TECHNICAL, ECONOMIC AND POLICY
CONSIDERATIONS AFFECTING FUTURE
PRODUCTION, MARKETING AND USE
OF CESIUM-137 AND STRONTIUM-90

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

DECEMBER 1972

Prepared for the U.S. Atomic Energy
Commission under Contract AT(45-1):1830

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
U.S. ATOMIC ENERGY COMMISSION
Under Contract AT(45-1)-1630

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

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CONTENTS

	Page
LIST OF FIGURES.	iv
LIST OF TABLES	vi
I. INTRODUCTION AND PRINCIPAL CONCLUSIONS.	1.1
II. SUMMARY	2.1
Fuel Reprocessor Views	2.1
Recovery from Power Reactor Fuels	2.2
Basic Values	2.4
Markets	2.5
Hanford Waste Management Products	2.7
Analysis of a Simulated Two-Phase Fission-Product Industry	2.9
III. FUEL REPROCESSOR INTERESTS	3.1
IV. RECOVERY FROM POWER REACTOR FUELS	4.1
Required Facilities	4.1
Capital Cost Estimates	4.4
Capital Cost Scaling.	4.15
Operating Cost Estimates	4.17
Levelized Price Calculations	4.20
CAESR Computer Program	4.22
Initial Results	4.31
V. BASIC VALUES	5.1
Isotope Properties	5.1
User Application	5.4
Cobalt-Cesium Economic Comparison	5.8
VI. MARKETS	6.1
FPDL Sales Experience	6.1
¹³⁷ Cs Market Survey	6.1
RASOR/RAMARK Computer Programs	6.5
Base Gamma-Radiation Market Projections	6.15
⁹⁰ Sr Market Projections	6.16

CONTENTS (contd)

	Page
VII. HANFORD WASTE MANAGEMENT PRODUCTS	7.1
Hanford Waste Encapsulation and Storage Facility	7.1
Options for Sales to Industry.	7.8
Cost of Standard HWM Capsules	7.12
Cost of HWM Capsules with Inserts	7.15
Cost of Special One-Inch HWM Capsules	7.18
Private Re-encapsulation Facility	7.21
Special Strontium Capsules	7.28
Conclusions.	7.28
VIII. ANALYSIS OF A SIMULATED TWO-PHASE FISSION PRODUCT INDUSTRY .	8.1
Objectives	8.1
Procedure	8.2
Apportionment of the Market	8.6
Case Descriptions.	8.18
Results	8.22
Conclusions.	8.44
ACKNOWLEDGEMENTS	9.1
REFERENCES	10.1
APPENDIX A: Figures and Tables	A.1

LIST OF FIGURES

	Page
IV-1 Cesium/Strontium Processing Facility Plan View	4.5
IV-2 Cesium/Strontium Processing Facility Section A-A View	4.6
IV-3 Comparison of Cost Scaling Factors	4.16
IV-4 Cesium Recovery Plant Capital Cost Scaling.	4.17
IV-5 CAESR Calculation Procedure.	4.24
IV-6 Learning Curve Capability with CAESR.	4.32
IV-7 Required ^{137}Cs Prices at Level Production Rates	4.39
IV-8 Required ^{90}Sr Prices at Level Production Rates	4.40
IV-9 Capital Charge Fraction of Required Price at Level Production Rates	4.41
V-1 Gamma Energy Comparison	5.4
V-2 Effect of ^{60}Co Salvage Value on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci	5.13
V-3 Effect of ^{137}Cs Salvage Value on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci	5.14
V-4 Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci as a Function of ^{60}Co and ^{137}Cs Salvage Values	5.15
V-5 Effect of $^{134}\text{Cs}/^{137}\text{Cs}$ Ratio on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci	5.16
V-6 Effect of ^{60}Co Salvage Value on HWM Cesium Value Relative to ^{60}Co at 40¢/Ci	5.20
V-7 Effect of ^{137}Cs Salvage Value on HWM Cesium Value Relative to ^{60}Co at 40¢/Ci	5.21
V-8 HWM Cesium Value Relative to ^{60}Co at 40¢/Ci as a Function of ^{60}Co and ^{137}Cs Salvage Values	5.22
VI-1 Growth Rates of New-Source Markets	6.16
VI-2 New-Source Radiation Market Projections as ^{60}Co	6.18
VI-3 Total Radiation Market Projections as ^{60}Co	6.18
VI-4 Base and High ^{90}Sr Projections from 1 MCi in 1971	6.19
VI-5 Growth Rates for ^{90}Sr Market Projections	6.19
VII-1 First Floor Plan of Hanford Waste Encapsulation and Storage Facility	7.2
VII-2 Cross Section Views of Hanford Waste Encapsulation and Storage Facility	7.3
VII-3 Chemical Conversion Processes in the WESF	7.6

LIST OF FIGURES (contd)

	Page
VII-4 Encapsulation Processes in the WESF.	7.7
VII-5 Marketing Alternatives for HWM ¹³⁷ Cs	7.9
VII-6 Effect of Inert Capsule Insert on Self-Absorption and Relative Capsule Capacity	7.17
VII-7 Relationship Between Increased Value of Encapsulated ¹³⁷ Cs and Capsule Capacity with Inert Insert in Capsule	7.17
VII-8 Cesium Re-encapsulation Process	7.21
VII-9 Cesium Re-encapsulation Facility - Floor Plan.	7.22
VII-10 Cesium Re-encapsulation Facility	7.23
VIII-1 Computer Program for Two-Phase Industry Simulation	8.3
VIII-2 Equivalent Market Comparisons for Three Different Radiation Sources	8.4
VIII-3 Example of Possible Two Phase Cesium Market Evolution	8.5
VIII-4 Basis for Gamma-Source Market Sharing with Gradual Phaseout of HWM Sales.	8.8
VIII-5 Basis for Gamma-Source Market Sharing with Abrupt Phaseout of HWM Sales.	8.8

LIST OF TABLES

	Page
II-1 Comparison of Cost and Value of HWM Cesium Marketing Options	2.8
II-2 Coordinated Price Requirements for Base Case PR-Cs Recovery and Low-Capital Cases for HWM-Cs Re-encapsulation . . .	2.11
II-3 Example of Reallocation of Capital Charges to Reduce Required for PR-Sr	2.12
III-1 Projected Annual Availability of ^{137}Cs and ^{90}Sr in Power Reactor Fuels	3.1
IV-1 Reference Plant Cost Estimate Summary	4.8
IV-2 Cesium-137 Plant Capital Cost Estimate	4.9
IV-3 Strontium-90 Plant Capital Cost Estimate	4.10
IV-4 Cesium-137 and Strontium-90 Combined Plant Capital Cost Estimate	4.11
IV-5 Comparison of Cost Estimates with Original Estimates . .	4.12
IV-6 Comparison of Cs/Sr Recovery Facility Cost Estimate with Similar Facility Estimates	4.14
IV-7 Range of Capital Costs Used for Reference Plant	4.14
IV-8 Cesium Recovery and Encapsulation Plant Operating Cost Estimate	4.18
IV-9 Strontium Recovery and Encapsulation Plant Operating Cost Estimate	4.19
IV-10 Example of Levelized Price Calculation	4.23
IV-11 Example CAESR Printout	4.27
IV-12 Example CAESR Summary Printout.	4.28
IV-13 Example CAESR Summary Printout.	4.29
IV-14 Base Case Inputs	4.33
IV-15 Results of Initial Price Requirement Calculations for Single-Product ^{137}Cs	4.35
IV-16 Results of Initial Price Requirement Calculations for Co-Product ^{137}Cs	4.36
IV-17 Results of Initial Price Requirement Calculations for Single-Product ^{90}Sr	4.37
IV-18 Results of Initial Price Requirement Calculations for Co-Product ^{90}Sr	4.38

LIST OF TABLES (contd)

	Page
V-1 Radioactive Properties	5.2
V-2 Fission Product Cesium Compositions	5.3
V-3 Cobalt and Power Reactor Cesium Source Parameters	5.5
V-4 Typical Dose Uniformity Ratios.	5.7
V-5 Power Reactor Cesium Source Values Relative to ^{60}Co at 40¢/Ci	5.12
V-6 HWM Cesium Source Parameters	5.18
V-7 HWM Cesium Source Values Relative to ^{60}Co at 40¢/Ci.	5.19
VI-1 ^{137}Cs Sales from ORNL.	6.2
VI-2 ^{90}Sr Sales from ORNL	6.2
VI-3 Present and Previous Price Schedules for Cesium and Strontium	6.3
VI-4 Cobalt-60 Source Replenishment Schedule Showing Annual Additions and Discards	6.7
VI-5 Cobalt-60 Source Replenishment Schedule Showing History of Individual Source Components.	6.8
VI-6 Cesium-137 Source Replenishment Schedule Showing Annual Additions and Discards	6.9
VI-7 Cesium-137 Source Replenishment Schedule Showing History of Individual Source Components.	6.10
VI-8 Cesium-137/134 Source Replenishment Schedule Showing Annual Additions and Discards	6.12
VI-9 Cesium-137/134 Source Replenishment Schedule Showing History of Individual Components	6.13
VI-10 Base Radiation Market Projection as ^{60}Co	6.17
VII-1 ARHCO Estimate for Annual Operating Cost Waste Encapsulation and Storage Facility	7.12
VII-2 Manpower Cost - Waste Encapsulation and Storage Facility	7.13
VII-3 HWM Encapsulation Costs	7.14
VII-4 ARHCO Estimate for Annual Operating Costs for HWM Capsules with Inserts	7.15
VII-5 Costs for Special HWM ^{137}Cs Capsules with Inserts	7.18
VII-6 ARHCO Estimate for Annual Operating Costs for Special 1-Inch Diameter ^{137}Cs Capsules	7.19

LIST OF TABLES (contd)

	Page
VII-7 Costs for Special 1-Inch Diameter HWM Capsules	7.20
VII-8 Cesium Re-encapsulation Facility Capital Cost Estimate. .	7.23
VII-9 Operation at CsCl ₂ Capsule Refabrication Plant	7.25
VII-10 ¹³⁷ Cs Re-encapsulation Operating Cost Estimate	7.26
VII-11 Comparison of Estimated Man-Hour Allocations for ¹³⁷ Cs Encapsulation Alternates	7.27
VII-12 Estimated Man-Hour Allocations for ¹³⁷ Cs Encapsulation Alternates	7.27
VII-13 Comparison of Cost and Value of HWM Cesium Marketing Options	7.28
VIII-1 Two-Phase Market Simulation Cases for Cesium	8.10
VIII-2 Two-Phase Market Simulation Cases for Strontium	8.11
VIII-3a RAMARK Output for Low Market, Gradual HWM Phaseout and 3b and 1980 Startup of Power Reactor Cesium Recovery . . .	8.12
VIII-4a RAMARK Output for Medium Market, Gradual HWM Phaseout and 4b and 1980 Startup of Power Reactor Cesium Recovery . . .	8.14
VIII-5a RAMARK Output for High Market, Gradual HWM Phaseout and 5b and 1980 Startup of Power Reactor Cesium Recovery . . .	8.16
VIII-6 Case Descriptions of Power Reactor Cesium Recovery . . .	8.19
VIII-7 Case Descriptions of Power Reactor Strontium Recovery . .	8.20
VIII-8 Separate Re-encapsulation Facility--Case Series Description	8.21
VIII-9 Separate Re-encapsulation Facility for HWM ¹³⁷ Cs Case Descriptions	8.23
VIII-10 Effect of Market Share on Price Requirements for Power Reactor Cesium Recovery.	8.24
VIII-11 Effect of Capital Cost on Price Requirements for Power Reactor Cesium Recovery.	8.26
VIII-12 Effect of Operating Cost on Price Requirements for Power Reactor Cesium Recovery.	8.27
VIII-13 Effect of Profitability Criteria on Price Requirements for Power Reactor Cesium Recovery.	8.28
VIII-14 Effect of Learning on Price Requirements for Power Reactor Cesium Recovery.	8.29
VIII-15 Base Case Price Requirements for Private Re-encapsulation Facility	8.31

LIST OF TABLES (contd)

	Page
VIII-16 Minimum Capital Case Price Requirements for Private Re-encapsulation Facility	8.32
VIII-17 Effect of Capital Cost on Price Requirements for Re-encapsulation of HWM ¹³⁷ Cs	8.33
VIII-18 Effect of Capital Cost on Profitability for Re-encapsulation of HWM ¹³⁷ Cs	8.34
VIII-19 Effect of Profitability on Price Requirements for Re-encapsulation of HWM ¹³⁷ Cs	8.35
VIII-20 Effect of Learning Rate on Price Requirements for Re-encapsulation of HWM ¹³⁷ Cs	8.37
VIII-21 Coordinated Price Requirements for Base Case PR-Cs Recovery and Low-Capital Cases for HWM Cs Re-encapsulation	8.38
VIII-22 Effect of Market Share on Price Requirements for Power Reactor Strontium Recovery.	8.39
VIII-23 Effect of Capital Cost on Price Requirements for Power Reactor Strontium Recovery.	8.40
VIII-24 Effect of Operating Cost on Price Requirements for Power Reactor Strontium Recovery.	8.41
VIII-25 Effect of Profitability Criteria on Price Requirements for Power Reactor Strontium Recovery.	8.42
VIII-26 Effect of Learning on Price Requirements for Power Reactor Strontium Recovery.	8.43
VIII-27 Example of Reallocation of Capital Charges to Reduce Required Price for Power Reactor ⁹⁰ Sr	8.45

TECHNICAL, ECONOMIC AND POLICY CONSIDERATIONS
AFFECTING FUTURE PRODUCTION, MARKETING AND
USE OF CESIUM-137 AND STRONTIUM-90

I. INTRODUCTION AND PRINCIPAL CONCLUSIONS

This report presents the results of an in-depth analysis and evaluation of: (a) the technical, economic and market factors relevant to future separation and distribution of fission-product cesium-137 and strontium-90 by the AEC and, subsequently, by the private nuclear fuel reprocessors; and (b) the policy alternatives available to the AEC as these affect and are affected by the market considerations and potential private participation. The study was sponsored by the USAEC Division of Isotopes Development, now a part of the Division of Applied Technology.

In addition to the work carried out at the Pacific Northwest Laboratory (PNL) in the preparation of this report, the results of other AEC-sponsored related studies were made available and utilized in developing the conclusions reached here. This includes work by the Brookhaven National Laboratory (BNL), the Atlantic Richfield Hanford Company (ARHCO), the Oak Ridge National Laboratory (ORNL), and the Atomic Energy Combined Operations and Planning Organization (AECOP). Dr. J. H. Cusack (BNL) contributed the chapter on Basic Values based on results of studies at both BNL and PNL. The basic economic premises underlying the identification and evaluation of the time and circumstances when private recovery and marketing of fission product cesium-137 and strontium-90 might become attractive were provided through discussions with the current and prospective private nuclear fuel reprocessors. Insight into the practical prospects and problems of utilizing these fission product isotopes was gained through discussions with a number of isotope users and distributors.

The study was carried out over the period from June 1970 to July 1971. Since completion of the study, additional information on strontium-90

markets* and on costs of producing the Hanford waste management capsules** have become available. However, this information does not alter the basic conclusions reached here.

The study addressed itself to the following major considerations:

- The time, cost and economic feasibility of cesium-137 and strontium-90 separation and marketing by the private nuclear fuel reprocessors. The effects of assumed market sizes, market growth rates, plant capacities, etc. on the private producers price requirements for these products were important aspects.
- The basic value of cesium-137 and strontium-90, relative to their competitors and their current, developing and envisioned applications. Of particular interest was the significant value enhancement, as compared to low exposure fuels, of power reactor produced cesium-137 that results from the high concentration of cesium-134 present.
- The compatibility of the fuel reprocessors' price requirements for cesium-134/137 and strontium-90 with the basic values of those products in the marketplace.
- The historical, current and projected markets for cesium-137 and strontium-90 in relation to the feasibility of private fission-product separation plants.
- The technical applications, suitability and required pricing for the cesium-137 and strontium-90 encapsulated sources to be produced under the AEC waste management program at Hanford. It was assumed that these could serve as an interim source of supply to the market, pending the advent of private fission-product separation facilities.
- The options available to the private nuclear fuel reprocessors with respect to entry into the fission product separations and distribution market; also, the options available to the AEC concerning the interim

* P. M. Wood, Possible Sr-90 Demands and Availability, AECOP-1053, September 30, 1971.

** J. D. Moore, Costs for Production of Strontium Dinitrate Sources, ARH-2637, October 24, 1972.

availability and pricing of the waste management sources and the interrelationship between these respective options.

The principal conclusions of this study, insofar as considerations of appropriate AEC policies is concerned, are that:

1. Steady market growth can be anticipated for both cesium-137 and strontium-90 if they are priced at levels compatible with market requirements. The market for cesium is a share of the gamma source market currently supplied almost exclusively by cobalt-60. The principal market for strontium is the U.S. Navy for devices needing remote power sources.
2. Private separation and marketing of fission-product cesium-137 and strontium-90 in the late 1970's or early 1980's by the nuclear fuel reprocessors is well within the realm of economic feasibility. However, the visible market will have to be substantially larger than current markets to permit pricing at levels compatible with market requirements.
3. By marketing the Hanford waste management cesium-137 and strontium-90 capsules and establishing a market, the AEC is in a position to enhance the prospect for later recovery and utilization of these materials as nuclear power by-products.
4. Prices can be established for the waste management capsules that are compatible with market requirements, consistent with the reprocessors later price requirements, and in accord with the AEC full cost recovery policy.
5. Several options are available to the AEC in methods for marketing the waste management capsules. For example, lower prices can be offered for large purchases, and special cesium capsules with hollow inserts or reduced diameter can be produced that will enhance the value of the contained cesium-137.
6. Even if no significant market should develop, the AEC is assuming no economic risk in offering the waste management sources for sale at prices consistent with market requirements and its own full cost recovery policy.

II. SUMMARY

The principal concern of this study was to identify the time and circumstances when recovery of fission-product cesium and strontium might be attractive to the nuclear fuel reprocessing industry and to explore AEC policy alternatives that might influence the evolution of a viable fission-product recovery industry. The major effort was related to ^{137}Cs recovery with a somewhat less comprehensive analysis of ^{90}Sr recovery.

FUEL REPROCESSOR VIEWS

An early step in the overall study was to arrange discussions with representatives of all of the companies known to be active or considering involvement in the nuclear fuel reprocessing business. The purpose of these discussions was to identify interests and attitudes toward fission product recovery, particularly cesium and strontium, and to develop realistic criteria for evaluating the feasibility of cesium and strontium recovery. Discussions were held with representatives of the General Electric Company's Nuclear Fuels Department and Midwest Fuel Recovery Operation, Gulf General Atomic Company, Nuclear Fuels Services, Allied Chemical Nuclear Products, Inc., and Atlantic Richfield Company's Nuclear Diversification Department. (The latter department has been disbanded since these interviews).

There was general agreement among these representatives on the principal areas of interest. Although emphasis varied, there was little difference of opinion on the basic requirements for feasibility of a fission product recovery project. The appropriate criteria for evaluating entry into a fission product recovery venture evolved as follows:

Return on Investment	15%/yr
Economic Life	10 yr
Income tax rate	50%
Depreciation method for tax calculation	Sum of years digits
Design and construction period	4 yr
No consideration should be given to use of borrowed capital.	

These criteria represent the appropriate assumptions for evaluating a decision to enter the business, but this does not mean that these criteria will necessarily be met once the project is a reality. The actual return for example might be higher or lower depending on markets, competition, etc.

The attitude toward recovery of cesium and strontium was uniformly skeptical. However, should markets develop that indicate a realistic profit potential, there is little question that one or more of the reprocessors would provide recovery facilities.

RECOVERY FROM POWER REACTOR FUELS

Determination of profitable price requirements for power reactor cesium and strontium required definition of the required facilities. A 1967 report⁽¹⁾ prepared for the New York State Atomic and Space Development Authority to explore the feasibility of extracting neptunium and other isotopes of interest from the waste streams of the Nuclear Fuel Services Plant at West Valley, New York was used for this purpose. This Multipurpose Plant Report provided a conceptual design of a neptunium recovery plant that could be expanded to recover various combinations of cesium, strontium, americium, curium, promethium and cerium if desired. Only the cesium and strontium recovery and encapsulation facilities were of interest in this present study, but the Multipurpose Plant Report was developed in a way that made separate definition of these facilities possible.

Design and equipment lists for the portions of the Multipurpose Plant to be used for cesium and strontium recovery were reviewed, and a somewhat modified design provided the basis for a capital cost estimate prepared by Vitro, Hanford Engineering Services (now Vitro Engineering Division of Automation Industries, Inc.). This reference plant capital cost estimate was as follows:

	<u>Capacity</u>	<u>Capital Cost</u>
Cesium only	29 MCi/yr	$\$14.3 \times 10^6$
Strontium only	28 MCi/yr	$\$14.6 \times 10^6$
Cs/Sr Co-Products	29/28 MCi/yr	$\$20.5 \times 10^6$

These estimates included a 20 percent escalation factor on a 1970 base estimate. All other costs were based on late 1970 dollar values. The assumption here was that all costs will escalate more or less uniformly, except for construction costs, which will escalate an additional 20 percent over other costs by the time the facilities are completed. A cost scaling relationship was used to convert the estimate to other capacities. Estimates of operating costs for the reference plant were also prepared and ranged as follows:

<u>Production, MCi/yr</u>	<u>Operating Costs, \$10⁶/yr</u>		
	<u>Cs only</u>	<u>Sr only</u>	<u>Cs/Sr</u>
5	1.0	1.0	1.9
29 of Cs and/or 28 of Sr	2.1	2.1	3.6

More general relationships for any size plant were also derived.

The computer program CAESR was developed to calculate optimized pricing requirements in a growing market for profitable recovery of cesium and strontium. The computer program provided for a market projection calculation and for the reprocessor to capture a varying portion of the market. There was provision for selection of a near-optimum plant size for each set of conditions. Prices were calculated as present-worth levelized prices; i.e., the single price that could be charged over the life of the project that would pay all costs and recover the initial investment with a specified return on investment.

An exploratory series of cases was first completed in which a basic assumption was that the market would first develop with AEC sales, but the AEC would then withdraw from the market as soon as a private facility was operating. Thus, this first plant would initially have 100 percent of the market. However, it was further postulated that a competitor would soon be operating and the first plant's share of the market would have declined to 50 percent of the market after five years. For these exploratory cases, the market was assumed to be expanding at a constant rate from a reasonably achievable base year sales assumption.

Results of these calculations indicated rather clearly that it was unlikely that profitable prices any lower than 20 to 30¢/Ci for either cesium or strontium could be achieved much before 1980. With ^{137}Cs presumed to be worth only around 10¢/Ci, this would not seem to offer a very attractive prospect for large scale marketing. However, upon examining the characteristics of power reactor cesium, the ^{134}Cs content of this material was found to increase the value substantially.

BASIC VALUES

An analysis of ^{137}Cs value relative to ^{60}Co was undertaken. Various factors that could affect this value were examined, such as dose intensity, dose uniformity, shielding requirements, and safety aspects. It was concluded that for most large scale applications the relative values of ^{137}Cs and ^{60}Co could be established solely on the basis of relative amounts of gamma radiation emitted.

Calculations were carried out to compare ^{137}Cs value to ^{60}Co value using a discounted cash flow technique. The basis for the calculations was as follows:

1. The values of two sources were assumed equal when their gamma energy production was equal.
2. Sources were replenished annually.
3. The radiation plaque was sized to hold twice as many capsules as were required for the initial source.
4. The initial source was capitalized.
5. Replenishments were treated as operating expenses.
6. Federal income taxes were taken as 50 percent.
7. A ten-year economic life was assumed.

Value determinations were made both for ^{137}Cs , as it will be encapsulated in the Hanford Waste Management (HWM) capsules, and for power reactor ^{137}Cs , encapsulated in optimum design capsules. The value of the HWM cesium is reduced because of the large self-absorption effect in the 2.6 inch

diameter capsules. The value of power reactor cesium is enhanced by the large gamma energy contribution of the contained ^{134}Cs (approximately 2.5 wt% ^{134}Cs at the time of use, producing more than twice the gamma energy of ^{137}Cs).

The base case values, defined as value relative to ^{60}Co at 40¢/Ci at a 15% return on investment, with salvage values of 20¢/Ci and 5¢/Ci for ^{60}Co and ^{137}Cs respectively, were found to be:

Power Reactor Cesium	26.9¢/Ci ^{137}Cs
HWM Cesium	8.2¢/Ci ^{137}Cs

MARKETS

A market survey was carried out by P. M. Wood and H. A. Harrell of the AEC Combined Operations and Planning Group⁽²⁾ to identify potential markets for ^{137}Cs in particular, and hard gamma sources in general, including ^{60}Co . This survey provided the basis for the market projections developed here. In conducting the survey, AEC data on past sales of ^{137}Cs were reviewed, literature on ^{137}Cs application was reviewed, and such information from the abandoned Isochem project as was available was also analyzed. Finally, the views of some suppliers and users of ^{137}Cs and ^{60}Co were obtained on specific points.

Encapsulated cesium is useful primarily as a source of high intensity gamma radiation for applications such as sterilization of medical supplies, medical teletherapy, chemical polymerization, food sterilization and pasteurization, sewage treatment, and other applications. In most of these applications, cesium has a direct competitor in ^{60}Co . Consequently, the market was evaluated in terms of the total market for high intensity gamma sources. From this basis, an estimate of the likely market share for cesium was then possible.

Two projections for gamma source requirements were developed from the survey. One, termed "probable", predicts gamma source requirements

growing to 16 MCi of ^{60}Co , or its equivalent, by 1980. Another, termed "possible", predicts gamma source requirements growing to 25 MCi of ^{60}Co , or its equivalent, by 1980.

Although ^{137}Cs , $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures or ^{60}Co can all be used interchangeably for many applications, the amounts required and the replenishment requirements are quite different. Calculation of replenishment requirements for a one-component source is straightforward. Calculation of replenishment requirements for a two-component source ($^{137}\text{Cs}/^{134}\text{Cs}$) is much more complicated and, even more so, when the replenishment requirements for a growing market are to be considered. In either case, if a radiation-source plaque size limit is included, the calculations are further complicated. The computer program RASOR (Radiation Source Replenishment) was written to carry out such calculations.

A second program, RAMARK (Radiation Market) combines the source replenishment schedule from RASOR with a market projection equation for initial source sales. It also develops a year-by-year total market requirement which includes initial sources sold each year plus replenishment requirements for all sources sold in all previous years. For different source materials, the differences in initial and replenishment requirements will result in quite different total annual curie requirements for the same basic market.

The base gamma-radiation market projections were developed in terms of ^{60}Co requirements. Starting from 2 MCi in 1970 and assuming a zero long-term equilibrium growth rate, initial growth rates and rate constants were selected to match the 1980 total radiation market projections of 16 and 25 MCi ^{60}Co . A third and higher projection was also developed starting from the same base growth rate as the 1980 projection of 25 MCi ^{60}Co , but approaching a long-term equilibrium growth rate of 5%/yr, rather than 0%. The 1980 requirement for this projection is 33 MCi ^{60}Co .

Relative to the market projections for gamma sources, an equivalent effort has not been made to define ^{90}Sr markets. However, the major probable customer for ^{90}Sr sources is the U.S. Navy, and their estimated requirements through 1977 were used as a basis for the ^{90}Sr market projections.

HANFORD WASTE MANAGEMENT PRODUCTS

Construction is underway on a Waste Encapsulation and Storage Facility (WESF) for packaging and interim storage of cesium and strontium removed from Hanford fuels reprocessing wastes. Encapsulation operations are scheduled to begin in July 1973. As currently planned, annual production rates are to be 30 MCi each of ^{137}Cs and ^{90}Sr .

These two isotopes, which are currently being separated from the Hanford wastes and stored in concentrated liquid form are to be converted to strontium fluoride and cesium chloride, and then double encapsulated and stored underwater for a number of years. The cesium capsules will hold 60,000 Ci of ^{137}Cs while the strontium capsules will hold 150,000 Ci of ^{90}Sr . Underwater storage is used for purposes of cooling and provides a shielding barrier while permitting visual observation of the stored capsules. The capsules are to be kept in underwater storage until the radioactive level has decayed sufficiently to permit safe storage at a permanent site.

With the decision made to separate and encapsulate highly refined fission-product cesium and strontium for waste management purposes, it has been suggested that these capsules be made available for industrial applications. A number of optional ways in which these capsules might be utilized has been examined. To assist in evaluating these various options, cost estimates were obtained from Atlantic Richfield Hanford Company (ARHCO), who will operate the WESF facility. However, except for the cost of standard HWM capsules, these estimates included allocated costs that would be incurred with or without the alternate being considered. Consequently, the ARHCO estimates were adjusted to an actual incremental cost basis for this analysis.

Capital and operating cost estimates were also developed for a private facility to take the standard HWM ^{137}Cs capsules and re-encapsulate them in a near optimum size. The principal incentives for this operation would be the value enhancement for the contained ^{137}Cs and the production

of capsules designed for use as radiation sources. The re-encapsulation process is quite simple and consists of remelting and casting into smaller molds, followed by double encapsulation.

The cost of producing the standard HMM cesium capsules and the alternative "special" capsules in limited quantities are compared relative to ^{60}Co in Table II.1. The costs are based on full cost recovery to the AEC, with the costs for the "special" capsules based on the actual incremental costs. The estimated minimum cost for producing new capsules in private facilities is also shown.

TABLE II-1. Comparison of Cost and Value of HMM Cesium Marketing Options

	Standard HMM Capsules	Standard HMM Capsules With Inserts		Special 1-Inch Capsules	New Capsules Produced In Private Facilities
		1-Inch Insert	1 1/2-Inch Insert		
Production Capability, MCi/yr	Up to 30	>4.6	>2.8	<0.8	2.4 and up
Cost Based on Full-Cost Recovery to the AEC, ¢/Ci	5.4	5.6	6.0	8.2	>8.4 plus capital charges
Value Relative to ^{60}Co at 40¢/Ci, ¢/Ci	8.0	8.3	8.7	11.0	11.0
Difference Between Cost and Value, ¢/Ci	2.6	2.7	2.7	2.8	<2.6

The following conclusions were reached regarding sale of the HMM capsules and other capsule options.

1. The standard HMM capsules should be offered in quantities of less than two million curies at their full market value of about 8¢/Ci.
2. These standard capsules should be offered for large quantity purchases of two million curies or more at no more than a full-cost recovery price (5.4¢/Ci). The difference between acquisition cost and market value provides a reasonable incentive for large scale marketing efforts. It also provides the possibility of re-encapsulation into optimum sized source capsules in private facilities.

3. To give all possible encouragement to useful applications of the HWM cesium capsules, modified capsules with hollow inserts that would reduce the number of curies per capsule should be offered as optional capsules, as long as production can be handled without additional staff. In small quantities, the price should be based on full market value of 8.3 to 8.7¢/Ci.
4. These same capsules (with inserts) should be offered in large quantities, two million curies or more, at a minimum full-cost-recovery price of 5.6 to 6.0¢/Ci.
5. Special capsules, such as one-inch diameter capsules should be offered in small quantities, that is as long as additional staff would not be required, at their full-market value of about 11¢/Ci.
6. The large scale private re-encapsulation of the HWM cesium is indicated to be a possibility if the standard HWM capsules can be acquired at no more than a full-cost-recovery price.
7. Once the WESF facility starts up, the actual production costs should be carefully analyzed and policies modified accordingly.

ANALYSIS OF A SIMULATED TWO-PHASE FISSION-PRODUCT INDUSTRY

A series of cases were prepared simulating the development of a ^{137}Cs and ^{90}Sr recovery industry where the gradually developing market is first supplied from Hanford waste management cesium and strontium resources (Phase I). When the market has grown large enough to justify the required large investment (Phase II), a private reprocessor commences recovery. The basic objective was to identify AEC policies that would be most appropriate for fostering eventual private recovery and marketing of cesium and strontium from power reactor fuel reprocessing.

The previously mentioned computer programs RASOR/RAMARK and CAESR were combined as a single program to carry out the simulation calculations. In these calculations, the base market was defined in terms of a projection of initial-source sales as ^{60}Co . The total market, including replenishments,

was then calculated. The initial-source base market was apportioned by RAMARK between ^{137}Cs and $^{137}\text{Cs}/^{134}\text{Cs}$, based on market-share fractions supplied as input. The balance remaining was the ^{60}Co share. The program then added replenishment requirements for all sales in all years for the three source materials. The annual totals represented the market for each source material as curies of that material. A basic ground rule for the market apportionment was that cesium sales (either type) would never be greater than 50 percent of the total gamma-source market. HWM strontium and power reactor strontium were considered equivalents, and no other material analogous to ^{60}Co was involved. Thus, in the case of strontium, the market (100 percent) was supplied by either HWM strontium, power reactor strontium, or a combination of these two materials only. The results of the market projection and apportionment were sent to CAESR which then calculated price requirements for profitable recovery and encapsulation of power reactor cesium or strontium and for re-encapsulation of HWM cesium in a private facility.

In evaluating the results of these calculations a feasible price for power reactor (PR) cesium was taken as 25-30¢/Ci ^{137}Cs or less. The feasible price for strontium might be as low as 10¢/Ci ^{90}Sr . The maximum feasible price increment (above the AEC price) for re-encapsulation of HWM cesium was taken as 5¢/Ci ^{137}Cs .

The price requirements for the base case PR cesium calculations are summarized in Table II.2 along with selected results for the HWM cesium re-encapsulation added-value price calculations. Results for HWM cesium re-encapsulation in a completely new facility are not shown here, because these price requirements were too far from feasibility. Table II.3 illustrates how a substantial part of the strontium cost could be allocated to cesium, if the high cesium market develops, thereby reducing the required strontium price substantially.

TABLE II-2. Coordinated Price Requirements for Base Case PR-Cs Recovery and Low-Capital Cases for HWM-Cs Re-encapsulation ($\text{\$/Ci }^{137}\text{Cs}$)

Market Projection

Base Case PR-Cs Recovery	64	57	53	50	38	35	45	40	36	36	27	25	36	29	25	29	20	18
50% Capital Case HWM-Cs Re-encaps.	9.5	5.7	5.1	16	7.7	6.1	7.4	4.8	4.5	13	6.3	5.2	6.6	4.5	4.1	12	6.1	4.9
Min. Capital Case HWM-Cs Re-encaps.	3.9	3.2	3.1	4.9	3.5	3.2	3.6	3.1	3.1	4.6	3.4	3.1	3.5	3.0	3.0	4.4	3.3	3.1

NOTE: Boxed values indicate feasible prices.
The re-encapsulation price requirements are incremental requirements above the AEC base price for HWM cesium.

TABLE II-3. Example of Reallocation of Capital Charges to Reduce Required Price for Power Reactor ⁹⁰Sr

	High Cs Market With High Sr Market Abrupt HWM Cs and Sr Phaseout		High Cs Market With Low Sr Market Abrupt HWM Cs and Sr Phaseout	
Recovery Startup	<u>1980</u>	<u>1982</u>	<u>1980</u>	<u>1982</u>
Plant Size, MCi/yr				
PR-Cs	20.9	27.4	20.9	27.4
PR-Sr	18.0	23.2	9.7	12.1
Base Case Price Required, ¢/Ci				
PR-Cs	20.4	17.8	20.4	17.8
PR-Sr	25.5	22.7	38.2	34.4
Prices Required with Reallocated Capital, ¢/Ci				
PR-Cs	30.0	27.3	30.0	27.0
PR-Sr	13.1	10.0	14.6	10.0
Total Sr Plant Cost, \$ millions	--	9.73	--	7.95
Portion of Sr Capital Investment Charged Off Against Cs, \$ millions	--	7.44	--	7.21

The following principal conclusions were reached as a result of this two-phase industry analysis.

1. The sale of HWM cesium and strontium capsules could result in markets growing sufficiently to justify the large capital investment required for facilities to recover these materials from power reactor fuel reprocessing wastes. Without an HWM products sales program, recovery from power reactor fuels cannot be predicted.
2. The earliest that such recovery operations can be anticipated is 1977. A more probable date would be closer to 1980.
3. Private industry could participate in the market development at an earlier date through re-encapsulation of the HWM cesium capsules. However, this only appears feasible in already existing and unused hot cell facilities. It does not appear possible to amortize a new facility based on this operation alone.
4. To encourage recovery of cesium and strontium from power reactor fuel wastes, the policy of the AEC regarding discontinuance of HWM sales should be to withdraw from the market just as rapidly as a PR fuel recovery operation could supply the demand. This would provide a significant advantage to the PR fuel recovery operation. Also, it would not be particularly damaging to someone engaged in re-encapsulation, since their investment would be minimal and their operations would be known from the start to be temporary.
5. Recovery of fission products from PR fuel wastes would be undertaken initially by only one reprocessor. However, competition should develop within a few years (five or less), if the market continued to grow.
6. Unless the cesium market growth is at least as large as the medium projection or unless the low-range capital cost is achieved, the feasibility of cesium recovery from PR fuels cannot be predicted.
7. If the high cesium market develops, it will be possible to absorb a significant part of the strontium recovery and encapsulation costs in the cesium price, should this prove necessary to provide an acceptable strontium price.

III. FUEL REPROCESSOR INTERESTS

Up to the present time, the only possible source of any large quantities of fission product isotopes has been the by-product waste solutions resulting from operation of the AEC's plutonium production reactors. Now, these reactors are being phased out of production but, at the same time, large nuclear power stations are coming on-line in increasing numbers. The total operating nuclear power capacity in mid-1971 was approaching 10,000 MW, and the long standing AEC forecast is for 150,000 MW of installed nuclear capacity by 1980.

In just a few years, the quantities of fission product isotopes potentially recoverable from power reactor fuels will exceed by a large margin any potential availability from AEC operations. Thus, any consideration of long-term, large-scale application for fission product isotopes must of necessity involve consideration of recovery by the power-reactor-fuel reprocessors. A current estimate of the quantities of fission-product ^{137}Cs and ^{90}Sr that are potentially recoverable from nuclear-power fuel reprocessing is shown in Table III-1. In comparison to the current level of sales (around 0.5 to 1 MCi respectively) the future availability is certainly very large.

TABLE III-1. Projected Annual Availability of ^{137}Cs and ^{90}Sr in Power Reactor Fuels

	^{137}Cs		^{90}Sr	
	Kg/yr	MCi/yr	Kg/yr	MCi/yr
1970	27	2.3	13	1.8
1975	640-720	56-63	300-330	42-47
1980	2,360-2,820	205-245	1,030-1,240	146-175
1985	5,200-7,000	450-610	2,200-2,900	310-420
1990	8,800-13,000	770-1,100	3,600-5,100	500-720
2000	17,000-30,000	1,400-2,700	6,300-12,000	900-1,700

Because future recovery of these isotopes so obviously involves the private fuel reprocessors, an early step in the overall study was to arrange discussions in mid-1970 with representatives of all of the companies known to be active or considering involvement in the nuclear fuel reprocessing business. The purpose of these discussions was to identify current interests and attitudes towards fission product recovery, particularly cesium and strontium, and to develop realistic criteria for evaluating the feasibility of cesium and strontium recovery.

The companies visited and persons with whom discussions were held were as follows:

General Electric Company
Nuclear Fuels Department, San Jose, Calif.
Robert G. Barnes, Manager Process Design (now Manager, Midwest Fuel Recovery Expansion Project).
Walter Graff, Manager, Plant Design.
Paul E. Christman, Manager, Marketing Group B.

General Electric Company
Midwest Fuel Recovery Operation, Morris, Ill.
S. E. Smolen, Plant Manager
Ray Lambert, Technology Manager

Gulf General Atomic Company, San Diego, Calif.
Richard Graham, Manager Nuclear Development
Arnold Fritsch, Allied-Gulf Nuclear Services Coordinator

Nuclear Fuel Services, West Valley, N. Y.
James Duckworth, Plant Manager
James Clark, Manager Technical Services

Allied Chemical Nuclear Products, Inc., Florham Park, N. J.
Arnold Ayres, Director of Technology

Atlantic Richfield Company
Nuclear Diversification Dept., Richland, Wash.
Lyle Zahn, Manager
(This Department has since been disbanded)

There was general agreement among these representatives on the principal areas of interest. Although emphasis varied, there was little difference of opinion on the basic requirements for feasibility of a fission product recovery project. The discussion that follows represents the consensus of views and does not necessarily represent the exact view of any one of those interviewed.

1. The attitude towards recovery of cesium and strontium was uniformly skeptical. All were familiar with the ISOCHEM experience and saw no present evidence of markets developing that would justify an investment in the required recovery facilities. However, should markets develop that indicate a realistic profit potential, there is little question that one or more of the reprocessors would provide recovery facilities.
2. The period 1970-75 is clearly not a feasible period for private-enterprise production of Cs/Sr. Approximately four years will be required from the time a decision is made to install Cs/Sr facilities to the time commercial operation of such facilities is begun. This is the estimated time required for design, licensing, construction, testing, and cold runs, based on the views and experience of the reprocessors. As of mid-1971 no plans were being made for any fission product recovery facilities. Thus, it would be mid-1975, at the earliest, before such facilities could be placed in operation.
3. There is a substantial difference in the business risk inherent in a fission product recovery venture compared to that in fuel reprocessing. The lead time for nuclear power plants is currently six to eight years, and the first fuel reprocessing requirements are one to two years later. Thus, it is possible for a reprocessor to obtain load commitments for the first few years of plant operation, before any construction funds are committed. Because of this, surprisingly enough, the reprocessing business is turning out to be a relatively low risk venture. A reprocessor is not going to commit large capital funds until he has a substantial committed load for his plant. He is going to feel reasonably sure that his investment will pay out before large amounts of capital are irrevocably committed.

There is no comparable way of assuring a market for any portion of the fission products that might be recovered. In fact, all markets

are quite speculative. Because of the much higher risk that appears to be associated with fission product recovery, present thinking among the processors is that the profitability requirements for Cs/Sr recovery, or any by-product for that matter, will be more restrictive than for the basic reprocessing business.

4. Complete recovery and marketing of all of the cesium and/or strontium processed through any existing or planned reprocessing plant is not a credible situation. The availability of either cesium or strontium is quite large relative to probable markets. For example, 300 MT/yr of reprocessed fuel is equivalent to about 24 MCi/yr of ^{137}Cs and 18 MCi/yr of ^{90}Sr . In comparison, current markets supplied by Oak Ridge's Fission Product Development Laboratory (FPDL) are on the order of 0.5 to 1 MCi/yr respectively. Thus, the smaller reprocessing plants appear to have the same options available to them for entering a fission product recovery business as do the larger plants. Furthermore, cesium and strontium recovery probably will not have a significant impact on waste management requirements because not enough will be recovered to affect basic procedures. In all cases, recovery of cesium or strontium would involve processing only a portion of the high level waste through the recovery facilities.
5. The appropriate criteria that a reprocessor would require for evaluating entry into a fission product recovery venture evolved as follows:

Return on Investment	15%/yr
Economic life	10 yr
Income tax rate	50%
Depreciation method for tax calculation	Sum of years digits
Design and construction period	4 yr
No consideration should be given to use of borrowed capital.	

These criteria represent the appropriate assumptions for evaluating a decision to enter the business, but this does not mean that these criteria will necessarily be met once the project is a reality. The actual return for example might be higher or lower depending on markets, competition, etc.

There was good agreement on these criteria, but there was some difference of opinion on how much the criteria might vary with different circumstances. The required prospective return could very well be higher than 15 percent and probably would never be less than 10 percent. A 15-year economic life might be appropriate in some situations.

IV. RECOVERY FROM POWER REACTOR FUELS

The feasibility of cesium and strontium recovery from power reactor fuels depends on the relationship between the price required for a profitable enterprise and the probable market price or value. The method and basis used to develop profitable price requirements is discussed in this chapter, while basic values are discussed in the following chapter.

REQUIRED FACILITIES

The basis for a definition of the facilities required for cesium and strontium recovery was a 1967 report by W. A. Rodger, S. L. Reese and S. S. Stanton.⁽¹⁾ This report was prepared for the New York State Atomic and Space Development Authority to explore the feasibility of extracting neptunium and other isotopes of interest from the waste streams of the Nuclear Fuel Services Plant at West Valley, New York. This report will be referred to hereafter as the Multipurpose Plant Report.

The Multipurpose Plant Report provided a conceptual design of a neptunium recovery plant that could be expanded to recover various combinations of cesium, strontium, americium, curium, promethium, and cerium, if desired. Only the cesium and strontium recovery and encapsulation facilities were of interest in this present study, but the Multipurpose Plant Report was developed in a way that made possible the separate definition of these facilities.

The Multipurpose Plant Report pointed out that the flowsheets were intended to represent "thoroughly workable processes," but not necessarily optimum conditions. When there was doubt as to the necessity of providing a particular process step, the step was included. Thus, the process design was intended to be conservative.

The process described in the Multipurpose Plant Report for recovery of cesium and strontium, and modified for the purposes of this present study by deletion of the neptunium recovery process, can be summarized as follows.

- ¹³⁷Cesium Process

The feed stream is the concentrated first cycle aqueous waste from a Purex type solvent extraction process designed for recovery of uranium and plutonium from spent power reactor fuels. Fuel exposures are expected to range from 25,000 to 30,000 MWd/MT. This process includes the following steps:

1. The feed stream is first clarified by centrifugation before any processing is attempted.
2. The feed stream is next partially neutralized, to 0.5 M HNO₃, and passed over one of a pair of columns filled with zeolite (molecular sieves). This will selectively remove the cesium allowing all of the other products to pass on through.
3. The absorbed cesium is washed with ammonium-carbonate ammonium-hydroxide to remove fission products and other contaminants. The cesium is then eluted from the column with 4 M ammonium carbonate at 60°C.
4. The cesium is concentrated by repeated crystallization on ammonium alum in one of a pair of crystallizers.
5. The ammonium cesium alum is put into solution at 70°C with oxalic acid and ammonium hydroxide. This solution is then cooled to 15°C, precipitating cesium tetroxalate.
6. The cesium tetroxalate is filtered, dried, and calcined to cesium oxide in a tray furnace.
7. The oxide is converted to chloride in a tantalum evaporator.
8. The chloride is dried, pelleted, and encapsulated for use.

- ⁹⁰Sr Process

The ⁹⁰Sr process includes the following steps:

1. The stream which passes through the columns in the Cesium Plant is further neutralized and its pH adjusted to between four and five. Buffering and chelating agents are added.

2. This adjusted feed is put into a solvent extraction column wherein it is contacted with a solvent consisting of D2EHPA* and TBP**. The strontium is selectively extracted into the solvent; the remaining products pass out the bottom of the column and are sent to waste treatment.
3. The strontium is stripped from the solvent into dilute nitric acid in a second solvent extraction column.
4. A second solvent extraction battery is provided to give additional decontamination of the strontium.
5. The strontium product from the second solvent extraction cycle is mixed with sodium carbonate, sodium hydroxide, and titanium oxide. This gives a precipitate of strontium titanate which is filtered and calcined.
6. The calcined strontium titanate is blended, pressed into pellets, fired at 1300°C, and encapsulated.

The proposed plant in the Multipurpose Plant Report was made up of six sub-plants plus a utility services facility referred to as Plant 7. Plant 1 was the neptunium facility, Plant 2 the cesium facility, Plant 3 the strontium facility, Plant 4 the cerium facility; Plant 5 the promethium, americium, and curium facility; and Plant 6 was a waste-handling facility. Plants 6 and 7, or some part of them, would be required for any process combination. Thus the facilities of interest in the present study consisted of Plants 2, 3, 6, and 7.

One of the topics discussed with the fuel reprocessors was their assessment of the validity of using the Multipurpose Plant Report as a basis for developing the costs of cesium and strontium recovery. Not all had seen or reviewed the report, and some fairly divergent viewpoints were expressed. The conclusions drawn from these discussions regarding use of the Multipurpose Plant Report were:

* D2EHPA = di-2-ethylhexyl phosphoric acid
** TBP = tributyl phosphate

- The basic process concept is reasonable, possibly optimistic in some respects, and overly complex in others.
- Provisions for maintaining the process facilities may not be adequate.
- The cost estimates substantially understate probable costs.
- The facility was conceived as an add-on plant and significant savings might be possible if recovery facilities could be designed as part of a total processing facility.
- The design would provide an appropriate basis for developing production costs for cesium and strontium recovery, providing construction costs were updated and treated as a parameter so that the effect of high and low cost extremes could be examined.

A plan view of the facility for cesium and strontium recovery adapted from the Multipurpose Plant design and consisting of Plants 2, 3, 6 and 7 is shown in Figure IV-1. A vertical section view through the two lines of manipulator cells is shown in Figure IV-2.

CAPITAL COST ESTIMATES

The design and the equipment lists for the portions of the multipurpose plant to be used for cesium and strontium recovery were reviewed with the assistance of J. R. LaRiviere, Staff Engineer, Separations and Waste Management Process Design Engineering, Atlantic Richfield Hanford Company. Mr. LaRiviere has been associated from the earliest concepts with the process design developments related to plans for recovering cesium and strontium from the Hanford Plant wastes. Following this review, a somewhat modified design was submitted to Vitro, Hanford Engineering Services for preparation of a new cost estimate.

The principal design modification for the cost estimate can be summarized as follows.

1. Because of the reliance on contact maintenance, the design basis of 250 operating days per year was considered much too optimistic and was reduced to 180 operating days per year.

FIGURE IV-1. Cesium/Strontium Processing Facility Plan View

FIGURE IV-2. Cesium/Strontium Processing Facility Section A-A View

This reduced the design capacity from 40 and 38 MCi per year for cesium and strontium to 29 and 28 MCi per year respectively.

2. Because experience with Hanford Waste Processing has shown that more purification cycles than provided in the original design will very likely be required for both cesium and strontium, two additional process hot cells (Nos. 7 and 8) were allocated for this purpose. The original design utilized only cells 4, 5, and 6 (Figure IV-1).
3. Equipment not originally listed but required in all manipulator cells included:
 - Cell filters
 - Miscellaneous tools
 - In-cell hoist
 - Sump and jet
 - Stainless steel lining
 - Washdown sprays
 - Fire detection instruments
 - Cell to cell pass throughs
4. Items of process equipment added included:
 - Ultrasonic decontamination tanks
 - Shielded storage tanks
 - Helium leak detection equipment
 - A third welding station
 - Ultrasonic weld detection device
 - Final calorimeter
 - Analytical equipment

5. The waste processing facilities, Plant 6, are located in Cells 3A, 3B, and 3C and consist mainly of tanks, pumps, evaporators, and related equipment. These facilities would be more than required for just the cesium and strontium plants, except that no provision was apparent for disposal of cell flushing wastes produced during decontamination for contact maintenance. Furthermore, waste disposal requirements are becoming progressively more stringent. It was assumed, therefore, that the entire waste facility, or something equivalent to it, would be required for either strontium or cesium recovery.

Cost estimates were prepared for separate single purpose ^{137}Cs and ^{90}Sr recovery plants and for a dual-purpose plant where both cesium and strontium would be recovered. The resulting estimates⁽³⁾ are summarized in Table IV-1, and a breakdown by major cost categories is shown in Tables IV-2, IV-3, and IV-4.

TABLE IV-1. Reference Plant Cost Estimate Summary

	(\$ millions)		
	Single Purpose ^{137}Cs Plant (29 MCi/yr)	Single Purpose ^{90}Sr Plant (28 Mci/yr)	Dual Purpose ^{137}Cs and ^{90}Sr (29 & 28 MCi/yr)
Construction	\$ 7.9	\$ 8.1	\$ 11.4
Structural	3.7 (47%)	3.7 (46%)	4.8 (42%)
Process	4.2 (53%)	4.4 (54%)	6.6 (58%)
Engineering and Home Office (20%)	<u>1.6</u>	<u>1.6</u>	<u>2.3</u>
Sub-total	9.5	9.7	13.7
Contingency (30%)	2.9	2.9	4.1
Escalation (20%)	<u>1.9</u>	<u>2.0</u>	<u>2.7</u>
TOTAL PROJECT	\$14.3	\$14.6	\$20.5

TABLE IV-2. Cesium-137 Plant Capital Cost Estimate

<u>Description</u>	<u>¹³⁷Cs Plant</u>	<u>Waste Facility</u>	<u>Utilities</u>	<u>Total</u>
Building	\$ 623,000	\$ 420,000	\$175,000	\$ 1,218,000
Elevator	52,000			52,000
Cell Concrete	440,000	257,000		697,000
Piling allowance	50,000	36,000		86,000
Cell det. & finishing allowance shielding windows & manipu- lators, hatches, paint, platforms, pans, etc.	1,219,000	260,000	12,000	1,491,000
Crane for cell hatch covers	70,000	70,000		140,000
Installed process equipment	1,144,000	568,000	263,000	1,975,000
Installed piping	975,000	426,000	140,000	1,541,000
Installed instrumentation	267,500	218,400	45,000	530,900
Installed equipment (elec.)	21,600	12,500	178,000	212,100
Total Construction Cost	4,862,100	2,267,900	813,000	7,943,000
Engineering & Design				1,589,000
Total plant w/o contingency				9,532,000
Contingency 30%				2,860,000
Escalation 20%				1,906,000
TOTAL PROJECT COST				<u>\$14,298,000</u>

The estimates include a contingency factor of 30 percent. This judgment is based on experience in estimating costs for this type of facility and experience with cost estimate variations between conceptual designs of this type and final design and actual construction costs.

TABLE IV-3. Strontium-90 Plant Capital Cost Estimate

<u>Description</u>	<u>90Sr Plant</u>	<u>Waste Facility</u>	<u>Utilities</u>	<u>Totals</u>
Building	\$ 623,000	\$ 420,000	\$175,000	\$1,218,000
Elevator	52,000			52,000
Cell concrete	440,000	257,000		697,000
Piling allowance	50,000	36,000		86,000
Cell det. & finishing allowance shielding windows & manipu- lators, hatches, paint, platforms, pans, etc.	1,219,000	260,000	12,000	1,491,000
Crane for cell hatch covers	70,000	70,000		140,000
Installed process equipment	1,236,000	568,000	263,000	2,067,000
Installed piping	1,050,000	426,000	140,000	1,616,000
Installed instrumentation	289,600	218,400	45,000	553,000
Installed equipment (elec.)	23,400	12,500	178,000	213,900
Total Construction Cost	5,053,000	2,267,900	813,000	8,133,900
Engineering & Design				1,627,100
Total plant w/o contingency				9,761,000
Contingency 30%				2,929,000
Escalation 20%				1,952,000
TOTAL PROJECT COST				<u>\$14,642,000</u>

The estimates also include a 20 percent escalation factor. Industrial construction costs have been increasing at a rate of approximately 10%/year or more for several years.⁽⁴⁾ However, the purchasing power of the dollar has been declining at a rate of about 5%/yr. There are indications that this disparity between general escalation rates and escalation in construction costs is beginning to taper off. However, it is expected that a disparity will continue for

**TABLE IV-4. Cesium-137 and Strontium-90 Combined
Plant Capital Cost Estimate**

<u>Description</u>	<u>¹³⁷Cs Plant</u>	<u>⁹⁰Sr Plant</u>	<u>Waste Facility</u>	<u>Utilities</u>	<u>Totals</u>
Building	\$ 500,500	\$ 500,500	\$ 420,000	\$175,000	\$1,596,000
Elevator	26,000	26,000			52,000
Cell concrete	366,500	366,500	257,000		990,000
Piling allowance	60,000	60,000	36,000		156,000
Cell det. & fin. allowance shielding windows & manip- ulators, hatches, paint, platforms, pans, etc.	797,000	797,000	260,000	12,000	1,866,000
Crane for cell hatch covers	35,000	35,000	70,000		140,000
Installed process equip.	1,138,500	1,230,500	568,000	263,000	3,200,000
Installed piping	857,000	923,000	426,000	140,000	2,346,000
Installed instrumentation	267,500	289,600	218,400	45,000	820,500
Installed equipment (elec.)	20,400	22,200	12,500	178,000	233,100
Total Construction Cost	4,068,400	4,250,300	2,267,900	813,000	11,399,600
Engr. & Design 20%					2,280,400
Total plant w/o contingency					13,680,000
Contingency 30%					4,104,000
Escalation 20%					2,736,000
TOTAL PROJECT COST					<u>\$20,520,000</u>

NOTE: The totals listed above for the two plants combined are not necessarily separable as allocated above. For example, one \$52,000 elevator is required for the two plants combined. Fifty percent is allocated to each process on an arbitrary basis for comparative purposes only.

several years.* All costs, prices, and values in this study are intended to represent constant 1970 dollar values. The processing facility can not be completed before mid-1975 at the earliest, as pointed out in Chapter III. The 20 percent escalation factor represents an approximation

* Since this study was completed in mid-1971, the wage and price freeze was imposed and the disparity between construction cost escalation and general cost escalation has narrowed substantially.

allowance for the accumulated disparity between construction costs and general escalation at the time when the processing facility would be completed.

There is obviously a substantial uncertainty in the estimates. For example, there is a question concerning whether adequate provision has been made for maintenance of the shielded process cells. On the other hand, if these facilities could be incorporated into the initial design of a reprocessing plant, some savings might result. Also, there may be more manipulator cells than necessary. All things considered, the uncertainty in the estimates is believed to be about ± 30 percent.

A comparison of the final cost estimates with the original Multipurpose Plant estimate is shown in Table IV-5. The increase in costs for the current estimate is substantial and in rough agreement with views expressed by the fuel reprocessors. A further comparison with two other estimates helps to provide perspective for judging the validity of the estimates.

TABLE IV-5. Comparison of Cost Estimates with Original Estimates
(Millions)

	Original Rodger Estimate (1967)	Estimates Prepared by Vitro (HES) For This Study		
		Base	With 30% Contingency	With Both 30% Contingency and 20% Escalation Allowance
Cs Plant Plus Waste and Utilities Plants	5.1	9.5	12.4	14.3
Sr Plant Plus Waste and Utilities Plants	5.2	9.7	12.6	14.6
Combined Cs/Sr Plants Plus Waste and Utilities Plants	7.6	13.7	17.8	20.5

In 1966, ISOICHEM, Inc. applied for a license and construction permit (AEC Docket No. 50-258) to construct a Fission Product Conversion and Encapsulation (FPCE) Plant at Hanford. The FPCE design had been intensively studied in an effort to reduce costs and still meet licensing requirements.

However, the project was abandoned in January 1967 because of high costs and lack of firm markets. The plant was designed to recover 40 MCi/yr each of ^{137}Cs and ^{90}Sr , 38 MCi/yr of ^{147}Pm and 2.6 kg/yr of ^{241}Am based on 220 operating days/yr. The feed streams were separate semi-refined solutions of cesium, strontium, and $^{147}\text{Pm}/^{241}\text{Am}$. Thus the FPCE Plant was more complex in the number of products but did not have the requirement for initial separation and purification of feed materials from high level liquid waste streams that is required of the Cs/Sr facility under consideration here. The last cost estimate for the FPCE in November 1966 was \$12.1 million,⁽⁵⁾ including engineering and a 10 percent contingency. The Engineering News Record Construction and Building Cost index indicates approximately 35 percent escalation from 1966 to 1970. This results in an adjusted 1970 cost of \$16.3 million.

Construction was recently started on a Waste Encapsulation and Storage Facility (WESF) at Hanford. This plant was designed to refine and encapsulate 30 MCi/yr each of ^{137}Cs and ^{90}Sr in large (60,000 Ci and 150,000 Ci respectively) capsules for waste management purposes. This facility has a much more limited processing capability than the FPCE design but incorporates the design experience accumulated from the FPCE Project. Estimated completion is mid-1973 and estimated cost is \$10.75 million. Based on the escalation allowance in the project estimate, the cost would be about \$9.6 million on a 1970 construction cost basis.

Estimates for the Cs/Sr recovery facility are compared in Table IV-6 with the two estimates just discussed. When the estimates are compared on a common basis of 1970 construction costs, considering the difference in facility design requirements, the Cs/Sr facility estimate looks altogether reasonable. An allowance of ± 30 percent should reasonably encompass the uncertainty.

The range of capital costs assigned to the reference plant for consideration in calculating price requirements is shown in Table IV-7. The cost for the strontium facilities is nearly identical to that of the cesium facility, but there does appear to be a small but real difference which is acknowledged in the Table IV-7 cost data.

TABLE IV-6. Comparison of Cs/Sr Recovery Facility Cost
Estimate with Similar Facility Estimates
(\$ Millions)

	<u>Estimates as Prepared</u>	<u>Estimates Adjusted to a 1970 Construction Cost Basis</u>
Current Cost Estimate by Vitro (HES) For Cs/Sr Facility		
Cs Plus Waste and Utilities Facilities (12 Manipulator Cells)	14.3	12.4
Sr Plus Waste and Utilities Facilities (12 Manipulator Cells)	14.6	12.6
Cs/Sr Co-Products Plus Waste and Utilities Facilities (24 Manipulator Cells)	20.6	17.8
Waste Encapsulation and Storage Facility 1973 Completion (7 Manipulator Cells)	10.75	9.6
Isochem FPCE Plant 1966 Estimate (21 Manipulator Cells)	12	16.3

TABLE IV-7. Range of Capital Costs Used for Reference Plant
(\$ Millions)

	<u>Low</u>	<u>Base</u>	<u>High</u>
Cesium Recovery:			
One product	(a)	14.3	18.5
Co-products (Cs share)	7	10	(a)
Strontium Recovery:			
One product	(a)	14.6	18.9
Co-products (Sr share)	7.2	10.4	(a)

- a. A "Low" one-product cost was not included since this can be represented by the "Base" co-product case. Likewise, a "High" co-product cost was not included since this can be represented by the "Base" one-product case.

CAPITAL COST SCALING

An objective of this study was to identify price requirements for varying market sizes. Since the single reference plant size would be inefficient for smaller markets and incapable of handling larger markets, a cost scaling relationship was used to define the capital cost for varying plant sizes.

The cost scaling equations is:

$$C_B = C_A (B/A)^S$$

Where: A = reference plant capacity

B = capacity of Plant B

C_A = reference plant capital cost

C_B = capital cost of Plant B

This relationship, also known as the six-tenths factor rule⁽⁶⁾ when S equals 0.6, has been used as a general rule applying to chemical process equipment. For heavily shielded, remotely operated, nuclear fuel reprocessing plants a scaling factor of 0.35 to 0.4 has been shown to apply.⁽⁷⁾

Because of the physically small scale of operations even when processing 30 MCi/yr of ^{137}Cs (approximately 12 ft³/yr of CsCl), a modified version of this scaling relationship was employed. Regardless of the scale of production, the same operations will be required and some minimum number of hot cells and physical plant will be needed. Referring to Table IV-1, the structural costs are shown to represent about 40 to 45 percent of the construction cost. The relationship adopted here takes 40 percent of the reference plant cost as a constant and scales the balance at a six-tenths factor as follows:

$$C_B = 0.4 C_A + 0.6 C_A (B/A)^{0.6}$$

The resulting scaling relationship is shown on the dashed curve on Figure IV-3, where it is compared with various scaling factors using the

conventional relationship. The result is roughly equivalent to an 0.3 scaling factor at capacity ratios less than 1.0 and an 0.4 factor at capacity ratios greater than 1.0. As it turned out in the application of this relationship, in nearly all of the cases where credible markets were considered, plant capacity ratios ranged below 1.0. Thus the relationship used is, for practical purposes, equivalent to an 0.3 scaling factor.

The results of this cost scaling in terms of dollar cost are shown in Figure IV-4 for the cesium plant. The strontium plant is nearly identical, but slightly higher as indicated previously in Table IV-7. Obviously the scaling relationship becomes more suspect the further the capacity ratio moves from the reference value of 1.0. However, even though cost calculations for some quite small plants were required, the sizes where feasible price relationships were shown to exist turned out to lie mostly in the 15 to 30 MCi capacity range. Thus, final conclusions are based on relatively small extrapolations from the reference plant size.

FIGURE IV-3. Comparison of Cost Scaling Factors

FIGURE IV-4. Cesium Recovery Plant Capital Cost Scaling

OPERATING COST ESTIMATES

The Multipurpose Plant Report also developed operating costs as a function of plant production. These estimates were used as the basis for operating costs for this study but with the following modifications.

- Direct Labor costs (operations, supervision, maintenance, and analytical) were increased by 15 percent at design capacity and scaled with throughput at an 0.6 factor. As noted previously, the design capacity was reduced from 40 and 38 Mci/yr to 29 and 28 Mci/yr for Cs and Sr respectively, so that the total increase in labor cost per unit of production was approximately 60 percent.

- Process chemical costs were unchanged.
- Maintenance parts and supplies were increased to 3 percent of capital costs per year scaled directly with throughput, plus a constant 1/2 percent of capital cost per year.
- Indirect and other supplies were increased by 15 percent.
- Utilities and services were unchanged.
- Overheads were increased to 100 percent of direct labor costs.
- General and administrative costs were taken as 25 percent of direct labor.
- Waste storage costs were unchanged.
- An allowance for local taxes and insurance at 2 percent of capital cost was added.
- An allowance for research and development costs at 1 percent of capital cost was added.

The resulting operating cost estimates for the reference cesium and strontium plants at four different production rates are shown in Tables IV-8 and IV-9 for cesium and strontium respectively. Depreciation, working

TABLE IV-8. Cesium Recovery and Encapsulation Plant
Operating Cost Estimate (\$ Thousands)

Production, MCi/yr	<u>5</u>	<u>10</u>	<u>24</u>	<u>29</u>
Direct Labor	160	230	400	450
Process Chemicals	6	9	21	25
Maintenance Parts and Supplies	140	215	420	495
Indirect and Other Supplies	15	18	35	40
Utilities and Services	7	9	16	18
Plant Overheads	160	230	400	450
General and Administrative Expenses	40	55	100	110
Waste Storage	8	13	30	36
Local Taxes and Insurance	290	290	290	290
Research and Development	<u>140</u>	<u>140</u>	<u>140</u>	<u>140</u>
Total Operating Cost	970	1210	1850	2050

TABLE IV-9. Strontium Recovery and Encapsulation Plant
Operating Cost Estimate (\$ Thousands)

Production, MCi/yr	<u>5</u>	<u>10</u>	<u>23</u>	<u>28</u>
Direct Labor	160	240	400	450
Process Chemicals	3	4	9	11
Maintenance Parts and Supplies	149	230	430	510
Indirect and Other Supplies	15	18	35	40
Utilities and Supplies	6	9	15	17
Plant Overheads	160	240	400	450
General and Administrative Expenses	40	55	100	110
Waste Storage	8	13	30	36
Local Taxes & Insurance	290	290	290	290
Research and Development	<u>150</u>	<u>150</u>	<u>150</u>	<u>150</u>
Total Operating Cost	980	1250	1860	2060

capital costs, return on investment, and federal income taxes are not included here but are included in the price calculations as discussed later.

Based on the estimates in Tables IV-8 and IV-9, more general relationships for operating costs were derived for any size plant in which the variable portion of operating costs for a dual-purpose (or co-product) plant were taken as 80 percent of the costs in a single purpose plant. These operating cost equations are as follows:

Cesium Recovery

Single Purpose Plants

$$(0.052 \times \text{Capital Cost}) + (45 \times \text{kCi/yr}) = \$/\text{yr}$$

Co-Product Plants

$$(0.052 \times \text{Capital Cost}) + (36 \times \text{kCi/yr}) = \$/\text{yr}$$

Strontium Recovery

Single Purpose Plants

$$(0.052 \times \text{Capital Cost}) + (47 \times \text{kCi/yr}) = \$/\text{yr}$$

Co-Product Plants

$$(0.052 \times \text{Capital Cost}) + (38 \times \text{kCi/yr}) = \$/\text{yr}$$

The capital cost in these equations in the co-product cases refers to the portion of capital cost assignable to cesium or to strontium only. Operating cost variations from -50 to +30 percent of the single-purpose plant operating costs were considered in the price calculations. Relative to the co-product operating costs, this variation is equivalent to approximately ± 45 percent. (The capital cost portion of the operating cost is lower for co-products because the capital cost itself is lower.)

LEVELIZED PRICE CALCULATIONS

With both the capital costs and operating costs defined as a function of plant size and production rate, it is then possible to calculate price requirements for profitable recovery of cesium or strontium for varying production rates in plants of various sizes. It should be emphasized here that the objective of these calculations was not to determine what prices should be charged at the market place, but rather to determine what price is required for a profitable enterprise. This calculated price can then be compared to probable market prices. If the market price is equal to or higher than the calculated price requirement, then a profitable enterprise is indicated. If the market price is lower than the calculated price, either a lower return or possibly a losing proposition is indicated.

Prices were calculated as levelized prices, or the single price at each set of conditions that would recover all operating costs and recover in addition, over the life of the project, the initial investment with a specified profit or return on the investment. The procedure involves a modification of the discounted cash flow procedure widely employed to determine return on investment. The interest rate of return is the interest rate that results

in the discounted net cash flow equalling zero over the economic life of the project. Likewise, the levelized price is the price that results in the net cash flow equalling zero for a specified rate of return over the economic life of the project. Derivation of the levelized price equation follows.

Levelized price	= P, \$/Ci
Throughput in year "n"	= T_n , Ci
Operating expenses in year "n"	= O_n , \$
Capital expenditures either for plant or working capital in year "n"	= C_n , \$
Depreciation for tax purposes in year "n"	= D_n , \$
Tax rate	= t, fraction
Present worth factor	= $f_n = 1/(1 + i)^n$
Last year of project life	= P

The levelized price is the single price that results in:

Sum of Present Worth Income = Sum of Present Worth Expenditures

$$\sum_{n=1}^{n=p} f_n (\text{Income})_n = \sum_{n=1}^{n=p} f_n (\text{Expenditures})_n \quad (1)$$

or

Present Worth of Net Cash Flow = Zero

Defining income and expenditures in terms of the variables defined above:

$$\begin{aligned} \sum_{n=1}^{n=p} f_n P T_n &= \sum_{n=1}^{n=p} f_n [O_n + C_n + (P T_n - O_n - D_n) t] \\ &= \sum_{n=1}^{n=p} f_n P T_n t + \sum_{n=1}^{n=p} f_n [O_n + C_n - O_n t - D_n t] \end{aligned} \quad (2)$$

and

$$\sum_{n=1}^{n=p} f_n P T_n (1-t) = \sum_{n=1}^{n=p} f_n [O_n (1-t) + C_n - D_n t] \quad (3)$$

Solving for P,

$$P = \frac{\sum_{n=1}^{n=p} f_n [O_n (1-t) + C_n - D_n t]}{\sum_{n=1}^{n=p} f_n T_n (1-t)}$$

or

$$P = \frac{\sum_{n=1}^{n=p} f_n \left[O_n + \frac{C_n - D_n t}{(1-t)} \right]}{\sum_{n=1}^{n=p} f_n T_n} \quad (4)$$

An example calculation is shown in Table IV-10. The annual net cash flows that results when this levelized price is used to recalculate revenues and cash flow can be seen in Table IV-11 in the next subsection.

CAESR COMPUTER PROGRAM

To carry out the many calculations required to determine price requirements for the parametric analyses, the computer program CAESR was developed. The name CAESR was derived from a contraction of the caesium spelling variation for cesium and the chemical symbol Sr for strontium.

The CAESR program calculates the price requirement for a near optimum (minimum cost) plant size for a predetermined market projection. The basic premise for employing the optimization procedure is that any entrepreneur would make a similar analysis before a decision to build a plant. Any other basis for plant size selection is simply "a shot in the dark". Whether or

TABLE IV-10. Example of Levelized Price Calculation

Capital Recovery Period = 10 Years
 Interest Rate of Return = 15%
 Federal Income Tax Rate = 50%
 Sum of Years Depreciation
 Over 10-yr Period for Taxes
 Cash Flow Discounted To 1979

Year	P.W. Factor,	Production, kCi		Operating Costs \$1000's		Capital Costs, \$1000's			
		Actual,	PW,	Actual,	PW,	Plant,	Working	Deprec	$\left[\frac{C_n - D_n t}{1 - t} \right]$
		T_n	$f_n T_n$	O_n	$f_n O_n$	C_n	C'_n	For Taxes, D_n	
1976	1.521	0				906			2756
1977	1.322	0				3171			8384
1978	1.150	0				4077			9378
1979	1.0	0				906	252		2316
1980	0.8696	14,900	12957	1008	877		17	1647	-1402
1981	0.7561	16,800	12702	1075	813		17	1483	-1094
1982	0.6575	18,600	12230	1142	751		16	1318	-846
1983	0.5718	20,400	11665	1205	689		13	1153	-644
1984	0.4972	21,800	10839	1257	625			988	-492
1985	0.4323	21,800	9424	1257	543			824	-356
1986	0.3759	21,800	8195	1257	473			659	-248
1987	0.3269	21,800	6800	1257	411			494	-162
1988	0.2843	21,800	6198	1257	357			329	-94
1989	0.2472	21,800	5389	1257	311		-315	165	-196
Totals		201,500	96399	11972	5850	9060	0	9060	17,300

Using equation (4),

$$\text{Levelized Price, } P = \frac{\sum_{n=0}^{n=p} f_n \left[O_n = \frac{C_n - D_n t}{(n-t)} \right]}{\sum_{n=0}^{n=p} f_n T_n} = \frac{(\$5,850,000 + \$17,300,000)}{96,399,000 \text{ Ci}} \times 100\text{¢/\$} = 23.9\text{¢/Ci}$$

$$= 6.0\text{¢/Ci Op. Cost} + 17.9\text{¢/Ci Cap. Cost}$$

not any given market projection has validity is certainly debatable. But, at least the right plant size and price requirement can be defined for the market projection, thus leaving the major uncertainty with the market projection alone. The procedure used in the calculations is illustrated in Figure IV-5.

The program first of all provides several optional market projection equations which are used to calculate annual market requirements for up to 30 years. The result of this calculation is illustrated by the curve labeled "Total Market Projection."

Since a profitable enterprise is nearly synonymous with competition, a single plant could not be expected to indefinitely supply the entire market. Thus, a provision is made for specifying a startup share of the

FIGURE IV-5. CAESR Calculation Procedure

market and an equilibrium share and for specifying the time interval in between. The program then makes a straight line interpolation between these points. For example, a 20 percent startup share with a 50 percent share after 5 years would mean 20, 26, 32, 38, 44, and 50 percent shares for the 1st, 2nd, 3rd, 4th, 5th, and 6th years respectively, with a 50 percent share continued on to any subsequent years. A 100 percent startup share with a 50 percent equilibrium share after 5 years would mean 100, 90, 80, 70, 60, and 50 percent shares for the 1st, 2nd, 3rd, 4th, 5th, and 6th years. The curve labeled "Maximum Market Share" in Figure IV-5 represents this component of the calculation.

Using the levelized price procedure already described and with production rate defined by the market share but limited by plant capacity, prices are calculated for three plant sizes to provide a basis for selecting the optimum size. To insure that calculations are carried out for plants appropriately sized for the market, a look-ahead procedure is used. Three look-ahead periods such as 3, 5, and 7 years are specified as input. Then the program selects one plant sized for the largest requirement in the first 3 years, a second plant sized for the largest requirement in the first 5 years and a third plant sized for the largest requirement in the first 7 years. Three look-ahead periods are indicated in Figure IV-5 that illustrate how three different plant sizes would be selected. The startup year is counted as the first year so that a 3-year look-ahead period for a 1977 startup would examine the requirement through 1979 but not through 1980.

The inset in Figure IV-5 shows how the three prices can be plotted to determine the optimum plant size at the minimum price requirement. A large plant has an advantage of lower initial cost per unit of capacity but operates for several years at inefficiently low production rates. A small plant costs more initially per unit of capacity but operates efficiently at high relative production rates throughout its life. Thus conditions for a minimum price situation are present. Since the lowest of the three prices was found in the early calculations to be close to the plotted minimum, the lowest of the three price calculations was routinely selected as the minimum value for most of the later calculations rather than plot all values.

The program was designed to carry out nine calculations for each case. These nine calculations are divided into three sets with each set having three subsets representing the three plant size calculations just discussed. The three primary sets can have different startup years or different market shares or both different startup years and different market shares.

Two print options are provided. A detailed cash flow analysis for each price calculation can be printed if desired. An example is shown in Table IV-11. A summary report for all nine calculations in a case is standard in any case. An example of the summary report is shown in Table IV-12. Note that the nine calculations are for three look-ahead periods for each of three different startup years. The market share is the same for each startup year but could be different.

The examples shown in Tables IV-11 and IV-12 are from an initial series of exploratory cases. The market share of 100 percent initially declining to 50 percent after five years was based on the assumptions that:

1. The market would continue to develop through AEC sales, but the AEC would withdraw from the market whenever private recovery facilities could supply the market.
2. Within five years after the first private recovery facilities were placed in production, a second competitor would begin production and share the market 50/50.

The effect of a competitor would more likely result in a sharp discontinuity when he entered the market but the gradual transition from 100 to 50 percent simulates the overall impact without having to define exactly which year the competitor enters the picture.

Because the production demand changes relatively slowly in the case illustrated in Table IV-12, the price variation is not very large within each set of three price calculations. A second example is shown in Table IV-13 where the price variation within each set is greater to illustrate more vividly the importance of plant size optimization.

TABLE IV-11. Example CAESR Printout

FISSION PRODUCT PROFITABILITY STUDY									
CASE NUMBER 9 PLANT NUMBER 8									
CASE DESCRIPTION									

PRODUCT				CS-137					
MARKET ASSUMED				2.0 MEGACURIES IN 1971 GROWING AT 25.0 PCT/YR					
FRACTION OF MARKET FOR PLANT				100.0 PERCENT (INITIAL) 50.0 PERCENT (AFTER 5 YEARS)					
LOOK AHEAD PERIOD				5 YEARS					
PLANT SIZE				21.8 MEGACURIES PER YEAR					
STARTUP YEAR				1980					
RETURN ON INVESTMENT REQUIRED				15.0 PERCENT					
ECONOMIC LIFE OF PROJECT				10 YEARS					
DEPRECIATION METHOD FOR TAXES				SUM OF THE YEARS DIGITS					
FEDERAL INCOME TAX RATE				50.0 PERCENT					
DESIGN AND CONSTRUCTION PERIOD				4 YEARS					

YEAR	PRODUCTION KILOCURIES	REVENUE (SALES)	CAPITAL COSTS	WORKING CAPITAL	OPERATING COSTS	INCOME TAX	NET INCOME	NET CASH FLOW	DISC. NET CASH FLOW
1976	0	0	906	0	0	0	-0	-906	-1378
1977	0	0	3171	0	0	0	-0	-3171	-4194
1978	0	0	4077	0	0	0	-0	-4077	-4689
1979	0	0	906	252	0	0	-0	-1158	-1158
1980	14900	3566	0	17	1008	455	2103	2086	1814
1981	16800	4021	0	17	1075	732	2214	2197	1661
1982	18600	4452	0	16	1142	996	2314	2298	1511
1983	20400	4883	0	13	1205	1262	2416	2403	1374
1984	21800	5218	0	0	1257	1486	2475	2475	1231
1985	21800	5218	0	0	1257	1569	2392	2392	1034
1986	21800	5218	0	0	1257	1651	2310	2310	868
1987	21800	5218	0	0	1257	1733	2228	2228	728
1988	21800	5218	0	0	1257	1816	2145	2145	610
1989	21800	5218	0	-315	1257	1898	2063	2378	588
TOTAL	201500	48230	9060	0	11972	13598	22660	3600	0

LEVELIZED SALES PRICE 23.9 CENTS PER CURIE									

TABLE IV-12. Example CAESR Summary Printout

FISSION PRODUCT PROFITABILITY STUDY									
SUMMARY REPORT									
CASE 9									
PRODUCT CS-137									
RETURN ON INVESTMENT REQUIRED				15.0 PERCENT					
ECONOMIC LIFE OF PROJECT				10 YEARS					
DEPRECIATION METHOD FOR TAXES				SUM OF THE YEARS DIGITS					
FEDERAL INCOME TAX RATE				50.0 PERCENT					
MARKET ASSUMED: 2.0 MEGACURIES IN 1971 GROWING AT 25.0 PERCENT PER YEAR									
MARKET CAPTURED, INITIALLY AT TO A CONSTANT AFTER	100.0 PCT 50.0 PCT 5 YRS				100.0 PCT 50.0 PCT 5 YRS			100.0 PCT 50.0 PCT 5 YRS	
STARTUP YEAR	1975				1977			1980	
DESIGN AND CONSTRUCTION PERIOD	4				4			4	
PLANT	1	2	3	4	5	6	7	8	9
LOOK AHEAD PERIOD	7	5	3	7	5	3	7	5	3
PLANT SIZE, MEGACURIES	9.3	7.2	6.1	14.6	11.2	9.5	28.4	21.8	18.6
PRESENT WORTHED AVERAGE THROUGHPUT, MCI/YR	6.9	6.3	5.8	10.7	9.9	9.0	21.0	19.3	17.7
LEVELIZED OPERATING COSTS, CENTS/CI	8.9	9.0	9.3	7.5	7.5	7.7	6.1	6.0	6.1
LEVELIZED CAPITAL COSTS, CENTS/CI	38.6	39.2	41.3	28.1	28.3	29.6	18.0	17.9	18.5
SALES PRICE, CENTS/CI	47.5	48.2	50.6	35.5	35.8	37.3	24.1	23.9	24.6

TABLE IV-13. Example CAESR Summary Printout

FISSION PRODUCT PROFITABILITY STUDY

SUMMARY REPORT

CASE 56

PRODUCT CS-137

RETURN ON INVESTMENT REQUIRED	15.0 PERCENT
ECONOMIC LIFE OF PROJECT	10 YEARS
DEPRECIATION METHOD FOR TAXES	SUM OF THE YEARS DIGITS
FEDERAL INCOME TAX RATE	50.0 PERCENT

MARKET ASSUMED: 2.0 MEGACURIES IN 1971 GROWING AT 25.0 PERCENT PER YEAR

4.29

MARKET CAPTURED, INITIALLY AT TO A CONSTANT AFTER	20.0 PCT 50.0 PCT 5 YRS			20.0 PCT 50.0 PCT 5 YRS			20.0 PCT 50.0 PCT 5 YRS		
STARTUP YEAR	1975			1977			1980		
DESIGN AND CONSTRUCTION PERIOD	4			4			4		
PLANT	1	2	3	4	5	6	7	8	9
LOOK AHEAD PERIOD	7	5	3	7	5	3	7	5	3
PLANT SIZE, MEGACURIES	9.3	5.2	2.4	14.6	8.2	3.8	28.4	16.0	7.5
PRESENT WORTHED AVERAGE THROUGHPUT, MCI/YR	4.6	3.4	2.0	7.2	5.3	3.2	14.0	10.4	6.3
LEVELIZED OPERATING COSTS, CENTS/CI	11.6	13.1	17.3	9.4	10.3	13.0	7.3	7.7	9.1
LEVELIZED CAPITAL COSTS, CENTS/CI	57.7	68.5	98.9	41.8	48.3	67.8	26.8	29.8	39.8
SALES PRICE, CENTS/CI	69.3	81.5	116.2	51.2	58.5	80.8	34.1	37.6	48.8

BNWL-1686

The CAESR program was designed with an alternative calculation mode. Rather than calculate the price for a given return on investment, the return on investment can be calculated if the price is provided as input.

After an initial series of exploratory cases were completed, a learning curve capability was added to the CAESR calculation. Increased production through learning has been shown to apply to most manufacturing processes.⁽⁸⁾ The learning effect was first recognized in the aircraft industry where it was shown that the learning rate was 80 percent between doubled production quantities. That is, the direct labor required for the second hundred units was only 80 percent as much as was required for the first hundred, and so on. It has also been shown that learning rates are steeper when the labor content is high, but technological learning and process bottleneck removal are also established means to increased production capacity in the process industries. Repetitive maintenance work is particularly susceptible to learning effects.

The following equation has been proposed for applying learning effects to chemical process units⁽⁹⁾ and is the learning equation incorporated in CAESR.

$$P = P_0 \left[1 + \left(\frac{P_\infty}{P_0} - 1 \right) (1 - e^{-kt}) \right]$$

where

P_0 = design capacity

P_∞ = ultimate capacity

P = capacity at time t

k = rate constant

The ratio $P_\infty/P_0 = 2$ and a value for k of 0.1 has been found to apply to several process units.⁽⁹⁾ The rate constant k is analogous to the decay constant in the radioactive decay equation.

The fission product recovery and encapsulation processes under consideration here have a high allowance for maintenance down time, a high manual dexterity content in both operation and maintenance in the manipulator cells, and should also be susceptible to substantial technological improvements. Thus, a learning curve allowance is appropriate and is, in fact, more realistic than assuming level production capability. A value of $P_{\infty}/P_0 = 2$ and $k = 0.15$ were selected for base values in this study. This results in a 50 percent capacity improvement after five years and a 75 percent improvement after 10 years. Most of this increase could be achieved simply by increasing the number of operating days per year. To provide perspective when the learning effect was included in the price calculations, calculations for both zero learning and a higher learning effect ($P_{\infty}/P_0 = 3$) were routinely included for comparison. Because of the large discounting factors, the effect on price requirements was found to be not as large as one might at first expect.

The inclusion of the learning equation in the CAESR calculations is illustrated in Figure IV-6. When a new plant first starts up, production would be limited by the market. During this period, however, learning and bottleneck removal would be taking place. When the market share reaches design capacity, production can increase beyond that limit because learning has increased the plant capacity beyond design capacity. Production thus follows the market share curve until it intersects with the learning curve. From there on production follows the learning curve.

INITIAL RESULTS

A series of exploratory cases were first completed. The base case capital and operating costs have been previously discussed and are restated in Table IV-14 along with other base case inputs. The capital expenditure pattern over the four-year design and construction period was derived from a "Universal Cash Flow Chart" suggested by H. C. Bauman.⁽¹⁰⁾

For these exploratory cases the market was assumed to be expanding at a constant rate from a reasonably achievable base-year sales assumption.

FIGURE IV-6. Learning Curve Capability with CAESR

TABLE IV-14. Base Case Inputs

Return on investment required	15%/yr
Economic life of project	10 yr
Income tax rate	50%
Depreciation method for taxes	Sum of years digits
Design and construction expenditures over 4-year construction period	
1st year	10%
2nd year	35%
3rd year	45%
4th year	10%
Reference Plant Capacity:	
Cesium	29 MCi/yr
Strontium	28 MCi/yr
Reference Plant Cost:	
Cesium single-product	\$14.3 million
Strontium single-product	\$14.6 million
Cesium co-product	\$10.1 million
Strontium co-product	\$10.4 million
Cost Scaling:	
Cap. Cost B = 40% of Ref. Cost + 60% of Ref. Cost	$\left[\frac{\text{Capac. B}}{\text{Ref. Capac.}} \right]^{0.6}$
Operating Cost:	
(0.052)(Capital Cost) + (factor)(production, Ci/yr)	
where, factor = 4.5¢/Ci for one-product Cs plant	
3.6¢/Ci for two-product Cs plant	
4.7¢/Ci for one-product Sr plant	
3.8¢/Ci for two-product Sr plant	
Working Capital:	
25% of operating cost allocated in advance	

Selected results from these calculations are summarized in Tables IV-15, 16, 17, and 18. Three market assumptions are shown where the growth rate is a constant 25 percent per year in each, and the base-year starting points are 1, 2, and 3 MCi sales in 1970, 1971, and 1972 respectively.

The price requirements for equivalent cases for ^{90}Sr are nearly identical to ^{137}Cs , but slightly higher. Since results were so nearly the same, not all of the strontium case variations were calculated. Tables IV-15 and 16 show results for ^{137}Cs price requirements for single product and co-product plants respectively. Tables IV-17 and 18 show parallel cases for ^{90}Sr to the extent that these were completed.

To further illustrate the effect of plant size and load on price requirements, price is plotted against plant size for both cesium and strontium in Figures IV-7 and 8 for base-case co-product conditions. Capacity factors based on level production rates are shown as parameters. Production rates are seldom constant for long, but varying production can be converted to an equivalent constant or levelized average rate by the relationship

$$\frac{\sum_{n=1}^{n=p} (f_n \times T_n)}{\sum_{n=1}^{n=p} (f_n)} = \text{levelized throughput}$$

where

f_n = present worth factor, year "n"

T_n = throughput, year "n"

P = last year of economic life

When learning curve capability is included, capacity factors greater than 100 percent of design capacity are possible.

Capital charges are by far the most important component of the price. This is shown in Figure IV-9 where the capital charge fraction of the price

TABLE IV-15. Results of Initial Price Requirement Calculations for Single-Product 137Cs

Conditions	Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
		—Startup Year—			—Startup Year—		
		1975	1977	1980	1975	1977	1980
		Market Assumed:		1.0 MCi in 1970 Growing at 25%/yr			
1. Base (a)	1	6	9	18	94	68	45
2. 100% Market Share	30	12	18	36	72	54	36
3. 20% Initial to 50% After 5 Years	50	6	9	18	138	100	64
4. 15-Year Life	201	6	9	18	83	60	39
5. 15-Year Life and 10% ROI	101	6	9	18	58	42	28
		Market Assumed:		2.0 MCi in 1971 Growing at 25%/yr			
1. Base (a)	2	9	15	22	67	50	34
2. 100 Market Share	31	19	29	57	53	41	29
3. 20% Initial to 50% After 5 Years	51	9	15	28	98	73	48
4. 15-Year Life	202	9	15	28	59	44	30
5. 15-Year Life and 10% ROI	102	6	15	28	42	32	22
		Market Assumed:		3.0 MCi in 1972 Growing at 25%/yr			
1. Base (a)	3	11	18	26	59	45	30
2. 100% Market Share	32	22	35	68	47	37	26
3. 20% Initial to 50% After 5 years	52	11	18	34	97	64	43
4. 15-Year Life	203	11	18	34	52	40	27
5. 15-Year Life and 10% ROI	103	11	18	34	37	28	20

a. 100% initial to 50% after 5 years

TABLE IV-16. Results of Initial Price Requirement
Calculations for Co-Product ^{137}Cs

Conditions	Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
		—Startup Year—			—Startup Year—		
		1975	1977	1980	1975	1977	1980
Market Assumed: 1.0 MCi in 1970 Growing at 25%/yr							
1. Base (a)	8	6	9	18	66	48	31
2. 100% Market Share	35	12	18	36	51	38	26
3. 20% Initial to 50% After 5 Years	55	6	9	18	97	70	45
4. 15-Year Life	208	6	9	18	58	43	28
5. 15-Year Life and 10% ROI	108	6	9	18	41	20	20
Market Assumed: 2.0 MCi in 1971 Growing at 25%/yr							
1. Base (a)	9	9	15	22	47	35	24
2. 100% Market Share	36	19	29	57	38	29	21
3. 20% Initial to 50% After 5 Years	56	9	15	28	69	51	34
4. 15-Year Life	209	9	15	28	42	31	21
5. 15-Year Life and 10% ROI	109	9	15	28	30	22	16
Market Assumed: 3.0 MCi in 1972 Growing at 25%/yr							
1. Base (a)	10	11	18	26	42	32	22
2. 100% Market Share	37	22	35	68	34	26	19
3. 20% Initial to 50% After 5 years	57	11	18	34	61	46	31
4. 15-Year Life	210	11	18	34	37	28	19
5. 15-Year Life and 10% ROI	110	11	18	34	26	20	14

a. 100% initial to 50% after 5 years

TABLE IV-15. Results of Initial Price Requirement
Calculations for Single-Product 137Cs

Conditions		Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
			—Startup Year—			—Startup Year—		
			1975	1977	1980	1975	1977	1980
			Market Assumed: 1.0 MCi in 1970 Growing at 25%/yr					
1. Base (a)	1	6	9	18	94	68	45	
2. 100% Market Share	30	12	18	36	72	54	36	
3. 20% Initial to 50% After 5 Years	50	6	9	18	138	100	64	
4. 15-Year Life	201	6	9	18	83	60	39	
5. 15-Year Life and 10% ROI	101	6	9	18	58	42	28	
			Market Assumed: 2.0 MCi in 1971 Growing at 25%/yr					
1. Base (a)	2	9	15	22	67	50	34	
2. 100 Market Share	31	19	29	57	53	41	29	
3. 20% Initial to 50% After 5 Years	51	9	15	28	98	73	48	
4. 15-Year Life	202	9	15	28	59	44	30	
5. 15-Year Life and 10% ROI	102	6	15	28	42	32	22	
			Market Assumed: 3.0 MCi in 1972 Growing at 25%/yr					
1. Base (a)	3	11	18	26	59	45	30	
2. 100% Market Share	32	22	35	68	47	37	26	
3. 20% Initial to 50% After 5 years	52	11	18	34	97	64	43	
4. 15-Year Life	203	11	18	34	52	40	27	
5. 15-Year Life and 10% ROI	103	11	18	34	37	28	20	

a. 100% initial to 50% after 5 years

TABLE IV-16. Results of Initial Price Requirement Calculations for Co-Product ^{137}Cs

Conditions	Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
		—Startup Year—			—Startup Year—		
		1975	1977	1980	1975	1977	1980
Market Assumed: 1.0 MCi in 1970 Growing at 25%/yr							
1. Base (a)	8	6	9	18	66	48	31
2. 100% Market Share	35	12	18	36	51	38	26
3. 20% Initial to 50% After 5 Years	55	6	9	18	97	70	45
4. 15-Year Life	208	6	9	18	58	43	28
5. 15-Year Life and 10% ROI	108	6	9	18	41	20	20
Market Assumed: 2.0 MCi in 1971 Growing at 25%/yr							
1. Base (a)	9	9	15	22	47	35	24
2. 100% Market Share	36	19	29	57	38	29	21
3. 20% Initial to 50% After 5 Years	56	9	15	28	69	51	34
4. 15-Year Life	209	9	15	28	42	31	21
5. 15-Year Life and 10% ROI	109	9	15	28	30	22	16
Market Assumed: 3.0 MCi in 1972 Growing at 25%/yr							
1. Base (a)	10	11	18	26	42	32	22
2. 100% Market Share	37	22	35	68	34	26	19
3. 20% Initial to 50% After 5 years	57	11	18	34	61	46	31
4. 15-Year Life	210	11	18	34	37	28	19
5. 15-Year Life and 10% ROI	110	11	18	34	26	20	14

a. 100% initial to 50% after 5 years

TABLE IV-17. Results of Initial Price Requirement Calculations for Single-Product 90Sr

Conditions		Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
			—Startup Year—			—Startup Year—		
			1975	1977	1980	1975	1977	1980
Market Assumed: 1.0 MCi in 1970 Growing at 25%/yr								
1. Base (a)	15	6	9	18	97	70	46	
2. 100% Market Share	40	12	18	36	74	55	38	
3. 20% Initial to 50% After 5 Years		--	--	--	--	--	--	
4. 15-Year Life		--	--	--	--	--	--	
5. 15-Year Life and 10% ROI	115	6	9	18	59	44	29	
Market Assumed: 2.0 MCi in 1971 Growing at 25%/yr								
1. Base (a)	16	9	15	22	69	52	35	
2. 100% Market Share	41	19	29	57	55	42	30	
3. 20% Initial to 50% After 5 Years		--	--	--	--	--	--	
4. 15-Year Life		--	--	--	--	--	--	
5. 15-Year Life and 10% ROI	116	9	15	28	43	33	23	
Market Assumed: 3.0 MCi in 1972 Growing at 25%/yr								
1. Base (a)	17	11	18	26	61	46	31	
2. 100% Market Share	42	22	35	68	49	38	27	
3. 20% Initial to 50% After 5 years		--	--	--	--	--	--	
4. 15-Year Life		--	--	--	--	--	--	
5. 15-Year Life and 10% RIO	117	11	18	34	38	29	21	

a. 100% initial to 50% after 5 years

TABLE IV-18. Results of Initial Price Requirement
Calculations for Co-Product ⁹⁰Sr

Conditions	Case No.	Optimum Plant Size, MCi			Required Price, ¢/Ci		
		—Startup Year—			—Startup Year—		
		1975	1977	1980	1975	1977	1980
Market Assumed: 1.0 MCi in 1970 Growing at 25%/yr							
1. Base (a)	22	6	9	18	70	51	33
2. 100% Market Share	45	12	18	36	54	40	28
3. 20% Initial to 50% After 5 Years		--	--	--	--	--	--
4. 15-Year Life		--	--	--	--	--	--
5. 15-Year Life and 10% ROI	122	6	9	18	43	32	21
Market Assumed: 2.0 MCi in 1971 Growing at 25%/yr							
1. Base (a)	23	9	15	22	50	38	25
2. 100% Market Share	46	19	29	57	40	31	22
3. 20% Initial to 50% After 5 Years		--	--	--	--	--	--
4. 15-Year Life		--	--	--	--	--	--
5. 15-Year Life and 10% ROI	123	9	15	28	31	24	17
Market Assumed: 3.0 MCi in 1972 Growing at 25%/yr							
1. Base (a)	24	11	18	26	45	34	23
2. 100% Market Share	47	22	35	68	36	28	30
3. 20% Initial to 50% After 5 years		--	--	--	--	--	--
4. 15-Year Life		--	--	--	--	--	--
5. 15-Year Life and 10% ROI	124	11	18	34	28	22	15

a. 100% initial to 50% after 5 years

FIGURE IV-7. Required ^{137}Cs Prices at Level Production Rates (Base-Case Co-Product Conditions)

FIGURE IV-8. Required ^{90}Sr Prices at Level Production Rates
(Base-Case Co-Product Conditions)

FIGURE IV-9. Capital Charge Fraction of Required Price at Level Production Rates (Base-Case Co-Product Conditions)

is plotted against plant size with capacity factor parameters. Capital charges account for 70 to 80 percent of the price requirement. This plot applies to either cesium or strontium.

Other conclusions indicated by these initial results were:

1. A substantial established market, or a very rapidly expanding market, will be needed to attract the capital investment required for fission product recovery from power reactor fuels.
2. The advantage of shared facility costs between two or more co-product isotopes may be required to establish feasibility.
3. Any developments that would indicate reduced investment risk and permit an entrepreneur to consider a lower return and/or a longer capital recovery period would enhance the possibility of fission product recovery.

Cesium-137 and ^{90}Sr are presently available from the AEC through the Oak Ridge FPDL at prices of 12.5¢/Ci and 20¢/Ci respectively plus encapsulation costs for orders larger than 150,000 Ci. Allowing 5 to 10¢/Ci for encapsulation brings current acquisition costs to around 20¢/Ci for ^{137}Cs and 25 to 30¢/Ci for ^{90}Sr . The initial calculations rather clearly indicated that it would not be possible for a private fuel reprocessor to recover and market cesium and strontium at prices even as low as these current prices much before 1980.

Considering that the fission product market at present prices has not shown the kind of growth that appears necessary to establish the feasibility of recovery from power reactor fuels, just being able to market power reactor cesium and strontium at present prices would not be likely to open up the required large markets. Power reactor cesium, however, turns out to possess a unique feature that enhances its value substantially.

V. BASIC VALUES

For most large scale applications, there are only minor differences in the value of ^{60}Co and power reactor cesium sources regarding their ability to do the job. That is, differences in facility requirements and costs, differences in utilization efficiency of emitted radiations, differences in depth-dose relationships, and differences in radiation facility operating costs all appear to be small. Thus, value relationships of these materials can be established based solely on the relative amounts of gamma radiation emitted.

The seemingly large differences in the properties of the isotopes and the resulting minor effects on user application are briefly discussed below. Reasonable plant parameter assumptions are then established leading to the calculation of power reactor cesium prices which would be competitive with the existing cobalt price structure.

ISOTOPE PROPERTIES

A comparison of the radiation emitted from ^{60}Co , ^{134}Cs , and ^{137}Cs is shown in Table V-1. As normally supplied to the user, cobalt sources range from 30 to 100 Ci/g in specific activity. The isotopic composition of cesium in exposed power reactor fuel will depend on reactor parameters; typical compositions are shown in Table V-2. One year after spent fuel removal from the reactor, the specific activity of the separated cesium (as cesium chloride) will average about 23.8 Ci ^{137}Cs /g. It will have associated with it 0.7 to 1.2 Ci ^{134}Cs per Ci ^{137}Cs dependent on reactor parameters. For most of the comparisons discussed later, a base case composition of 0.88 Ci ^{134}Cs per Ci ^{137}Cs has been chosen. This is representative of BWR fuel exposed to 25,000 MWd/MT. The ^{134}Cs content of PWR fuel would be a little higher for the same exposure.

Gamma energy as a function of source age for cobalt and for base case power reactor cesium is shown in Figure V-1.

TABLE V-1. Radioactive Properties

	^{134}Cs	^{137}Cs	^{60}Co
Half-life, yr	2.10	30.2	5.26
Activity, Ci/g	1271	86.5	1131
Decay Energy, W/Ci			
Gamma	9.48×10^{-3}	3.35×10^{-3}	14.9×10^{-3}
Beta	0.85×10^{-3}	1.0×10^{-3}	0.56×10^{-3}
W/g (pure)			
Gamma	12.05	0.29	16.8
Beta	1.08	0.084	0.64

Decay Energy Spectrum						
	^{134}Cs		^{137}Cs		^{60}Co	
	MeV	%	MeV	%	MeV	%
Beta	1.453	0.2	1.18	5	1.48	0.12
	0.892	1.5				
	0.658	61	0.514	95	0.663	0.008
	0.410	9				
	0.282	0.5			0.315	99.87
	0.086	27				
Gamma	1.40	0.1				
	1.365	3.0			1.3325	100
	1.168	1.85			1.1732	100
	1.039	1.06				
	0.802	9.5				
	0.796	89				
	0.605	98	0.6616	85		
	0.569	15.8				
	0.563	8.82	0.032	5.82		
	0.475	1.54	0.0365	1.31		

TABLE V-2. Fission Product Cesium Compositions

Reactor Type	Initial Enrichment	Exposure, MWd/MT	Cesium Composition, wt% (Upon Removal from Reactor)			Isotopic Ratio, Ci ^{134}Cs /Ci ^{137}Cs One Year After Removal from Reactor
			^{134}Cs	^{137}Cs	$^{133} \& ^{135}$	
BWR	2.50	20,000	2.87	40.6	56.5	0.76
	2.50	30,000	3.74	40.8	55.5	0.92
	2.50	40,000	4.40	41.2	54.4	1.15
	2.0	25,000	3.66	41.6	54.7	0.88
	2.5(a)	25,000	3.33	40.7	56.0	0.88
	3.0	25,000	3.05	39.9	57.0	0.83
PWR	3.25	20,000	2.84	41.9	55.3	0.73
	3.25	30,000	3.89	42.1	54.0	1.00
	3.25	40,000	4.78	42.4	52.8	1.22
	2.50	25,000	3.82	43.0	53.2	0.96
	3.00	25,000	3.51	42.3	54.2	0.90
	3.50	25,000	3.26	41.6	55.1	0.85

a. Base case chosen for comparison purposes

FIGURE V-1. Gamma Energy Comparison

USER APPLICATION

In addition to the economics of source purchase per se (which will be discussed below), a user must be concerned with the effects of source choice upon plant design, operation, and safety and upon product quality. To facilitate a brief discussion of some of these factors, consider the source choice with which a user might be faced. Table V-3 lists parameters for a currently available cobalt source and for two possible power reactor cesium sources.

Dose Intensity

If high dose rate is a process requirement, cesium sources are at a distinct disadvantage when compared to cobalt as shown in the last line of Table V-3. Most potentially large volume uses of gamma sources are not so restricted, however; total dose rather than dose rate is the controlling

TABLE V-3. Cobalt and Power Reactor Cesium Source Parameters

Source Identification	Co-1	Cs-2	Cs-3
Isotope	^{60}Co	$^{137}\text{Cs}/^{134}\text{Cs}$	$^{137}\text{Cs}/^{134}\text{Cs}$
Length, in.	12	21	21
OD, in.	0.303	0.6	1.1
Total Stainless Steel Cladding Thickness, in.	0.026	0.04	0.04
Isotope Weight, ^(a) g/source	86.6	161	644
Specific Activity, Ci/g:			
^{60}Co	50		
^{137}Cs		23.8	23.8
^{134}Cs		20.9	20.9
Total Activity, Ci/Source:			
^{60}Co	4330		
^{137}Cs		3830	15,320
^{134}Cs		3370	13,500
Self Absorption, % ^(b)	20.3	19.0	27.7
Emitted Gamma Energy, % ^(b)	79.7	81.0	72.3
Emitted Gamma Energy Intensity, ^(c) W/ft ²	1020	208	403

a. As CsCl for sources Cs-2 and Cs-3.

b. When assembled as a large plaque.

c. From one side of a large plaque.

factor. If the target size is small, dose intensity can become a critical factor. Practically restricting examples of this sort are few, the major example being teletherapy units.

The major portion of the projected gamma source market would be utilized in the treatment of bulk or packaged materials in facilities which allow uniform, continuous irradiation and which maximize the target absorption of the emitted radiation. Under such conditions, emitted gamma energy intensity (at least over the range shown in Table V-3) is rarely a controlling factor in facility design. Existing cobalt-powered facilities (e.g., medical product sterilization plants) normally utilize fairly wide spacing of cobalt sources within the source plaque. Substitution of power reactor cesium sources in such plants would reduce but not eliminate the vacant space within the plaque.

Dose Uniformity

A radiation processor is primarily concerned with the minimum dose required to accomplish a particular product objective. Delivered doses above this minimum are essentially wasted. The ratio of the maximum to the minimum dose received by a target (the uniformity ratio) is dependent upon target geometry and composition, target and source configuration and upon source properties.

The facility designer attempts to attain the lowest uniformity ratio consistent with the imposed parameters of product treatment. For any given facility, the choice of cobalt or of power reactor cesium sources will (fortuitously) have no significant effect on the uniformity ratio achieved. This statement can be illustrated by utilizing existing designer aids to predict the dose uniformity to be expected in typical facilities (Table V-4).

Shielding

Radiation processing facility hot cells are normally constructed of concrete or high density concrete to provide the requisite shielding; smaller units may use lead for this purpose. The thickness of a particular shield material required depends on total source power and the photon energy of the isotope. Pure ^{137}Cs requires considerably thinner shielding

TABLE V-4. Typical Dose Uniformity Ratios^(a)

Facility Purpose	Product Density, g/cm ³	Target Thickness, in.	Number of Passes	Uniformity Ratio ^(b)		
				Cobalt	Power Reactor	Base Case Cesium
Medical Product Sterilization	0.3	10	6	1.16		1.15
Food Irradiation	0.9	4	4	1.13		1.13

- a. Facilities are assumed to be two direction, multi-pass units 60 in. x 60 in. plaque and a 2 in. source-to-target air gap.
- b. From BNL 50145 (T-516) Revised, "Tabulated Dose Uniformity Ratio and Minimum Dose Data for Gamma Irradiator Design," and BNL 50316, "Dose Distribution, Dose Uniformity, and Minimum Dose Data for Square Cs-134 Source Plaques."

than ⁶⁰Co; when compared at equal power, about 20 percent less concrete or 40 percent less lead is required. The admixture of ¹³⁴Cs (with its high energy photons) in the power reactor cesium sources increases shielding requirements to approximately those for ⁶⁰Co.

Facility Size

As previously noted, the maximum emitted gamma energy intensity attainable using power reactor cesium sources is less than that attainable from cobalt sources. This will rarely affect facility size since most current and projected radiation processing plaques are assembled at well below their maximum attainable gamma energy intensity.

Those unusual processing situations which show a significant dependency of facility size upon source choice will be few enough as to have little effect on the general conclusions derived in this report.

Safety

The accumulated body of cobalt facility operating experience is large enough to allow the designer to be reasonably confident in predicting long range source behavior. The effects of cobalt source failure and the mechanics of meeting and recovering from accidental situations have been well investigated.

Much less operating experience has been accumulated with cesium sources and fewer designers are familiar with them. Major current concern centers on the high solubility of cesium chloride; for example, the accidental shattering of a pool-stored source will lead to its rapid dissolution. Those experimenters active in cesium source development are aware of the relative ease with which dissolved cesium chloride can be completely removed by ion exchange beds and feel that no undue hazard exists. Nevertheless, it is indisputable that more development, testing, and operating experience must be accumulated and published before the average designer will be as comfortable with cesium as he is with cobalt. Such experience is currently being gained by a limited group of investigators and users.

COBALT-CESIUM ECONOMIC COMPARISON

If a potential radiation processor were faced with a choice of isotopic gamma sources, his ultimate decision would be based on the specific combination of economic and design factors peculiar to his process, his industry and his company. Any statement of the sort, "Isotope X at A¢/Ci is competitive with Isotope Y at B¢/Ci" will be strictly accurate only for a particular, clearly defined case. There is need, nevertheless, for a generalized approach to an economic comparison between cobalt and cesium sources. The following represents such an approach.

The assumptions made herein should be carefully noted. The data presented provide reasonable estimates of the price which could be paid for various types of cesium sources without incurring an economic penalty when compared with presently available cobalt sources.

Current Price Structures

The somewhat sporadic sales of cobalt and the limited number of suppliers leads to fairly significant fluctuation in its sales price. Recent sales have centered about 40¢/Ci for large quantities of doubly encapsulated material. There is disagreement on future price trends assuming a steadily growing market. Price reduction pressures may be generated by quantity production savings and the possible entry of additional suppliers. Cobalt is activated in power reactors at the cost of increased fuel enrichment or decreased fuel exposure; current trade-offs could change significantly in the future (particularly in the United States) resulting in increased costs assessable to cobalt production. The effects upon cobalt prices of the recently announced increase in Canadian production to an eventual 15 MCi per year are unknown. On balance, it is probable that a level price of 40¢/Ci (in 1971 dollars) may be assumed for the foreseeable future. This is the assumption made for the base case comparison discussed below although the effects of cobalt price changes are briefly indicated.

The current price structure for cesium sources is an artificial one based on the U.S. AEC supported charge of 12.5¢/Ci in large quantities. Two important aspects of this price should be carefully noted:

1. The 12.5¢/Ci charge is for the source material (CsCl) only and does not include encapsulation charges. Additional charges for encapsulation can easily run to 10¢/Ci or more since the work is done under experimental rather than production conditions.
2. Currently available material is essentially pure ^{137}Cs . Power reactor material will contain ^{134}Cs which will more than triple the power output associated with ^{137}Cs alone. For example, 1 kilocurie of pure ^{137}Cs will yield 3.35 watts of gamma power (ignoring self-absorption); 1 kilocurie of base case power reactor ^{137}Cs with its associated ^{134}Cs will yield 11.7 watts.

Since the encapsulated price of currently available cesium is roughly one-half that of cobalt while its power output is only one-quarter that of

cobalt (on a per curie basis), cesium can currently compete with cobalt only in those few circumstances where the lower shielding requirements of ^{137}Cs are an over-riding factor.

Future Fission Product Profitability

Assumptions

As indicated above, power reactor cesium sources, if available, could be substituted for cobalt sources with no major changes in facility design, safety, product quality, etc. The designer choice would then reduce to a consideration of source costs and the selection of that source which showed the most favorable financial result over the projected life of the facility.

Using a present worth technique, the values of proposed power reactor cesium sources were determined relative to cobalt sources under a wide variety of parametric conditions. These parameters included source geometry, return on investment, projected plant lifetime, source salvage value, etc. The results presented below summarize the most representative of these calculated values. It is recognized that the assumptions made and the necessarily simplified approach introduced an uncertainty, perhaps ± 20 percent, in the calculated values. It is believed, however, that a generally conservative attitude has been maintained.

The basis for the reported calculations was as follows:

1. The value of two sources are assumed equal when their emitted gamma energy productions are equal.
2. Sources are replenished annually.
3. The initial source is capitalized.
4. Replenishments are treated as operating expenses.
5. Federal income taxes are taken as 50 percent.
6. A 10-year economic plant life is assumed.
7. The value of encapsulated ^{60}Co is 40¢/Ci.

8. The salvage value of the sources and the rate of return on investment are treated as variables.
9. Source geometries and content are as shown in Table V-3.

Salvage value, the net worth of used sources at the end of the plant lifetime, is difficult to predict. If a continuing large demand for sources exists, it is reasonable to assume that a market price for used sources will establish itself. These lower specific activity sources would certainly be discounted below new sources. For the base case, it is assumed that this discount will be 50 percent for ^{60}Co and roughly the same for the ^{137}Cs content of the power reactor sources. Since the ^{134}Cs content of these used sources would be low, no salvage credit is taken for it. The base case salvage value chosen for ^{137}Cs (5¢/Ci) will be justified in the discussion of HWM capsule values.

Values

Selected values calculated for the power reactor cesium sources are listed in Table V-5. Note that all source values are expressed as ¢/Ci ^{137}Cs . The parametric effects of return on investment and salvage value upon source values are shown in Figures V-2 and V-3. In Figure V-2, the effect of ^{60}Co salvage value is shown at a constant cesium salvage value; in Figure V-3, the effect of cesium salvage value is shown at a constant ^{60}Co salvage value. The points labelled "base case" represent 15 percent return on investment and salvage values of 20¢/Ci for ^{60}Co and 5¢/Ci for ^{137}Cs . Base case values for sources Cs-2 and Cs-3 are 26.9 and 24.2¢/Ci ^{137}Cs , respectively.

As would be expected, a larger diameter source (with its greater self-absorption) has a lower value per curie. In the example case shown in Figures V-2 and V-3, the value is reduced about 10 percent when source diameter is about doubled.

It is recognized that future source market conditions might be such that used sources could represent an expense rather than an income, i.e., money might have to be spent to store or otherwise dispose of these sources.

TABLE V-5. Power Reactor Cesium Source Values ($\text{¢/Ci } ^{137}\text{Cs}$)
Relative to ^{60}Co at 40¢/Ci

SOURCE ^(a)		Cs-2	Cs-3
RETURN ON INVESTMENT, %	SALVAGE VALUES		
0	Zero	25.3	22.6
	Base Case ^(b)	24.2	21.9
10	Zero	26.8	23.8
	Base Case	26.3	23.7
15	Zero	27.2	24.2
	Base Case	<u>26.9</u> ^(c)	<u>24.2</u> ^(c)
	Zero	27.4	24.6
	Base Case	27.4	24.6

a. Source Properties as shown in Table V-3.

b. Base Case Salvage Values: $20\text{¢/Ci } ^{60}\text{Co}$
 $5\text{¢/Ci } ^{137}\text{Cs}$

c. Base Case

FIGURE V-2. Effect of ^{60}Co Salvage Value on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci. ^{137}Cs Salvage Value - 5¢/Ci; Isotope Ratio - 0.88 Ci $^{134}\text{Cs}/^{137}\text{Cs}$.

FIGURE V-3. Effect of ^{137}Cs Salvage Value on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci. ^{60}Co Salvage Value - 20¢/Ci; Isotope Ratio - 0.88 Ci $^{134}\text{Cs}/^{137}\text{Cs}$.

The over-all effects of salvage value upon source value at 15 percent return on investment can be seen in Figure V-4.

While base case ^{134}Cs content was chosen as 0.88 Ci/Ci ^{137}Cs , the content could vary substantially, as discussed previously. The effect of such variation on power reactor source value is substantial, as shown in

Figure V-5. For base case conditions, source CS-2 value would vary from 24.0 to 32.0¢/Ci ^{137}Cs over a ^{134}Cs content range of 0.7 to 1.2 Ci/Ci ^{137}Cs .

FIGURE V-4. Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci as a Function of ^{60}Co and ^{137}Cs Salvage Values. Isotope Ratio - 0.88 Ci ^{134}Cs / ^{137}Cs ; Return on Investment - 15%.

FIGURE V-5. Effect of $^{134}\text{Cs}/^{137}\text{Cs}$ Ratio on Power Reactor Cesium Value Relative to ^{60}Co at 40¢/Ci. ^{60}Co Salvage Value - 20¢/Ci; ^{137}Cs Salvage Value - 5¢/Ci.

All calculations thus far have assumed a ^{60}Co source value of 40¢/Ci. Any variation of this assumption will directly affect the calculated power reactor cesium source values. Thus, if the "base case" Cs-2 source value is 26.9¢/Ci ^{137}Cs based on 40¢/Ci ^{60}Co , it will be $(\frac{30}{40})$ (26.9) or 20.2¢/Ci ^{137}Cs based on 30¢/Ci ^{60}Co .

Summarizing, the value of power reactor cesium compared to 40¢/Ci ^{60}Co over reasonable ranges of ^{134}Cs content (0.7 to 1.2 Ci ^{134}Cs /Ci ^{137}Cs), return on investment (10 to 20 percent), diameter (0.6 to 1.1 inches OD), and salvage value (0 to 20¢/Ci ^{60}Co and 0 to 5¢/Ci ^{137}Cs) will be 19.7 to 34.0¢/Ci ^{137}Cs with 27¢/Ci ^{137}Cs being a reasonable base value.

Hanford Waste Management (HWM) Capsule Values

Long before the possible production of power reactor cesium, HWM cesium will be produced in long-term-storage capsules. These HWM capsules may be of interest as irradiation sources. They will contain 60,000 curies of ^{137}Cs with essentially no ^{134}Cs . Their value relative to ^{60}Co at 40¢/Ci is of interest as is the value of the same isotopic material encapsulated in more efficient, i.e., smaller diameter, form. Properties of the HWM capsules and of a smaller diameter unit are presented in Table V-6. Relative values for these sources, presented in the same manner as were the power reactor cesium data, are shown in Table V-7 and Figures V-6, V-7, and V-8. When these data are considered in comparison with the power reactor cesium data, the value added to the power reactor cesium source by ^{134}Cs is striking. For example, the value of power reactor cesium source Cs-3 at base case conditions is 24.2¢/Ci ^{137}Cs while the value of a comparable pure ^{137}Cs source (Cs-4) is only 11.1¢/Ci ^{137}Cs .

The value of the HWM storage capsules when used as sources (Cs-1) will range from 7.6 to 9.1¢/Ci ^{137}Cs dependent upon rate of return on investment (10 to 20%) and salvage value 0 to 20¢/Ci ^{60}Co and 0 to 5¢/Ci ^{137}Cs . At the same base case conditions chosen for power reactor cesium sources (15% ROI, salvage values of 20¢/Ci ^{60}Co and 5¢/Ci ^{137}Cs), the HWM source value will be 8.2¢/Ci ^{137}Cs .

Decayed power reactor cesium sources will contain a reduced and perhaps negligible concentration of ^{134}Cs . Hence, if a salvaged power reactor cesium source is to be re-used, it must be considered as a ^{137}Cs source, similar to the HWM sources. This consideration, then, explains the relatively low power reactor cesium source salvage values used above.

It has been stated earlier that the somewhat lower maximum gamma energy intensity available from power reactor cesium than from cobalt would not generally affect facility size. The maximum intensities available from HWM cesium are still lower (see Table V-6) and facility size may be affected.

TABLE V-6. HWM Cesium Source Parameters

Source Identification	Cs-1 ^(a)	Cs-4
Isotope	^{137}Cs	^{137}Cs
Length, in.	20.775	20.775
OD, in.	2.625	1.125
Total Stainless Steel Cladding Thickness, in.	0.204	0.064
Isotope Weight, ^(b) g/source	2520	570
Specific Activity, Ci $^{137}\text{Cs/g}$	23.8	23.8
Total Activity, Ci $^{137}\text{Cs/source}$	60,000	13,600
Self Absorption, ^(c) %	0.495	0.297
Emitted Gamma Energy, ^(c) %	0.505	0.703
Emitted Gamma Energy Intensity, ^(d) W/ft ²	135	99

-
- a. Projected HWM storage capsule
 - b. As CsCL
 - c. When assembled as a large plaque
 - d. From one side of a large plaque

TABLE V-7. HWM Cesium Source Values ($\text{¢}/\text{Ci}^{137}\text{Cs}$)
Relative to ^{60}Co at $40\text{¢}/\text{Ci}$

SOURCE ^(a)		Cs-1	Cs-4
RETURN ON INVESTMENT, %	SALVAGE VALUES		
0	Zero	10.8	15.0
	Base Case ^(b)	12.6	16.0
10	Zero	8.5	11.9
	Base Case	9.1	12.2
15	Zero	7.8	11.0
	Base Case	<u>8.2</u> ^(c)	<u>11.1</u> ^(c)
	Zero	7.6	10.6
	Base Case	7.8	10.7
20	Zero	7.6	10.6
	Base Case	7.8	10.7

a. Source Properties as shown in Table V-6

b. Base Case Salvage Values: $20\text{¢}/\text{Ci}^{60}\text{Co}$
 $5\text{¢}/\text{Ci}^{137}\text{Cs}$

c. Base Case

FIGURE V-6. Effect of ^{60}Co Salvage Value on HWM Cesium Value Relative to ^{60}Co at 40¢/Ci. ^{137}Cs Salvage Value - 5¢/Ci.

FIGURE V-7. Effect of ^{137}Cs Salvage Value on HWM Cesium Value Relative to ^{60}Co at 40¢/Ci . ^{60}Co Salvage Value - 20¢/Ci .

FIGURE V-8. HWM Cesium Value Relative to ^{60}Co at 40¢/Ci as a Function of ^{60}Co and ^{137}Cs Salvage Values. Return on Investment - 15%.

That is, a larger HWM cesium than cobalt source plaque might be required in a given facility; this in turn would require a larger cell volume in the cesium case. The financial penalty incurred would be somewhat offset by the lower shielding requirements for ^{137}Cs (see discussion on shielding above). The resultant facility cost penalty, if any, would act to reduce the relative HWM source values calculated above. This effect is quite dependent on individual facility design details; it is probable, however, that the effect on source value will usually be small.

VI. MARKETS

Both ^{137}Cs and ^{90}Sr have been available for industrial applications for a number of years through the Oak Ridge National Laboratories (ORNL) Fission Product Development Laboratory (FPDL). The feed materials for FPDL encapsulation have been supplied as crude concentrates from AEC's Hanford, Washington plant as a by-product of waste management operations since 1961.

FPDL SALES EXPERIENCE

Sales experience for ^{137}Cs and ^{90}Sr from the Oak Ridge FPDL is summarized in Tables VI-1 and 2. These tables show that sales of both ^{137}Cs and ^{90}Sr have experienced significant but erratic growth over the past ten years.

The present AEC price schedule for ^{137}Cs and ^{90}Sr was established in November 1965 when prices were reduced in an effort to stimulate the market to enhance the feasibility of the ISOCHEM corporation's planned Fission Product Conversion and Encapsulation (FPCE) Plant. The magnitude of the hoped-for market stimulation did not materialize and, as noted in Chapter IV, plans for the FPCE Plant were cancelled in January 1967. However, relative to previous sales, the domestic sales of both ^{137}Cs and ^{90}Sr did show substantial gains after the 1965 price reduction, but not nearly enough to justify the FPCE Plant. Both the present price schedule and the schedule prior to 1965 are shown in Table VI-3.

^{137}Cs MARKET SURVEY

A market survey was carried out by P. M. Wood and H. A. Harrel of the AEC Combined Operations and Planning Group⁽²⁾ to identify potential markets for ^{137}Cs in particular, and hard gamma sources in general, including ^{60}Co . In conducting this survey, AEC data on past sales of ^{137}Cs and literature on ^{137}Cs applications were reviewed, and the available information from the abandoned Isochem project was also analyzed. Finally, the views of some suppliers and users of ^{137}Cs and ^{60}Co on specific points were obtained.

TABLE VI-1. ^{137}Cs Sales From ORNL

<u>Fiscal Year</u>	<u>Curies</u>
1946-55	2,202
1956	2,855
1957	2,848
1958	5,641
1959	15,424
1960	88,566
1961	21,099
1962	143,714
1963	103,820
1964	282,023
1965	349,989
1966	70,002
1967	567,985
1968	554,310
1969	380,210
1970	175,382
1971 ^(a)	94,480
Total Deliveries	2,860,550
Outstanding Orders ^(a)	559,606
Net Sales ^(a)	3,420,156

a. As of 2/28/71.

TABLE VI-2. ^{90}Sr Sales From ORNL

<u>Fiscal Year</u>	<u>Curies</u>
1946-55	286
1956	66
1957	23
1958	16
1959	105
1960	262
1961	17,801
1962	336,803
1963	1,281
1964	8,719
1965	1,015
1966	109,262
1967	396,282
1968	1,177,433
1969	953,616
1970	369,095
1971 (10 months)	736,577
Total	4,108,643

TABLE VI-3. Present and Previous Price Schedules for Cesium and Strontium

<u>Present AEC Price Schedule, \$/Ci</u>		
	<u>^{137}Cs</u>	<u>^{90}Sr</u>
0-5000 Ci	0.50	0.50
5001-50,000 Ci	0.45	0.30
50,001-150,000 Ci	0.35	0.25
Over 150,000 Ci	0.125	0.20

<u>AEC Price Schedule Prior to November 1965, \$/Ci</u>		
	<u>^{137}Cs</u>	<u>^{90}Sr</u>
0-20,000 Ci	1.00	
20,000-100,000 Ci	0.75	
Over 100,000 Ci	0.50	
0-5000 Ci		2.00
5000-30,000 Ci		1.00
Over 30,000 Ci		0.75

Encapsulated cesium is useful primarily as a source of high intensity gamma radiation for applications such as sterilization of medical supplies, medical teletherapy, chemical polymerization, food sterilization and pasteurization, sewage treatment, and other applications.

In most applications, cesium has a direct competitor in ^{60}Co . Since cesium and ^{60}Co are such direct competitors, the market was evaluated in terms of the total market for high intensity gamma sources. From this basis, an estimate of the likely market share for cesium is then possible.

For certain applications, the lower gamma energy of ^{137}Cs and its longer half-life give it a decided advantage over ^{60}Co or $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures. These applications include portable irradiators, portable teletherapy and portable radiography units, where the less stringent

shielding requirements are an advantage. The long half-life is also an advantage in these units as less frequent calibration is necessary. This latter factor has led to the choice of ^{137}Cs in at least one large research application. However, the potential market for applications that strongly favor ^{137}Cs is small, on the order of 100,000 Ci/yr by 1980.

In two potentially large volume applications, stationary high-intensity teletherapy units and compact heat sources, ^{137}Cs and $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures cannot compete with ^{60}Co because of their low specific activity. In all other large-volume applications for sources of high intensity gamma radiation, ^{137}Cs and $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures can compete on an economic basis with ^{60}Co . These applications are those where 25 to 50 Ci/g ^{60}Co is presently used. This grade of ^{60}Co is currently available at 40 to 50 ¢/Ci. If cesium can be produced and encapsulated at a cost equal to or below its value relative to ^{60}Co , then it could capture a substantial portion of the market. (Relative values of ^{137}Cs and ^{60}Co were discussed in the previous section.)

The most promising applications for either ^{137}Cs , $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures, or ^{60}Co are those that require penetrating radiation. The largest and most rapidly growing of these, other than teletherapy mentioned above, is sterilization of medical supplies. In this application, gamma radiation has an advantage over chemicals, steam, or accelerators since large pre-sealed containers can be sterilized and remain closed and sterile until used. Gamma radiation is also advantageous in certain chemical processing applications, such as when large bulk quantities of materials are irradiated (for example, cartons of bulk chemicals) or when the nature of the process equipment makes a compact source advantageous. However, for most chemical process and polymerization applications, gamma sources such as ^{60}Co or cesium find strong competition from accelerators and catalysts.

A potentially large market for gamma sources is food irradiation. Most suppliers of irradiators in this country are pessimistic about ever getting the Food and Drug Administration (FDA) approval of irradiated food consumption in this country. Although Israel is already marketing irradiated food, most developing countries tend to follow the advice of the U.S. FDA. Nevertheless, food irradiation offers a large potential future market.

No one seems to have much hope for the use of gamma sources for sewage treatment, other than companies directly involved in such a commercial undertaking.

Two projections for gamma source requirements were developed from this survey. One termed "probable," predicts gamma source requirements growing to 16 MCi of ^{60}Co or its equivalent, by 1980. Another, termed "possible," predicts gamma source requirements growing to 25 MCi of ^{60}Co or its equivalent by 1980.

These market projections are based on the assumption that applications for food irradiation develop only to a modest extent because of the negative attitude of the FDA. It is also assumed that large scale applications for sewage treatment do not develop because of economics. If the situation should reverse in either of these applications, the potential market for gamma sources could be double that projected by 1980. Current prospects are still highly conjectural.

RASOR/RAMARK COMPUTER PROGRAMS

Although ^{137}Cs , $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures, or ^{60}Co can all be used interchangeably for many applications, the amounts required and the replenishment requirements vary widely. Calculation of replenishment requirements for a one-component source is straightforward. Calculation of replenishment requirements for a two-component source ($^{137}\text{Cs}/^{134}\text{Cs}$) is a good deal more complicated and doubly so when the replenishment requirements for a growing market are to be considered. In either case, if a radiation-source plaque size limit is included, the calculations are further complicated.

The computer program RASOR, for Radiation Source Replenishment, was written to carry out such calculations. This program calculates a specific 30-year history for a radiation source that is equivalent to some specified reference source. Source replenishments are calculated at specified periods, such as annually, so that the mid-period gamma power is equal to the mid-period power of the reference source. Thus, the integrated gamma energy output is equal to that of the reference source.

A 1 MCi ^{60}Co source was used as the reference source in all calculations here and annual replenishments were standard. A plaque size ratio of 2.0 was used. This means that the source plaque has double the space required for the initial source. Source plaques are likely to have even more excess space than this. However, the results from these calculations were also used to provide input for the relative value calculations discussed in the preceding section, and this is considered a conservative assumption for valuing $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures. A plaque size ratio of 2.0 is large enough that source discards do not increase market requirements significantly, especially in a growing market, but is also small enough to be a conservative assumption for the value calculations.

Two output tables are produced by the program for each source calculation. The first table provides a period-by-period schedule of additions and discards, as well as the net plaque contents in terms of both megacuries and kilowatts. Results for ^{60}Co are shown in Table VI-4. The discards show the year of addition for the component discarded, its original intensity, and its intensity at discard. All quantities are calculated as of the beginning of a period. Thus, the first discard required to make room for new replenishment material is 0.049 MCi and takes place in year No. 10. The original strength was 0.16 MCi showing that 16 percent of the original source material was removed to make room for replenishment material.

The second table shows the year-by-year history of each component in the plaque after decay losses and any discards, as in Table VI-5, for the ^{60}Co results. The units are megacuries, and the columns show the source activity at the beginning of each year and how much each component is contributing to total source strength. The program produces a 30-year schedule of which only the first 20 years are shown here.

The equivalent tables for a pure ^{137}Cs source plaque are shown in Tables VI-6 and VI-7. Because of the 30-year half-life for ^{137}Cs , no discards are required. The net source strength at the beginning of each year is 14.06 kW compared to 14.85 kW for the ^{60}Co , but at mid-year both will equal 13.90 kW.

TABLE VI-4. Cobalt-60 Source Replenishment Schedule Showing Annual Additions and Discards

<div>COMPONENT 1 = CO-60</div> <div>ORIGINAL COMPOSITION:</div> <div>100.00 % CO-60</div> <div>REPLENISHMENT PERIOD - ANNUAL</div> <div>PLAQUE SIZE RATIO - 2.000</div>									
SOURCE ADDITIONS			SOURCE DISCARDS				NET SOURCE		
YEAR	MCI	KW	YEAR	ORIGINAL INTENSITY MCI	KW	DISCARD INTENSITY MCI	KW	MCI	KW
1	9.998-01	1.485+01						9.998-01	1.485+01
2	1.235-01	1.833+00						9.998-01	1.485+01
3	1.235-01	1.833+00						9.998-01	1.485+01
4	1.235-01	1.833+00						9.998-01	1.485+01
5	1.235-01	1.833+00						9.998-01	1.485+01
6	1.235-01	1.833+00						9.998-01	1.485+01
7	1.235-01	1.833+00						9.998-01	1.485+01
8	1.235-01	1.833+00						9.998-01	1.485+01
9	1.235-01	1.833+00						9.998-01	1.485+01
10	1.724-01	2.560+00	1	1.603-01	2.380+00	4.894-02	7.268-01	9.998-01	1.485+01
11	1.686-01	2.503+00	1	1.686-01	2.503+00	4.512-02	6.701-01	9.998-01	1.485+01
12	1.613-01	2.395+00	1	1.613-01	2.395+00	3.784-02	5.620-01	9.998-01	1.485+01
13	1.554-01	2.308+00	1	1.554-01	2.308+00	3.196-02	4.746-01	9.998-01	1.485+01
14	1.506-01	2.236+00	1	1.506-01	2.236+00	2.715-02	4.031-01	9.998-01	1.485+01
15	1.466-01	2.177+00	1	1.466-01	2.177+00	2.317-02	3.440-01	9.998-01	1.485+01
16	1.453-01	2.158+00	1	5.698-02	8.462-01	7.891-03	1.172-01	9.998-01	1.485+01
			2	8.832-02	1.312+00	1.395-02	2.072-01		
17	1.458-01	2.165+00	2	3.514-02	5.218-01	4.866-03	7.226-02	9.998-01	1.485+01
			3	1.107-01	1.643+00	1.749-02	2.597-01		
18	1.466-01	2.177+00	3	1.279-02	1.899-01	1.771-03	2.630-02	9.998-01	1.485+01
			4	1.235-01	1.833+00	1.951-02	2.897-01		
			5	1.036-02	1.538-01	1.867-03	2.772-02		
19	1.475-01	2.191+00	5	1.131-01	1.680+00	1.787-02	2.654-01	9.998-01	1.485+01
			6	3.443-02	5.113-01	6.206-03	9.216-02		
20	1.482-01	2.201+00	6	8.903-02	1.322+00	1.407-02	2.089-01	9.998-01	1.485+01
			7	5.916-02	8.785-01	1.066-02	1.584-01		
21	1.489-01	2.211+00	7	6.430-02	9.548-01	1.016-02	1.509-01	9.998-01	1.485+01
			8	8.456-02	1.256+00	1.524-02	2.263-01		
22	1.495-01	2.221+00	8	3.890-02	5.776-01	6.145-03	9.126-02	9.998-01	1.485+01
			9	1.107-01	1.643+00	1.995-02	2.962-01		
23	1.503-01	2.231+00	9	1.281-02	1.902-01	2.023-03	3.004-02	9.998-01	1.485+01
			10	1.375-01	2.041+00	2.478-02	3.679-01		
24	1.497-01	2.222+00	10	3.495-02	5.190-01	5.522-03	8.200-02	9.998-01	1.485+01
			11	1.147-01	1.703+00	2.066-02	3.070-01		
25	1.491-01	2.215+00	11	5.388-02	8.001-01	8.512-03	1.264-01	9.998-01	1.485+01
			12	9.526-02	1.415+00	1.717-02	2.550-01		
26	1.488-01	2.210+00	12	6.604-02	9.807-01	1.043-02	1.549-01	9.998-01	1.485+01
			13	8.277-02	1.229+00	1.492-02	2.216-01		
27	1.486-01	2.207+00	13	7.265-02	1.079+00	1.148-02	1.704-01	9.998-01	1.485+01
			14	7.599-02	1.128+00	1.370-02	2.034-01		
28	1.486-01	2.206+00	14	7.462-02	1.108+00	1.179-02	1.751-01	9.998-01	1.485+01
			15	7.396-02	1.098+00	1.333-02	1.980-01		
29	1.486-01	2.207+00	15	7.266-02	1.079+00	1.148-02	1.705-01	9.998-01	1.485+01
			16	7.597-02	1.128+00	1.369-02	2.033-01		
30	1.487-01	2.209+00	16	6.933-02	1.030+00	1.095-02	1.627-01	9.998-01	1.485+01
			17	7.939-02	1.179+00	1.431-02	2.125-01		

TABLE VI-5. Cobalt-60 Source Replenishment Schedule Showing History of Individual Source Components

(READ YEAR OF REPLENISHMENT VERTICALLY AND YEAR OF LIFE HORIZONTALLY) (SUM SHOWS NET PLAQUE ACTIVITY AT THE BEGINNING OF EACH YEAR AFTER ADDITIONS AND ANY DISCARDS)										
YEAR	1	2	3	4	5	6	7	8	9	10
1	9.998-01	8.763-01	7.681-01	6.733-01	5.901-01	5.173-01	4.534-01	3.974-01	3.483-01	3.053-01
2		1.235-01	1.082-01	9.485-02	8.314-02	7.287-02	6.387-02	5.599-02	4.907-02	4.301-02
3			1.235-01	1.082-01	9.485-02	8.314-02	7.287-02	6.387-02	5.599-02	4.907-02
4				1.235-01	1.082-01	9.485-02	8.314-02	7.287-02	6.387-02	5.599-02
5					1.235-01	1.082-01	9.485-02	8.314-02	7.287-02	6.387-02
6						1.235-01	1.082-01	9.485-02	8.314-02	7.287-02
7							1.235-01	1.082-01	9.485-02	8.314-02
8								1.235-01	1.082-01	9.485-02
9									1.235-01	1.082-01
10										1.724-01
SUM	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01

YEAR	11	12	13	14	15	16	17	18	19	20
1	2.676-01	2.346-01	2.056-01	1.802-01	1.580-01	1.385-01	1.214-01	1.064-01	9.324-02	8.172-02
2	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02	1.951-02	1.710-02	1.499-02	1.314-02	1.151-02
3	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02	1.951-02	1.710-02	1.499-02	1.314-02
4	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02	1.951-02	1.710-02	1.499-02
5	5.599-02	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02	1.951-02	1.710-02
6	6.387-02	5.599-02	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02	1.951-02
7	7.287-02	6.387-02	5.599-02	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02	2.225-02
8	8.314-02	7.287-02	6.387-02	5.599-02	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02	2.539-02
9	9.485-02	8.314-02	7.287-02	6.387-02	5.599-02	4.907-02	4.301-02	3.770-02	3.305-02	2.897-02
10	1.511-01	1.325-01	1.161-01	1.018-01	8.920-02	7.818-02	6.853-02	6.007-02	5.265-02	4.615-02
11	1.686-01	1.478-01	1.295-01	1.135-01	9.951-02	8.722-02	7.645-02	6.701-02	5.873-02	5.148-02
12		1.613-01	1.414-01	1.239-01	1.086-01	9.521-02	8.345-02	7.315-02	6.411-02	5.620-02
13			1.554-01	1.362-01	1.194-01	1.047-01	9.174-02	8.041-02	7.048-02	6.178-02
14				1.506-01	1.320-01	1.157-01	1.014-01	8.890-02	7.792-02	6.830-02
15					1.466-01	1.285-01	1.126-01	9.874-02	8.655-02	7.586-02
16						1.453-01	1.274-01	1.116-01	9.785-02	8.577-02
17							1.458-01	1.278-01	1.120-01	9.819-02
18								1.466-01	1.285-01	1.126-01
19									1.475-01	1.293-01
20										1.482-01
SUM	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01	9.998-01

TABLE VI-6. Cesium-137 Source Replenishment Schedule Showing Annual Additions and Discards

COMPONENT 1 = CS-137									
ORIGINAL COMPOSITION:									
100.00 % CS-137									
REPLENISHMENT PERIOD - ANNUAL									
PLAQUE SIZE RATIO - 2.000									
SOURCE ADDITIONS			SOURCE DISCARDS				NET SOURCE		
YEAR	MCI	KW	YEAR	ORIGINAL INTENSITY MCI	KW	DISCARD INTENSITY MCI	KW	MCI	KW
1	4.201+00	1.406+01						4.201+00	1.406+01
2	9.531-02	3.190-01						4.201+00	1.406+01
3	9.531-02	3.190-01						4.201+00	1.406+01
4	9.531-02	3.190-01						4.201+00	1.406+01
5	9.531-02	3.190-01						4.201+00	1.406+01
6	9.531-02	3.190-01						4.201+00	1.406+01
7	9.531-02	3.190-01						4.201+00	1.406+01
8	9.531-02	3.190-01						4.201+00	1.406+01
9	9.531-02	3.190-01						4.201+00	1.406+01
10	9.531-02	3.190-01						4.201+00	1.406+01
11	9.531-02	3.190-01						4.201+00	1.406+01
12	9.531-02	3.190-01						4.201+00	1.406+01
13	9.531-02	3.190-01						4.201+00	1.406+01
14	9.531-02	3.190-01						4.201+00	1.406+01
15	9.531-02	3.190-01						4.201+00	1.406+01
16	9.531-02	3.190-01						4.201+00	1.406+01
17	9.531-02	3.190-01						4.201+00	1.406+01
18	9.531-02	3.190-01						4.201+00	1.406+01
19	9.531-02	3.190-01						4.201+00	1.406+01
20	9.531-02	3.190-01						4.201+00	1.406+01
21	9.531-02	3.190-01						4.201+00	1.406+01
22	9.531-02	3.190-01						4.201+00	1.406+01
23	9.531-02	3.190-01						4.201+00	1.406+01
24	9.531-02	3.190-01						4.201+00	1.406+01
25	9.531-02	3.190-01						4.201+00	1.406+01
26	9.531-02	3.190-01						4.201+00	1.406+01
27	9.531-02	3.190-01						4.201+00	1.406+01
28	9.531-02	3.190-01						4.201+00	1.406+01
29	9.531-02	3.190-01						4.201+00	1.406+01
30	9.531-02	3.190-01						4.201+00	1.406+01

TABLE VI-7. Cesium-137 Source Replenishment Schedule Showing History of Individual Source Components

(HEAD YEAR OF REPLENISHMENT VERTICALLY AND YEAR OF LIFE HORIZONTALLY)
(SUM SHOWS NET PLANT ACTIVITY AT THE BEGINNING OF EACH YEAR AFTER ADDITIONS AND ANY DISCARDS)

YEAR	1	2	3	4	5	6	7	8	9	10
1	4.201+00	4.106+00	4.012+00	3.921+00	3.832+00	3.745+00	3.660+00	3.577+00	3.496+00	3.417+00
2		9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02
3			9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02
4				9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02
5					9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02
6						9.531-02	9.315-02	9.104-02	8.897-02	8.695-02
7							9.531-02	9.315-02	9.104-02	8.897-02
8								9.531-02	9.315-02	9.104-02
9									9.531-02	9.315-02
10										9.531-02
SUM	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00

YEAR	11	12	13	14	15	16	17	18	19	20
1	3.339+00	3.264+00	3.190+00	3.117+00	3.047+00	2.977+00	2.910+00	2.844+00	2.779+00	2.716+00
2	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02	6.912-02	6.755-02	6.602-02	6.452-02	6.306-02
3	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02	6.912-02	6.755-02	6.602-02	6.452-02
4	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02	6.912-02	6.755-02	6.602-02
5	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02	6.912-02	6.755-02
6	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02	6.912-02
7	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02	7.073-02
8	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02	7.237-02
9	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02	7.405-02
10	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02	7.577-02
11	9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02	7.753-02
12		9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02	7.933-02
13			9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02	8.117-02
14				9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02	8.305-02
15					9.531-02	9.315-02	9.104-02	8.897-02	8.695-02	8.498-02
16						9.531-02	9.315-02	9.104-02	8.897-02	8.695-02
17							9.531-02	9.315-02	9.104-02	8.897-02
18								9.531-02	9.315-02	9.104-02
19									9.531-02	9.315-02
20										9.531-02
SUM	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00	4.201+00

The results for the $^{137}\text{Cs}/^{134}\text{Cs}$ mixed source from power reactor fuel are shown in Tables VI-8 and VI-9. The activity shown in Table VI-8 is the activity of the ^{137}Cs component. The second table shows activity for both the ^{137}Cs and ^{134}Cs . Note that, unlike ^{60}Co or pure ^{137}Cs , the net source strength is not always constant at the start of each year. A constant equilibrium activity for the ^{137}Cs component is reached only after 17 years and for ^{134}Cs after 18 years.

The replenishment requirements for ^{60}Co are shown in Table VI-4 to be 0.124 MCi/yr for an initial 1.0 MCi source, or 12.4%/yr for the first 9 years. These increase to 17.2 percent when the first discard takes place and then approach an equilibrium value of 14.9 percent.

The replenishment requirements for the pure ^{137}Cs source are shown in Table VI-6 to be 0.0953 MCi/yr for an initial 4.20 MCi source, or 2.27%/yr. There is no change over the 30-year period of calculation.

The replenishment requirements for the mixed $^{137}\text{Cs}/^{134}\text{Cs}$ source are shown in Table VI-8 to decline from 0.265 MCi ^{137}Cs in year No. 2 for an initial 1.333 MCi, or 19.9 percent, to 0.192 MCi ^{137}Cs or 14.4 percent in year No. 7 when the first discard is required. This is because the portion of plaque power that is supplied by the ^{137}Cs component steadily increases. The ^{137}Cs , because of its longer half-life, does not die out as fast as the ^{134}Cs component. (If the plaque size ratio were 4.0 or larger, the replenishment requirement would decline to 0.0895 MCi ^{137}Cs in year No. 30 or 6.7 percent of the original ^{137}Cs . The plaque at that time would contain 3.49 MCi ^{137}Cs and 0.293 MCi ^{134}Cs .) In year No. 8, source additions at first increase to 0.267 MCi ^{137}Cs or 20.0 percent as discards are required to make room for replenishments. From there on, additions again decline and reach an equilibrium value of 0.244 MCi/yr or 18.3 percent at about year No. 20. The plaque at that time contains 2.385 MCi ^{137}Cs and 0.748 MCi ^{134}Cs . If the starting composition is different, the equilibrium composition would shift in the same direction also.

The subroutine RAMARK, for Radiation Market, combines the source replenishment schedule from RASOR with a market projection equation for

**TABLE VI-8. Cesium-137/134 Source Replenishment Schedule
Showing Annual Additions and Discards**

COMPONENT 1 = CS-137									
COMPONENT 2 = CS-134									
ORIGINAL COMPOSITION:									
40.50 % CS-137									
2.44 % CS-134									
ACTIVITY RATIO CS-137/CS-134 = .8858									
REPLENISHMENT PERIOD - ANNUAL									
PLAQUE SIZE RATIO - 2.000									
SOURCE ADDITIONS			SOURCE DISCARDS				NET SOURCE		
YEAR	MCI	KW	YEAR	ORIGINAL MCI	INTENSITY KW	DISCARD MCI	INTENSITY KW	MCI	KW
1	1.333+00	1.565+01						1.333+00	1.565+01
2	2.654-01	3.116+00						1.568+00	1.552+01
3	2.461-01	2.890+00						1.779+00	1.541+01
4	2.288-01	2.687+00						1.967+00	1.530+01
5	2.134-01	2.506+00						2.136+00	1.521+01
6	1.995-01	2.343+00						2.287+00	1.512+01
7	1.916-01	2.250+00	1	1.188-02	1.395-01	1.035-02	4.840-02	2.416+00	1.505+01
8	2.667-01	3.132+00	1	2.667-01	3.132+00	2.271-01	9.824-01	2.401+00	1.506+01
9	2.587-01	3.039+00	1	2.587-01	3.039+00	2.153-01	8.758-01	2.390+00	1.507+01
10	2.528-01	2.969+00	1	2.528-01	2.969+00	2.056-01	7.972-01	2.383+00	1.507+01
11	2.481-01	2.914+00	1	2.481-01	2.914+00	1.972-01	7.370-01	2.380+00	1.507+01
12	2.442-01	2.867+00	1	2.442-01	2.867+00	1.897-01	6.892-01	2.380+00	1.507+01
13	2.434-01	2.858+00	1	5.051-02	5.932-01	3.835-02	1.364-01	2.381+00	1.507+01
			2	1.029-01	2.265+00	1.498-01	5.444-01		
14	2.429-01	2.853+00	2	7.251-02	8.515-01	5.505-02	1.959-01	2.383+00	1.507+01
			3	1.704-01	2.001+00	1.324-01	4.811-01		
15	2.427-01	2.850+00	3	7.568-02	8.888-01	5.746-02	2.044-01	2.384+00	1.507+01
			4	1.670-01	1.962+00	1.298-01	4.715-01		
16	2.428-01	2.851+00	4	6.181-02	7.258-01	4.693-02	1.670-01	2.385+00	1.507+01
			5	1.810-01	2.125+00	1.406-01	5.108-01		
17	2.433-01	2.857+00	5	3.243-02	3.809-01	2.462-02	8.761-02	2.386+00	1.507+01
			6	1.995-01	2.343+00	1.550-01	5.633-01		
			7	1.127-02	1.324-01	8.961-03	3.348-02		
18	2.446-01	2.872+00	7	1.803-01	2.117+00	1.401-01	5.089-01	2.385+00	1.507+01
			8	6.430-02	7.551-01	5.111-02	1.910-01		
19	2.443-01	2.869+00	8	2.024-01	2.377+00	1.572-01	5.713-01	2.385+00	1.507+01
			9	4.188-02	4.919-01	3.329-02	1.244-01		
20	2.441-01	2.866+00	9	2.169-01	2.547+00	1.685-01	6.122-01	2.385+00	1.507+01
			10	2.721-02	3.195-01	2.163-02	8.082-02		
21	2.439-01	2.865+00	10	2.256-01	2.649+00	1.753-01	6.369-01	2.385+00	1.507+01
			11	1.831-02	2.151-01	1.456-02	5.440-02		
22	2.439-01	2.864+00	11	2.298-01	2.699+00	1.785-01	6.487-01	2.385+00	1.507+01
			12	1.404-02	1.649-01	1.116-02	4.171-02		
23	2.438-01	2.864+00	12	2.301-01	2.702+00	1.788-01	6.496-01	2.385+00	1.507+01
			13	1.372-02	1.612-01	1.091-02	4.077-02		
24	2.438-01	2.864+00	13	2.297-01	2.697+00	1.784-01	6.483-01	2.385+00	1.507+01
			14	1.420-02	1.667-01	1.128-02	4.217-02		
25	2.439-01	2.864+00	14	2.287-01	2.686+00	1.777-01	6.457-01	2.385+00	1.507+01
			15	1.513-02	1.777-01	1.203-02	4.494-02		
26	2.439-01	2.864+00	15	2.276-01	2.673+00	1.768-01	6.425-01	2.385+00	1.507+01
			16	1.629-02	1.913-01	1.295-02	4.839-02		
27	2.439-01	2.864+00	16	2.265-01	2.660+00	1.759-01	6.393-01	2.385+00	1.507+01
			17	1.743-02	2.046-01	1.385-02	5.176-02		
28	2.439-01	2.864+00	17	2.258-01	2.652+00	1.754-01	6.375-01	2.385+00	1.507+01
			18	1.808-02	2.123-01	1.437-02	5.370-02		
29	2.439-01	2.864+00	18	2.265-01	2.660+00	1.760-01	6.394-01	2.385+00	1.507+01
			19	1.739-02	2.042-01	1.382-02	5.164-02		
30	2.439-01	2.864+00	19	2.269-01	2.665+00	1.763-01	6.405-01	2.385+00	1.507+01
			20	1.700-02	1.996-01	1.351-02	5.049-02		

**TABLE VI-9. Cesium-137/134 Source Replenishment Schedule
Showing History of Individual Components**

(COMPONENT 2 SHOWN BELOW COMPONENT 1 IN EACH YEAR)

(READ YEAR OF REPLENISHMENT VERTICALLY AND YEAR OF LIFE HORIZONTALLY)

(SUM SHOWS NET PLAQUE ACTIVITY AT THE BEGINNING OF EACH YEAR AFTER ADDITIONS AND ANY DISCARDS)

YEAR	1	2	3	4	5	6	7	8	9	10
1	1.333+00 1.181+00	1.303+00 8.486-01	1.273+00 6.103-01	1.244+00 4.387-01	1.216+00 3.154-01	1.188+00 2.268-01	1.161+00 1.630-01	1.135+00 1.172-01	1.109+00 8.426-02	1.084+00 6.057-02
2		2.694-01 2.351-01	2.594-01 1.690-01	2.535-01 1.215-01	2.477-01 8.735-02	2.421-01 6.280-02	2.366-01 4.514-02	2.312-01 3.246-02	2.260-01 2.333-02	2.209-01 1.677-02
3			2.461-01 2.180-01	2.405-01 1.567-01	2.351-01 1.127-01	2.297-01 8.100-02	2.245-01 5.823-02	2.194-01 4.187-02	2.144-01 3.010-02	2.096-01 2.164-02
4				2.288-01 2.027-01	2.236-01 1.457-01	2.186-01 1.048-01	2.136-01 7.532-02	2.088-01 5.415-02	2.040-01 3.893-02	1.994-01 2.799-02
5					2.134-01 1.890-01	2.085-01 1.359-01	2.038-01 9.769-02	1.992-01 7.023-02	1.947-01 5.049-02	1.903-01 3.630-02
6						1.995-01 1.768-01	1.950-01 1.271-01	1.906-01 9.136-02	1.863-01 6.568-02	1.820-01 4.722-02
7							1.916-01 1.697-01	1.872-01 1.220-01	1.830-01 8.770-02	1.788-01 6.305-02
8								2.567-01 2.362-01	2.505-01 1.698-01	2.547-01 1.221-01
9									2.587-01 2.292-01	2.529-01 1.648-01
10										2.528-01 2.239-01
SUM	1.333+00	1.568+00	1.779+00	1.967+00	2.136+00	2.287+00	2.416+00	2.401+00	2.390+00	2.383+00

YEAR	11	12	13	14	15	16	17	18	19	20
1	1.060+00 4.355-02	1.036+00 3.131-02	1.012+00 2.251-02	9.891-01 1.618-02	9.666-01 1.163-02	9.447-01 8.363-03	9.233-01 6.013-03	9.023-01 4.323-03	8.819-01 3.108-03	8.619-01 2.234-03
2	2.156-01 1.206-02	2.110-01 8.670-03	2.062-01 6.233-03	2.015-01 4.481-03	1.969-01 3.222-03	1.925-01 2.316-03	1.881-01 1.665-03	1.838-01 1.197-03	1.796-01 8.606-04	1.756-01 6.187-04
3	2.048-01 1.556-02	2.002-01 1.118-02	1.956-01 8.040-03	1.912-01 5.780-03	1.869-01 4.156-03	1.826-01 2.988-03	1.785-01 2.148-03	1.744-01 1.544-03	1.705-01 1.110-03	1.666-01 7.981-04
4	1.949-01 2.012-02	1.905-01 1.447-02	1.861-01 1.040-02	1.819-01 7.476-03	1.778-01 5.375-03	1.737-01 3.864-03	1.698-01 2.778-03	1.660-01 1.997-03	1.622-01 1.436-03	1.585-01 1.032-03
5	1.859-01 2.610-02	1.817-01 1.676-02	1.776-01 1.349-02	1.736-01 9.697-03	1.696-01 6.972-03	1.658-01 5.012-03	1.620-01 3.603-03	1.583-01 2.590-03	1.547-01 1.862-03	1.512-01 1.339-03
6	1.779-01 3.395-02	1.739-01 2.441-02	1.699-01 1.755-02	1.661-01 1.261-02	1.623-01 9.068-03	1.586-01 6.519-03	1.550-01 4.687-03	1.515-01 3.370-03	1.481-01 2.422-03	1.447-01 1.742-03
7	1.748-01 4.533-02	1.708-01 3.259-02	1.669-01 2.343-02	1.631-01 1.684-02	1.594-01 1.211-02	1.558-01 8.706-03	1.523-01 6.259-03	1.488-01 4.499-03	1.454-01 3.235-03	1.421-01 2.326-03
8	2.449-01 8.778-02	2.433-01 6.311-02	2.378-01 4.537-02	2.324-01 3.262-02	2.271-01 2.345-02	2.220-01 1.686-02	2.169-01 1.212-02	2.120-01 8.713-03	2.072-01 6.264-03	2.025-01 4.503-03
9	2.471-01 1.185-01	2.415-01 8.516-02	2.360-01 6.123-02	2.307-01 4.402-02	2.255-01 3.164-02	2.203-01 2.275-02	2.153-01 1.636-02	2.105-01 1.176-02	2.057-01 8.443-03	2.010-01 6.077-03
10	2.471-01 1.610-01	2.415-01 1.137-01	2.360-01 8.321-02	2.306-01 5.982-02	2.254-01 4.301-02	2.203-01 3.092-02	2.153-01 2.223-02	2.104-01 1.598-02	2.056-01 1.149-02	2.010-01 8.260-03
11	2.481-01 2.198-01	2.425-01 1.580-01	2.370-01 1.136-01	2.316-01 8.167-02	2.264-01 5.871-02	2.212-01 4.221-02	2.162-01 3.035-02	2.113-01 2.182-02	2.065-01 1.568-02	2.018-01 1.128-02
12		2.442-01 2.163-01	2.386-01 1.555-01	2.332-01 1.118-01	2.279-01 8.036-02	2.227-01 5.778-02	2.177-01 4.154-02	2.128-01 2.986-02	2.079-01 2.147-02	2.032-01 1.543-02
13			2.434-01 2.156-01	2.379-01 1.550-01	2.325-01 1.114-01	2.272-01 8.011-02	2.220-01 5.759-02	2.170-01 4.140-02	2.121-01 2.977-02	2.073-01 2.140-02
14				2.429-01 2.152-01	2.374-01 1.547-01	2.320-01 1.112-01	2.268-01 7.996-02	2.216-01 5.748-02	2.166-01 4.133-02	2.117-01 2.971-02
15					2.427-01 2.150-01	2.372-01 1.546-01	2.318-01 1.111-01	2.266-01 7.989-02	2.214-01 5.743-02	2.164-01 4.129-02
16						2.428-01 2.150-01	2.373-01 1.546-01	2.319-01 1.111-01	2.266-01 7.990-02	2.215-01 5.744-02
17							2.433-01 2.155-01	2.377-01 1.549-01	2.323-01 1.114-01	2.271-01 8.006-02
18								2.446-01 2.167-01	2.390-01 1.558-01	2.336-01 1.120-01
19									2.443-01 2.164-01	2.387-01 1.556-01
20										2.441-01 2.162-01
SUM	2.380+00	2.380+00	2.381+00	2.383+00	2.384+00	2.385+00	2.386+00	2.385+00	2.385+00	2.384+00
SUM	7.498-01	7.496-01	7.491-01	7.485-01	7.479-01	7.474-01	7.472-01	7.475-01	7.477-01	7.477-01

initial source sales. It then develops a year-by-year total market requirement which includes initial sources sold each year plus replenishment requirements for all sources sold in all previous years. As can be seen from the replenishment schedules just discussed, the different initial and replenishment requirements for different source materials will result in quite different total annual curie requirements for the same basic market.

For a base market defined in terms of any given radiation source, RAMARK can apportion the market among up to three source materials and define the separate requirements for each. This capability will be discussed in more detail in Chapter VIII. For the present, only the base market calculation will be discussed.

A number of different market growth equations have been proposed and used for projection purposes. The Gompertz curve, $M = K \cdot AB^n$, where M = market, n = year and K , A , and B are constants, is one of the better known equations. The equation adopted for use in this study was as follows:⁽⁹⁾

MARKET PROJECTION EQUATION

Market:

$$M = M_0 e^{[r_\infty T + (r_0 - r_\infty)(1 - e^{-kT})/k]}$$

Growth Rate:

$$r = r_\infty + (r_0 - r_\infty)e^{-kT}$$

These equations are derived from the relationships:

$$dr/dT = -k(r - r_\infty)$$

$$dM/dT = rM$$

Where: M = market at time T
 M_0 = market at $T = 0$
 r_0 = growth rate at $T = 0$
 r_∞ = long run equilibrium growth rate
 k = rate constant.

This equation has great flexibility and, in addition, the constants have a physically significant definition, which is not generally true of other equations. It provides for a rapid initial growth rate, r_0 , which decays exponentially to a long-run equilibrium growth rate, r_∞ , which can be zero if desired. The decay of $(r_0 - r_\infty)e^{-kT}$ is analogous to the radioactive decay equation. The half-life of this rate decay can be defined as $0.693/k$.

BASE GAMMA-RADIATION MARKET PROJECTIONS

The base gamma-radiation market projections were developed in terms of ^{60}Co requirements. Starting from 2 MCi in 1970 and assuming a zero long-term equilibrium growth rate, $r_\infty = 0$, initial growth rates and rate constants were selected for RAMARK to match the 16 and 25 MCi ^{60}Co in 1980 total radiation market projections developed as "probable" and "possible" projections in the market survey.

Initial rates were found to be 25 and 35%/yr decaying with rate constants equivalent to 7-year and 6-year half-lives, respectively. Since even the higher rate is not an extravagant assumption relative to initial rates that can develop for new products, a third and higher projection was made without increasing the initial rate but using the lower rate constant and including a long-term equilibrium rate, r_∞ , of 5%/yr.

The growth rates for the three projections are plotted against calendar time in Figure VI-1 where they are identified as low, medium, and high projections. The market projections from the RAMARK printouts are shown in Table VI-10. The new-source portion of the projections are plotted in Figure VI-2 and the total market including source replenishment requirements is shown in Figure VI-3.

FIGURE VI-1. Growth Rates of New-Source Markets

^{90}Sr MARKET PROJECTIONS

Relative to the market projections for gamma sources, an equivalent effort was not made to define ^{90}Sr markets. However, the major probable customer for ^{90}Sr sources is the U.S. Navy and their estimated requirements through 1977 were used as a basis for the ^{90}Sr market projections.

Figure VI-4 shows the high, medium, and base (or low) projections developed from the Navy requirement estimates and the FY 70 and FY 71 ^{90}Sr sales from the Oak Ridge FPD. An additional 20 MCi of ^{90}Sr to be supplied by mid-1976 was under serious consideration at the time the projections were prepared.

The base point for the projections is 1 MCi in 1971. The long-term equilibrium rate was zero in all three cases. The growth rates are shown in Figure VI-5. The only difference between the medium and high case is a small increase in the rate constant for growth-rate decay in the medium case.

TABLE VI-10. Base Radiation Market Projection as ^{60}Co (MCi)

Year	Low Case			Medium Case			High Case		
	Initial Sources	Replenish-ments	Total	Initial Sources	Replenish-ments	Total	Initial Sources	Replenish-ments	Total
1970	2.00	.00	2.00	2.00	.00	2.00	2.00	.00	2.00
1971	2.54	.24	2.78	2.78	.25	3.03	2.79	.25	3.04
1972	3.14	.56	3.70	3.73	.59	4.32	3.81	.59	4.40
1973	3.82	.95	4.77	4.85	1.05	5.90	5.06	1.06	6.12
1974	4.56	1.42	5.98	6.13	1.65	7.78	6.58	1.68	8.26
1975	5.36	1.98	7.34	7.55	2.41	9.96	8.38	2.50	10.9
1976	6.19	2.65	8.84	9.10	3.34	12.4	10.5	3.53	14.0
1977	7.06	3.41	10.5	10.7	4.46	15.2	12.9	4.83	17.7
1978	7.96	4.28	12.2	12.4	5.79	18.2	15.6	6.42	22.0
1979	8.86	5.36	14.2	14.2	7.42	21.6	18.7	8.45	27.1
1980	9.77	6.57	16.3	15.9	9.30	25.2	22.1	10.9	33.0
1981	10.6	7.91	18.5	17.7	11.4	29.1	25.8	13.8	39.6
1982	11.5	9.37	20.9	19.4	13.8	33.2	29.9	17.2	47.1
1983	12.4	11.0	23.4	21.1	16.4	37.5	34.3	21.1	55.4
1984	13.2	12.7	25.9	22.6	19.3	41.9	39.1	25.6	64.7
1985	14.1	14.5	28.6	24.2	22.4	46.6	44.1	30.8	74.9
1986	14.6	16.5	31.3	25.7	25.7	51.4	49.5	36.7	86.2
1987	15.6	18.5	34.1	27.0	29.3	56.3	55.1	43.4	98.5
1988	16.3	20.8	37.1	28.3	33.1	61.4	61.1	50.8	112.
1989	17.0	23.0	40.0	29.5	37.1	66.6	67.4	59.1	127.
1990	17.6	25.5	43.1	30.6	41.3	71.9	74.0	68.3	142.

FIGURE VI-2. New-Source Radiation Market Projections as ^{60}Co

FIGURE VI-3. Total Radiation Market Projections as ^{60}Co

FIGURE VI-4. Base and High ^{90}Sr Projections from 1 MCi in 1971

FIGURE VI-5. Growth Rates for ^{90}Sr Market Projections

VII. HANFORD WASTE MANAGEMENT PRODUCTS

Construction is underway on a Waste Encapsulation and Storage Facility (WESF)^(11,12,13) for packaging and interim storage of cesium and strontium removed from Hanford fuels reprocessing wastes. Encapsulation and subsequent water basin storage activities are scheduled to begin in July 1973. As currently planned, annual production rates are to be 30 MCi each of ^{137}Cs , packaged as the chloride, and ^{90}Sr as the fluoride. This chapter outlines the scope of this project and examines possible options for making the Hanford Waste Management (HWM) sources available for industrial applications.

HANFORD WASTE ENCAPSULATION AND STORAGE FACILITY

The radioactive liquid wastes generated by chemical processing operations at Hanford during the past 25 years are stored in large underground tanks of 1/2- to 1-million gallon capacity. These wastes, together with those currently being generated, contain various fission products, including ^{90}Sr and ^{137}Cs . These two isotopes, which are currently being separated from the Hanford wastes in the B-Plant and stored in concentrated liquid form, are to be converted to strontium fluoride and cesium chloride, and then double encapsulated and stored underwater for a number of years.

The new facility is to be located adjacent to the waste fractionation plant (B Plant) on the Hanford Reservation. Design has been completed by Hanford Engineering Services, a division of Vitro Corporation. Atlantic Richfield Hanford Company (ARHCO) operates the waste fractionation plant for the AEC and will also operate the encapsulation and storage plant. The final capsules will contain about 7 lb of SrF_2 , including 150,000 Ci ^{90}Sr , or 5 1/2 lb of CsCl , including 60,000 Ci ^{137}Cs .

The new plant will be comprised of two sections: a hot cell facility and a capsule storage facility. Figure VII-1 shows a plan view of the facility and Figure VII-2 shows two partial cross-section views.

FIGURE VII-1. First Floor Plan of Hanford Waste Encapsulation and Storage Facility

CROSS SECTION OF PROCESS CELL FACILITY

CROSS SECTION OF CAPSULE STORAGE FACILITY

FIGURE VII-2. Cross Section Views of Hanford Waste Encapsulation and Storage Facility

The hot cell facility will contain six shielded cells. Three cells are 8 x 8 ft; one cell is 8 x 10 ft; one cell is 8 x 16 ft; and one cell is 8 x 18 2/3 ft. The two end cells are 13 ft 6 in. high and others are 12 ft 10 in. high. The front and rear faces of the cells will be constructed of 35 in. of high density concrete. This amount of shielding will permit handling of one megacurie of either isotope in the cells with radiation readings in the operating gallery of less than one mR/hr. Viewing of the cell will be accomplished from the operating gallery through thick lead glass windows; each window is equipped with two master-slave manipulators for performing the in-cell operations. Piping changes and valve replacements will be made using the manipulators, as will the normal processing functions such as turning valve handles, handling process filters, passing product and capsules from one cell to the other, and cleaning up. An in-cell bridge hoist is to be installed in each cell except the solid waste load-out cell, Cell A, for processing operations and maintenance.

Cover blocks will be installed over the top of each of the cells to provide access. Top entry on a routine basis will be made only in the waste cell. Solid waste from the cells will be packaged in small cans and passed down the line, cell by cell, to the waste cell where the cans will be loaded into a drum. The drum will be placed in a shielded cask and transported by truck to the solids disposal site. Originally these waste drums were to be lowered into a vertical caisson and stored underground. Now, since waste management objectives may call for a retrieval method of waste storage, current plans propose storing this waste in Cell 4 of the 221-B Building.

Both end cells (Cell "A" is the waste cell and Cell "G" is the final packaging cell) will be kept clean so as to permit manned entry through a large shielding door at the rear of each cell.

In the canyon area, the crane is operated by personnel through a series of shielding windows strategically located around the perimeter to furnish complete viewing of the canyon. The crane will be operated by remote radio controls that can be moved from window to window, as needed. A television system will be provided to assist in the more difficult areas of crane operation.

The storage area will consist of a series of water pools, each 4 1/2 x 22 by 18 ft deep. The capsules will be moved out of the final packaging cell, through a transfer chute to a submerged transfer aisle. As seen in Figure VII-2, operators working with long handled tongs will pick up the capsules and move them to a storage rack in one of the basins. During the operations, 13 ft of water cover over the capsules will be maintained to act as a shield and will protect the operators from radiation.

Two process operations will be performed in the new facility; namely, the strontium fluoride conversion and packaging process and the cesium chloride conversion and packaging process. Concentrated strontium nitrate will be transferred from B plant to the new facility for conversion to strontium fluoride. This operation and the packaging steps will be performed in the hot cells. Strontium processing will be performed on a batch basis, handling up to 150,000 Ci/batch. In the cesium process, the feed is transferred from B plant as a concentrated cesium carbonate solution into a metering tank, on the basis of about 480,000 Ci/batch. The two processes are described schematically in Figure VII-3 and VII-4.

The cesium process is particularly simple. Hydrochloric acid is added slowly to convert the cesium carbonate to cesium chloride. The reaction is carried on at ambient pressure and is exothermic. The cesium chloride solution is transferred to a melt pot in which the cesium chloride is evaporated to dryness and then melted at 675°C. The melt pot will be fabricated of 18-18-2 stainless steel and an inert gas purge will be used to minimize the oxidation of the metal. The molten cesium chloride will be transferred by vacuum through heated lines to stainless steel capsules in which the salt will solidify to form a cesium chloride "slug". A cap is then welded on the filled capsule; it is weighed, leak tested and decontaminated. This capsule is then placed in an outer container of stainless steel and a cap is welded on and a final weld check performed.

In the strontium process, sodium fluoride is added to convert the strontium nitrate to sodium fluoride. The reaction is relatively rapid and conducted at moderate temperature. The strontium fluoride slurry is filtered by drawing it by vacuum through sintered-stainless-steel filter elements.

CESIUM CHLORIDE CONVERSION PROCESS

STRONTIUM FLUORIDE CONVERSION PROCESS

FIGURE VII-3. Chemical Conversion Processes in the WESF

FIGURE VII-4. Encapsulation Processes in the WESF

Then air is drawn across the filter cake which, due to its self-heating characteristics, dries and falls from the filter when tilted. The cake is sintered in an electric furnace and the sintered strontium fluoride is then packed into Hastelloy-C-276 capsules using an air powered compactor. From there on the sealing and double encapsulation process is like the cesium encapsulation except that the outer capsule is also Hastelloy-C-276.

The outer diameters of both the inner and outer capsules, 2.250 in. and 2.625 in., are the same for both cesium and strontium. There are small differences in the inside diameters, 2.060 and 2.407 in. for cesium and 2.010 and 2.385 in. for strontium. The overall outside length of the cesium capsules is slightly longer than the strontium capsules; 20.775 in. compared to 20.100 in. The cesium capsules will hold 60,000 Ci of ^{137}Cs while the strontium capsules will hold 150,000 Ci of ^{90}Sr .

The heat output of each capsule is determined by calorimetry to identify the actual radioisotope content for handling purposes. The capsule is then ready for storage in the water pool. Underwater storage is used for purposes of cooling and provides a shielding barrier while permitting visual observation of the stored capsules.

The capsules will be kept here until the radioactive level has decayed sufficiently to permit safe storage at a permanent site. The temperature and activity level of the water will be monitored continuously.

OPTIONS FOR SALES TO INDUSTRY

With the decision made to separate and encapsulate highly refined fission-product cesium and strontium for waste management purposes, it has naturally occurred to those interested in fostering the utilization of this by-product resource to suggest that these capsules be made available for industrial applications. A number of possible optional ways which these capsules might be utilized have been examined. The options that are believed to merit consideration are first defined and discussed in a qualitative way and then the major alternatives are definitively analyzed.

Alternatives or options that merit consideration for marketing the HWM ^{137}Cs sources to industrial users are shown schematically in Figure VII-5.

FIGURE VII-5. Marketing Alternatives for HWM ^{137}Cs

1. The standard HWM capsules could be sold "as is" to radiation users. The radiation utilization would be inefficient because of the high self-absorption in the large capsules (approximately 50 percent) but if the selling price were discounted accordingly, they would be satisfactory source capsules. They also limit the flexibility of plaque design because of the large amount of activity in a single capsule and no ability to provide other than a single specific source activity. This option has the strong advantage of requiring no further processing and a minimum AEC involvement.
2. The standard HWM capsules could be sold "as is" at a discounted price for quantity purchases to a private marketing organization, who would in turn market them to the radiation users. This arrangement has the advantage of simplifying the AEC's involvement because

of dealing with fewer customers and at the same time provides an incentive for a private organization to promote the utilization of these sources.

Furthermore, the marketing organization could provide technical and design services related to irradiator design installation and operation which may be very important to the radiation processor. The radiation processors will not necessarily have competency on their staff to make optimum selection or use of an irradiator. One of the points emphasized in discussions with radiation users regarding their selection of a source of supply was the matter of their confidence in the competency and stability of their supplier. One possibility would be for one or more of the fuel reprocessors to enter the radiation-source supply business at minimum cost and risk by marketing the HWM sources as a preliminary step towards establishing a fission product recovery operation.

3. By installing a hollow sealed tube in the center of the capsule prior to filling, the standard HWM capsules can be very simply modified to reduce the number of curies contained in a capsule and also reduce the proportion of radiation lost through self-absorption.
4. The modified standard HWM capsule with an insert could also be made available with quantity discounts for resale by a private marketing organization as in the second option. This may or may not be practical depending on decisions on how costs are allocated by the AEC.
5. Special source capsules designed as radiation sources could be fabricated in the WESF facility. This option has the advantage of providing more efficient utilization of the radiation by reducing self-absorption and raising the value of the contained ¹³⁷Cs. Preliminary analysis indicates this option would probably be limited to relatively small quantities, because costs would exceed benefits with large-scale production. For this reason, it is not shown as an option for the private marketing organization.

6. The HWM capsules could be sold "as is" and re-encapsulated into more nearly optimum source capsule in a private re-encapsulation facility. Analysis of this option has shown that it is probably feasible only if most of the required facilities are already in place (existing hot cells). The requirement for a private marketing organization is inherent in this option. The marketing organization could, however, be an integral component of the re-encapsulation organization.

To assist in evaluating these various options ARHCO was requested to supply the following cost information:⁽¹⁴⁾

- Detailed breakdown at the estimated annual capacity of operating costs for producing cesium capsules of the present design.
- The incremental operating costs for producing cesium chloride capsules with an inert insert occupying one-fourth of the cesium volume with the external capsule dimensions to be identical to present design at rates of 10 and 100 capsules annually.
- The incremental costs for fabricating one-inch diameter cesium chloride capsules (nominally, one-fourth of the cesium chloride volume in the present design capsules at a rate of 40 capsules per year and at a rate of 400 capsules per year.
- The estimated cost of loading one present design capsule into a shipping cask and loading and unloading the cask from a truck or railroad car; the same estimate for 9 capsules, for 4 one-inch diameter capsules, and for 36 one-inch diameter capsules.
- The estimated cost and method of the disposal of high level cell waste.

This information was supplied in an ARHCO report, ARH-2101⁽¹⁵⁾, and supplemented by information obtained in discussions with the author.

COST OF STANDARD HWM CAPSULES

Annual operating costs estimated by ARHCO⁽¹⁵⁾ for the WESF are shown by major categories and totals in Table VII-1. The unit cost per capsule and per curie is also shown. The out-of-pocket costs are the direct costs including employee benefits. The full cost includes all present overhead charges. The details of the manpower allocation and costs are shown in Table VII-2.

Capsule cask-loading was estimated to be \$2300/cask-loading, whether one or nine HWM capsules are loaded and whether four or 36 one-inch capsules are loaded.

TABLE VII-1. ARHCO Estimate for Annual Operating Cost
Waste Encapsulation and Storage Facility

	<u>Strontium</u>		<u>Cesium</u>		<u>Total</u>	
	<u>Out-of-Pocket Cost</u>	<u>Full Cost</u>	<u>Out-of-Pocket Cost</u>	<u>Full Cost</u>	<u>Out-of-Pocket Cost</u>	<u>Full Cost</u>
Manpower	\$ 270,000	\$ 754,000	\$ 305,000	\$ 846,100	\$ 575,000	\$1,600,000
Chemicals	2,300	3,800	4,000	6,600	6,300	10,400
Utilities	18,600	36,500	17,400	33,900	36,000	70,400
Capsules	87,400	144,000	47,500	78,400	134,900	222,400
Liquid Waste Processing	300	1,725	100	540	400	2,265
Miscellaneous	30,700	50,600	24,500	40,500	55,200	91,100
Total Costs Rounded	\$410,000	\$1,000,000	\$400,000	\$1,010,000	\$ 810,000	\$2,010,000
Total Cost Per Capsule	\$ 2,050	\$ 5,000	\$ 800	\$ 2,020		
Total Cost Per Curie	\$ 0.014	\$ 0.033	\$ 0.013	\$ 0.034		

TABLE VII-2. Manpower Cost - Waste Encapsulation and Storage Facility

	Strontium			Cesium			Totals		
	Number of Men	\$1000's		Number of Men	\$1000's		Number of Men	\$1000's	
		Out-of-Pocket	Full Cost		Out-of-Pocket	Full Cost		Out-of-Pocket	Full Cost
Processing									
Operators	10.8	130	429	13.2	158	521	24	288	950
Specialist	0.5	7.5	24.8	0.5	7.5	24.8	1	15	49.6
Supervision	2.3	34	--(a)	2.7	41	--(a)	5	75	--(a)
	<u>13.6</u>			<u>16.4</u>			<u>30</u>		
Maintenance									
Millwright	1	12	39.6	1	12	39.6	2	24	79.2
Instrument	0.5	6	19.8	0.5	6	19.8	1	12	39.6
Electrician	0.5	6	19.8	0.5	6	19.8	1	12	39.6
Pipefitter	0.5	6	19.8	0.5	6	19.8	1	12	39.6
Other	0.5	6	19.8	0.5	6	19.8	1	12	39.6
Supervision	0.5	7.5	--(a)	0.5	7.5	--(a)	1	15	--(a)
	<u>3.5</u>			<u>3.5</u>			<u>7</u>		
Services									
Process Control									
Engr.	0.5	7	23.1	0.5	7	23.1	1	14	46.2
Radiation									
Monitor	2.0	24	79.1	2	24	79.1	4	48	158.2
Analytical Lab.	2.0	24	79.1	2	24	79.1	4	48	158.2
Totals	<u>21.6</u>	<u>270</u>	<u>754</u>	<u>24.4</u>	<u>305</u>	<u>846</u>	<u>46</u>	<u>575</u>	<u>1,600</u>

(a) Supervision full-cost is included in labor full-cost.

Encapsulation costs on a full cost recovery basis which includes a 15 percent AEC service charge, a depreciation charge at 6 percent of capital per year and a cask-loading charge of 0.4¢/Ci (nine HWM capsules) are shown in Table VII-3. The full cost FOB Hanford is shown to be essentially the same for either strontium or cesium at 5.3 and 5.4¢/Ci.

TABLE VII-3. HWM Encapsulation Costs (¢/Ci)

ARHCO Costs	⁹⁰ Sr	¹³⁷ Cs
Out of Pocket		
Labor	0.9	1.02
Other	0.46	.32
Sub-total	<u>1.36</u>	<u>1.34</u>
Overhead		
Labor	1.62	1.80
Other	.35	.23
Sub-total	<u>1.97</u>	<u>2.03</u>
Total ARHCO	3.33	3.37
AEC Costs		
15% Service	0.50	0.50
Depreciation at 6%/year	1.08	1.08
Total for Full Cost Recovery	<u>4.91</u>	<u>4.95</u>
Cask Loading	0.4	0.4
Total FOB Hanford Cost	5.3	5.4

The possibility of a shipping cost disadvantage for the HWM sources relative to ⁶⁰Co supplier and user locations has not been evaluated, but it should not be greater than about 1¢/Ci.

The value of the HWM ¹³⁷Cs has been shown to be about 8¢/Ci relative to ⁶⁰Co at 40¢/Ci.

This leaves only 2 1/2¢/Ci for marketing costs and transport disadvantage costs if the capsules could be purchased on a full cost recovery basis. This is equivalent to \$25,000/MCi which, considering the present size of the ¹³⁷Cs market, is not an excessive marketing effort for a megacurie of sales.

Thus a reasonable policy would be to sell the standard capsules on a large volume basis, say greater than 2×10^6 Ci, at no more than full cost recovery, but in smaller lots the price could be closer to its full market value of around 8¢/Ci.

COST OF HWM CAPSULES WITH INSERTS

Cost estimates were developed by ARHCO⁽¹⁵⁾ for the production of capsules with either one-inch diameter inserts or 1 1/2 inch diameter inserts. The ARHCO report stated: "Either type is considered feasible for production in annual quantities of 10 or 100 without additions to the planned work force or modifications to the equipment as now designed." A capital outlay of \$1000 was estimated to be required for a beam balance to weigh the capsules after filling. The estimates are shown in Table VII-4 and indicate no difference in unit costs for 10 or 100 capsules.

TABLE VII-4. ARHCO Estimate for Annual Operating Costs
for HWM Capsules with Inserts

Insert Diameter	<u>1 In.</u>		<u>1 1/2 In.</u>	
Number of Capsules per year	10	100	10	100
MCi ¹³⁷ Cs/yr	0.46	4.6	0.28	2.8
Out-of-Pocket Cost				
Net Labor, \$	3,050	30,500	3,660	36,600
Capsule, \$	510	4,900	880	8,600
Total, \$	3,560	35,400	4,540	45,200
\$ / Capsule	356	354	454	452
\$ / Ci	0.8	0.8	1.6	1.6
Full Cost				
Net Labor, \$	8,460	84,600	10,200	102,000
Capsule, \$	840	8,000	1,400	14,000
Total, \$	9,300	92,600	11,600	116,000
\$ Capsule	930	926	1,160	1,160
¢ / Ci	2.0	2.0	4.2	4.2

The operating cost estimates were said to "represent net operating costs for the special source production above the normal waste management encapsulation of an equivalent amount of ^{137}Cs ." However, they are not incremental costs and include a large proportion of allocated costs that represent a share of labor and overhead costs that would be incurred whether or not special capsules were produced. "Out-of-pocket" costs do not mean additional cash costs since they are mostly labor costs, yet no additional staff is required. Because of this, the actual incremental cost would be more nearly represented by the "out-of-pocket" estimate without the labor component.

An estimate of the increased value of the capsules and contained ^{137}Cs was prepared, based on the reduced self-absorption of the gamma energy. The reduced gamma-ray self-absorption is shown in Figure VII-6 where it is compared with the relative capsule capacity. Although the reduced self-absorption is not very great, it does have a significant effect on the value of contained ^{137}Cs as shown in Figure VII-7. This plot also shows how the capsule contents vary with size of the insert. The increased value is 0.3¢/Ci for a one-inch diameter insert and 0.7¢/Ci for a 1.5-inch diameter insert. In terms of \$/capsule value, the maximum value increase is in the range of a 1.5 to 1.7-inch diameter insert. Even though the increased value is significant, it is substantially less than even the "out-of-pocket" cost as estimated by ARHCO in Table VII-4.

A full cost recovery estimate on the basis of the actual incremental cost discussed above is shown in Table VII-5. Here the inserts show a small net advantage, even when the overhead associated with the incremental cost is included. This type of capsule offers very little gain in terms of higher value, but it does provide a simple inexpensive way to provide a range of alternative lower-intensity capsules with the increased capsule cost offset by the increased value of the source material.

The insert-capsules show enough promise that they should be more closely evaluated. The AEC would benefit from an incremental cost policy along the

FIGURE VII-6. Effect of Inert Capsule Insert on Self-Absorption and Relative Capsule Capacity

FIGURE VII-7. Relationship Between Increased Value of Encapsulated ^{137}Cs and Capsule Capacity with Inert Insert in Capsule

lines suggested in Table VII-5. There is no advantage to anyone when costs that are going to be incurred in any event are loaded into the charges for special capsules. If all actual increased costs are recovered and if increased flexibility to meet radiation user requirements is provided, the AEC objective of fostering increased isotope uses would be served.

TABLE VII-5. Costs for Special HWM ^{137}Cs Capsules with Inserts, ¢/Ci (Allocated Labor Costs Excluded)

<u>ARHCO Costs</u>	<u>1-inch Dia Inserts</u>	<u>1 1/2-inch Dia Inserts</u>
Out-of-Pocket	0.11	0.31
Overhead	0.07	0.19
Total ARHCO	<u>0.18</u>	<u>0.50</u>
 <u>AEC Costs</u>		
15% Service	0.03	0.08
Depreciation	0.01	0.02
Total AEC	<u>0.04</u>	<u>0.10</u>
Total Incremental	0.2	0.6
Full Cost for Standard HWM Capsule	5.0	5.0
Cask Loading	0.4	0.4
Total FOB Hanford Cost	5.6	6.0

COST OF SPECIAL ONE-INCH HWM CAPSULES

Cost estimates were also developed by ARHCO⁽¹⁵⁾ for producing special one-inch diameter capsules. The capsule design was one-inch outside diameter with a 32-mil wall sealed in a 1 1/8 inch O.D. outer capsule, also with a 32-mil wall. Capsule capacity would be 13,600 Ci ^{137}Cs . An estimated \$84,000 would be required for capital items to produce the special capsules.

The operating cost estimates are shown in Table VII-6. Costs were estimated for producing 40 and 400 one-inch capsules per year either all in one campaign or in intermittent batches of only 10 capsules at a time. These costs are "net operating costs" on the same basis as the insert-capsule estimates. The ARHCO report also stated: "Forty capsules can be produced in successive or intermittent batches annually without increasing the plant work force. To produce 400 capsules annually, however, it would be necessary to increase the work force by 30 to 40 percent, ...".

The one-inch capsules increase the value of the contained ^{137}Cs by approximately 38 percent because of reduced self-absorption of the gamma rays. This would increase the value of the cesium from 8¢/Ci to 11¢/Ci. However, the 3¢/Ci net increase would barely meet the ARHCO estimated "out-of-pocket" cost for the lowest cost case, 400 capsule/yr in one campaign.

TABLE VII-6. ARHCO Estimate for Annual Operating Costs for Special 1-Inch Diameter ^{137}Cs Capsules

Production Mode	One Campaign		Intermittent	
Capsules per Year	40	400	40	400
MCi ^{137}Cs /yr	0.544	5.44	0.544	5.44
Out-of-Pocket Cost				
Net Labor, \$	24,400	146,000	30,500	218,000
Capsules, \$	6,400	23,400	6,400	23,400
Total, \$	30,800	170,000	36,900	242,000
\$/Capsule	770	425	920	605
¢/Ci	5.7	3.1	6.8	4.5
Full Cost				
Net Labor, \$	67,600	482,000	84,600	720,000
Capsules, \$	10,500	38,600	10,500	38,600
Total, \$	78,100	521,000	95,100	759,000
\$/Capsule	1,950	1,300	2,480	1,900
¢/Ci	14.4	9.6	17.5	14.0

As in the case of the insert-capsules, the actual incremental cost at the 40 capsules/yr level would be more nearly represented by the "out-of-pocket" estimate without the labor component since additional operating staff is not required. A full cost recovery estimate on this basis is shown in Table VII-7.

It would be appropriate to offer this option up to the point where additional operating staff would be required, approximately 0.8 MCi/yr. Since the upper limit on production is relatively low, this option is probably not one that would provide enough incentive for a private marketing organization (Figure VII-5) to promote.

TABLE VII-7. Costs for Special 1-Inch Diameter HWM Capsules, ¢/Ci (Allocated Labor Costs Excluded)

Production, MCi/yr	0.5	0.8 ^(a)
<u>ARHCO Costs</u>		
Out-of-Pocket	1.18	1.18
Overhead	0.75	0.75
	<u>1.93</u>	<u>1.9</u>
<u>AEC Costs</u>		
15% Service	0.3	0.3
Depreciation	1.0	0.6
	<u>1.3</u>	<u>0.9</u>
Total Incremental	3.2	2.8
Full Cost for Standard HWM Capsule	5.0	5.0
Cask Loading	0.4	0.4
Total FOB Hanford Cost	8.6	8.2

a. The 0.8 MCi/yr production is the estimated maximum possible without additional staff.

PRIVATE RE-ENCAPSULATION FACILITY

Both capital and operating cost estimates were developed for a private facility to take the standard HWM ^{137}Cs capsules and re-encapsulate them in a more nearly optimum size. The principal incentives would be the value enhancement for the contained ^{137}Cs and production of capsules designed for use as radiation sources.

The conceptual re-encapsulation process is quite simple. The standard HWM capsules are refabricated by remelting and casting into smaller molds. The CsCl_2 slugs are double encapsulated in the conventional manner. This process is shown schematically in Figure VII-8.

FIGURE VII-8. Cesium Re-encapsulation Process

The process could probably be carried out in existing hot cell facilities, such as those at General Electric Company's Vallecitos Laboratory, the Lockheed-Georgia Nuclear Laboratory at Dawsonville, Georgia, or Westinghouse facilities at Waltz Mill, Pennsylvania. If a new facility were to be built for this purpose, there would be advantages related to waste handling and disposal and the availability of other services for locating near a reprocessing facility such as Hanford (Washington State), Nuclear Fuel Services (New York State), or the Allied/Gulf Plant (South Carolina).

A preliminary design was prepared representing the minimum facility requirements. Figure VII-9 shows the floor plan and a sketch of an exterior view is shown in Figure VII-10. A capital cost estimate was prepared with the assistance of Vitro, Hanford Engineering Services. This estimate totaling \$1.8 million is summarized in Table VII-8. The escalation allowance is less than for the Cs/Sr recovery facility, because it was assumed to be built for 1974 operation. The escalation allowance, as with the Cs/Sr facility, is intended to represent net construction cost escalation over and above general cost escalation.

FIGURE VII-9. Cesium Re-encapsulation Facility - Floor Plan

FIGURE VII-10. Cesium Re-encapsulation Facility

TABLE VII-8. Cesium Re-encapsulation Facility
Capital Cost Estimate

Architectural and Structural	\$ 250,000
Hot Cell Construction	200,000
Manipulators	70,000
Process and Hot Cell Equipment	300,000
Additions for Grass Roots Plant	40,000
Home Office and Field Expense	215,000
Total Construction	\$1,075,000
Engineering and Design	270,000
Contingency 30%	320,000
Escalation 10%	110,000
	\$1,775,000
	Rounded to \$1,800,000

Operating cost estimates were prepared for one, two, and three shifts, five days per week, and for full round-the-clock seven days per week operation. These estimates were based on the sequence of operations shown in Table VII-9 for fabricating four one-inch diameter capsules, 15,000 Ci each, from standard HWM capsules. The operating crew would consist of two operators and a shift supervisor who would also handle radiation monitoring. Minor process maintenance would be handled by the process operators and major maintenance would be by contract.

The operating cost estimates are shown in Table VII-10. In preparing these estimates it was assumed that the time operating efficiency was 40 percent at the one-shift/day level increasing to 50 percent at a three-shift/day level. The direct applied manhours of work was estimated at only 20 percent of total operator (two men/shift) time for one-shift/day and 25 percent at three-shifts/day. Thus it should be possible to increase production capability. For this reason a learning effect was incorporated in the variable portion of the operating cost. The unit costs at the bottom of Table VII-10 show how this affects the unit operating cost. The operating cost equation developed from these estimates was as follows:

$$\text{Operating Cost} = 0.028 \times \text{Capital Cost} + \frac{4.4 \text{ ¢/Ci}}{(P/P_{\infty})}$$

where P/P_{∞} is the learning ratio described in Chapter IV. For this application, $P_{\infty}/P_0 = 2.0$ and $k = 0.35$.

This is the relationship used in the next section to develop re-encapsulation costs. It is intended to be optimistic; an organization undertaking this job would probably have to stretch in every respect to meet this schedule, but that would not be unusual for a small organization attempting to break into a new field.

It is worth comparing the man-hour requirements for the basic estimate with those derived from the estimates for standard HWM capsules for insert capsules and for re-encapsulation in one-inch capsules in the WESF facility.

TABLE VII-9. Operation at CsCl_2 Capsule Refabrication PlantOperation

- 1 Railroad car or truck arrives at unloading station.
- 2 Crane is attached to cask - cask contains four large HWM capsules.
- 3 Crane transports cask to storage well.
- 4 Bolts removed from lid of cask under water.
- 5 Cask lid is removed under water.
- 6 Capsules transferred into the clean cell using underwater transfer system and capsules placed in storage.
- 7 One capsule at a time is taken from storage and transferred to the contaminated cell using sphincter seal-jack arrangement.
- 8 Capsule is positioned in pipe cutter, and inner and outer end caps are removed from one end. End caps go to waste storage.
- 9 Capsule placed in melting furnace, open-end down.
- 10 CsCl_2 is melted and gravity cast into 1-inch diameter molds.
- 10a Old capsule can is placed in waste storage.
- 11 Molds are disassembled from feeding device, weighed, and inspected for completeness of filling.
- 12 Mold is transferred to clean cell transfer, packed and placed in transfer mechanism.
- 12a Clean can is placed under transfer port.
- 12b Transfer port is opened.
- 13 CsCl_2 slug is slipped through transfer port into a clean can.
- 13a Mold is reassembled to feeding device for next casting.
- 13b Transfer port is sealed.
- 14 A temporary cap is placed on capsule. Capsule is transferred to weld area.
- 15 Capsule is welded shut. Capsule is leak tested, ultrasonic inspected, weighed, and measured by calorimetry.
- 16 Capsule is inserted into a second can and welded shut.
- 17 Decontamination, if necessary, and identification.
- 18 Transfer to storage.
- 19 Sixteen 1-inch capsules loaded into cask in reverse process to unloading cask.

TABLE VII-10. ^{137}Cs Re-encapsulation Operating Cost Estimate

Number of Shifts	1	2	3	4
Production, MCi/yr	2.4	5.2	8.7	12.6
1. Labor				
Operators @ \$4.7/yr	18,900	37,800	56,700	85,000
Supervision @ \$5.9/hr	<u>11,800</u>	<u>23,600</u>	<u>35,400</u>	<u>47,200</u>
Total	30,700	61,400	92,100	132,200
2. Maintenance ^(a)				
3% of Capital $\times \left(\frac{\text{Production}}{\text{Capacity}} \right)$	10,300	22,300	37,300	54,000
25% of Labor	<u>7,700</u>	<u>15,400</u>	<u>23,000</u>	<u>33,000</u>
Total	18,000	37,700	60,300	87,000
3. Administration and Plant Overhead including employee benefits				
25% of Labor, plus	7,700	15,400	23,000	33,000
100% of Labor & Maintenance	<u>48,700</u>	<u>99,100</u>	<u>152,400</u>	<u>219,200</u>
	55,400	114,500	175,400	252,200
4. Utilities @ \$500/MCi/yr	1,200	2,600	4,400	6,300
5. Waste Disposal	3,300	7,100	11,900	17,300
6. Capsules & Misc. Materials @ \$100/capsule	16,000	35,000	58,000	84,000
7. Local Taxes & Insurance @ 2% of Capital Cost	36,000	36,000	36,000	36,000
8. Total Manufacturing Cost				
\$/yr	160,600	294,300	438,100	615,000
¢/Ci	6.69	5.66	5.03	4.88
After 5 yrs ¢/Ci	4.81	3.65	3.10	2.92

a. Assumes operators will handle minor process maintenance.

These comparisons are shown in Tables VII-11 and 12. The labor allocation for the insert-capsules in particular appears excessive. After a period of shakedown, the WESF capacity may turn out to be significantly greater than the design capacity.

TABLE VII-11. Comparison of Estimated Man-Hour Allocations for ^{137}Cs Encapsulation Alternates (Man-hours per Capsule)

	<u>Processing</u>	<u>Maintenance</u>	<u>Services</u> ^(a)	<u>Total</u>
Standard HWM Capsule	65.6	14.0	19.5	97.6
Net Allocation for				
1-inch Insert	33	8	10	51
1 1/2-inch Insert	40	9	12	61
Net Allocation for Special 1-inch Capsules				
At 40 per year	83	19	25	127
At 400 per year	59	14	18	91
Separate Re-encapsulation Facility Estimate				
1 Shift 5 days/week	38 ^(b)	10 ^(c)	(d)	48
3 Shifts 7 days/week	31 ^(b)	8 ^(c)	(d)	39

a. Process Control Engineering, Radiation Monitoring, and Analytical Lab

b. Includes Radiation Monitoring

c. Contract maintenance

d. Except for Radiation Monitoring, services are included in overhead.

TABLE VII-12. Estimated Man-hour Allocations for ^{137}Cs Encapsulation Alternates (Man-hours per 1000 Ci)

	<u>Processing</u>	<u>Maintenance</u>	<u>Services</u>	<u>Total</u>
Standard HWM Capsule	1.1	0.2	0.3	1.6
Net Added for				
1-inch Insert	0.7	0.2	0.2	1.1
1 1/2-inch Insert	1.4	0.3	0.4	2.2
Net Added for Special 1-inch Capsules				
At 40 per year	6.1	1.4	1.8	9.3
At 400 per year	4.4	1.0	1.3	6.7
Separate Re-encapsulation Facility Estimate				
1 Shift 5 days/week	2.5	0.7	--	3.2
3 Shifts 7 days/week	2.1	0.5	--	2.6

SPECIAL STRONTIUM CAPSULES

Preparation of special strontium capsules for sale to the Navy for loading into radioisotope power generators for deep ocean implant purposes is under consideration.⁽¹⁶⁾ Several options are being considered for producing these capsules either as strontium dititinate or strontium fluoride. Whatever option is finally decided upon it appears that the capsules could be produced on a full cost recovery basis for around 10¢/Ci in the WESF facility.

CONCLUSIONS

The cost of producing the standard HWM cesium capsules and the alternative "special" capsules in limited quantities are compared in Table VII-13 with their value relative to ⁶⁰Co. The costs are based on full cost recovery to the AEC, with the costs for the "special" capsules based on the actual incremental costs as previously described. The estimated minimum cost for producing new capsules in private facilities is also shown, but this alternative is examined in greater detail in the next chapter. The following conclusions were reached regarding sale of the HWM capsules:

TABLE VII-13. Comparison of Cost and Value
of HWM Cesium Marketing Options

	Standard HWM Capsules	Standard HWM Capsules With Inserts		Special 1-Inch Capsules	New Capsules Produced In Private Facilities
		1-Inch Insert	1 1/2-Inch Insert		
Production Capability, MCi/yr	Up to 30	>4.6	>2.8	<0.8	2.4 and up
Cost Based on Full-Cost Recovery to the AEC, ¢/Ci	5.4	5.6	6.0	8.2	>8.4 plus capital charges
Value Relative to ⁶⁰ Co at 40¢/Ci, ¢/Ci	8.0	8.3	8.7	11.0	11.0
Difference Between Cost and Value, ¢/Ci	2.6	2.7	2.7	2.8	<2.6

1. The standard HWM capsules should be offered in quantities less than 2 million curies at their full market value of about 8¢/Ci for ^{137}Cs and 10¢/Ci for ^{90}Sr .
2. These standard capsules should be offered for large quantity purchases of 2 million curies or more at no more than a full-cost-recovery price (5.4¢/Ci). The difference between acquisition cost and market value provides a reasonable incentive for large-scale marketing efforts, and it also allows the possibility of private-facility re-encapsulation into more optimum-sized source capsules.
3. To give all possible encouragement to useful applications of the HWM cesium capsules, modified capsules with hollow inserts that would reduce the number of curies per capsule should be offered as an optional capsule as long as production can be handled without additional staff. In small quantities of 8.3 to 8.7¢/Ci the price should be based on full market value.
4. The same capsules (with inserts) should be offered in large quantities, 2 million curies or more at a minimum full-cost-recovery price of 5.6 to 6.0¢/Ci.
5. Special cesium capsules, such as 1-inch diameter capsules, should be offered in small quantities at their full market value of about 11¢/Ci; that is, as long as additional staff would not be required.
6. The large-scale re-encapsulation of the HWM cesium in private commercial facilities is indicated to be a possibility if the standard HWM capsules can be acquired at no more than a full-cost-recovery price.
7. Once the WESF facility starts up, the actual production costs should be carefully analyzed and policies modified or confirmed accordingly.

VIII. ANALYSIS OF A SIMULATED TWO-PHASE FISSION PRODUCT INDUSTRY

The results of the exploratory calculation of pricing requirements for cesium and strontium recovery from power reactor fuels discussed in Chapter IV demonstrated quite conclusively that a substantial growth in markets would be required before such recovery would be feasible. The value of power reactor cesium was shown in Chapter V to be enhanced very substantially by its ^{134}Cs component so that feasible cost-price/value relationships can be visualized at reasonably foreseeable market demands. Reasonable prospects for growth in the markets for gamma radiation sources, including both ^{137}Cs and ^{60}Co , were shown in Chapter VI. The possibility of marketing both cesium and strontium recovered for waste management purposes at Hanford at prices that would represent both full cost recovery to the government and competitive market values was shown in Chapter VII. The next and final step in this study was to explore the possibility of marketing the HWM cesium and strontium in a way that would result in the market for these materials growing to the size where private recovery from power reactor fuels would be feasible.

A series of cases were prepared simulating the development of a ^{137}Cs and ^{90}Sr recovery industry where the gradually developing market is first supplied from Hanford waste management cesium and strontium resources (Phase I). After this, a private reprocessor commences recovery when the market has grown large enough to justify the required large investment (Phase II). From the preceding discussions it should be obvious that there are many variables in this problem that cannot be reduced to a single value. By exploring the effect of these variables as ranges, the important and less important variables are identified and the overall uncertainty in the final conclusions is reduced to a relatively low level.

OBJECTIVES

The basic objective of this simulation was to identify AEC policies that would be most appropriate for fostering eventual private recovery and marketing of cesium and strontium from power reactor fuel reprocessing. The principal questions of interest were as follows:

Phase I - Marketing of HWM Cesium and Strontium

1. Is the re-encapsulation of HWM cesium in private facilities to produce more nearly optimum radiation sources a real possibility?
2. Could such a Phase I processor stay in business long enough to be profitable?
3. How would a Phase I processor be displaced by a Phase II processor?

Note: Re-encapsulation of HWM strontium was not considered but may be a possibility if HWM strontium capsules are not satisfactory heat source capsules.

Phase II - Recovery and Marketing of Power Reactor Cesium and Strontium

1. How does availability of HWM materials affect prospects for Phase II processing?
2. When will markets be large enough to justify Phase II processing?
3. What choices relative to the viability of Phase I and Phase II processing does the AEC have for phasing out the availability of HWM sources?

PROCEDURE

The computer programs already described in Chapters IV and VI were combined as a single program to carry out the simulation calculations. This is shown schematically in Figure VIII-1.

Because of the difference in gamma radiation energy output between pure ^{137}Cs (HWM cesium) and $^{137}\text{Cs}/^{134}\text{Cs}$ mixtures (power reactor cesium), the requirements in terms of ^{137}Cs curies will be quite different for these two materials, even when they are supplying exactly the same market. The requirement in terms of ^{60}Co is different from either cesium source. This difference is illustrated in Figure VIII-2. Here initial source and total

FIGURE VIII-1. Computer Program for Two-Phase Industry Simulation

FIGURE VIII-2. Equivalent Market Comparisons for Three Different Radiation Sources

requirements, including replenishments, for these three materials are compared when each supplies a market equivalent to a ^{60}Co market growing from 0 to 10 MCi/yr over a 10-year period. To illustrate further, when reference is made to ^{137}Cs supplying some fraction of a market which is expressed as curies of ^{60}Co , the equivalent ^{137}Cs requirement is not obvious without a calculation based on initial source and replenishment requirements. RASOR and RAMARK, were described in part in Chapter VI. However, the description of how RAMARK apportions the market was deferred to this chapter of the report.

A schematic representation of the type of market division that was foreseen for this two-phase simulation is shown in Figure VIII-3 where all market quantities are shown in terms of standard reference units. Apportionment

FIGURE VIII-3. Example of Possible Two Phase Cesium Market Evolution

of an expanding market among the three source materials is the basis of the simulation procedure. The market indicated as the HWM share in Figure VIII-3 provides the basis for price or profitability calculations by CAESR for a re-encapsulation facility. The market indicated as the power reactor cesium share provides the basis for CAESR calculation of required prices for recovery from power reactor fuels.

The base market is defined in terms of a projection of initial-source sales as ^{60}Co , and the total base market including replenishments is calculated as described in Chapter VI. The initial-source base market is then apportioned by RAMARK between ^{137}Cs and $^{137}\text{Cs}/^{134}\text{Cs}$, based on fractions supplied as input. The balance remaining is the ^{60}Co share. The program then adds in replenishment requirements for all sales in all of the years for the three source materials. The annual totals represent the market share for each source material as curies of that material. In specifying market fractions for RAMARK, different fractions can be specified for as many years as desired. If two different fractions several years apart are specified, the program makes a straight line interpolation for the intervening years; and the last specified fraction is continued to the end of the problem. This calculation will be illustrated with examples in the next section.

APPORTIONMENT OF THE MARKET

It is, of course, not possible to examine all conceivable market combinations. Thus, it was necessary to define some general ground rules outlining the situations to be examined. These were as follows:

1. Cesium sales (either type) would never be greater than 50 percent of the total gamma-source market.
2. HWM cesium sales to industry would start in 1973 at 10 percent of the gamma-source market. This amounts to a range of 1.6 to 2.1 MCi ^{137}Cs in 1973, which is reasonable relative to current FPD sales experience.

3. Sale of ^{137}Cs from FPDL would continue between now and 1973; but with low priced HWM cesium announced as becoming available in 1973, any sizable purchases would probably be deferred until then.
4. Cesium sales (combined total of either type) would reach 50 percent of the gamma-source market in 1980.
5. Announced AEC policy would be to withdraw from HWM marketing whenever private recovery facilities, based on power reactor fuels, could supply the market.
6. Two modes for withdrawing HWM cesium from the market would be considered: gradual displacement by power reactor cesium where these sales would reach 10 percent of total gamma-source markets in the startup year and displace all HWM sales in five years; and abrupt displacement by power reactor cesium where these sales would completely displace all HWM sales in the startup year.
7. Three startup years for power reactor cesium recovery would be considered: 1977, 1980, and 1982. Recovery feasibility before 1977 was unlikely based on the earlier results and looking beyond 1982 was too speculative. Interpolation would be satisfactory for intermediate years if needed.

These ground rules were believed to encompass a broad enough range to establish the conditions for feasibility of cesium recovery from power reactor fuels and to provide adequate information for defining appropriate AEC policies. The basis for gamma-source market sharing is shown graphically in Figures VIII-4 and 5 for gradual and abrupt phase-out of HWM cesium sales.

The ground rules for strontium recovery were similar to those for cesium, but were less complex because HWM strontium and power reactor strontium were considered equivalents and no other material analogous to ^{60}Co was involved. The total market (100 percent) was supplied by either HWM strontium, power reactor (PR) strontium, or a combination of just these two materials. Items 5, 6, and 7 above were applicable except in the case of gradual displacement by power reactor strontium, in which case

FIGURE VIII-4. Basis for Gamma-Source Market Sharing with Gradual Phaseout of HWM Sales

FIGURE VIII-5. Basis for Gamma-Source Market Sharing with Abrupt Phaseout of HWM Sales

PR strontium sales were 20 percent of total strontium sales the first year and reached 100 percent in five years.

A four-digit numbering system was adopted to identify the various cases. The first digit identified the market as low, medium, or high; the second digit identified the recovery startup year and whether HWM phase-out was gradual or abrupt; and the last two digits were used to identify economic input variations such as capital cost, return on investment, etc., and whether the calculations were for power reactor recovery or HWM re-encapsulation. The case series are defined in Table VIII-1 for cesium and in Table VIII-2 for strontium.

The output tables from the RAMARK calculations are shown for three example cesium cases in Tables VIII-3, 4, and 5. It is worth noting how rapidly the market share for HWM cesium grows relative to the base market (as curies of ^{60}Co), even though the fractional share for HWM cesium is always less than 40 percent. Note also that the annual total market for HWM cesium is only a little larger than the annual initial-source requirement; but for both the power reactor cesium and ^{60}Co , the annual replenishment market after a few years is larger than the annual initial-source market.

The annual total requirements for all three source materials is plotted for each cesium case on Figures A-1 through A-18 in the Appendix. The cumulative requirement for the HWM cesium over the total period through 1990 is shown as Σ in the right hand side of each of the plots. The total availability of HWM cesium is classified and also will depend to some extent on how long the N-Reactor continues to operate. (Operation of the N-Reactor through 1974 is currently assured). However, the HWM cesium required for some of the high market cases probably exceeds availability.

TABLE VIII-1. Two Phase Market Simulation Cases for Cesium
(Case Series Numbers in Parentheses)

TABLE VIII-2. Two-Phase Market Simulation Cases for Strontium
(Case Series Numbers in Parentheses)

Market Projection

HWM
Phaseout

Startup of
Power Reactor
Sr Recovery

Case
Series
Numbers

TABLE VIII-3a. RAMARK Output for Low Market, Gradual
HWM Phaseout and 1980 Startup of Power
Reactor Cesium Recovery (4200 Series)

RADIATION-SOURCE MARKET PROJECTION								
YEAR	BASE MARKET PROJECTION MEGACURIES OF CO-60			FRACTION OF BASE	H W M CS-137 SHARE MEGACURIES OF CS-137			TOTAL
	INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL	
1970	2.000	.000	2.000	.000	.000	.000	.000	.000
1971	2.537	.247	2.784	.000	.000	.000	.000	.000
1972	3.148	.560	3.707	.000	.000	.000	.000	.000
1973	3.827	.949	4.775	.100	1.608	.000	1.608	1.608
1974	4.567	1.421	5.987	.157	3.015	.036	3.052	3.052
1975	5.361	1.985	7.345	.214	4.826	.105	4.931	4.931
1976	6.198	2.647	8.843	.271	7.067	.214	7.282	7.282
1977	7.068	3.412	10.479	.329	9.757	.375	10.132	10.132
1978	7.961	4.285	12.245	.386	12.902	.596	13.498	13.498
1979	8.868	5.365	14.231	.443	16.499	.889	17.388	17.388
1980	9.777	6.577	16.352	.400	16.430	1.263	17.693	17.693
1981	10.682	7.914	18.593	.320	14.359	1.636	15.995	15.995
1982	11.572	9.378	20.948	.240	11.668	1.962	13.629	13.629
1983	12.443	10.968	23.408	.160	8.364	2.226	10.590	10.590
1984	13.289	12.682	25.968	.080	4.466	2.416	6.882	6.882
1985	14.104	14.522	28.623	.000	.000	2.518	2.518	2.518
1986	14.885	16.486	31.368	.000	.000	2.518	2.518	2.518
1987	15.630	18.571	34.198	.000	.000	2.518	2.518	2.518
1988	16.336	20.773	37.106	.000	.000	2.518	2.518	2.518
1989	17.004	23.086	40.087	.000	.000	2.518	2.518	2.518
1990	17.632	25.505	43.134	.000	.000	2.518	2.518	2.518
1991	18.222	28.024	46.242	.000	.000	2.518	2.518	2.518
1992	18.772	30.639	49.407	.000	.000	2.518	2.518	2.518
1993	19.285	33.341	52.622	.000	.000	2.518	2.518	2.518
1994	19.762	36.125	55.883	.000	.000	2.518	2.518	2.518
1995	20.204	38.986	59.185	.000	.000	2.518	2.518	2.518
1996	20.613	41.917	62.525	.000	.000	2.518	2.518	2.518
1997	20.990	44.915	65.900	.000	.000	2.518	2.518	2.518
1998	21.338	47.974	69.307	.000	.000	2.518	2.518	2.518
1999	21.658	51.090	72.743	.000	.000	2.518	2.518	2.518

TABLE VIII-3b. RAMARK Output for Low Market, Gradual
HWM Phaseout and 1980 Startup of Power
Reactor Cesium Recovery (4200 Series)

YEAR	POWER REACTOR CS-137/CS-134 SHARE				REMAINING CO-60 SHARE			
	FRACTION OF BASE	MEGACURIES OF CS-137			FRACTION OF BASE	MEGACURIES OF CO-60		
		INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL
1970	.000	.000	.000	.000	1.000	2.000	.000	2.000
1971	.000	.000	.000	.000	1.000	2.537	.247	2.784
1972	.000	.000	.000	.000	1.000	3.147	.560	3.707
1973	.000	.000	.000	.000	.900	3.443	.949	4.392
1974	.000	.000	.000	.000	.843	3.849	1.374	5.223
1975	.000	.000	.000	.000	.786	4.211	1.849	6.060
1976	.000	.000	.000	.000	.729	4.514	2.369	6.884
1977	.000	.000	.000	.000	.671	4.745	2.927	7.671
1978	.000	.000	.000	.000	.614	4.889	3.513	8.402
1979	.000	.000	.000	.000	.557	4.939	4.214	9.153
1980	.100	1.303	.000	1.303	.500	4.888	4.941	9.828
1981	.160	2.563	.259	2.822	.500	5.340	5.674	11.014
1982	.260	4.011	.751	4.761	.500	5.785	6.460	12.245
1983	.340	5.639	1.495	7.135	.500	6.220	7.302	13.522
1984	.420	7.439	2.512	9.951	.500	6.643	8.198	14.840
1985	.500	9.400	3.816	13.216	.500	7.050	9.147	16.197
1986	.500	9.920	5.426	15.346	.500	7.441	10.147	17.588
1987	.500	10.417	7.120	17.536	.500	7.813	11.196	19.010
1988	.500	10.888	8.896	19.784	.500	8.166	12.288	20.455
1989	.500	11.333	10.770	22.103	.500	8.500	13.418	21.918
1990	.500	11.751	12.755	24.506	.500	8.814	14.610	23.424
1991	.500	12.144	14.864	27.008	.500	9.109	15.862	24.971
1992	.500	12.511	17.109	29.620	.500	9.384	17.168	26.553
1993	.500	12.853	19.402	32.255	.500	9.640	18.523	28.163
1994	.500	13.171	21.743	34.914	.500	9.879	19.920	29.799
1995	.500	13.465	24.134	37.599	.500	10.100	21.354	31.454
1996	.500	13.738	26.575	40.312	.500	10.304	22.823	33.127
1997	.500	13.989	29.067	43.056	.500	10.493	24.323	34.816
1998	.500	14.221	31.606	45.827	.500	10.667	25.853	36.520
1999	.500	14.434	34.190	48.624	.500	10.827	27.410	38.237

TABLE VIII-4a. RAMARK Output for Medium Market, Gradual
HWM Phaseout and 1980 Startup of Power
Reactor Cesium Recovery (5200 Series)

RADIATION-SOURCE MARKET PROJECTION							
YEAR	BASE MARKET PROJECTION MEGACURIES OF CO-60			FRACTION OF BASE	H W M ' CS-137 SHARE MEGACURIES OF CS-137		
	INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL
1970	2.000	.000	2.000	.000	.000	.000	.000
1971	2.783	.247	3.030	.000	.000	.000	.000
1972	3.737	.591	4.326	.000	.000	.000	.000
1973	4.858	1.052	5.908	.100	2.041	.000	2.041
1974	6.137	1.652	7.787	.157	4.051	.046	4.098
1975	7.558	2.409	9.965	.214	6.804	.138	6.942
1976	9.098	3.342	12.439	.271	10.375	.293	10.668
1977	10.734	4.465	15.197	.329	14.817	.528	15.345
1978	12.437	5.791	18.225	.386	20.153	.864	21.018
1979	14.180	7.424	21.601	.443	26.383	1.321	27.705
1980	15.938	9.303	25.238	.400	26.782	1.920	28.702
1981	17.688	11.429	29.113	.320	23.777	2.528	26.305
1982	19.407	13.804	33.207	.240	19.567	3.067	22.634
1983	21.080	16.428	37.504	.160	14.169	3.511	17.680
1984	22.691	19.298	41.984	.080	7.626	3.833	11.458
1985	24.229	22.411	46.636	.000	.000	4.006	4.006
1986	25.688	25.761	51.444	.000	.000	4.006	4.006
1987	27.061	29.339	56.394	.000	.000	4.006	4.006
1988	28.346	33.133	61.473	.000	.000	4.006	4.006
1989	29.543	37.132	66.669	.000	.000	4.006	4.006
1990	30.651	41.324	71.968	.000	.000	4.006	4.006
1991	31.673	45.695	77.361	.000	.000	4.006	4.006
1992	32.613	50.234	82.839	.000	.000	4.006	4.006
1993	33.473	54.925	88.391	.000	.000	4.006	4.006
1994	34.259	59.758	94.009	.000	.000	4.006	4.006
1995	34.974	64.719	99.686	.000	.000	4.006	4.006
1996	35.624	69.799	105.416	.000	.000	4.006	4.006
1997	36.214	74.986	111.193	.000	.000	4.006	4.006
1998	36.747	80.272	117.011	.000	.000	4.006	4.006
1999	37.229	85.647	122.868	.000	.000	4.006	4.006

**TABLE VIII-4b. RAMARK Output for Medium Market, Gradual
HWM Phaseout and 1980 Startup of Power
Reactor Cesium Recovery (5200 Series)**

POWER REACTOR CS-137/CS-134 SHARE					REMAINING CO-60 SHARE				
YEAR	FRACTION OF BASE	MEGACURIES OF CS-137			FRACTION OF BASE	MEGACURIES OF CO-60			TOTAL
		INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL	
1970	.000	.000	.000	.000	1.000	2.000	.000	2.000	
1971	.000	.000	.000	.000	1.000	2.783	.247	3.030	
1972	.000	.000	.000	.000	1.000	3.736	.591	4.326	
1973	.000	.000	.000	.000	.900	4.371	1.052	5.423	
1974	.000	.000	.000	.000	.843	5.171	1.592	6.763	
1975	.000	.000	.000	.000	.786	5.937	2.230	8.167	
1976	.000	.000	.000	.000	.729	6.627	2.963	9.590	
1977	.000	.000	.000	.000	.671	7.205	3.782	10.987	
1978	.000	.000	.000	.000	.614	7.638	4.671	12.309	
1979	.000	.000	.000	.000	.557	7.898	5.712	13.610	
1980	.100	2.124	.000	2.124	.500	7.968	6.816	14.784	
1981	.180	4.244	.423	4.667	.500	8.842	7.954	16.800	
1982	.260	6.720	1.237	7.963	.500	9.702	9.217	18.919	
1983	.340	9.553	2.487	12.041	.500	10.538	10.598	21.136	
1984	.420	12.703	4.212	16.915	.500	11.343	12.096	23.438	
1985	.500	16.148	6.445	22.593	.500	12.112	13.703	25.815	
1986	.500	17.120	9.218	26.338	.500	12.841	15.414	28.255	
1987	.500	18.035	12.142	30.177	.500	13.528	17.218	30.746	
1988	.500	18.892	15.216	34.107	.500	14.170	19.104	33.276	
1989	.500	19.689	18.462	38.151	.500	14.768	21.064	35.832	
1990	.500	20.428	21.905	42.333	.500	15.322	23.131	38.453	
1991	.500	21.109	25.567	46.676	.500	15.833	25.303	41.136	
1992	.500	21.735	29.465	51.200	.500	16.303	27.560	43.872	
1993	.500	22.303	33.446	55.754	.500	16.733	29.910	46.652	
1994	.500	22.832	37.509	60.341	.500	17.126	32.342	49.468	
1995	.500	23.309	41.654	64.963	.500	17.484	34.831	52.313	
1996	.500	23.742	45.880	69.622	.500	17.808	37.374	55.183	
1997	.500	24.135	50.187	74.322	.500	18.103	39.971	58.074	
1998	.500	24.491	54.570	79.061	.500	18.370	42.614	60.984	
1999	.500	24.812	59.022	83.833	.500	18.610	45.301	63.912	

TABLE VIII-5a. RAMARK Output for High Market, Gradual HWM Phaseout and 1980 Startup of Power Reactor Cesium Recovery (6200 Series)

YEAR	BASE MARKET PROJECTION MEGACURIES OF CO-60			FRACTION OF BASE	H W M CS-137 SHARE MEGACURIES OF CS-137		
	INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL
	-----	-----	-----		-----	-----	-----
1970	2.000	.000	2.000	.000	.000	.000	.000
1971	2.798	.247	3.044	.000	.000	.000	.000
1972	3.809	.592	4.401	.000	.000	.000	.000
1973	5.062	1.063	6.124	.100	2.127	.000	2.127
1974	6.580	1.688	8.266	.157	4.344	.048	4.392
1975	8.384	2.500	10.882	.214	7.547	.147	7.694
1976	10.490	3.535	14.022	.271	11.962	.318	12.280
1977	12.911	4.830	17.738	.329	17.822	.589	18.412
1978	15.657	6.424	22.077	.386	25.372	.994	26.366
1979	18.733	8.455	27.184	.443	34.854	1.569	36.424
1980	22.142	10.897	33.034	.400	37.206	2.360	39.566
1981	25.883	13.792	39.669	.320	34.794	3.204	37.999
1982	29.956	17.188	47.138	.240	30.202	3.994	34.196
1983	34.356	21.135	55.484	.160	23.093	4.679	27.772
1984	39.082	25.681	64.755	.080	13.134	5.203	18.337
1985	44.127	30.878	74.996	.000	.000	5.501	5.501
1986	49.490	36.776	86.255	.000	.000	5.501	5.501
1987	55.167	43.423	98.579	.000	.000	5.501	5.501
1988	61.157	50.868	112.012	.000	.000	5.501	5.501
1989	67.459	59.157	126.602	.000	.000	5.501	5.501
1990	74.074	68.339	142.396	.000	.000	5.501	5.501
1991	81.004	78.459	159.445	.000	.000	5.501	5.501
1992	88.254	89.565	177.800	.000	.000	5.501	5.501
1993	95.829	101.704	197.513	.000	.000	5.501	5.501
1994	103.738	114.923	218.639	.000	.000	5.501	5.501
1995	111.990	129.271	241.237	.000	.000	5.501	5.501
1996	120.596	144.798	265.369	.000	.000	5.501	5.501
1997	129.570	161.557	291.100	.000	.000	5.501	5.501
1998	138.926	179.600	318.497	.000	.000	5.501	5.501
1999	148.682	198.982	347.633	.000	.000	5.501	5.501

**TABLE VIII-5b. RAMARK Output for High Market, Gradual
HWM Phaseout and 1980 Startup of Power
Reactor Cesium Recovery (6200 Series)**

YEAR	POWER REACTOR CS-137/CS-134 SHARE				REMAINING CO-60 SHARE			
	FRACTION OF BASE	MEGACURIES OF CS-137			FRACTION OF BASE	MEGACURIES OF CO-60		
		INITIAL SOURCES	REPLENISHMENTS	TOTAL		INITIAL SOURCES	REPLENISHMENTS	TOTAL
1970	.000	.000	.000	.000	1.000	2.000	.000	2.000
1971	.000	.000	.000	.000	1.000	2.797	.247	3.044
1972	.000	.000	.000	.000	1.000	3.809	.592	4.401
1973	.000	.000	.000	.000	.900	4.555	1.063	5.618
1974	.000	.000	.000	.000	.843	5.545	1.625	7.170
1975	.000	.000	.000	.000	.786	6.586	2.310	8.895
1976	.000	.000	.000	.000	.729	7.641	3.123	10.764
1977	.000	.000	.000	.000	.671	8.667	4.066	12.733
1978	.000	.000	.000	.000	.614	9.615	5.137	14.752
1979	.000	.000	.000	.000	.557	10.434	6.422	16.856
1980	.100	2.951	.000	2.951	.500	11.068	7.840	18.908
1981	.180	6.210	.588	6.798	.500	12.939	9.368	22.306
1982	.260	10.382	1.781	12.163	.500	14.975	11.142	26.116
1983	.340	15.570	3.720	19.290	.500	17.175	13.191	30.366
1984	.420	21.879	6.555	28.434	.500	19.537	15.536	35.073
1985	.500	29.409	10.449	39.858	.500	22.059	18.198	40.257
1986	.500	32.984	15.584	48.567	.500	24.740	21.197	45.936
1987	.500	36.767	21.282	58.050	.500	27.578	24.548	52.126
1988	.500	40.759	27.600	68.359	.500	30.572	28.266	58.838
1989	.500	44.959	34.629	79.588	.500	33.722	32.361	66.083
1990	.500	49.367	42.474	91.841	.500	37.029	36.916	73.945
1991	.500	53.986	51.243	105.229	.500	40.493	41.957	82.450
1992	.500	58.818	61.044	119.862	.500	44.117	47.504	91.622
1993	.500	63.867	71.666	135.533	.500	47.904	53.577	101.481
1994	.500	69.138	83.161	152.299	.500	51.858	60.194	112.052
1995	.500	74.638	95.582	170.220	.500	55.983	67.376	123.359
1996	.500	80.373	108.983	189.356	.500	60.286	75.146	135.431
1997	.500	86.354	123.419	209.773	.500	64.771	83.529	148.300
1998	.500	92.590	138.939	231.529	.500	69.449	92.552	162.000
1999	.500	99.091	155.589	254.680	.500	74.325	102.243	176.568

CASE DESCRIPTIONS

The individual case variations within each of the market-case series (Figures VIII-1 and 2) are shown in Tables VIII-6 and 7 for power reactor cesium and strontium respectively. (The discontinuity in the case numbering system resulted from deletion of some earlier case variations.) Reading from left to right in these tables, the variable continues as the last value cited until a new value is noted. Thus, the market share (market captured by one reprocessor) is indicated to be 100 percent initially and declining to 50 percent at equilibrium for all cases. However, as discussed in Chapter IV, three subset case variations can be included in each case calculation; and market share variations of a constant 100 percent and a constant 50 percent were included for each case. The 100 percent initial share to a 50 percent equilibrium share after five years is the base case assumption and is intended to represent competition within five years (see Chapter IV for further clarification of this assumption).

For the re-encapsulation of HWM cesium in a private facility, the procedure used for price calculations was modified. The capital cost was held constant at any capacity requirement less than the reference capacity of 12.6 MCi/yr. Above the reference capacity, 50 percent rather than 60 percent of the cost was scaled as an 0.6 power function and 50 percent was held constant.

The possibility of feasible production costs for the re-encapsulation appeared to be so slim and the period of operation so short that no consideration was given to sharing the market with a competitor. Since it is not obvious what year would be most appropriate for starting such re-encapsulation, three different startup years were tested as subsets within each case, rather than varying the market share. Table VIII-8 shows the startup years tested. The results for the startup year with the lowest cost are those reported and discussed in the next section.

The capital cost is the principal variable examined for the re-encapsulation facility. The estimated cost, one-half of the estimated cost, and a \$100,000 capital cost are considered. The \$100,000 represents

TABLE VIII-6. Case Descriptions of Power Reactor Cesium Recovery
(Co-products Base Case)

Case	<u>--21</u>	<u>--22</u>	<u>--23</u>	<u>--24</u>	<u>--28</u>	<u>--29</u>	<u>--31</u>	<u>--32</u>	<u>--33</u>	<u>--34</u>
Description	<u>Base Case</u>	<u>Single Prod.</u>	<u>Low Cap.</u>	<u>High Cap.</u>	<u>Low Oper. Cost</u>	<u>High Oper. Cost</u>	<u>Lower ROI</u>	<u>Longer Econ. Life</u>	<u>Zero Learn.</u>	<u>High Learn.</u>
Market Share, %										
Initial	100									
Equilibrium	50									
Ref. Cap. Cost, \$10 ⁶										
Scaled	6.0	8.6	4.2	11.1	6.0					
Constant	4.0	5.7	2.8	7.4	4.0					
Total	10.0	14.3	7.0	18.5	10.0					
Scale Factor	0.6									
Op. Cost Factors										
Frac. of Cap.	0.052				0.026	0.068	0.52			
Variable, \$/KCi	36	45	36	45	22.5	59	36			
Work Cap. Fraction	0.25									
R.O.I., %	15						10	15		
Economic Life, yr	10							15	10	
Learning Curve										
Ultimate Capac.	2.0									
Rate Const.	0.15								1.0	3.0

TABLE VIII-7. Case Descriptions of Power Reactor Strontium Recovery
(Co-products Base Case)

Case	--21	--22	--23	--24	--28	--29	--31	--32	--33	--34
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn.	High Learn.
Market Share, %										
Initial	100									
Equilibrium	50									
Ref. Cap. Cost, \$10 ⁶										
Scaled	6.2	8.8	4.3	11.4	6.2					
Constant	4.2	5.8	2.9	7.5	4.2					
Total	10.4	14.6	7.2	18.9	10.4					
Scale Factor	0.6									
Op. Cost Factors										
Frac. of Cap.	0.052				0.026	0.068	0.052			
Variable, \$/KCi	38	47	38	47	23	61	38			
Work Cap. Fraction	0.25									
R.O.I., %	15						10	15		
Economic Life, yr	10							15	10	
Learning Curve										
Ultimate Capac.	2.0								1.0	3.0
Rate Const.	0.15									

TABLE VIII-8. Separate Re-encapsulation Facility--Case Series Description
(Case Series Numbers in Parentheses)

8.21

probable minimum expenditures to modify and utilize an existing hot cell facility. In addition to calculating the price required for a fixed return on investment, the program option for calculating ROI for a given price was also utilized here. For this purpose, a 5¢/Ci price was used as the maximum added-value price that would be feasible over and above the acquisition cost of the HWM cesium. As discussed previously, the increased value resulting from re-encapsulation alone is only 3¢/Ci; but conceivably, up to 5¢/Ci might be allocatable to this process with the added leverage gained through quantity discounts for purchasing HWM cesium. If HWM cesium can be purchased in large lots at a lower price than in small lots, and the reason for the large lot purchase is to re-encapsulate for resale, the difference between acquisition cost and selling price could be as much as 5 1/2¢/Ci.)

The individual case variations for the re-encapsulation calculations are shown in Table VIII-9. The (Price) or (ROI) notation in each case description designates whether price or return on investment was to be calculated.

RESULTS

PR Cesium Recovery

The results of the price requirement calculations for the PR cesium cases are shown in detail in Tables A-1 through A-54 in the Appendix and are summarized here in Tables VIII-10 through VIII-14. A standard format was adopted for these summary tables that would help to relate the results to the market assumed and the method of phasing out the HWM cesium sales. Each table compares a major variable with the base case results. The feasible price for PR cesium for profitable recovery was assumed to be 25 to 30¢/Ci ¹³⁷Cs or less. To assist in identifying feasible conditions, any prices of 30¢/Ci or less are enclosed in boxes.

Table VIII-10 shows the effect of market share on price requirements. The market share is obviously a very important consideration and anyone considering investment in this business would want to carefully analyze this factor. This table also illustrates the very great advantage of an abrupt phaseout of HWM cesium sales. Both of these effects, market share and HWM phaseout mode, are important because of the capital intensive nature of the

TABLE VIII-9. Separate Re-encapsulation Facility
for HWM ¹³⁷Cs Case Descriptions

Case	--41	--42	--43	--44	--45	--46	--47	--48
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Market Share, %								
Initial	100							
Equilibrium	100							
Ref. Cap. Cost, \$10 ⁶								
Scaled	0.9		0.45		0.1		0.9	
Constant	0.9		0.45		0		0.9	
Total								
Scale Factor	0.6							
Op. Cost Factors								
Frac. of Cap.	0.028							
Variable, \$/KCi	44							
Work Cap. Fraction	0.25							
R.O.I., %	15	---	15	---	15	---	10	15
Economic Life, yr	10							
Learning Curve								
Ultimate Capac.	2.0							0.15
Rate Const.	0.35							
Sales Price, ¢/Ci	---	5.0	---	5.0	---	5.0	---	---

TABLE VIII-10. Effect of Market Share on Price Requirements for Power Reactor Cesium Recovery
(¢/Ci ^{137}Cs)

Market Projection

HWM Sales
Phaseout

Startup of
Power Reactor
Cs Recovery

100% Share

45 41 38 37 29 27

33 29 27 28 22 20

27 22 20 23 17 15

Base Case

64 57 53 50 38 35

45 40 36 36 27 25

36 29 25 29 20 18

50% Share

75 67 61 61 47 42

52 46 42 43 33 30

41 33 28 34 25 21

venture. A relatively high production rate is necessary to reduce the unit charges for capital costs to an acceptable level.

The other side of the capital charge question is the magnitude of the capital investment itself. Table VIII-11 shows a comparison of price requirements at the four capital costs considered (refer to Table VIII-6). The advantage for co-product facilities is apparent. The low capital effect is nearly identical to the 100 percent market share in the previous table.

The relative insensitivity of price requirements to operating cost is illustrated in Table VIII-12. A variation of approximately ± 45 percent in operating cost has hardly any effect on the conditions indicated to be required for recovery feasibility.

The effect of another capital related item, the profitability criteria, is shown in Table VIII-13. Either increasing the economic life to 15 years or reducing the required return on investment to 10 percent expands the area of feasibility substantially. If firm and expanding market opportunities are demonstrated by HWM cesium sales, some relaxation in the profitability criteria might be considered. Thus HWM sales could have a compounding effect on PR cesium recovery feasibility.

The learning effect, Table VIII-14, has only a minor impact on the conditions for feasible prices. There is a definite advantage but the magnitude is not large enough to shift feasibility areas very much.

Re-encapsulation of HWM Cesium

The price requirements calculated for re-encapsulation of HWM cesium in private facilities is the added-value price above the acquisition cost from the AEC (assumed to be around $5\frac{1}{2}\text{¢/Ci}$). The value of the re-encapsulated ^{137}Cs relative to 40¢/Ci ^{60}Co would be about 11¢/Ci . Some allowance should be made for marketing costs, at least $1\frac{1}{2}\text{¢/Ci}$. Thus, the maximum added value price was assumed to be 5¢/Ci . As previously pointed out, the increased value due to re-encapsulation alone that results from reduced gamma photon self-absorption is only 3¢/Ci . Whether or not another 2¢/Ci could be credited to re-encapsulation would depend on AEC

TABLE VIII-11. Effect of Capital Cost on Price Requirements for Power Reactor Cesium Recovery
(¢/Ci ¹³⁷Cs)

Market Projection

HWM Sales
Phaseout

Startup of
Power Reactor
Cs Recovery

Low Capital

46 41 38 36 28 26

Base Case
(Co-Products)

64 57 53 50 38 35

One Product

91 81 74 70 54 50

High Capital

117 104 95 89 68 63

33 29 27 26 20 19

45 40 36 36 27 25

64 56 51 50 38 35

81 71 65 63 48 44

26 21 19 22 15 14

36 29 25 29 20 18

50 40 35 41 29 25

63 51 44 51 35 31

TABLE VIII-12. Effect of Operating Cost on Price Requirements for Power Reactor Cesium Recovery
(¢/Ci ¹³⁷Cs)

Market Projection

Low Oper. Costs (Reduced Approx. 45%)	59	52	48	45	35	32	41	36	33	32	24	22	32	26	22	26	18	16
Base Case	64	57	53	50	38	35	45	40	36	36	27	25	36	29	25	29	20	18
High Oper. Costs (Increased Approx. 45%)	69	62	57	54	42	39	49	44	40	39	31	29	39	32	28	33	24	21

TABLE VIII-13. Effect of Profitability Criteria on Price Requirements for Power Reactor Cesium Recovery ($\text{\$/Ci }^{137}\text{Cs}$)

Market Projection

Base Case
(15% ROI, 10 yr)

Longer Economic
Life, 15 yr

Lower ROI, 10%

64	57	53	50	38	35	45	40	36	36	27	25	36	29	25	29	20	18
51	46	42	42	32	30	36	32	30	30	23	22	28	23	20	24	18	16
46	41	38	36	29	27	32	29	26	26	21	19	25	21	18	22	16	14

TABLE VIII-14. Effect of Learning on Price Requirements for Power Reactor Cesium Recovery ($\text{\$/Ci }^{137}\text{Cs}$)

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982
Zero Learning	72	64	59	55	41	37	51	45	41	40	29	27	41	33	29	33	23	20
Base Case	64	57	53	50	38	35	45	40	36	36	27	25	36	29	25	29	20	18
Higher Learning (50% Increase)	60	54	49	49	38	35	42	37	33	35	27	25	34	27	23	27	20	18

policy for sale of the HWM capsules; that is, quantity discounts and the real market place value enhancement for re-encapsulation. The re-encapsulated cesium might, in reality, be more salable than the HWM capsules.

A 5¢/Ci added-value price is used in this discussion as the feasibility criterion for a re-encapsulation facility. Results are also presented where the return on investment was calculated for a specified 5¢/Ci added-value price, regardless of profitability. This provides another measure for gaging nearness to feasibility.

The results of the calculations for the re-encapsulation facility are shown in detail in Tables A-55 through A-72 in the Appendix and are summarized here in Tables VIII-15 through VIII-21.

Table VIII-15 shows the base case price calculations and the ROI for a 5¢/Ci price. Optimum startup year for the facility is also shown and indicates an advantage for delaying startup to a higher-load year, even though the length of operating life may be shorter because of displacement by PR fuel recovery operations. However, no case was found here that met the 5¢/Ci feasibility criterion.

Table VIII-16 is a similar comparison for the minimum capital cases. Every case here meets the feasibility criterion indicating the possibility of carrying out the re-encapsulation in an already existing facility. The return on investment is substantial; but this by itself is misleading since the dollar amount is small, \$100,000, and a large prior investment was necessary to provide the facility.

Another comparison in Table VIII-17 shows price requirements for the base case compared with results for a capital cost of one-half the base case cost and with results for the minimum capital cases. Only a few situations show feasibility even at one-half of the base case capital. The return on investment for the same cases with a 5¢/Ci added-value sales price is shown in Table VIII-18.

The effect of relaxed profitability criteria is shown in Table VIII-19, where base case results are compared with price requirements at a 10 percent ROI. The prices are lower but still only one case meets the 5¢/Ci criteria.

TABLE VIII-15. Base Case Price Requirements for Private Re-encapsulation Facility

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Cs Recovery	1977			1977			1977			1977			1977			1977		
	1980			1980			1980			1980			1980			1980		
	1982			1982			1982			1982			1982			1982		
Optimum Startup Year For Re-encapsulation	'75	'76	'77	'74	'76	'76	'75	'76	'77	'74	'76	'76	'75	'76	'77	'74	'76	'76
Net Added-Value Price Required, ¢/Ci ¹³⁷ Cs	16	8.2	7.1	28	12	9.0	11	6.6	6.0	21	9.5	7.3	9.9	5.9	5.3	19	8.7	6.7
Return on Investment at 5¢/Ci Net, %/yr	-8.5	2.1	4.8	-16	-5.3	1.1	-4.7	6.6	9.1	-15	-1.5	4.7	-2.3	9.4	13	-14	0.1	6.7

TABLE VIII-16. Minimum Capital Case Price Requirements for Private Re-encapsulation Facility

TABLE VIII-17. Effect of Capital Cost on Price Requirements for Re-encapsulation of HWM ^{137}Cs ($\text{\$/Ci}^{137}\text{Cs}$)

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977			1977			1977			1977			1977			1977		
	1980			1980			1980			1980			1980			1980		
	1982			1982			1982			1982			1982			1982		
<u>Base Case</u>	16	8.2	7.1	28	12	9.0	11	6.6	6.1	21	9.5	7.3	9.9	5.9	5.3	19	8.7	6.7
50% of Base Case Capital	9.5	5.7	5.1	16	7.7	6.1	7.4	4.8	4.5	13	6.3	5.2	6.6	4.5	4.1	12	6.1	4.9
Minimum Capital	3.9	3.2	3.1	4.9	3.5	3.2	3.6	3.1	3.1	4.6	3.4	3.1	3.5	3.0	3.0	4.4	3.3	3.1

TABLE VIII-18. Effect of Capital Cost on Profitability for Re-encapsulation of HWM ¹³⁷Cs
(ROI %/yr)

TABLE VIII-19. Effect of Profitability on Price Requirements for Re-encapsulation of HWM ^{137}Cs ($\$/\text{Ci } ^{137}\text{Cs}$)

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977			1977			1977			1977			1977			1977		
	1980			1980			1980			1980			1980			1980		
	1982			1982			1982			1982			1982			1982		
Base Case 15% ROI	16	8.2	7.1	28	12	9.0	11	6.6	6.1	21	9.5	7.3	9.9	5.9	5.3	19	8.7	6.7
Reduce ROI to 10%	13	6.9	6.0	24	10	7.4	9.6	5.7	5.1	18	7.9	6.2	8.3	5.1	4.6	17	7.3	5.7

The effect of a slower learning rate is shown in Table VIII-20. The high learning rate in the base case produces up to a 1¢/Ci lower price than would be required otherwise.

The final comparison in this series, Table VIII-21, shows price requirements for PR cesium recovery alongside the re-encapsulation price requirements at 50 percent of the base case capital cost and the minimum capital cost. The gradual phaseout of HWM sales is clearly an advantage to the re-encapsulation operation if a significant capital investment is involved. It is still an advantage with only minimum capital cost, but not nearly so great. On the other hand, the abrupt phaseout is a great advantage to feasibility of PR cesium recovery. One concludes that the abrupt phaseout is the best policy. It is a substantial benefit to PR recovery and only a minor disadvantage to re-encapsulation; since, in any event, re-encapsulation appears feasible only in already existing hot cell facilities.

PR Strontium Recovery

The results of the price requirement calculations for the PR strontium recovery cases are shown in detail in Tables A-73 through A-126 in the Appendix and are summarized here in Tables VIII-22 through VIII-26. These tables are parallel comparisons to the cesium results shown in Tables VIII-10 through VIII-14, and the results are closely similar. The conclusions relating to the effects of the important variables for PR cesium all hold true for PR strontium also. However, the market value of strontium for the only presently known large customer, the U.S. Navy, is only about 10¢/Ci ⁹⁰Sr. None of the price calculations come very close to this value. Substantially larger markets would be required to bring prices down to that level.

Another way to reduce the strontium price would be to absorb some of the strontium costs in the cesium price to gain the advantages of co-product production for cesium. There are only a few of the base-case PR cesium results where the required price is low enough to provide leverage to absorb a significant part of the PR strontium cost. The 1980 and 1982 startups for the high cesium market with abrupt HWM sales phaseout are used to illustrate the possibility. Since there is no reason that a high cesium market should

TABLE VIII-20. Effect of Learning Rate on Price Requirements for Re-encapsulation of HWM ^{137}Cs
(¢/Ci ^{137}Cs)

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982
Base Case	16	8.2	7.1	28	12	9.0	11	6.6	6.1	21	9.5	7.3	9.9	5.9	5.3	19	8.7	6.7
Learning Rate Reduced	16	9.1	7.6	29	13	9.8	12	7.4	6.9	22	10	8.2	10	6.8	5.8	20	9.6	7.5

TABLE VIII-21. Coordinated Price Requirements for Base Case PR-Cs Recovery and Low-Capital Cases for HWM Cs Re-encapsulation (ϕ /Ci 137Cs)

Market Projection	Low (4000)						Medium (5000)						High (6000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977			1977			1977			1977			1977			1977		
	1980			1980			1980			1980			1980			1980		
	1982			1982			1982			1982			1982			1982		
Base Case PR-Cs Recovery	64	57	53	50	38	35	45	40	36	36	27	25	36	29	25	29	20	18
50% Capital Case HWM-Cs Re-encaps.	9.5	5.7	5.1	16	7.7	6.1	7.4	4.8	4.5	13	6.3	5.2	6.6	4.5	4.1	12	6.1	4.9
Min. Capital Case HWM-Cs Re-encaps.	3.9	3.2	3.1	4.9	3.5	3.2	3.6	3.1	3.1	4.6	3.4	3.1	3.5	3.0	3.0	4.4	3.3	3.1

TABLE VIII-22. Effect of Market Share on Price Requirements for Power Reactor Strontium Recovery
(¢/Ci 90Sr)

Market Projection	Low (7000)						Medium (8000M)						High (8000)					
HWM Sales Phaseout	Gradual						Gradual						Gradual					
Startup of Power Reactor Cs Recovery	1977						1977						1977					
	1980						1980						1980					
	1982						1982						1982					
100% Share	46	38	35	36	29	26	38	32	29	29	24	22	32	25	23	26	20	18
Base Case	67	52	45	48	38	34	56	41	37	39	31	29	44	34	29	33	26	23
50% Share	77	61	55	59	45	41	60	49	45	47	37	33	50	38	34	40	29	26

TABLE VIII-23. Effect of Capital Cost on Price Requirements for Power Reactor Strontium Recovery
(¢/Ci ⁹⁰Sr)

Market Projection	Low (7000)						Medium (8000M)						High (8000)					
HWM Sales Phaseout	Gradual			Abrupt			Gradual			Abrupt			Gradual			Abrupt		
Startup of Power Reactor Cs Recovery	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982	1977	1980	1982
Low Capital	48	37	33	35	28	25	38	30	27	28	23	21	32	25	21	24	19	17
<u>Base Case</u> (Co-Products)	67	52	45	48	38	34	56	41	37	39	31	29	44	34	29	33	26	23
One-Product	93	72	63	67	53	48	74	57	51	54	43	40	60	47	40	45	35	31
High Capital	119	92	80	85	67	60	94	72	64	68	54	50	77	59	50	57	44	39

TABLE VIII-24. Effect of Operating Cost on Price Requirements for Power Reactor Strontium Recovery
(¢/Ci ^{90}Sr)

TABLE VIII-25. Effect of Profitability Criteria on Price Requirements for Power Reactor Strontium Recovery

(¢/Ci ⁹⁰Sr)

Market Projection

Low
(7000)

Medium
(8000M)

High
(8000)

HWM Sales
Phaseout

Gradual

Abrupt

Gradual

Abrupt

Gradual

Abrupt

Startup of
Power Reactor
Cs Recovery

1977

1980

1982

1977

1980

1982

1977

1980

1982

1977

1980

1982

1977

1980

1982

1977

1980

1982

Base Case
(15% ROI, 10 yr)

67 52 45 48 38 34

56 41 37 39 31 29

44 34 29 33 26 23

Longer Economic
Life, 15 yr

53 44 39 42 34 31

43 35 31 34 28 26

35 28 25 28 23 21

Lower ROI, 10%

48 38 33 36 29 27

38 30 27 29 24 22

31 25 22 25 20 18

TABLE VIII-26. Effect of Learning on Price Requirements for Power Reactor Strontium Recovery

(¢/Ci ^{90}Sr)

Market Projection	Low (7000)						Medium (8000M)						High (8000)					
HWM Sales Phaseout	Gradual						Gradual						Gradual					
Startup of Power Reactor Cs Recovery	1977						1977						1977					
	1980						1980						1980					
	1982						1982						1982					
Zero Learning ^(a)	74		50		60		40		49		35							
Base Case	67	52	45	48	38	34	56	41	30	39	31	29	44	34	29	33	26	23
Higher Learning ^(a) (50% Increase)	62		48		48		39		41		32							

a. Comparisons for 1980 and 1982 startup are not available because of an error in the input data.

imply a high strontium market, these cesium cases are combined with corresponding strontium cases representing both the high and low strontium market projections.

The capital charges for strontium were transferred to the cesium up to the point where the cesium price was increased to 30¢/Ci or the strontium price reduced to 10¢/Ci. The results of this re-allocation of capital charges are shown in Table VIII-27. These results show that it would be possible under some circumstances to market strontium at a price as low as 10¢/Ci with cesium priced in the feasible range (25 to 30¢/Ci). However, in these cases there is not enough leverage to provide a real advantage to co-product cesium production. It is doubtful that an entrepreneur would undertake such a marginal project, at least not without expectation of higher strontium values within a reasonable time period.

CONCLUSIONS

The following principal conclusions were reached as a result of this two phase industry analysis:

1. The sale of HWM cesium and strontium capsules could result in markets for these materials growing to the size where the large capital investment in facilities for recovery from power-reactor fuel reprocessing wastes can be justified. Without an HWM products sales program, recovery from power reactor fuels cannot be predicted.
2. The earliest that such recovery operations can be anticipated is 1977 and a date closer to 1980 is more likely.
3. Private industry could participate in the market development at an earlier date through re-encapsulation of the HWM cesium capsules. However, this only appears feasible in already existing and unused hot cell facilities. It does not appear possible to amortize a new facility based on this operation alone.
4. The policy of the AEC regarding discontinuance of HWM sales should be to withdraw from the market just as rapidly as a PR

TABLE VIII-27. Example of Reallocation of Capital Charges to Reduce Required Price for Power Reactor ^{90}Sr

	High Cs Market With High Sr Market Abrupt HWM Cs & Sr Phaseout		High Cs Market With Low Sr Market Abrupt HWM Cs & Sr Phaseout	
	1980	1982	1980	1982
Recovery Startup				
Plant Size, MCi/yr				
PR-Cs	20.9	27.4	20.9	27.4
PR-Sr	18.0	23.2	9.7	12.1
Base Case Price Required, ¢/Ci				
PR-Cs	20.4	17.8	20.4	17.8
PR-Sr	25.5	22.7	38.2	34.4
Prices Required with Reallocated Capital, ¢/Ci				
PR-Cs	30.0	27.3	30.0	27.0
PR-Sr	13.1	10.0	14.6	10.0
Total Sr Plant Cost, \$Millions	---	9.73	---	7.95
Portion of Sr Capital Investment Charged off Against Cs, \$Million	---	7.44	---	7.21

fuel recovery operation could supply the demand. This would provide a significant advantage to the PR fuel recovery operation and would not be particularly damaging to someone engaged in re-encapsulation; their investment would be minimal and their operations would be known to be of a temporary nature from the start.

5. Recovery of fission products from PR fuel wastes would be undertaken initially by only one reprocessor; but competition should develop within a few years, probably five or less, if the market continued to grow.
6. Unless the cesium market growth is at least as large as the medium projection or unless the low-range capital cost is achieved, the feasibility of cesium recovery from PR fuels cannot be predicted.
7. If the high cesium market develops, it will be possible to absorb a significant part of the strontium recovery and encapsulation costs in the cesium price, should this prove necessary to provide a marketable strontium price.

ACKNOWLEDGEMENTS

The author is indebted to a number of persons who made substantial contributions to this study. Without their help the comprehensive scope of this report would not have been possible. A principal person among these is B. M. Cole who was responsible for the expert computer programming that was essential for the analysis. Another is C. H. Bloomster who developed the conceptual design for the HWM cesium re-encapsulation facility. The comments of J. R. LaRiviere, Atlantic Richfield Hanford Company, were a substantial help in developing a realistic definition of facility requirements for cesium and strontium recovery. J. D. Moore and G. L. Borshein, also Atlantic Richfield Hanford Company, developed the cost data for the Hanford Waste Encapsulation Facility. R. L. Lysher and D. E. Anderson, Vitro Engineering, provided the capital cost estimates for the cesium and strontium recovery facilities and the re-encapsulation facility. The market analysis of P. M. Wood, AEC Combined Operation and Planning, provided the basis for the market projections. The comments and views of the reprocessing company representatives, who were identified in Chapter III, were most valuable, particularly in the early stages when the study plan was evolving. The representatives of the isotope users and suppliers who were visited during the course of the study provided insight to user requirements. Besides contributing Chapter V, Dr. J. H. Cusack, BNL, provided constructive comments throughout the study. The assistance and contributions of all of these persons are gratefully acknowledged.

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APPENDIX A

FIGURE A-1. Market Apportionment for Low Projection with Gradual HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (4100 Series)

FIGURE A-2. Market Apportionment for Low Projection with Gradual HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (4200 Series)

FIGURE A-3. Market Apportionment for Low Projection with Gradual HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (4300 Series)

FIGURE A-4. Market Apportionment for Low Projection with Abrupt HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (4500 Series)

FIGURE A-5. Market Apportionment for Low Projection with Abrupt HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (4600 Series)

FIGURE A-6. Market Apportionment for Low Projection with Abrupt HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (4700 Series)

FIGURE A-7. Market Apportionment for Medium Projection with Gradual HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (5100 Series)

FIGURE A-8. Market Apportionment for Medium Projection with Gradual HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (5200 Series)

FIGURE A-9. Market Apportionment for Medium Projection with Gradual HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (5300 Series)

FIGURE A-10. Market Apportionment for Medium Projection with Abrupt HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (5500 Series)

FIGURE A-11. Market Apportionment for Medium Projection with Abrupt HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (5600 Series)

FIGURE A-12. Market Apportionment for Medium Projection with Abrupt HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (5700 Series)

FIGURE A-13. Market Apportionment for High Projection with Gradual HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (6100 Series)

FIGURE A-14. Market Apportionment for High Projection with Gradual HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (6200 Series)

FIGURE A-15. Market Apportionment for High Projection with Gradual HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (6300 Series)

FIGURE A-16. Market Apportionment for High Projection with Abrupt HWM Sales Phaseout and 1977 Startup of Power Reactor Cesium Recovery (6500 Series)

FIGURE A-17. Market Apportionment for High Projection with Abrupt HWM Sales Phaseout and 1980 Startup of Power Reactor Cesium Recovery (6600 Series)

FIGURE A-18. Market Apportionment for High Projection with Abrupt HWM Sales Phaseout and 1982 Startup of Power Reactor Cesium Recovery (6700 Series)

TABLE A-1. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	4121	4122	4123	4124	4128	4129	4131	4132	4133	4134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.7	8.7	8.7	8.7	8.7	8.7	8.7	13.0	13.0	8.7
Levelized Load, MCi	7.1	7.1	7.1	7.1	7.1	7.1	7.7	9.7	6.8	7.5
Levelized Operating Costs, ¢/Ci	8.7	11.7	7.1	13.9	4.8	12.5	8.2	7.7	9.5	8.4
Levelized Capital Costs, ¢/Ci	36.7	52.3	25.7	67.7	36.4	37.0	23.7	27.1	42.6	35.0
Required Net Price, ¢/Ci	45.3	64.1	32.9	81.5	41.2	49.5	32.0	34.9	52.1	43.4

A.10

TABLE A-2. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	4221	4222	4223	4224	4228	4229	4231	4232	4233	4234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.0	10.0	10.0	10.0	10.0	10.0	10.0	15.3	15.3	10.0
Levelized Load, MCi	8.2	8.2	8.2	8.2	8.2	8.2	8.9	11.3	8.0	8.7
Levelized Operating Costs, ¢/Ci	8.1	11.0	6.8	12.9	4.5	11.8	7.8	7.3	8.9	7.9
Levelized Capital Costs, ¢/Ci	32.8	46.9	23.1	60.6	32.6	33.1	21.3	24.5	38.3	31.1
Required Net Price, ¢/Ci	41.0	57.8	29.8	73.5	37.1	44.9	29.0	31.8	47.2	38.9

A.11

TABLE A-3. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	4321	4322	4323	4324	4328	4329	4331	4332	4333	4334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	11.2	11.2	11.2	11.2	11.2	11.2	11.2	17.0	17.0	17.0
Levelized Load, MCi	9.3	9.3	9.3	9.3	9.3	9.3	10.1	12.6	9.0	9.7
Levelized Operating Costs, ¢/Ci	7.7	10.4	6.5	12.1	4.3	11.3	7.4	7.1	8.4	8.1
Levelized Capital Costs, ¢/Ci	30.0	42.9	21.1	55.4	29.8	30.3	19.5	22.8	35.2	32.5
Required Net Price, ¢/Ci	37.8	53.3	27.6	67.6	34.1	41.6	26.9	29.8	43.6	40.5

A.12

TABLE A-4. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	4521	4522	4523	4524	4528	4529	4531	4532	4533	4534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	14.2	6.6
Levelized Load, MCi	9.3	9.3	9.3	9.3	9.3	9.3	9.9	10.7	8.7	9.0
Levelized Operating Costs, ¢/Ci	7.7	10.3	6.5	12.0	4.3	11.2	7.4	7.1	8.3	7.3
Levelized Capital Costs, ¢/Ci	29.7	42.3	20.8	54.7	29.4	29.9	19.5	23.3	34.2	27.2
Required Net Price, ¢/Ci	37.3	52.7	27.3	66.8	33.7	41.2	27.0	30.4	42.5	34.6

A.13

TABLE A-5. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	4621	4622	4623	4624	4628	4629	4631	4632	4633	4634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.3	10.3	10.3	10.3	10.3	10.3	14.2	10.3	18.1	10.3
Levelized Load, MCi	12.1	12.1	12.1	12.1	12.1	12.1	13.8	13.1	12.4	13.2
Levelized Operating Costs, ¢/Ci	6.7	8.9	5.8	10.2	3.8	9.9	6.6	6.5	7.2	6.5
Levelized Capital Costs, ¢/Ci	22.6	32.2	15.9	41.6	22.4	22.8	15.2	19.0	26.0	20.8
Required Net Price, ¢/Ci	29.3	41.1	21.6	51.8	26.2	32.8	21.8	25.4	33.2	27.3

A.14

TABLE A-6. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	4721	4722	4723	4724	4728	4729	4731	4732	4733	4734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	11.9	11.9	11.9	11.9	11.9	11.9	11.9	16.1	20.2	11.9
Levelized Load, MCi	14.0	14.0	14.0	14.0	14.0	14.0	14.5	17.0	14.1	14.9
Levelized Operating Costs, ¢/Ci	6.4	8.5	5.6	9.7	3.6	9.6	6.3	6.1	6.9	6.2
Levelized Capital Costs, ¢/Ci	20.4	29.1	14.4	37.6	20.2	20.6	13.8	16.7	23.8	19.2
Required Net Price, ¢/Ci	26.8	37.6	19.9	47.3	23.8	30.2	20.1	22.8	30.6	25.4

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TABLE A-7. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	5121	5122	5123	5124	5128	5129	5131	5132	5133	5134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.3	14.3	14.3	14.3	14.3	14.3	14.3	21.7	21.7	14.3
Levelized Load, MCi	11.6	11.6	11.6	11.6	11.6	11.6	12.7	16.2	11.2	12.4
Levelized Operating Costs, ¢/Ci	7.1	9.6	6.1	11.1	4.0	10.5	6.9	6.5	7.8	6.9
Levelized Capital Costs, ¢/Ci	25.8	36.8	18.1	47.5	25.5	26.0	16.6	19.2	30.5	24.3
Required Net Price, ¢/Ci	32.9	46.3	24.2	58.6	29.6	36.6	23.5	25.7	38.3	31.2

TABLE A-8. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	5221	5222	5223	5224	5228	5229	5231	5232	5233	5234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	16.9	16.9	16.9	16.9	16.9	16.9	16.9	26.3	26.3	26.3
Levelized Load, MCi	14.0	14.0	14.0	14.0	14.0	14.0	15.2	19.4	13.6	14.9
Levelized Operating Costs, ¢/Ci	6.7	8.9	5.8	10.2	3.8	10.0	6.5	6.2	7.3	7.0
Levelized Capital Costs, ¢/Ci	22.7	32.3	15.9	41.7	22.4	22.9	14.7	17.2	26.9	24.6
Required Net Price, ¢/Ci	29.4	41.3	21.7	52.0	26.2	32.9	21.1	23.4	34.2	31.6

A.17

BNWL-1686

TABLE A-9. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	5321	5322	5323	5324	5328	5329	5331	5332	5333	5334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	29.4	19.3
Levelized Load, MCi	16.0	16.0	16.0	16.0	16.0	16.0	17.4	18.7	15.4	16.8
Levelized Operating Costs, ¢/Ci	6.4	8.5	5.6	9.7	3.7	9.6	6.2	6.0	7.0	6.3
Levelized Capital Costs, ¢/Ci	20.7	29.5	14.5	38.0	20.5	20.9	13.4	16.0	24.7	19.7
Required Net Price, ¢/Ci	27.1	38.0	20.1	47.8	24.1	30.5	19.6	22.0	31.7	26.0

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BNWL-1686

TABLE A-10. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	5521	5522	5523	5524	5528	5529	5531	5532	5533	5534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	17.3	17.3	17.3	17.3	17.3	17.3	17.3	10.5	23.6	10.5
Levelized Load, MCi	15.1	15.1	15.1	15.1	15.1	15.1	16.1	13.1	14.2	14.4
Levelized Operating Costs, ¢/Ci	6.5	8.6	5.6	9.9	3.7	9.7	6.3	6.5	7.0	6.2
Levelized Capital Costs, ¢/Ci	21.2	30.2	14.9	39.0	20.9	21.4	13.9	19.0	24.8	19.2
Required Net Price, ¢/Ci	27.7	38.8	20.5	48.8	24.6	31.1	20.2	25.5	31.8	25.4

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TABLE A-11. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	5621	5622	5623	5624	5628	5629	5631	5632	5633	5634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	17.2	17.2	17.2	17.2	17.2	17.2	17.2	24.0	30.9	17.2
Levelized Load, MCi	20.2	20.2	20.2	20.2	20.2	20.2	21.0	25.2	20.9	22.2
Levelized Operating Costs, ¢/Ci	5.8	7.6	5.1	8.5	3.3	8.7	5.7	5.5	6.2	5.6
Levelized Capital Costs, ¢/Ci	15.8	22.6	11.2	29.1	15.6	16.0	10.7	12.8	18.6	14.4
Required Net Price, ¢/Ci	21.6	30.1	16.3	37.6	19.0	24.8	16.4	18.4	24.8	20.0

A.20

BNWL-1686

TABLE A-12. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	5721	5722	5723	5724	5728	5729	5731	5732	5733	5734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	20.3	20.3	20.3	20.3	20.3	20.3	20.3	27.6	34.8	20.3
Levelized Load, MCi	23.8	23.8	23.8	23.8	23.8	23.8	24.8	29.1	24.1	25.5
Levelized Operating Costs, ¢/Ci	5.5	7.3	5.0	8.1	3.2	8.4	5.5	5.4	5.9	5.4
Levelized Capital Costs, ¢/Ci	14.2	20.2	10.0	26.1	14.0	14.4	9.6	11.7	16.9	13.2
Required Net Price, ¢/Ci	19.7	27.5	15.0	34.1	17.2	22.8	15.0	17.1	22.8	18.6

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TABLE A-13. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>6121</u>	<u>6122</u>	<u>6123</u>	<u>6124</u>	<u>6128</u>	<u>6129</u>	<u>6131</u>	<u>6132</u>	<u>6133</u>	<u>6134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	20.5	20.5	20.5	20.5	20.5	20.5	20.5	33.9	33.9	20.5
Levelized Load, MCi	16.6	16.6	16.6	16.6	16.6	16.6	18.1	25.1	16.6	18.7
Levelized Operating Costs, ¢/Ci	6.4	8.5	5.5	9.6	3.6	9.5	6.1	5.8	6.9	6.1
Levelized Capital Costs, ¢/Ci	20.3	29.0	14.3	37.4	20.1	20.5	13.1	14.6	24.2	18.0
Required Net Price, ¢/Ci	26.7	37.4	19.8	47.0	23.7	30.1	19.2	20.3	31.2	24.1

TABLE A-14. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	6221	6222	6223	6224	6228	6229	6231	6232	6233	6234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	28.4	28.4	28.4	28.4	28.4	28.4	28.4	48.6	48.6	48.6
Levelized Load, MCi	23.2	23.2	23.2	23.2	23.2	23.2	25.3	35.6	23.5	26.8
Levelized Operating Costs, ¢/Ci	5.8	7.7	5.2	8.6	3.4	8.8	5.6	5.4	6.3	6.0
Levelized Capital Costs, ¢/Ci	16.3	23.3	11.5	30.0	16.1	16.5	10.5	11.9	19.6	17.3
Required Net Price, ¢/Ci	22.1	30.9	16.6	38.6	19.5	25.3	16.1	17.2	25.9	23.3

TABLE A-15. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>6321</u>	<u>6322</u>	<u>6323</u>	<u>6324</u>	<u>6328</u>	<u>6329</u>	<u>6331</u>	<u>6332</u>	<u>6333</u>	<u>6334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	36.2	36.2	36.2	36.2	36.2	36.2	36.2	60.6	60.6	36.2
Levelized Load, MCi	29.7	29.7	29.7	29.7	29.7	29.7	32.4	44.5	29.8	33.3
Levelized Operating Costs, ¢/Ci	5.5	7.2	4.9	8.0	3.2	8.4	5.3	5.2	5.9	5.3
Levelized Capital Costs, ¢/Ci	14.0	19.9	9.9	25.7	13.8	14.2	9.0	10.4	17.1	12.5
Required Net Price, ¢/Ci	19.5	27.2	14.8	33.7	17.0	22.6	14.4	15.6	23.0	17.8

TABLE A-16. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	6521	6522	6523	6524	6528	6529	6531	6532	6533	6534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	24.5	24.5	24.5	24.5	24.5	24.5	24.5	36.4	36.4	13.7
Levelized Load, MCi	21.2	21.2	21.2	21.2	21.2	21.2	22.8	29.0	20.4	19.1
Levelized Operating Costs, ¢/Ci	5.9	7.8	5.2	8.8	3.4	8.9	5.7	5.5	6.4	5.7
Levelized Capital Costs, ¢/Ci	16.9	24.1	11.9	31.1	16.7	17.1	11.1	13.0	20.3	15.6
Required Net Price, ¢/Ci	22.8	31.9	17.1	39.9	20.1	26.0	16.8	18.5	26.7	21.4

A.25

BNWL-1686

TABLE A-17. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>6621</u>	<u>6622</u>	<u>6623</u>	<u>6624</u>	<u>6628</u>	<u>6629</u>	<u>6631</u>	<u>6632</u>	<u>6633</u>	<u>6634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	39.6	39.6	39.6	39.6	39.6	39.6	39.6	39.6	55.5	26.1
Levelized Load, MCi	36.4	36.4	36.4	36.4	36.4	36.4	38.6	41.4	34.4	35.5
Levelized Operating Costs, ¢/Ci	5.2	6.8	4.7	7.5	3.1	8.0	5.1	5.0	5.5	5.0
Levelized Capital Costs, ¢/Ci	11.9	16.9	8.4	21.8	11.7	12.1	7.8	9.4	14.3	10.4
Required Net Price, ¢/Ci	17.1	23.7	13.1	29.2	14.7	20.1	13.0	14.5	19.8	15.4

TABLE A-18. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	6721	6722	6723	6724	6728	6729	6731	6732	6733	6734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	34.3	34.3	34.3	34.3	34.3	34.3	50.8	50.8	50.8	34.3
Levelized Load, MCi	40.3	40.3	40.3	40.3	40.3	40.3	49.6	53.3	38.7	46.2
Levelized Operating Costs, ¢/Ci	5.0	6.5	4.6	7.0	2.9	7.7	4.9	4.8	5.3	4.8
Levelized Capital Costs, ¢/Ci	10.2	14.5	7.2	18.6	10.0	10.4	68	8.1	12.3	8.9
Required Net Price, ¢/Ci	15.1	20.9	11.8	25.7	12.9	18.1	11.7	13.0	17.5	13.7

TABLE A-19. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>4121</u>	<u>4122</u>	<u>4123</u>	<u>4124</u>	<u>4128</u>	<u>4129</u>	<u>4131</u>	<u>4132</u>	<u>4133</u>	<u>4134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.2	5.2	5.2	5.2	5.2	5.2	5.2	6.5	6.5	3.4
Levelized Load, MCi	4.3	4.3	4.3	4.3	4.3	4.3	4.6	5.4	4.0	4.3
Levelized Operating Costs, ¢/Ci	11.0	15.0	8.8	18.1	5.9	15.6	10.5	9.8	11.9	10.5
Levelized Capital Costs, ¢/Ci	53.4	76.2	37.4	98.6	53.0	53.7	35.0	40.7	60.2	49.8
Required Net Price, ¢/Ci	64.4	91.2	46.2	116.8	59.0	69.3	45.5	50.5	72.1	60.2

TABLE A-20. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	<u>4221</u>	<u>4222</u>	<u>4223</u>	<u>4224</u>	<u>4228</u>	<u>4229</u>	<u>4231</u>	<u>4232</u>	<u>4233</u>	<u>4234</u>
					Low	High		Longer		
Description	Base	Single	Low	High	Oper.	Oper.	Lower	Econ.	Zero	High
	Case	Prod.	Cap.	Cap.	Cost	Cost	ROI	Life	Learn	Learn
Plant Size, MCi	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.7	7.7	3.8
Levelized Load, MCi	5.1	5.1	5.1	5.1	5.1	5.1	5.4	6.3	4.7	5.0
Levelized Operating Costs, ¢/Ci	10.1	13.8	8.2	16.5	5.5	14.4	9.7	9.1	11.0	9.6
Levelized Capital Costs, ¢/Ci	47.1	67.3	33.1	87.1	46.8	47.5	31.0	36.3	53.4	43.9
Required Net Price, ¢/Ci	57.3	81.1	41.2	103.6	52.3	61.9	40.7	45.5	64.4	53.5

A.29

TABLE A-21. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>4321</u>	<u>4322</u>	<u>4323</u>	<u>4324</u>	<u>4328</u>	<u>4329</u>	<u>4331</u>	<u>4332</u>	<u>4333</u>	<u>4334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	8.5	4.4
Levelized Load, MCi	5.7	5.7	5.7	5.7	5.7	5.7	6.1	6.6	5.3	5.6
Levelized Operating Costs, ¢/Ci	9.5	13.0	7.7	15.5	5.2	13.7	9.2	8.7	10.3	9.1
Levelized Capital Costs, ¢/Ci	43.0	61.4	30.2	79.4	42.7	43.3	28.3	33.5	48.3	39.7
Required Net Price, ¢/Ci	52.6	74.4	38.0	94.9	47.9	57.0	37.5	42.2	58.9	48.8

A.30

TABLE A-22. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	4521	4522	4523	4524	4528	4529	4531	4532	4533	4534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.3	5.3	5.3	5.3	5.3	5.3	5.3	6.3	7.1	5.3
Levelized Load, MCi	5.8	5.8	5.8	5.8	5.8	5.8	6.0	6.6	5.5	5.8
Levelized Operating Costs, ¢/Ci	9.2	12.5	7.5	14.8	5.0	13.2	9.0	8.6	9.8	9.1
Levelized Capital Costs, ¢/Ci	40.4	57.7	28.4	74.6	40.1	40.7	27.4	33.0	45.3	40.0
Required Net Price, ¢/Ci	49.6	70.1	35.9	89.4	45.2	53.9	36.3	41.6	55.1	49.1

A.31

TABLE A-23. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	4621	4622	4623	4624	4628	4629	4631	4632	4633	4634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.6	8.3
Levelized Load, MCi	8.5	8.5	8.5	8.5	8.5	8.5	8.7	9.4	8.0	8.5
Levelized Operating Costs, ¢/Ci	7.8	10.5	6.5	12.2	4.3	11.4	7.7	7.4	8.1	7.8
Levelized Capital Costs, ¢/Ci	30.4	43.4	21.4	56.1	30.2	30.7	20.9	24.9	32.6	30.4
Required Net Price, ¢/Ci	38.2	53.9	27.9	68.3	34.5	42.0	28.6	32.3	40.7	38.2

TABLE A-24. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	4721	4722	4723	4724	4728	4729	4731	4732	4733	4734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.8	9.5
Levelized Load, MCi	9.7	9.7	9.7	9.7	9.7	9.7	9.8	10.7	9.2	9.7
Levelized Operating Costs, ¢/Ci	7.4	10.0	6.3	11.6	4.2	10.9	7.3	7.1	7.6	7.4
Levelized Capital Costs, ¢/Ci	27.7	39.6	19.5	51.2	27.5	28.0	19.1	22.7	29.4	27.7
Required Net Price, ¢/Ci	35.2	49.5	25.8	62.7	31.7	38.9	26.5	29.8	37.0	35.2

TABLE A-25. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	5121	5122	5123	5124	5128	5129	5131	5132	5133	5134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.6	8.6	8.6	8.6	8.6	8.6	8.6	10.9	10.9	5.4
Levelized Load, MCi	7.1	7.1	7.1	7.1	7.1	7.1	7.7	8.9	6.6	7.0
Levelized Operating Costs, ¢/Ci	8.6	11.7	7.1	13.8	4.8	12.5	8.3	7.9	9.3	8.2
Levelized Capital Costs, ¢/Ci	36.5	52.0	25.6	67.3	36.2	36.8	23.9	28.0	41.7	33.6
Required Net Price, ¢/Ci	45.1	63.7	32.7	81.1	40.9	49.2	32.2	35.8	51.1	41.8

A.34

BNWL-1686

TABLE A-26. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	5221	5222	5223	5224	5228	5229	5231	5232	5233	5234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	13.2	6.4
Levelized Load, MCi	8.6	8.6	8.6	8.6	8.6	8.6	9.2	10.0	8.0	8.4
Levelized Operating Costs, ¢/Ci	8.0	10.7	6.7	12.6	4.4	11.6	7.7	7.3	8.6	7.6
Levelized Capital Costs, ¢/Ci	31.7	45.2	22.3	58.5	31.4	32.0	20.8	24.7	36.5	29.0
Required Net Price, ¢/Ci	39.7	56.0	28.9	71.1	35.9	43.6	28.5	32.0	45.1	36.6

TABLE A-27. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>5321</u>	<u>5322</u>	<u>5323</u>	<u>5324</u>	<u>5328</u>	<u>5329</u>	<u>5331</u>	<u>5332</u>	<u>5333</u>	<u>5334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	14.7	7.5
Levelized Load, MCi	9.8	9.8	9.8	9.8	9.8	9.8	10.5	11.4	9.1	9.7
Levelized Operating Costs, ¢/Ci	7.6	10.2	6.4	11.8	4.2	11.1	7.3	7.0	8.1	7.2
Levelized Capital Costs, ¢/Ci	28.8	41.2	20.3	53.2	28.6	29.1	19.1	22.4	33.0	26.1
Required Net Price, ¢/Ci	36.4	51.3	26.6	65.0	32.8	40.2	26.3	29.5	41.1	33.3

TABLE A-28. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	5521	5522	5523	5524	5528	5529	5531	5532	5533	5534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.4	8.4	8.4	8.4	8.4	8.4	8.4	10.4	11.8	8.4
Levelized Load, MCi	9.3	9.3	9.3	9.3	9.3	9.3	9.6	10.8	8.9	9.5
Levelized Operating Costs, ¢/Ci	7.4	10.0	6.3	11.6	4.2	10.9	7.3	7.1	8.0	7.4
Levelized Capital Costs, ¢/Ci	28.0	40.0	19.7	51.7	27.8	28.3	18.9	23.0	32.0	27.4
Required Net Price, ¢/Ci	35.5	50.0	26.0	63.3	31.9	39.2	26.2	30.0	40.0	34.8

TABLE A-29. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>5621</u>	<u>5622</u>	<u>5623</u>	<u>5624</u>	<u>5628</u>	<u>5629</u>	<u>5631</u>	<u>5632</u>	<u>5633</u>	<u>5634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	15.5	13.8
Levelized Load, MCi	14.3	14.3	14.3	14.3	14.3	14.3	14.6	15.8	13.6	14.3
Levelized Operating Costs, ¢/Ci	6.5	8.6	5.6	9.8	3.7	9.6	6.4	6.2	6.7	6.5
Levelized Capital Costs, ¢/Ci	20.9	29.8	14.7	38.5	20.7	21.1	14.3	17.1	22.6	20.9
Required Net Price, ¢/Ci	27.4	38.4	20.3	48.3	24.4	30.8	20.7	23.3	29.3	27.4

A.38

TABLE A-30. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>5721</u>	<u>5722</u>	<u>5723</u>	<u>5724</u>	<u>5728</u>	<u>5729</u>	<u>5731</u>	<u>5732</u>	<u>5733</u>	<u>5734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.8	16.2
Levelized Load, MCi	16.5	16.5	16.5	16.5	16.5	16.5	16.8	18.3	15.7	16.5
Levelized Operating Costs, ¢/Ci	6.2	8.2	5.4	9.3	3.5	9.3	6.1	5.9	6.4	6.2
Levelized Capital Costs, ¢/Ci	19.0	27.1	13.4	34.9	18.8	19.2	13.1	15.5	20.2	19.0
Required Net Price, ¢/Ci	25.2	35.3	18.8	44.2	22.3	28.5	19.2	21.5	26.6	25.2

A.39

TABLE A-31. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>6121</u>	<u>6122</u>	<u>6123</u>	<u>6124</u>	<u>6128</u>	<u>6129</u>	<u>6131</u>	<u>6132</u>	<u>6133</u>	<u>6134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.3	12.3	12.3	12.3	12.3	12.3	12.3	17.0	17.0	7.0
Levelized Load, MCi	10.2	10.2	10.2	10.2	10.2	10.2	11.1	13.7	9.6	9.4
Levelized Operating Costs, ¢/Ci	7.4	10.0	6.3	11.6	4.2	10.9	7.2	6.8	8.1	7.2
Levelized Capital Costs, ¢/Ci	28.0	40.0	19.7	51.7	27.8	28.3	18.2	20.9	32.9	26.3
Required Net Price, ¢/Ci	35.5	50.0	26.0	63.3	31.9	39.2	25.4	27.7	41.0	33.6

TABLE A-32. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	6221	6222	6223	6224	6228	6229	6231	6232	6233	6234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	17.1	17.1	17.1	17.1	17.1	17.1	17.1	24.3	24.3	9.7
Levelized Load, MCi	14.4	14.4	14.4	14.4	14.4	14.4	15.5	19.4	13.6	13.2
Levelized Operating Costs, ¢/Ci	6.6	8.8	5.7	10.1	3.8	9.8	6.4	6.1	7.2	6.4
Levelized Capital Costs, ¢/Ci	22.0	31.4	15.5	40.6	21.8	22.2	14.3	16.7	26.1	20.4
Required Net Price, ¢/Ci	28.6	40.2	21.2	50.6	25.5	32.1	20.7	22.8	33.3	26.8

A.41

BNWL-1686

TABLE A-33. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	6321	6322	6323	6324	6328	6329	6331	6332	6333	6334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	21.7	21.7	21.5	21.7	21.7	21.7	21.7	30.3	30.3	12.7
Levelized Load, MCi	18.4	18.4	18.4	18.4	18.4	18.4	19.8	24.4	17.3	17.2
Levelized Operating Costs, ¢/Ci	6.2	8.2	5.4	9.2	3.5	9.2	6.0	5.8	6.7	5.9
Levelized Capital Costs, ¢/Ci	18.7	26.6	13.1	34.4	18.5	18.9	12.2	14.4	22.2	17.0
Required Net Price, ¢/Ci	24.8	34.8	18.5	43.6	22.0	28.1	18.2	20.2	28.9	22.9

TABLE A-34. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	<u>6521</u>	<u>6522</u>	<u>6523</u>	<u>6524</u>	<u>6528</u>	<u>6529</u>	<u>6531</u>	<u>6532</u>	<u>6533</u>	<u>6534</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	11.0	11.0	11.0	11.0	11.0	11.0	14.7	18.2	18.2	11.0
Levelized Load, MCi	12.5	12.5	12.5	12.5	12.5	12.5	14.2	16.5	12.5	13.6
Levelized Operating Costs, ¢/Ci	6.7	8.9	5.7	10.2	3.8	9.9	6.5	6.3	7.2	6.4
Levelized Capital Costs, ¢/Ci	22.3	31.9	15.7	41.2	22.1	22.6	15.0	17.8	25.9	20.6
Required Net Price, ¢/Ci	29.0	40.8	21.5	51.3	25.9	32.5	21.5	24.1	33.1	27.0

A.43

TABLE A-35. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>6621</u>	<u>6622</u>	<u>6623</u>	<u>6624</u>	<u>6628</u>	<u>6629</u>	<u>6631</u>	<u>6632</u>	<u>6633</u>	<u>6634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	23.8	20.9
Levelized Load, MCi	23.0	23.0	23.0	23.0	23.0	23.0	23.8	25.2	20.9	23.5
Levelized Operating Costs, ¢/Ci	5.6	7.4	5.0	8.2	3.3	8.5	5.5	5.4	5.9	5.6
Levelized Capital Costs, ¢/Ci	14.8	21.1	10.4	27.2	14.6	15.0	10.0	12.3	17.0	14.5
Required Net Price, ¢/Ci	20.4	28.5	15.4	35.4	17.9	23.5	15.6	17.7	22.9	20.1

TABLE A-36. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% after 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>6721</u>	<u>6722</u>	<u>6723</u>	<u>6724</u>	<u>6728</u>	<u>6729</u>	<u>6731</u>	<u>6732</u>	<u>6733</u>	<u>6734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	30.5	27.4
Levelized Load, MCi	29.9	29.9	29.9	29.9	29.9	29.9	30.9	32.8	27.2	30.2
Levelized Operating Costs, ¢/Ci	5.3	6.9	4.8	7.7	3.1	8.1	5.2	5.2	5.5	5.3
Levelized Capital Costs, ¢/Ci	12.5	17.9	8.9	23.1	12.4	12.8	8.5	10.4	14.3	12.4
Required Net Price, ¢/Ci	17.8	24.8	13.7	30.7	15.5	20.9	13.8	15.5	19.9	17.7

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TABLE A-37. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	4121	4122	4123	4124	4128	4129	4131	4132	4133	4134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	4.4	4.4	4.4	4.4	4.4	4.4	4.4	6.5	6.5	4.4
Levelized Load, MCi	3.6	3.6	3.6	3.6	3.6	3.6	3.9	4.9	3.4	3.8
Levelized Operating Costs, ¢/Ci	12.2	16.8	9.6	20.4	6.5	17.1	11.5	10.5	13.4	11.8
Levelized Capital Costs, ¢/Ci	62.3	88.9	43.7	115.1	61.9	62.7	40.3	45.0	70.7	59.3
Required Net Price, ¢/Ci	74.5	105.7	53.3	135.6	68.4	79.8	51.8	55.5	84.1	81.4

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BNWL-1686

TABLE A-38. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	<u>4221</u>	<u>4222</u>	<u>4223</u>	<u>4224</u>	<u>4228</u>	<u>4229</u>	<u>4231</u>	<u>4232</u>	<u>4233</u>	<u>4234</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.0	5.0	5.0	5.0	5.0	5.0	5.0	7.7	7.7	5.0
Levelized Load, MCi	4.1	4.1	4.1	4.1	4.1	4.1	4.5	5.7	4.0	4.4
Levelized Operating Costs, ¢/Ci	11.2	15.4	8.9	18.6	6.1	15.9	10.6	9.7	12.3	10.8
Levelized Capital Costs, ¢/Ci	55.3	78.9	38.8	102.2	54.9	55.7	35.8	40.2	62.8	52.3
Required Net Price, ¢/Ci	66.5	94.3	47.7	120.8	61.0	71.5	46.4	49.9	75.1	63.1

TABLE A-39. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	4321	4322	4323	4324	4328	4329	4331	4332	4333	4334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.6	5.6	5.6	5.6	5.6	5.6	5.6	8.5	8.5	5.6
Levelized Load, MCi	4.7	4.7	4.7	4.7	4.7	4.7	5.1	6.3	4.5	4.9
Levelized Operating Costs, ¢/Ci	10.6	14.4	8.5	17.4	5.7	15.0	10.0	9.3	11.6	10.3
Levelized Capital Costs, ¢/Ci	50.5	72.0	35.4	93.2	50.1	50.8	32.7	37.3	57.7	48.3
Required Net Price, ¢/Ci	61.1	86.5	43.9	110.6	55.9	65.8	42.7	46.6	69.3	58.6

TABLE A-40. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	4521	4522	4523	4524	4528	4529	4531	4532	4533	4534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.3	5.3	5.3	5.3	5.3	5.3	5.3	7.1	7.1	3.3
Levelized Load, MCi	4.6	4.6	4.6	4.6	4.6	4.6	4.9	5.8	4.4	4.5
Levelized Operating Costs, ¢/Ci	10.5	14.4	8.4	17.3	5.7	14.9	10.1	9.5	11.4	10.1
Levelized Capital Costs, ¢/Ci	50.1	71.4	35.1	92.5	49.7	50.4	33.0	38.5	56.8	47.2
Required Net Price, ¢/Ci	60.6	85.8	43.6	109.8	55.4	65.3	43.0	48.0	68.2	57.4

TABLE A-41. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>4621</u>	<u>4622</u>	<u>4623</u>	<u>4624</u>	<u>4628</u>	<u>4629</u>	<u>4631</u>	<u>4632</u>	<u>4633</u>	<u>4634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	9.0	5.2
Levelized Load, MCi	6.6	6.6	6.6	6.6	6.6	6.6	6.9	7.5	6.2	6.6
Levelized Operating Costs, ¢/Ci	8.8	11.9	7.2	14.1	4.8	12.7	8.5	8.2	9.5	8.4
Levelized Capital Costs, ¢/Ci	37.8	53.9	26.5	69.7	37.5	38.0	25.2	30.1	42.5	35.1
Required Net Price, ¢/Ci	46.6	65.8	33.8	83.8	42.3	50.7	33.8	38.2	52.0	43.6

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BNWL-1686

TABLE A-42. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	4721	4722	4723	4724	4728	4729	4731	4732	4733	4734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.0	6.0	6.0	6.0	6.0	6.0	8.0	8.0	10.1	6.0
Levelized Load, MCi	7.0	7.0	7.0	7.0	7.0	7.0	7.8	8.5	7.1	7.5
Levelized Operating Costs, ¢/Ci	8.3	11.2	6.9	13.2	4.6	12.0	8.1	7.8	8.9	8.0
Levelized Capital Costs, ¢/Ci	34.1	48.6	23.9	62.9	33.8	34.4	23.0	27.3	38.4	32.0
Required Net Price, ¢/Ci	42.4	59.8	30.8	76.1	38.4	46.4	31.1	35.1	47.3	40.0

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BNWL-1686

TABLE A-43. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	5121	5122	5123	5124	5128	5129	5131	5132	5133	5134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.2	7.2	7.2	7.2	7.2	7.2	7.2	10.9	10.9	7.2
Levelized Load, MCi	5.8	5.8	5.8	5.8	5.8	5.8	6.4	8.1	5.6	6.2
Levelized Operating Costs, ¢/Ci	9.5	12.9	7.7	15.4	5.2	13.6	9.0	8.3	10.4	9.1
Levelized Capital Costs, ¢/Ci	12.6	60.7	29.9	78.6	42.2	42.9	27.5	30.9	49.1	40.1
Required Net Price, ¢/Ci	52.0	73.6	37.6	93.9	47.4	56.4	36.5	39.2	59.4	49.2

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BNWL-7686

TABLE A-44. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	5221	5222	5223	5224	5228	5229	5231	5232	5233	5234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	13.2	8.5
Levelized Load, MCi	7.0	7.0	7.0	7.0	7.0	7.0	7.6	8.2	6.8	7.4
Levelized Operating Costs, ¢/Ci	8.7	11.8	7.2	13.9	4.8	12.6	8.3	8.0	9.5	8.4
Levelized Capital Costs, ¢/Ci	37.0	52.8	26.0	68.3	36.7	37.3	23.9	28.6	42.9	34.8
Required Net Price, ¢/Ci	45.7	64.6	33.2	82.2	41.5	49.9	32.2	36.6	52.4	43.2

TABLE A-45. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	5321	5322	5323	5324	5328	5329	5331	5332	5333	5334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.7	9.7	9.7	9.7	9.7	9.7	9.7	14.7	14.7	9.7
Levelized Load, MCi	8.0	8.0	8.0	8.0	8.0	8.0	8.7	10.9	7.7	8.4
Levelized Operating Costs, ¢/Ci	8.2	11.1	6.8	13.0	4.6	11.9	7.8	7.4	9.0	8.0
Levelized Capital Costs, ¢/Ci	33.5	47.8	23.5	61.8	33.2	33.8	21.7	25.2	39	31.9
Required Net Price, ¢/Ci	41.7	58.9	30.4	74.8	37.8	45.7	29.5	32.6	48.0	39.9

A.54

BNWL-1686

TABLE A-46. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	5521	5522	5523	5524	5528	5529	5531	5532	5533	5534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.6	8.6	8.6	8.6	8.6	8.6	8.6	11.8	11.8	5.3
Levelized Load, MCi	7.6	7.6	7.6	7.6	7.6	7.6	8.1	9.6	7.1	7.2
Levelized Operating Costs, ¢/Ci	8.3	11.3	6.9	13.3	4.6	12.1	8.0	7.7	9.1	8.0
Levelized Capital Costs, ¢/Ci	34.5	49.3	24.2	63.7	34.2	34.8	22.7	26.7	39.8	32.2
Required Net Price, ¢/Ci	42.9	60.5	31.2	77.0	38.9	46.9	30.7	34.4	48.9	40.3

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BNWL-1686

TABLE A-47. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>5621</u>	<u>5622</u>	<u>5623</u>	<u>5624</u>	<u>5628</u>	<u>5629</u>	<u>5631</u>	<u>5632</u>	<u>5633</u>	<u>5634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.0	12.0	8.6	12.0	12.0	12.0	12.0	12.0	15.5	8.6
Levelized Load, MCi	11.1	11.1	10.1	11.1	11.1	11.1	11.7	12.6	10.5	11.1
Levelized Operating Costs, ¢/Ci	7.1	9.6	6.1	11.0	4.0	10.5	7.0	6.7	7.6	6.8
Levelized Capital Costs, ¢/Ci	25.8	36.8	18.2	47.5	25.5	26.0	17.2	20.5	29.3	23.5
Required Net Price, ¢/Ci	32.9	46.3	24.2	58.5	29.5	36.5	24.1	27.2	37.0	30.4

TABLE A-48. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	5721	5722	5723	5724	5728	5729	5731	5732	5733	5734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.2	10.2	10.2	10.2	10.2	10.2	10.2	13.8	17.4	10.2
Levelized Load, MCi	11.9	11.9	11.9	11.9	11.9	11.9	12.4	14.5	12.1	12.8
Levelized Operating Costs, ¢/Ci	6.7	9.0	5.8	10.3	3.8	10.0	6.6	6.4	7.2	6.5
Levelized Capital Costs, ¢/Ci	22.9	32.6	16.1	42.1	22.6	23.1	15.5	18.5	26.4	21.4
Required Net Price, ¢/Ci	29.6	41.6	21.9	52.4	26.5	33.1	22.1	24.9	33.6	27.9

A.57

BNWL-1686

TABLE A-49. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>6121</u>	<u>6122</u>	<u>6123</u>	<u>6124</u>	<u>6128</u>	<u>6129</u>	<u>6131</u>	<u>6132</u>	<u>6133</u>	<u>6134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.2	10.2	10.2	10.2	10.2	10.2	17.0	17.0	17.0	10.2
Levelized Load, MCi	8.3	8.3	8.3	8.3	8.3	8.3	10.6	12.6	8.3	9.4
Levelized Operating Costs, ¢/Ci	8.1	11.0	6.8	12.9	4.5	11.8	7.7	7.1	8.8	7.6
Levelized Capital Costs, ¢/Ci	32.9	46.9	23.1	60.6	32.6	33.1	21.0	22.8	38.0	29.2
Required Net Price, ¢/Ci	41.0	57.9	29.8	73.5	37.1	45.0	28.7	29.8	46.8	36.8

A.58

BNWL-1686

TABLE A-50. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	6221	6222	6223	6224	6228	6229	6231	6232	6233	6234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.2	14.2	14.2	14.2	14.2	14.2	14.2	24.3	24.3	14.2
Levelized Load, MCi	11.6	11.6	11.6	11.6	11.6	11.6	12.7	17.8	11.8	13.2
Levelized Operating Costs, ¢/Ci	7.1	9.6	6.1	11.1	4.0	10.5	6.8	6.3	7.8	6.7
Levelized Capital Costs, ¢/Ci	25.8	36.9	18.2	47.6	25.6	26.1	16.6	18.2	30.2	22.8
Required Net Price, ¢/Ci	33.0	46.4	24.2	58.7	29.6	36.6	23.5	24.5	37.9	29.5

TABLE A-51. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	6321	6322	6323	6324	6328	6329	6331	6332	6333	6334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	18.1	18.1	18.1	18.1	18.1	18.1	18.1	30.3	30.3	18.1
Levelized Load, MCi	14.9	14.9	14.9	14.9	14.9	14.9	16.2	22.3	14.9	16.7
Levelized Operating Costs, ¢/Ci	6.6	8.8	5.7	10.0	3.7	9.8	6.3	6.0	7.1	6.3
Levelized Capital Costs, ¢/Ci	21.8	31.1	15.3	40.1	21.6	22.0	14.0	15.7	25.8	19.5
Required Net Price, ¢/Ci	28.4	39.8	21.0	50.1	25.3	31.8	20.4	21.7	33.0	25.7

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TABLE A-52. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	<u>6521</u>	<u>6522</u>	<u>6523</u>	<u>6524</u>	<u>6528</u>	<u>6529</u>	<u>6531</u>	<u>6532</u>	<u>6533</u>	<u>6534</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.3	12.3	12.3	12.3	12.3	12.3	12.3	18.2	12.3	12.3
Levelized Load, MCi	10.6	10.6	10.6	10.6	10.6	10.6	11.4	14.5	8.5	11.4
Levelized Operating Costs, ¢/Ci	7.3	9.8	6.2	11.4	4.1	10.8	7.1	6.7	8.2	7.0
Levelized Capital Costs, ¢/Ci	27.0	38.6	19.0	49.8	26.8	27.3	17.7	20.2	33.7	25.1
Required Net Price, ¢/Ci	34.3	48.4	25.2	61.2	30.9	38.0	24.7	26.8	42.0	32.1

A.61

TABLE A-53. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	6621	6622	6623	6624	6628	6629	6631	6632	6633	6634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	19.8	19.8	19.8	19.8	19.8	19.8	19.8	27.7	27.7	13.1
Levelized Load, MCi	18.2	18.2	18.2	18.2	18.2	18.2	19.3	23.4	17.2	17.8
Levelized Operating Costs, ¢/Ci	6.1	8.1	5.4	9.1	3.5	9.2	6.0	5.8	6.6	5.9
Levelized Capital Costs, ¢/Ci	18.4	26.2	12.9	33.8	18.2	18.6	12.1	14.5	21.7	16.5
Required Net Price, ¢/Ci	24.5	34.3	18.3	42.9	21.7	27.8	18.1	20.3	28.3	22.4

A.62

TABLE A-54. Detail of Price Requirements for Optimum Power
Reactor Cesium Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	6721	6722	6723	6724	6728	6729	6731	6732	6733	6734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	34.8	17.1
Levelized Load, MCi	23.4	23.4	23.4	23.4	23.4	23.4	24.8	26.6	22.0	23.1
Levelized Operating Costs, ¢/Ci	5.7	7.5	5.1	8.4	3.3	8.7	5.6	5.5	6.1	5.5
Levelized Capital Costs, ¢/Ci	15.6	22.2	11.0	28.6	15.4	15.8	10.3	12.4	18.5	13.9
Required Net Price, ¢/Ci	21.3	29.8	16.1	37.1	18.7	24.5	15.9	17.9	24.6	19.4

TABLE A-55. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	4141	4142	4143	4144	4145	4146	4147	4148
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1975	1974	1974	1974	1974	1974	1974	1975
Plant Size, MCi	7.3	4.9	4.9	4.9	4.9	4.3	4.9	7.3
Levelized Load, MCi	5.0	4.0	4.8	4.3	4.8	4.9	4.7	5.0
Levelized Operating Costs, ¢/Ci	4.1	4.0	3.4	3.4	3.0	3.1	3.9	4.5
Levelized Capital Costs, ¢/Ci	11.5	1.0	6.0	1.6	0.9	1.9	8.9	11.5
Required Net Price, ¢/Ci	15.6		9.5		3.9		12.8	16.0
ROI at Net Price of 5¢/Ci		-8.5		-2.0		32.4		

A.64

BNWL-1686

TABLE A-56. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	4241	4242	4243	4244	4245	4246	4247	4248
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1976	1974	1976	1976	1976
Plant Size, MCi	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
Levelized Load, MCi	11.8	11.2	11.8	11.8	9.9	11.1	11.8	11.8
Levelized Operating Costs, ¢/Ci	3.3	3.0	3.1	3.0	2.7	3.2	3.2	3.8
Levelized Capital Costs, ¢/Ci	4.9	2.0	2.6	2.0	0.5	1.8	3.6	5.3
Required Net Price, ¢/Ci	8.2		5.7		3.2		6.9	9.1
ROI at Net Price of 5¢/Ci		2.1		10.5		49.1		

TABLE A-57. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	4341	4342	4343	4344	4345	4346	4347	4348
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1977	1977	1977	1977	1974	1977	1977	1977
Plant Size, MCi	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4
Levelized Load, MCi	16.5	16.6	16.5	16.5	11.6	15.0	16.6	16.5
Levelized Operating Costs, ¢/Ci	3.2	3.1	3.0	3.0	2.6	3.2	3.1	3.6
Levelized Capital Costs, ¢/Ci	4.0	1.9	2.1	2.0	0.5	1.8	2.9	4.0
Required Net Price, ¢/Ci	7.1		5.1		3.1		6.0	7.6
ROI at Net Price of 5¢/Ci		4.8		14.2		51.1		

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BNWL-1686

TABLE A-58. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	4541	4542	4543	4544	4545	4546	4547	4548
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1974	1974	1974	1974	1974	1974	1974	1974
Plant Size, MCi	4.9	4.9	4.9	4.9	4.9	4.9	4.9	7.3
Levelized Load, MCi	2.4	1.1	2.4	1.2	2.4	2.4	2.2	2.4
Levelized Operating Costs, ¢/Ci	5.4	7.6	4.3	5.1	3.4	3.5	5.5	5.8
Levelized Capital Costs, ¢/Ci	23.0	-2.6	11.6	-0.1	1.5	1.5	18.5	23.1
Required Net Price, ¢/Ci	28.4		16.0		4.9		24.0	28.9
ROI at Net Price of 5¢/Ci		-15.9		-12.6		15.2		

A.67

BNWL-1686

TABLE A-59. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	4641	4642	4643	4644	4645	4646	4647	4648
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1974	1974	1974	1974	1974	1975
Plant Size, MCi	10.1	10.1	10.1	10.1	10.1	10.1	10.1	13.5
Levelized Load, MCi	7.0	5.8	6.5	6.2	6.5	6.3	6.5	7.0
Levelized Operating Costs, ¢/Ci	3.9	3.5	3.2	3.1	2.9	3.1	3.6	4.2
Levelized Capital Costs, ¢/Ci	8.2	1.5	4.5	1.9	0.7	1.9	6.5	8.4
Required Net Price, ¢/Ci	12.1		7.7		3.5		10.1	12.6
ROI at Net Price of 5¢/Ci		-5.3		2.4		39.7		

A.68

BNWL-1686

TABLE A-60. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Low
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	4741	4742	4743	4744	4745	4746	4747	4748
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1974	1974	1976	1974	1975
Plant Size, MCi	10.1	13.5	10.1	13.5	13.5	10.1	13.5	17.4
Levelized Load, MCi	10.4	10.6	10.4	10.1	9.7	10.7	10.0	10.6
Levelized Operating Costs, ¢/Ci	3.4	3.0	3.2	2.9	2.7	3.2	3.1	3.8
Levelized Capital Costs, ¢/Ci	5.6	2.0	2.9	2.1	0.5	1.8	4.3	6.1
Required Net Price, ¢/Ci	9.0		6.1		3.2		7.4	9.8
ROI at Net Price of 5¢/Ci		1.1		9.4		47.3		

A.69

BNWL-1686

TABLE A-61. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	5141	5142	5143	5144	5145	5146	5147	5148
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1975	1974	1974	1974	1974	1974	1974	1975
Plant Size, MCi	10.7	6.9	6.9	10.7	6.9	10.7	6.9	10.7
Levelized Load, MCi	7.5	6.3	7.1	6.8	7.1	7.2	7.0	7.5
Levelized Operating Costs, ¢/Ci	3.8	3.5	3.3	3.2	2.9	3.2	3.6	4.2
Levelized Capital Costs, ¢/Ci	7.7	1.5	4.1	1.8	0.7	1.8	6.0	7.7
Required Net Price, ¢/Ci	11.4		7.4		3.6		9.6	11.9
ROI at Net Price of 5¢/Ci		-4.7		3.1		40.3		

A.70

BNWL-1686

TABLE A-62. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	5241	5242	5243	5244	5245	5246	5247	5248
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1976	1974	1976	1974	1976
Plant Size, MCi	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Levelized Load, MCi	18.4	16.9	18.4	18.4	15.4	16.7	16.3	17.0
Levelized Operating Costs, ¢/Ci	3.1	2.9	3.0	3.0	2.6	3.2	2.9	3.6
Levelized Capital Costs, ¢/Ci	3.4	2.1	1.8	2.0	0.4	1.8	2.8	3.7
Required Net Price, ¢/Ci	6.6		4.8		3.1		5.7	7.4
ROI at Net Price of 5¢/Ci		6.6		16.5		55.5		

A.71

BNWL-1686

TABLE A-63. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	5341	5342	5343	5344	5345	5346	5347	5348
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1977	1977	1977	1977	1974	1977	1977	1977
Plant Size, MCi	27.7	27.7	27.7	27.7	10.7	27.7	27.7	39.8
Levelized Load, MCi	26.7	27.0	26.7	26.4	13.5	23.5	27.0	26.7
Levelized Operating Costs, ¢/Ci	3.1	3.0	2.9	3.0	2.7	3.2	3.0	3.5
Levelized Capital Costs, ¢/Ci	2.9	2.0	1.6	2.0	0.4	1.8	2.1	3.4
Required Net Price, ¢/Ci	6.0		4.5		3.1		5.1	6.9
ROI at Net Price of 5¢/Ci		9.1		19.3		55.1		

TABLE A-64. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	5541	5542	5543	5544	5545	5546	5547	5548
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1974	1974	1974	1974	1974	1974	1974	1974
Plant Size, MCi	10.7	6.9	10.7	6.9	6.9	10.7	6.9	10.7
Levelized Load, MCi	3.4	1.6	3.4	1.8	3.4	3.7	3.1	3.4
Levelized Operating Costs, ¢/Ci	4.8	6.3	4.1	4.6	3.4	3.5	5.0	5.2
Levelized Capital Costs, ¢/Ci	16.6	-1.3	8.4	0.4	1.2	1.5	13.5	16.6
Required Net Price, ¢/Ci	21.4		12.5		4.6		18.4	21.8
ROI at Net Price of 5¢/Ci		-14.7		-10.6		21.5		

TABLE A-65. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	5641	5642	5643	5644	5645	5646	5647	5648
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1974	1974	1974	1975	1974	1974
Plant Size, MCi	15.3	15.3	15.3	15.3	15.3	10.7	15.3	15.3
Levelized Load, MCi	10.6	9.2	9.8	9.7	9.8	10.3	9.8	9.5
Levelized Operating Costs, ¢/Ci	3.7	3.3	3.1	3.0	2.8	3.3	3.3	3.9
Levelized Capital Costs, ¢/Ci	5.8	1.7	3.2	2.0	0.6	1.7	4.6	6.5
Required Net Price, ¢/Ci	9.5		6.3		3.4		7.9	10.4
ROI at Net Price of 5¢/Ci		-1.5		7.3		45.7		

A.74

BNWL-1686

TABLE A-66. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: Medium
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	5741	5742	5743	5744	5745	5746	5747	5748
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1974	1974	1976	1976	1976
Plant Size, MCi	15.3	21.0	15.3	21.0	21.0	15.3	15.3	15.3
Levelized Load, MCi	15.7	16.3	15.7	15.2	15.0	16.0	15.3	14.2
Levelized Operating Costs, ¢/Ci	3.3	2.9	3.1	2.8	2.7	3.3	3.2	3.8
Levelized Capital Costs, ¢/Ci	4.0	2.1	2.1	2.2	0.5	1.7	3.0	4.4
Required Net Price, ¢/Ci	7.3		5.2		3.1		6.2	8.2
ROI at Net Price of 5¢/Ci		4.7		13.5		53.5		

A.75

TABLE A-67. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	6141	6142	6143	6144	6145	6146	6147	6148
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1975	1974	1974	1974	1974	1974	1974	1975
Plant Size, MCi	12.3	12.3	7.7	7.7	7.7	7.7	12.3	12.3
Levelized Load, MCi	9.2	8.1	8.5	8.3	8.5	8.2	8.6	9.2
Levelized Operating Costs, ¢/Ci	3.6	3.3	3.1	3.1	2.9	3.1	3.4	4.0
Levelized Capital Costs, ¢/Ci	6.3	1.7	3.5	1.9	0.6	1.9	5.0	6.4
Required Net Price, ¢/Ci	9.9		6.6		3.5		8.3	10.4
ROI at Net Price of 5¢/Ci		-2.3		5.8		44.1		

A.76

BNWL-1686

TABLE A-68. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	6241	6242	6243	6244	6245	6246	6247	6248
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1976	1976	1976	1974	1976	1976	1976
Plant Size, MCi	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Levelized Load, MCi	23.6	23.8	23.6	23.3	19.3	20.3	23.8	21.2
Levelized Operating Costs, ¢/Ci	3.0	3.0	2.9	3.0	2.6	3.2	3.0	3.5
Levelized Capital Costs, ¢/Ci	2.9	2.0	1.5	2.0	0.4	1.8	2.1	3.2
Required Net Price, ¢/Ci	5.9		4.5		3.0		5.1	6.8
ROI at Net Price of 5¢/Ci		9.4		19.8		57.8		

A.77

BNWL-1686

TABLE A-69. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

A.78

Case	6341	6342	6343	6344	6345	6346	6347	6348
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1977	1977	1977	1977	1974	1977	1977	1977
Plant Size, MCi	36.4	36.4	36.4	36.4	36.4	36.4	36.4	36.4
Levelized Load, MCi	38.2	38.5	38.2	36.6	24.5	30.8	39.1	37.7
Levelized Operating Costs, ¢/Ci	3.0	2.9	2.9	3.0	2.5	3.2	2.9	3.4
Levelized Capital Costs, ¢/Ci	2.3	2.1	1.3	2.0	0.4	1.8	1.7	2.4
Required Net Price, ¢/Ci	5.3		4.1		3.0		4.6	5.8
ROI at Net Price of 5¢/Ci		13.1		23.8		58.9		

BNWL-1686

TABLE A-70. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	6541	6542	6543	6544	6545	6546	6547	6548
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1974	1974	1974	1974	1974	1974	1974	1974
Plant Size, MCi	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
Levelized Load, MCi	3.9	1.9	3.9	2.2	3.9	4.4	3.5	3.9
Levelized Operating Costs, ¢/Ci	4.6	5.7	4.0	4.3	3.4	3.4	4.7	5.0
Levelized Capital Costs, ¢/Ci	14.7	-0.7	7.5	0.7	1.1	1.6	11.8	14.7
Required Net Price, ¢/Ci	19.3		11.5		4.4		16.5	19.8
ROI at Net Price of 5¢/Ci		-13.8		-9.1		24.5		

A.79

BNWL-1686

TABLE A-71. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	6641	6642	6643	6644	6645	6646	6647	6648
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1974	1974	1975	1974	1974
Plant Size, MCi	18.4	18.4	18.4	18.4	18.4	12.3	18.4	18.4
Levelized Load, MCi	12.9	11.2	12.9	11.7	11.7	11.9	11.7	11.3
Levelized Operating Costs, ¢/Ci	3.6	3.2	3.4	3.0	2.8	3.3	3.2	3.8
Levelized Capital Costs, ¢/Ci	5.1	1.8	2.7	2.0	0.5	1.7	4.1	5.8
Required Net Price, ¢/Ci	8.7		6.1		3.3		7.3	9.6
ROI at Net Price of 5¢/Ci		0.1		9.2		49.3		

A.80

BNWL-1686

TABLE A-72. Separate Re-encapsulation Facility for HWM ¹³⁷Cs.
Net price required or ROI at 5¢/Ci net.

Market Projection: High
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	6741	6742	6743	6744	6745	6746	6747	6748
Description	Base Case (Price)	Base Case (ROI)	Capital Reduced 50% (Price)	Capital Reduced 50% (ROI)	Minimum Capital (Price)	Minimum Capital (ROI)	10% ROI (Price)	Reduced Learning Rate (Price)
Optimum Startup	1976	1974	1976	1974	1974	1976	1974	1975
Plant Size, MCi	18.4	26.4	18.4	26.4	26.4	18.4	26.4	36.4
Levelized Load, MCi	19.1	20.4	19.1	18.6	18.8	19.2	19.8	21.5
Levelized Operating Costs, ¢/Ci	3.2	2.9	3.1	2.8	2.6	3.3	2.9	3.5
Levelized Capital Costs, ¢/Ci	3.5	2.1	1.9	2.2	0.5	1.7	2.8	4.0
Required Net Price, ¢/Ci	6.7		4.9		3.1		5.7	7.5
ROI at Net Price of 5¢/Ci		6.7		15.9		55.1		

TABLE A-73. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>7121</u>	<u>7122</u>	<u>7123</u>	<u>7124</u>	<u>7128</u>	<u>7129</u>	<u>7131</u>	<u>7132</u>	<u>7133</u>	<u>7134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	13.5	9.0
Levelized Load, MCi	7.4	7.4	7.4	7.4	7.4	7.4	8.0	8.7	7.1	7.5
Levelized Operating Costs, ¢/Ci	9.0	11.9	7.4	14.0	4.9	12.8	8.5	8.2	9.6	8.7
Levelized Capital Costs, ¢/Ci	37.5	52.3	26.0	67.6	37.2	37.8	24.2	28.9	43.5	36.8
Required Net Price, ¢/Ci	46.4	64.3	33.4	81.7	42.1	50.6	32.8	37.1	53.1	45.5

TABLE A-74. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	<u>7221</u>	<u>7222</u>	<u>7223</u>	<u>7224</u>	<u>7228</u>	<u>7229</u>	<u>7231</u>	<u>7232</u>	<u>7233</u>	<u>7234</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4		
Levelized Load, MCi	10.0	10.0	10.0	10.0	10.0	10.0	10.8	11.8		
Levelized Operating Costs, ¢/Ci	7.9	10.5	6.7	12.2	4.4	11.5	7.6	7.3		
Levelized Capital Costs, ¢/Ci	30.1	42.1	20.9	54.4	29.9	30.4	19.6	23.2		
Required Net Price, ¢/Ci	38.1	52.6	27.6	66.6	34.2	41.9	27.3	30.5		

TABLE A-75. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>7321</u>	<u>7322</u>	<u>7323</u>	<u>7324</u>	<u>7328</u>	<u>7329</u>	<u>7331</u>	<u>7332</u>	<u>7333</u>	<u>7334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6		
Levelized Load, MCi	11.6	11.6	11.6	11.6	11.6	11.6	12.5	13.5		
Levelized Operating Costs, ¢/Ci	7.6	10.0	6.4	11.5	4.2	11.0	7.3	7.0		
Levelized Capital Costs, ¢/Ci	27.3	38.2	19.0	49.4	27.1	27.6	17.9	21.3		
Required Net Price, ¢/Ci	34.9	48.2	25.4	60.9	31.3	38.6	25.2	28.3		

A.84

BNWL-1686

TABLE A-76. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	<u>7521</u>	<u>7522</u>	<u>7523</u>	<u>7524</u>	<u>7528</u>	<u>7529</u>	<u>7531</u>	<u>7532</u>	<u>7533</u>	<u>7534</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.1	8.1	8.1	8.1	8.1	8.1	8.1	10.8	13.5	8.1
Levelized Load, MCi	9.5	9.5	9.5	9.5	9.5	9.5	9.9	11.3	9.6	10.0
Levelized Operating Costs, ¢/Ci	7.7	10.1	6.5	11.7	4.3	11.2	7.6	7.3	8.1	7.3
Levelized Capital Costs, ¢/Ci	28.3	39.5	19.7	51.1	28.1	28.6	19.2	23.3	32.4	27.1
Required Net Price, ¢/Ci	36.0	49.7	26.2	62.8	32.3	39.8	26.7	30.6	40.5	34.4

A.85

BNWL-1686

TABLE A-77. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>7621</u>	<u>7622</u>	<u>7623</u>	<u>7624</u>	<u>7628</u>	<u>7629</u>	<u>7631</u>	<u>7632</u>	<u>7633</u>	<u>7634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1		
Levelized Load, MCi	13.9	13.9	13.9	13.9	13.9	13.9	14.3	15.0		
Levelized Operating Costs, ¢/Ci	6.8	8.9	5.9	10.1	3.8	10.0	6.7	6.5		
Levelized Capital Costs, ¢/Ci	21.8	30.4	15.1	39.2	21.5	22.0	14.8	18.2		
Required Net Price, ¢/Ci	28.5	39.3	21.0	49.3	25.3	32.0	21.5	24.7		

A.86

BNWL-1686

TABLE A-78. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Base
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>7721</u>	<u>7722</u>	<u>7723</u>	<u>7724</u>	<u>7728</u>	<u>7729</u>	<u>7731</u>	<u>7732</u>	<u>7733</u>	<u>7734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8		
Levelized Load, MCi	16.4	16.4	16.4	16.4	16.4	16.4	16.8	17.6		
Levelized Operating Costs, ¢/Ci	6.5	8.4	5.6	9.5	3.6	9.6	6.4	6.3		
Levelized Capital Costs, ¢/Ci	19.5	27.3	13.6	35.2	19.3	19.8	13.4	16.5		
Required Net Price, ¢/Ci	26.0	35.7	19.3	44.8	23.0	29.4	19.8	22.8		

A.87

BNWL-1686

TABLE A-79. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	8121-M	8122-M	8123-M	8124-M	8128-M	8129-M	8131-M	8132-M	8133-M	8134-M
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	18.7	12.6
Levelized Load, MCi	10.3	10.3	10.3	10.3	10.3	10.3	11.2	12.1	9.8	10.4
Levelized Operating Costs, ¢/Ci	7.9	10.4	6.6	12.1	4.3	11.4	7.5	7.3	8.4	7.6
Levelized Capital Costs, ¢/Ci	29.6	41.4	20.6	53.5	29.4	29.9	19.2	22.8	34.8	29.3
Required Net Price, ¢/Ci	37.5	51.8	27.2	65.6	33.7	41.3	26.7	30.1	43.2	36.9

TABLE A-80. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	<u>8221-M</u>	<u>8222-M</u>	<u>8223-M</u>	<u>8224-M</u>	<u>8228-M</u>	<u>8229-M</u>	<u>8231-M</u>	<u>8232-M</u>	<u>8233-M</u>	<u>8234-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
Levelized Load, MCi	13.7	13.7	13.7	13.7	13.7	13.7	14.8	16.0		
Levelized Operating Costs, ¢/Ci	7.1	9.4	6.1	10.8	4.0	10.5	6.9	6.7		
Levelized Capital Costs, ¢/Ci	24.4	34.1	17.0	44.1	24.2	24.7	15.9	18.9		
Required Net Price, ¢/Ci	31.5	43.5	23.1	54.9	28.1	35.1	22.8	25.6		

TABLE A-81. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>8321-M</u>	<u>8322-M</u>	<u>8323-M</u>	<u>8324-M</u>	<u>8328-M</u>	<u>8329-M</u>	<u>8331-M</u>	<u>8332-M</u>	<u>8333-M</u>	<u>8334-M</u>
<u>Description</u>	<u>Base Case</u>	<u>Single Prod.</u>	<u>Low Cap.</u>	<u>High Cap.</u>	<u>Low Oper. Cost</u>	<u>High Oper. Cost</u>	<u>Lower ROI</u>	<u>Longer Econ. Life</u>	<u>Zero Learn</u>	<u>High Learn</u>
Plant Size, MCi	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8		
Levelized Load, MCi	15.6	15.6	15.6	15.6	15.6	15.6	16.8	17.9		
Levelized Operating Costs, ¢/Ci	6.9	9.0	5.9	10.3	3.8	10.1	6.7	6.5		
Levelized Capital Costs, ¢/Ci	22.4	31.3	15.6	40.5	22.2	22.6	14.7	17.7		
Required Net Price, ¢/Ci	29.3	40.3	21.5	50.7	26.0	32.7	21.3	24.2		

A.90

BNWL-1686

TABLE A-82. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

A.91	Case	<u>8521-M</u>	<u>8522-M</u>	<u>8523-M</u>	<u>8524-M</u>	<u>8528-M</u>	<u>8529-M</u>	<u>8531-M</u>	<u>8532-M</u>	<u>8533-M</u>	<u>8534-M</u>
	Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
	Plant Size, MCi	11.2	11.2	11.2	11.2	11.2	11.2	11.2	15.0	18.7	11.2
	Levelized Load, MCi	13.2	13.2	13.2	13.2	13.2	13.2	13.7	15.6	13.3	13.8
	Levelized Operating Costs, ¢/Ci	6.9	9.0	5.9	10.2	3.8	10.1	6.7	6.6	7.2	6.5
	Levelized Capital Costs, ¢/Ci	22.3	31.2	15.5	40.2	22.1	22.5	15.1	18.6	25.9	21.4
	Required Net Price, ¢/Ci	29.2	40.1	21.4	50.4	25.9	32.6	21.8	25.2	33.1	27.9

TABLE A-83. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>8621-M</u>	<u>8622-M</u>	<u>8623-M</u>	<u>8624-M</u>	<u>8628-M</u>	<u>8629-M</u>	<u>8631-M</u>	<u>8632-M</u>	<u>8633-M</u>	<u>8634-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower- ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8		
Levelized Load, MCi	19.0	19.0	19.0	19.0	19.0	19.0	19.6	20.6		
Levelized Operating Costs, ¢/Ci	6.2	8.1	5.5	9.0	3.5	9.2	6.1	6.0		
Levelized Capital Costs, ¢/Ci	17.6	24.5	12.2	31.7	17.4	17.8	12.0	14.7		
Required Net Price, ¢/Ci	23.8	32.6	17.7	40.7	20.9	27.0	18.1	20.7		

A.92

BNWL-1686

TABLE A-84. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>8721-M</u>	<u>8722-M</u>	<u>8723-M</u>	<u>8724-M</u>	<u>8728-M</u>	<u>8729-M</u>	<u>8731-M</u>	<u>8732-M</u>	<u>8733-M</u>	<u>8734-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4		
Levelized Load, MCi	22.2	22.2	22.2	22.2	22.2	22.2	22.7	23.6		
Levelized Operating Costs, ¢/Ci	6.0	7.8	5.3	8.7	3.4	9.0	5.9	5.9		
Levelized Capital Costs, ¢/Ci	16.0	22.4	11.2	28.9	15.8	16.2	11.0	13.7		
Required Net Price, ¢/Ci	22.0	30.2	16.5	37.5	19.2	25.2	16.9	19.5		

A.93

BNWL-1686

TABLE A-85. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>8121</u>	<u>8122</u>	<u>8123</u>	<u>8124</u>	<u>8128</u>	<u>8129</u>	<u>8131</u>	<u>8132</u>	<u>8133</u>	<u>8134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower- ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	25.8	16.3
Levelized Load, MCi	13.3	13.3	13.3	13.3	13.3	13.3	14.5	15.6	13.0	14.0
Levelized Operating Costs, ¢/Ci	7.2	9.5	6.1	10.9	4.0	10.5	6.9	6.7	7.6	6.8
Levelized Capital Costs, ¢/Ci	24.7	34.6	17.2	44.7	24.5	25.0	16.0	19.1	29.4	23.4
Required Net Price, ¢/Ci	31.9	44.1	23.4	55.5	28.5	35.5	22.9	25.8	37.0	30.3

A.94

BNWL-1686

TABLE A-86. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	8221	8222	8223	8224	8228	8229	8231	8232	8233	8234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.3		
Levelized Load, MCi	19.9	19.9	19.9	19.9	19.9	19.9	21.6	23.4		
Levelized Operating Costs, ¢/Ci	6.4	8.3	5.6	9.4	3.6	9.5	6.2	6.0		
Levelized Capital Costs, ¢/Ci	18.9	26.5	13.2	34.2	18.7	19.1	12.3	14.6		
Required Net Price, ¢/Ci	25.3	34.8	18.8	43.6	22.3	28.6	18.4	20.6		

TABLE A-87. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>8321</u>	<u>8322</u>	<u>8323</u>	<u>8324</u>	<u>8328</u>	<u>8329</u>	<u>8331</u>	<u>8332</u>	<u>8333</u>	<u>8334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7		
Levelized Load, MCi	24.0	24.0	24.0	24.0	24.0	24.0	25.9	28.2		
Levelized Operating Costs, ¢/Ci	6.1	7.9	5.4	8.9	3.4	9.1	5.9	5.8		
Levelized Capital Costs, ¢/Ci	16.9	23.6	11.8	30.5	16.7	17.1	11.0	13.0		
Required Net Price, ¢/Ci	23.0	31.6	17.2	39.4	20.1	26.2	16.9	18.8		

TABLE A-88. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	<u>8521</u>	<u>8522</u>	<u>8523</u>	<u>8524</u>	<u>8528</u>	<u>8529</u>	<u>8531</u>	<u>8532</u>	<u>8533</u>	<u>8534</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	13.6	13.6	13.6	13.6	19.8	13.6	19.4	19.4	25.8	13.6
Levelized Load, MCi	16.1	16.1	16.1	16.1	18.0	16.1	19.0	20.5	17.0	18.0
Levelized Operating Costs, ¢/Ci	6.5	8.4	5.6	9.5	3.6	9.6	6.3	6.1	6.7	6.0
Levelized Capital Costs, ¢/Ci	19.4	27.1	13.5	35.0	19.2	19.7	12.9	15.5	22.5	17.4
Required Net Price, ¢/Ci	25.9	35.6	19.2	44.5	22.8	29.2	19.2	21.6	29.2	23.4

A.97

BNWL-1686

TABLE A-89. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	<u>8621</u>	<u>8622</u>	<u>8623</u>	<u>8624</u>	<u>8628</u>	<u>8629</u>	<u>8631</u>	<u>8632</u>	<u>8633</u>	<u>8634</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5		
Levelized Load, MCi	26.5	26.5	26.5	26.5	26.5	26.5	27.4	28.6		
Levelized Operating Costs, ¢/Ci	5.7	7.4	5.1	8.1	3.2	8.6	5.6	5.6		
Levelized Capital Costs, ¢/Ci	13.9	19.5	9.7	25.1	13.8	14.2	9.4	11.7		
Required Net Price, ¢/Ci	19.6	26.9	14.9	33.3	17.0	22.7	15.1	17.3		

A.98

BNWL-1686

TABLE A-90. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>8721</u>	<u>8722</u>	<u>8723</u>	<u>8724</u>	<u>8728</u>	<u>8729</u>	<u>8731</u>	<u>8732</u>	<u>8733</u>	<u>8734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0		
Levelized Load, MCi	33.2	33.2	33.2	33.2	33.2	33.2	34.2	36.0		
Levelized Operating Costs, ¢/Ci	5.5	7.0	4.9	7.7	3.1	8.3	5.4	5.3		
Levelized Capital Costs, ¢/Ci	12.2	17.0	8.5	22.0	12.0	12.4	8.3	10.2		
Required Net Price, ¢/Ci	17.6	24.1	13.5	29.7	15.1	20.6	13.7	15.5		

A.99

TABLE A-91. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>7121</u>	<u>7122</u>	<u>7123</u>	<u>7124</u>	<u>7128</u>	<u>7129</u>	<u>7131</u>	<u>7132</u>	<u>7133</u>	<u>7134</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	6.7	3.4
Levelized Load, MCi	4.4	4.4	4.4	4.4	4.4	4.4	4.7	5.2	4.2	4.4
Levelized Operating Costs, ¢/Ci	11.5	15.4	9.1	18.6	6.1	16.2	11.0	10.4	12.1	10.6
Levelized Capital Costs, ¢/Ci	55.7	77.6	38.6	100.4	55.3	56.1	36.7	42.9	61.6	51.0
Required Net Price, ¢/Ci	67.2	93.1	47.7	118.9	61.5	72.2	47.7	53.3	73.7	61.7

A.100

TABLE A-92. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	7221	7222	7223	7224	7228	7229	7231	7232	7233	7234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.0	5.0	5.0	5.0	5.0	5.0	5.0	7.4		
Levelized Load, MCi	5.7	5.7	5.7	5.7	5.7	5.7	6.0	6.8		
Levelized Operating Costs, ¢/Ci	9.7	12.9	7.9	15.3	5.2	13.8	9.4	9.2		
Levelized Capital Costs, ¢/Ci	42.6	59.3	29.5	76.7	42.2	42.9	28.5	35.2		
Required Net Price, ¢/Ci	52.2	72.2	37.4	91.9	47.5	56.6	37.9	44.3		

A.101

BNWL-1686

TABLE A-93. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>7321</u>	<u>7322</u>	<u>7323</u>	<u>7324</u>	<u>7328</u>	<u>7329</u>	<u>7331</u>	<u>7332</u>	<u>7333</u>	<u>7334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1		
Levelized Load, MCi	6.9	6.9	6.9	6.9	6.9	6.9	7.3	7.5		
Levelized Operating Costs, ¢/Ci	8.8	11.7	7.3	13.8	4.8	12.7	8.6	8.4		
Levelized Capital Costs, ¢/Ci	36.5	50.9	25.3	65.8	36.2	36.8	24.5	30.4		
Required Net Price, ¢/Ci	45.3	62.6	32.6	79.5	41.0	49.5	33.1	38.8		

A.102

BNWL-1686

TABLE A-94. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	7521	7522	7523	7524	7528	7529	7531	7532	7533	7534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.6	6.5
Levelized Load, MCi	6.5	6.5	6.5	6.5	6.5	6.5	6.6	7.1	6.3	6.5
Levelized Operating Costs, ¢/Ci	9.2	12.2	7.5	14.4	5.0	13.2	9.1	8.8	9.2	9.0
Levelized Capital Costs, ¢/Ci	39.1	54.6	27.2	70.5	38.8	39.4	27.1	32.8	40.8	39.1
Required Net Price, ¢/Ci	48.3	66.8	34.7	84.9	43.8	52.6	36.3	41.6	50.0	48.1

A.103

TABLE A-95. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	7621	7622	7623	7624	7628	7629	7631	7632	7633	7634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7		
Levelized Load, MCi	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.7		
Levelized Operating Costs, ¢/Ci	8.0	10.5	6.7	12.2	4.4	11.5	8.0	7.8		
Levelized Capital Costs, ¢/Ci	30.3	42.3	21.0	54.6	30.0	30.6	21.3	26.5		
Required Net Price, ¢/Ci	38.2	52.8	27.7	66.8	34.4	42.1	29.2	34.3		

A.104

BNWL-1686

TABLE A-96. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>7721</u>	<u>7722</u>	<u>7723</u>	<u>7724</u>	<u>7728</u>	<u>7729</u>	<u>7731</u>	<u>7732</u>	<u>7733</u>	<u>7734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1		
Levelized Load, MCi	11.2	11.2	11.2	11.2	11.2	11.2	11.1	11.4		
Levelized Operating Costs, ¢/Ci	7.5	9.9	6.4	11.4	4.1	10.9	7.5	7.4		
Levelized Capital Costs, ¢/Ci	26.9	37.6	18.7	48.6	26.7	27.2	19.0	24.0		
Required Net Price, ¢/Ci	34.4	47.5	25.1	60.0	30.8	38.1	26.6	31.4		

TABLE A-97. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	8121-M	8122-M	8123-M	8124-M	8128-M	8129-M	8131-M	8132-M	8133-M	8134-M
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	4.7
Levelized Load, MCi	6.1	6.1	6.1	6.1	6.1	6.1	6.5	7.1	5.3	6.1
Levelized Operating Costs, ¢/Ci	10.1	13.1	8.0	15.6	5.3	14.0	9.4	8.9	10.5	9.0
Levelized Capital Costs, ¢/Ci	46.0	60.9	30.3	78.6	43.3	43.9	28.7	33.7	49.8	39.3
Required Net Price, ¢/Ci	56.1	74.0	38.2	94.2	48.6	57.9	38.2	42.6	60.3	48.3

TABLE A-98. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	<u>8221-M</u>	<u>8222-M</u>	<u>8223-M</u>	<u>8224-M</u>	<u>8228-M</u>	<u>8229-M</u>	<u>8231-M</u>	<u>8232-M</u>	<u>8233-M</u>	<u>8234-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0		
Levelized Load, MCi	7.9	7.9	7.9	7.9	7.9	7.9	8.3	8.6		
Levelized Operating Costs, ¢/Ci	8.3	11.0	6.9	12.9	4.6	12.0	8.1	8.0		
Levelized Capital Costs, ¢/Ci	33.0	46.0	22.9	59.4	32.7	33.3	22.1	27.5		
Required Net Price, ¢/Ci	41.4	57.0	29.8	72.3	37.3	45.3	30.2	35.4		

TABLE A-99. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>8321-M</u>	<u>8322-M</u>	<u>8323-M</u>	<u>8324-M</u>	<u>8328-M</u>	<u>8329-M</u>	<u>8331-M</u>	<u>8332-M</u>	<u>8333-M</u>	<u>8334-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5		
Levelized Load, MCi	9.5	9.5	9.5	9.5	9.5	9.5	9.9	10.3		
Levelized Operating Costs, ¢/Ci	7.8	10.2	6.5	11.9	4.3	11.3	7.6	7.4		
Levelized Capital Costs, ¢/Ci	28.9	40.3	20.1	52.1	28.6	29.2	19.4	24.0		
Required Net Price, ¢/Ci	36.7	50.5	26.6	63.9	32.9	40.4	27.0	31.4		

A.108

BNWL-1686

TABLE A-100. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	8521-M	8522-M	8523-M	8524-M	8528-M	8529-M	8531-M	8532-M	8533-M	8534-M
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.2	9.0
Levelized Load, MCi	9.0	9.0	9.0	9.0	9.0	9.0	9.1	9.7	8.7	9.0
Levelized Operating Costs, ¢/Ci	8.0	10.6	6.7	12.3	4.4	11.6	8.0	7.7	8.0	7.8
Levelized Capital Costs, ¢/Ci	30.7	42.9	21.4	55.4	30.5	31.0	21.3	26.0	32.0	30.7
Required Net Price, ¢/Ci	38.8	53.5	28.1	67.8	34.9	42.6	29.3	33.7	40.0	38.6

A.109

BNWL-1686

TABLE A-101. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

A.110

Case	<u>8621-M</u>	<u>8622-M</u>	<u>8623-M</u>	<u>8624-M</u>	<u>8628-M</u>	<u>8629-M</u>	<u>8631-M</u>	<u>8632-M</u>	<u>8633-M</u>	<u>8634-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5		
Levelized Load, MCi	12.8	12.8	12.8	12.8	12.8	12.8	12.8	13.2		
Levelized Operating Costs, ¢/Ci	7.1	9.3	6.1	10.7	4.0	10.4	7.1	7.0		
Levelized Capital Costs, ¢/Ci	24.2	33.8	16.8	43.7	24.0	24.5	17.0	21.4		
Required Net Price, ¢/Ci	31.3	43.2	22.9	54.4	27.9	34.9	24.2	28.4		

TABLE A-102. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>8721-M</u>	<u>8722-M</u>	<u>8723-M</u>	<u>8724-M</u>	<u>8728-M</u>	<u>8729-M</u>	<u>8731-M</u>	<u>8732-M</u>	<u>8733-M</u>	<u>8734-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8		
Levelized Load, MCi	15.2	15.2	15.2	15.2	15.2	15.2	15.1	15.3		
Levelized Operating Costs, ¢/Ci	6.8	8.9	5.9	10.1	3.8	10.0	6.8	6.8		
Levelized Capital Costs, ¢/Ci	21.9	30.6	15.2	39.5	21.6	22.1	15.5	19.6		
Required Net Price, ¢/Ci	28.6	39.5	21.1	49.6	25.4	32.1	22.3	26.4		

A.111

TABLE A-103. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	8121	8122	8123	8124	8128	8129	8131	8132	8133	8134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	12.9	5.7
Levelized Load, MCi	8.1	8.1	8.1	8.1	8.1	8.1	8.7	9.5	7.6	7.7
Levelized Operating Costs, ¢/Ci	8.6	11.5	7.1	13.4	4.7	12.4	8.3	7.9	9.1	8.1
Levelized Capital Costs, ¢/Ci	35.1	49.0	24.4	63.3	34.8	35.4	22.9	27.1	40.2	32.5
Required Net Price, ¢/Ci	43.7	60.4	31.5	76.7	39.5	47.8	31.2	35.0	49.4	40.5

A.112

BNWL-1686

TABLE A-104. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	8221	8222	8223	8224	8228	8229	8231	8232	8233	8234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.4	9.4	9.4	9.4	9.4	9.4	9.4	14.6		
Levelized Load, MCi	10.6	10.6	10.6	10.6	10.6	10.6	11.1	13.8		
Levelized Operating Costs, ¢/Ci	7.5	9.8	6.3	11.3	4.1	10.9	7.3	7.0		
Levelized Capital Costs, ¢/Ci	26.6	37.2	18.5	48.0	26.4	26.9	17.8	20.9		
Required Net Price, ¢/Ci	34.1	47.0	24.8	59.3	30.5	37.8	25.1	27.9		

A.113

BNWL-1686

TABLE A-105. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	8321	8322	8323	8324	8328	8329	8331	8332	8333	8334
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0		
Levelized Load, MCi	13.6	13.6	13.6	13.6	13.6	13.6	14.3	14.8		
Levelized Operating Costs, ¢/Ci	6.8	8.9	5.9	10.2	3.8	10.1	6.7	6.6		
Levelized Capital Costs, ¢/Ci	22.2	31.0	15.4	40.0	21.9	22.4	14.9	18.5		
Required Net Price, ¢/Ci	29.0	39.9	21.3	50.2	25.8	32.5	21.5	25.1		

A.114

BNWL-1686

TABLE A-106. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	8521	8522	8523	8524	8528	8529	8531	8532	8533	8534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	11.7	10.9
Levelized Load, MCi	11.6	11.6	11.6	11.6	11.6	11.6	11.8	12.7	10.7	11.6
Levelized Operating Costs, ¢/Ci	7.3	9.6	6.2	11.0	4.0	10.6	7.2	7.0	7.4	7.1
Levelized Capital Costs, ¢/Ci	25.3	35.3	17.6	45.6	25.1	25.6	17.3	20.8	27.7	25.3
Required Net Price, ¢/Ci	32.6	44.9	23.8	56.6	29.1	36.2	24.5	27.7	35.1	32.4

A.115

BNWL-1686

TABLE A-107. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	8621	8622	8623	8624	8628	8629	8631	8632	8633	8634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0		
Levelized Load, MCi	17.9	17.9	17.9	17.9	17.9	17.9	18.0	19.0		
Levelized Operating Costs, ¢/Ci	6.4	8.4	5.6	9.4	3.6	9.5	6.4	6.3		
Levelized Capital Costs, ¢/Ci	19.1	26.7	13.3	34.5	18.9	19.3	13.3	16.3		
Required Net Price, ¢/Ci	25.5	35.1	18.9	43.9	22.5	28.8	19.7	22.5		

A.116

BNWL-1686

TABLE A-108. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 100 to 50% at 5 yr
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	8721	8722	8723	8724	8728	8729	8731	8732	8733	8734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2		
Levelized Load, MCi	22.3	22.3	22.3	22.3	22.3	22.3	22.3	23.1		
Levelized Operating Costs, ¢/Ci	6.1	7.9	5.4	8.8	3.4	9.1	6.1	6.0		
Levelized Capital Costs, ¢/Ci	16.6	23.3	11.6	30.0	16.4	16.9	11.7	14.5		
Required Net Price, ¢/Ci	22.7	31.2	17.0	38.8	19.9	25.9	17.7	20.5		

A.117

BNWL-1686

TABLE A-109. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	7121	7122	7123	7124	7128	7129	7131	7132	7133	7134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	6.7	4.5
Levelized Load, MCi	3.7	3.7	3.7	3.7	3.7	3.7	4.0	4.3	3.5	3.8
Levelized Operating Costs, ¢/Ci	12.6	17.0	9.9	20.6	6.7	17.6	11.9	11.3	13.7	12.3
Levelized Capital Costs, ¢/Ci	63.9	89.0	44.3	115.0	63.4	64.3	41.3	49.2	72.8	62.8
Required Net Price, ¢/Ci	76.5	106.0	54.2	135.6	70.2	81.9	53.2	60.5	86.4	75.1

A.118

TABLE A-110. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

A.119	Case	7221	7222	7223	7224	7228	7229	7231	7232	7233	7234
	Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
	Plant Size, MCi	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2		
	Levelized Load, MCi	5.0	5.0	5.0	5.0	5.0	5.0	5.4	5.9		
	Levelized Operating Costs, ¢/Ci	10.8	14.4	8.6	17.3	5.8	15.2	10.3	9.7		
	Levelized Capital Costs, ¢/Ci	50.5	70.4	35.0	91.1	50.1	50.9	32.9	38.8		
	Required Net Price, ¢/Ci	61.3	84.9	43.7	108.4	55.9	66.1	43.1	48.5		

TABLE A-111. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>7321</u>	<u>7322</u>	<u>7323</u>	<u>7324</u>	<u>7328</u>	<u>7329</u>	<u>7331</u>	<u>7332</u>	<u>7333</u>	<u>7334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3		
Levelized Load, MCi	5.8	5.8	5.8	5.8	5.8	5.8	6.2	6.8		
Levelized Operating Costs, ¢/Ci	10.0	13.4	8.1	16.0	5.4	14.3	9.6	9.2		
Levelized Capital Costs, ¢/Ci	45.2	63.1	31.4	81.5	44.8	45.5	29.6	35.2		
Required Net Price, ¢/Ci	55.2	76.5	39.5	97.5	50.3	59.8	39.2	44.3		

A.120

BNWL-1686

TABLE A-112. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	7521	7522	7523	7524	7528	7529	7531	7532	7533	7534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	4.0	4.0	4.0	4.0	4.0	4.0	4.0	5.4	6.7	4.0
Levelized Load, MCi	4.8	4.8	4.8	4.8	4.8	4.8	4.9	5.7	4.8	5.0
Levelized Operating Costs, ¢/Ci	10.5	14.0	8.4	16.8	5.7	14.9	10.3	9.8	11.1	10.0
Levelized Capital Costs, ¢/Ci	48.6	67.6	33.7	87.3	48.2	48.9	32.9	39.1	54.0	46.4
Required Net Price, ¢/Ci	59.1	81.6	42.1	104.1	53.8	63.7	43.1	48.9	65.1	56.4

A.121

BNWL-1686

TABLE A-113. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	7621	7622	7623	7624	7628	7629	7631	7632	7633	7634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0		
Levelized Load, MCi	6.9	6.9	6.9	6.9	6.9	6.9	7.2	7.5		
Levelized Operating Costs, ¢/Ci	8.8	11.7	7.3	13.7	4.8	12.6	8.6	8.4		
Levelized Capital Costs, ¢/Ci	36.3	50.6	25.2	65.4	36.0	36.6	24.7	30.3		
Required Net Price, ¢/Ci	45.1	62.3	32.5	79.1	40.8	49.2	33.4	38.7		

A.122

BNWL-1686

TABLE A-114. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Low
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>7721</u>	<u>7722</u>	<u>7723</u>	<u>7724</u>	<u>7728</u>	<u>7729</u>	<u>7731</u>	<u>7732</u>	<u>7733</u>	<u>7734</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4		
Levelized Load, MCi	8.2	8.2	8.2	8.2	8.2	8.2	8.4	8.8		
Levelized Operating Costs, ¢/Ci	8.2	10.9	6.9	12.7	4.5	11.9	8.1	7.9		
Levelized Capital Costs, ¢/Ci	32.3	45.0	22.4	58.1	32.0	32.5	221.1	27.2		
Required Net Price, ¢/Ci	40.5	55.9	29.3	70.8	36.5	44.4	30.2	35.1		

A.123

BNWL-1686

TABLE A-115. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	<u>8121-M</u>	<u>8122-M</u>	<u>8123-M</u>	<u>8124-M</u>	<u>8128-M</u>	<u>8129-M</u>	<u>8131-M</u>	<u>8132-M</u>	<u>8133-M</u>	<u>8134-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	9.3	6.3
Levelized Load, MCi	5.1	5.1	5.1	5.1	5.1	5.1	5.6	6.0	4.9	5.2
Levelized Operating Costs, ¢/Ci	10.6	14.2	8.5	17.0	5.7	15.0	10.1	9.6	11.4	10.3
Levelized Capital Costs, ¢/Ci	49.3	68.8	34.2	88.9	49.0	49.6	31.9	38.0	56.7	48.8
Required Net Price, ¢/Ci	59.9	83.0	42.7	105.9	54.7	64.6	42.0	47.6	68.1	59.1

A.124

BNWL-1686

TABLE A-116. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	8221-M	8222-M	8223-M	8224-M	8228-M	8229-M	8231-M	8232-M	8233-M	8234-M
	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6		
Levelized Load, MCi	6.9	6.9	6.9	6.9	6.9	6.9	7.4	8.0		
Levelized Operating Costs, ¢/Ci	9.3	12.4	7.6	14.6	5.0	13.3	8.9	8.5		
Levelized Capital Costs, ¢/Ci	39.9	55.7	27.7	72.0	39.6	40.2	26.0	30.9		
Required Net Price, ¢/Ci	49.2	68.1	35.3	86.6	44.6	53.5	34.9	39.3		

A.125

TABLE A-117. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>8321-M</u>	<u>8322-M</u>	<u>8323-M</u>	<u>8324-M</u>	<u>8328-M</u>	<u>8329-M</u>	<u>8331-M</u>	<u>8332-M</u>	<u>8333-M</u>	<u>8334-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9		
Levelized Load, MCi	7.8	7.8	7.8	7.8	7.8	7.8	8.4	9.0		
Levelized Operating Costs, ¢/Ci	8.8	11.7	7.3	13.7	4.8	12.6	8.5	8.2		
Levelized Capital Costs, ¢/Ci	36.3	50.7	25.2	65.5	36.0	36.6	23.8	28.7		
Required Net Price, ¢/Ci	45.1	62.4	32.4	79.2	40.8	49.2	32.3	36.8		

A.126

BNWL-1686

TABLE A-118. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	<u>8521-M</u>	<u>8522-M</u>	<u>8523-M</u>	<u>8524-M</u>	<u>8528-M</u>	<u>8529-M</u>	<u>8531-M</u>	<u>8532-M</u>	<u>8533-M</u>	<u>8534-M</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	5.6	5.6	5.6	5.6	5.6	5.6	5.6	7.5	9.3	5.6
Levelized Load, MCi	6.6	6.6	6.6	6.6	6.6	6.6	6.9	7.8	6.6	6.9
Levelized Operating Costs, ¢/Ci	9.0	11.9	7.4	14.0	4.9	12.9	8.8	8.5	9.4	8.6
Levelized Capital Costs, ¢/Ci	37.5	52.3	26.0	67.5	37.2	37.8	25.4	30.7	42.3	36.0
Required Net Price, ¢/Ci	46.5	64.2	33.4	81.5	42.1	50.6	34.2	39.2	51.7	44.6

A.127

BNWL-1686

TABLE A-119. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	8621-M	8622-M	8623-M	8624-M	8628-M	8629-M	8631-M	8632-M	8633-M	8634-M
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4		
Levelized Load, MCi	9.5	9.5	9.5	9.5	9.5	9.5	9.8	10.3		
Levelized Operating Costs, ¢/Ci	7.8	10.2	6.5	11.8	4.3	11.3	7.6	7.5		
Levelized Capital Costs, ¢/Ci	28.8	40.1	20.0	51.8	28.5	29.0	19.6	24.0		
Required Net Price, ¢/Ci	36.5	50.3	26.5	63.6	32.8	40.3	27.3	31.5		

A.128

BNWL-1686

TABLE A-120. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: Medium
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	<u>8721-M</u>	<u>8722-M</u>	<u>8723-M</u>	<u>8724-M</u>	<u>8728-M</u>	<u>8729-M</u>	<u>8731-M</u>	<u>8732-M</u>	<u>8733-M</u>	<u>8734-M</u>
<u>Description</u>	<u>Base Case</u>	<u>Single Prod.</u>	<u>Low Cap.</u>	<u>High Cap.</u>	<u>Low Oper. Cost</u>	<u>High Oper. Cost</u>	<u>Lower ROI</u>	<u>Longer Econ. Life</u>	<u>Zero Learn</u>	<u>High Learn</u>
Plant Size, MCi	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2		
Levelized Load, MCi	11.1	11.1	11.1	11.1	11.1	11.1	11.4	11.8		
Levelized Operating Costs, ¢/Ci	7.3	9.7	6.3	11.1	4.1	10.7	7.3	7.1		
Levelized Capital Costs, ¢/Ci	25.8	36.1	18.0	46.6	25.6	26.1	17.7	22.0		
Required Net Price, ¢/Ci	33.2	45.7	24.2	57.7	29.7	36.8	25.0	29.2		

A.129

TABLE A-121. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Gradual

Case	8121	8122	8123	8124	8128	8129	8131	8132	8133	8134
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Levelized Load, MCi	6.7	6.7	6.7	6.7	6.7	6.7	7.3	7.8	5.1	7.0
Levelized Operating Costs, ¢/Ci	9.4	12.5	7.7	14.8	5.1	13.4	8.9	8.5	10.9	8.9
Levelized Capital Costs, ¢/Ci	40.5	56.5	28.1	73.0	40.2	40.8	26.1	31.2	53.0	38.4
Required Net Price, ¢/Ci	49.9	69.0	35.7	87.8	45.3	54.2	35.0	39.7	63.9	47.3

A.130

BNWL-1686

TABLE A-122. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Gradual

Case	8221	8222	8223	8224	8228	8229	8231	8232	8233	8234
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2		
Levelized Load, MCi	10.0	10.0	10.0	10.0	10.0	10.0	10.8	11.7		
Levelized Operating Costs, ¢/Ci	8.0	10.5	6.7	12.2	4.4	11.5	7.6	7.3		
Levelized Capital Costs, ¢/Ci	30.2	42.3	21.0	54.6	30.0	30.5	19.6	23.3		
Required Net Price, ¢/Ci	38.2	52.8	27.7	66.8	34.4	42.0	27.2	30.7		

A.131

BNWL-1686

TABLE A-123. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Gradual

Case	<u>8321</u>	<u>8322</u>	<u>8323</u>	<u>8324</u>	<u>8328</u>	<u>8329</u>	<u>8331</u>	<u>8332</u>	<u>8333</u>	<u>8334</u>
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8		
Levelized Load, MCi	12.0	12.0	12.0	12.0	12.0	12.0	12.9	14.1		
Levelized Operating Costs, ¢/Ci	7.5	9.8	6.3	11.3	4.1	10.9	7.2	6.9		
Levelized Capital Costs, ¢/Ci	26.7	37.3	18.5	48.2	26.4	26.9	17.4	20.5		
Required Net Price, ¢/Ci	34.1	47.1	24.9	59.5	30.6	37.8	24.6	27.4		

A.132

BNWL-1686

TABLE A-124. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1977
HWM Sales Phaseout: Abrupt

Case	8521	8522	8523	8524	8528	8529	8531	8532	8533	8534
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	6.8	9.7	9.7	9.7	9.7	9.7	9.7	9.7	12.9	6.8
Levelized Load, MCi	8.1	9.0	9.0	9.0	9.0	9.0	9.5	10.2	8.5	9.0
Levelized Operating Costs, ¢/Ci	8.2	10.7	6.8	12.5	4.5	11.8	7.9	7.6	8.5	7.6
Levelized Capital Costs, ¢/Ci	32.1	43.9	21.8	56.7	31.2	31.7	20.9	25.0	35.9	28.8
Required Net Price, ¢/Ci	40.4	54.7	28.6	69.2	35.6	43.5	28.8	32.6	44.4	36.4

A.133

TABLE A-125. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1980
HWM Sales Phaseout: Abrupt

Case	8621	8622	8623	8624	8628	8629	8631	8632	8633	8634
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3		
Levelized Load, MCi	13.2	13.2	13.2	13.2	13.2	13.2	13.7	14.3		
Levelized Operating Costs, ¢/Ci	6.9	9.0	5.9	10.2	3.8	10.1	6.8	6.6		
Levelized Capital Costs, ¢/Ci	22.3	31.2	15.5	40.3	22.1	22.6	15.1	18.7		
Required Net Price, ¢/Ci	29.2	40.2	21.5	50.5	25.9	32.7	21.9	25.4		

A.134

BNWL-1686

TABLE A-126. Detail of Price Requirements for Optimum Power
Reactor ⁹⁰Sr Recovery (Co-Products Base Case)

Market Projection: High
Market Share: 50%
Power Reactor Recovery Starts: 1982
HWM Sales Phaseout: Abrupt

Case	8721	8722	8723	8724	8728	8729	8731	8732	8733	8734
Description	Base Case	Single Prod.	Low Cap.	High Cap.	Low Oper. Cost	High Oper. Cost	Lower ROI	Longer Econ. Life	Zero Learn	High Learn
Plant Size, MCi	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5		
Levelized Load, MCi	16.6	16.6	16.6	16.6	16.6	16.6	17.1	18.0		
Levelized Operating Costs, ¢/Ci	6.4	8.4	5.6	9.4	3.6	9.5	6.3	6.2		
Levelized Capital Costs, ¢/Ci	19.2	26.8	13.4	34.6	19.0	19.4	13.1	16.0		
Required Net Price, ¢/Ci	25.6	35.2	19.0	44.0	22.6	28.9	19.4	22.2		

A.135

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