process)

<u>Case</u>	<u>Neutron Flux n/cm²/sec</u>	<u>Spectral Index</u>	<u>Process Losses, %</u>	<u>Total Pm-147 Production Cost, \$/W of aged Pm-147^(a)</u>	
				<u>5%/yr Inventory Charge</u>	<u>12.5%/yr Inventory Charge</u>
1	1 x 10 ¹³	0.2	1.0	1,600-19,000	3,000-32,000
2	3 x 10 ¹³	0.2	1.0	670- 8,000	1,200-13,000
3	6 x 10 ¹³	0.2	1.0	460- 5,400	820- 8,800
4	6 x 10 ¹³	0.05	1.0	340- 4,100	620- 6,600
4a	6 x 10 ¹³	0.05	0.25	300- 3,700	570- 6,200
5	1 x 10 ¹⁴	0.05	1.0	250- 3,000	460- 4,900

(a) Based on a one-year irradiation, 0.33 W/g Pm-147 (pure)
 and target inventory of 1.2 MT/MT in reactor.

as neutron flux is reduced from 3×10^{13} to 1×10^{13} n/cm²/sec. At the other end of the neutron flux range considered, the effect of flux is not nearly as great--an increase in neutron flux from 6×10^{13} to 1×10^{14} n/cm²/sec reduces production costs only about 20%.

Only a moderate reduction in production costs is indicated for a reduction in process losses below the 1% loss assumed as a basis for this study. Reducing the process loss from 1% to 0.25% at a flux of 6×10^{13} n/cm²/sec (cases 4 and 4a) produces only about a 10% reduction in production cost. This would be an important savings but not likely to make or break the economic feasibility of the process.

The importance of utilizing the softest possible neutron spectrum is indicated by comparing cases 3 and 4. At 6×10^{13} n/cm²/sec, a reduction of the spectral index from 0.2 to 0.05 reduces production costs approximately 25%.

The importance of inventory charges is illustrated by the effect of an increase from 5% to 12.5% in which case total production costs are increased 50 to 100%.

5.2.9 Optimum Irradiation Period. To confirm the assumption that a one-year target irradiation cycle would be near optimum, production costs for several irradiation periods were calculated for case 3. The results are shown graphically in Figure 13 and demonstrate a definite optimum close to a one-year irradiation period.

5.3 Irradiation in a Recirculating Loop

Brief consideration was given to the possibility of irradiating neodymium in a solution circulating through a reactor loop. This would have the advantages of eliminating the target encapsulation requirement and the aging requirement since Pm-147 could be removed by continuous processing as it was formed thus largely preventing Pm-148 formation.

FIGURE 13

Effect of Irradiation Time Cycle on Promethium-147 Production Costs
(Nd-146 Irradiation Process)

The disadvantage would be in the increased reactor space requirement. For example an $\text{Nd}(\text{NO}_3)_3$ solution would require 2000 liters/MT of Nd compared to 170 liters/MT of Nd as Nd_2O_3 . Even with the advantage of increasing Pm-147 utilization by a factor of two through elimination of the aging requirement, the reactor space requirement would still be six times greater than for Nd_2O_3 irradiation.

It is improbable that savings would offset the increased reactor costs. However, if detailed consideration is given to Pm-147 production by Nd-146 irradiation, this possibility should be kept in mind and if irradiation costs (or reactor space costs more specifically) should turn out to be small in comparison to encapsulation and Pm-aging inventory costs, then a more detailed evaluation of solution irradiation should be undertaken.

One other possibility for a loop irradiation process would be for the utilization of a molten salt rather than an aqueous solution. This would improve the density but would require a molten salt process for separation of Pm-147 from Nd-146. Investigation of this possibility might be worthwhile in any further study of promethium production from neodymium irradiation.

5.4 General Competitive Considerations

It is apparent from the preceding discussion that production of Pm-147 by irradiation of Nd-146 is going to be an expensive process. To evaluate the feasibility of producing Pm-147 by this process, a consideration of possible market price is helpful.

The AEC announced⁽¹⁹⁾ price reductions last year on Sr-90, Ce-144, Cs-137 and Pm-147. It was announced that these prices were set at levels approaching the prices expected to be charged by the Isochem Inc FPCE* Plant at Hanford. The new prices went into effect on November 10, 1965 with Pm-147 priced as low as \$0.20/curie in large quantities or \$560/W (the previous minimum price was

* A "Fission Products Conversion and Encapsulation Plant," privately owned and operated as a joint venture by Martin-Marietta Corporation and the U. S. Rubber Company.

was \$1.75/curie in over 50,000 curie lots). This new price may have been established more by consideration of pricing Pm-147 competitively with Pu-238, expected to sell for around \$300 to \$500 or \$500 to \$900/W, than by production costs. Since Pm-147 may eventually have to be priced well below Pu-238 on a \$/watt basis because of its shorter half-life, further Pm-147 price reduction sometime in the future is a reasonable prospect. For example, for a heat source application requiring a 2-year life, approximately twice as many Pm-147 watts would be required initially as compared to Pu-238.

The prospects are not attractive for producing Pm-147 by irradiation of Nd-146 and pricing it competitively with either Pu-238 or fission product Pm-147, since it would be necessary to assume that all of the low estimates of production costs could be realized and this appears to be unlikely.

Large quantities of Pm-147 may of course be required for its own unique properties irrespective of Pu-238 demands. In this case production of Pm-147 by Nd-146 irradiation might be a feasible means of meeting the requirement if sale prices above current levels can be considered.

6.0 APPENDIXCALCULATIONS FOR ND-146 IRRADIATION PROCESS COSTS

Y = Once-through yield of Pm-147 at reactor discharge

$$= 2.44 \times 10^{-16} \Lambda_1 \Lambda_2 N_1^0 \left[\frac{e^{-\Lambda_1 t}}{(\Lambda_2 - \Lambda_1)(\Lambda_3 - \Lambda_1)} + \frac{e^{-\Lambda_2 t}}{(\Lambda_1 - \Lambda_2)(\Lambda_3 - \Lambda_2)} + \frac{e^{-\Lambda_3 t}}{(\Lambda_1 - \Lambda_3)(\Lambda_2 - \Lambda_3)} \right] = \frac{g \text{ Pm-147 (unaged)}}{\text{MT Nd-146}}$$

where N_1^0 = initial Nd-146, atoms/g

Λ_1 = Nd-146 decay constant in neutron flux

$$= \phi \sigma_1 = \phi \times 2 \times 10^{-24} \text{ sec}^{-1}$$

Λ_2 = Nd-147 decay constant in neutron flux

$$= (\lambda_2 + \phi \sigma_2) = 7.23 \times 10^{-7} \text{ sec}^{-1}, (\phi \sigma_2 \text{ is negligible})$$

Λ_3 = Pm-147 decay constant in neutron flux

$$= (\lambda_3 + \phi \sigma_3) = [8.39 \times 10^{-9} + \phi(235 + 3220 \text{ r}) \times 10^{-24}] \text{ sec}^{-1}$$

$$C = \text{Number of cycles per year} = \frac{365 \text{ days/yr}}{\text{days/cycle}} = \text{yrs}^{-1}$$

$$= \text{MT Nd-146 charged/yr/MT Nd-146 in reactor} = \text{MT/yr/MT}$$

R = Tons Nd-146 recycled

$$= (C)(e^{-\Lambda_1 t})(1 - L_1) = \text{MT/yr/MT}$$

where L_1 = Separations process loss fraction

E = Encapsulation losses

$$= (C) \left[\frac{1}{(1 - L_2)} - 1 \right] = \text{MT/yr/MT}$$

where L_2 = Encapsulation loss fraction

M = Make-up Nd-146

$$= (C) + (E) - (R) = \text{MT/yr/MT}$$

P = Production rate of aged Pm-147

$$= (0.5)(C)(Y)(1-L_1) = \text{g aged Pm-147/yr/MT Nd-146 in reactor}$$

(The 0.5 factor accounts for the loss of Pm-147 during the one half-life aging period for Pm-148 decay.)

Y* = Ultimate yield of aged Pm-147

$$= \frac{(P)}{(M)} \times \left(\frac{1}{1000}\right) = \frac{\text{g aged Pm-147}}{\text{kg Nd-146}}$$

or $\frac{\text{kg aged Pm-147}}{\text{MT Nd-146}}$

F* = Natural Nd feed required

$$= \frac{1}{(0.172)(f)(Y^*)} = \frac{\text{kg natural Nd}}{\text{g aged Pm-147}}$$

where f = fraction of available Nd-146 recovered from natural Nd in isotope separation process.

f = 0.8 used in these calculations

Natural Nd Cost:

$$(F^*) \times \frac{(3.03 \text{ g/W})}{(0.454 \text{ kg/lb})} \times (\text{unit cost, \$/lb Nd}) = \$/\text{W}$$

Isotope Separation Cost:

$$\frac{(3.03 \text{ g/W})}{(Y^*)} \times (\text{unit cost, \$/kg}) = \$/\text{W}$$

Encapsulation or Reprocessing Cost:

$$\frac{(C)}{(P)} \times (1000 \text{ kg/MT}) \times (3.03 \text{ g/W}) \times (\text{unit cost, \$/kg}) = \$/\text{W}$$

Irradiation Cost:

$$\frac{1}{(P)} \times (170 \text{ L/MT}) \times (3.03 \text{ g/W}) \times (1000 \text{ cc/L})$$

$$\times (\text{unit cost, \$/cc-yr}) = \$/\text{W}$$

Target Inventory Cost:

on raw material value,

$$\frac{(3.03 \text{ g/W})}{(P)} \times \frac{(16,000 \text{ lb natural Nd})}{\text{MT Nd-146}} \times (\text{unit cost Nd, \$/lb})$$

$$\times \frac{(\text{inventory charge, \%/yr})}{100} \times (I) = \$/\text{W}$$

on isotope separation value,

$$\frac{(3.03 \text{ g/W})}{(P)} \times (1000 \text{ kg/MT}) \times (\text{unit separation cost, \$/kg}) \times \frac{(\text{inventory charge, \%/yr})}{100} \times (I) = \$/W$$

on encapsulation value,

$$\frac{(3.03 \text{ g/W})}{(P)} \times (1000 \text{ kg/MT}) \times (\text{unit encapsulation cost, \$/kg}) \times \frac{(\text{inventory charge, \%/yr})}{100} \times \frac{(I + 1)}{2} = \$/W$$

where I = inventory ratio, MT/MT in Reactor

Pm-147 Inventory Cost:

$$(\text{total of all other costs, \$/W}) \times (T) \times \frac{(\text{inventory charge, \%/yr})}{100} = \$/W$$

where T = Pm-147 aging time, yr

T = 2 yr used in these calculations

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