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Report

Light Water Reactor Fuel Reprocessing and Recycling

Energy Research & Development Administration

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NOTICE

THIS DOCUMENT WAS ORIGINALLY INTENDED TO PROVIDE THE BASIS FOR AN ENVIRONMENTAL IMPACT STATEMENT TO ASSIST ERDA IN MAKING DECISIONS WITH RESPECT TO POSSIBLE LIGHT WATER REACTOR FUEL REPROCESSING AND RECYCLING PROGRAMS.

THE ADMINISTRATION HAS RECENTLY MADE A DECISION TO INDEFINITELY DEFER REPROCESSING. CONSEQUENTLY, ERDA IS NO LONGER CONSIDERING PROGRAMS TO AGGRESSIVELY DEVELOP REPROCESSING AND RECYCLING IN THE UNITED STATES AND THEREFORE THE NEED FOR AN ENVIRONMENTAL IMPACT STATEMENT TO ASSIST IN MAKING REPROCESSING PROGRAM DIRECTION DECISIONS NO LONGER EXISTS. NEVERTHELESS, SINCE THIS DOCUMENT CONTAINS USEFUL INFORMATION ON NUCLEAR POWER IN GENERAL AND THE NUCLEAR FUEL CYCLE IN PARTICULAR, ERDA IS ISSUING THIS DOCUMENT AS A REPORT TO ASSIST THE PUBLIC IN ITS CONSIDERATION OF NUCLEAR POWER ISSUES. ANY QUESTIONS OR COMMENTS ON THE DOCUMENT SHOULD BE REFERRED TO G. W. CUNNINGHAM, DIRECTOR, DIVISION OF WASTE MANAGEMENT, PRODUCTION AND REPROCESSING, U.S. ERDA, WASHINGTON, D. C. 20545.

ERDA-1554-D

PRELIMINARY

DRAFT
ENVIRONMENTAL IMPACT STATEMENT

REPROCESSING & RECYCLE
IN THE
LIGHT WATER REACTOR FUEL CYCLE

FEBRUARY 1977

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION

FOREWORD

PURPOSE OF THIS ENVIRONMENTAL IMPACT STATEMENT

This environmental impact statement provides a generic discussion of the environmental effects of closing the fuel cycle for light water nuclear power reactors (LWRs) by recovering uranium and plutonium from the spent LWR fuels for possible recycling. It is intended to be used by the Energy Research and Development Administration (ERDA) in making decisions concerning reprocessing and recycling facilities and programs consistent with ERDA's Reprocessing Evaluation Program initiated pursuant to the President's Nuclear Policy Statement of October 28, 1976. ERDA's program to commercialize LWR fuel reprocessing and recycling has been suspended while the extensive evaluation program is being undertaken. The evaluation program will be aimed at assessing the potential of existing and alternative concepts and arrangements for reducing worldwide proliferation risks. The purpose of this statement is to lay an environmental foundation for the resulting decisions.

Resource utilization, environmental effects, and costs of a range of options, including no recycle of spent fuels, are compared in the statement. Individual facilities are treated on a model basis. In this respect, the statement also will serve as

a background document for the separate environmental impact statements that might be required for individual facilities that may be proposed for construction.

This environmental statement considers the "back end" of the LWR fuel cycle. In the context of this statement, the back end of the LWR fuel cycle includes all operations on irradiated fuel after the fuel is removed from the spent fuel storage basin at the nuclear power plant site; long-term storage or disposal of radioactive waste is not included. A separate environmental statement is being prepared on long-term storage or disposal of radioactive waste from commercial nuclear power sources. The primary technical areas addressed in this statement include: 1) spent fuel shipment, receipt, and temporary storage, 2) shearing and/or dissolution of the spent fuel, 3) chemical separation of uranium, plutonium, higher actinides, and fission products leading to separated or combined streams of uranium and plutonium, 4) preparation of intermediate forms for recyclable products, such as uranium hexafluoride (UF_6) and plutonium dioxide (PuO_2), 5) removal of radioactive effluents, 6) shipment of intermediate product forms, 7) fabrication of recycled uranium, plutonium, and higher actinides into fuel assemblies for LWRs, 8) refabrication of LWR spent fuel for additional irradiation in a heavy water reactor, 9) interim treatment and storage of waste products before final disposition, and 10) facility decommissioning.

The statement does not present a definitive picture of the LWR industry, but it does indicate the parameters involved if a decision is made to stimulate development of the back end of the fuel cycle. In addition to information generated as a result of ERDA's Reprocessing Evaluation Program, much of the information needed before final decisions are made will be generated by the Nuclear Regulatory Commission (NRC) and by ERDA research and development programs now in progress. For example, costs of the control technologies required to remove the radiological effluents from offgases and to store them safely will only come from detailed cost estimates after the control equipment has been factored into actual plant designs. These detailed estimates and safety analyses of the various alternatives must be available to complete cost-benefit and environmental analyses.

This statement compares the following alternatives for the LWR fuel cycle:

- Recycle of uranium and plutonium (the base case)
- Recycle of uranium only
- No recycle
- Coprocessing
- Tandem fuel cycle
- Alternative versions of the base case.

  Longer cooling before reprocessing (5 years rather than 1 year).

  Delayed startup of fuel reprocessing (5-year delay compared to base case).

Omission of improved offgas controls assumed in the base case.

Retrofitting an older plant with improved offgas controls.

Siting variations to determine the effects of reprocessing plants

(1) located separately from MOX fabrication plants
(2) located so that transportation of spent fuel is minimized
(3) located so that transportation of radioactive waste is minimized.

- Higher and lower LWR nuclear industry growth rates.

To perform the analyses contained in this statement, continued growth of the front end of the LWR fuel cycle through the year 2000 is assumed to be independent of decisions about the back end of the cycle. The relationships between front end requirements and back end alternatives are discussed in section 5.

New and updated comparisons of costs and environmental effects have been generated for the comparison sections of this statement. These sections are:

Section 3 - Environmental Effects

Section 5 - Alternatives

Section 9 - Cost-Benefit Analysis

Safeguarding plutonium from sabotage and theft is a major consideration in the decision-making process with regard to handling separated plutonium. Section 10 describes and analyzes ways of safeguarding plutonium from sabotage and theft. This section attempts to put all the considerations into perspective and to describe the ongoing programs.

RELATIONSHIP TO OTHER ENVIRONMENTAL REVIEWS

The main thrust of this statement is to compare the anticipated effects of the reprocessing and recycle industry with those of no recycle.

The *Generic Environmental Statement on Mixed Oxide Fuels (GESMO)* (NUREG-0002) covers much the same ground and provides much of the descriptive material for the present statement. However, in GESMO the emphasis is in the comparison between recycle of uranium and recycle of uranium plus plutonium.

Other closely related environmental reviews which provide direct input to the present statement include:

- *Nuclear Energy Center Site Survey-1975* (NECSS-75, NUREG-0001) provides source terms for radiological releases and descriptions of typical sites and population densities.
- *Final Environmental Statement - Liquid Metal Fast Breeder Reactor Program* (ERDA-1535) and the current program plan of the ERDA Division of Safeguards and Security provides much of the information for the section on Safeguards.
- *Final Environmental Statement on Expansion of U. S. Uranium Enrichment Capacity* (ERDA-1543) provides information for the section on required characteristics of the environment in which fuel cycle facilities may be situated.

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1. SUMMARY

This section summarizes the information of major significance in each of the other sections of the environmental statement.

BACKGROUND

Anticipated Benefits

Benefits of closing the LWR fuel cycle by reprocessing and recycling both uranium and plutonium include better utilization of U.S. resources and lower costs. By the year 2000, uranium ore requirements would be reduced by about 24% and overall costs* would be reduced by about 7% ($18 billion) compared to indefinite fuel storage (no recycle).

Nuclear Industry Projections

Growth of the light water reactor (LWR) nuclear power industry according to the low projection of ERDA's Office of Planning and Analysis is used as the basis for this environmental statement. In this projection, the industry grows to a total of 507 LWRs by the year 2000, which is the end of the period covered in this statement. The LWR industry is assumed to grow at the same rate throughout this period whether the spent fuel is

*Cost comparisons in this section include deferred costs, which are defined as costs required to complete processing, storage and disposal of irradiated fuel discharged through the year 2000. Deferred costs (and credits) are discussed in section 9.

recycled or not. Material flows estimated for the year 2000 for the no recycle case and for recycle of uranium and plutonium are shown in Figures 2.2, 2.3, and 2.4. The number of individual facilities that would be required by the year 2000 is given in Table 2.1.

Description of Model Facilities

The LWR industry and the individual facilities described in this statement are based on technology that has already been developed, although not necessarily demonstrated on a commercial scale.

In the base case of uranium and plutonium recycle 7 reprocessing plants, each having a capacity of 1500 metric tons (MT) of spent fuel per year, would be required by the year 2000 based on processing spent fuel after a decay time of 1 year. Plant design is based on the Purex solvent extraction process for separation of the uranium and plutonium products from the waste streams. Included in the reprocessing complex are facilities to convert uranium to UF_6 and plutonium to PuO_2.

Integral with the reprocessing plants are facilities for fabricating mixed oxide fuel by mechanically blending recycled PuO_2 and natural UO_2. Each of the seven mixed oxide (MOX) fuel fabrication plants required by the year 2000 has a capacity of 350 metric tons per year.

Support facilities for uranium processing by the year 2000 would include about 50 mine-mill complexes, 5 UF_6 conversion

plants, 10 uranium enrichment plants (including facilities to meet foreign requirements), and 10 UO_2 fuel fabrication plants.

Additional facilities for transportation, interim waste management, and storage of plutonium would also be required.

Estimated annual radiological effluents from each reprocessing plant include 1,100,000 curies of tritium (^{3}H), 14,000,000 curies of krypton-85 (^{85}Kr), and 700 curies of carbon-14 (^{14}C), if no retention is assumed. The base case assumes that ^{3}H, ^{14}C, and ^{85}Kr releases are reduced by improved offgas controls to 1% of the values given above from plants starting up after 1985. Also released would be about 3 curies of iodine-129 (^{129}I), based on 95% retention, and 2.5 curies of transuranics (Pu, Am, Cm), including 0.4 curie of alpha emitters based on process decontamination factors of 2×10^{8} to 5×10^{8}. The base case assumes that ^{129}I and alpha transuranic releases are reduced by improved offgas controls to 10% of the values given above from plants starting up after 1985.

Annual radiological effluents from each MOX fuel fabrication plant are estimated to be about 0.07 curie of transuranics (0.002 curie of alpha emitters) if a decontamination factor of 4×10^{9} is assumed. Improved offgas controls are assumed to reduce these releases to 10% of these values from plants starting up after 1985. Radiological effects from the front end of the fuel cycle result primarily from the release of ^{222}Rn from mining, milling, and the uranium mill tailing piles. In the base case, the tailings piles are assumed to be covered with soil such that ^{222}Rn releases are 10% of the uncovered values.

Characterization of the Existing Environment

Many areas of the country are suitable for the construction of reprocessing and mixed oxide (MOX) fuel fabrication plants; however, seismic and meteorological conditions might eliminate some specific sites. The power, water, manpower, and transportation networks required can be provided by most areas. Economics and environmental tradeoffs must be considered in the site-selection procedure and in choices between large centralized plants and smaller dispersed plants. The characteristics for specific sites will need to be assessed in the environmental statements supporting proposed individual reprocessing or MOX fuel fabrication plants.

ENVIRONMENTAL EFFECTS

Construction

Environmental effects of fuel cycle facilities during the construction phase include land use considerations, effects of siltation on local waters, and physical, economic, political, and service impacts on local communities. These construction phase effects are highly site-specific, and should be addressed in the environmental assessments of actual facilities.

Local Effects of Operation of Back End Facilities

Radioactivity from Normal Operation

The calculated whole-body 50-year-dose commitments resulting from the annual releases of radioactivity from fuel reprocessing

plants (FRP) and mixed oxide fuel fabrication plants (MOX) are compared to the radiation doses from natural sources in the following table.

Local Radiation Effects

	Hypothetical Individual Receiving Max. Dose, mrem		*Population Dose 50-Mile Radius Population (10^6 Persons)*		
	From FRP-MOX Plants	*Natural Sources*	*From FRP-MOX Plants*	*Natural Sources (assume 100 mrem/yr)*	*From FRP-MOX Plants, avg/person*
Pre-1985 Plants	34	100-250	1300 man-rem	100,000 man-rem	1.3 mrem
Post-1985 Plants	0.4	100-250	17 man-rem	100,000 man-rem	0.02 mrem

Radioactivity — Potential Accidents

The radiation doses estimated for several postulated accidents in the reprocessing and MOX fabrication plants are all less than 1 rem to an individual receiving the maximum dose, well within current or anticipated future standards for the effects of such infrequent events.

Occupational Exposure

Occupational exposures are expected to be controlled to an average level of about 500 man-rem per year in each collocated reprocessing and MOX fabrication facility. The individual annual doses are expected to average 400 mrem with a maximum of 1000 mrem; these values are well within present limits.

Transportation

In the year 2000, transportation of fuel material, waste, and products are estimated to result in about 410 man-rem per year to transport workers (average about 35 mrem per year per

worker) and 340 man-rem per year to the general public (average about 0.03 mrem per year per person).

Transportation accidents will result in far greater risks of bodily injury or death from common causes than the risk of adverse health effects due to releases of radioactivity.

Thermal Effluents

No significant thermal effects on receiving bodies of water are expected to be associated with reprocessing or MOX fabrication plants. State standards, approved by the Environmental Protection Agency and incorporated in the National Pollutant Discharge Elimination System permit program, will be met to limit thermal pollution.

Chemical Effluents

Emissions of SO_2, NO_x, CO, fluorides, and hydrocarbons from reprocessing and MOX plants and support facilities are all calculated to result in ambient air concentrations within the National Primary Standards. These calculated concentrations are also well below concentrations that have been observed to be injurious to biota.

Chemical concentrations in liquid effluents are calculated to be within standards for fresh water intended for public supply.

Occupational Exposure to Chemicals

Exposure of workers to airborne chemicals (fluorides, fluorine, nitric acid, tributyl phosphate, for example) are

controlled by Federal limits under the Occupational Health and Safety Act. Adherence to these regulations is expected to provide adequate worker protection in the reprocessing and MOX plants.

Effects on the Community

Potential community effects of reprocessing and MOX plants are physical, economic, service-related, and aesthetic in nature. These are highly site-specific and should be addressed in the environmental assessments for actual facilities.

Cumulative Effects from Operation Through the Year 2000

Estimated cumulative radiation doses to local (50-mile radius), United States, and worldwide populations from operation of the LWR reprocessing and recycling industry through the year 2001 (including effects through 2101 of nuclides persisting in the environment) are as follows.

	Exposure, man-rem
Whole Body	
^{85}Kr	140,000
^{3}H	110,000
^{14}C	**990,000**
Other	20,000
Lung	
^{85}Kr	290,000
Thyroid	
^{129}I	330,000
Bone	
Pu, Am, Cm	100,000

The population dose commitments can be compared to the cumulative dose (over the period 1981-2101) from natural background sources of radiation of 2×10^{11} man-rem. A natural background dose rate of 100 mrem per person per year was assumed for the 120-year period for the worldwide population. The calculated incidences of fatal cancers due to fuel recycling operations (using upper-limit dose-effect factors which probably overestimate the actual effects considerably) represent a rate per 100,000 population per year of about 0.004 in the 50-mile-radius regions around the plants, about 0.0001 in the United States, and about 0.00003 worldwide. The current United States death rate caused by malignancies is 168 per year per 100,000 population. Cancer death rates in other nations range from about 20 to 200 per year per 100,000 population. It is worth stressing the fact that these cancer rates due to fuel recycling operations are only calculated values. Cancer rates of these very low magnitudes, if real, would be practically impossible to substantiate statistically.

The increased ^{14}C content in the biosphere resulting from releases from the reprocessing plants would reach a value of approximately 0.15% of the naturally produced ^{14}C in the year 2001. The average individual whole body dose from naturally produced ^{14}C is about 1 mrem/yr; thus, the additional dose from ^{14}C would be about 0.0015 mrem/yr per person in the year 2001.

UNAVOIDABLE ADVERSE ENVIRONMENTAL EFFECTS

Environmental effects that cannot be avoided if spent fuel is reprocessed and recycled include (a) minor health effects

from the small radiological effluents remaining after additional effluent controls are installed, (b) normal effects of construction operations, use of electric power, land use, and (c) potential effects of accidents to the fuel cycle facilities.

ALTERNATIVES

Four major alternatives to the base case of reprocessing and recycle of uranium and plutonium are recycle of uranium only, no recycle, coprocessing, and the tandem fuel cycle:

- The advantage of recycling only uranium is that movement of plutonium is curtailed and safeguarding the plutonium from theft or intentional dispersion would be simplified. Disadvantages include the use of about 13% more uranium ore by the year 2000, an increased cost of about $25 billion, and increased exposure of the population from release of ^{222}Rn from mining, milling, and mill tailings.
- Advantages of no recycle are that safeguards requirements are greatly simplified, and radiological releases from the back end of the fuel cycle are nearly eliminated. Disadvantages include a 32% increase in uranium ore requirements and associated population exposure from ^{222}Rn, an increased cost of about $18 billion, and increased usage of land, and power resources associated with mining, milling, and enrichment uranium.
- The advantage of coprocessing to form a combined stream of recycled uranium and plutonium is that safeguards requirements would be simplified. The plutonium would remain in

a dilute form, and complicated technology would be required to convert the plutonium into a form suitable for nuclear explosives. The main disadvantage is an increased cost of about $16 billion.

- In the tandem cycle, safeguards requirements are greatly simplified because the fuel, after irradiation in LWRs and then in heavy water reactors (HWRs), is treated the same as in the no recycle case. However the tandem cycle would cost about $64 billion more than the base case because of cost penalties associated with construction and operation of HWRs.

Five variations of the base case were also evaluated, as well as fuel cycles with larger and smaller numbers of LWRs.

- A cooling period of 5 years rather than 1 year results in an 11% increase in uranium ore requirements by the year 2000, a cost decrease of about $1 billion, and an increase in total health effects.
- A delay of 5 years in startup of fuel reprocessing results in a calculated 13 percent decrease in health effects from back end operations because more of the reprocessing would be done in plants with improved offgas controls. Uranium ore requirements through the year 2000 would increase 9 percent and costs would increase $1 billion.
- If the post-1985 offgas improvements and mill tailings cover are not implemented, the estimated increase is 2800 health

effects from front end operations and 1750 health effects from back end operations. Costs would decrease about $1 billion.

- If the one reprocessing plant with existing offgas control equipment is retrofitted with improved offgas controls in 1985 and controls for all post-1985 plants are also provided, the estimated decrease is 550 health effects. Costs would increase about $0.5 billion.
- Three variations in siting were examined. Location of the reprocessing and mixed oxide fuel fabrication facilities at different sites results in additional plutonium safeguards requirements and a slightly increased risk of population exposure and accidents because of the greater transportation mileage. Location of integrated reprocessing/MOX fabrication facilities to minimize transportation of spent fuel or transportation of radioactive waste has minor environmental impact and negligible effect on cost.

Assessment of the alternatives of Pu-U recycle, U recycle only, and no recycle for growth projection of larger (600) and smaller (400) numbers of LWRs in the year 2000 show no relative differences within a given growth projection compared to the similar assessment for the base case of 507 LWRs.

SHORT-TERM USES AND LONG-TERM PRODUCTIVITY

Short-term gains (through the year 2000) of closing the LWR fuel cycle consist of the savings in uranium ore requirements

(with the associated reductions in environmental effects) and total costs. Short-term losses consist of the environmental effects from radiological releases and the increased risk of release or diversion of the plutonium product.

Long-term gains include primarily the improved overall utilization of U.S. resources, such as providing fuel for recycle in breeder reactors for the even more advantageous use of these resources after the year 2000. Long-term losses include primarily the commitment of custodianship of the reprocessing and recycle facilities through decommissioning.

LAND-USE PLANS, POLICIES, AND CONTROLS

No conflict is foreseen with existing Federal, state, and local land-use plans or policies.

IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES

Irreversible commitments associated with closing the LWR fuel cycle include 1) the permanent commitment of about 110 acres of land for reprocessing plants and about 30 acres for storage of radioactive wastes in commercial burial grounds (does not include land required for wastes stored at Federal repositories), 2) the annual expenditure of about 2.1×10^8 MW-hr of electrical energy of which 60% is expected to be supplied by fossil fuel by the year 2000, and 3) the utilization of 10,000 to 15,000 workers in reprocessing and mixed oxide fabrication plants by the year 2000.

COST-BENEFIT ANALYSIS

Based on the resource, environmental, and economic analyses in this environmental statement, it is concluded that no excessive adverse environmental effects would result from an LWR reprocessing and recycle industry. Therefore, this statement finds no technical reason to delay programs that will provide the information needed on costs, environmental effects, and other factors of importance for further decision making with regard to the back end of the LWR fuel cycle.

The alternatives of recycling uranium only (and storing plutonium) and no recycle would increase uranium demand, environmental effects, and costs compared to the base case of recycling uranium and plutonium. The alternative of coprocessing would cause similar environmental effects and uranium demand as the base base case but with increased cost. The tandem cycle would increase uranium demand, reduce environmental effects, and increase costs substantially. Delaying reprocessing increases uranium demand and changes cost only slightly. Environmental effects would be similar except that health effects from back end operations would be greater or less than in the base case depending on the quantity of fuel assumed to be reprocessed in plants with existing offgas controls.

The alternatives of not including improved control technology or of retrofitting the improvements to older plants should be evaluated on a cost-benefit basis as the technology for the

various controls is developed and their costs become better defined.

SAFEGUARDS

Safeguards will be provided to reduce public risk from acts or threats by individuals or groups against fuel cycle facilities. Physical protection systems and instrument response systems are in use or under development by ERDA and NRC to reduce the likelihood of attempted thefts of plutonium or sabotage and to reduce the likelihood of success if attempted. A combination of post-theft recovery techniques and physical forms of the plutonium-uranium products will reduce the likelihood that a terrorist could successfully threaten society even if he has obtained these materials. Finally, the constantly improving safeguards technology would force terrorists to commit ever-increasing resources that would increase the likelihood of detection and nullification. These components form a hierarchy of positive safeguards measures that would be balanced to achieve the objective of no significant increased public risk of death, injury, or property damage from nuclear fuel cycle activities.

2. BACKGROUND

A. PROPOSED ACTION AND ANTICIPATED BENEFITS

This statement is intended to assist ERDA in making decisions involving programs and projects that could lead to closing the LWR fuel cycle. The statement considers costs, benefits, and consequences of facilities and operations required to close the back end of the LWR fuel cycle. Operations that may possibly require further development and/or demonstration include: 1) spent fuel shipment and temporary storage, 2) shearing and/or dissolution of the spent fuel, 3) chemical separation of uranium, plutonium, higher actinides, and fission products, leading to separated or combined streams of uranium and plutonium, 4) preparation of intermediate forms for recyclable products (such as UF_6 and PuO_2), 5) removal of radioactive effluents from offgases, 6) shipment of intermediate product forms, 7) fabrication of recycled uranium, plutonium, and higher actinides into fuel assemblies for LWRs, 8) refabrication of LWR spent fuel for additional irradiation in a heavy water reactor, 9) interim treatment and storage of waste products before final disposition, and 10) facility decommissioning. Program objectives may range from providing additional information on technical feasibility, safety, safeguards, economics, and environmental effects to demonstrations of processes.

Incentives for such programs are found in the major potential benefits that may be realized by closing the LWR fuel cycle. These benefits are summarized below. The bases for the anticipated benefits are developed in Sections 5 and 9.

1. Utilization of Resources

The major benefit of closing the LWR fuel cycle is in utilization of U.S. resources, as described in Sections 5 and 9. Recycle of uranium and plutonium in LWR reactors results in the most advantageous short-term use (up to the year 2000) of the nation's uranium resources. It also could provide fuel for the orderly development of uranium and plutonium recycle in breeder reactors for the even more advantageous use of these resources after the year 2000. Both of these consequences help to reduce U.S. dependence on foreign sources of energy.

Prompt introduction of LWR fuel recycle is estimated to reduce U.S. uranium ore and enrichment requirements by about 25% by the year 2000. Ultimately, utilization of uranium resources could be increased by a factor of 50 or more by the implementation of a nuclear industry based on breeder reactors. Full utilization of U.S. uranium would allow conservation of fossil fuel resources with reductions in foreign fuel imports, better utilization of fossil fuels for transportation and for the chemical industry, and improvement in the likelihood of achieving national energy goals.[1]

2. Cost

Additional benefits of closing the LWR fuel cycle are in the area of economics. Recycle of uranium and plutonium results in a reduction in the requirements for mining, milling, and enriching uranium. The resultant reduction in demand for manpower in front end of the cycle will be more than offset by the increased demand for manpower in recycle facilities. The total front-end costs, however, are larger than the corresponding recycle costs, and savings of about $16 billion (FY-1977 $), or about 7% of the total fuel cycle cost, excluding reactors, are estimated. This estimate includes the reprocessing, recycling, and waste storage costs for all fuel discharged from the reactors by the end of the year 2000.

3. Other

Studies have been made of the environmental effects of nuclear and fossil fuel power.[2,3] To some extent, the closing of the back end of the fuel cycle will result in utility decisions to build nuclear rather than fossil fuel power plants. The substitution of nuclear power for an equivalent amount of power from coal-fired plants reduces nonradioactive effluents released to the atmosphere (e.g., SO_2, CO, HG, As, and hydrocarbons) by factors of 10^3 or more. Other benefits associated with substituting nuclear power for fossil-fuel power include a tenfold or greater reduction in fatalities from mining and transportation accidents.

B. NUCLEAR INDUSTRY PROJECTIONS

1. Introduction and Summary

In this environmental statement, the impacts (on environment, economics, and resources) of closing the LWR fuel cycle in different ways are examined. The reference or base case assumes prompt reprocessing and recycle of uranium and plutonium. Differences from other major alternatives (uranium recycle only, no recycle, coprocessing, and the tandem fuel cycle) involve recycle facilities, materials processed, and uranium feed chain activity (mines, mills, UF_6 conversion plants, and uranium enrichment plants).

This section describes projections of the size and nature of the LWR industry* in the year 2000 in terms of the sizes, nature, and numbers of different fuel cycle facilities, both with and without spent fuel recycle. These projections are used as a basis for the environmental effects assessments which are presented in Section 3. The year 2000 has been chosen as the reference period because projections of the growth of the LWR industry indicate that a mature LWR industry could develop by then. Also, the influence of the breeder reactors on the nuclear power industry is currently expected to become appreciable by the year 2000, so that the pattern of the industry and of plutonium usage may change appreciably after that time.

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* As of July 1, 1976, 60 nuclear power plants, 8.1% of the nation's installed electrical generating capability, were licensed to operate, and 178 additional nuclear power plants were under construction or in design.

The estimated number of fuel cycle facilities which will constitute the year 2000 LWR industry, both with and without spent fuel recycle are summarized in Table 2.1.

TABLE 2.1

The Mature LWR Industry in the Year 2000

LWR Industry Components	*Number of Plants Without U or Pu Recycle*	*Number of Plants With U Recycle Only*	*Number of Plants With U and Pu Recycle*
Light Water Reactors	507	507	507
Fuel Reprocessing	0	7	7
Mine-Mill Complexes	72	60	51
UF_6 Conversion	6	5	5
Uranium Enrichment[a]	11	11	10
UO_2 Fuel Fabrication	11	11	10
Mixed Oxide Fuel Fabrication	0	0	7
Waste Management	2[b,c]	1[c]	1[c]
Pu Storage Facility	0	1	0

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a. Includes facilities for foreign demand assumed to be about 40% of domestic demand (see Appendix A, Table A-4).

b. Facility for interim storage of spent fuel.

c. Facility for final storage.

2. Nuclear Power Growth

The Office of Planning and Analysis of the Energy Research and Development Administration has, for a number of years, published its estimates of future growth of nuclear power.[4] The estimates are made after consulting in detail with industry regarding future plans and expectations of power demands. The estimates show the forecast growth of nuclear power generating capacity in the U.S. and foreign countries, and also provide data on the raw materials and fuel cycle production levels needed to meet anticipated demands. The 1975 forecasts of nuclear power growth through the year 2000 have been used in this statement;[5] the low nuclear growth projection was selected as the most likely case.* It has been used throughout this statement as the reference case.

The low projection postulates that conservation measures and rising electricity prices will cause reductions in demand from historic growth rates. However, the availability and prices of direct energy sources are such as to cause continuing substitution of electric energy for direct energy uses. The projection of nuclear energy presumes that in the short term, nuclear power

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* The most recent ERDA projections of U.S. installed nuclear capacity for the year 2000 have been presented at the Atomic International Conference on Uranium, September 14, 1976 at Geneva, Switzerland. These projections for installed nuclear capacity in the year 2000 forecast 380 gigawatts, 510 gigawatts, and 620 gigawatts for the low, mid, and high case, respectively. In these forecasts, the low case (380 gigawatts) assumes that the nuclear fuel cycle is not closed and the mid and high cases assume uranium and plutonium recycle.

plants continue to be delayed by numerous problems creating slippages in announced schedules. During the long term, high capital costs and long lead times are expected to limit installed LWR nuclear capacity to about 33% of the total projected electrical generating capacity in the year 2000. The projected LWR nuclear power capacity is shown in Table 2.2. No new LWRs are projected after the year 2000. In the year 2001, four PWRs and four BWRs are assumed to be retired.

TABLE 2.2

Projected LWR Power Capacity
(United States - Low Projection)[a]

	Power Capacity, electrical megawatts		
Calendar Year	*PWR*	*BWR*	*Total*
1976	26,000	17,000	43,000
1977	33,000	18,000	51,000
1978	39,000	18,000	57,000
1979	42,000	20,000	62,000
1980	48,000	22,000	70,000
1981	54,000	26,000	80,000
1982	66,000	34,000	100,000
1983	77,000	40,000	117,000
1984	88,000	47,000	135,000
1985	103,000	53,000	156,000
1986	117,000	62,000	179,000
1987	131,000	70,000	201,000
1988	146,000	76,000	222,000
1989	163,000	82,000	245,000
1990	178,000	90,000	268,000
1991	195,000	98,000	293,000
1992	213,000	107,000	320,000
1993	230,000	115,000	345,000
1994	248,000	124,000	372,000
1995	266,000	133,000	399,000
1996	283,000	141,000	424,000
1997	298,000	149,000	447,000
1998	312,000	156,000	468,000
1999	325,000	163,000	488,000
2000	338,000	169,000	507,000

a. ERDA-OPA 1975 projection.[5]

The projected growth of the U.S. electrical generating industry from the present through the year 2000 is plotted in Figure 2.1. The forecast growth of the LWRs in meeting the U.S. nuclear power requirements is also shown. Electrical energy production grows at 5.8% per annum through 1985 and then declines to 4.75% per annum growth through the year 2000. In Reference 5, High Temperature Gas-Cooled Reactors (HTGR) and Fast Breeder Reactors (FBR) are forecast to provide about 20% of the total nuclear capacity in the year 2000. However, these reactors and their supporting fuel cycle facilities are not considered in this environmental statement.

3. Year 2000 — The Base Case

The impacts of recycling uranium and plutonium from light-water-cooled reactors have been assessed for the overall LWR industry for the period 1976 through 2000, and incremental effects have been assessed for the industry in the year 2000.

a. Rationale for Selecting the Year 2000

The year 2000 has been selected for the assessment of the incremental impacts on the environment because by then all components of the industry are expected to have developed to a mature status. The technologies expected to be employed at that time are largely known today. Most have evolved beyond the development stages, and many have been proven in practice.

Delays in the forecasted startup of reprocessing and recycling operations led to the choice of the year 2000 for assessing

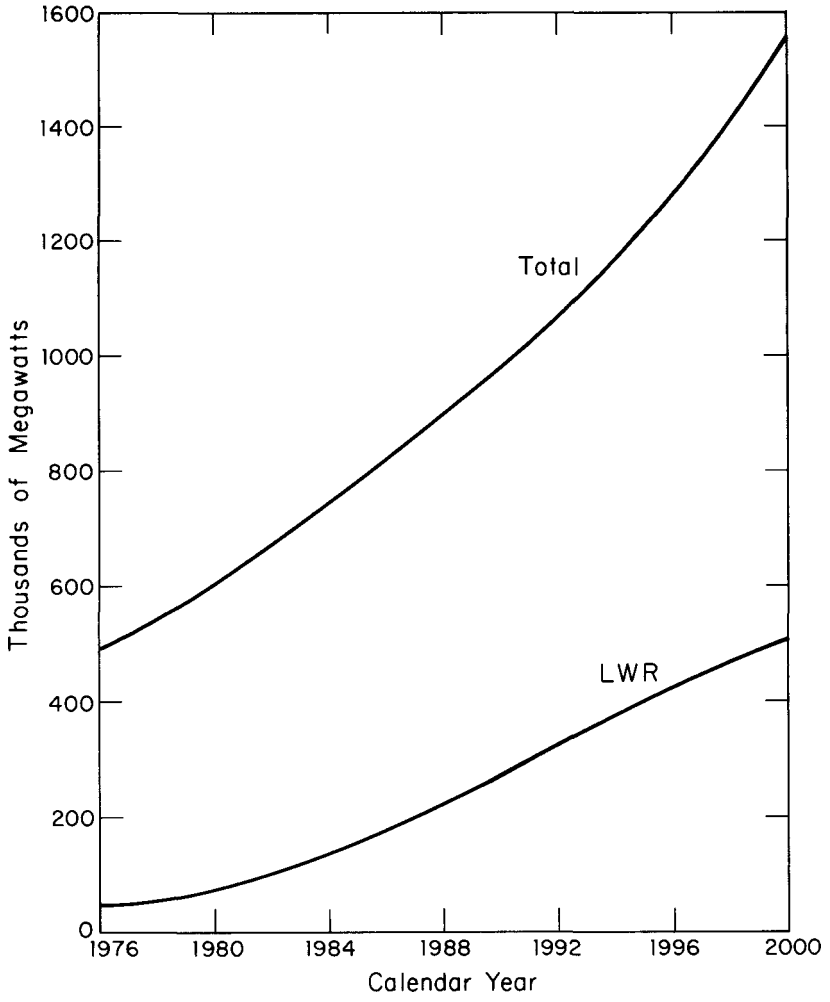

FIGURE 2.1. Central Station Electrical Generating Capacity in the United States as Projected by ERDA-OPA 1975 Low Projection

the incremental impacts. In the present study, reprocessing is assumed to begin in 1981, and recycling of plutonium is assumed to begin in 1983. Within 3 to 4 years after a Federal government decision to recycle uranium or uranium and plutonium, Allied-General Nuclear Services could provide reprocessing services.[6]

b. Characteristics of the Impact on the Environment for Year 2000

The impact of fuel recycle in light-water-cooled reactors on the year 2000 environment exhibits both beneficial and adverse components. The beneficial component is primarily that caused by the reduction in the new uranium supply and enrichment functions due to substitution of recycle components for a portion of the ^{235}U in the reload fuel required to sustain the LWR industry. The adverse components are increased requirement for waste handling and treatment, increased quantity of plutonium in various steps of the industry, and increased release of radioactivity to the environment.

The industry-wide environmental impacts are assessed by estimating the impact of individual model fuel cycle facilities and then factoring those assessments into the projected schedule for the introduction of the facilities in the LWR industry. The number of such model facilities estimated to constitute the LWR industry in the year 2000, both with and without spent fuel recycle, is the subject of this section. Assessment of the impacts of individual model facilities and of the reprocessing and recycle industry as a whole is presented in Section 3.

c. The Mature LWR Industry Around Year 2000

The LWR industry in the year 2000 is expected to consist of approximately 507 reactors supported by front and back end activities. These activities and material flows forecast for the year 2000 are shown schematically in Figures 2.2, 2.3, and 2.4 for three principal fuel cycles. The industry without fuel recycle is shown in Figure 2.2, that with uranium recycle only is shown in Figure 2.3, and that with both uranium and plutonium recycle is shown in Figure 2.4. The number of facilities required in each case are also noted in Table 2.1.

The projected LWR industry as described in this section — the base case against which the incremental impacts of other alternatives are compared — includes both uranium and plutonium recycle. Implicit are the assumptions that spent fuel will be reprocessed, that uranium in those fuels will be recovered and recycled to LWRs, that plutonium will be recovered and recycled, and that solidified high-level wastes and solid wastes containing TRU isotopes will be managed by the Federal government. Other cases can be hypothesized, and the more salient of those are discussed as the alternatives in Section 5 and Section 9.

4. Components of the LWR Industry Around Year 2000

The components which constitute the LWR industry are described below, both with and without spent fuel recycle; and the differences between the cases are discussed.

a. Reactors

In the LWR industry of the year 2000, about 507 reactors of 1000-MWe generating capacity each are projected. This number is assumed to be independent of spent fuel recycle. Thus, without

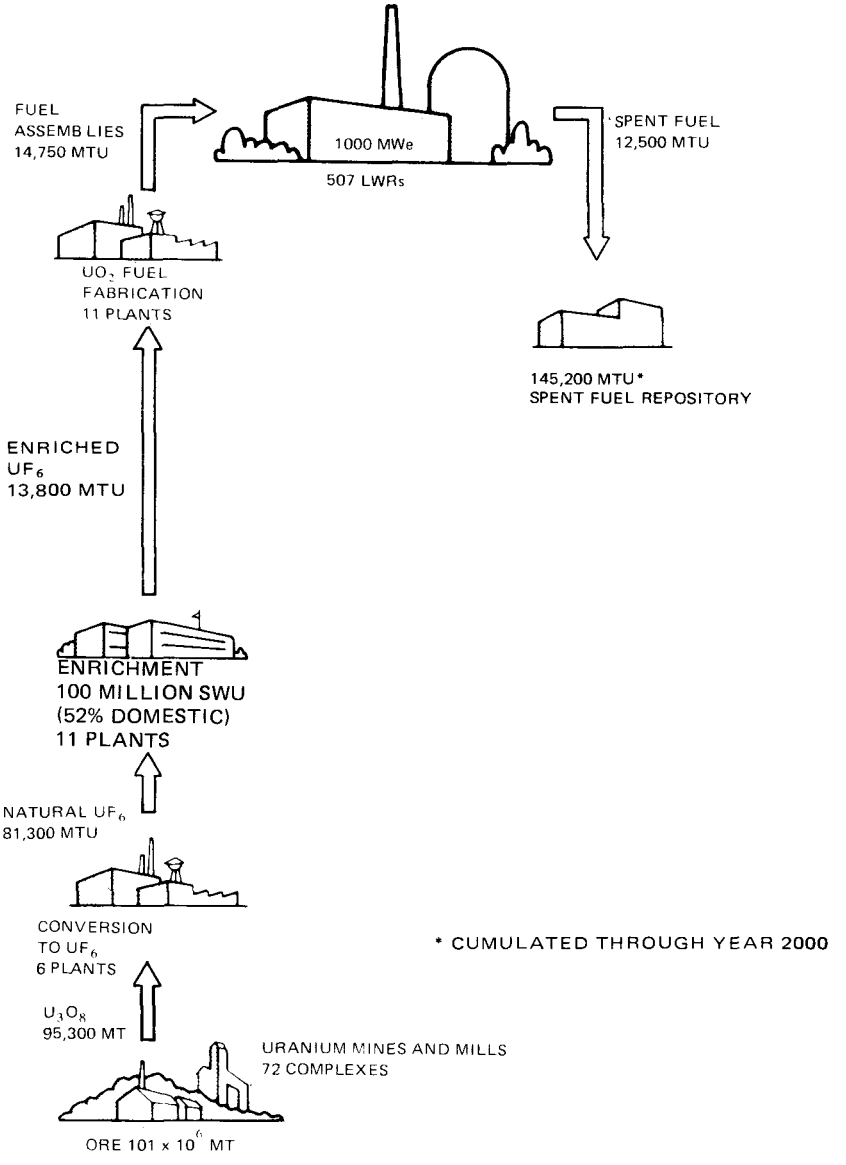

FIGURE 2.2. The Model LWR Industry In The Year 2000 With No Recycle

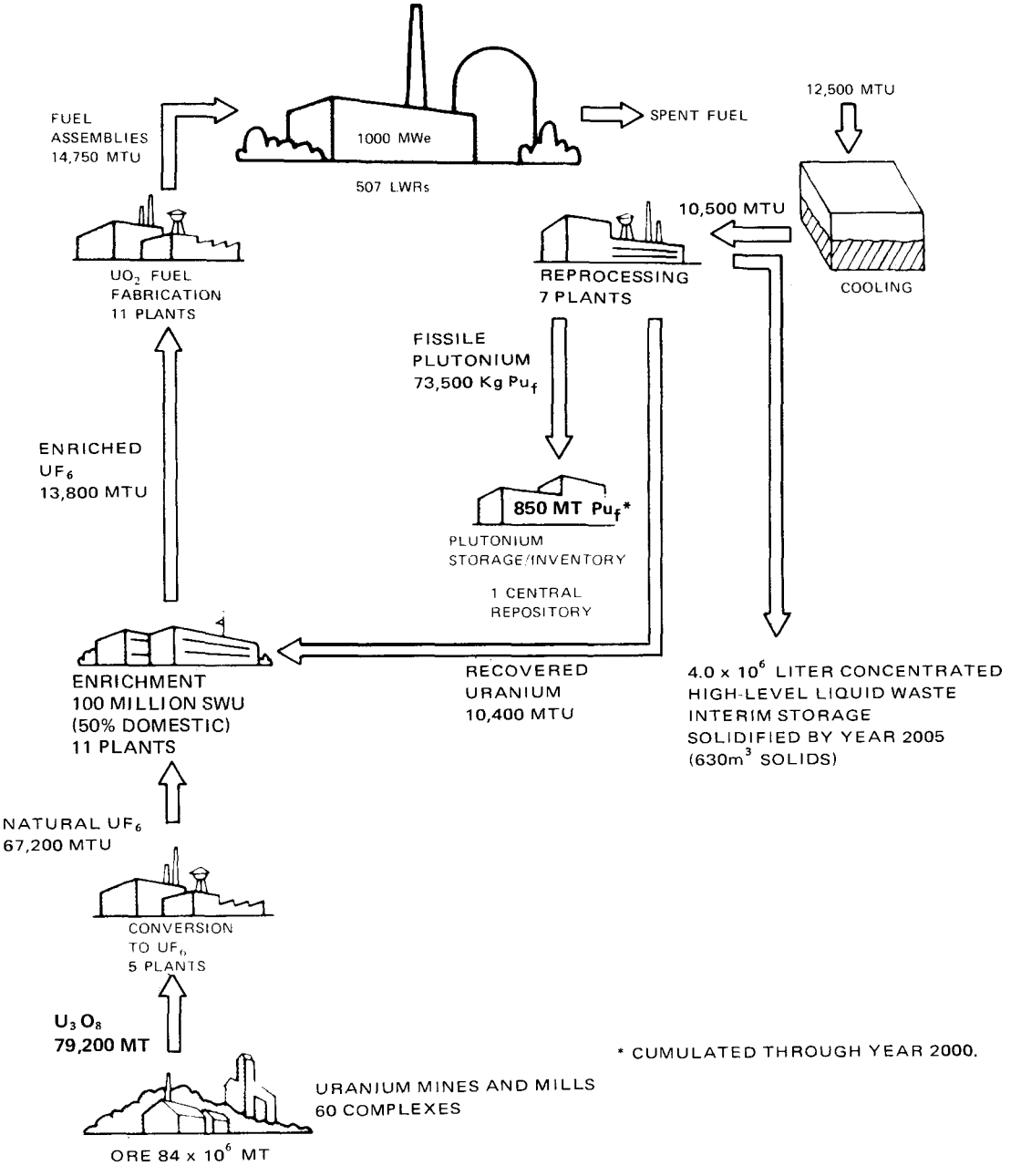

FIGURE 2.3. The Model LWR Industry in the Year 2000 With Uranium Recycle

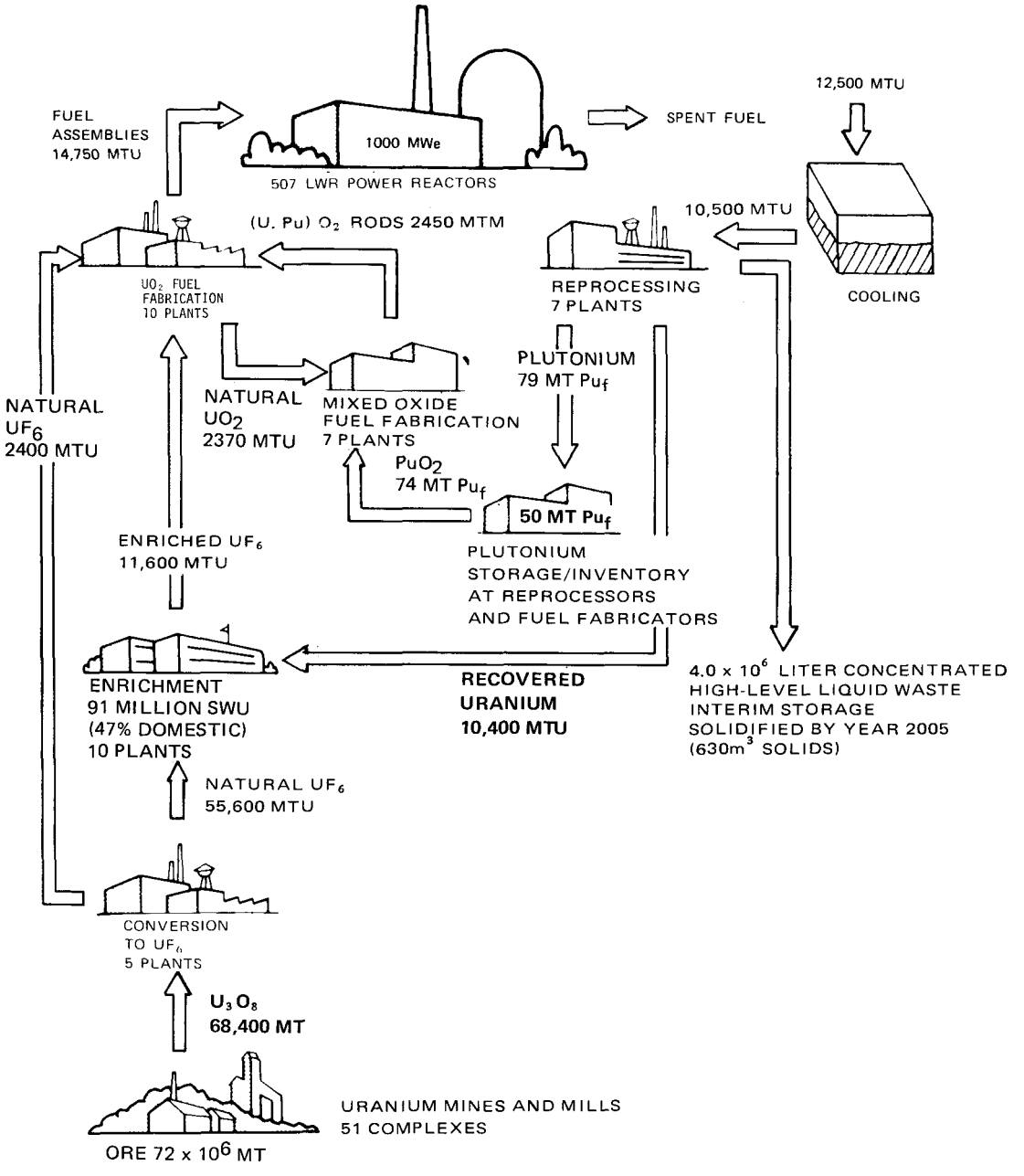

FIGURE 2.4. The Model LWR Industry In The Year 2000 With Uranium and Plutonium Recycle

plutonium recycle, the 507 LWRs will be fueled solely with slightly enriched UO_2, either new or partly recycled. With plutonium recycle, about 420 of the reactors are assumed to contain some mixed oxide fuel amounting to about 16% of the total fuel for the LWR industry in the year 2000. The remaining LWRs are assumed to be fueled solely with slightly enriched UO_2.

The LWR reactors are assumed to be one-third Boiling Water Reactors (BWR) and two-thirds Pressurized Water Reactors (PWR). When plutonium is recycled, the reactor is assumed to operate with a maximum of about 25% of the fuel assemblies containing mixed oxide; the remainder of the fuel assemblies contain slightly enriched UO_2 only. Typical characteristics of LWR fuel charges are compared in Table 2.3 for operation with and without plutonium recycle.

b. Fuel Reprocessing

The projected reprocessing schedule of about 10,500 MTU of spent fuel from LWRs in the year 2000 is anticipated to be met by operating the existing Allied-General Nuclear Service (AGNS) reprocessing plant and six additional model plants, which are assumed to have design capacities of about 1500 MTU per year, either with or without plutonium recycle. However, a proportionately smaller number of larger plants may well be used since they are expected to offer appreciable cost reduction. The anticipated startup dates of new reprocessing plants and mixed

TABLE 2.3

LWR Fuel Charge Characteristics[a,b]

	PWR	*BWR*
Initial Core, Average[c]		
Irradiation Level, MWDth/MTU	22,600	17,000
Fresh Fuel, MTU	76.38	117.20
Fresh Fuel Assay, wt % ^{235}U	2.26	2.03
Spent Fuel, MTU	74.00	114.50
Spent Fuel Assay, wt % ^{235}U	0.74	0.86
Replacement Loadings[c] (Annual Rate Without Pu Recycle and 75% Plant Factor)		
Irradiation Level, MWDth/MTU	32,600	27,500
Fresh Fuel, MTU	25.46	29.30
Fresh Fuel Assay, wt % ^{235}U	3.21	2.73
Spent Fuel, MTU	24.30	28.20
Spent Fuel Assay, wt % ^{235}U	0.90	0.84
Replacement Loadings[c] (Annual Rate With Pu Recycle and 75% Plant Factor)		
Irradiation Level, MWDth/MTU	32,600	27,500
Fresh Fuel, MTU	25.46	29.30
Fresh Fuel Assay, wt % ^{235}U	2.80	2.39
Fissile Pu Recycled, MT	0.167	0.163
Spent Fuel, MTU	24.30	28.20
Spent Fuel Assay, wt % ^{235}U	0.90	0.84

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a. Derived from Reference 1.

b. For model reactors of 1000 MWe capacity. MWDth is thermal megawatt days, MTU is metric tons of uranium.

c. In the present study, spent fuels are assumed to contain 6.6 kg of fissile plutonium per metric ton of uranium for fuel cycles in which plutonium is not being recycled. Where plutonium is recycled in appreciable quantities the fissile plutonium content of spent fuel is assumed to be 7.5 kg per metric ton of uranium.

oxide fuel (MOX) fabrication plants (and total capacities) are shown in Table 2.4. These startup dates follow from an assumed decay time of 1 year between reactor discharge and reprocessing of a given batch of spent fuel.

The capacities of reprocessing plants are almost independent of plutonium recycle. However, the plutonium handling portions of those plants will have to be slightly enlarged in order to handle increased plutonium flow concomitant to implementation of plutonium recycle. Such increases amount to about 4% on an industry-wide average basis.

Anticipated flows of materials from reactor discharge through reprocessing projected through the year 2000 are given in Table A.1 in Appendix A. Spent LWR fuels are assumed to cool for at least one year before reprocessing.

c. Mixed Oxide Fuel Fabrication

Implementation of plutonium recycle will require production of about 2450 MTHM/yr* of mixed oxide fuels in the year 2000. Production is projected to take place in seven facilities that are collocated with reprocessing plants of equivalent production capacity. Startup of MOX plants (Table 2.4) is assumed to be either the same year as the collocated reprocessing plant or one year later (except that the first MOX plant lags startup of the AGNS plant by two years).

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* MTHM is metric tons of heavy metal (uranium and plutonium).

TABLE 2.4

Projected Number of Plants and Capacities Required for Reprocessing LWR Fuels

	Reprocessing Plants			*Mixed Oxide Fuel Plants*		
Year	*Number Added*	*Total Number*	*Total Capacity, MTU/yr*[a]	*Number Added*	*Total Number*	*Total Capacity, MTHM/yr*[b]
1976-1980	-	0	0	-	0	0
1981	1 (AGNS)	1	600	-	0	0
1982	-	1	1,000	-	0	0
1983	-	1	1,500	1	1	175
1984	-	1	1,500	-	1	350
1985	-	1	1,500	-	1	350
1986	1	2	2,100	-	1	350
1987	1	3	3,100	1	2	525
1988	1	4	4,600	1	3	875
1989	1	5	6,100	1	4	1,225
1990	1	6	7,600	1	5	1,575
1991	-	6	8,500	1	6	1,925
1992	-	6	9,000	-	6	2,100
1993	-	6	9,000	-	6	2,100
1994	1	7	9,600	-	6	2,100
1995	-	7	10,000	1	7	2,275
1996	-	7	10,500	-	7	2,450
1997	-	7	10,500	-	7	2,450
1998	-	7	10,500	-	7	2,450
1999	-	7	10,500	-	7	2,450
2000	-	7	10,500	-	7	2,450

a. Plant capacities are 40% the first year, 67% in year 2, 100% in year 3. The schedule is based on processing after 1 year decay.

b. The capacity of MOX plants is equivalent to that of a collocated reprocessing plant. MOX plants operate at 50% capacity in the first year, 100% in year 2.

d. Supporting Uranium Cycle

Spent fuel recycle in LWRs will decrease the requirements for fresh uranium mining, milling, and enrichment. Implementation of uranium recycle only is predicted to decrease mining requirements through the year 2000 by about 14%. Implementation of plutonium recycle in LWRs is expected to further decrease the demand for U_3O_8 by an additional 10% for a total reduction of 24% through the year 2000; this decrease will be accompanied by similar decreases in most of the individual components of the supporting uranium cycle. The components of that supporting uranium cycle in the LWR industry are:

- Mine-mill complexes
- UF_6 conversion
- U enrichment
- UO_2 fuel fabrication

(1) Mine-Mill Complexes

Mine-mill complexes consist of one mill producing 1360 MT U_3O_8 (yellow cake) per year and the associated mines which provide ore to the mill.* In the year 2000, about 68,400 MT of U_3O_8 is expected to be needed to support LWRs operating with uranium and plutonium recycle. This will require the processing of about 73 million MT of ore containing 0.1% U_3O_8 (present ores contain about

* Milling capability of model mills is assumed to increase during the study period to offset the expected decrease in ore grade.

0.2% U_3O_8) in about 51 model mine-mill complexes, assuming 95% recovery and conversion of uranium to U_3O_8. With uranium recycle only, the uranium requirement is increased to about 79,200 MT of U_3O_8, and with no recycle the U_3O_8 demand is further increased to 95,300 MT. The U_3O_8 demand and number of mine-mill complexes projected through the year 2000 are given in Table A.2 of Appendix A. (Front-end operations for a given year are sized to meet reactor requirements the following year.)

(2) UF_6 Conversion

The UF_6 conversion requirement for the year 2000 is projected to be about 55,600 MTU/yr with plutonium recycle, 67,200 MTU/yr with uranium recycle only, and 81,300 MTU/yr with no recycle. Those requirements are projected to be met, respectively, by 5, 5, and 6 model UF_6 conversion plants in the year 2000. The production capacity of each is about 15,000 MTU/yr.

Two types of model plants are expected to exist in approximately equal numbers and equal aggregate processing capabilities by the year 2000. One type of plant is based on solvent extraction purification and is usually referred to as the wet process for UF_6 conversion. It is characterized by large volumes of liquid effluents. The other process, hydrofluor, is based on nonaqueous technology wherein purification is accomplished by distillation of volatile uranium hexafluoride. It is characterized by relatively low volumes of liquid effluents.

The UF_6 demand schedule and number of plants projected through the year 2000 are given in Table A.3 of Appendix A.

(3) Uranium Enrichment

The year 2000 uranium enrichment industry is anticipated to include the three existing gaseous diffusion plants upgraded to an aggregate separative work capacity* of 28 million SWU/yr,[7] and additional model plants of 9 million SWU/yr capacity to meet projected domestic and foreign demands. With plutonium and uranium recycle, the anticipated total demand for separative work in the year 2000 is 91 million SWU in ten enrichment plants. Support of domestic LWRs on uranium and plutonium recycle will require about 43 million SWU; the remaining separative work is assumed to meet foreign demands. The inventory of separative work accumulated during the 1980s will have been reduced to about 10 million SWU by the year 2000, equivalent to about 3 months' demand. With uranium recycle only, the anticipated separative work demand in the year 2000 increases to 100 million SWU (about 50 million SWU for LWRs), and the number of enrichment plants increases to eleven. With no recycle, the anticipated separative work production is also 100 million SWU (52 million SWU for LWRs). It is quite likely that at least some of the new enrichment facilities will be of the gas centrifuge or other advanced types.

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* A separative work unit (SWU) is a measure of the effort expended to separate a quantity of uranium of a given assay into two components, one having a higher percentage of ^{235}U and one having a lower percentage.

A hypothetical schedule of separative work, assumed foreign sales, and new plant startups projected through the year 2000 are given in Table A.4 of Appendix A. This is not an official schedule, but rather is given to illustrate the effect of back-end fuel cycle options on the need for front-end facilities.

(4) UO_2 Fuel Fabrication

In the year 2000, an LWR industry operating without plutonium recycle would be expected to produce 13,800 MTU of UO_2 fuel assemblies (during the year 2000 14,750 MTU of UO_2 fuel fabricated in 1999 would be charged into LWRs). This level of effort is anticipated to require six existing UO_2 fuel fabrication plants upgraded to an aggregate fabrication capacity of 6300 MTU/yr and five additional model plants of 1500 MTU/yr capacity each. With plutonium recycle, ten UO_2 fuel fabrication plants (including additions of four model plants) will be required by the year 2000. Two types of conversion processes are expected to be in use. In one process, UF_6 is reacted with water and ammonia to yield a precipitate of ammonium diuranate and large volumes of liquid effluents. In the other process, UF_6 is reacted with steam and hydrogen to yield UO_2. The latter process, often referred to as the dry conversion process or direct conversion, is expected, when fully developed, to produce lower volumes of effluents containing less pollutants than are characteristic of the ammonium diuranate process.

Each model UO_2 fuel fabrication facility will be capable of producing about 1500 MTU/yr of finished UO_2-containing fuel assemblies and of accepting completed rods containing mixed oxides for assembly into finished LWR mixed oxide fuel assemblies. The facility will also be capable of converting natural UF_6 into ceramic-grade UO_2 for use in mixed oxide fuel fabrication facilities. The model facility is also assumed to have capability for reprocessing its own scrap using a nitric-acid-based aqueous process.

The UO_2 fuel fabrication schedule and number of plants projected through the year 2000 are given in Table A.5 of Appendix A.

e. Transportation

The impact of the LWR industry in the year 2000 on transportation, both with and without spent fuel recycle, is assessed in terms of the number of shipments of fuel per year to and from the reactors and of various shipments of plant feed stocks, products, scrap or waste substances. Without spent fuel reprocessing, shipments to and from the reactors are essentially unchanged from the base recycle case, but shipments of spent fuel in its final waste form are substituted for those of processed wastes. The more important effects of plutonium recycle on transportation, as summarized in Tables 2.5 and 2.6 are: 1) introduction of the shipment of mixed oxide fuel rods from the mixed oxide fuel plant to the UO_2 fuel plant and subsequent shipment of mixed oxide-containing fuel assemblies to reactors; 2) introduction of the shipment of

TABLE 2.5

Shipments of Fuel Material for Year 2000

Type of Shipment	*Probable Mode of Transport*	*Quantity Shipped per Year, MT*			*Average Shipments per Year*			*Est. Avg. Shipping Distance, miles*	*Total Shipping Distance per Year, miles*[a]		
		Pu & U Recycle	*Uranium Recycle*	*No Recycle*	*Pu & U Recycle*	*Uranium Recycle*	*No Recycle*		*Pu and U Recycle*	*Uranium Recycle*	*No Recycle*
Natural UO_2 to MOX fuel fabrication plant	Truck	3,000	-	-	160	-	-	200	64,000	-	-
MOX fuel rods to UO_2 fuel fabrication plant	Truck	2,500	-	-	430	-	-	200	170,000	-	-
Unirradiated fuel assemblies to reactor	Truck	15,000	15,000	15,000	2,500	2,500	2,500	1,000	5,000,000	5,000,000	5,000,000
Irradiated fuel assemblies to fuel reprocessing plant or storage	Truck[b]	2,500	2,500	2,500	3,700	3,100	3,100	500	3,700,000	3,100,000	3,100,000
	Rail	10,000	10,000	10,000	2,500	2,100	2,100	1,000	5,000,000	4,200,000	4,200,000
PuO_2 to storage or other uses	Truck	*c*	100	-	*c*	200	-	300	*c*	120,000	-
UF_6 from fuel reprocessing plant to enrichment plant	Truck	11,000	11,000	-	560	560	-	200	220,000	220,000	-
Total				Truck:	7,400	6,400	5,600		9,200,000	8,200,000	8,100,000
				Rail:	2,500	2,100	2,100		5,000,000	4,200,000	4,200,000

a. Includes return trip for empty containers.

b. Assumes that 20% of irradiated fuel assemblies are shipped by truck.

c. If the fuel reprocessing plant and mixed fuel fabrication plant are collocated, 260 shipments are required to transport 130 MT of PuO_2 a total distance of 78,000 miles and return the empty containers the same distance.

TABLE 2.6

Shipments of Waste Materials from the Back End of the Pu-U Recycle for the Year 2000[a]

	Probable Mode of Transport	*Quantity Shipped Each Year*[b]		*Average Shipments Each Year*		*Estimated Average Shipping Distance, miles*	*Total Shipping Distance Each Year, miles*[c]	
		Pu and U Recycle	*Uranium Recycle*	*Pu & U Recycle*	*Uranium Recycle*		*Pu and U Recycle*	*Uranium Recycle*
To Federal Repository								
Reprocessing Plants								
Solid High-Level Waste	Rail	630 m^3	630 m^3	270	270	1800	970,000	9,700,000
Cladding Hulls[d]	Rail	3400 MT	3400 MT	420	420	1800	1,500,000	1,500,000
Other TRU Wastes[d]	Rail	5.6×10^3 m^3	5.6×10^4 m^3	2,000	2,000	1800	7,200,000	7,200,000
Kr-Filled Cylinders	Rail	590 units	590 units	100	100	1800	360,000	360,000
MOX Fuel Fabrication Plants								
TRU Wastes[d]	Rail	2.0×10^4 m^3		710		1800	2,600,000	
			Total: Rail	3,500	2,800		13,000,000	10,000,000
To Commercial Burial Grounds								
Non-TRU Wastes from FRP[e]	Truck	2.6×10^4 m^3	$2.6\ 10^4$ m^3	1,900	1,900	500	1,900,000	1,900,000

a. With no spent fuel recycle, about 2,700 rail shipments may be required to transport spent fuel assemblies packaged in a solid waste form from an interim storage facility to a Federal repository.

b. Estimates from ERDA-76-43, Vol. 4, *Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle.*[8] Does not include decommissioning wastes.

c. Includes return trip for empty containers.

d. Compaction or other treatment for volume reduction.

e. No volume reduction.

irradiated fuel from reactors to fuel reprocessing plants (for plutonium recycle, the number of shipments is increased over that needed for uranium recycle only because increased radiation and heat evolution from spent mixed oxide fuels causes shipment sizes to be decreased); 3) a marked decrease in shipments of PuO_2 to storage facilities and a corresponding increase in transfers or shipments of PuO_2 to mixed oxide fuel fabrication plants if not collocated with the fuel reprocessing plants; and 4) introduction of shipments of transuranium-contaminated wastes from the mixed oxide plants.

f. Waste Management

In addition to those waste management activities conducted as integral parts of the operation of model facilities, there are other facility components of the LWR fuel cycle whose only functions are the management of radioactive wastes. Radioactive wastes are produced in all the various components of the LWR fuel cycle. However, over 99% of the activity in the wastes is produced at the reprocessing plants as high-level waste, i.e., wastes which contain almost all fission products and actinides, including about 0.5% of the uranium and plutonium present in the spent fuel from LWRs. All of the other radioactive wastes are categorized as other-than-high-level wastes. They are generated during reactor operations, MOX fuel fabrication, fuel reprocessing, and UO_2-support cycle operations other than mines and mills.

The long-term management of solidified high-level wastes and solid wastes contaminated with transuranic nuclides will be the responsibility of ERDA and will be addressed in another environmental statement that is under preparation. Interim storage of these wastes is discussed in Section 2C, and an allowance for costs for long-range management of these wastes is included in the economic and cost benefit analyses in Sections 5 and 9.

Solid radioactive wastes which contain more than 10 nCi/g transuranium alpha activity are assumed, for this environmental statement, to be compacted (or incinerated) and transferred to ERDA for storage in accordance with proposed amendments to 10 CFR Part 20.[9]

Solid wastes which contain less than 10 nCi/g transuranium alpha activity* are expected to be managed by burial at commercially operated burial sites. With present burial ground practices, an acre of land is estimated to accommodate approximately 10,000 m^3 of wastes. About 5 million m^3 of wastes will be buried through the year 2000 assuming no incineration or compaction of the wastes from reactors, uranium preparation facilities, and fuel reprocessing plants. Methods to reduce the volume of solid waste, such as incineration, are now under development, and if these methods are successful, the volume of waste could be reduced substantially.

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* Cutoff limit of 10 nCi/g is currently being investigated by NRC and may be changed, but the approach is expected to be similar regardless of the cutoff limit.

With no reprocessing and recycle, the back end of the fuel cycle is eliminated so that waste management activities consist of managing the radioactive spent fuel and over 4 million m^3 of waste to commercially operated burial grounds. Interim storage of spent fuel assemblies is required until means for permanent disposal or long-term storage are established. A generic environmental statement on interim spent fuel storage is in preparation by the Nuclear Regulatory Commission. A preliminary allowance for permanent storage costs is included in the cost analyses.

g. Plutonium Storage

Plutonium storage facilities adequate for near-term storage requirements of the LWR industry with plutonium recycle are expected to be included as integral portions of fuel reprocessing plants and mixed oxide fuel fabrication plants. However, the storage of plutonium concomitant to an LWR industry with spent fuel reprocessing but without plutonium recycle (about 900 MT of fissile plutonium in storage by about year 2000) would require special facilities. For the purposes of this statement, one such storage-only facility is projected to be adequate through about year 2000. That facility will, of necessity, be required to meet the same exacting demands for operational safety, safeguards, and resistance to accidents and adverse natural phenomena as does a mixed oxide fuel plant or a reprocessing plant.

C. DESCRIPTION OF MODEL FACILITIES

1. Introduction

This section describes model facilities for each of the operations of the back end of the fuel cycle. These operations include chemical separation of uranium, plutonium, and waste components of the spent fuel, conversion of the plutonium to PuO_2, conversion of the recovered uranium to UF_6, fabrication of UO_2-PuO_2 fuel elements, interim waste management, storage of plutonium, storage of spent fuel, and transportation of radioactive materials.

Much of the descriptive material for these model facilities is condensed from the Generic Environmental Statement on Mixed Oxide Fuels (GESMO)[6] and the Technical Alternatives Document on waste management.[8] The reader is referred to the original documents for additional details, especially with regard to the front end of the fuel cycle.

2. Irradiated Fuel Reprocessing

Irradiated fuel is reprocessed to recover usable fissile material (uranium and plutonium) from spent reactor fuel elements after storage (assumed to be one year) in which time short-lived radionuclides decay. During the operation of a reactor, the buildup of fission products and depletion of fissile material requires that one-fourth to one-third of the fuel elements be

replaced annually. The discharged fuel elements contain about one-fourth of the ^{235}U that was in the fuel before irradiation, plus any unburned plutonium that was used to enrich the fuel before irradiation or produced from ^{238}U during irradiation. In the base case for this environmental statement, recovered uranium is recycled to the reactor after re-enrichment in the gaseous diffusion plant, and recovered plutonium is blended with natural uranium before recycle to the reactor.

a. Model Fuel Reprocessing Plant

The model fuel reprocessing plant (FRP) has a capacity of 1500 MTU/year. With adoption of plutonium recycle, mixed oxide (MOX) fuel would represent up to 17% of annual plant throughput. The processes include:

- Fuel element chopping.
- Nitric acid leaching.
- Purex solvent extraction.
- UF_6 production from uranyl nitrate by thermal decomposition and anhydrous processing.
- PuO_2 production from plutonium nitrate by the oxalate process.

Spent fuel assemblies are received at the reprocessing plant via truck or rail in heavily shielded shipping casks. The assemblies are spaced arrays of sealed tubular rods containing UO_2 or MOX pellets. The uranium and plutonium have been partially transformed by irradiation into heavier radionuclides, including

americium and curium, and into lighter fission products, including noble gases. The tubes encapsulating the fuel are normally made of Zircaloy, although stainless steel has also been used.

After storage to permit short half-life radionuclides to decay (assumed to be one year in this statement including 4 to 6 months in reactor cooling basin), the fuel elements are chopped into short pieces to expose the oxide. The oxide is leached by hot nitric acid, and the tubing pieces (hulls) are soaked in hot nitric acid and water to dissolve uranium, transuranics, and fission products. After this process, the hulls will still contain radioactivity resulting from activation of the Zircaloy and residual fuel. After adjustments of the nitric acid concentration, the leach solution is processed through solvent extraction and/or ion exchange systems. The solvent extraction step may be carried out in pulse columns,[10] centrifugal contactors, or mixer-settlers.[11] Ion exchange equipment may consist of agitated bed or fixed bed columns of ion exchange resin.[12] These process steps separate the fission products, uranium, and plutonium (Figure 2.5).

The purified uranium product is converted to uranium hexafluoride (UF_6) and is shipped to the gaseous diffusion plant for re-enrichment. The process used for converting uranyl nitrate to UF_6 is shown in Figure 2.6.[13]

The purified plutonium product is converted to plutonium oxide (PuO_2) for shipping to the MOX fuel fabrication plant. The most probable method for converting plutonium nitrate to plutonium dioxide is oxalate precipitation and calcination (Figure 2.7).

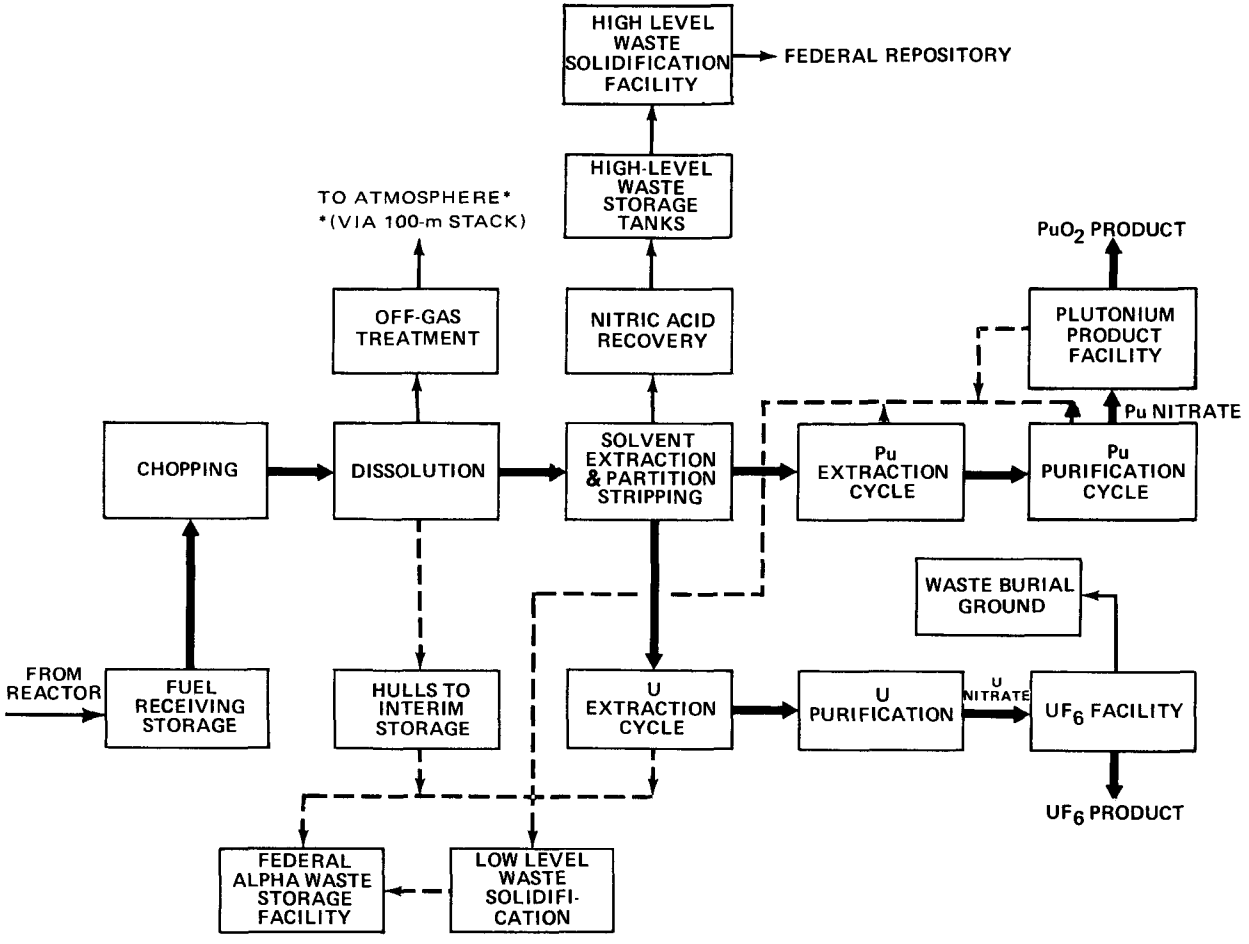


FIGURE 2.5. Simplified Flow Diagram of Reprocessing Plant Complex

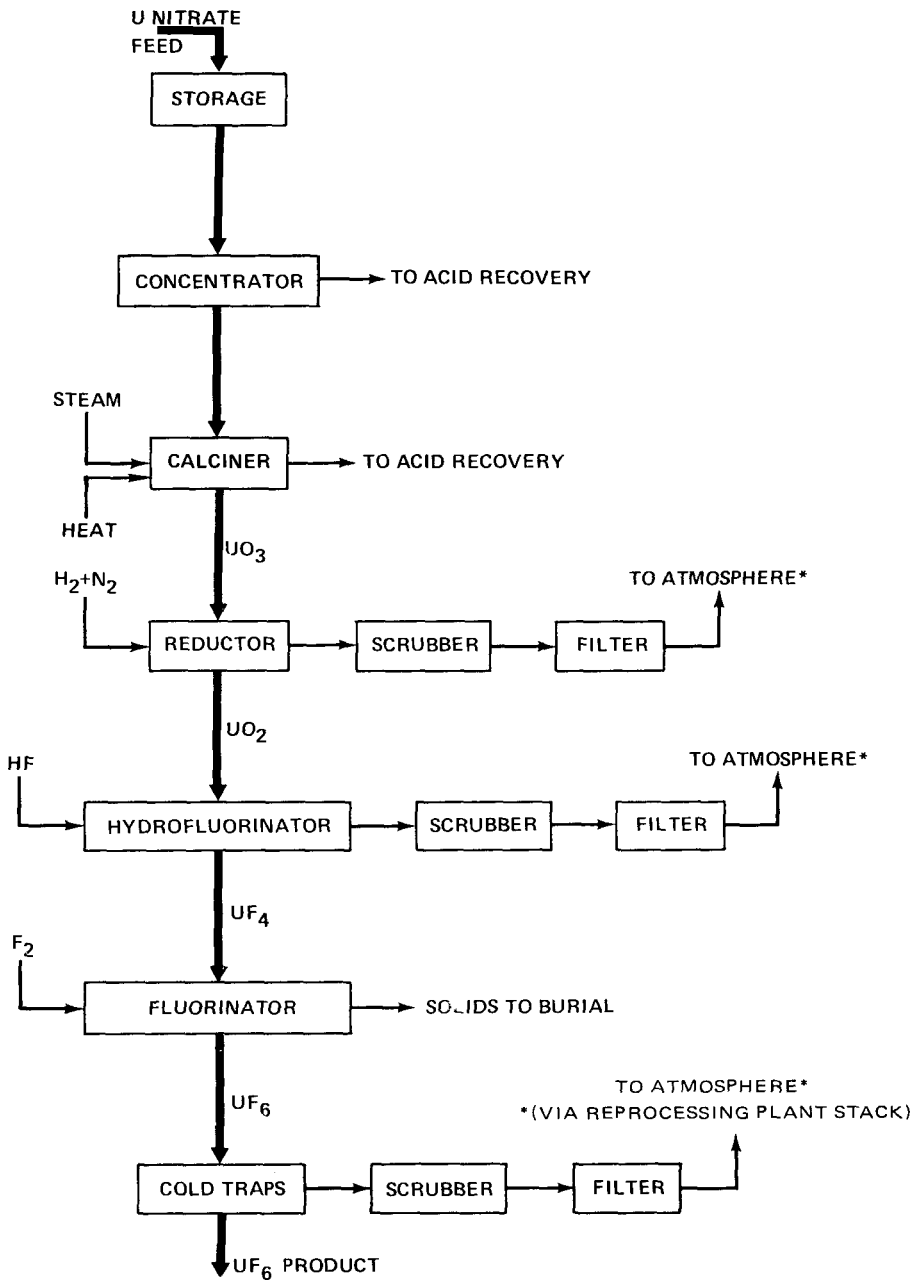


FIGURE 2.6. UF_6 Conversion Facility

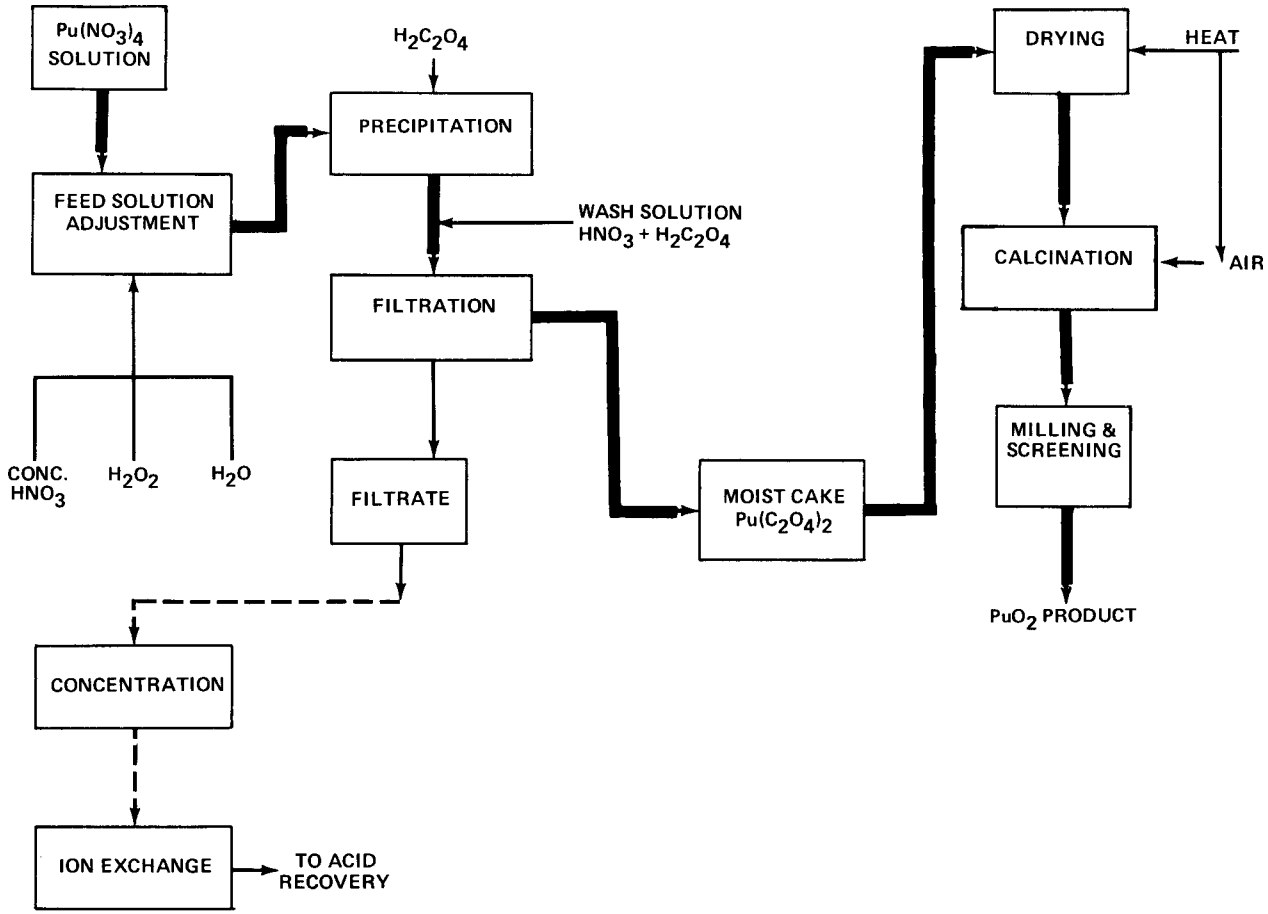


FIGURE 2.7. Oxalate Conversion Flowsheet for PuO_2

Waste management operations are expected to result in retention of the high-level wastes with almost no release to the environment. Typically, a concentrated liquid acid waste from the reprocessing plant is held in cooled multibarrier stainless steel tanks on the reprocessing site for a year or more to allow short-lived fission products to decay, and then the solution is processed further. Federal regulations[14] require that within five years after their generation the high-level liquids must be converted to solids, and within ten years after their generation the solids must be transferred to a Federal repository.

Reprocessing plants now in the planning stage provide for storing solid waste materials such as hulls and fuel hardware onsite in vaults, concrete containers, or engineered soil structures (berms).[15] Other low-specific-activity solid wastes are packaged and may be shipped to commercial burial grounds for long-term storage or may be stored onsite. NRC is considering regulations that would prohibit the disposal by burial in soil of transuranic elements in concentrations exceeding 10 nCi/g of waste and would require that waste materials containing such elements above that limit be transferred to ERDA for storage as soon as practical, but within 5 years after generation. These wastes would be shipped to a suitable Federal repository in the future.

The reprocessing plants are located in structures designed to withstand design basis earthquakes and other natural phenomena (tornadoes, hurricanes, floods, etc.) as appropriate based on the location of each plant. Plant auxiliaries include standby

diesels for emergency power; fire protection systems; water treatment systems; boilers to produce plant steam; electrical switchgear; and sanitary waste treatment systems. All exhausts from the processes are discharged through a 100-m stack after filtration and purification as described below.

Personnel exposure to radiation is controlled by shielding for normal operations and by use of special work permits for maintenance operations. Contamination of air in personnel-inhabited areas is minimized by controlled flow ventilation with air flow from areas of low (or no) contamination to ones of progressively higher contamination.

b. Radioactive Effluents

Estimated atmospheric releases of radionuclides from plants in operation in the early 1980s are listed in Table 2.7. It is assumed for purposes of this environmental statement that fuel reprocessing plants coming on line in the late 1980s will include equipment that is currently under development for further reduction of radiological releases. The effluent control system for these later plants and other components of the waste management systems are shown in Figure 2.8. It is assumed that all plants after AGNS and NFS include the following equipment:

- A voloxidation step in the head-end system removes tritium. It is estimated that greater than 99% of the tritium will be evolved as tritiated water vapor when the irradiated fuel is oxidized in air at temperatures over 350°C. The tritiated

TABLE 2.7

Radionuclides Released to the Atmosphere from the Fuel Reprocessing Plant[16]

(Basis: 1500 MT/yr, LWR Fuel, 365-day Cooling)

Nuclide[a]	*Ci/yr*	*Nuclide*	*Ci/yr*
^{3}H	1,100,000[b]	^{134}Cs	0.49
^{14}C	700[b]	^{137}Cs	0.50
^{85}Kr	14,000,000[b]	^{141}Ce	0.001
^{89}Sr	0.02	^{144}Ce	1.3
^{90}Sr	0.2	^{147}Pm	0.26
^{90}Y	0.2	^{154}Eu	0.022
^{91}Y	0.03	^{155}Eu	0.020
^{95}Zr	0.07	^{238}Pu	0.075[c]
^{95}Nb	0.02	^{239}Pu	0.0036[c]
^{103}Ru	0.003	^{240}Pu	0.0075[c]
^{106}Ru	0.52	^{241}Pu	2.1[c]
^{110m}Ag	0.006	^{242}Pu	0.00006[c]
^{125}Sb	0.025	^{241}Am	0.0022[c]
^{127m}Te	0.005	^{243}Am	0.00063[c]
^{129}I	3.0[c]	^{242}Cm	0.11[c]
^{131}I	3×10^{-7}	^{244}Cm	0.15[c]

---

a. Includes contributions from radionuclides released during waste solidification, UF_6 conversion, and PuO_2 conversion.

b. Releases of ^{3}H, ^{14}C, and ^{85}Kr are assumed to be reduced to 1% of the values shown for plants starting up after AGNS. See Table 2.8.

c. Releases of ^{129}I, Pu, Am, and Cm are assumed to be reduced to 10% of the values shown for plants starting up after AGNS. See Table 2.8.

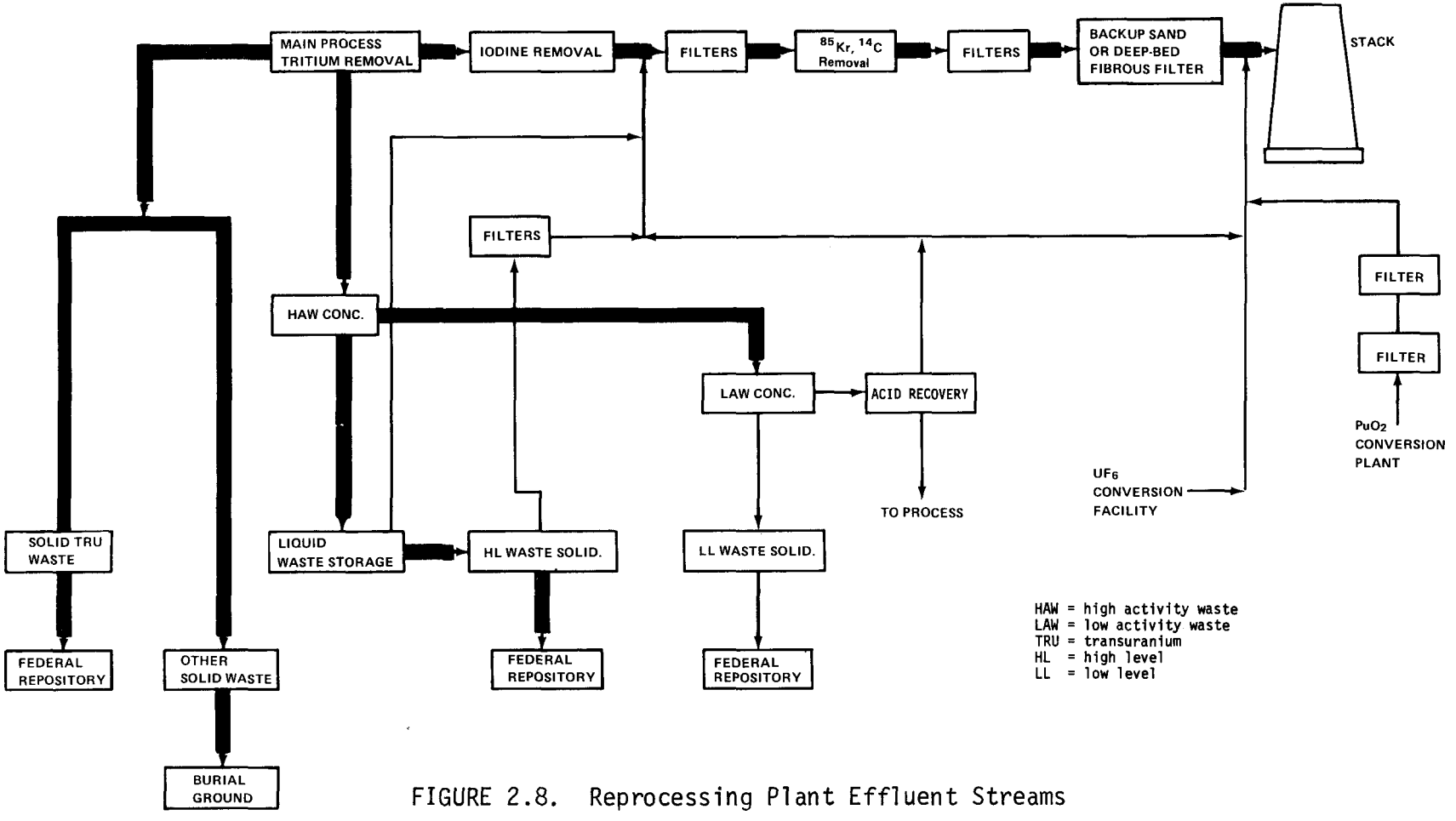


FIGURE 2.8. Reprocessing Plant Effluent Streams

water vapor is separated from the air and packaged for storage while the tritium decays, thus reducing the tritium release by a factor of 100.[15,17]

- The amount of ^{85}Kr released to the atmosphere is decreased by a factor of 100 by selective absorption equipment downstream of the NO_x absorber. The noble gases are absorbed in a fluorocarbon at low temperature (<0°C), stripped, compressed, and bottled in cylinders for storage while the krypton decays.[15,17]

- The amount of ^{14}C released is decreased by a factor of 100 by recovery in the ^{85}Kr recovery system, after the carbon is catalytically oxidized to CO_2.[15] The recovered CO_2 is converted to calcium carbonate by direct reaction with a slurry of slaked lime and packaged for storage along with other long-lived wastes.[18]

- Iodine evolution equipment volatilizes iodine from the dissolver solution so that iodine can be removed by the $Hg(NO_3)_2$-HNO_3 scrubber system. The retained ^{129}I is converted to a nonvolatile solid, sodium iodate, which is packaged for storage with other long-lived wastes, providing an estimated additional decontamination factor of 10.[17]

- The release of uranium, plutonium, and other particulates is decreased by a factor of 10 by a sand or deep-bed fibrous filter in the off-gas system.[17] All off-gas is passed through the backup filter before discharge through the 100-m stack.

The anticipated effectiveness of the effluent control systems for reprocessing and mixed oxide fuel fabrication plants is shown in Table 2.8. Overall cost estimates given in Section 9 for plants subsequent to AGNS include allowances for off-gas control technology. Safety aspects and environmental effects of long-term storage of the recovered radionuclides will be addressed in a subsequent environmental statement.

c. Nonradioactive Effluents

Effluents from the model reprocessing plant and supporting facilities are expected to contain primarily the chemicals shown in Table 2.9.

About 1/3 of the NO_x results from the nitric acid leaching of uranium and plutonium oxides from the Zircaloy hulls. About 2/3 of the NO_x and the SO_2 results from supporting fossil-fuel burning operations. For comparison, in 1974 transportation vehicles in the USA emitted 0.7 million MT of SO_x, 9.7 million MT of NO_x, 67 million MT of CO, and 12 million MT of hydrocarbons.[19]

Fluorine is introduced into the fuel cycle in the UF_6 conversion step that is associated with the reprocessing plant and is removed from the fuel material in the fuel fabrication step. As a result, fluorides appear in the airborne effluents from several steps of the cycle.

TABLE 2.8

Retention Factors for Radionuclides in Model Fuel Cycle Facilities[a]

Nuclide	*Reprocessing Plant Based on Current Technology*[16]	*Reprocessing Plant with Additional Off-Gas Controls*	*Mixed Oxide Fuel Fabrication Plant*[16]	*Mixed Oxide Fuel Fabrication Plant with Additional Off-Gas Controls*
^{3}H	1.0	100	NA[b]	NA
^{14}C	1.0	100	NA	NA
^{85}Kr	1.0	100	NA	NA
^{129}I	20	200	NA	NA
Pu	2×10^{8}	2×10^{9}	4×10^{9}	4×10^{10}
Am	5×10^{8}	5×10^{9}	4×10^{9}	4×10^{10}
Other Particulates	5×10^{8}	5×10^{9}	NA	NA

a. Release fraction = 1/retention factor (complete process including effluent treatment and retention in process streams).
b. NA = not applicable.

TABLE 2.9

Chemical Pollutants Released from Model Reprocessing Plant and Supporting Facilities[16]

Liquid Effluents	*Approximate Quantity, MT/yr*	*Atmospheric Effluents*	*Approximate Quantity, MT/yr*
Sulfate	20	SO_2	250
Nitrate	10	NO_x	300
Chloride	10	CO	2
Sodium and potassium	200	Fluorides	5
		Hydrocarbons	0.6

d. Heat Discharge

The model reprocessing plant discharges about 300 million to 330 million Btu/hr, predominantly from an open cooling tower (water-air). Water use at a reprocessing plant can range from a low of about 900 gpm (all process heat rejection to a cooling tower) to 90,000 gpm (once-through heat exchanger).

In arid areas, dry cooling towers may be selected because they use a closed system and do not require make-up water. Such towers require larger land area, considerably higher capital costs, and much more auxiliary power to operate cooling tower fans and circulating water pumps than evaporative cooling towers.

e. Effluent Monitoring

(1) Radiological

All reprocessing plant process effluents are monitored to determine the quantities of radionuclides that are released to the environment. This information provides the source terms for calculations of environmental effects. It also provides a basis for determining compliance with specific regulations and for evaluation of the effectiveness of effluent treatment methods.

The monitoring systems used depend on the characteristics of the effluents to be monitored. Measurements are made as close as practical to the point of final release to the environment, after all waste treatment and effluent controls have been effected, and before dilution with other waste streams. Release points may be stacks or ducts for airborne emissions and pipes or basins for

liquid discharges. Monitoring frequencies depend on the expected magnitude of normal unavoidable releases or the potential for abnormal releases. Types of monitoring range from continuous recording of radiation readings to periodic sampling and routine radiation counting.

(2) Nonradiological

Each reprocessing site is required to obtain a National Pollutant Discharge Elimination System (NPDES) permit from either the appropriate state agency or from the Environmental Protection Agency. These permits specify pollutant limitations (including thermal) in the effluent streams and the frequency and type of sampling required to provide the data requested under the permit. The NPDES permit conditions describe the minimum nonradiological effluent monitoring program. This program is supplemented as necessary by site-specific programs designed to ensure that no unexpected or unrecognized adverse environmental effects result from nonradiological effluents.

f. Cost

The model 1500-MT/yr reprocessing plant is estimated to cost about $1 billion to build and about $60 million per year in operating expenses in FY-1977 dollars.

3. Production of Mixed Oxide Fuels for LWRs

Recycle of plutonium in light-water-cooled reactors requires production of a mixed uranium dioxide-plutonium dioxide fuel.

Mixed oxide (MOX) fuel for light-water-cooled reactors consists of ceramic pellets (<5% PuO_2 with natural UO_2) in Zircaloy tubes. Mixed oxide fuel may be used to form separate fuel assemblies (PWR concept), or used as islands of mixed oxide rods surrounded by enriched UO_2 rods in a single assembly (BWR concept). With either concept, other assemblies in the core may be made entirely of enriched UO_2 rods.

a. Model Mixed Oxide Fuel Fabrication Plant

The model MOX plant has a capacity of 350 MT/yr of fuel containing <5% PuO_2. The process includes:

- Oxide powder preparation.
- Mechanical blending of UO_2 and PuO_2 powders.
- Pelletizing, sintering, and grinding of the mixed oxide.
- Scrap recovery.
- Waste treatment to recover plutonium and to prepare the waste for disposal.

The PuO_2 is assumed to be received from a collocated reprocessing plant. The isotopic composition of the plutonium received at the fabrication plant is a function of the radiation history of the fuel recovered at the reprocessing plant, the amount of plutonium that was recycled in the fuel from the reprocessing plant, and the time between recovery of plutonium at the reprocessing plant and its use at the fabrication plant.

The isotopic composition of three types of plutonium aged one year between reprocessing and fabrication is listed in Table 2.10. The composition of equilibrium recycle plutonium is that resulting from reprocessing an annual fuel reload that contained plutonium at 115% of the amount needed for a Self Generation Reactor (1.15 SGR level). The industry average is the most probable long-term composition of the major portion of the plutonium fabricated for LWR fuel.

The UO_2 and PuO_2 powders are mechanically blended and processed to fuel rods in the following steps:

- Blending of feed powders for the process powders (these may include PuO_2, PuO_2-UO_2, or recycled scrap).
- Pretreatment of mixed UO_2 and PuO_2 powders by comminution, compaction, and granulation to desired consistency.
- Pelletizing.
- Sintering of the pellets.
- Grinding to finished dimensions.
- Cleaning and drying the pellets.
- Loading the pellets into fuel rods, decontaminating the rod ends, and welding the end caps.

The process is illustrated in Figure 2.9.

The model MOX plant is assumed to consist of a main manufacturing building designed to withstand earthquakes and other natural phenomena including tornadoes, hurricanes, and floods. The plant complex also includes separate warehouse and administration facilities; field storage tanks for chemicals such as ammonia, nitrogen, and hydrogen; and miscellaneous other facilities.

TABLE 2.10

Examples of Isotopic Content of Plutonium, wt %
(Aged 1 Year After Reprocessing)

	Experimental Plutonium[a]	*Average LWR Plutonium*[b]	*Equilibrium Recycle Plutonium*[c]
^{238}Pu	1.9	1.2	3.4
^{239}Pu	63.0	53.0	41.7
^{240}Pu	19.0	25.8	27.1
^{241}Pu	12.0	13.5	15.4
^{242}Pu	3.8	6.0	11.7
^{241}Am	0.6	0.7	0.7

a. Yankee fuel irradiated to 35,000 MWD/MT.[20]
b. Industry average composition with Pu recycle in the 1990s.[21]
c. ORIGEN Calculations for core reload with 115% of the Pu needed for a Self Generation Reactor (SGR).[22] At equilibrium, the SGR recycles all of the plutonium it produces.

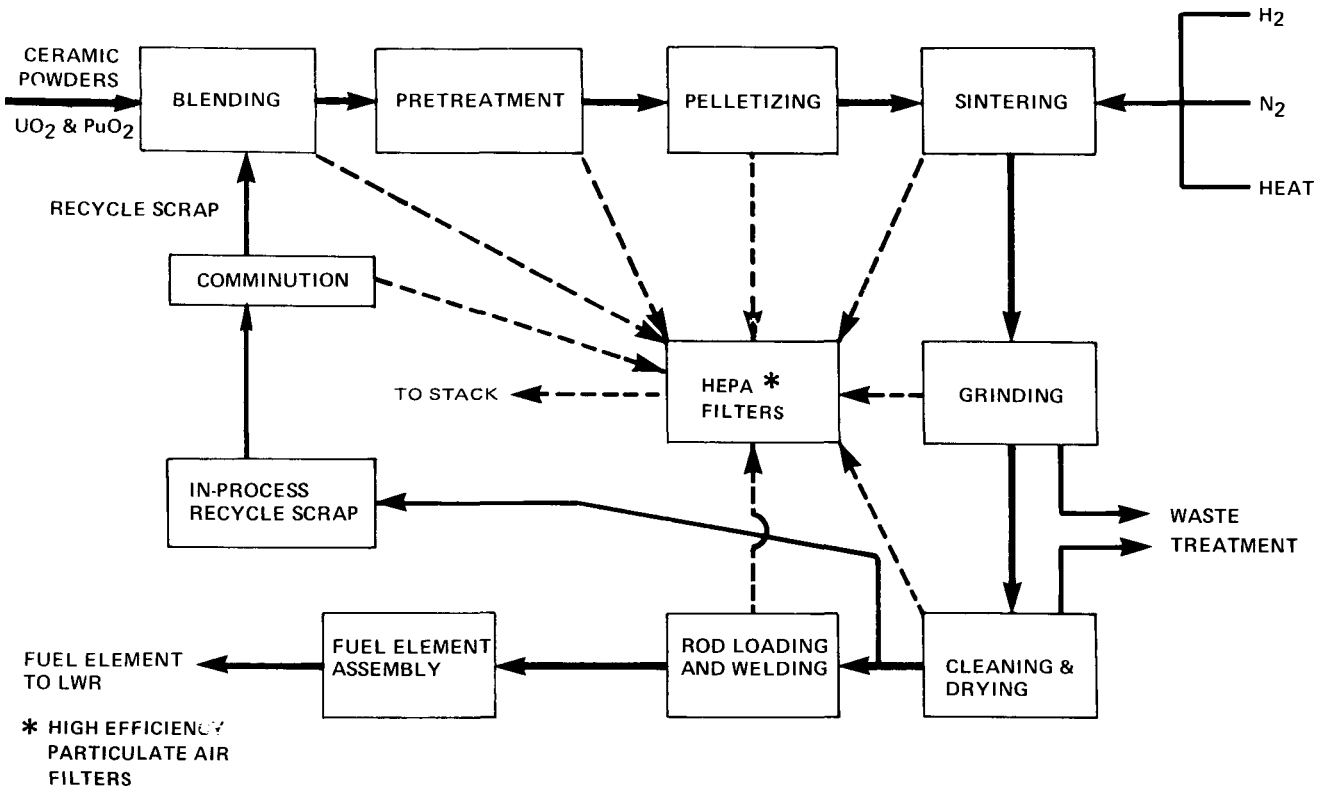


FIGURE 2.9. Fuel Fabrication - Mechanical Processing Block Diagram

Multiple levels of confinement are used to limit the release of plutonium from the MOX manufacturing building. The manufacturing building is maintained at negative pressure relative to the outside. Plutonium-handling operations are carried out inside equipment located within process enclosures (glove boxes or shielded cells) maintained at negative pressures relative to the adjacent areas of the manufacturing building. The pressure differentials are maintained so that air flows from noncontaminated areas into areas of potentially higher contamination levels, thus limiting the spread of radioactivity. Equipment forms the first level of plutonium confinement; the process enclosures form the second level of confinement; the manufacturing building forms the third level. To ensure that the required pressure differentials are maintained, spare filter banks, ventilation fans, and controls are provided, and independent emergency power systems are activated automatically in the event of loss of normal plant power.

Air ventilation streams discharged from the manufacturing building to the atmosphere are filtered through high efficiency particulate air (HEPA) filters. Figure 2.10 shows the schematic air flow diagram. The model plant ventilation system exhausts air from the process enclosures (glove boxes) through three HEPA filters, with the first HEPA filter located on the glove box. This arrangement minimizes contamination of the ventilation ducts.

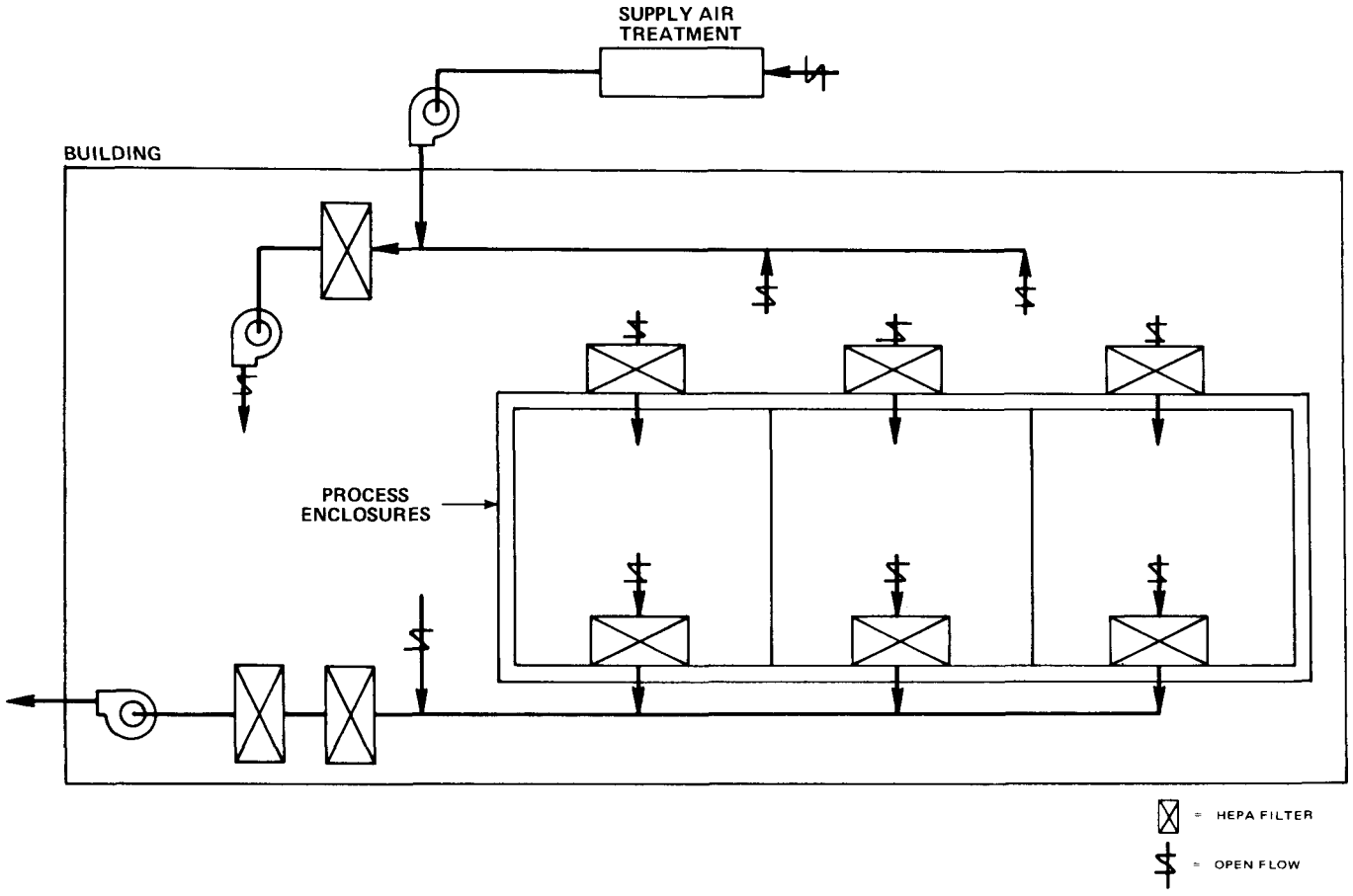


FIGURE 2.10. Simplified Air Filtration Flow Diagram - Commercial-Scale Mixed Oxide Fuel Fabrication Plant

A double confinement concept is also used in the process cooling water system design. Process cooling is accomplished by a closed primary loop circulating system that is cooled by a secondary cooling water system. Heat is removed from the secondary system via a cooling tower.

The MOX plant is designed and operated to minimize the probability of accidents. Where practical, equipment is designed with nuclear-safe geometry to prevent criticality. Where control of geometry is not practical, extensive control procedures are used to reduce the likelihood of criticality accidents.

Extensive precautions are also taken against fire. Flammable materials are kept to a minimum in process areas. Each process enclosure has an automatic fire detection and Halon protection system or equivalent, while in all other areas water sprinklers are used. The final filter bank is protected against fire by sprinklers in the plenum leading to the filter. Water from these sprinklers is drained from the plenum to tanks of nuclear-safe design. Water from sprinklers in operating areas collects in a nuclear-safe slab configuration.

b. Radioactive Effluents

The major radionuclides released to the atmosphere from the MOX plant are listed in Table 2.11.[15] Plant retention factors used in calculating these releases are listed in Table 2.8. The model MOX plant is assumed to be collocated on the same site as the

TABLE 2.11

Radionuclides Released to the Atmosphere from Model MOX Plant[16]

Basis: 350 MT/yr

Nuclide	*Amount Released*[a] *wt%*	*mg/yr*	*Ci/mg*	*Ci/yr*[b]
^{238}Pu	2.0	0.089	0.017	0.0015
^{239}Pu	45.5	1.98	0.000061	0.00012
^{240}Pu	25.0	1.11	0.00023	0.00026
^{241}Pu	15.5	0.69	0.099	0.068
^{242}Pu	12.0	0.54	0.0000039	0.0000021
^{241}Am	-	0.03	0.0034	0.0001
Total	100%	4.4	-	0.068β
				0.002α

a. Assuming a one-year delay between reprocessing plant and fuel fabrication plant.

b. Releases are assumed to be reduced to 10% of the values shown for plants starting up after 1985. (See Table 2.8)

reprocessing plant and to exhaust atmospheric releases through a common 100-m stack. The sand or deep-bed fibrous filter that is assumed to be added to the off-gas system for reprocessing plants constructed after 1985 is assumed to also serve the MOX plant and to reduce particulate emission by a factor of 10.

c. Nonradioactive Effluents

The fabrication process for mixed oxide fuel is expected to release nonradioactive gaseous effluents such as nitrogen, hydrogen, steam, argon, and helium. The nitrogen and hydrogen are cover gases in the pellet sintering furnaces and are used in the reduction step of any large scrap recovery operation. Argon and helium may be released from welding or fuel rod leak testing procedures.

Excess water from radwaste system operations is evaporated into the plant ventilation system and ventilated to the atmosphere.

Chemicals that may be released as a result of the operation of the MOX plant and supporting fuel burning facilities are listed in Table 2.12.

Table 2.13 estimates the chemical and sanitary liquid effluent flows. For the model plant, approximately 20 gpm of sanitary and cooling tower blowdown are discharged as liquid effluents together with 1/3 gpm of such streams as laboratory waste and scrub water. The latter effluents are collected in tanks and discharged after radiometric analyses indicate concentrations of radionuclides are less than limits in 10 CFR 20.[9] Small amounts of phosphate (<0.5 lb/day) and nitrate (<10 lb/day) are present in the discharge stream.

TABLE 2.12

Chemical Pollutants Released to the Atmosphere from Model MOX Plant and Supporting Facilities[16]

Chemical	*Approximate Quantity, MT/yr*
SO_2	350
NO_x	200
CO	4
Hydrocarbons	1.4

TABLE 2.13

Liquid Effluents from Mixed Oxide Fuel Fabrication Plant

Stream	*Amount, gal/day*
Laboratory and other aqueous wastes	500
Sanitary	16,000
Cooling tower blowdown	12,000

d. Heat Discharge

MOX fuel fabrication is not an energy intensive process, and the radioactive heat generated in the plutonium feed material is not large (about 0.01 watt/g). Almost all electrical energy used in the MOX plant is discharged as heat from the cooling tower(s), either as evaporative loss or in the blowdown. In addition, wastes such as showers, sinks, kitchen, and laundry can contain hot water. It is estimated the MOX plant will release about 15,000,000 Btu/hr to the biosphere.

e. Effluent Monitoring

As for the reprocessing plant, all MOX plant process effluents are monitored to determine the quantities of radioactive and non-radioactive pollutants that are released to the environment. This monitoring information provides source terms for calculations of environmental effects and a basis for determining compliance with specific regulations and evaluating effluent controls. A NPDES permit will be required, as described for the reprocessing plant.

f. Cost

The model 350-MT/yr plant for MOX fuel fabrication is estimated to cost about $100 million to build and about $50 million per year in operating expenses in FY-1977 dollars.

4. Waste Treatment and Interim Storage

a. Introduction

Wastes containing radioactive isotopes are generated in all segments of the nuclear fuel cycle. Radioisotopes in the wastes from the steps of the uranium feed chain and from the fuel fabrication operations for enriched uranium are primarily those associated with natural uranium. Recycle of uranium increases the ^{236}U content. Radioisotopes in wastes from the mixed oxide fuel fabrication step, from the reactor, and from the reprocessing operations contain man-made isotopes (plutonium and other actinide elements, fission products, and activation products). Most of the radioactive wastes from back-end operations are generated in reprocessing of spent fuels to recover plutonium and uranium.

The high-level waste from the reprocessing of spent fuel is the most significant radioactive waste from the standpoint of potential hazard and difficulty of handling. This waste contains almost all of the fission products, transplutonium elements (actinides of atomic number greater than 94), neptunium, and a small fraction (about 1/2%) of the uranium and plutonium that was initially in the spent fuels. This high-level waste generates substantial heat (3 to 4 kW per metric ton of LWR fuel processed, 10 years after discharge) and requires cooling. It emits large amounts of potentially hazardous ionizing radiation, and it must be isolated or contained for thousands of years to ensure that significant quantities of the toxic radionuclides do not enter man's environment.

Other potential wastes to be stored are tritium, ^{14}C, and the radioactive noble gases removed from the gaseous effluents from the fuel reprocessing plant.

Long-term or permanent treatment and storage of the high-level wastes and the other wastes judged to require storage in a Federal repository will be the subject of a separate environmental statement that is under preparation. The present statement includes only the onsite treatments and temporary storage that can be regarded as a direct part of LWR fuel recycle operations.

b. High-Level Waste

(1) Composition

Typical transuranium content and the total fission product content of spent fuel from LWRs after one year decay is given in Table 2.14. About 0.5% of the plutonium plus all of the other components listed make up the radioactive portion of the high-level liquid waste resulting from the chemical separations processes. Table 2.15 lists the nonradioactive materials that make up the remainder of the high-level waste.

Heat released from the high-level waste is shown in Figure 2.11 as a function of time after reprocessing. Table 2.16 gives the estimated heat output after 10 years, by which time all such waste would be expected to be solidified and sent to a Federal repository.

(2) Liquid Storage

After reprocessing, the high-level waste is stored in its

TABLE 2.14

Comparison of Typical Transuranium Compositions of Spent Fuel
(Basis: per metric ton, 33,000 MWD/MT, Aged 1 year)[a]

	Enriched UO_2 Fuel			*Mixed Oxide Fuel*			*Average Mix*[b]		
Isotope	*Grams*	*Curies*	*Watts, thermal*	*Grams*	*Curies*	*Watts, thermal*	*Grams*	*Curies*	*Watts, thermal*
^{237}Np	480	0.34	0.010	120	0.085	0.0025	430	0.30	0.0089
^{238}Pu	160	2800	91	1100	19,000	610	300	5200	170
^{239}Pu	5300	320	10	12,000	740	23	6300	380	12
^{240}Pu	2200	480	15	8800	1900	60	3200	690	22
^{241}Pu	1000	100,000	4.3	6000	610,000	25	1800	180,000	7.4
^{242}Pu	350	1.4	0.041	4200	15	0.48	930	3.4	0.11
^{241}Am	46	160	5.3	460	1600	53	110	380	12
^{243}Am	95	18	0.67	2700	510	19	490	92	3.4
^{242}Cm	5.1	17,000	620	72	240,000	8800	15	50,000	1800
^{244}Cm	30	2400	84	1700	140,000	4800	280	23,000	790
F.P.[c]	29,000	4,200,000	19,000	29,000	4,500,000	21,000	29,000	4,200,000	19,000

a. Reference 22, Tables 4.3, 4.6, B-1, and B-2.

b. On the basis that about 15% of fuel is mixed oxide fuel, the remainder is enriched UO_2 fuel.

c. Fission products are not transuranium elements, but are added for comparison.

TABLE 2.15

Nonradioactive Composition of Typical Liquid High-Level Wastes from LWR Fuels (Excluding H_2O)[a]

Constituent	*Grams per Metric Ton of Fuel Processed*
H	380
Fe	1100
Ni	110
Cr	230
NO_3	66,000
PO_4	900
Total	69,000

a. The total weight of nonradioactive constituents of the liquid high-level wastes is approximately twice the total weight of the radioactive constituents.

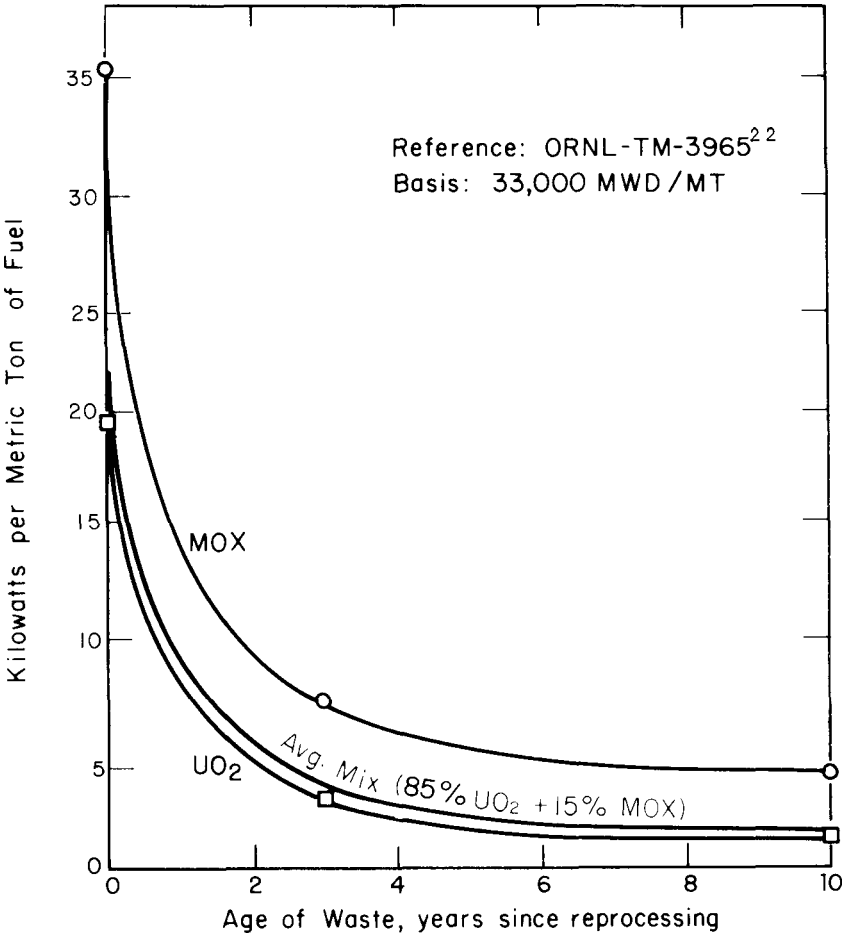


FIGURE 2.11. Approximate Heat Release of LWR Waste as a Function of Age

TABLE 2.16

Estimated Heat Output in High-Level Waste (Basis: 33,000 MWd/MT, 0.5% Loss of Pu to Waste at 1 Year, Waste Aged 10 Years)[a]

	Watts per Metric Ton of Fuel[b]		
Isotope	*Enriched UO_2 Fuel*	*Mixed Oxide Fuel*	*Average Waste Mix*[c]
^{237}Np	0.010	0.0026	0.0089
^{238}Pu	3.0	40	8.6
^{239}Pu	0.050	0.12	0.061
^{240}Pu	0.14	3.9	0.70
^{241}Pu	0.013	0.078	0.023
^{242}Pu	0.00020	0.0024	0.00053
^{241}Am	5.4	53	13
^{243}Am	0.66	19	3.4
^{242}Cm	0.26	6.5	1.2
^{244}Cm	57	3200	530
F.P.[d]	1000	850	980
Total	1100	4200	1600

---

a. Calculated from Reference 22, Tables 5.8, 5.10, B-1, and B-2.

b. In addition to the radionuclides listed, about 5000 g of uranium and 20 to 200 g of other actinides are in the waste. These contribute 1 to 40 W.

c. On the basis that fuels processed are about 15% mixed oxide, the remainder is enriched UO_2 fuel.

d. Excluding ^{3}H, noble gases, and 99.9% of halogens. These are removed from waste during reprocessing.

acidic liquid form in cooled stainless steel tanks until it is converted to a solid form for longer term storage. Present regulations would limit the storage of these liquid wastes to a period of 5 years.

Although storage of waste in tanks is considered an interim measure, waste can be stored in this manner indefinitely if surveillance is continued, with transfer to new tanks if necessary. To date (over 20 years experience) corrosion of stainless steel waste tanks has been negligible, and the lifetimes of these tanks have not yet been determined as no leaks have occurred.[8]

In storage systems for acidic liquid wastes, the waste is contained by multiple barriers designed for minimum dependence on people or surveillance devices. However, procedural controls are also provided for continuous monitoring of the storage systems. Required functions such as cooling and surveillance are ensured by backup systems so that acceptable conditions are maintained at all times.

If waste were to leak through the primary stainless steel tank, it would be collected in a secondary container from which it could be transferred to another tank. Retrieval of waste from tank storage is simplified by minimizing the volume of insoluble solids and/or providing agitation in the tank to keep solids from settling.

Each 1500-MTU/yr reprocessing plant is expected to generate about 850 m^3, or 225,000 gal, of concentrated high-level waste each year. Thus, about 1,200,000 gal of storage capacity would be required at each plant if liquid wastes were to be stored no longer than 5 years.

(3) Solidification

One of the major steps in the management of high-level wastes from LWR fuel reprocessing will be conversion of the liquid wastes to solids before interim storage and transporation. U.S. policy is to convert these wastes to a "dry solid" which is "chemically, thermally, and radiolytically stable...".[14] Although solidification of high-level wastes is not now practiced commercially, programs in the U.S. and abroad have resulted in development of several solidification options that are ready for demonstration in a commercial plant, and many others that could be implemented after varying degrees of development.[23-34] These processes are listed in Table 2.17 by their estimated development status.[8] Table 2.17 is not all-inclusive, but it does indicate the broad scope of research and development that is being conducted.

Considerations that are common to the solidification processes are discussed below, followed by brief descriptions of those processes that are ready for demonstration on a commercial scale.

General Considerations

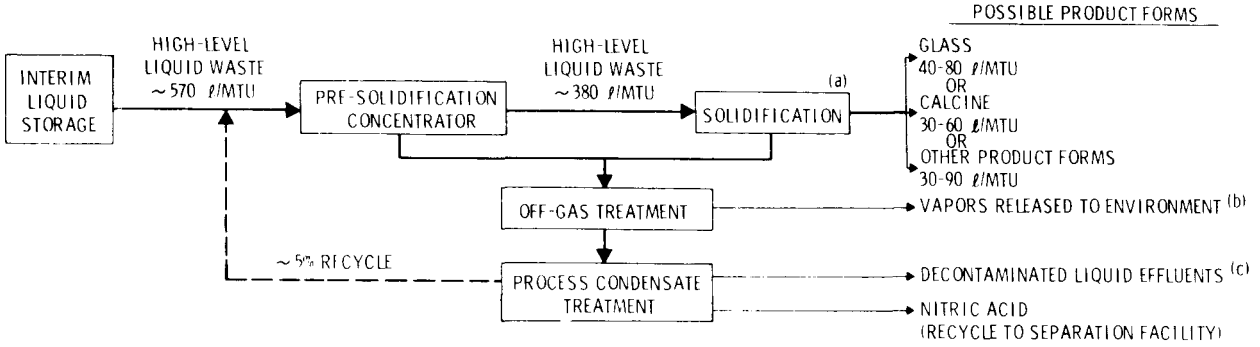
The function of solidification processing is to convert high-level wastes to a stable solid form. In the process, waste volume may be decreased by a factor of 5 to 10, and secondary wastes may be produced. Estimated volumes of the possible solid forms and secondary wastes are shown in Figure 2.12. A separate major facility at each reprocessing site is required for waste

TABLE 2.17

Development Status of High-Level Waste Solidification Processes[8]

Treatment Category	*Ready for Demonstration*[a]	*Requires Further Development*	
		Short-Term[c]	*Long-Term*[d]
Vitrification	In-can melting	British rising level glass	
	French rotary kiln-continuous melter[b]	German spray calciner-continuous melter	
		Continuous ceramic melter	
Drying and calcination	Fluidized bed	Wiped/scraped film evaporator	
	Pot calcination		
	Rotary kiln		
	Spray calcination		
Other solidification processes			Supercalcine
			Metal matrix
			Sintering
			Glass ceramics
			Coated pellets
			Ion exchange

a. Less than 1 year to be ready for engineering detail design.
b. Construction of a plant which will use this process to vitrify the high-level waste from the Marcoule reprocessing plant is nearing completion.
c. Less than 5 years to be ready for engineering detail design.
d. Greater than 5 years to be ready for engineering detail design.



(a) THE OPERATION OF AN HLLW SOLIDIFICATION FACILITY WILL ALSO GENERATE BETWEEN 0.2 AND 0.8 m^3/MTU OF MISCELLANEOUS SOLID RADIOACTIVE WASTE, INCLUDING NONCOMPACTED GENERAL PROCESS TRASH, ION-EXCHANGE AND ADSORPTION BEDS AND FAILED PROCESS EQUIPMENT.

(b) THE VOLUME OF GASES RELEASED, INCLUDING BUILDING AND CELL VENTILATION, WILL BE 2000-3000 m^3/min.

(c) THE DECONTAMINATED LIQUID EFFLUENTS RANGE FROM 600-1800 ℓ/MTU AND MAY OPTIONALLY BE VAPORIZED FOR INCLUSION WITH THE GASEOUS EFFLUENTS.

FIGURE 2.12. Generalized High-Level Waste Solidification Processing[8]

solidification and for treatment of secondary wastes. Releases of radioactive materials from such a facility are included in the estimated radioactive effluents from the reprocessing plant (Table 2.8) used to calculate environmental effects in Section 3 of this statement. Retention factors used to obtain the release estimates are listed in Table 2.8.

Solid waste forms resulting from conversion of high-level wastes will probably be encased in sealed metal canisters for interim storage or transportation to a Federal repository.

Solidification processes that are ready for demonstration produce either a dry powder or granular material (calcine), or a coherent vitrified material (glass). Calcine could also be an intermediate form in the future conversion to glass. In Europe and India, decisions have been made to convert all high-level wastes to glass.

Calcination Processes

Fluidized Bed Calcination. Liquid waste is atomized into a fluidized bed and heated by in-bed combustion to 500 to 600°C. Evaporation leaves the oxide powder deposited on the granular bed material, which is removed from the calciner continuously or intermittently into a storage canister. The calcine is heated to 900°C for complete denitration before sealing of the canister.

Pot Calcination. Liquid is continuously added to and boiled away in a processing vessel that also serves as the storage container. When the container becomes full of a process cake of friable calcine, no more liquid is added. Furnace temperature is adjusted to maintain the center of the container at 900°C to complete calcination.

Rotary Kiln Calcination. Deacidified liquid waste is introduced at the upper end of a rotary cylinder heated externally to about 500°C. The waste is dried and almost completely denitrated before it leaves the lower end. Offgases are scrubbed with water to remove entrained particulates for recycling. The calcine product is heat treated at 900°C to ensure total decomposition of nitrate before loading into storage canisters. The final product form is a finely divided oxide powder.

Spray Calcination. Atomized droplets fall through a heated chamber (700°C) where flash evaporation results in fine oxide particles. The oxide powder is separated from the offgas by sintered stainless steel filters. The calcine is heated to 900°C in its storage container for complete denitration.

Vitrification Processes

In-Can Melting. Glass-making solid frit is added to the storage canister at a rate proportional to the delivery of calcine from a spray or rotary kiln calciner. The blend is melted in the storage container at 1000 to 1100°C to form a borosilicate glass

containing about 30 wt % waste oxides. Most waste oxides are accommodated in the glass structure, but a few occur as separate phases that are dispersed in the glass matrix.

French Rotary Kiln - Continuous Metallic Melter. Glass frit is introduced to a vitrification furnace concurrently with calcine leaving a rotary kiln. Continuous melting occurs at about 1150°C, and the vitrified product is allowed to flow to storage containers in predetermined batches. Solidification results in a borosilicate glass.

Storage Considerations

The effect of helium generation in the vitrified waste requires additional investigation. However, serious internal stresses were not observed in studies on borosilicate glass doped with curium oxide in which helium buildups were produced by alpha particle generation or pressure equilibration.[35] In a cannister of vitrified UO_2-3% PuO_2, containing a 10% void plenum, the internal pressure would not exceed 1200 psi if all helium formed in 10^6 years were to be released. This pressure falls within the range of common experience.

A canister filled with calcine particles (pot or fluidized bed) would be expected to have sufficient voids to handle high-level wastes from mixed oxide fuels.

Temporary storage of solidified high-level waste could consist of either open bins or sealed canisters stored retrievably in a secondary containment structure on the reprocessing plantsite.

Long-term storage of solidified high-level waste will be the subject of another environmental statement.

c. Solid Waste Management

Solid radioactive waste from the 1500-MTU/yr fuel recycle complex is classified in three categories for processing. The first category, miscellaneous waste, includes small items of waste from production and laboratory operations, such as protective clothing, glassware, plastic bags and sheets, decontamination residues, etc. The annual volume of waste in this category is about 250,000 ft^3, which contains 100,000 Ci of fission products and 3000 Ci of transuranium nuclides (TRU) with half-lives >85 years. Zircaloy fuel cladding hulls and stainless steel and Inconel fuel assembly components represent the second category. This waste, amounting to 18,000 ft^3/yr, contains the largest amount of solid waste radioactivity (7×10^6 Ci of fission products, 3×10^7 Ci of activation products, and 7×10^3 Ci of TRU nuclides) with half-lives greater than 85 years. Obsolete and discarded process equipment, such as vessels, piping, cabinets, and glove boxes are included in the third category. Approximately 1×10^6 Ci of fission products and 3×10^3 Ci of TRU nuclides with half-lives greater than 85 years are associated with an annual volume of 14,000 ft^3.

Miscellaneous waste will be separated initially into two fractions: those with TRU contents greater than 10 nCi/g and those with TRU contents less than 10 nCi/g. Waste containing greater than 10 nCi/g will be sorted according to combustibility. Combustible TRU waste (>10 nCi/g) will be incinerated and fixed in a stable matrix. Noncombustible TRU waste (>10 nCi/g) will be decontaminated and reduced in size. Processed waste (>10 nCi/g) will be doubly encapsulated in durable containers and shipped offsite to a repository for long-term storage.

Miscellaneous waste contaminated with fission products and TRU nuclides (<10 nCi/g) will be separated into combustible and noncombustible fractions. Combustibles will be incinerated and packaged for interim storage in a commercial or onsite burial ground. Noncombustible material will also be packaged for interim storage in the burial ground.

Zircaloy hulls and associated fuel assembly components will be processed to reduce their volume and potential for pyrophoricity. Processing may include melting or compaction. The processed metal will be encapsulated in durable containers for shipment offsite. Zircaloy fines will be oxidized to reduce pyrophoricity and then fixed in a stable matrix with incinerator ash.

Obsolete and damaged process equipment will be assumed to be contaminated with TRU nuclides to greater than 10 nCi/g. It will be disassembled and decontaminated. Equipment decontaminated to less than 10 nCi/g will be packaged for interim storage in the burial ground. Equipment that remains contaminated to greater than 10 nCi/g will be reduced in size and packaged in durable containers for shipment to an offsite repository.

Degraded tributyl phosphate-hydrocarbon solvent will be burned in the TRU waste incinerator. The solvent, amounting to about 20,000 gal/yr, will contain 35 Ci of fission products and 8 Ci of TRU nuclides. The residue after incineration will be fixed in a stable matrix together with the other ash and doubly encapsulated for shipment offsite.

5. Storage of Plutonium

During recycle, about two years will elapse between the time plutonium is discharged from a reactor to the time it is reinserted as a mixed oxide assembly. Over much of this period, the plutonium must be stored to await processing, transportation, or recharge. This storage capacity will be provided at the reprocessing and fuel fabrication facilities. If the plutonium is not recycled but is stored for possible future use or eventual disposal, a separate, licensed storage facility will be needed.

a. Storage Requirements with Recycle

Storage requirements with plutonium recycle are dictated by

in-process and scrap recovery needs. As shown in Figure 2.13, most of the recovered plutonium is assumed to be fabricated into MOX fuel and recharged into reactors with little delay. The quantities of fissile plutonium shown in Figure 2.13 are based on the production of fresh plutonium, i.e., plutonium whose isotopic composition has not changed through radioactive decay. The ^{241}Pu content is assumed not to change in estimating the storage capacity because the storage conditions are based on the initial plutonium fissile content, not on the final fissile content. The curves in Figure 2.13 can be used to estimate the quantities of fissile plutonium available for use if corrected for the radioactive decay of ^{241}Pu.

b. Storage Conditions

Because of its value, hazard potential, and nuclear weapons implications, plutonium will have to be stored under rigidly controlled conditions. These "safeguards" conditions are discussed in Section 10.

Temporary plutonium storage at reprocessing plants may be as a nitrate solution, but it is assumed that any longer term storage will be as plutonium oxide. Safety considerations associated with storage will be reviewed in detail by the Nuclear Regulatory Commission as each application is received. For either solution or solid storage, the review includes consideration of the provision for criticality prevention, radiation and contamination control, and fire prevention. Plutonium generates some

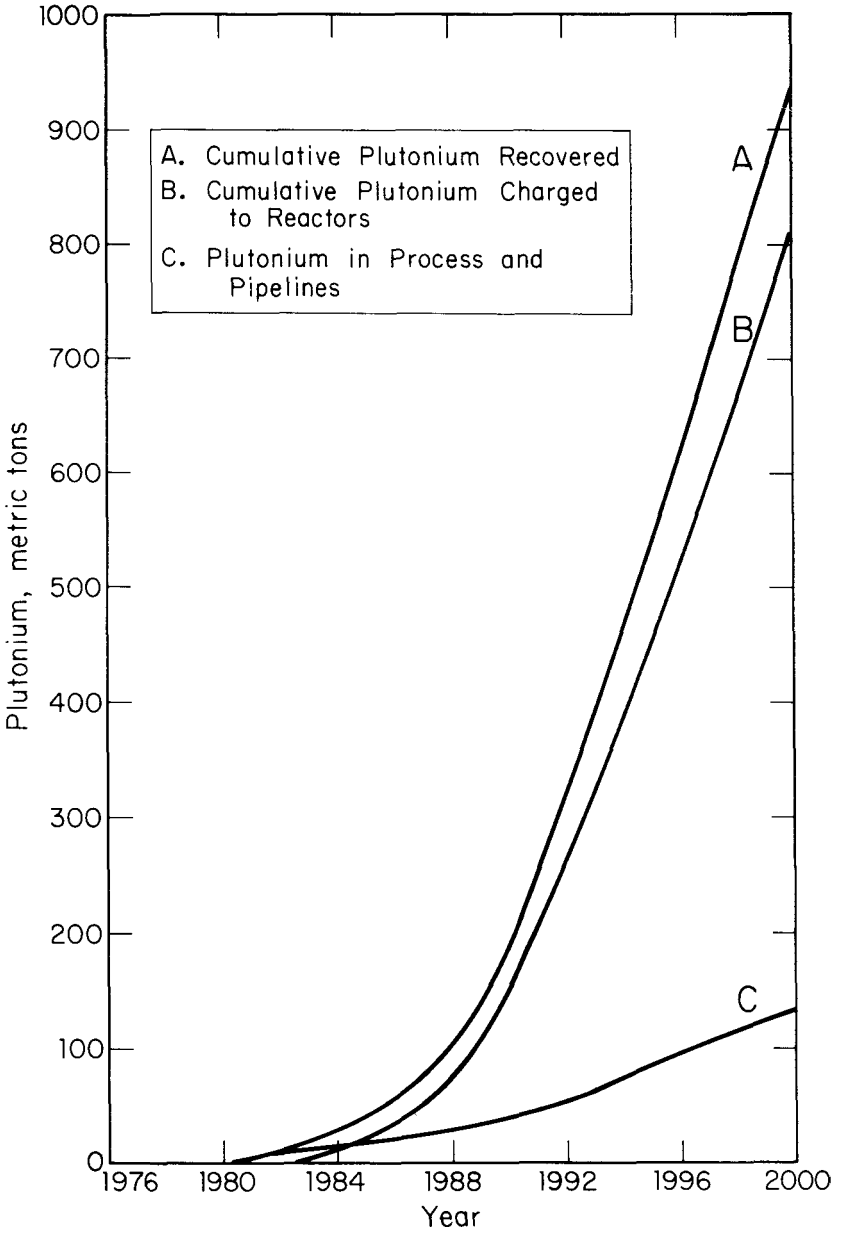


FIGURE 2.13. Fissile Plutonium Recovered and Utilized with Plutonium Recycle

heat because of the radioactive decay of its isotopes (about 14 watts/kg for the recycle plutonium considered in this statement), but air cooling is adequate and the handling of a failure of cooling provisions is not considered an important safety consideration for operating personnel.

Another factor that would influence plutonium storage is the quantity of ^{241}Am that would accumulate through decay of ^{241}Pu. Within one year after the chemical purification of plutonium, the americium becomes an important contributor to the gamma dose rate, principally because of the 60 keV γ-rays emitted when the ^{241}Am decays to ^{237}Np. Because gamma dose rates in subsequent fuel manufacturing or handling operations would be excessive with old LWR plutonium, it would be necessary to chemically repurify the oxide before shipment for fabrication into fuel rods. A licensed storage facility at a separate site would then need to provide chemical processing equipment with adequate confinement and shielding. This would increase the cost of such a facility considerably. For the model FRP and MOX plants, it is assumed that the storage facility is integral with the plant and that any plutonium reprocessing required is performed in existing plant facilities.

c. Storage Without Recycle

In the absence of a plutonium recycle industry, about 1200 metric tons of plutonium would have to be stored by the year 2000. In comparing this with the storage capacity of about 100 metric

tons required at various facilities by the year 2000 with a plutonium recycle industry, the difference of about 1100 metric tons of plutonium would require the construction of additional storage space, either at existing sites or at a new site specifically designed for this purpose.

Each reprocessing plant will provide nitrate-to-oxide conversion facilities. Because the solid form will be required for shipping, it is likely that the plutonium will be stored in that form. Another likely possibility is that the plutonium may be stored in shipping containers to avoid a repackaging step. This choice depends somewhat on an economic analysis of repackaging costs versus any facility capital and operating savings from bulk storage. If the reprocessors do not provide additional storage capacity and such storage is provided by a licensed facility elsewhere, the shipping containers would most likely be used for storage.

Shipping containers for nonrecycled plutonium may be similar to present-day designs. One container, which may be considered and has been used for plutonium transport, is a right circular cylinder about 2 ft in diameter by 6 ft high. Such a container would occupy at least 4 ft^2 of floor space, if not stacked. Using this container as a model, and assuming nuclear safety considerations require no separation between groups of containers in a single layer, an estimated 0.9 million ft^3 of storage space would be required by the year 2000.

A maximum of approximately 340 Btu of decay heat per hour would be released from each such container. If a single storage location were provided, it would have to accommodate about 160,000 containers by the year 2000 and would release about 54 million Btu per hour (16,000 kW).

6. Storage of Irradiated Fuel

Temporary storage for discharged irradiated fuel must be provided to allow decay of the short-lived fission products before processing and to provide lag capacity during fuel recycle. Currently such storage is provided by water basins at the reactors and at the reprocessing plants. For the model plant, a storage time of one year is specified before reprocessing, but the alternatives section of this report investigates the economic and environmental effects of longer storage times, including indefinite storage rather than reprocessing. Although the LWR fuel is designed to provide for containment of its contents, some portion of the discharged fuel may leak radioactivity and require recanning or special containment in addition to the water shielding. Also, the integrity of irradiated fuel in underwater storage for very long periods of time is unknown, and additional treatments may be necessary for long-term storage. Irradiated fuel contains all the fission products normally contained in high-level wastes from reprocessing plus about 200 times as much uranium and plutonium as normally discharged to the wastes.

7. Transportation of Radioactive Materials

a. Overview of Transportation Steps

The transportation steps involving radioactive materials in the back end of the LWR fuel cycle are shown in Figure 2.14. They include:

- Shipment of irradiated fuel assemblies to the fuel reprocessing plant.
- Shipment of recovered UF_6 from the reprocessing plant to the enrichment plant.
- Shipment of recovered PuO_2 from the reprocessing plant to the MOX plant. In the base case, the FRP and MOX plants are assumed to be on the same site, but the effects of separate siting are discussed in the alternatives section.
- Shipment of UO_2 and fuel rods between the MOX and UO_2 fuel fabrication plants.
- Shipment of unirradiated fuel from the fabrication plants to the reactors.
- Shipment of waste to commercial burial ground and Federal repositories.

With a throwaway fuel cycle, the irradiated fuel from the reactors would be shipped to an interim storage site to allow radioactive decay for several years in a water basin. After appropriate reduction of the radioactive heat generation rate, the irradiated fuel would be packaged in a suitable waste form for transport to a Federal repository for permanent disposal.

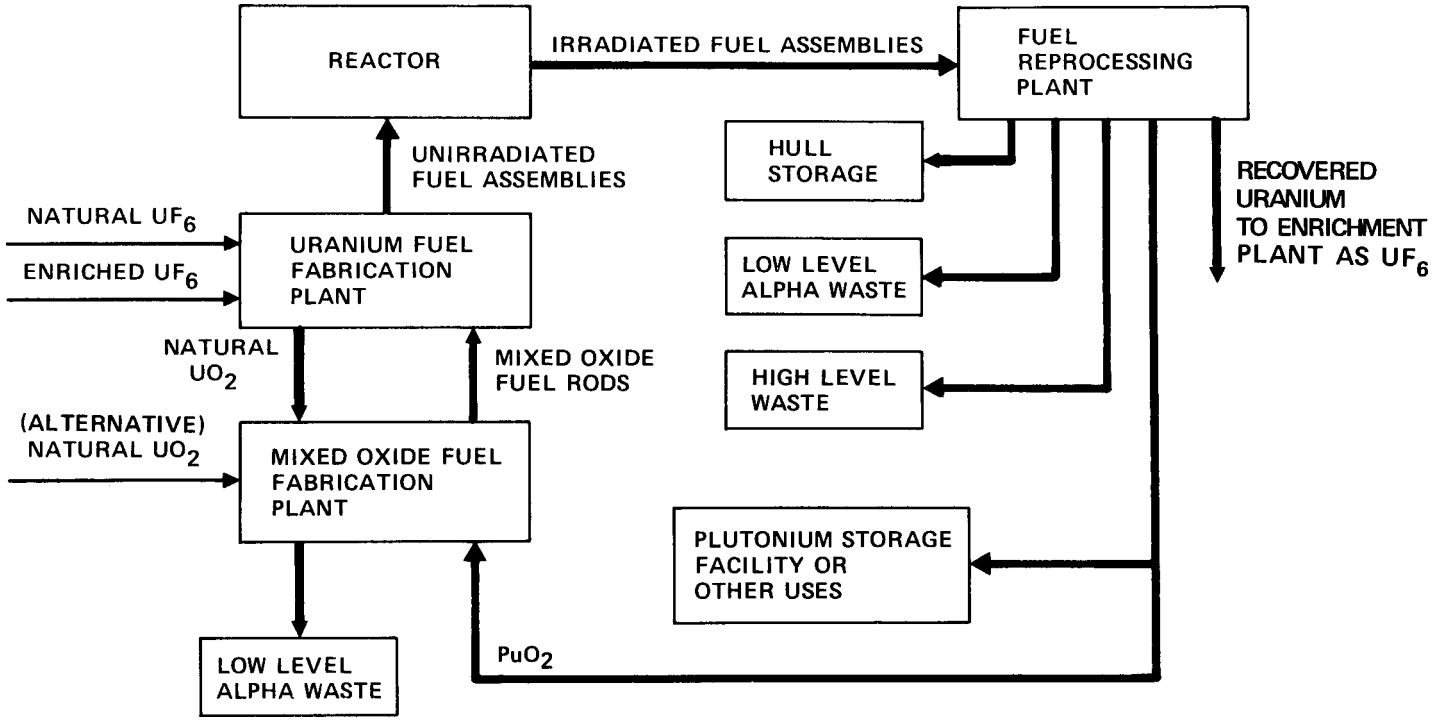


FIGURE 2.14. Flow Diagram for Mixed Oxide Fuel Cycle

With uranium only or plutonium and uranium recycle, waste shipments would increase relative to the throwaway cycle, and several forms of uranium and plutonium would be shipped distances of 200 or 300 miles. The total shipping distances for the back end of the cycle relative to the throwaway cycle would increase about 30% for uranium recycle and about 50% for uranium and plutonium recycle, primarily because the volumes of wastes are larger.

Fuel recycle would reduce the number of shipments required to supply uranium for milling and conversion processes in the front end of the fuel cycle.

b. Regulatory Standards and Requirements

Radioactive materials are packaged and transported under guidelines and regulations established by the Nuclear Regulatory Commission (NRC) and the Department of Transportation (DOT). Certain aspects, such as limitations on gross weight of trucks and transportation not subject to Federal regulations, are regulated by the states. Most states have adopted regulations pertaining to intrastate transportation of radioactive materials which require the shipper to conform to the packaging, labeling, and marking requirements of the DOT to the same extent as if the transportation were subject to the rules and regulations of that agency.

Most shipments of radioactive material move in routine commerce and on conventional transportation equipment and are therefore subject to the same transportation environment, including

accidents, as nonradioactive cargo. On some railways, however, spent fuel and radioactive wastes are shipped only on special trains rather than as routine commerce. Although a shipper may impose some conditions on the carriage of his shipment, such as exclusive use of the vehicle, speed limitations, route specification, and providing an escort, most of the traffic conditions to which his shipment are subjected and the probability of his shipment being involved in a highway or railroad accident are not subject to his control.

Packages containing radioactive materials are designed to resist impact, fire, and other stresses encountered in accident environments.[36] The probability of releasing radioactivity in an accident environment is a function of the package design, the mode of transportation and the parameters of the accident environment. The probability of release of small amounts of radioactive materials with minor local effects only is estimated to be 10^{-2} to 10^{-4} per accident.[37] The probability of releasing large amounts of the contents of the package with major contamination of the area and possible health effects to persons on the scene and to a lesser degree the general population is estimated to be 10^{-4} to 10^{-7} per accident[37] dependent upon contents and package design.

Should radioactive materials be released in an accident environment, trained personnel equipped to monitor the area and competent to act as advisors are available through an Intergovernmental Radiological Assistance Program. Radiological Emergency

Assistance Teams are dispatched in response to calls for emergency assistance. These teams assist in advising as to methods of cleanup and the extent to which cleanup may be necessary. For further discussion see Section IV G, Appendix A, of GESMO.[6]

c. Packaging Descriptions

(1) Irradiated Mixed Oxide Fuel Assemblies

Casks for shipping irradiated fuel assemblies on rail cars are normally designed to weigh no more than 100 tons, a weight routinely handled by rail. These casks provide massive shielding and high heat dissipation capacity. A typical cask[38] (Figure 2.15) is expected to have heat dissipation capacity of about 100 KW (340,000 Btu/hr), which corresponds to a capacity of 10 PWR or 24 BWR UO_2 assemblies based on a 72,000 Btu/hr heat load per metric ton of heavy metal after reactor discharge and 120 days cooling time.

A typical cask for transporting irradiated fuel by truck would be designed to contain 2 PWR or 4 BWR assemblies and weigh about 25 MT when loaded. Larger casks weighing more than 25 MT would require special permits for transporting overweight loads and are not considered for this study.

The irradiated mixed oxide assemblies will raise the average heat generation rate in irradiated fuel by about 10 to 20%, and the mixed oxide assemblies will have neutron radiation levels that are about two orders of magnitude higher than the levels for irradiated UO_2 fuel.[39] These differences in irradiated fuel

characteristics will be met by addition of more neutron shielding around the fuel cask and a reduction in the average number of assemblies per shipment by about 20% (to about 8 PWR or 20 BWR assemblies per rail cask and to 1 PWR or 3 BWR assemblies per truck cask of the assumed design). Such design changes are expected to leave the gross characteristics of the irradiated fuel casks, such as weight, overall size, and heat dissipation capacity, basically unchanged.

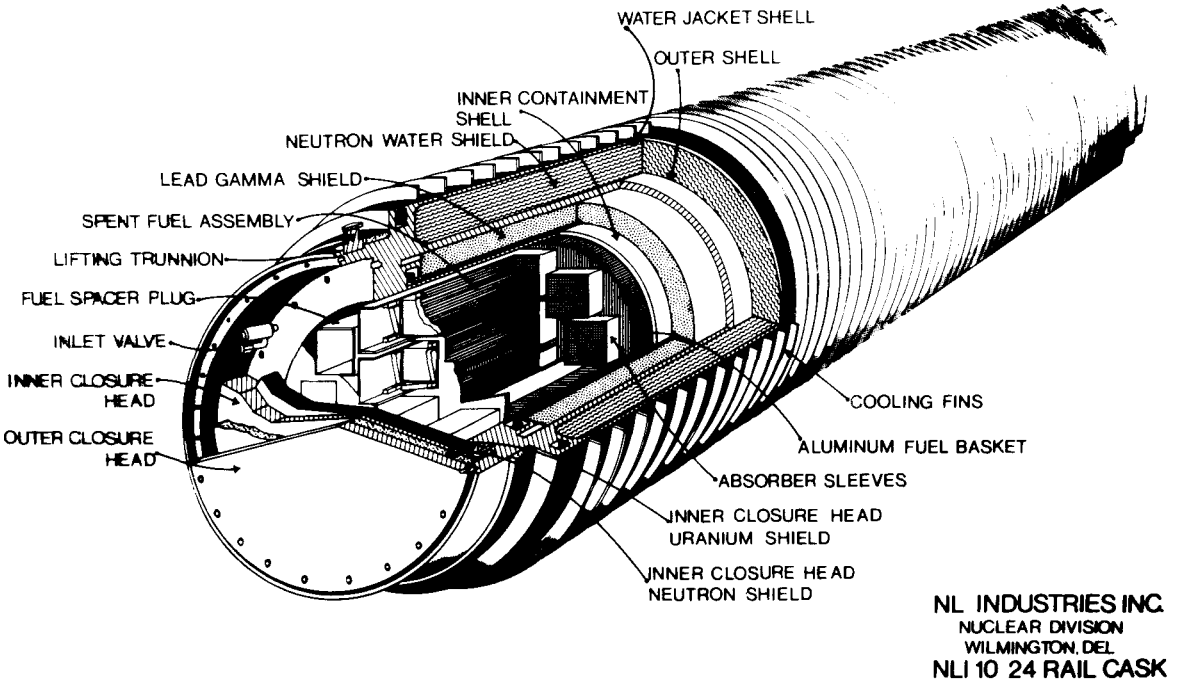


FIGURE 2.15. Typical Cask for Shipping Irradiated Fuel (NLI-10/24)

(2) UF_6

Natural and slightly enriched UF_6 is transported either in cylinders with a capacity of 10 metric tons of UF_6 and a gross weight of 11.6 metric tons or in cylinders with a capacity of 12.7 MT of UF_6 and a gross weight of 15 MT. Cylinders used for shipping slightly enriched UF_6 would be packaged within a protective outer packaging (overpack).

(3) Plutonium Oxide Packaging

Present plutonium oxide packages transport a few kilograms of the oxide contained in sealed metal cans within an inner, gasketed steel container supported within an outer steel drum of from 10- to 110-gal capacity. The gasketed steel cylinder is supported within the steel drum by thermal and shock insulating material such as cane fiberboard, vermiculite, or foamed phenolic plastic. For the present package designs, mass limits of up to 4.5 kg plutonium per package are defined primarily by heat dissipation requirements for plutonium which contains low percentages of ^{238}Pu.

A conceptualized semitrailer, Integrated Container-Vehicle (ICV),[6] is expected to be the transport vehicle-package used by licensed facilities for plutonium oxide. The ICV consists of a cylindrical steel secondary pressure vessel containing a number of primary pressure vessels loaded with plutonium oxide. The primary pressure vessels would carry four canisters; each would hold 18 kg of plutonium. Seven primary pressure vessels would be carried in the vehicle, giving a payload of about 500 kg of plutonium oxide.

(4) Unirradiated Natural UO_2

Typically, unirradiated UO_2 is packaged in 55-gal steel drums which have a capacity of about 0.38 MT.

(5) Unirradiated Fuel Assemblies

Both mixed oxide and UO_2 unirradiated fuel assemblies are assumed to be transported in metal containers that support the fuel along its entire length. The MOX packages may have to be modified slightly to include neutron and gamma shielding in order to meet DOT regulations pertaining to external radiation dose levels. The present packages containing unirradiated fuel for two PWR assemblies weigh up to 4000 kg and the packages containing unirradiated fuel for two BWR assemblies weigh up to 1400 kg.

(6) High-Level Waste

Solidified fission product waste from fuel reprocessing will be shipped for long-term storage in a Federal waste repository. Such shipments must meet, in addition to regulatory requirements, the limits for size, weight, containment, radiation, and heat generation rate for the individual waste containers to be established for the repository. These requirements are expected to result in the transportation of cylindrical containers of solidified waste with a maximum heat generation rate of about 5 kW (17,000 Btu/hr) each. A conceptual cask[8] would be approximately 3 m in diameter and 5 m long and be fabricated of carbon steel with lead or depleted uranium for gamma shielding and borated

water for attenuation of neutrons. Each cask is expected to hold about 2.4 m^3 of solidified waste and to weigh less than 100 MT.[8] The corresponding maximum heat load of 45 kW (150,000 Btu/hr) is about one-half that of the cask for shipping irradiated fuel.

Permanent storage alternatives for high-level wastes are described in a separate environmental statement.

(7) Cladding Hulls

This study assumes that cladding hulls will be shipped to a Federal waste repository as transuranium waste. Decontamination or other options such as recovery of Zircaloy would reduce the transportation impact.

A cask being designed for shipping hulls from 1 day's processing from AGNS will weigh about 100 MT.[40] A conceptual cask proposed by Blomeke and Perona would weigh 81 MT and would have a capacity of 9 days of reprocessing activity. They assumed lower burnup and less residual fuel than the AGNS study.[41] The cask would accommodate 27 cans of 22 cm diameter.

Because the characteristics of the cladding and treatment options are not well defined and no experience exists for such a cask, this study assumes the model cask will weigh about 100 MT and will contain about 8 MT of compacted cladding hulls from 5 days of processing.

(8) Other Radioactive Wastes

Other radioactive wastes have various physical forms and radiological properties. DOT specification containers, primarily 55-gal steel drums, will be used for most of these solid wastes which are segregated according to transuranium element content. Large items such as filters and faulty equipment would be packaged in wooden or fiberglass boxes or metal bins.

Drums of dry solid waste containing greater than 10 nCi/g of transuranium elements and moderate gamma radiation levels would be placed inside a steel cargo container 8 x 8 x 20 ft. Two cargo containers could be put inside an ATMX-600 type rail car[42] that would have a total waste capacity of 1000 ft^3 (28.3 m^3). Alternatively, for transport by truck, the drums may be loaded in a Type B overpack which provides thermal and impact protection in an accident environment. Drums of such waste with high gamma levels would be shipped in Type B overpacks which provide shielding. One example[8] is the NECO B2 overpack with a capacity of fifteen 55-gal drums.

Salts from the evaporation of any intermediate level wastes incompatible with vitrification would be immobilized in concrete, asphalt or ureaformaldehyde resin. The fixed waste would be placed in steel cans or steel drums, each with an assumed capacity of $\sim$7 ft^3. These wastes would be classified as TRU waste and would be transported to a Federal repository in a Type B overpack with shielding.

Radioactive gases are assumed to be collected in the offgas treatment system. Krypton alone or with other noble gases would be packaged in pressurized 50-liter cylinders. The filled cylinder would be placed in a water-filled cask weighing about 6.4 MT. Six of these casks would be shipped on a rail car.[43] Tritium, radioiodine and ^{14}C would be chemically fixed in a solid which would be packaged in steel drums. It is assumed that the collected radioactive gases will be shipped to a Federal repository.

d. Transportation Conditions

(1) Irradiated Mixed Oxide Fuel Assemblies

Because of the weight of casks for irradiated fuel, most shipments are expected to be made by rail. However, some nuclear power plants (approximately 10 to 20%) do not have rail service to the plantsite. For this reason, these plants are restricted to highway shipments using lighter, smaller capacity casks. Only a few of the nuclear power facilities are located on navigable waterways. The assumed model distance by rail from the nuclear power plant to the fuel reprocessing plant is 1000 miles. It is assumed that 20% of the irradiated assemblies are transported to the fuel reprocessing plant by truck for a model distance of 500 miles.

In the year 2000, approximately 2500 shipments by rail and 3700 shipments by truck will be required to transport 12,500 MT of irradiated heavy metal from all reactors in the fuel cycle.

(2) UF_6

The shipments of slightly enriched UF_6 from the fuel reprocessing plant to the enrichment plant are to be made by exclusive-use truck with two cylinders (holding 10 MT of UF_6 per cylinder) loaded per vehicle. Shipments are transported an assumed distance of about 200 miles. A total of about 560 shipments would be required to transport 11,000 MT of UF_6 in the year 2000.

Natural UF_6 from the conversion plant may be shipped to the UO_2 fuel fabrication facility for conversion to UO_2 before transshipping to the mixed oxide fuel fabrication facility or directly to the mixed oxide fuel fabrication facility for conversion to UO_2. These shipments would be made by exclusive-use truck with two cylinders (10 MT of UF_6 per cylinder) loaded per vehicle.

Shipments directly to the mixed oxide fuel fabrication facility are transported an assumed distance of 300 miles. A total of about 160 shipments would be required to transport 3000 MT of UF_6 in the year 2000. Without plutonium recycle, this material would be transported to the UO_2 fuel fabrication facility.

(3) Plutonium Oxide

In the base case, plutonium oxide transfers will be made on a single site between collocated FRP and MOX plants.

If the MOX plants are not collocated with fuel reprocessing plants, then all the plutonium would be transported by an Integrated Container-Vehicle (ICV) with a capacity of 0.5 MT of plutonium oxide. In the absence of plutonium recycle, in the year 2000, there would be about 200 shipments to transport 98 MT of plutonium from the reprocessing plant to storage facility assuming 71% fissile plutonium. With plutonium recycle, 260 shipments would be required to transport 130 MT of plutonium to the mixed oxide fuel fabrication plant assuming 60% fissile plutonium.

Industry planning indicates that if the mixed oxide fuel fabrication plants and the fuel reprocessing plants are not collocated they will be near each other, and thus the plutonium shipping distance should average no more than 300 miles.

(4) Unirradiated Natural UO_2

The shipments of natural UO_2 from the UO_2 fuel fabrication plant to the MOX fuel fabrication plant are assumed to be made by exclusive-use truck with approximately 50 drums (holding 0.38 MT UO_2 per drum) loaded per vehicle. The resulting net weight per vehicle is thus about 19 MT of UO_2. Shipments are transported an average distance of 200 miles. A total of about 160 shipments will be required in the year 2000 to provide the industry's needs for natural uranium oxide to be blended with plutonium oxide.

(5) Unirradiated Mixed Oxide Fuel Assemblies

In keeping with present practice, essentially all shipments from the UO_2 fuel fabrication plants to the reactors are expected to be made by exclusive-use truck. Safeguards considerations will probably require that shipments of unirradiated fuels containing plutonium continue to be made by exclusive-use vehicle. The present practice of shipping six packages of PWR fuel (12 assemblies) or 16 packages of BWR fuel (32 assemblies) per truck is expected to continue with mixed oxide rods, although the individual packages may be heavier because of the additional neutron shielding. The net weight per vehicle is assumed to average 5.8 MT (heavy metal). The shipments of fuel assemblies from the UO_2 fuel fabrication plants are assumed to involve an average transport distance of 1000 miles. (The average distance from the fuel fabrication plant to 83 reactors at 55 sites was determined to be about 1000 miles, with distances ranging from 25 to 3000 miles.) The packages would be loaded on the truck at the fuel fabrication plant by the shipper, transported by the carrier directly to the nuclear power plant, and unloaded by the power plant personnel, with no intermediate offloading, storage, or intervehicular transfers enroute. No other shipments would be loaded on the vehicle except by the shipper himself.

Based on full loads, 430 shipments are required to transport the 2500 MT (heavy metal) mixed oxide fuel for a distance of 200 miles from the MOX fabrication plants to the UO_2 fuel fabrication

plants in the year 2000. About 2500 shipments of fuel assembly shipments are required from the UO_2 fabrication plants to reactors with or without plutonium recycle.

(6) High-Level Waste

The expected 100-MT gross weight of each high-level waste cask requires that all high-level waste shipments be made by rail. The shipments of high-level waste are assumed to be transported 1800 miles because of the possible siting of the waste repository in a western state and the location of the fuel reprocessing plants in the eastern part of the country. Present regulations require shipment of solidified wastes to a repository before 10 years have elapsed since fission product separation, so that wastes from the 11,000 MT of fuel to be reprocessed in the year 2000 may be shipped in the following decade. Therefore, the fuel to be reprocessed in the year 2000 represents a commitment to make about 270 high-level waste shipments by the year 2010.

(7) Cladding Hulls

The assumed gross weight of 100 MT of each cask for cladding hulls requires that these shipments will be made by rail. As with high-level wastes these casks are assumed to be transported 1800 miles to a Federal waste repository. Cladding hull wastes from 11,000 MT of fuel to be processed in the year 2000 represent a commitment to make about 420 shipments.

(8) Other Radioactive Wastes

The solid wastes and immobilized salts of intermediate-level liquid wastes containing greater than 10 nCi/g of transuranium elements are assumed to be transported 1800 miles to a waste repository in the western U.S. It is assumed that combustible wastes are incinerated where practical. The TRU wastes would be transported to a Federal repository by rail with about 28.3 m^3 of TRU waste per car or about 2800 carloads in the year 2000.

About 100 carloads of krypton-filled cylinders in casks[43] would be transported by rail to the Federal repository. Also transported there would be solids containing ^{14}C, tritium and iodine, estimated to be about five carloads in the year 2000.

Uncompacted solid wastes containing less than 10 nCi/g of transuranium elements are assumed to be transported 500 miles from fuel reprocessing plants to a commercial burial ground. It is assumed that these wastes would be transported by truck, each loaded with 13.4 m^3 of waste. About 1900 truckloads would be transported in the year 2000.

D. CHARACTERIZATION OF THE ENVIRONMENT OF MODEL SITES

1. Model Sites for Reprocessing and Mixed Oxide Fuel Fabrication Plants

The locations of the model plants described in Section 2C are assumed to meet the site selection criteria outlined later in Section 2D2. For purposes of evaluating the impact of plant operation on the environment, several assumptions were made regarding the sites; these were taken primarily from the Nuclear Energy Center Site Survey - 1975 (NECSS-75)[16] and are enumerated below.

a. Land Use

The reprocessing and mixed oxide fuel fabrication (MOX) plants are located on the same site, within a fenced area of about 6000 acres.[16] This provides a 1.5-mile buffer zone surrounding the plants. A sample site layout is shown in Figure 2.16. The MOX plant supporting the reprocessing plant at Allied-General Nuclear Services (AGNS) (Table 2.4) may not be located at that site; these two plants will then be exceptions to the model facilities assumptions.

b. Population

The population within a 50-mile radius of the site center is one million. The distribution is lower than that used in NECSS-75 (3.5 million) for the reasons cited in the LMFBR environmental statement[44]: "A site for a fuel-cycle facility is

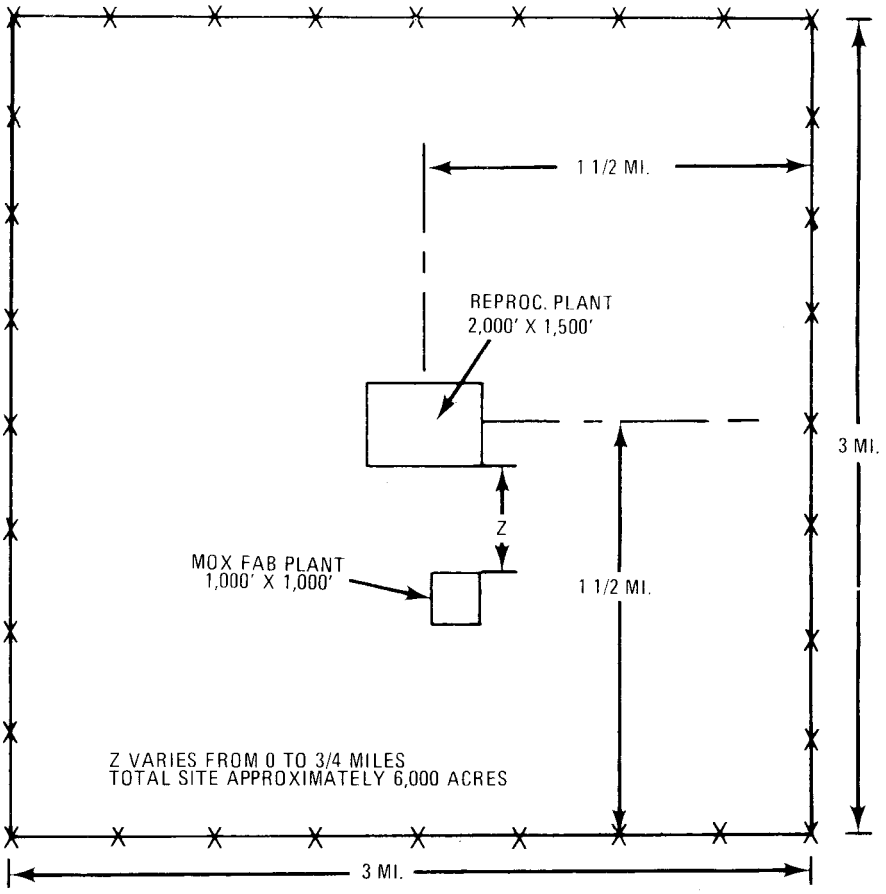


FIGURE 2.16. Schematic Diagram of Collocated Facility Site[16]

not likely to be selected within a heavily populated area. Many potential sites have populations of less than 500,000 within a radius of 50 miles; actual sites will probably be selected from among these areas. Since increases in population may occur over the years in the vicinity of a fuel-cycle facility, a population of 1,000,000 people uniformly distributed within a 50-mile radius was used..." The same population distribution was used in the Expansion of U.S. Uranium Enrichment Capacity environment statement.[45]

c. Manpower

The peak construction contractor manning for engineering and mechanical, structural, and electrical construction activities is approximately 1500 persons.[16]

A total of approximately 900 workers is required to operate the reprocessing plant, including the UF_6, PuO_2, and waste solidification operations[15], and 300 to operate the MOX fabrication plant.[46]

d. Power and Water

Power requirements[16] are approximately 90,000 (MW-hr)/yr for a reprocessing plant and 60,000 (MW-hr)/yr for a MOX plant.

Operation of a reprocessing plant requires about 2×10^6 to 4×10^6 gal/day of water.[16,47] A maximum of 0.6×10^6 gal/day will be consumed through heat dissipation; the remainder will

be returned to the receiving body of water, conveying some plant wastes. A MOX plant requires about 0.1×10^6 gal/day, 2/3 of which will be dissipated to the atmosphere.

e. Meteorology

The meteorological model used in Section 3B1 to calculate the dispersion of atmospheric pollutants released from the model plants is adapted from WASH-1535.[44] The model and assumptions are described in Appendix B.

2. Site Considerations for Reprocessing and Mixed Oxide Fuel Fabrication Plants

This section was condensed from the similar section in ERDA-1543.[45] The site characteristics described in this section are those that must be evaluated for specific facility site selection and addressed in the environmental statements for those facilities.

Many areas of the country are suitable for the construction of reprocessing and mixed oxide fuel fabrication plants although various site-specific characteristics, such as seismic and meteorological conditions, must be considered. The power, water, manpower, and transportation networks required can be provided by most areas, but no one site is likely to have all of the preferred characteristics. Economics and environmental tradeoffs must be considered during the site selection procedure.

a. Site Requirements

(1) General Location

There are advantages in locating reprocessing and MOX fabrication plants near each other and other fuel cycle plants. A shared-site facility in which a reprocessing plant is built adjacent to a MOX fabrication plant allows support facilities to be shared between both plants. This arrangement can result in less land being required, a reduction in total construction time and cost, more efficient use of personnel and facilities, and reduced transportation of nuclear materials.

The site should be located in proximity to developed systems, such as commercial communication, highways, railroads, and power networks. The proximity to sources of required materials should be considered during site selection.

(2) Isolation

An existing population of 100,000 or more within a reasonable traveling distance of the site would aid in the provision and absorption of construction and operating personnel. Local business centers and retail establishments are desirable to provide for the needs of workers and their families. In less-populated areas, housing must be provided and utilities and community services enlarged and upgraded. The number of people displaced should be minimal, and future population projections should not indicate large increases in the communities near the plant.

(3) Housing (as related to manpower)

Appropriate housing must be available to support the construction and operation manpower required. Space for both long-term housing and temporary housing (trailer parks) should be available, in addition to existing housing. Sufficient utilities and services including power, sanitary water, sewerage, waste disposal, schools, medical facilities, and shopping centers must be available or be provided.

(4) Transportation

Transportation systems are required to transport material, equipment, and irradiated fuel to and from the site. A site location on a primary road and in proximity to major road networks and a railroad spur is desirable. The distance from such systems influences the extent of construction needed to provide the desired facilities. Air and water transportation systems are desirable, but not essential.

(5) Power

The site should be located in proximity to existing power supplies to minimize costs and power losses. The environmental effects of construction of transmission lines will thus also be minimized.

(6) Fuel Required for Heating

Heating requirements could be satisfied using natural gas, oil, or coal. The availability and costs of these fuels deter-

mine which is most economical to use. Coal will probably be used because of its potential availability.

(7) Waste Disposal

Some radioactive-contaminated solid wastes require storage and/or incineration within security fencing as discussed in Section 2C. Incineration requires less ground area. Uncontaminated solid wastes may be disposed of outside the plant by burial in a sanitary landfill or by incineration.

Treatment of contaminated liquid wastes is discussed in Section 2C. Uncontaminated liquid wastes may be held in holding ponds or piped to treatment facilities. Sanitary sewage may be treated and disposed of at the site or pipelines may be connected to public sewage systems. Gaseous effluents will be treated as required to meet controlling regulations and standards.

Federal, state, and local standards must be considered in determining the adequacy of prospective sites. The Environmental Protection Agency is responsible for regulating air and water pollution, drinking water quality, solid waste disposal, environmental radiation, and noise levels. State and local agencies are concerned with these areas as well as zoning, public convenience and necessities, pollution control, wildlife, and recreation.

b. Topography

The configuration of the site including its relief and the position of its natural and man-made features must be considered in addition to the cost of the land. A relatively level area

requiring a minimum of site preparation including demolition, clearing, grubbing, excavation, and fill is desirable. Such site selection reduces construction costs but the cost of the land may be high.

The amount of excavation required could range from several hundred thousand cubic yards to several million cubic yards, depending on the topography and optimum elevation for the particular site. The most economic site elevation depends on excavation, drainage, elevation of roads and railroads, and suitability of foundation materials. The relocation of roads and railroads at the site should be minimized.

c. Geology

Geological factors are considered in order to meet safety and engineering requirements and to anticipate geological problems, including foundation and ground water considerations. The site location should be described geologically and the formations extending under the site should be identified. Stratigraphy, history of the strata, seismology, and soil descriptions are factors to be considered.

(1) Stratigraphy

Stratigraphy is concerned with the sequence of rock types formed on the earth's surface. Each stratum is defined by its composition, distribution, succession, and geologic era. Information on geologic structure aids in determining seismic risk,

foundation design, and occurrence and movement of groundwater.

Geological characteristics will usually reveal the presence of groundwater and its probable movement. The flow path in relation to possible points of contaminant entrance to the biosphere is important. A low groundwater table with minimum movement under possible containment areas is desirable. Regions containing shale and clay are desirable because they impede the movement of water and help prevent movement of contamination by ion exchange and absorption.

(2) History

Geologic history describes the forces active on the strata from the time of their formation to the present. Layers formed in early eras may have been eroded or worn down, uplifted, tilted, or overturned at several different times in later eras. The occurrence of upheaval forces and erosion depicts the history of the earth in the particular area studied. The more active the history, the more complicated the geologic survey becomes. Undisturbed beds would be the ideal condition.

(3) Seismology

(a) Regional Tectonics

Tectonics refers to the mechanisms and results of breakage and warpage in the earth's surface, especially folding and faulting. The site should not be located near active fault zones or epicenters that could cause an earthquake that would significantly damage major plant facilities.

(b) Recent Seismic History

In choosing a site, the probability of seismic activity must be carefully considered. The history of earthquake and attendant phenomena in the area should be studied, including the time, frequency, location, and intensity of the tremors. These studies and the maximum probable seismic intensity may be used to evaluate the risk of seismic damage at the site. The severity of damage is determined by whether the earthquake causes splitting and shearing, or general movement. A site located in a low seismic zone is desirable for minimizing seismic risk.

(c) Seismic Risk

Seismic risk zones existing across the country rated by Modified Mercalli (M.M.) Intensity Scale are shown in Figure 2.17.[48] Differences in zones are generally due to different geologic formations beneath a site. To reduce risk, the site should be located in a low seismic activity zone, and/or seismic design of buildings should be considered. Sesimic design may involve the use of equivalent static eqrthquake loads and/or the use of a dynamic analysis of the structure. In a high-risk area, the dynamic design is a preferable approach for critical systems.

The stability characteristics and amplification factors of the soil are important with regard to seismic activity. The occurrence of liquefaction in saturated silty clay soils or sand could cause excessive damage. Fills would be required to replace these soils.

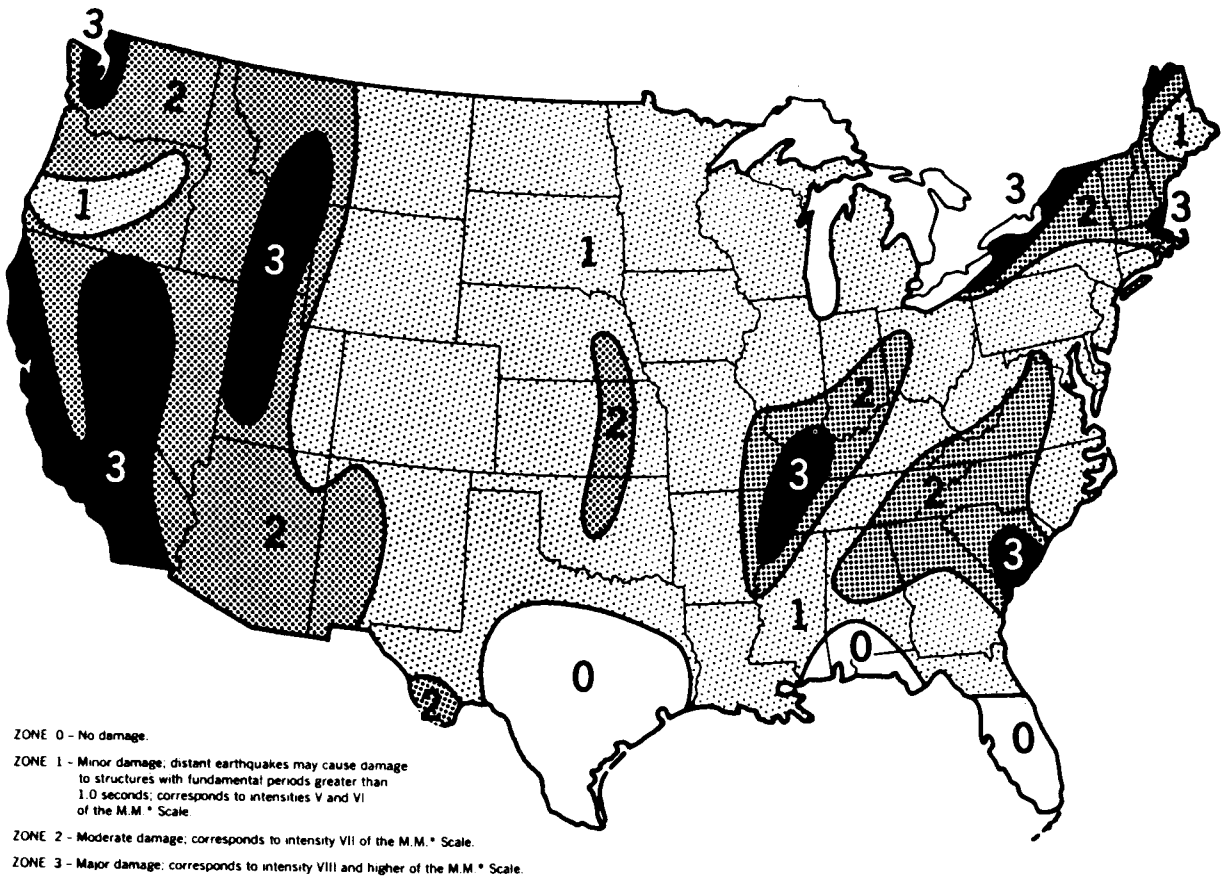


FIGURE 2.17. Seismic Risk Map for Conterminous United States[48]

(4) Soil Description

Soil profiles may be used to describe soil conditions beneath the site. Soils are described by their origin and by their characteristics, including shear strength, density, compressibility, permeability, color, structure of the soil, and composition (grain size, shape, plasticity, mineralogy, etc.). These characteristics will determine the suitability of the soil for foundation material.

d. Hydrology

Hydrologic characteristics (origin, distribution, and properties of water) of a region are largely determined by its climate and its geologic structure. Hydrologic factors will affect the design of heat dissipation systems and water treatment facilities; these factors must be considered in safety evaluations of accidental releases of radionuclides or chemicals.

(1) Surface Waters

Surface waters include streams, rivers, lakes, and oceans. Most surface waters can be adapted for use as a water supply, depending on the degree of treatment that will be provided. The drainage patterns and hydrologic properties in a drainage basin are determined by rainfall characteristics, topography of the land, soil characteristics, and the type of vegetation and covering in the area. These factors affect the amount of surface water available for use. The size and characteristics of the river drainage area, along with the 7-day, 10-year low flow,

provide information for determining the adequacy of flow for use by a reprocessing or MOX plant.

Before surface water is selected for water supply, the location of intake and discharge lines in relation to navigable waters, the water depth near shore, the effects of tidal action in oceans and estuaries, the history of storm damage, and the aquatic life cycles in the region of the intake and discharge structures must be considered. The use of surface water should not interfere with present uses or activities in the drainage basin, and the downstream population should not be adversely affected.

(2) Groundwater

Groundwater normally offers a naturally purer water supply than surface water. Factors that must be considered in using groundwater for water supply include the effective water content or maximum volume of water than can be withdrawn (function of effective porosity and storage coefficient of the water-bearing material); the ability of the aquifer to transmit water in necessary quantities to wells (function of permeability and transmissivity) and the suitability of the water for the intended use. Additional factors include the reliability and permanence of the available supply with respect to both quantity and quality of water, and the current and planned uses of the groundwater.

Ion exchange rate in soils and groundwater movement rate should be determined and used in analyzing the effects of accidental spills or leaks.

e. Meteorology

Meteorology is an important factor in the siting of reprocessing and MOX fabrication plants. Wind loads, snow loads, and precipitation influence the design and construction cost. Relative humidity, air temperature, and wind characteristics affect the operation of cooling towers. Prevailing wind direction, wind speed, and atmospheric stability affect the dispersion of emissions. Regional meteorology also affects regional hydrology.

(1) Regional

Physical features such as mountains or oceans influence the average course or condition of weather over a period of years (climatology). The movement of air masses and storm patterns also affect the climatology.

(2) Local

Building designs must provide appropriate protection from severe storms, such as tornadoes and hurricanes, maximum wind speeds, ice storms, snow storms, and thunderstorms. Sites should preferably be located in areas with a low probability of tornadoes and hurricanes. Hurricanes occur primarily along the east coast;[49] tornado areas are shown in Figure 2.18.

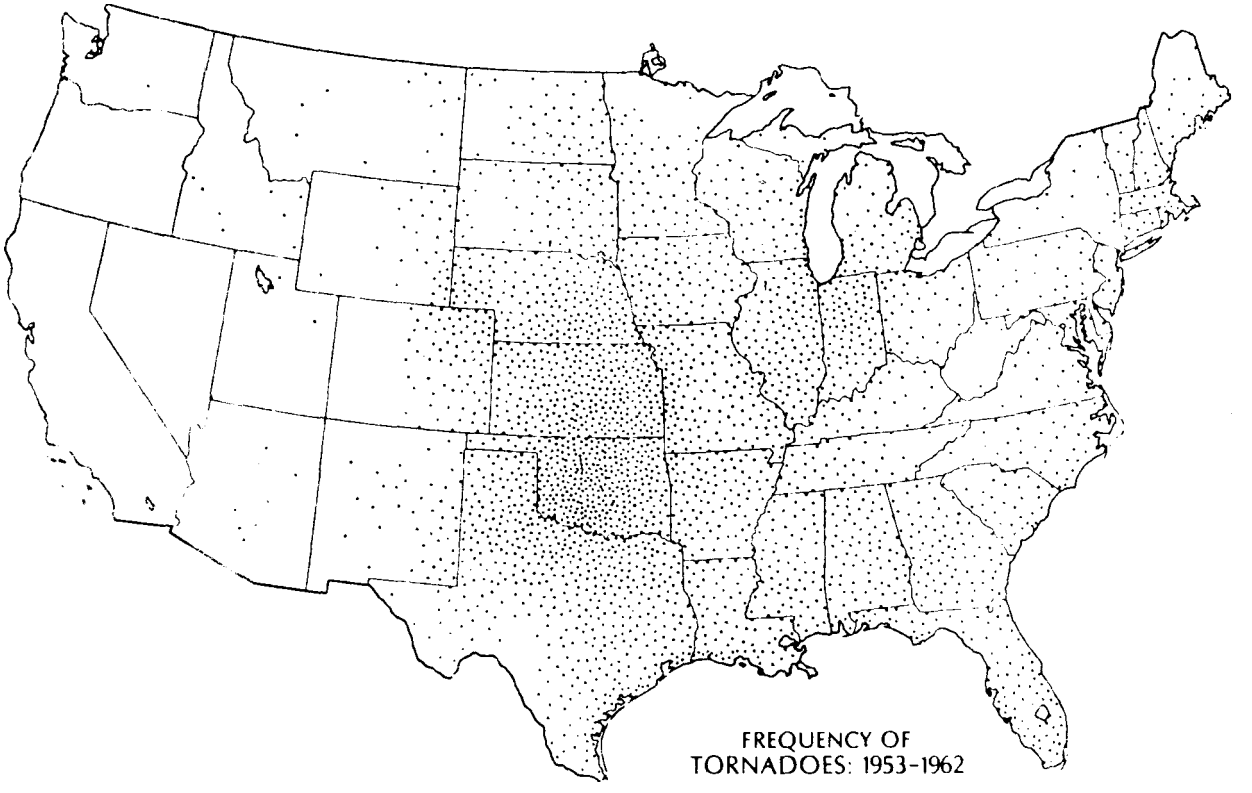


FIGURE 2.18. Frequency of Tornadoes, 1953-1962.[49] (Each dot represents the approximate location of two occurrences during the ten-year period.)

Atmospheric emissions are affected by wind speed and direction, the air temperature, and the occurrence of air stagnations. Areas with air pollution problems should be avoided. Special precautions may be necessary in areas with high pollution potentials (Figure 2.19).

f. Ecology

Descriptions of the terrestrial and aquatic ecology of a potential site and its environs, along with information on engineering design, effluents, land use, and water use, form the basis for assessing the potential ecological impacts of any large facility such as a reprocessing or MOX fabrication plant.

(1) Terrestrial

The terrestrial ecology of a site can be characterized by identifying the important flora and fauna in the region, their habitats and distribution, and the relationships between species and their environment. As set forth in the NRC Regulatory Guide 4.2,[50] a plant or animal species is "important" if 1) it is commercially or recreationally valuable; 2) it is rare or endangered; 3) it affects the well-being of some important species within the above two criteria; or, 4) it is critical to the structure and function of the regional ecological system. A "rare or endangered" species is any species officially designated as such by the U.S. Fish and Wildlife Service. Further, in any siting plan, the local and regional distribution of habitats must be compared with projected losses due to siting.

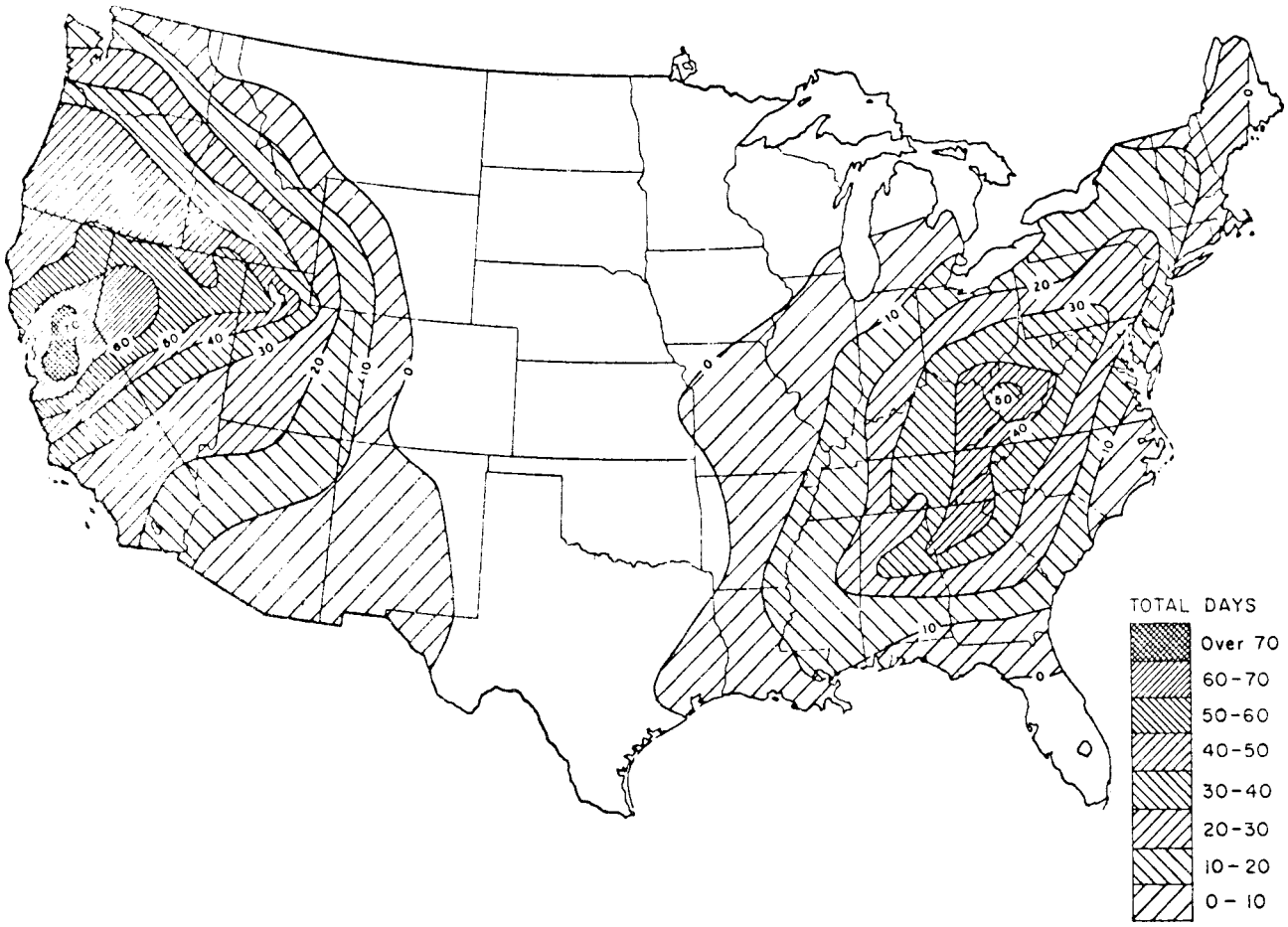


FIGURE 2.19. Days of High Air Pollution Potential Forecasted[49]

Attention must be given to the abundance of important species, to area utilization, to life histories of important species and their normal seasonal population fluctuations and habitat requirements, and to the identification of food webs. The status of ecological succession and pre-existing environmental stresses are also important considerations in selecting sites with minimum potential for undesirable impacts.

Federal reserve lands include the national parks, forests, monuments, and wildlife refuges as shown in the *National Atlas*.[49] State reserve lands include state forests and state parks. These Federal and state lands are generally administered to preserve and manage recreational, watershed, timber, range, and wildlife resources. Concomitantly, many natural wildlife habitats are preserved. Although a reprocessing or MOX fabrication plant of the present design requires a relatively small amount of land, siting within the above-mentioned areas would probably be ecologically undesirable.

Sites should not normally be selected if they contain special habitats used by one or more of the life stages of important commercial, recreational, or rare and endangered species. This exclusion therefore applies to such areas as breeding, nursery and wintering grounds, and migratory routes used by important species.

Fresh, brackish, and salt water marsh ecosystems usually provide habitat for many important species. These ecosystems are highly productive and provide food sources as well as protective

cover for juvenile aquatic species and breeding and migrating bird species. In addition, many of these areas have been drained and filled or otherwise disturbed, leading to speculation that the resource may be critically reduced if current development of these areas continues.[51] For these reasons, marsh ecosystems should normally be avoided in siting a plant.

(2) Aquatic

Aquatic ecology broadly refers to the complex interrelationships among aquatic organisms and the physical and chemical characteristics of the aquatic environment. These physical and chemical conditions tend to limit the kinds of plant-animal communities able to live in an aquatic environment.

In siting a reprocessing or MOX fabrication plant — whether on or near a lake, river, estuary, or ocean — the same general ecological criteria must be considered for the local surface waters potentially affected by construction and operation of the plant. As with terrestrial ecology, these considerations include important species, habitat requirements and utilization by important species, interspecific relationships, local and regional habitat availability, and pre-existing environmental stresses.

Although potential sites must be evaluated on a case-by-case basis, the best sites from the standpoint of aquatic biota are rivers with large flow volumes (100 cfs as a minimum; 1000 cfs preferred). Lakes, although acceptable, are generally less

desirable than rivers as sites. Estuaries and coastal zones are even less desirable and in most cases should be avoided. Other special aquatic environments that should normally be avoided as plantsites include water bodies within Federal and state reserved lands and habitats used by important recreational, commercial, or rare and endangered species as well as any aquatic environment already undergoing heavy stress from heat or other pollutants.

g. Political Structure

(1) Local Government

The governments of the nearby cities, as well as the county government with jurisdiction over the facilities, will be considered when a specific site is selected. All applicable permits must be obtained (i.e., construction, health, sewage disposal, and occupational). The tax structure and jurisdiction will be addressed. The operation of local government and the health, safety, security, educational, and other such services are of concern.

(2) State Government

The state government will be considered when a specific site is selected. The above considerations with regard to the state government will also be made in the site-specific environmental assessment. All applicable state effluent standards must be met and the required state discharge permits must be obtained.

h. Land Use

(1) Present

Factors regarding land use which must be considered when siting a plant include: 1) the compatibility of plant construction and operation with local and regional land resource plans, 2) the effects of removal of agricultural land from production, and 3) the potential effects of gaseous effluents from the plant on local and regional land use.

The primary responsibility for land use regulation and planning lies at the state and local level. Major categories of land use include rural residential, urban residential, industrial, agricultural, and natural. Under most existing state and local land use policies, a nuclear facility would be sited by ordinance in an industrial-use zone. If feasible sites in industrial-use zones are not available, the impacts of forfeiting current land use on the land required for the plant and on surrounding regions must be evaluated.

Federal and state lands set aside for conservation, aesthetics, and recreational use, should not normally be considered for siting a plant. These lands are generally administered on the basis of multiple-use and sustained-yield policies. The five use categories specified for national forests (comprising 25% of federally owned land) are: 1) outdoor recreation, 2) timber, 3) watershed protection, 4) wildlife, and 5) range.[49]

Coastal regions of the U.S. are a highly valuable resource

for recreational use and aesthetic values. More than 50% of the U.S. population lives in counties bordering the Great Lakes and the ocean.[52] The oceans are also an important source of food, particularly in the coastal and estuarine zones.

Whether or not agricultural land should be removed from food production for use as a site for a plant depends on the quality of the farm land and the value of the crop produced. Use of Class I agricultural land, as defined by the U.S. Department of Agriculture,[53] for a site should be avoided. Of all land inventoried in the U.S., 44% (631 million acres) is in Classes I, II, and III and is suitable for regular cultivation. Of this land, 7% (47 million acres) is Class I.[53]

The potential effects of gaseous effluents on local and regional land use should be considered when choosing a site. A number of agricultural and native plant species are especially sensitive to air pollutants. Although air pollution control measures designed into the plants seek to eliminate most problem effluents, release of air pollutants may interfere with surrounding land use and/or require large buffer zones, and therefore should be carefully considered in plant siting.

(2) Projected

Federal and state agencies and the public are becoming increasingly aware of the need for conserving land for agricultural use, preserving scenic areas, protecting the rural environment, and preserving wetlands and natural regions as educational and

scientific resources. Proposed Federal land-use legislation, which would encourage states to protect critical areas and control large-scale development and growth, has been considered by Congress. A number of states have enacted comprehensive land-use laws (e.g., Florida and Oregon); other states are formulating similar legislation or have laws concerning coastal zone, shoreline, or wetland regulation.[54] Although the exact direction of future land-use legislation is not known, regulations are likely to become more conservative and stringent as the amount of undeveloped land in the U.S. diminishes.

After the useful life of a plant, the land may possibly be used for an updated nuclear facility. Other future uses of the land may be precluded; for example, the potential agricultural productivity may be reduced because of soil compaction or possible toxic substances in the soils covering holding ponds and landfills. All these factors should be considered when selecting a plantsite and in anticipating future decommissioning options (dismantlement, entombment, or protective storage).

i. Water Use

(1) Present

Two criteria should be applied when considering sites for a plant: 1) availability of water for withdrawal and consumption, and 2) compatibility of proposed water use with existing water uses.

Comparison of the mean annual runoff with current consumptive use of water indicates the present water quantity situation is favorable in all areas except the Rio Grande, lower and upper Colorado, California, and Great Basin regions (Figure 2.20). Because of periodically recurring drought conditions, the Texas-Gulf and Missouri regions also would face an unfavorable water supply-demand balance.[55] Regional summaries do not disclose local water shortages within a region. This is particularly true within regions such as Columbia-North Pacific, Missouri, and Arkansas-White-Red, where water flows through arid lands, or in the high plains of Texas and central Arizona where use of ground water exceeds recharge. Although water availability for plant operation must be determined on a site-specific basis, the seven shaded regions in Figure 2.20 would require specific consideration because of the water supply-demand conditions outlined above.

State water-use classifications identify uses to be made of a particular stretch of a river, lake, or coastal water, such as recreation, drinking water, industrial, agricultural, fish and wildlife propagation, or a combination of these uses.[56] Ideally, siting should subscribe to an industrial water-use category and should be consistent with local and regional water and land resource management plans. Surface waters in Federal and state reserve lands, waters designated under the Wild and Scenic Rivers Act of 1968,[54] and important recreational waters

REGION WITH AN UNFAVORABLE WATER SUPPLY-DEMAND RATIO;
1970 CONSUMPTIVE USE GREATER THAN ONE-THIRD TOTAL WATER AVAILABILITY.

AT FLOWS AVAILABLE 95 % OF THE YEAR, WATER SUPPLY-CONSUMPTIVE
USE RATIO LESS THAN TWO.

FIGURE 2.20. Water Resources Regions in the U.S.[57]

such as coastal shorelines should not ordinarily be considered for siting.

(2) Projected

Projections[55] of water use and total consumptive water use in the U.S. for the year 2000 indicate that the seven regions shaded on Figure 2.20[57] plus the Arkansas-White-Red region will have unfavorable water supply-demand ratios.

The objective of the Federal Water Pollution Control Act and Amendments of 1972[58] is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" ... It is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985, and "wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983." Whether or not these goals are achieved on the timetable established in the Act, water quality in U.S. surface waters will probably improve in future years. Therefore, the spectrum of water uses for a currently polluted body of surface water may broaden to include such things as water sports and fish and shellfish propagation. Therefore, both current and future water quality standards must be considered in siting a plant as well as in designing plant waste treatment facilities.

j. Radiological Characteristics

Radiation to man is primarily from natural radiation sources (background), but man-made radionuclides (fallout) do contribute to exposure. Both sources are discussed in this section to provide a perspective for the facility radiological assessment. The radiological characteristics at the site selected and the neighboring environs should be determined before beginning plant construction. The present discussion gives an indication of the radiation level likely to exist, based on the U.S. average.[59]

(1) Natural Radiation

The natural background radiation dose to man is received from cosmic rays and from external and internal terrestrial radiation sources. Cosmic ray radiation varies with altitude and latitude. The dose equivalent rate for cosmic radiation on a state basis ranges from 38 mrem/yr in Florida to 75 mrem/yr in Wyoming with an average of 44 for the contiguous U.S.[59] An even wider variation occurs in the terrestrial gamma whole-body dose rate, which ranges from about 15 to 35 mrem/yr in the Atlantic and Gulf Coastal Plains to a high of 140 mrem/yr on the Colorado Plateau.[59] The average for the country is reported to be 40 mrem/yr.[59] The internal whole-body dose resulting from the naturally occurring radioisotopes ^{40}K, ^{14}C, ^{3}H, ^{226}Ra, and ^{228}Ra and their decay products is believed to be fairly uniform around

the country with an average whole-body dose rate of 18 mrem/yr.[59] Thus, the average whole-body dose rate from all natural radiation sources in the U.S. is 102 mrem/yr.[59]

(2) Fallout Radiation

The total annual whole-body dose from a global fallout is reported to have dropped from 13 mrem in 1963 to 4.0 in 1969.[59] The 4.0 mrem is divided as follows: 0.9 mrem from external radiation, 2.1 mrem from ^{90}Sr, 0.4 mrem from ^{137}Cs, and 0.6 mrem from ^{14}C. It is emphasized that these are average values and that actual values could vary by a factor of 2 or more because of variation in fallout and diet.[59] However, in view of the large variations in natural radiation discussed above, the variation in fallout dose is likely to have a minor effect on the total dose.

k. Regional Landmarks

(1) Historic, Archaeological, and Cultural

The *National Atlas*[49] provides historic and cultural information about the U.S. Prehistoric sites and cultural complexes are described (pp. 129 to 131), the exploration and settlement of the U.S. are discussed (pp. 134 to 139), and battle sites are shown (p. 143). A cumulative revision of the *National Register of Historic Places* is given in the *Federal Register* of February 4, 1975, 40(24) F.R., pp. 5242-5345; additions are published in the *Federal Register* on the first Tuesday of each month. For a

specific site the State Liaison Officer for Historic Preservation should be contacted regarding properties under consideration for nomination to the *National Register for Historic Places*. An archaeological survey of the plantsite area should be conducted before construction is started. Plans for preservation of significant areas should be included in a site-specific assessment.

(2) Scenic and Natural

The *National Registry of Natural Landmarks* appears in the *Federal Register* of September 5, 1973, 38(171) F.R., pp. 23982-23985. Additions to the list are given in the *Federal Register* of June 10, 1974 39(112) F.R., pp. 20405-20456, and October 18, 1974, 39(203), pp. 37225-37226.

Federal lands and their uses (including national parks) are discussed in the *National Atlas*.[49] Plans for preservation of scenic or natural areas of significance affected by a specific plant should be included in the site-specific assessment.

E. ENVIRONMENTAL MONITORING PROGRAM

This section is adapted from the monitoring program outlined in the LMFBR Environmental Statement.[44]

The purpose of the radiological environmental monitoring program for the LWR fuel recycle facilities is to permit the assessment of radiation dose to the public from operation of the facilities and to maintain surveillance for long-term buildup of radioactivity in the environment. Because the predicted radioactivity releases are very low, the limits of detection may preclude their observation in the environment, and environmental monitoring may serve chiefly to provide upper-limit estimates of dose along critical pathways. Therefore, estimates of human exposure will also depend on detailed isotopic analysis at the points of release, together with the use of suitable models for dispersion and movement of radionuclides through the environment. Parameters in the models should be determined from site-specific data with regard to meteorology, hydrology, demography, land and water use, water chemistry, and local food chains.

The monitoring program is conducted in two phases: a preoperational phase before plant startup, and an operational phase beginning with plant startup and continuing throughout the life of the plant. The objectives of the preoperational phase are:

- Evaluation of environmental radiation levels and fluctuations attributable to natural background, fallout, and other sources. Media analyzed include air, water, soil, milk, sediment, and

aquatic biota. Measurements emphasize analyses for specific radionuclides, particularly those whose origins may later be subject to doubt. Statistical evaluations of sources of measurement variability are also required.

- Identification of significant population groups, pathways, and radionuclides. This effort depends greatly on parallel programs for the accumulation of meteorological, hydrological, and demographic data for the site, together with information on local food sources, land use, and trace element analysis of potential receiving waters.
- Development and evaluation of sampling and analysis techniques and procedures.
- Training of appropriate plant personnel in the use of these techniques and procedures.

The early stages of the operational monitoring phase are a continuation of the preoperational phase. This phase should be particularly intensive during the first two or three years of plant operation with special programs and with frequent evaluation of data to develop better understanding of important pathways and behavior of radionuclides in the local environment.

Sampling should focus chiefly on media impinging directly on man, such as air and water; on foods consumed directly by man, such as milk, fish and leafy vegetables; and on media such as aquatic plants and sediments that may be sensitive indicators of the presence of radioactivity in the environment. Whenever

practicable, samples are analyzed for specific radionuclides to permit dose estimates to be made for man and important biota. In addition, all potentially radioactive effluents are monitored at their point of release and analyzed in accordance with Nuclear Regulatory Commission guides.

The radiological environmental monitoring program should be supplemented, when warranted, by programs designed to assess the impact of the discharge of nonradiological pollutants (including thermal effects) on the nearby environs.

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3. ENVIRONMENTAL EFFECTS

A. EFFECTS OF CONSTRUCTING REPROCESSING AND MIXED OXIDE FUEL FABRICATION PLANTS

This section was condensed from the similar section in ERDA-1543,[1] modified by information pertinent to fuel reprocessing and mixed oxide fuel (MOX) fabrication plants in NUREG-0001.[2]

1. General Description

The site for a reprocessing plant and a collocated MOX plant covers an area of about 6000 acres, not including areas required for transmission lines and for access to highways and railways. A temporary construction site adjacent to the plant requires additional acreage.

While the plants are under construction, some land and water areas will be disturbed and modified where permanent structures are to be located and where other areas are to be used for temporary access, storage of material and equipment, and disposal of excavated earth. The extent of dredging of water areas and clearing, leveling, and filling of land areas depends on the particular site. Special precautions must be taken to minimize erosion, siltation, and destruction of biota during construction operations and during the interim period before the disturbed areas are put into final form.

2. Effects on Land Use

A full assessment of the probable impact of committing a site of 6000 acres for LWR fuel reprocessing and MOX plants must deal with such factors as 1) previous or potential land use, 2) presence or absence of historical, archaeological, or cultural resources, and 3) need for offsite facilities. This assessment must also deal with various considerations required to foster judicious site selection. The construction of any large facility modifies land where permanent structures are located and where adjacent areas are used for access, storage, lay-down areas, office space, and parking.

Erosion of exposed areas with the potential for siltation of adjacent aquatic systems should be minimized. Erosion control measures are discussed in Federal agency guides[3,4] which suggest: 1) limiting vegetation removal to an absolute minimum, especially along stream and river banks; 2) selecting proper sites for excavation-spoil stockpiles; 3) limiting the steepness of inclines; 4) minimizing traffic on the construction site, particularly during critical periods such as spring thaw; 5) early stabilizing and replanting of exposed soils; and 6) providing runoff channels and settling areas to collect and settle surface water runoff before releases to bodies of natural surface water.

3. Effects on Water Use

Water use during construction is a few hundred thousand gal/day. This use of water would account for a small fraction of the flow of a 100-cfs (65 million gal/day) river or a small percentage of the available ground water supply in many areas of the U.S.

Excavations for foundations of major structures often require extensive dewatering, in which ground water entering the excavation is pumped out to the surface water. Depending on the local ground water recharge, this dewatering may temporarily lower the water table in production wells in the vicinity or may affect flow gradients in the ground water in other ways, thus affecting the quality of ground water. Careful attention must be given to the condition of the water to be disposed of during the dewatering process.

Construction work may include intake and discharge structures for the water system and associated channel dredging to ensure dependable flow. Water quality is not expected to be altered for more than short periods during construction of these structures. Water traffic or shorelines may be temporarily affected if breakwaters or barge landings are needed during construction of the plant.

4. Effects on Ecology

Changes in the local ecology are expected during the disruptions accompanying the construction activities, with reversal

of some changes and restoration to a new equilibrium after completion of these activities. For birds and fish, permanent impacts can be ameliorated in some cases by providing bypass routes or feeding stations for migratory species. For trees and other vegetation, carefully controlled procedures can minimize effects during construction and maximize recovery.

Clearing of wooded land will result in a loss of wildlife habitat. During such clearing and construction, animals will seek shelter in adjacent wooded areas; however, there may be increased mortality among displaced animals. Some foraging species may be benefited by this activity as new shrubs and low brush develop from natural regeneration.

The areas on the site that are not used for permanent facilities can be reclaimed by landscaping and reseeding. Such measures minimize the long-term impact on terrestrial biota in the area.

During construction, impacts on aquatic biota can result from siltation of local surface waters, from release and runoff of toxic substances, and from release of treated sewage effluent.

The major potential for adverse impacts on aquatic ecosystems is associated with an increase of suspended solids and siltation in local surface waters resulting from runoff of eroded soil. Turbid water, besides being aesthetically displeasing, will often be avoided by fish, although fingerlings and adults often are quite resistant to high concentrations of

suspended solids for short periods. Fish may seek cover and stop feeding because of difficulty in finding food in turbid water, or, they may even cease migrating. High suspended solids have been shown to depress growth, affect length-weight relationships, and increase the incidence of fin rot and thickened gill epithelia. It is possible that at high suspended sediment concentrations the potential to resist other stresses is reduced. Hiding places and food supplies may be destroyed by siltation destroying weed beds and benthic organisms. Spawning may be affected by siltation of spawning grounds. Egg mortality may increase by silt smothering eggs or diminishing the flow of interstitial water within the redds, thereby limiting the amount of available oxygen.

Runoff with a high organic content can exert a high oxygen demand and lead to local depletion of oxygen in the sediments or even up into the water column if the water currents are such that there is no fresh supply of oxygenated water.

The benthic community structure is strongly dependent on the type of substrate available, and studies of the influence of siltation on benthic organisms have shown pronounced effects. The substrate, of course, is changed physically by suspended solids settling out. The oxygen demand of organics in the silt can affect the degree of oxygenation of the sediments. Benthic productivity can be affected by turbidity and can cause a decrease in primary productivity by reduction of light penetration. Changes in bottom topography and current patterns can also lead

to very noticeable impacts. State and local standards and regulations may provide guidance in minimizing the effects of siltation from construction runoff.

Depending on the nature of the site and its past uses, erosion and runoff of exposed soils can also result in the pollution of local surface waters by toxic substances such as insecticides and herbicides. These substances are often concentrated in the aquatic food chain with potentially serious effects on some species. For some sites (e.g., former agricultural land), these potential problems contribute an additional reason for erosion controls.

Other potential impacts (biochemical oxygen demand, suspended solids, dissolved solids, nutrient chemicals, and chlorine) on aquatic biota during construction can result from sewage effluents. Until the onsite sewage treatment plant is completed, sanitary wastes usually have to be transported offsite to an existing sewage treatment facility. Although this method avoids effects on aquatic biota in surface waters near the site, the receiving water at the offsite treatment plant could be adversely affected by the added effluents. Evaluation of these potential problems and recommendations for mitigating measures on a site-by-site basis are necessary.

5. Effects on Surrounding Communities

a. Physical

(1) Air Pollution

The air pollution potential during construction should be significant only in the immediate vicinity of the construction activity, where dust must be reduced to an acceptable level, such as by frequent spraying of disturbed surface soil.

(2) Traffic

Construction of a reprocessing or MOX fabrication plant will cause a significant increase in truck traffic around the plantsite. Traffic control measures should be implemented as required to control truck traffic and ensure safe operations in the vicinity of communities, intersections in rural areas, and school bus pickup points.

Construction workers will also increase the traffic in the area. Special efforts are required to prevent an increased number of accidents during the period of peak construction.

(3) Noise

Noise levels during construction of a plant will be of the same magnitude as those for any similar construction project. Construction equipment should be monitored for compliance with all applicable regulations regarding noise abatement.

(4) Population Displacement

Although plants may be built close to a metropolitan area of 100,000 people or more, the site is most likely to be rural in nature, located on the fringe of the metropolitan region. The site selection process includes consideration of ways to minimize displacement of the local population.

b. Economic

The economic impact of plant construction can be adverse or beneficial on the specific situation. In most cases, temporary adverse effects will be offset by longer-range benefits.

Because the peak construction force for a plant is greater than the actual operating force, the economic impact of the plant felt by the local community is greater during the construction phase than during the operating phase.

The employment during the construction phase can have a significant impact on any local area. The impact will vary from community to community, depending on the local economic base. A significant portion of the labor force may be recruited from outside the immediate area. This migration of workers and their families, together with those individuals providing support services for the workers, can affect the economy of the area. The employment of a large labor force can strain existing public and private services and facilities unless advance plans are made for handling such an influx of workers.

The decline in workers following the construction phase can have a noticeable effect on local services. If the operating force disperses itself throughout a metropolitan region, the decline in the economic base of the immediate area surrounding the plant may be greater than if the operating staff chooses to cluster itself within the immediate vicinity of the plant.

c. Political

(1) Local Government

During the siting phase, all applicable permits must be obtained from the various local agencies, the tax structure must be discussed with local officials, and any problems that arise between the plant owner and the local jurisdiction must be discussed, including discharges to municipal sewer systems, impact grants for schools, hospitals, etc.

(2) Other Political Considerations

Federal and state licenses and permits must also be obtained, taxes must be paid, and regulations must be followed. Hearings will be held to present positions and arguments. In all these areas, a continual ongoing interaction, from the time a site is approved until the operation of the plant, is needed between the plant owner and state and Federal officials.

d. Services

(1) Schools

The adequacy of the existing school system to accommodate the influx of children of the construction workers and service employees will have to be analyzed. Depending on whether the plant is located in or near a metropolitan area, new school buildings or temporary classroom facilities may have to be made available. Due to the number of construction workers coming to the site, the school system may be inadequate to handle the expected influx of students. With a peak of 1500 construction workers, each having an average of 1.75 children, an addition of 2600 students to a school district is possible. If the plant is located near a metropolitan area, many workers will not relocate and therefore their children will not be considered an addition to the local school rolls.

(2) Water and Sewage

During construction of the plant, adequate water and sewer facilities are needed for the workers. The availability of these services is a factor in the siting of the plant. If these services are not already available, new services have to be provided either by building new facilities or by contracting with a nearby local jurisdiction for use of their facilities.

(3) Solid Waste Disposal

The availability of solid waste disposal is also a factor in the siting of the plant. The development of new facilities

and the extent to which such development should be permitted or controlled is the responsibility of both the plant operator and local authorities.

(4) Utilities

One of the factors to be examined in siting a plant is the availability of existing power to deal with the increased demand from both the plant and influx of workers into the area.

(5) Public Health and Medical Facilities

The need for medical facilities during the construction period is greater than during the operating period of the plant because of 1) the increased number of workers during construction and 2) the likelihood of accidents occurring during the construction phase which would not occur during the operation of the plant. Medical teams should be available to handle accidents if they should occur.

Within any local community there is a need for public health services and specialized clinical facilities. Where these medical services are not currently available, they may be developed, depending on the anticipated case load and the short- and long-range need for them by construction and operating workers and their families.

e. Aesthetic Effects

The specific location of the proposed plant construction is a primary factor in determining the aesthetic effect at the site.

The plant will be visible from certain angles, although it may be hidden by high bluffs, trees, and other foliage. Aesthetic impact is caused by earth movement, erosion, dust, construction debris, heavy equipment, construction buildings, and unadorned partially completed structures.

B. LOCAL EFFECTS OF OPERATION OF BACK-END FACILITIES

1. Radioactive Releases During Routine Operations

The radiation doses resulting from radioactive releases during routine operations are assessed in this section for 1) the hypothetical individual who receives the maximum dose, and 2) the population within a 50-mile (80 km) radius of each model facility. The assumptions made and calculational techniques used are described in Appendix B. The doses estimated in this section are from one year's operation of a model reprocessing-recycling facility; the cumulative effects on the local populations of operation of all back-end facilities through end of reprocessing (the year 2001 for the base case) are included in Section 3C, together with effects on United States and worldwide populations. Comparison with other causes of these effects is given in both this section and in Section 3C.

a. Summary of Assumptions and Models (see Appendix B)

(1) Siting and Meteorology

The model plants are assumed to be located on 6000-acre sites, with a distance of 1.5 miles (2.4 km) between the plant and the site boundary (Section 2D1). Site meteorology is adapted from WASH-1535;[5] a uniform wind rose is assumed for population dose calculations; however, a maximum-to-average factor of 2.0 at the perimeter is assumed for maximum individual dose calculations. Values used for diffusion factors ($\bar{\chi}/Q$) are 1×10^{-7} sec/m^3 for the perimeter maximum, 4×10^{-9} sec/m^3 for a 50-mile radius

integrated average with undepleted cloud, and 2×10^{-9} sec/m^3 for a 50-mile radius integrated average with depleted cloud. A deposition velocity of 1 cm/sec is assumed for radioiodine and particulates.[5]

(2) Population Distribution

The population surrounding each model facility is assumed to total one million, uniformly distributed in the area between the 1.5- and 50-mile radii locations. The population density is thus 127 persons/square mile (49/km^2). The rationale for the population assumption is given in Section 2D1.

(3) Releases

(a) Fuel Reprocessing Plants

The radionuclides estimated to be released from a fuel reprocessing plant (FRP) processing 1500 MT/yr of LWR plutonium fuel are listed in Table 3.1.

The releases are the same as those used in NUREG-0001,[2] with the exception that a 365-day cooling time was assumed as being reasonable for the nuclear power industry, rather than 150 days. The gaseous effluents from the various facilities at each FRP are assumed to be released from a 100-m stack. The assumption is made that no radionuclides are released to the environment with liquid effluents. This assumption is consistent with the AGNS reprocessing plant flowsheet.[6]

TABLE 3.1

Radionuclides Released to the Atmosphere from Model Fuel Reprocessing Plant[2]

(Basis: 1500 MT/yr, LWR-Pu Fuel, 365-day Cooling)

Nuclide[a]	*Ci/yr*	*Nuclide*	*Ci/yr*
^{3}H	1,100,000[b]	^{134}Cs	0.49
^{14}C	700[b]	^{137}Cs	0.50
^{85}Kr	14,000,000[b]	^{141}Ce	0.001
^{89}Sr	0.02	^{144}Ce	1.3
^{90}Sr	0.2	^{147}Pm	0.26
^{90}Y	0.2	^{154}Eu	0.022
^{91}Y	0.03	^{155}Eu	0.020
^{95}Zr	0.07	^{238}Pu	0.075[c]
^{95}Nb	0.02	^{239}Pu	0.0036[c]
^{103}Ru	0.003	^{240}Pu	0.0075[c]
^{106}Ru	0.52	^{241}Pu	2.1[c]
^{110m}Ag	0.006	^{242}Pu	0.00006[c]
^{125}Sb	0.025	^{241}Am	0.0022[c]
^{127m}Te	0.005	^{243}Am	0.00063[c]
^{129}I	3.0[c]	^{242}Cm	0.11[c]
^{131}I	3×10^{-7}	^{244}Cm	0.15[c]

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a. Includes contributions from radionuclides released during waste solidification, UF_6 conversion, and PuO_2 conversion.

b. Releases of ^{3}H, ^{14}C, and ^{85}Kr are assumed to be reduced to 1% of the values shown for plants starting up after AGNS.

c. Releases of ^{129}I, Pu, Am, and Cm are assumed to be reduced to 10% of the values shown for plants starting up after AGNS.

The effects of improved offgas control technology are shown as footnotes in Table 3.1 and are discussed in Section 2C2. In this assessment of the base case, the improved offgas controls are assumed to be installed in the six 1500-MT plants that start up between 1986 and 1997, and the AGNS plant is not assumed to be provided with these improvements. The effects of alternative approaches [(1) retrofitting AGNS when the improvements are assumed available, and (2) not providing improved controls for any of the 7 plants] are assessed in Section 5.

(b) Mixed Oxide Fuel Fabrication

The radionuclides released to the atmosphere with gaseous effluents from a mixed oxide fuel fabrication plant consist of uranium, plutonium, and americium isotopes. Because of the relatively long half-lives and lower radiotoxicity of uranium isotopes, they do not contribute significantly to the radiological impact of the gaseous effluents from this facility. Estimated release rates of plutonium and americium isotopes (Table 3.2) are based on a total plutonium release of 4.4 mg/yr from a 350-MT/yr mixed oxide facility processing fuel which has decayed for one year since leaving the fuel reprocessing plant. These values are those used in NUREG-0001.[2] The radionuclides are assumed to be released from a 100-m stack serving both the FRP and MOX plant at a collocated site (Section 2C3). As in the case of the fuel reprocessing plant, no radionuclides are assumed to be released with liquid effluents from the mixed oxide plant.

TABLE 3.2

Radionuclides Released to the Atmosphere from Model MOX Plant[2]

Basis: 350 MT/yr

Nuclide	*Amount Released*[a] *wt %*	*mg/yr*	*Ci/mg*	*Ci/yr*[b]
^{238}Pu	2.0	0.089	0.017	0.0015
^{239}Pu	45.5	1.98	0.000061	0.00012
^{240}Pu	25.0	1.11	0.00023	0.00026
^{241}Pu	15.5	0.69	0.099	0.068
^{242}Pu	12.0	0.54	0.0000039	0.0000021
^{241}Am	-	0.03	0.0034	0.0001
Total	100%	4.4	-	0.068β 0.002α

a. Assuming a one-year delay between reprocessing plant and fuel fabrication plant.

b. Releases are assumed to be reduced to 10% of the values shown for plants starting up after 1985. (See Table 2.8.)

(c) Waste Management Facilities

Releases of radioactivity from waste management operations at the reprocessing and mixed oxide plants are included in this assessment. Releases from solidification of high-level liquid waste are incorporated in the numbers in Table 3.1. Other waste management operations are assessed in the following paragraphs.

The amount of plutonium that might be emitted from an incineration operation to reduce the volume of combustible materials at the TRU waste management facility is given in Table 3.3. The estimate includes volume reduction of wastes from both fuel reprocessing and mixed oxide fuel fabrication.

TABLE 3.3

Plutonium Released to the Atmosphere from the Alpha-Waste Incinerator[2]

Source of Waste	*Plutonium Released, mg/yr*[a]
MOX Plant (350 MT/yr)	
Fuel Preparation	0.021
Fuel Fabrication	0.041
LWR Reprocessing (1500 MT/yr)	0.023
Total	0.085

a. For purposes of dose evaluation, the composition is assumed to be the same as that given in Table 3.2.

In the year 2002, waste handling operations at the TRU facilities would involve waste from about 11,000 MTHM of spent fuel annually. Under these conditions, the facilities would release plutonium at a rate of about 0.6 mg/yr. Hence, assuming equal isotopic composition of plutonium at the TRU waste management facilities and the mixed oxide fabrication plant, the radiological emissions from total TRU waste management facilities are about 14% of those from the model mixed oxide fabrication plant. For equal source-receptor distance, release height, and meteorology, the TRU waste management facility would result in 14% of the dose commitment from a model mixed oxide plant.

b. Dose Commitment

(1) Methodology

Radiation doses and dose commitments to the population within 50 miles of the model fuel recycle facility from radionuclides released to the atmosphere are calculated for the following dose pathways: air submersion, inhalation, transpiration (for tritium oxide only), contaminated ground surface, and contamination of agricultural products produced in the vicinity of the facility.

A hypothetical individual is assumed to reside continuously at the site boundary at the point of the highest atmospheric concentrations. Doses for this hypothetical individual and the 50-mile-radius population discussed in this section represent a 50-year dose commitment from exposure to one year of releases from the model facilities.

The term "dose commitment" is associated with an intake of a radionuclide and is defined as the total radiation dose to a reference organ resulting from that intake, which will accrue during the remaining lifetime of the individual.[4] This definition is intended to include the contribution of any radioactive daughters which are formed in the body as the parent nuclide decays. The exposed individual is assumed to be an adult (20 years of age) at time of intake who will live to an age of 70 years. Thus, the dose commitment as used in this report is a 50-year dose commitment.

Doses to the local population from worldwide cycling of radionuclides, from exposure to annual releases from the year of startup to the end of reprocessing, and from nuclides persisting in the local environment for significant periods of time following release are estimated in Section 3C. The term "dose commitment" is often applied to this type of calculation of long-term doses resulting from radionuclide releases, but is not used in this way in this report.

The calculations of dose commitment first consider the most significant radionuclides, ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I individually. The dose from these nuclides, shown in Tables 3.4 and 3.5, is calculated for the various pathways to man for each nuclide and summed for each body organ receiving a dose from that nuclide. The second step in the dose commitment calculation is the consideration of other nuclides and pathways to man; these are calculated for convenience by pathway, and summed for each body

organ as was done for individual nuclides. The nuclide and pathway calculations do not include overlap; these are summed to give the total organ dose.

Further discussion of the dose calculation methodology is given in Appendix B.

(2) Calculations for Collocated Fuel Reprocessing and Mixed Oxide Fabrication Plants

The results of the dose calculations for collocated 1500 MT/yr FRP and 350 MT/yr MOX sites are given in Table 3.4 for the hypothetical individual who receives the maximum dose and in Table 3.5 for the 50-mile-radius population. Doses are given for whole body and organs used in Section 3C to estimate health effects resulting from radiation doses. The tables show doses with and without the effluent control improvements assumed to be available in 1986.

The 50-year dose commitment to the hypothetical individual receiving the maximum dose from one year's operation of each fuel reprocessing and MOX plant is about 34 mrem to the whole body and all organs except thyroid. Dose commitment to the thyroid is 87 mrem. These doses would be reduced to 0.4 mrem (for whole body) and 5.9 mrem (for thyroid) for plants with improved offgas controls. Bone dose is estimated to be 28 mrem without improved offgas controls and 2.5 mrem with improved offgas controls. For

TABLE 3.4

Estimated 50-Year Radiation Dose Commitment to Hypothetical Individual Receiving the Maximum Dose from 1 Year of Operation of Collocated Plants[a]

	50-Year Dose Commitment, mrem							
	Specific Nuclides				*Other Nuclides by Vector (see text)*			
Organ	^{3}H	^{14}C	^{85}Kr	^{129}I	*Exposure to Contaminated Ground*	*Inhalation*[b]	*Foodstuff*[b]	*Total*
a. Without Improved Offgas Controls								
Whole Body	29	2.9	0.7		0.09[c]	0.7	0.3	34
Thyroid	29	1.3		57				87
Bone	-	1.8	0.9			21.9	3.0	28
Red Marrow	29	4.9	0.8					35
Lungs	29	1.2	1.4			0.7		32
b. With Improved Offgas Controls								
Whole Body	0.29	0.03	0.007		0.009[d]	0.07	0.03	0.4
Thyroid	0.29	0.01		5.6				5.9
Bone		0.02	0.009			2.2	0.3	2.5
Red Marrow	0.29	0.05	0.008					0.3
Lungs	0.29	0.01	0.014			0.07		0.4

a. One 1500 MT/yr FRP and one 350 MT/yr MOX plant; releases as given in Tables 3.1 and 3.2.

b. Due to nuclides other than ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.

c. First year dose; after 20 years, dose is 2.1 mrem/yr (1981 startup).

d. First year dose; after 15 years, dose is 0.14 mrem/yr (1986 startup).

TABLE 3.5

Estimated 50-Year Radiation Dose Commitment to 50-Mile-Radius Population from 1 Year of Operation of Collocated Model Plants[a]

	50-Year Dose Commitment, man-rem							
	Specific Nuclides				*Other Nuclides, by Vector (see text)*			
Organ	^{3}H	^{14}C	^{85}Kr	^{129}I	*Exposure to Contaminated Ground*	*Inhalation*[b]	*Foodstuff*[b]	*Total*
a. Without Improved Offgas Controls								
Whole Body	1160	110	30		2[c]	30	6	1300
Thyroid	1160	50		1100				2300
Bone		70	30			900	60	1100
Red Marrow	1160	200	30					1400
Lung	1160	50	60			30		1300
b. With Improved Offgas Controls								
Whole Body	12	1.1	0.3		0.2[d]	3	0.6	17
Thyroid	12	0.5		110				120
Bone		0.7	0.3			90	6.0	100
Red Marrow	12	2.0	0.3					15
Lung	12	0.5	0.6			3		16

a. One 1500 MT/yr FRP and one 350 MT/yr MOX plant; releases as given in Tables 3.1 and 3.2; population = 1 x 10^6, uniformly distributed.

b. Due to nuclides other than ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.

c. First year dose; after 20 years, dose is 40 man-rem/yr (1981 startup).

d. First year dose; after 15 years, dose is 3 man-rem/yr (1986 startup).

comparison, exposure to natural radiation sources in the U.S. ranges from 100 mrem/yr to 250 mrem/yr, averaging 130 mrem/yr.

The 50-year population dose commitment is about 1300 man-rem to all organs except thyroid (2300 man-rem) from one year's operation of each fuel reprocessing and MOX plant. Tritium is the major contributor to the organ doses (except thyroid). The thyroid dose commitment from ^{129}I is comparable to that from ^{3}H. Improved offgas controls would reduce these doses to about 17 man-rem (for whole body and most organs), 120 man-rem (for thyroid), and 100 man-rem (for bone). For comparison, the population dose from natural radiation sources (assuming 100 mrem/yr per person) is 100,000 man-rem/yr for the 10^6 people living within a 50 mile radius of each FRP-MOX site. Thus, without offgas control improvements, the average annual whole body dose to an individual in this population is increased about 1.3% or 1.3 mrem; with improved controls, the increase is about 0.02% or 0.02 mrem.

(3) Proposed Environmental Standards for the Uranium Fuel Cycle

The Environmental Protection Agency has proposed standards (40 CFR 190) that would limit the public radiation dose resulting from planned discharges from uranium fuel cycle facilities to 25 mrem/yr whole body dose, 75 mrem/yr thyroid dose, and 25 mrem/yr other organs dose. The doses for the hypothetical individual receiving the maximum dose from the model plant without improved controls (Table 3.4a) exceed these proposed standards.

If these standards are adopted, reduction of tritium and ^{129}I releases would be necessary for the model reprocessing plant; as shown in Table 3.4b, the improved controls for these nuclides (assumed to be installed in post-1985 plants) would be adequate to meet the standards. The off-gas control improvements are discussed in Section 2C. Because the maximum doses calculated for an individual near the model FRP-MOX site are strongly dependent on assumptions made regarding tritium and ^{129}I uptake via locally grown foodstuffs, the site-specific doses from operation of actual plants may be considerably different. Because the assumptions made in calculating the doses are generally conservative, in most cases, operation of the actual plants would be anticipated to result in lower doses that could be within one or more of the proposed standards. These doses might lead to different conclusions regarding the need for improved off-gas retention systems. As presently written, the dose limitations would be effective 24 months after final publication of the standards.

The proposed standards also would limit the release of ^{85}Kr to 5×10^4 Ci/GWe-yr, ^{129}I to 5 mCi/GWe-yr, and TRU alpha emitters (half-life >1 yr) to 0.5 mCi/GWe-yr. A 1500 MTU/yr reprocessing plant will service about 50 GWe-yr of generated electrical power each year. This proposed standard would thus limit the annual releases from such a plant to the values shown in Table 3.6, compared to releases both with and without improved offgas controls.

TABLE 3.6

Releases Compared to Proposed Standards

	1500 MT/yr Reprocessing Plant, curies/year		
Nuclide	*Proposed Standard (40 CFR 190)*	*No Improved Controls*[a]	*Improved Controls*[a]
^{85}Kr	2.5×10^6	14×10^6	0.14×10^6
^{129}I	0.25	3.0	0.3
TRU alpha	0.025	0.24	0.024

---

a. Releases are given in Tables 3.1 and 3.2; assumed decontamination factors are given in Table 2.10.

The assumed improved controls would be adequate for ^{85}Kr, but marginal for ^{129}I and TRU alpha. As currently written, the TRU alpha standard would be effective 24 months after final publication of the standards, and the ^{85}Kr and ^{129}I standards on January 1, 1983.

The potential effect of these proposed standards on the full reprocessing industry is addressed in Section 3C.

c. Effects of Radioactive Effluents on Biota Other than Man

The dose to biota from normal operation of the reprocessing and mixed oxide fabrication plants will be from atmospheric releases only, because no radioactive liquid effluents will be released to the environment during normal operations. This is consistent with the AGNS reprocessing plant flowsheet.[6] These doses will be similar in magnitude to the doses to man from

atmospheric releases, which are discussed in Section 3B1. The conclusions of the BEIR report[8] are that no other living organisms are very much more radiosensitive than man. Therefore, no detectable radiological impact is expected in the terrestrial biota from operation of the reprocessing plant.

2. Environmental Effects of Potential Accidents

a. Assumptions

Postulated accidents and source terms discussed in this section are taken from WASH-1327[9] and dose conversion factors from ORNL-4992[7] and WASH-1327.[9] The assumed atmospheric dispersing conditions are taken from NRC Regulatory Guide 1.3[10] for 0-8 hour release time. These conditions result in a diffusion factor ($\bar{\chi}/Q$) of 1×10^{-5} sec/m^3 at the site boundary distance of 1.5 miles (2.4 km), the point of maximum exposure of an individual. Accident releases from both the reprocessing and MOX plants are assumed to be from the 100-m stack on the site. The magnitude of explosions, fires, and pressure surges from criticality accidents is assumed not to be sufficient to breach the facility structures. Filters remotely located relative to the accident location are assumed to remain intact.

The accidents described in this section are expected to occur infrequently; also the magnitude of those accidents which do occur are expected to be less than the magnitudes described.

b. Reprocessing Plants

Infrequent accidents that may occur at reprocessing plants or PuO_2 conversion facilities include:

- Criticality.
- High-level waste concentrator or calciner explosion (reprocessing only).
- Plutonium concentrator explosion.

The dose commitments from these accidents have been calculated for the hypothetical individual who is exposed to the maximum dose. These doses are given in Table 3.7. The maximum dose commitment listed is 480 mrem to the bone; this would result from the highly unlikely event of an explosion in the plutonium concentrator and dispersal of the plutonium to the public zone.

(1) Criticality Accident

A criticality incident in a reprocessing plant or PuO_2 conversion plant is an unlikely event because equipment and processes are designed to prevent such incidents. Safe spacing is assured in storage basins by physically spacing the fuel elements in storage racks in a safe pattern even when one is dropped. Process systems and controls are designed to prevent assembly of an unsafe array. Nevertheless, a criticality accident is postulated in which a burst of 10^{19} fissions occur. For comparison, criticalities in AEC facilities summarized in WASH-1192[11] range from 3×10^{15} to 5×10^{17} fissions for metal systems in air (7 cases) and from 1.1×10^{16} to 1.3×10^{18} for solution systems with the exception of one incident with 4×10^{19} fissions (10 cases, total, for solution systems). All noble gases and 25% of the halogens (or halides) are assumed to be discharged from the plant stack

A dose to the thyroid of 200 mrem is calculated for such an accident. This thyroid dose is approximately 10 times greater than the dose to other organs.

TABLE 3.7

Environmental Impact of Accidents at the Fuel Reprocessing Plant

Accident	*Maximum Individual 50-Year Dose Commitment, mrem*
Criticality	200 (thyroid)
Waste Concentrator Explosion	93 (bone)
Pu Concentration Explosion	480 (bone)

(2) Waste Concentrator Explosion

During operation of the solvent-extraction process in the reprocessing plant, solvent degradation products are generated and may be carried over into the waste streams. These nitrated degradation products (red oil) have caused product concentrator explosions in the past because of rapid decomposition. Red oil explosions can be prevented by eliminating accumulation of organic materials in the waste and by controlling the process temperature in the concentrator. Modern plants install equipment and controls designed to preclude a red oil explosion; however, an accident may still be possible.

Waste concentrators are installed in highly shielded cells with a volume of 100,000 ft^3 (3000 m^3). The explosion releases are estimated to be about 150 gal (600 ℓ) of waste solution into the cell as a finely divided mist. A substantial fraction of the mist would rain-out or plate-out on the cell surfaces. The droplets remaining in the air would be carried through the ventilation ducts to the high-efficiency particulate air filters (HEPA's). Moisture separators upstream of the filters would remove most of the mist.

The plant ventilation filters are located some distance from the reprocessing plant process cells. The waste concentrator explosion expends the bulk of its energy in destruction of the concentrator. Pressures developed in the vessel are dampened by expansion into the cell and are attenuated in the ductwork. The

Plate-out of the droplets on the cell walls and floors and the filtration system is assumed to result in a reduction in the fraction of material released to 5×10^{-7}. The material leaving the final filter is estimated to be 420 mg of waste.

Table 3.8 lists the nuclides that contribute significantly to the offsite dose. Maximum offsite dose commitment is estimated to be about 93 mrem (bone).

(3) Plutonium Concentrator Explosion

The explosion of a plutonium concentrator in the reprocessing plant is typical of credible accidents in which plutonium is released to a cell or glove box area. The plutonium processing equipment tends to be smaller and to be installed in smaller rooms (cells or glove boxes) than the waste concentrator discussed above. The release rate from this accident is derived by assuming that the room (cell or glove box) atmosphere contains the same mass of radioactivity per unit volume as the atmosphere of the waste concentrator cell. For a 1000-m^3 waste concentrator cell volume, and a waste concentrator accident release of 420 mg of waste, the plutonium concentrator release is:

$$\frac{1000}{3000} \times 420 = 140 \text{ mg}$$

The remotely located final filters are assumed not to be affected by the explosion.

Table 3.9 shows the isotopic releases and the bone dose commitment to the maximally exposed individual. WASH-1327[9] releases were adjusted to provide the same isotopic ratios to ^{239}Pu as given in Table 3.1.

TABLE 3.8

Waste Concentrator Explosion

Nuclide	*Half-Life*	*Release, mCi*	*Maximum Individual 50-Year Bone Dose Commitment, mrem*
^{241}Am	433 yr	0.50	2.4
^{242}Cm	163 days	65.0	7.6
^{244}Cm	17.9 yr	27.0	78.0
^{90}Sr	29 yr	160.0	4.1
^{144}Ce	284 days	165.0	0.5
Total			93

TABLE 3.9

Plutonium Concentrator Explosion

Plutonium Isotope	*Half-Life*	*Release, mCi*	*Maximum Individual 50-Year Bone Dose Commitment, mrem*
238	88 yr	19	250
239	2.4×10^4 yr	0.9	14
240	6540 yr	1.9	29
241	15 yr	650	185
Total			480

(4) Other Accidents

A range of other accidents is possible, but they are expected to have smaller effects than the accidents tabulated in previous tables. Among the possible accidents are:

- First cycle solvent fire.
- Second cycle (Pu cycle) solvent fire.
- Ion exchange (Pu cycle) fire.
- Fuel element drop.

c. MOX Fabrication Plants

Mixed oxide fuel fabrication plants are required to be designed, fabricated, constructed, tested, and operated under rigid quality assurance programs. Quality assurance includes all those planned and systematic actions necessary to provide adequate confidences that structures, systems, components, and operations will perform satisfactorily is service.

All operations at MOX fuel fabrication plants that involve handling plutonium except in shipping containers or sealed fuel rods are typically carried out inside glove boxes. These glove boxes provide confinement of plutonium in the event of process equipment failure. The process building and equipment and supports are designed to withstand impacts due to natural phenomena related to tornadoes, earthquakes, and floods.

During the life of a mixed oxide fuel fabrication plant, some equipment (or accessory) failures will occur. Monitors are installed to detect equipment failure or potentially damaging

process upset conditions and to provide corrective action automatically. The ventilation system is designed to function during and after accidents and to discharge all plant ventilation air through high efficiency particulate air filters before it is released to the atmosphere. Ventilation air is released to the atmosphere via the 100-m stack shared with the reprocessing plant on the collocated site.

Infrequent accidents that may occur over the plant life include a criticality incident, an explosion, or a fire. These accidents may have offsite environmental effects. In all accidents except the criticality accident, the offsite effects result from plutonium dioxide penetrating the HEPA filters. A criticality accident leads to offsite exposures from iodine and noble gases released from the nuclear excursion.

Table 3.10 summarizes the offsite effects of these accidents. Although the plutonium dioxide powder which forms most of the plant inventory is insoluble, the dose commitments for the bone have been based on soluble plutonium. This assumption leads to greater dose commitments. The criticality accident dominates the offsite accident effects; fires or explosions yield calculated offsite effects of only 1 to 3 mrem.

The offsite consequences of a criticality accident, 20 to 66 mrem to the thyroid for the maximum individual exposure, is comparable to the dose to an individual from a criticality accident at a UO_2 fabrication plant. The slightly different fission product

TABLE 3.10

Summary of Offsite Impacts to Maximum Exposed Individual from MOX Fuel Fabrication Plant Accidents

Accident	*Pu Isotope*	*Release, mCi*	*50-Year Dose Commitment, mrem* 1.2 km to perimeter[b]	2.4 km to perimeter[b]
Criticality	*a*		66 (thyroid)	20 (thyroid)
Fire or Explosion	238	0.034	1.5	0.45
	239	0.0028	0.1	0.04
	240	0.0058	0.3	0.09
	241	1.5	1.4	0.44
		Total	3.3 (bone)	1.0 (bone)

a. Fission product releases are more significant in the criticality accident than Pu releases. Thyroid doses from radioiodine are the largest effects. Pu releases are estimated to be 3.54×10^{-4} mCi (α).

b. See Figure 2.16.

yield and the presence of small amounts of plutonium particulate do not significantly alter the effects of a PuO_2 criticality accident relative to those of a UO_2 criticality accident.

(1) Criticality

Nuclear criticality safety is a major consideration in plant design and NRC licensing. The plant equipment is instrumented, designed, and arranged to preclude accidental criticality unless several independent failures occur. In a plutonium plant, the number of independent failures required would be 2 or 3. For operations under administrative control (that is, where adherence to specific operating procedures is necessary to preclude criticality), the Nuclear Regulatory Commission requires that two

independent levels of review be carried out by technically qualified personnel before implementation of the operations. All operations involving nuclear criticality safety are governed by written and approved procedures. All personnel involved in the operations receive instructions in the specific procedures as well as periodic training sessions in criticality safety. No changes in the approved procedures are permitted without a two-level review and approval.

The number of fissions in the postulated accident has been estimated to be 10^{18}, and all of the noble gases (krypton and xenon) and 25% of the iodine formed in the fissions are assumed to escape. For comparison, criticalities in AEC facilities summarized in WASH-1192[11] range from 3×10^{15} to 5×10^{17} fissions for metal systems in air (7 cases). No criticality accidents have occurred to date in process operations where undermoderation is a primary method of control.[9] In addition, 500 g of plutonium is assumed to be made airborne in the glove box by the criticality excursion. The overall filter retention factor (of three HEPA's in series) for PuO_2 is assumed[9] to be 10^9. The maximum offsite individual dose is 20 mrem (thyroid) at the site perimeter distance of 1.5 miles (2.4 km). The MOX plant could be located as close to the perimeter as 0.75 mile (1.2 km) (Figure 2.16); in this case, the maximum dose would be 66 mrem.

(2) Fire

Unlike a criticality excursion or an explosion, a fire is usually not an instantaneous event, and it very often starts from a small flame source. The design, construction, and operation of fuel fabrication plants considers in detail the possibility of a fire, and equipment and procedures are used for prevention. Regulatory Guide 3.16[12] presents methods for a fire protection program which should prevent, detect, extinguish, limit, or control fires and explosions and their accompanying hazards and damaging effects. Licensees must operate within these or equivalent constraints. Under these conditions, the probability of having a fire of the magnitude considered in this statement is considered highly unlikely. In general, operators have time to react to and extinguish small fires. The process materials, oxides of uranium and plutonium, are not themselves flammable. The final filters are protected against fire by water spray systems installed in the duct some distance upstream of the final filters. Mist deflectors or demisters are installed between the water spray system and the filters to remove large drops of water. The water from the sprays collects in the bottom of the ducts and flows to a fire-water collection tank. This tank is either a safe-geometry tank or a poison-controlled tank to preclude a criticality accident resulting from a fire.

The final HEPA filters are located some distance from the glove boxes. This distance and the water spray system are

sufficient to protect the filters against the effects of the fire. The fire is, however, assumed to destroy the local filters located on the glove boxes. Plutonium (and uranium) oxides reach the final filters. Based on an assumed room volume of 1000 m^3 and an air loading of 100 mg/m^3 for plutonium oxide particulate, 100 g of plutonium reaches the two remaining filters. Each of the filters is assumed to remove 99.9% of the particulate reaching it,[9] so that a total of 0.1 mg of plutonium passes through the filters and is released from the 100-m stack. Assuming the isotopic content given in Table 3.2, the maximum offsite individual dose is 1.0 mrem (bone) at the site boundary (2.4 km). For a distance to the site boundary of 1.2 km, the dose is 3.3 mrem (bone).*

(3) Explosion

An explosion in a mixed oxide fuel fabrication plant can occur at the sintering furnace, at the clean scrap reduction operation, in the dirty scrap recycle operation, or at locations where combustible material may be located. Sintering furnaces and the clean scrap reduction operations use hydrogen diluted with an inert gas. The hydrogen is mixed with the diluent gas outside of the building. Several sets of redundant controls are installed on the gas supply to prevent gases with high concentrations of hydrogen from entering the building. The dirty scrap process

*Consequences of a fire in a MOX facility involving a higher estimate of plutonium release is discussed on page 10.19.

uses a solvent, generally kerosene, that does not present a major explosive hazard. The use of solvents in process enclosures is limited.

The consequences of an explosion are similar to those of a fire. The amount of plutonium reaching and passing through the filters is estimated to be the same as that in the fire (see above) and has the same offsite effects.

(4) Other Accidents

The possible range of accidents that can occur in a mixed oxide fuel fabrication plant include such accidents as loss of a process enclosure window and glove failures. These accidents may result in local (within plant) contamination; their offsite effects are expected to be very small relative to the accidents described above.

Undetected contamination can be conveyed offsite on personnel by a deliberate act or failure to comply with monitoring procedures. The offsite effects would be small compared to fire or explosion offsite effects and limited to local areas frequented by the contaminated person(s).

3. Occupational Exposure

Federal regulations[13] require that occupational external dose to an individual not exceed 5 rem/yr or a cumulated value of 5(N-18) rem, where N is the present age of the worker. Estimates of personnel exposure anticipated in nuclear facilities

often assume an average personnel dose (not including administrative and other personnel who are not exposed to occupational radiation) of 40% of the maximum, or 2 rem/yr average for a 5 rem/yr limit.[9] It is anticipated that allowable personnel exposure will be reduced through regulatory incorporation of "as low as reasonably achievable" limits. Although such limits have not been determined for fuel reprocessing or MOX plants, for the purposes of this evaluation the criterion of 1 rem/yr maximum exposure required of new ERDA plutonium facilities[14] is assumed to apply to all back-end operations of the commercial fuel cycle. Average exposure is assumed to be 40% of the 1 rem limit, or 400 mrem/(year-person).

Personnel exposure is assumed to be limited by the use of shielding and procedural controls, not by supplementing the work force. The total reprocessing plant work force is assumed to be 900;[15] therefore, the annual occupational exposure is 360 man-rem. The MOX plant force is assumed to be 300,[16] and the annual occupational exposure is assumed to be 120 man-rem. These man-rem doses are substantially lower than those estimated in References 9 and 16, but they are more in line with anticipated design and operational improvements to reduce occupational exposure.

Occupational exposures for the fuel reprocessing and recycling industry are discussed in Section 3C.

4. Population Exposure from Transportation

Effects are estimated in this section for the transportation steps in the back end of the fuel cycle with Pu-U recycle. These effects are relatively independent of the fuel recycle option selected. The throwaway fuel cycle requires that irradiated fuel be shipped from the reactor to a storage site, prepared for disposal, and then shipped to a Federal repository. Similarly, unirradiated fuel must be shipped to the reactors in both the recycle and throwaway options.

The estimates of environmental effects from transportation indicated below are considered conservative in that they overestimate the effects. Estimates of shipment miles are taken from WASH-1327[9] and EPA-520/3-75-023.[17] Assumed population densities are conservatively high because site locations and hence population densities along transport routes are indeterminant. Also, radiation levels in the cab of trucks and around the load on trucks and rail cars are assumed to be the maximum radiation levels permitted by DOT regulations[18] causing overestimates of exposures during shipments. Much of the discussion is adapted from WASH-1327.[9]

a. Radiation Exposures in Normal Conditions of Transport

The shipment miles involved for the transportation of radioactive materials in the back end of the LWR fuel cycle to support reprocessing in the year 2000 are listed in Table 3.11.

TABLE 3.11

Summary of Shipments to Support Fuel Reprocessing in the Year 2000 - Back End with Pu-U Recycle[a]

Material Shipped	*Mode of Transportation*	*Number of Shipments Per Year*	*Shipment[b] Miles Per Year*	*Probability of Small Release Per Vehicle Mile[c]*	*Projected Probability of Small Release Per Year*
Natural UO_2	Truck	160	32,000	$\sim 10^{-8}$[d]	3.2×10^{-4}
UF_6 (FRP to enrichment plant)	Truck	560	110,000	$\sim 10^{-10}$[e]	1.1×10^{-5}
Mixed oxide fuel rods	Truck	430	85,000	$\sim 10^{-10}$[f]	8.5×10^{-6}
Unirradiated fuel assemblies to reactors	Truck	2,500	2,500,000	$\sim 10^{-10}$[f]	2.5×10^{-4}
Irradiated fuel assemblies to reprocessing plants	Truck Rail	3,700 2,500	1,800,000 2,500,000	3×10^{-9}[e] 7×10^{-9}[e]	5.6×10^{-3} 1.8×10^{-2}
PuO_2; AGNS to MOX fuel fabrication plant[g]	Truck	260	78,000	10^{-8}[h]	7.8×10^{-4}
Wastes to Federal repository (high-level, cladding, and TRU wastes)	Rail	3,500	6,400,000	2×10^{-10}[e]	1.3×10^{-3}
Wastes to commercial burial grounds	Truck	1,900	950,000	$\sim 10^{-9}$[i]	9.5×10^{-4}
Totals		15,000	14,000,000		2.7×10^{-2} Once in 37 years

a. Assumes the fuel reprocessing facility and the mixed oxide fuel fabrication facility are collocated.
b. Mileages with radioactive load; does not include return trips with empty containers.
c. Container damage is assumed to consist of microscopic openings such as hairline cracks or pinholes. Assumed releases are 0.3% of ^{85}Kr, 0.02% of ^{131}I and 0.001% of fission products from irradiated fuel casks, 0.005% of solidified high-level waste from the cask and 0.001% or less of the contents of Pu from the package.[17]
d. Estimated value to release significant portion of the UO_2 load.
e. From Reference 17.
f. Estimated, assuming special safeguards equipment, escorts, and restrictions in speed and routes.
g. Assuming MOX plant is not collocated at AGNS.
h. From Reference 19. This value does not take credit for improvements of future designs to increase resistance to accident environments and special safeguards equipment, escorts, and procedures.
i. Estimated; waste is assumed to be in protective package for transport of this non-TRU waste.

Tables 2.5 and 2.6 further describe these shipments. Dose estimates from these shipments in the year 2000 are indicated in Table 3.12.

The following paragraphs describe the bases used to estimate these radiation doses to transport workers and to members of the general public as incurred under normal circumstances of transportation.

(a) Trucks

Truck Drivers. The radiation level is assumed to be 0.02 mrem/hr inside the cab of the truck transporting UO_2 or UF_6 and 0.4 mrem/hr at 3 ft from the surface of the truck.[20] For other shipments the radiation level is assumed to be 2 mrem/hr inside the cab of a truck and 16 mrem/hr at 3 ft from the surface of the truck based on DOT maximum radiation limits.

For trips of 200, 300, or 500 miles, drivers are assumed to spend about 1/2 hour at three feet from the side of the truck. For trips of 1000 miles, drivers are assumed to spend 1 hour at three feet from the side of the truck.

An average speed of 50 mph is assumed to estimate the radiation dose to the two drivers while they occupy the cab. An overall average speed of 40 mph with an escort is assumed for point-to-point transport of fuel elements and plutonium. Waste shipments by exclusive-use vehicles are assumed to be operated point-to-point with no layovers.

TABLE 3.12

Dose Estimates for Shipments Supporting Reprocessing in the Year 2000[a] with Plutonium Recycle

Type of Shipment	Mode of Transport	Transport Workers		General Public	
		Cumulative Dose, man-rem	No. of People[b]	Cumulative Dose, man-rem	No. of People
UF_6 from fuel reprocessing plant to enrichment plant	Truck	0.20	100	0.14	6×10^5
Natural UO_2 to MOX[c] fuel fabrication plant	Truck	0.06	30	0.04	5×10^5
PuO_2 from AGNS to MOX fuel fabrication plant[d]	Truck	1.4	10	0.6	1×10^5
MOX fuel rods to UO_2 fuel fabrication plant	Truck	13	120	4.6	5×10^5
Unirradiated fuel assemblies to reactor	Truck	56	730	27	7×10^6
Irradiated fuel assemblies to fuel reprocessing plant	Truck Rail	200 28	1×10^3 4×10^3	98 65	11×10^6
Wastes to Federal repository (high-level, cladding, and TRU wastes)	Rail	62	6×10^3	120	2×10^6
Wastes (non-TRU) to commercial burial grounds	Truck	53	500	26	1×10^6
Totals		410	1.2×10^4	340	e

a. This base case assumes the fuel reprocessing plant and MOX fuel fabrication plant are collocated. Only shipments involving the back end of the cycle are shown. The number of trips and miles traveled shown in Table 3.11 are used to calculate this table.

b. Prorated from WASH-1327.[9]

c. This type of shipment is deleted if UF_6 from the conversion plant is transported to the mixed oxide fuel fabrication facility for conversion to UO_2.

d. Assuming MOX plant is not collocated at AGNS.

e. Some of the population is exposed to several types of shipments and values in the last column are not directly additive. It is estimated that the population exposed is about 12 to 15 million.

Escorts. Escort vehicles are assumed to travel an average distance of 100 ft or more from the truck carrying the load. The average exposure rate of escort personnel is assumed to be 0.1 mrem/hr.

Truck Servicing. Normal servicing of the truck may require two garagemen to spend about 10 minutes around the cab of the truck once per day or every 1000 miles. The cumulative annual dose to all garagemen servicing trucks transporting packages of radioactive materials is less than 1% of the dose to truck drivers.

Onlookers. Members of the general public (onlookers) are normally excluded from load operations, but exposures might occur at enroute truck stops for fuel and eating. Trucks are placarded on both sides and the front and rear as "Radioactive." Members of the general public are unlikely to remain near a truck more than a few minutes. If a person spends three minutes at an average distance of 3 ft from the truck, the dose would be about 0.002 mrem from UO_2 fuels and 0.8 mrem from other shipments. On the average, 2 persons are assumed to be so exposed per 200 miles of travel.

Highway Traffic. 165 vehicles are assumed to pass the truck each hour at a relative speed of 10 mph. Each vehicle contains 2 people, and they are exposed at a distance of 6 ft from the side of the truck. The dose to occupants of traffic vehicles would be about 4×10^{-5} man-rem/truck mile.

People Along the Route. The radiation level at 6 ft from a vehicle loaded with packages of fuel material or wastes will be no more than 10 mrem/hr. For unirradiated fuel and UF_6, the radiation level is no more than 0.1 mrem/hr at 6 ft. The mean population density along the route east of the Mississippi River is assumed to be 300 persons per square mile, and west of the Mississippi River, the population density is assumed to be 100 persons per square mile. For reference, the projected average population for the year 2000 is about 100 persons per square mile in the conterminous United States.[17]

People located within 1500 ft of the highway are exposed to 99% of the calculated accumulated dose and those within 2250 ft are exposed to 99.9% of the total accumulated dose calculated according to Reference 21.

(b) Rail

Train Brakemen and Crew. For each 1000 miles of rail shipments, 10 train brakemen are assumed to spend 5 minutes each 6 ft from the side of the car on which the cask is carried. It is also assumed that five crewmen occupy an average distance of 300 ft from the cask car during train operation.

Other Rail Traffic. It is assumed that 300 passengers or crew members of other trains per day pass the radioactive shipment at a relative speed of 30 mph. They pass at a distance of 10 ft from the shipment. The cumulative dose to these persons would be about 3×10^{-6} man-rem/car mile.

Onlookers. Members of the general public (onlookers) are normally excluded from loading and unloading operations, but some exposures might occur enroute at railroad stations. Railroad cars carrying irradiated fuel shipments are placarded on both sides as "Radioactive." A member of the general public who spends 3 minutes at an average distance of 3 ft from the rail car might receive a dose of as much as 0.8 mrem. On the average, 10 persons are assumed to be so exposed for each 1000 miles of rail shipments.

People Along the Route. Approximately 250,000 persons are assumed to reside within 1/2 mile of the rail line along the 1000-mile route over which the irradiated fuel is transported. Approximately 330,000 persons are assumed to reside along any 1800-mile (1100 miles west of Mississippi River) route over which waste is transported. The regulatory radiation level limit of 10 mR/hr at 6 ft from the vehicle was used to calculate the integrated dose to persons in an area between 100 ft and 1/2 mile on both sides of the shipping route. The shipment was assumed to average 8.3 mph. See Reference 21 for the details of the calculations.

b. Radiation Exposures in Transportation Accidents

Packages for transportation of radioactive materials are designed to resist impact, fire, and other stresses in an accident environment which potentially could damage the containment features

of the packages. These packages are designed to meet Federal regulatory requirements and their integrity must be demonstrated for hypothetical accident tests.[22] The Nuclear Regulatory Commission reviews the details of package design, performance testing, and safety analyses to ensure that regulatory requirements are fulfilled.

Quality assurance testing during the fabrication of the packages before each use and in some cases after loading are required to ensure integral containment before transportation of the radioactive materials is permitted. Packages meeting the above requirements are expected to withstand severe accidents without being breached.

Radioactive materials and wastes shipped in the year 2000 are in solid form except for ^{85}Kr which is shipped from reprocessing plants in pressurized cylinders contained in protective packaging. The spent fuel is contained within cladding but some of the ^{85}Kr and ^{131}I diffuses through the intact cladding into the coolant and void space above the coolant in the cask. Also, it is believed conservative to assume that 0.25% of the cladding on the fuel rods may be perforated and permit some release to the cask cavity of the gases normally retained by the cladding in the void spaces of the fuel rods.

The risk of releasing radioactive materials in an accident has been assessed in several theoretical studies but since few

accidents have occurred, little experience data is available. Studies currently in progress are expected to provide data which are expected to permit quantification of the risk of releasing radionuclides from spent fuel casks and other large heavy casks subjected to accident environments. Full-scale tests of such casks are scheduled for 1977 by Sandia Laboratory.[23]

A study conducted by Holmes and Narver, Inc.[17] for EPA used fault tree analyses to estimate the probability of release of small, medium, and large amounts of radioactivity in accident environments. Releases and associated radiation exposures of the general population were estimated for the nuclear industry through the year 2020. A study of the risk of releasing plutonium during shipments by truck was made at Battelle-Northwest Laboratories using fault tree analyses and available experience.[19] Also, studies of the severities of reported transportation accidents involving all types of hazardous materials were completed at Sandia Laboratory.[24]

Estimated probabilities for releases of small quantities of radioactive materials as a consequence of a transportation accident are shown in Table 3.11. The probability of releasing large quantities (for solids, 0.1 to 0.5% of the contents) is estimated to be 10^{-2} to 10^{-3} less than the probability of releasing small quantities of radioactive materials.

The most probable small release involves loss of some heat transfer medium and possibly some fission product gases from a spent fuel cask subjected to an extra severe accident environment. The probability of the release of a small amount of radioactivity during the large number of shipments of solidified wastes to a Federal repository is estimated to be about 10% of that from shipment of casks containing spent fuel. It is concluded from a Holmes and Narver study[17] that the radiation risk to the general population from radioactive materials released during transportation accidents is less than 0.001 whole body rem per person per year, assuming the accident occurs in an area of average population density. The routine exposure of the population from environmental sources such as cosmic rays and natural radioisotopes in the earth's crust averages about 0.13 rem per person per year in the conterminous United States.

Packaging is designed to prevent criticality under normal and severe accident conditions. Considering the requirements for package design, severe cask damage and subsequent conditions necessary to form a critical array, and safeguard and escort controls for the packages during transport of unirradiated and irradiated fuel, the probability of a criticality excursion in an accident environment is extremely small.

In accident environments involving vehicles carrying packages containing radioactive materials, the risk due to common causes

of bodily injury or death resulting from traffic accidents far overshadows the risk of adverse health effects due to radiological effects caused by release of radioactive materials from a severely damaged package. In truck accidents, for instance, non-fatal injuries occur in 33% of all truck accidents and fatal injuries occur in 3% of all truck accidents. Release of radioactive material sufficient to cause exposure of persons in the vicinity of the accident that may result in radiological injury is estimated to occur in less than 0.001% of accidents involving trucks carrying radioactive materials.

Probability rates for non-radiological injuries and fatalities from common traffic accident causes are shown in Table 3.13 for truck and rail shipments. It is estimated that

TABLE 3.13

Risks from Common Traffic Accident Causes During Transportation of Fuel Material and Wastes for the Base Case[a]

Mode and Probability Description	*Total Miles*	*Injuries*	*Fatalities*
Truck			
Probability/accident		0.51[b]	0.03
Probability/vehicle mile[c]		9×10^{-7}	5×10^{-8}
In year 2000[d]	1.1×10^{7}	10	0.6
Through year 2000[e]	1.3×10^{8}	120	7
Rail			
Probability/accident		2.7	0.2
Probability/car mile[f]		4×10^{-7}	3×10^{-8}
In year 2000[d]	1.8×10^{7}	7	0.5
Through year 2000[e]	2.1×10^{8}	85	6

a. Probabilities from WASH-1238, Appendix C.[21]
b. Injuries occur in 33% of accidents.
c. Probability of an accident per vehicle mile is 1.7×10^{-6}.
d. All transportation involved to support the reprocessing industry of the year 2000 and delayed transportation of resulting wastes.
e. Same as *a* but integrating for reprocessing through the year 2000.
f. Probability of an accident per rail/car mile is 1.4×10^{-7}.

17 injuries and 1.1 fatalities would be caused by shipments required to support the reprocessing industry of the year 2000 and about 200 injuries and 13 fatalities to support reprocessing operations through the year 2000.

Accident environments may inflict structural damage to packages containing high-level wastes, irradiated fuel, and plutonium oxide and may compromise the shielding integrity of the package. The radiation levels from the package could increase and expose persons involved in the accident, onlookers and persons responding to the emergency. There would be a very small exposure of the general population.

The regulatory requirements on packaging design, fabrication, and use include provisions to guard against human errors or equipment malfunctions. There are also administrative requirements that fissile and large quantity packages be tested before each use as to proper assembly, proper closure, equilibrium temperature, pressure, and presence of neutron absorbers.

It can be postulated that as a result of human error, a package of almost any type could be shipped without proper closures. The probability of improper assembly which results in a faulty closure is estimated to be less than 10^{-6} for large irradiated fuel shipping casks using data from a Holmes and Narver study[25] and is estimated to be about 10^{-4} to 10^{-5} for packages shipped in large numbers with multiple containers per shipment, such as packages of alpha wastes or plutonium. The

probability of a package not being properly closed is reduced by the requirements for quality assurance and package tests before and after loading operations. Furthermore, there is a redundancy of 2 or 3 for containment in plutonium and other package designs, so that reliance is not placed on single containment enclosure.

In the shipment of a large number of drums of solid wastes, it is possible that, as a result of human error, some of the drums may not be properly closed. It is estimated that about one in 10,000 packages[19] may not be properly closed when shipped. Because drums or other type packages are usually shipped with a large protective overpack, the probability of a release to the environment from the sealed overpack is very low. If an improperly closed package were to open within the overpack or rail car, the solid form of the waste material would limit the extent of the contamination of the surrounding waste containers and the inside surfaces of the overpack or rail car. No significant radiation exposures would result in transit and the rail car or overpack would be opened at the Federal repository under controlled conditions.

5. Effects of Thermal Effluents

This section was adapted from ERDA-1543,[1] with minor revisions.

a. Description

Most of the waste heat generated by the process and auxiliary equipment of the model reprocessing and MOX fabrication plants is removed by a recirculating cooling water system and dissipated to the atmosphere through a mechanical-draft cooling tower. A maximum of about 200 gpm of water is discharged to the atmosphere from the reprocessing plant and 40 gpm from the MOX plant. The principal sources of liquid thermal discharge are the cooling tower blowdown, boiler blowdown from the steam plant, and laundry effluents. The cooling tower blowdown and the boiler blowdown could be discharged to a primary holding pond; the laundry effluents could be discharged to the sewage treatment facility.

b. Water Consumption

Consumptive loss of water from operation of a reprocessing and MOX plant amounts to about 0.5 cfs. So long as siting restrictions are followed and careful water use evaluations are made in selecting a site, the loss of 0.5 cfs of the water source flow volume should have no measurable effect on competing water uses.

c. Thermal Standards

In accordance with provisions of the Federal Water Pollution

Control Act and Amendment of 1972, the Environmental Protection Agency (EPA) has published effluent guidelines and standards for various pollutant source categories. As yet, guidelines and standards specifically applicable to a reprocessing or fuel fabrication plant source-category have not been promulgated. However, most states are promulgating thermal standards under the state participatory provisions of EPA's National Pollutant Discharge Elimination System (NPDES). These standards, which are subject to approval by the EPA, are used in writing NPDES discharge permits. A plant operator must obtain the required NPDES discharge permit from a state agency, or from the EPA if the state where the plant is to be located has not adopted standards acceptable to the Federal agency. Many of the state thermal standards specify a maximum temperature increase (ΔT) at the edge of the mixing zone, a temperature ceiling that cannot be exceeded irrespective of allowable ΔT, and a maximum mixing zone size which is often defined as some fraction of the total receiving body. Many of the states limit the ΔT to 3-5°F. In some cases, however, the maximum allowed temperature specified by a state for a given body of water is very near the summer ambient temperature.

6. Effects of Non-Radioactive Effluents

Release rates of nonradioactive materials listed in *Nuclear Energy Center Site Survey - 1975*[2] were used to estimate concentrations of effluents shown in Tables 3.14 and 3.15.

a. Gaseous Effluents

The annual average and short-term ambient air concentrations of gaseous effluents at the site boundary are shown and compared to National Primary Ambient Air Standards[26] in Table 3.14.

Fuel reprocessing and MOX operations and supporting facilities are estimated to release an average of 19 g/sec of SO_2 and to result in an annual average concentration of 1 $\mu g/m^3$ at the site boundary, which is 1.5 mi (2.4 km) from the release point. This concentration is about 1% of annual concentrations at which adverse health effects have been noted or adverse effects on vegetation have been observed.[27]

Releases of CO are estimated to average 0.2 g/sec and to result in an annual average concentration of 0.01 $\mu g/m^3$. No health effects are observed until concentrations exceed 10 mg/m^3.[28] Vegetation is not affected by the CO releases.[28]

The NO_x (as NO_2) release rate is estimated to be 16 g/sec and to result in an annual average concentration of 0.8 $\mu g/m^3$ (0.0004 ppm) at the site boundary. This concentration is less than 1% of the concentration at which adverse health effects have been observed[29] and also is much less than the concentrations of 0.25 to 1.0 ppm reported[30-32] to induce leaf and fruit damage to sensitive plants.

TABLE 3.14

Ambient Air Concentrations of Nonradioactive Effluents

Pollutant	Concentration,[a] μg/m³		National Primary Standard, μg/m³	
	Annual Average	Short Term[b]	Annual Average	Short Term
SO_2	1	100 (30 ppb)	80	365 (24 hr)
CO	0.01	1 (1 ppb)	NS[c]	10 (8 hr) 40 (1 hr)
NO_2	0.8 (0.0004 ppm)	80 (0.04 ppm)	100	NS
Fluorides	0.008 (0.01 ppb)	0.8 (1 ppb)	0.5[d]	2.9 (24 hr)[d] 3.7 (12 hr)
Hydrocarbons	0.003	0.3	NS	160 (3 hr)

a. Calculated at site boundary using $\bar{\chi}/Q = 5 \times 10^{-8}$ sec/m³.

b. Calculated at site boundary using $\bar{\chi}/Q = 5 \times 10^{-6}$ sec/m³.

c. NS means no national standard.

d. The most restrictive state (Washington) standard was used. No national standards exist for fluorides.

Fluoride releases are estimated to average 0.16 g/sec. The annual average concentration of 0.008 μg/m³ (0.01 ppb) is 10% of the minimum concentration reported to produce chronic, sublethal injuries to sensitive plants.[33]

Releases of hydrocarbons are estimated to average 0.06 g/sec, which causes an annual average concentration of 0.003 μg/m³. Gaseous hydrocarbons do not directly cause adverse health effects.[34]

b. Liquid Effluents

Estimated release rates of sulfates, nitrates, chlorides, sodium, and potassium are shown in Table 3.15. The average concentrations of these chemicals in liquid effluents from the site are within standards for fresh water intended for public supply as shown in the table.

TABLE 3.15

Concentrations of Nonradioactive Liquid Effluents

Pollutant	*Release Rate, g/day*	*Concentration, ppm*	*Water Quality Standard,*[35] *ppm*[a]
$SO_4^=$	5.5×10^4	7	250
NO_3^-	2.7×10^4	3.5	10
Cl^-	2.7×10^4	3.5	250
Na^+, K^+	5.5×10^5	70	1000[b]

a. For fresh water (public supply).

b. From BNWL-1815.[36] No standard for Na^+ or K^+ in Reference 35.

Sanitary wastes may be discharged over land through a spray irrigation network to avoid the need for an NPDES Permit. If they are discharged in this manner, the only other significant chemical discharge will involve orthophosphates from cooling tower blowdown, a discharge of 1.7 kg of phosphate per day to the holding reservoir. The holding reservoir is assumed to be about 3 m deep with a surface area of approximately 50,000 m^2. If the phosphate removal capacity of such a reservoir can be maintained at about 30 mg of phosphate per m^2 per day, the phosphate concentration in water discharged from the holding reservoir would meet Federal criteria (25 to 100 µg/l) for phosphate discharges in streams.[35] If the phosphate removal capacity of the reservoir is inadequate, alternative procedures would be followed. Alternatives might involve either treatment for cooling towers that do not use phosphates (or other unacceptable compounds) or installation of phosphate removal equipment in the system before discharge into the holding reservoir.

c. Conclusion

The chemical releases to the atmosphere and liquid effluents from a collocated FRP-MOX site should have no significant impact on air or water quality in the vicinity of the site.

7. Occupational Exposure to Chemicals

29 CFR 1910[37] specifies limits and controls required for exposure to chemicals as legislated by the Occupational Health and Safety Act. Concentrations in air of chemicals to which the worker is exposed will normally be maintained by engineering controls such as ventilation at less than the action level values specified in Subpart Z of Part 1910.[37]

Potential exposure of the worker is limited because the chemicals are normally introduced into the process within ventilated enclosures designed to contain radioactivity. Exposures may occur in storage areas, during transport of chemicals from the storage areas and during preparation of the chemicals for the processes. The current action level values for some of the required chemicals are:

Fluorides	- 2.5 mg/m^3
Fluorine	- 0.1 ppm - 0.2 mg/m^3
Nitric Acid	- 2 ppm - 5 mg/m^3
Tributyl Phosphate	- 5 mg/m^3

When concentrations are above an action level, routine monitoring is required rather than audit monitoring. When threshhold limit values are exceeded, workers will wear personal protective equipment including respiratory protection as prescribed in Subpart I of Part 1910.[37] Engineering controls would be added or modified to reduce transient high concentrations to less than threshhold limit values. Records are required for each worker exposed to chemicals at concentrations greater than threshhold limit values.

8. Effects on the Community

This section closely follows a similar discussion in ERDA-1543.[1]

a. Physical

(1) Air Pollution

Nonradioactive pollutants in air discharged during operation of reprocessing and MOX facilities will emanate primarily from the steam plant; however, some gaseous effluents will be emitted from the process buildings (Section 3B6). Because all effluents are at lower concentrations than specified by local, state, and Federal standards, no significant impact is anticipated.

(2) Noise

Noise from normal plant operation will be well below applicable regulations at the site boundaries.

b. Economic

Construction and operation of the FRP-MOX facilities will raise the economic base of the community. A peak construction force of about 1,500 persons is required to build collocated FRP-MOX facilities, and about 1,200 persons will operate the facilities (Section 2D1). The economic base in the community may decline slightly after construction is completed, but the degree of impact will depend on the size of the community and the number of transient versus resident employees in the labor force during construction activities.

The operating facility will in general have a positive long-term impact by stimulating the local economy and by adding to the social and economic well-being of the community; however, some communities may consider this a negative impact. The operating facility and workers will pay local and state taxes. The workers and their families will support commercial, medical, social, and recreational services. The degree of economic impact is site specific and should be evaluated for each site.

c. Service-Related

(1) Schools

The impact on schools is determined by the number of families moving into the surrounding community during construction, the net change in school-aged children after construction is completed, and the capacity of existing schools to accept additional students. There will be more students during the operation of the plant than before construction started if the new facility adds to an already stable community situation. The degree of impact will be influenced by the type of community (rural or metropolitan) and therefore will be site specific.

(2) Medical and Social Services

The long-range need for medical, public health, and social services will depend on the distance from a metropolitan area. If the site is located in a relatively rural area, medical and other services may be developed depending on the anticipated case

load for the construction and operations workers, their families, and those new families who provide commercial and public services for employees at the site.

(3) Housing

The demand for housing during the operating period of the plants will increase compared with the pre-construction period. The degree of this demand will depend on the availability of a metropolitan area for commuting, the availability of existing housing, and other factors. New homes built during the construction period and pre-existing units will allow operating workers options as to location and housing preference in the area. At all times, strict zoning regulations should be followed, and adequate space should be made available for persons to work and maintain leisure activities within the community.

(4) Commercial Services

The demand for new merchandising facilities during the operating period of the plants will depend on the relationship of the plantsite to an existing metropolitan area. If the site is not within commuting distance of a city or metropolitan area, new commercial facilities will have to be built close to most of the workers.

d. Aesthetic Effects

The specific location of the proposed plants will be a primary

factor in determining the aesthetic effect at the site. The plant will be visible from certain angles. The site may be chosen to obscure the plant by high bluffs, trees, and other foliage. Plumes from the cooling tower and steam plant stack will be visible. Some aesthetic impact will be caused by transmission lines, railroads, parking areas, and facilities associated with the steam plant.

C. CUMULATIVE EFFECTS FROM OPERATION THROUGH THE YEAR 2000

1. Scope of the Industry

In Section 2B, the reprocessing and mixed oxide fuel fabrication requirements are projected to grow such that by the year 2000 (base case), six new 1500 MT/yr reprocessing plants will be in operation in addition to Allied-General Nuclear Services (1500 MT/yr). Six new MOX fabrication plants (350 MT/yr each) are similarly projected to be constructed between 1983 and 2000 to provide plutonium recycle capabilities. If reprocessing starts in 1981 and proceeds according to the schedule shown in Table 3.16, a total of about 145,000 MT uranium and 1000 MT plutonium will be discharged from the 507 reactors by the year 2000 and processed by 2001 (actually including some reprocessing in early 2002). By that date, about 34,000 MT of mixed oxide fuel will have been fabricated for recycle. Startup dates for the reprocessing and fabrication plants are given in Table 3.17.

2. Radiation Dose Effects

The population doses resulting from radioactive releases from the fuel reprocessing and MOX fabrication industry (1981-2001 for the base case) are calculated for local (50-mile radius), U.S., and world populations. Effects of long-lived nuclides for a 100-year period following end of reprocessing are included to provide an assessment of effects of persistent nuclides. The year 2001 is used as the basis for the 100-year period in the base case because it is the last full year of reprocessing, and

TABLE 3.16

Projected Growth of Reprocessing and Mixed Oxide Fuel Fabrication

Year	Reprocessing		Mixed Oxide Fuel Fabrication
	MT U/yr	MT Pu/yr	MT/yr
1981	600	4.0	
1982	1,000	6.6	
1983	1,500	9.9	175
1984	1,500	9.9	350
1985	1,500	9.9	350
1986	2,100	13.9	350
1987	3,100	20.5	525
1988	4,600	30.4	875
1989	6,100	40.3	1,223
1990	7,600	50.2	1,575
1991	8,500	63.7	1,925
1992	9,000	67.5	2,100
1993	9,000	67.5	2,100
1994	9,600	72.0	2,100
1995	10,000	75.0	2,275
1996	10,500	78.8	2,450
1997	10,500	78.8	2,450
1998	10,500	78.8	2,450
1999	10,500	78.8	2,450
2000	10,500	78.8	2,450
2001	10,500[a]	78.8	NA
2002	6,464	48.5	NA
Total	145,000	1,063	28,175

a. Fuel processed in 2001 and 2002 is discharged from the reactors by the end of year 2000. 2001 is nominally used as the year of completion of study period reprocessing.

TABLE 3.17

Startup Dates for Fuel Reprocessing (FRP) and Mixed Oxide Fabrication (MOX) Plants

FRP[a]		MOX[b]	
Plant	*Date*	*Plant*	*Date*
AGNS	1981	1	1983
No. 1	1986	3	1987
No. 2	1987	4	1988
No. 3	1988	5	1989
No. 4	1989	6	1990
No. 5	1990	7	1991
No. 6	1994	8	1995

a. FRP throughput is 40% in the first year, 67% in the second year, and 100% in the third year.

b. MOX throughput is 50% in the first year and 100% in the second year.

less than half of the reprocessing in the year 2002 results from the fuel discharged from the reactors in the year 2000.

a. Local

The 50-yr radiation dose commitment to the population living within a 50-mile radius of the seven collocated reprocessing and MOX plants is calculated for the reprocessing period using the source terms from Tables 3.1 and 3.2, U-Pu throughput values from Table 3.16, and the dose estimates for operation of the model plants (Section 3B1), assuming improved offgas controls for plants starting up after 1985 (see Table 3.5). Details of assumptions and calculational methods are given in Appendix B.

The population doses (man-rem) are given in Table 3.18 for the nuclides and dose pathways (discussed in Section 3B1) that

contribute significantly to the total dose commitment. The 31,000 whole body man-rem dose is 0.03% of the 1×10^8 man-rem dose from natural radiation sources received by the population within the 50-mile radius of the 7 plants during the 120-yr period (assuming 100 mrem/yr from natural sources per person).

b. United States

Radiation doses to the U.S. population are estimated using the source terms described above and the distribution and uptake models and dose conversion factors described in Appendix B.

TABLE 3.18

Population Radiation Dose from Reprocessing and Mixed Oxide Fuel Fabrication (Base Case), 1981-2001[a]

		Population Dose, man-rem			
Critical Organ	*Nuclide or Pathway*	*Local (50-mile radii)*	*U.S. (less local)*	*World (less U.S.)*	*Total*
Whole Body	^{14}C	2.6×10^3	5.9×10^4	9.3×10^5	9.9×10^5
	^{85}Kr	5.9×10^2	9.0×10^3	1.3×10^5	1.4×10^5
	^{3}H	2.4×10^4	6.5×10^4	1.6×10^4	1.1×10^5
	Exposure to Contaminated Ground	3.4×10^3	1.4×10^4	-	1.7×10^4
	Inhalation[b]	7.3×10^2	2.1×10^3	-	2.8×10^3
	Foodstuffs[b]	1.5×10^2	5.1×10^2	-	6.6×10^2
	Total	3.1×10^4	1.5×10^5	1.1×10^6	1.3×10^6
Thyroid	^{129}I	7.4×10^4	2.6×10^5	-	3.3×10^5
Bone[c]	Inhalation[b]	2.4×10^4	6.8×10^4	-	9.2×10^4
	Foodstuffs[b]	1.7×10^3	6.1×10^3	-	7.8×10^3
	Total	2.6×10^4	7.4×10^4		1.0×10^5
Lung[c]	^{85}Kr	1.2×10^3	1.9×10^4	2.7×10^5	2.9×10^5
Red Marrow[c]	^{14}C	4.5×10^3	1.0×10^5	1.6×10^6	1.7×10^6

a. Continued effects of 1981-2001 releases are included through the year 2101.

b. Includes contribution from nuclides other than ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. (See discussion in Section 3B1.)

c. Doses in addition to organ dose from whole body irradiation.

Several radionuclides released in the gaseous effluents from a fuel reprocessing and recycle plant will spread from the localities of the plants to part of the total U.S. land area, and some will be diluted worldwide. ^{85}Kr, ^{14}C, and ^{3}H expose the U.S. population before subsequent dispersion throughout the world, but ^{129}I and radioactive particulates (primarily actinides) are assumed to be deposited only on U.S. soil. Model reprocessing and MOX fuel fabrication plants are assumed to be located in the east or midwest, therefore, only the population in the eastern U.S. is exposed to releases of radioactivity before worldwide distribution.

Table 3.18 includes the population dose to the U.S. population from releases from the reprocessing and mixed oxide fuel fabrication plants during 1981-2001. These estimates include the dose to the population through the year 2101 to account for the effects of longer-lived nuclides. The 150,000 man-rem whole body dose is 0.003% of the 4.4×10^{9} man-rem dose from natural radiation sources received by the population within the 120-year period (assuming 100 mrem/yr natural radiation per person).

c. World

Environmental effects from ^{3}H, ^{14}C, and ^{85}Kr released in fuel reprocessing are estimated to include worldwide population doses resulting from global cycling. Details of models and calculations for these worldwide exposures are given in Appendix B.

The summary of worldwide doses is given in Table 3.18. ^{14}C contributes about 85% of the whole body dose and is the major radiation dose effect of the fuel reprocessing and fabrication operations. In calculating the 100-year doses, the 1.9%/yr world population growth rate is perhaps extended beyond a reasonable time (the 2100 population would be 42×10^9 people, 10 times the present population). Approximating a lower growth rate by assuming a constant population after the year 2030 (as done for U.S.), results in about a 30% decrease in ^{14}C dose estimates.

The 1.1×10^6 man-rem whole body dose is 0.0006% (0.0006 mrem/yr per person) of the 2×10^{11} man-rem dose from natural radiation sources received by the population within the 120-year period (assuming 100 mrem/yr per person).

d. Proposed Environmental Standards for the Uranium Fuel Cycle

As discussed in Section 3B1, the Environmental Protection Agency has proposed standards (40 CFR 190) that would limit fuel cycle releases per GWe-year to 5×10^4 Ci of ^{85}Kr, 5 mCi of ^{129}I, and 0.5 mCi TRU alpha emitters with half-lives greater than one year. As presently written, the proposed standards would be effective for TRU alpha emitters beginning 24 months after final publication and on January 1, 1983 for ^{85}Kr and ^{129}I.

A comparison of the releases allowed under the proposed standards with the estimated base case releases is given in

Table 3.19. The allowable releases were calculated using the separations schedule given in Table A-1 for the base case, assuming a 75% reactor power production factor to calculate actual GWe generated.

TABLE 3.19

Annual Releases Compared to Proposed Standards

	^{85}Kr, Cri		^{129}I, Ci		TRU Alpha, Ci	
	Allowed	*Estimated*	*Allowed*	*Estimated*	*Allowed*	*Estimated*
1981	NA		NA		0.03	0.1
1983	4.4×10^6	14.0×10^6	0.44	3.0	0.044	0.25
1985	5.9×10^6	14.0×10^6	0.58	3.0	0.058	0.25
1990	10.1×10^6	15.0×10^6	1.0	4.2	0.10	0.35
1995	15.0×10^6	15.0×10^6	1.5	4.7	0.15	0.39
2000	19.0×10^6	15.0×10^6	1.9	4.8	0.16	0.4

As shown in Table 3.19, the estimated releases exceed the proposed standards throughout the study period. This is primarily due to releases from the AGNS plant without the improved offgas control technology assumed to be installed in plants constructed after 1985.

If AGNS was retrofitted with improved controls, industry releases starting in 1986 would be well within the ^{85}Kr standard and very close to the standards for ^{129}I and TRU alpha. This option is discussed further in Section 5 under Alternative 4.

3. Health Effects

Health effects (cancers and serious genetic defects) are estimated from the 120-year population dose estimate (Table 3.18) for local, U.S., and worldwide populations. One approach to estimating health effects is to use the linear dose-effect relationships derived from the BEIR report[8] by the EPA.[38,39] No threshold dose is assumed for health effects. These dose-effect estimates are quite uncertain and probably overestimate the actual effects considerably. Most other interpretations[40] of the BEIR report lead to dose-effect estimates that are lower than those obtained using the EPA factors. The following is a quote from the EPA analysis of the fuel cycle:[39]

"The numerical risk estimates used are primarily from the BEIR report. What must be emphasized is that though these numbers may be used as the best available for the purpose of risk-cost benefit analyses, they cannot be used to accurately predict the number of casualties. For a given dose equivalent, the BEIR report estimates a range for the health impact per million exposed persons. For example, the BEIR results from a study of the major sources of cancer mortality data yield an absolute risk* estimate of 54 to 123 deaths annually per 10^6 persons per rem for a 27-year followup period. Depending on the

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* Absolute risk estimates are based on the reported number of cancer deaths per rad that have been observed in exposed population groups, e.g., Hiroshima, Nagasaki, etc.

details of the risk model used, the BEIR Committee's relative risk* estimate is 160-450 deaths per 10^6 persons per rem. It is seen that the precision of these estimates is at best about a factor of 3 to 4, even when applied to sample populations studied on the basis of the same dose rates. The application of the BEIR risk estimates to exposures at lower dose rates and to population groups more heterogeneous than those studied increases the uncertainty in the risk estimates. Considering the limitations of presently available data and the lack of an accepted theory of radiocarcinogenesis, emphasis should be placed on the difference in risk estimates between the various procedures and countermeasures discussed in this report rather than on the absolute numbers. Where the absolute numbers must be used for risk-cost-benefit balancing, it should be remembered that these risk estimates are likely to be revised as new information becomes available. Notwithstanding these disclaimers, it is also pertinent to note that we are in a better position to evaluate the true risks and the accompanying uncertainties from low levels of radiation than from low concentrations of other environmental pollutants which might affect populations in the vicinity of a fuel reprocessing plant."

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* Relative risk estimates are based on the percentage increase of ambient cancer mortality per rem.

The position of the National Council on Radiation Protection[41] is:

"The linear dose-effect hypothesis has been coming into frequent use in analyses in which population exposures are expressed in the form of person-rem, including doses of 1 mrem/yr or less to population groups and doses to individual organs, with linear extrapolation to damage estimates through the use of the NAS-BEIR Committee report values. The indications of a significant dose rate influence on radiation effects would make completely inappropriate the current practice of summing of doses at all levels of dose and dose rate in the form of total person-rem for purposes of calculating risks to the population on the basis of extrapolation of risk estimates derived from data at high doses and dose rates.

The NCRP wishes to caution governmental policy-making agencies of the unreasonableness of interpreting or assuming "upper limit" estimates of carcinogenic risks at a low radiation level, derived from linear extrapolation from data obtained at high doses and dose rates as actual risks, and of basing unduly restrictive policies on such an interpretation or assumption. The NCRP has always endeavored to ensure public awareness of the hazards of ionizing radiation, but it has equally determined to ensure that such hazards are not greatly overestimated. Undue concern, as well as carelessness with regard to radiation hazards, is considered detrimental to the public interest."

While appreciating the NCRP position regarding use of the linear dose-effect extrapolations, it is considered necessary to make an estimate of the ultimate effects of the radioactive releases from the fuel cycle. To this end, the EPA factors are used in this report to provide upper-limit health effects estimates. The probability that the effects are lower than the calculated values (see next section) must be recognized when using the estimates in a cost-benefit assessment. They must also be compared with other causes of similar effects, so that true cost-benefit comparisons can be made that do not result in unduly restrictive policies or unwarranted expenditures of resources or dollars.

The Rasmussen study[40] of latent somatic effects from ionizing radiation recognizes the possibility that both dose and dose rate are important considerations influencing the selection of dose-effect factors. This study presents three different estimates of radiation risk: the upper-bound estimate, the central estimate, and the lower-bound estimate. The upper-bound estimate essentially uses the BEIR report values with minor modifications relating to the G.I. tract, bone, and thyroid gland. The central estimate modifies the upper-bound estimate by correction for risk reduction due to both the ameliorating effects of dose protraction and the lesser effectiveness of very small doses. A frequently quoted numerical relationship regarding radiogenic carcinogenesis is that low-dose-rate exposures are about one-fifth as effective as

high-dose-rate exposures for the same total exposure. Rasmussen uses a dose effectiveness factor of 0.2 (for most organs) to obtain his central estimate. The lower-bound estimate recognizes the possibility that radiation effects may be nonlinear at very low doses.

In this analysis of the LWR fuel reprocessing and recycle industry, the EPA dose-effect factors are used for making comparisons of the base case and 15 alternative cases (Section 5, Alternatives). Similar calculations were made using the Rasmussen central estimate dose-effect factors. A comparison of health effects from the base case fuel cycle and alternatives is given in Table 9.5a (EPA factors) and 9.5b (Rasmussen factors).

a. Dose-Effect Factors

The factors used by the EPA and the Rasmussen study (central estimates) to estimate health effects from man-rem population doses and their estimate of the frequency of mortality are given in Table 3.20.

The EPA factors for cancer incidences were derived using the BEIR Committee "relative risk" estimates; the factors used in the Rasmussen study[40] were adapted from the BEIR Committee's "absolute risk" estimates. The Rasmussen upper-bound (no dose-rate dependence) results in dose-effect factors for fatal cancers about 50% of the values given in Table 3.20 for lung, bone, and red marrow (leukemia). The Rasmussen central estimate includes (for most organs) a dose-effectiveness factor of 0.2 for dose rates less

than 1 rem/day, thus reducing lung, bone, and red marrow values to those shown in Table 3.20. The thyroid dose conversion factor used in the Rasmussen report is 13.4 fatal cancers/10^6 man-rem compared to the EPA value of 15 given in Table 3.20. The comparative total cancer deaths per 10^6 man-rem are: 200 (EPA), 135 (Rasmussen upper bound), and 58 (Rasmussen central estimate). References 8 and 40 should be consulted for further discussion of this subject and the interpretive variations kept in mind when utilizing the health effect estimates in Table 3.21a, and in Section 5, Alternatives and Section 9, Cost-Benefit Analysis.

The EPA factor for estimating genetic effects is 300 cases per 10^6 man-rem; this apparently was derived from Table 4 of the BEIR report[8] and represents the sum of first generation and equilibrium cases as shown in Table 3.22. A similar analysis in the draft GESMO report[9] uses only the equilibrium case. The differences (EPA factor is 16% greater than GESMO) are not considered significant in respect to the wide range of possible genetic effects given in the BEIR report.

The genetic risk includes the full spectrum of genetic defects. Their effects may range from a lethal action at or near birth to minor metabolic consequences that may be nearly undetectable. This environmental statement sums genetic and cancer risks as total health effects.

TABLE 3.20

Dose-Effect Conversion Factors

	EPA Relative Risk				*Rasmussen Central Estimate*			
	Health Effects/ 10^6 man-rem (Cancers)	*Fatal Health Effects/ 10^6 man-rem (Cancers)*	*% Mortality*	*Reference*	*Health Effects/ 10^6 man-rem (Cancers)*	*Fatal Health Effects/ 10^6 man-rem (Cancers)*	*% Mortality*	*Reference*
Whole Body	400	200	50	39	116	58	50	40
Lung	50	50	100	39	4.4	4.4	100	40
Bone	32	16	50	38	1.8	1.4	80	40
Red Marrow (Leukemia)	54	54	100	38	5.7	5.7	100	40
Thyroid	60	15	25	42	134	13.4	10	40
	(Genetic Effects)							
Gonads[a]	300	-	-	39	258	-	-	9

a. Serious genetic effects; one-half the exposed population is assumed to be subject to genetic effects.

TABLE 3.21

Calculated Health Effects from Fuel Cycle Operations
(1981-2001, including effects through 2101)
(Fatalities in Parentheses)

a. Calculated Upper-Limit Health Effects[a]
(Malignancies) Using EPA Dose Effect Factors

	Local	*U.S.*	*World*	*Total*
Whole Body	13 (7)	60 (30)	430 (215)	503 (252)
Lung[b]	<1 (<1)	1 (1)	14 (14)	15 (15)
Bone[b]	1 (<1)	2 (1)	-	3 (2)
Red Marrow[b] (Leukemia)	<1 (<1)	5 (5)	86 (86)	91 (91)
Thyroid[b]	4 (1)	16 (4)	-	20 (5)
	18 (8)	84 (41)	530 (315)	632 (365)
Fatalities/10^5 Population Per Year	0.004	0.00008	0.00003	

b. Calculated Central Estimate Health Effects[a]
(Malignancies) Using Rasmussen Dose-Effect Factors

	Local	*U.S.*	*World*	*Total*
Whole Body	4 (2)	17 (9)	125 (62)	146 (73)
Lung[b]	<1 (<1)	<1 (<1)	1 (1)	1 (1)
Bone[b]	<1 (<1)	<1 (<1)	-	<1 (<1)
Red Marrow[b] (Leukemia)	<1 (<1)	1 (1)	9 (9)	10 (10)
Thyroid[b]	10 (1)	35 (4)	-	45 (5)
	14 (3)	53 (14)	135 (72)	202 (89)
Fatalities/10^5 Population Per Year	0.003	0.00005	0.000007	

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a. See text for discussion of dose-effect factors used in the calculations and probable overestimation of health effects.

b. Organ health effects in addition to those included in whole body dose estimates.

TABLE 3.22

Genetic Effects Factors (Cases per 10^6 man-rem)

Effect	*BEIR (Reference 1)*[a] *Range* 1st Gen.	Equil.	*Geometric Mean* 1st Gen.	Equil.	*Sum*	*EPA*[39]	*GESMO*[9]
Dominant diseases	10-100	50-500	32	158	190	-	158
Congenital anomalies Anomalies expressed later Constitutional and degenerative diseases	1-100	10-1000	10	100	110	-	100
Total	11-200	60-1500	42	258	300	300	258

a. BEIR report, Table 4 (p. 57) includes effects of 5 rem per generation per 10^6 population. The derivations above assume that effects from 1 rem are proportional.

b. Reprocessing and MOX Fabrication Health Effects

When the population doses given in Table 3.18 and the factors in Table 3.20 are combined, upper limit health effects can be calculated for the base case of closing the fuel cycle (Tables 3.21a, 3.21b, and 3.24).

The calculated statistical incidences of fatal cancers resulting from closing the fuel cycle per 100,000 population per year for the 120-year period are given in Table 3.21a (using EPA dose-effect factors) and 3.21b (using Rasmussen dose-effect factors). These values are extremely low compared to the observed causes of death given in Table 3.23 for the U.S. in 1973 and would be impossible to identify as being specifically caused by fuel cycle operations even for the local 50-mile-radius population.

Genetic effects are estimated using both EPA and GESMO gonad dose-effect factors (Appendix B) (^3H, ^{14}C, and ^{85}Kr contribute significantly to the total dose). 50% of the population is assumed to be subject to genetic effects. These effects are those

described by the EPA[39] as "very serious genetic effects such as congenital anomalies, constitutional and degenerative diseases, etc." Table 3.24 includes the genetic effect estimates and the frequency of these effects per 10^5 population each year. For comparison, about 200,000 babies are born in the U.S. each year with some type of mental or physical defect,[45] a frequency of 67 cases per 10^5 population per year.

TABLE 3.23

Causes of Death in the United States[43,44]

Cause (1973)	*Deaths Per Year Per 10^5 Population*
Malignancies	168
Major cardiovascular diseases	494
Influenza and pneumonia	29
Bronchitis, emphysema and asthma	14
Cirrhosis of liver	16
Suicide	12
Homicide	9
Accidents	55
Other causes	145
Total	942
Accidents (1973)	
Motor vehicle	26
Falls	8
Fires, burns	3
Drowning	3
Poisoning	3
Firearm	1
Aircraft	1
Electric current	0.5
Lightning	0.06
Bites and stings	0.02
Other	10
Total	55

TABLE 3.24

Estimated Health Effects[a] (Serious Genetic Effects) from Fuel Cycle Operations (1981-2001, including effects through 2101)

	Local	*U.S.*	*World*	*Total*
Genetic Effects from Fuel Cycle (Using EPA Dose-Effect Factors)	4	17	71	91
Genetic Effects from Background Radiation (Using EPA Dose-Effect Factors)	13,500	3,300,000	61,000,000	
Genetic Effects from Fuel Cycle (Using GESMO Dose-Effect Factors)	4	14	61	79
Genetic Effects from Background Radiation (Using GESMO Dose-Effect Factors)	11,600	2,800,000	52,000,000	

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a. See text for discussion of dose-effect factors.

4. Other Effects

a. Occupational Exposure and Accidental Deaths from Reprocessing and MOX Fabrication

Exposure of back-end fuel cycle workers to external radiation during the period 1981-2001 is estimated to be about 46,000 man-rem for the base case. This estimate is based on the average dose of 400 mrem per year per worker described in Section 3B3. If the linear dose-effect relationships described in Section 3C3 are applied to occupational exposure, the 46,000 man-rem whole body dose would be estimated from the EPA risk factors to result in 18 cancer cases (50% fatal) and 10 serious genetic effects (assuming 75% of the work force is susceptible to genetic doses). As previously discussed, this is expected to be a considerable overestimation of the actual effects; see Table 9.5b for an estimation of health effects based on Rasmussen study. The current rate of 170 cancer deaths per 100,000 population per year (Table 3.23) implies that about 210 members of the fuel recycle plants' work force will die from other causes of cancer in the 20-year period from 1981 to 2001. If the 9 deaths calculated above actually occurred in addition to other causes, they would represent a 4% increase in the death rate from cancer for the work force.

It would be likely that the death rate from occupational accidents in the reprocessing and recycling industry would approximate the chemical industry experience[44] of 0.03 deaths per 10^6 man-hours worked, a total of 7 in the 20-year period.

b. Front End Effects

The most significant health effects of operation of the front end of the fuel cycle (mining through reactors), which are affected by closing the fuel cycle, occur in mining and milling uranium. Closing the fuel cycle decreases the occupational and public health effects of the uranium mining and milling industry by decreasing the amount of uranium mined. The comparative health effects of fuel cycle options are described in Section 5, Alternatives.

(1) Miner Radiation Exposure

Exposure of underground miners to radon and its daughters has been estimated[46] to result in 10^{-4} probable cancer deaths per "working-level month."* Assuming 200 working-level months per reactor-year** and 7160 reactor-years, a total of 140 lung cancer deaths would be predicted from EPA dose factors (see Table 9.5b for estimate based on Rasmussen study) from mining operations supporting the base case of 507 reactors by the year 2000 (with Pu-U recycle). At the current rate of 170 cancer deaths per 100,000 population per year (Table 3.23), about 540

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* A working-level month is defined as exposure for 170 hours to an atmosphere containing enough short-lived radon daughter products per liter to yield 1.3×10^5 MeV.

** This value is twice that used in WASH-1224 because 0.1% U_3O_8 in ore is assumed in this study compared to the 0.2% assumed in WASH-1224.[6] Included in the derivation of WLM/reactor-year is the assumption that uranium mining is 58% underground, 32% open pit, and 10% in phosphate deposits. The exposure of miners to radon is greatest in underground mining.

members of the underground mining work force will die from other causes of cancer during the period 1976-2000. About 90 of these will be from lung cancer. Improved mining procedures should reduce the exposure to radon and subsequently the incidence of lung cancers in future years. In fact, recent mining experience suggests miner exposures are closer to 2 WLM per miner-year rather than 4, the value used in the estimate given above; this would reduce the 140 lung cancer deaths estimated above to 70.

(2) Miner Accidental Deaths

The death rates from occupational accidental deaths are significantly higher for various mining operations than for many other industries.[44,47] Accidental deaths resulting from uranium mining to support the base case through the year 2000 are estimated to be 1400, based on WASH-1224.[46] The frequency is 0.6 deaths per 10^6 man-hours worked; this rate can be compared to 0.58 per 10^6 man-hours for U.S. coal mining,[44] 0.53 per 10^6 for U.S. metal mining,[44] and 0.4 per 10^6 for coal mining in Great Britain.[47]

(3) Population Radiation Exposure

The most significant source of radiation exposure to the general population from front end operations will be the radon (^{222}Rn) from mining, from milling, and from mill tailings piles that dry out after the mills are shut down.[38] ^{222}Rn is a product of the uranium decay chain and it will continue to be produced

in tailings piles over the long lifetime of its precursors. To compare variations in front end effects caused by the alternatives involved in closing the fuel cycle, the GESMO calculation of long-term ^{222}Rn doses[9] is used. The estimated health effects to the general population (cancers and genetic effects) are 1470, from mining and milling and 3100 from tailings piles (uncovered) over a 100-year period following shutdown of mills supply uranium for the base case nuclear power industry (507 GWe by year 2000). These estimates are based on EPA dose-effect factors; see Table 9.5b for comparison with Rasmussen study dose-effect factors. Radon releases can be reduced by covering mill tailings piles with earth to allow more time for decay before the radon diffuses to the atmosphere. Twelve feet of earth cover has been estimated[13] to reduce ^{222}Rn releases to one-tenth of the value without earth cover; in this statement all mill tailings are assumed to be covered in this manner, and the number of health effects resulting from the release of ^{222}Rn and its daughters from the tailing piles is reduced to 310 (includes 125 cancer deaths). The 125 U.S. cancer deaths over a 100-year period would represent a rate of 0.0006 per year per 100,000 population. Cancer deaths in the U.S. in 1973 from all causes were about 170 per year per 100,000 population.[43,49]

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4. UNAVOIDABLE ADVERSE ENVIRONMENTAL EFFECTS

A. RADIOLOGICAL

Health effects resulting from releases of radioactivity from reprocessing and mixed oxide fuel fabrication plants through the year 2001 are summarized in Section 3. The radiation doses to individuals are a small percentage of doses from natural background radiation. However, if the individual dose is multiplied by the large exposed population and if the linear nonthreshold dose/effects model is assumed, the number of statistically predicted health effects becomes an unavoidable adverse effect deserving assessment in this statement. The assessment presented in Section 3C3 shows that the number of cancer cases, fatal cancers, and serious genetic effects predicted to result from the closing the fuel cycle are low compared to the number of cases of these health effects resulting from other causes.

B. POTENTIAL ACCIDENTS

The potential adverse effects of possible accidents are well within the limits given in accepted standards (10 CFR 100, ERDA Manual 6301) for assessing the effects of unlikely events.

C. OTHER

Other unavoidable adverse environmental effects are the effects of construction, land use requirements, water and power requirements, and chemical discharges. These are not large in terms of available resources or environmental impact, or in comparison to the front end of the fuel cycle.

5. ALTERNATIVES

A. INTRODUCTION

Recycle of uranium and plutonium from spent LWR fuel with 507-GWe reactor operation by year 2000 is the base case considered in this environmental statement. Fifteen alternative fuel cycles that differ from the base case are assessed in this section (Table 5.1). One major alternative is to reprocess the spent reactor fuel and to recycle only the uranium; the plutonium would be stored under adequate safeguards for possible future use in breeder reactors or eventual disposal. A second major alternative is to store the spent fuel indefinitely for either possible future reprocessing or eventual disposal (throwaway fuel cycle).

These alternatives also include five variations of the base case.

- A cooling period of 5 years rather than 1 year before reprocessing.
- A 5-year delay in startup of fuel reprocessing.
- No improvements in control of offgases.
- Retrofit of Barnwell Nuclear Fuel Plant (AGNS) with improved offgas control.

TABLE 5.1

LWR Fuel Cycles Considered in This Statement

Fuel Cycle	*Recycle of* *Uranium*	*Plutonium*	*Reactor Schedule (Year 2000)*
Base Case — Recycle uranium and plutonium; 1 year fuel decay	Yes	Yes	507 GWe
Alternative 1 — Same as base case except cool fuel 5 years prior to reprocessing	Yes	Yes	507 GWe
Alternative 2 — Same as base case except delay startup of fuel reprocessing 5 years	Yes	Yes	507 GWe
Alternative 3 — Same as base case except no earth cover over tailings piles and no offgas controls for reprocessing plants built after year 1985	Yes	Yes	507 GWe
Alternative 4 — Same as base case except retrofit the AGNS reprocessing plant with offgas controls. Additional cover over tailings piles.	Yes	Yes	507 GWe
Alternative 5 — Site variations	Yes	Yes	507 GWe
5a - Same as base case except locate reprocessing and MOX fabrication plants at different sites			
5b - Same as base case except locate reprocessing plants to minimize transportation of irradiated fuel	Yes	Yes	507 GWe
5c - Same as base case except locate reprocessing plants near Federal repositories to minimize transportation of radioactive waste	Yes	Yes	507 GWe
Alternative 6 — Recycle uranium	Yes	No	507 GWe
Alternative 7 — Throwaway	No	No	507 GWe
Alternative 8 — Coprocessing	Yes	Yes	507 GWe
Alternative 9 — Tandem Cycle	No	No	507 GWe
Alternative 10 — Same as base case except larger number of LWRs	Yes	Yes	600 GWe
Alternative 11 — Same as Alternative 6 except larger number of LWRs	Yes	No	600 GWe
Alternative 12 — Same as Alternative 7 except larger number of LWRs	No	No	600 GWe
Alternative 13 — Same as base case except smaller number of LWRs	Yes	Yes	400 GWe
Alternative 14 — Same as Alternative 6 except smaller number of LWRs	Yes	No	400 GWe
Alternative 15 — Same as Alternative 7 except smaller number of LWRs	No	No	400 GWe

- Three variations on siting —

  Locate fuel reprocessing and MOX fabrication at different sites.

  Locate fuel reprocessing to minimize transportation of spent fuel.

  Locate fuel reprocessing to minimize transportation of radioactive waste to terminal storage.

In addition, two alternative technologies are considered for the base case: (1) coprocessing, in which the uranium and plutonium content of spent fuel is recovered and recycled in a single process stream, and (2) the tandem cycle, in which spent LWR fuel is refabricated into fuel for heavy water reactors (HWR), irradiated in HWRs, and stored or disposed of as in the throwaway fuel cycle.

The major fuel cycle modes of full recycle, uranium recycle only, and no recycle are compared for different LWR growth projections. Schedules are considered for bases both larger and smaller (600 and 400 reactors by the year 2000) than the base case schedule of 507 reactors by year 2000.

In the following discussion, the alternatives are compared to the base case in terms of their estimated overall costs and benefits. The comparison is extended to include effects of the front end of the fuel cycle. Costs include capital and operating expenditures for processes in both front and back ends of the fuel cycle.* Benefits include, besides possible cost reductions, possible improvements in the future development and use of natural

***Costs are shown for operations through the year 2000.**

resources, and possible reductions in environmental effects. The environmental effects that are emphasized are the dose commitments to offsite populations from releases of long-lived radioactive materials. Possible effects of sabotage or diversion of plutonium on the environmental effects assessment are discussed in Section 10.

For the comparisons presented in this section and in Section 9, unit costs for alternative LWR fuel cycles were projected to the year 2000 based on FY-1977 dollars. Although these projections are subject to the uncertainties in any long-range cost projections, they were made primarily for comparisons between alternative fuel cycles. Differences between the costs of alternatives should be less sensitive to forecasting assumptions than the absolute costs of the alternatives would be.

B. FUEL CYCLE OPERATIONS WITH BASE CASE REACTOR SCHEDULE (507 LWRs in Year 2000)

1. Base Case — Recover and Recycle Uranium and Plutonium

a. Description

The reprocessing of spent LWR fuel after decay for one year and prompt return of the recovered plutonium and uranium into the fuel cycle closes the fuel cycle and is the mode against which all other alternatives are compared.

Uranium ore is extracted from the earth by one of two methods: open pit mining or underground mining. For this front-end segment of the fuel cycle, a combined mine-mill complex was selected as the model because this represents a significant portion of the existing industry and is consistent with the current trend in the diverse uranium mining-milling industry.

In the milling operation, uranium is extracted from the ore and is concentrated as a semi-refined U_3O_8 product. The concentrate is shipped from uranium mills to UF_6 conversion plants. The UF_6 is then used as feed to the isotopic enrichment plants. Recycled uranium, when available, enters the main fuel cycle stream at this point by being shipped as UF_6 from reprocessing plants to enrichment plants. The recycled uranium loses its identity in the enrichment plants. Enriched uranium as UF_6 is shipped from enrichment plants to UO_2 fuel fabrication plants. Simultaneously, recycled plutonium is refabricated into mixed oxide fuel at an integrated reprocessing-refabrication plant. Also shipped to this integrated facility is the required amount

of natural uranium in the form of UO_2. Fuel rods containing mixed oxide fuel are shipped to uranium fuel fabrication plants. Within the uranium fuel fabrication plants, fuel elements containing both uranium and mixed oxide fuel rods are assembled. After assembly, the fuel elements are shipped from the uranium fabrication plants to the reactors.

Following irradiation for approximately three to four years, spent fuel assemblies are shipped from the reactors to reprocessing plants (after allowing for onsite cooling for about 4 to 6 months). At the reprocessing plants, the fuel assemblies are dissolved and chemically treated by the Purex process and ion exchange separation steps to obtain three primary output streams. Total cooling time between discharge from the reactor and chemical processing is assumed to be a minimum of one year. One product stream is recycled uranium (as UF_6), which is sent to the enrichment plants. A second stream is high-level fission product waste. This waste may be stored onsite as a liquid for five years and then converted to a solid for an additional five years storage pending ultimate disposal in a Federal repository. The third stream is the recovered plutonium.

To allow for mismatch of reprocessing and mixed oxide fabrication schedules, some facilities will probably be required for plutonium storage. Such facilities could be located at the reprocessing facility for storage of either nitrate solution or oxide or at the fabrication facility where storage of oxide could

be provided. If reprocessing and recycling are not carried out in an integrated plant, plutonium will have to be shipped from the reprocessing plants to the mixed oxide fabrication plants.

The plutonium recycle industry has been discussed in detail in Section 2. In reactors containing plutonium, an upper limit of about 20% of a core's fissile loading is assumed to be plutonium. At equilibrium, approximately 33% of a core's fissile loading is plutonium in a reactor that recycles all of the plutonium that it produces. However, in the expanding nuclear economy forecasted, the supply of plutonium would lag demand. By the year 2000, about 16% of all fuel charged to LWRs would be mixed oxide and approximately 85% of all reactors would contain recycled plutonium.

The fuel cycle for the base case, for uranium recycle only (Alternative 6), and no reprocessing and recycle (Alternative 7), are schematically shown in Figure 5.1. Attendant waste management requirements for these fuel cycles are shown in Figure 5.2.

b. Effects on LWR Fuel Cycle Operations

(1) Materials Processed

In Section 2A, 507 LWRs are projected for the year 2000, each capable of generating 1000 MWe. The corresponding fuel cycle industry with closed fuel cycle in the year 2000 will require the mining of about 72 million metric tons of ore per year (0.1% U_3O_8) and milling of approximately 68,400 MT per year of U_3O_8 in 51 mine-mill complexes. Total U_3O_8 requirements through the year 2000 are forecast to be 1.05×10^6 MT.

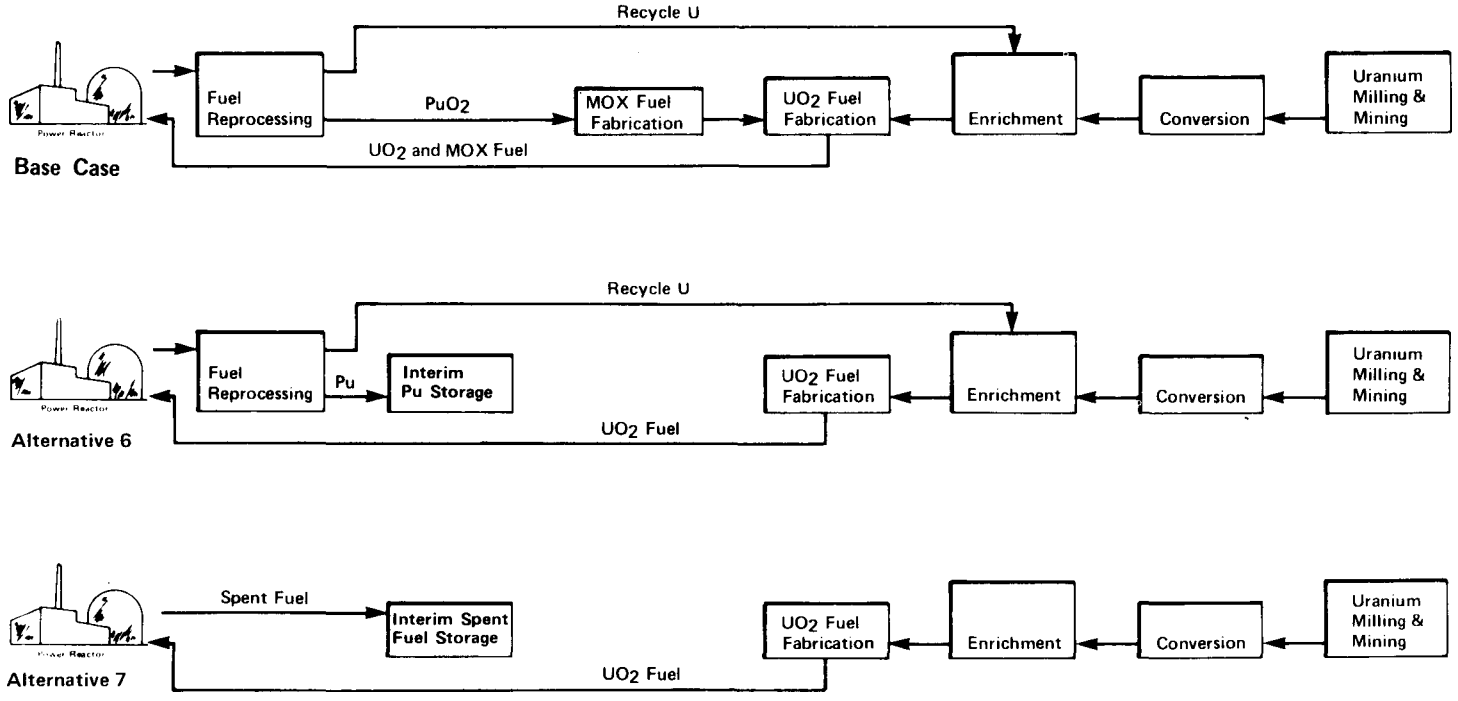

FIGURE 5.1. Alternative LWR Fuel Cycles

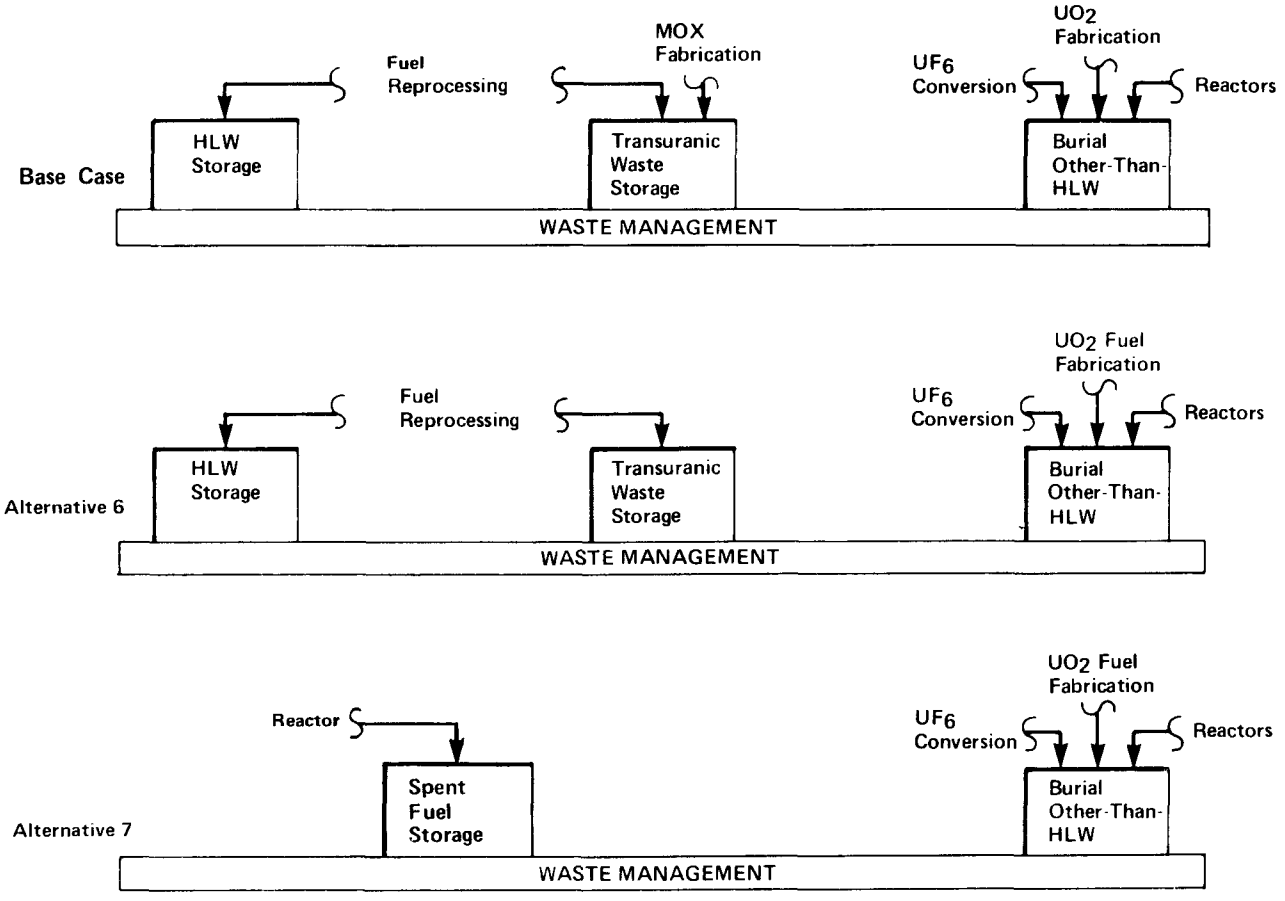

FIGURE 5.2. Waste Management Requirements for Alternative LWR Fuel Cycles

The natural uranium conversion industry will need to produce 55,600 MTU as UF_6 to meet year 2000 requirements. This material, along with recycled uranium, will serve as feed to the ten uranium enrichment plants producing about 91 million SWU per year. Domestic demand for separative work in the year 2000 will require about 43 million SWU; the remainder is assumed to meet foreign needs. The year 2000 projections further indicate that there will be 10 production-scale UO_2 fabrication plants having a total capacity of approximately 12,300 MTU per year.

Industry operation with recycle of plutonium requires that approximately 10,500 MTU of spent fuel will be processed in 7 plants in the year 2000. About 1380 MT of plutonium (68% fissile plutonium) are forecast to be separated from spent fuel through the year 2000. Plutonium is assumed to be fabricated into MOX fuel in the same year that it is recovered from the spent fuel. In the year 2000, seven MOX fuel fabrication facilities, collocated with the reprocessing plants, will be required for the fabrication operation. This operation will require that about 109 MT of plutonium (containing 74 MT of fissile plutonium) be processed to produce 2450 MT of mixed oxide fuel. Transportation of fuel materials is expected to require 9900 shipments in the year 2000. This transportation includes shipments of unirradiated fuel assemblies to reactors, irradiated fuel assemblies to fuel reprocessing plants, recycled UF_6 to enrichment plants, and MOX fuel rods to UO_2 fuel fabrication plants. Projected material flows for the base case are given in Appendix A, Tables A-1 through A-5.

(2) Use of Natural Resources

The entire LWR fuel cycle in the year 2000 is projected to require about 711,000 acres of land for temporary use and about 53,000 acres of land that is committed permanently.[1,2] This fuel cycle includes nuclear reactors and facilities for front end operations, for recycle, and for waste management.

The segments of the industry requiring the largest land commitment are the mining-milling operations. These operations require 390,000 acres of temporarily committed land and 29,000 acres of permanently committed land, or 55% of nuclear industry totals for temporarily committed land and 51% for permanently committed land.

Most of the land that is permanently committed from mining-milling operations is associated with the tailings pile. Where topsoil is available, some of this land could be returned to productive use (e.g., grazing) by increasing the thickness of earth cover from 12 to 20 ft.[2] However, activities involving excavation would be prohibited.

The reactor sites require the second largest commitment of land: 248,000 acres temporarily committed and 23,000 acres permanently committed (35% of nuclear industry totals for temporarily committed land and 40% for permanently committed land). Land commitments attributable to reactors are the same for all fuel cycle alternatives supporting a given size of LWR industry (507 reactors for the base case projection).

The integrated reprocessing MOX fabrication sites require 42,000 acres of temporarily committed land and 110 acres of permanently committed land. These values are 6% of the industry totals for temporarily committed land and 0.2% for permanently committed land. Waste storage is expected to require about 1000 acres of temporarily committed land and about 500 acres of permanently committed land through the year 2000.

Water is used in the nuclear industry both as a coolant and for process requirements. However, the water is returned to the biosphere and is not irretrievably committed although it may become unavailable to local customers. In the year 2000, approximately 5×10^{13} gallons will be used (90% by reactors) irrespective of fuel cycle mode.

The uranium enrichment component of the closed fuel cycle uses 98% of the electrical energy required by the fuel cycle for the model plant assumption of gaseous diffusion enrichment. The total electrical requirements are 210 million MW-hr in year 2000. The 507 LWRs will produce about 3300 million MW-hr in annual operation at an average load factor of 74%. Thus, the direct electrical requirements of the nuclear fuel cycle to produce fuel for the LWRs are about 6% of the energy produced by the reactors in a year of operation.

Additionally, approximately 34 billion ft^3 of natural gas are consumed in the year 2000 by the industry for process heat;

much of this gas is used in the milling operation. This quantity of natural gas could be used to generate about 3 million MW-hr of electricity, which is less than 0.1% of the annual output of the 507 LWRs.

The annual energy requirement for constructing and fueling new LWRs is expected to be about 10% of the output of existing LWRs through the year 2000. This estimate is based on comparing the projected LWR growth rate (ERDA-OPA; low projection) with growth rates of 10% and 20%. These growth rates have been calculated to result in overall energy demands of 6% and 16% of the produced energy, respectively.[3]

(3) Waste Management

The industry is expected to generate in the year 2000 about 4.0×10^6 liters of concentrated high-level waste. Within 5 years, this high-level liquid waste will be converted to about 630 m^3 of dry solid. The dry solid must be shipped to a Federal repository by the year 2010. In the year 2000 reprocessing and plutonium recycle operations are also expected to generate about 72,000 m^3 of wastes containing transuranics (19,000 m^3 from MOX facilities) which will be stored onsite pending ultimate disposal. In addition, nearly 400,000 m^3 of radioactive waste (mostly from reactors) will be buried at sites licensed to receive such wastes. Transportation of wastes associated with industry operations in the year 2000 is expected to require 5400 shipments.

(4) Effluents and Environmental Effects

(a) Radiological

The environmental effects potentially of most concern that are associated with recycling uranium and plutonium result from radioactive effluents. The major effluents from back end operations are from the reprocessing plants where the fuel is dissolved and separated into product and waste streams. Effluents from these plants are discussed in detail in Section 3 of this environmental statement and are summarized below. The environmental effects estimated for reprocessing plant effluents are based on plant operations through the year 2001 (through the year 2007 for Alternative 1) to include spent fuel discharged in the year 2000 and then cooled 1 year before reprocessing (5 years for Alternative 1). The major effluent from front end operations affected by recycle options is ^{222}Rn (and daughters) emanating from mining and milling and from inactive mill tailings piles.

Radionuclide releases to the atmosphere that contribute significantly to either the worldwide or regional population dose commitment are listed below.

- Tritium (^{3}H) — About 1,100,000 Ci/yr of tritium is released from a 1500 MTU/yr reprocessing plant when no retention is assumed. The annual release from plants started up after 1985 is reduced to 11,000 Ci as a result of assumed off-gas controls. All tritium is assumed to be released as tritiated water vapor. The estimated total population radiation dose

resulting from operation of the projected number of plants through the year 2001 is 110,000 man-rem including local, U.S., and worldwide populations.

- Krypton-85 (^{85}Kr) – About 14,000,000 Ci/yr of this noble gas is released from each 1500 MTU/yr reprocessing plant when no retention is assumed. This release is reduced to 140,000 Ci/yr for plants starting up after 1985 as a result of assumed off-gas controls. The estimated total population radiation doses resulting from the industry operating through the year 2001 are 140,000 whole-body man-rem and 290,000 lung man-rem including local, U.S., and worldwide populations.

- Carbon-14 (^{14}C) – About 700 Ci/yr of ^{14}C is released from each reprocessing plant as CO and CO_2 when no retention is assumed. This release is reduced to 7 Ci/yr for plants starting up after 1985 as a result of assumed offgas controls. The estimated total population radiation dose resulting from the industry operating through the year 2001 are 990,000 whole-body man-rem and 1,700,000 red marrow man-rem including local, U.S., and worldwide populations.

- Iodine-129 (^{129}I) – About 3 Ci/yr of ^{129}I is released from each reprocessing plant when advanced retention systems are not assumed. This release amounts to 5% of the ^{129}I produced by reactor irradiation. The release is reduced to 0.3 Ci/yr for plants starting up after 1985 as a result of assumed

off-gas controls. The estimated population radiation dose through the year 2101 from releases through the year 2001 is 330,000 thyroid man-rem including local and U.S. populations.

- Transuranics (Pu, Am, Cm) — About 2.5 Ci/yr of transuranics is released from each reprocessing plant when advanced retention systems are not assumed. The following fractions of the materials processed are assumed to be released:

  $Pu = 5 \times 10^{-9}$
  $Am = 2 \times 10^{-9}$
  $Cm = 2 \times 10^{-9}$

  Of the total released, the beta-emitter ^{241}Pu contributes 2.1 curies, the long-lived alpha emitters of plutonium and americium contribute 0.1 Ci, and $^{242,244}Cm$ contribute 0.3 Ci. These releases are reduced to 0.25 Ci/yr for plants starting up after 1985 as a result of assumed off-gas controls. The estimated population radiation dose from releases through the year 2001 is 100,000 man-rem bone dose including local and U.S. populations. As discussed in Section 3B, the MOX fuel fabrication plant also is expected to release a small fraction of the plutonium and americium processed (2.5×10^{-10}). The population dose from the MOX plant releases is estimated to be an additional 1500 man-rem bone dose.

- Radon-222 and Daughters (^{222}Rn) — The release of radon-222 from mining and milling and from inactive mill tailings piles (12 ft of earth cover is assumed) results in 2,700,000 man-rem whole-body dose, plus additional organ exposures of 810,000 man-rem lung dose, and 8,700,000 man-rem bone dose through the year 2101.

Health Effects. As discussed in Section 3C, the man-rem population doses can be used to estimate resultant health effects (cancers and serious genetic defects). The dose-effect factors used in this report assume a linear relationship with no threshold and probably overestimate the actual effects considerably. Factors used in other studies are generally lower (see Section 3C for further discussion) and lead to effects estimates as much as a factor of 10 lower than those developed in this report.

The health effects estimated to result from the back end of the fuel cycle for the base case population doses are:

Cancers:	whole body	-	503	(252 fatal)
	lung	-	15	(15 fatal)
	bone	-	3	(2 fatal)
	red marrow (leukemia)	-	91	(91 fatal)
	thyroid	-	20	(5 fatal)
			632	(365 fatal)
Genetic Effects		-	91	

The cancers listed for various organs other than whole body are in addition to cancers included in the whole body estimate and are caused by specific nuclide effects (e.g., ^{129}I thyroid

irradiation). ^{222}Rn releases from front end operations (mining, milling, and mill tailings piles) cause an estimated 1790 population health effects. Effects are calculated through the year 2101 to include a 100-year consideration of the environmental persistence of nuclides released through 2001. The 365 fatalities from back end operations represent an average increase of 0.00002 fatalities per year per 10^5 population over the 120-year period. The current U.S. death rate from malignancies is 170 per year per 10^5 population.

Although it is not correct to add cancers and genetic effects, this is done for perspective in this section and Section 9 to give comparative health effect totals (720 for the base case).

(b) Non-Radiological

Estimated quantities of chemicals discharged in airborne and liquid effluents from reprocessing and MOX fuel fabrication plants and supporting facilities are given in Section 2C. An assessment of these releases (Section 3B6) shows that all are well within existing standards and no adverse environmental effects are expected.

(c) Thermal

Waste heat from back-end fuel cycle facilities represents less than 1% of the heat generated by reactors and enrichment plants and hence is not a major consideration in decisions regarding recycle. Environmental statements for individual facilities proposed for construction will address the means of heat dissipation to the local environment.

(d) Occupational

Occupational exposure to external radiation at the reprocessing and fuel fabrication plants (assumed to average 0.4 rem/yr per employee) is estimated to be 46,000 whole-body man-rem through the year 2001. If the same linear dose/effect relationship used for population exposure is assumed, this dose could result in 18 cancer cases (50% fatal) to the work force and 10 serious genetic defects. Front end operations over the same period are estimated to incur 140 latent cancer deaths to uranium miners through a 12,400,000 man-rem occupational lung exposure and 1400 deaths from mining accidents (Section 3C4). Whereas the cancer deaths are projected on the basis of the hypothetical, conservative dose/effect relationship, the deaths from mining accidents are based on industry accident statistics.

(5) Economic Considerations

The cost of fuel cycle operations, exclusive of reactor costs, needed to support the LWR industry (507 GWe) through the year 2000 is estimated to be 223 billions of 1977 dollars. This cost is a small fraction of the total cost of generating nuclear electrical power and would be borne by the consumer. Front end operations (mining, enrichment, and UO_2 fuel fabrication) account for 80% of these costs. Back end operations (reprocessing, storage, MOX fuel fabrication, and waste management) account for the remainder. The total cost of reactors through the year 2000 is 700 billions of 1977 dollars and is not appreciably affected by choice of fuel cycle.

(6) Safeguards Considerations

Safeguards measures which have been implemented and are under consideration are discussed in Section 10. In the following section, the availability of plutonium arising from base case operations is described with reference to needs for safeguarding.

In an LWR industry operating with prompt recycle of plutonium and uranium, bulk plutonium will be present at the reprocessing plant finishing lines and adjunct storage areas of the integrated reprocessing-MOX fabrication complex. Later, at the same site, the plutonium will become available in process as bulk mixed oxide while being fabricated into fuel rods. Mixed oxide fuel rods will be transported to UO_2 fabrication plants and fabricated into fresh fuel assemblies. These assemblies will be transported to the LWR power plants and stored for some period of time before loading into the cores. Safeguards will be required for all phases of this part of the fuel cycle. Plutonium will be present in the irradiated assemblies which will be stored at the reactor and then transported to storage facilities at the integrated reprocessing plants. Bulk plutonium mixed with fission products will be present in process at the reprocessing plant before separations processing. Targets for theft or diversion and sabotage of plutonium in transit and at fixed processing plants are discussed in detail in Section 10.

2. Alternative Versions of the Base Case

a. Introduction

Five different versions of the base case are considered. Although the number and type of facilities, the size of process streams, and environmental effects may differ, the recycling configuration remains the same, i.e., recovering uranium and plutonium separately from spent fuel and returning them to the fuel cycle.

Impacts on materials, environment, costs, and safeguards are compared to the base case in the following discussions. The alternatives are:

- Longer cooling period (Alternative 1).
- Delay in startup of reprocessing (Alternative 2).
- No improvements in control of offgases (Alternative 3).
- Retrofit of AGNS with improved offgas control (Alternative 4).
- Siting Variations —

  Reprocessing and MOX fabrication plants at different sites (Alternative 5a)

  Reprocessing plants located to minimize transportation of spent fuel (Alternative 5b)

  Reprocessing plants located to minimize transportation of radioactive waste to terminal storage.

b. Longer Cooling Time (Alternative 1)

Both positive and negative effects result from storage of spent irradiated fuel for a longer period than is necessary to meet shipping constraints and reprocessing plant design limits. The inventory of short-lived nuclides in the spent fuel will decrease, thereby reducing population and occupational exposures associated with releases of these nuclides. However, the primary benefit of recycle, conservation of a limited natural resource, will be delayed, and the fissile ^{241}Pu that decays during the extended storage represents an irretrievable loss.

Alternative 1 assumes that irradiated fuel is stored (cooled) 5 years before reprocessing. Compared to the base case (1 year cooling), cooling for 5 years affects operations through the year 2000 as follows: back end activities are reduced and front end requirements are increased. The quantity of spent fuel reprocessed through the year 2000 decreases by 45,100 MTU (to 83,100 MTU). But the total reprocessing activity (all spent fuel discharged through the year 2000) and the total amount of plutonium separated remain the same as the base case. In the year 2000, one less reprocessing plant would be needed. Material flows for Alternative 1 are given in Appendix A, Table A-6.

Front end operations through the year 2000 would be increased to compensate for decreased recycled streams. Mining requirements through the year 2000 would increase 11% to 1,165,000 MT U_3O_8. Mining demand in the year 2000 would be increased 6%.

The principal effect on effluents compared to the base case (one year fuel cooling) are: 1) A delay in the release of radiological and chemical effluents from the back end of the fuel cycle. 2) An increase in the quantities released because reprocessing of spent fuel discharged through the year 2000 continues under Alternative 1 into the year 2007 (Table A.6) and results in nearly five additional years of operation of the AGNS plant (assumed to operate with existing offgas controls) compared to the base case. The increased release from AGNS more than offsets radioactive decay resulting from the additional cooling. 3) An increase in the ^{222}Rn and chemicals released because of the increased mining, milling, and enrichment of uranium through the year 2000.

Compared to the base case, population health effects attributable to reprocessing activities through the year 2000 decrease from 680 to 670 under the linear EPA dose-effect factors (^{14}C has the greatest impact). However, health effects attributable to radiological effluents from reprocessing all spent fuel discharged through the year 2000 increase under Alternative 1 from 720 to 900, as shown below:

Cancers: whole body - increased from 503 to 640 (50% fatal). Front end effects are increased from 1790 to 1960; however, the increase would be offset by corresponding reductions

in the period 2001-2006 as recycled streams reduce mining requirements.

thyroid - unchanged at 20 (25% fatal).

lung - decreased from 15 to 13 (100% fatal).

leukemia - increased from 92 to 113 (100% fatal).

bone - unchanged at 3 (50% fatal).

Genetic Effects - increased from 91 to 109.

Over the long term, well beyond the end of this study period, little difference would be expected in health effects from reprocessing spent LWR fuel cooled one year or five years. With five-year cooling, tritium and ^{85}Kr releases would decrease about 20%, but the population dose (to an equivalent population) would decrease only about 3%. If reprocessing spent fuel cooled for five years is assumed to result in a four-year delay in radiological releases compared to reprocessing fuel cooled one year, then the projected growth in population during the four years (8% increase) would result in population exposures that exceeded those from reprocessing fuel cooled only one year.

Occupational health effects (28) and accidental deaths (7) from back end operations are the same as those for the base case. Increased uranium mining and milling increases the front end occupational health effects by 18 (from 143 to 161) and accidental

deaths by 200 (from 1400 to 1600); however, these would be offset by an equivalent decrease in mining health effects and accidental deaths as recycled streams from reprocessing reduce mining requirements in the period 2001-2006.

Storage of spent fuel for five years before reprocessing results in a slight increase in fuel cycle costs (~2 billions of 1977 dollars) through the year 2000.

Total safeguards requirements are also unchanged. The amount of plutonium processed through the year 2000 is decreased by 36%, but this reduction results from the delay before reprocessing, and the total plutonium produced in Alternative 1 is about the same as for the base case.

c. Delayed Startup of Fuel Reprocessing (Alternative 2)

The startup of commercial fuel reprocessing plants in the United States is contingent upon affirmative decisions to proceed by the government and industry. Alternative 2 assumes that startup of the AGNS plant is delayed until 1986 and that startup of subsequent model reprocessing plants begins in 1991 (5 years later than assumed in the base case).

Compared to the base case, delayed startup of reprocessing reduces the quantity of spent fuel reprocessed through the year 2000 by 34,500 MTU (to 93,700 MTU). However, the total reprocessing activity and the total amount of plutonium separated from all LWR fuel discharged through the year 2000 remain the same as

for the base case. In the year 2000, seven reprocessing plants would be needed, as in the base case. Material flows for Alternative 2 are given in Appendix A, Table A-7.

Front end operations through the year 2000 would be increased to compensate for decreased recycled streams. Mining requirements through the year 2000 would increase 9% to 1,136,000 MT U_3O_8. Mining demand in the year 2000 would be unchanged from the base case.

A 5-year delay in reprocessing would decrease population health effects attributed to reprocessing activities through the year 2000 from 680 to 470, primarily because releases from 5-years operation of the AGNS plant (assumed to operate with existing offgas controls) would be eliminated. However, for long-term operation of a reprocessing industry (well beyond the end of the study period), population health effects would be unaffected by a 5-year delay in startup.

Under Alternative 2, the health effects attributed to reprocessing all LWR fuel discharged through the year 2000 would decrease from 720 to 630, primarily because AGNS is projected to operate for 20 years in Alternative 2 compared to 22 years for the base case. Radiological effects compared to the base case would be:

Health Effects

Cancers: whole body - decreased from 503 to 440 (50% fatal); front end health effects are increased from 1790 to 1950

thyroid - no change at 20 (25% fatal)

lung - decreased from 15 to 11 (100% fatal)

leukemia - decreased from 92 to 81 (100% fatal)

bone - no change at 3 (50% fatal)

Genetic Effects - decreased from 91 to 66

Occupational Effects

From front end operations - increase in miner cancers from 143 to 155

- increase in miner accidental deaths from 1400 to 1500

From back end operations - no change in worker health effects or accidental deaths from base case

Delay of 5 years in startup of AGNS and the succeeding model reprocessing plant results in a slight increase in fuel cycle costs (∿2 billions of 1977 dollars) through the year 2000.

Total safeguards requirements are also unchanged. The amount of plutonium processed through the year 2000 is decreased by 29%. This reduction results from the delayed reprocessing, and the total plutonium commitment in Alternative 2 is about the same as for the base case.

d. No Improvements in Control of Offgases (Alternative 3)

This alternative assumes that no additional offgas controls beyond those currently available and planned for operation in the early 1980s are provided for any of the reprocessing plants. Thus, the radioactive releases to the atmosphere estimated in Table 2.7 prevail for each reprocessing plant. Total releases from back end operations of the fuel cycle based on LWR operation through the year 2000 are compared in Table 5.2 for the nuclides that contribute to the offsite population exposure. Also, the additional population dose from release of ^{222}Rn that would be expected if the tailings piles were not covered with 12 ft of earth is discussed.

Calculation of health effects from the doses given in Table 5.2 shows that:

- Estimated total offsite health effects (worldwide plus regional) would be increased by a factor of 3.4 (from 720 to 2470).
- Most of the increase is due to the estimated worldwide effects of dispersal of ^{14}C.

The estimated total health effects, based on the conservative EPA dose-effect factors described in Section 3C, are within the variation in estimates of health effects from exposure to natural background radiation. This is especially true in the case of ^{14}C, where the estimated total releases from the LWR fuel reprocessing

TABLE 5.2

Estimated Radioactive Releases and Population Doses from Fuel Reprocessing Plants Based on LWR Operation Through the Year 2000

	Base Case (Additional Offgas Controls after AGNS)				*Alternative 3 (No Additional Offgas Controls)*			
	Release from AGNS, Ci	*Release from Other Plants, Ci*	*Total Release, Ci*	*Population[a] Dose, man-rem*	*Release from AGNS, Ci*	*Release from Other Plants, Ci*	*Total Release, Ci*	*Population[a] Dose, man-rem*
^{3}H	2.1×10^{7}	8.6×10^{5}	2.2×10^{7}	1.1×10^{5}[b]	2.1×10^{7}	8.9×10^{7}	1.1×10^{8}	4.7×10^{5}[b]
^{14}C	1.3×10^{4}	5.4×10^{2}	1.4×10^{4}	9.9×10^{5}[b]	1.3×10^{4}	5.5×10^{4}	6.8×10^{4}	4.5×10^{6}[b]
^{85}Kr	2.7×10^{8}	1.1×10^{7}	2.8×10^{8}	1.4×10^{5}[b]	2.7×10^{8}	1.1×10^{9}	1.4×10^{9}	6.3×10^{5}[b]
^{129}I	57	23	80	3.3×10^{5}[c]	57	233	290	1.1×10^{6}[c]
TRU Alpha	6.7	2.7	9.4	1.0×10^{5}[d]	6.7	27.2	33.9	3.2×10^{5}[d]

a. Local, U.S., Worldwide populations (see Appendix B for dose distribution).

b. Whole body dose.

c. Thyroid dose.

and recycle industry amount to less than the ^{14}C that occurs naturally in the same affected environment, and where ^{14}C provides about 1% of the total population exposure to naturally occurring radioactivity.

Other differences in health effects to offsite populations would be related to offgas controls in the front end of the fuel cycle. A major source of these effects is the ^{222}Rn gas released from the piles of mill tailings. With the control system included in the base case (12 ft of earth cover added to tailings piles), the estimated total health effects (lung cancer) from operations through the year 2000 are 1790 (300 from tailings). Without the earth cover, estimated effects would total 4610 (3100 from tailings).

Preliminary cost estimates for the individual offgas control systems are discussed in Section 9 and were obtained by escalating estimates given in References 4 and 5 and adding an allowance for uncertainties in technology and for handling and storage of wastes. The control steps described in Section 2C (voloxidation, catalytic oxidation of carbon to CO_2, selective absorption of ^{85}Kr and ^{14}C, iodine evolution from dissolver solutions, and a sand filter) for a model plant built after year 1985 are estimated to cost about 30 million (1977 dollars) in capital monies and 11 million in annual charges. Total incremental savings (capital and annual) from eliminating offgas controls in the six model reprocessing plants projected to start up after 1985 are estimated to be about 1 billion (1977) dollars.

Total cost for covering all tailings piles that result from base case milling operations with 12 feet of earth is estimated to be 43 million dollars based on costs given in Reference 3 and escalated to FY-1977 dollars.

e. Retrofit AGNS with Improved Offgas Controls (Alternative 4)

This alternative assumes that the Barnwell Nuclear Fuel Plant (AGNS) is retrofitted in 1986 with improved offgas control equivalent to that included in new model reprocessing plants coming online in 1986 and thereafter (see Table 2.8). With these additional controls, the total estimated health effects would decrease by 550 (to 170).

The cost for such retrofit is extremely uncertain, but it is expected to be much greater than for equivalent controls in new plants. A very rough estimate for the cost of retrofitting AGNS is 80 million dollars capital cost and 20 million annual charges. Thus, retrofitting AGNS could increase operating costs by about 1/3. These costs are obtained as described in Section 9 by escalating estimates for retrofitting control systems given in References 4 and 5 to 1977 dollars, and assigning a retrofit penalty to cost estimates for which retrofit estimates were incomplete. The estimate for AGNS includes the same allowance for waste handling and uncertainties that were included in the estimates for control equipment in new plants (see Section 9). The total incremental cost for retrofitting AGNS estimated by this method would be about 500 million (1977) dollars.

This alternative also assumes increasing the mill tailings cover to 20 ft. This additional cover is estimated[2] to reduce radon releases by a factor of five compared to the base case. Estimated health effects would be reduced by 110 to 1680.

Proposed Fuel Cycle Standards

In Section 3C, the ^{85}Kr, ^{129}I, and TRU alpha releases for the base case were compared to the proposed EPA standards that would limit these releases on the basis of GWe generated. It was shown that the standards would be exceeded by base case releases throughout the study period, even though plants started up after 1985 would have improved offgas controls. If AGNS were retrofitted in 1985, the releases for this alternative would compare to the standards as shown:

	^{85}Kr, Ci		*^{129}I, Ci*		*TRU Alpha ($T_{\frac{1}{2}}$ > 1 yr)*	
Year	*Allowed*	*Estimated*	*Allowed*	*Estimated*	*Allowed*	*Estimated*
1981	NA[a]	NA[a]	NA[a]	NA[a]	0.03	0.1
1983	4.4×10^6	1.4×10^7	0.44	3.0	0.044	0.25
1985	5.9×10^6	1.4×10^7	0.58	3.0	0.058	0.25
1990	1.0×10^7	7.1×10^5	1.0	1.5	0.10	0.13
1995	1.5×10^7	9.3×10^5	1.5	2.0	0.15	0.17
2000	1.9×10^7	9.3×10^5	1.9	2.1	0.16	0.18

a. Not applicable.

The proposed EPA standards as presently written would be effective for TRU alpha emitters beginning 24 months after final publication and on January 1, 1983 for ^{85}Kr and ^{129}I. It is evident from the table above that in the event the standards are adopted, controls will be necessary before 1985 and retrofitted to existing plants. Variance provisions in the standard may provide some leeway in the timing for individual plant compliance with the numerical standards. Some additional control improvement beyond the assumption given in Table 2.8 would also be required to ensure compliance for ^{129}I and TRU alpha releases.

f. Site Variations (Alternatives 5a, 5b, and 5c)

Three siting alternatives to the base case are examined in this section to assess the significance of different transportation requirements. Population densities are assumed to be unchanged from the base case.

(1) Reprocessing and MOX Fabrication at Different Sites (Alternative 5a)

Material requirements and process flows for reprocessing and MOX fabrication plants located at separate sites would be the same as for the base case. The facilities are assumed to start up on the same schedule as the collocated facilities in the base case. Slight differences in operation might result, e.g., onsite incineration of TRU wastes might not be economical, but these differences are judged to be insignificant.

The largest changes in environmental effects from those of the base case result from total increased population exposure of about 15 man-rem from transportation of PuO_2 and the increased risk of accidents because of the greater transportation mileage (80,000 miles in the year 2000). The increased dosage corresponds to about 0.006 statistical health effect, and the increased shipping would be expected to result in 0.008 statistical fatalities from traffic accidents.

Fuel cycle costs would be the same as for the base case. Some economies might accrue to the collocated complex in the base case if the complex were operated by the same company. However, the differences would not affect the total fuel cycle costs significantly, because back end operations contribute only 20% of the total.

The main difference from the base case is that the purified plutonium oxide is more vulnerable to sabotage attack or theft during shipment between the fuel reprocessing plant and the MOX plants than when confined to the substantial processing facilities with more effective safeguards controls.

(2) Reprocessing Plants Located to Minimize Transportation of Spent Fuel (Alternative 5b)

Locating integrated reprocessing/MOX fabrication plants to minimize transportation of spent fuel (Alternative 5b) primarily affects radiological exposures to the general population and to transportation workers and the risks of conventional transportation

accidents. If the same population density is assumed for each site, regardless of its location, the differential effects associated with Alternative 5b are small. Material requirements and process flows would be the same as for the base case and fuel cycle costs would be essentially unchanged because transportation costs are small compared to the total cost of the fuel cycles.

According to a study by Holmes and Narver,[6] the average distance required to ship spent LWR fuel to reprocessing plants could be reduced to 600-700 miles if new plants were located near Salt Lake City, Dallas, Cincinnati, and St. Paul. This study assumed that existing reprocessing plants were located in West Valley, New York, Barnwell, South Carolina, and Morris, Illinois.

In Alternative 5b, 90% of the spent fuel shipped to reprocessing plants is assumed to travel by rail over an average distance of 600 miles (down 400 miles from the base case). The remaining shipments are assumed to travel by truck over an average distance of 250 miles (down 250 miles from the base case). The distance traveled by spent fuel decreases 50% to 2.2 million miles in the year 2000. Compared to the base case, the associated radiation exposure to the general population is reduced 60% (to 70 man-rem) and exposure to transportation workers is reduced 70% (to 70 man-rem) in the year 2000. For perspective, the dose from one year's operation of the seven reprocessing/MOX plants of the

base case to the seven million persons assumed to reside within a 50-mile-radius of these plants is estimated to be 1400 man-rem (Table 3.5).

(3) Reprocessing Plants Located Near Federal Waste Repositories (Alternative 5c)

Locating integrated reprocessing/MOX plants near Federal repositories to eliminate transportation of radwaste (Alternative 5c) primarily affects radiological exposures to the general population and to transportation workers and the risks of conventional transportation accidents. Material requirements, process flows and fuel cycle costs would be about the same as those for the base case because transportation costs are a small fraction of the total fuel cycle costs.

In Alternative 5c, 3500 rail shipments of waste to Federal repositories are eliminated. This action would require additional transportation of spent fuel (each shipment is increased 800 miles to 1800 miles), but the added transportation would occur primarily in states where population densities are low. Shipments of MOX fuel from the integrated facilities to uranium fuel fabrication plants are assumed to increase 1600 miles to 1800 miles per shipment. The resultant effects on transportation would be:

- Rail mileage (loaded casks) would decrease 50% (to 4.5 million miles).
- Truck mileage (filled shipping containers) would increase 190% (to 8.5 million miles).

Radiation exposures in the year 2000 would be expected to increase because of increased transportation by truck. Exposures to transportation workers would increase about 160% (to 970 man-rem). Exposures to the general population would increase about 20% (to 400 man-rem). However, exposures to the local populations are reduced because regions around the reprocessing/MOX plants are more sparsely populated than in the base.

3. Recycle Uranium Only (Alternative 6)

a. Description

Alternative 6 is the reprocessing of spent fuel after decay for one year, the storage of the plutonium for future use or eventual disposal, and the recycling of the recovered uranium in the existing LWR-UO_2 industry. As in the base case, the installed generating capacity of LWRs is projected to be 507 GWe in the year 2000. The primary fuel material under this alternative would be virgin uranium supplemented by recycled uranium when it becomes available from the reprocessing plants.

Plutonium could possibly be stored at the reprocessing plants in the form of nitrate solution for short periods. The plutonium nitrate solution would be converted to plutonium oxide at the reprocessing plants, and then the oxide would be shipped to a plutonium storage facility, which could be located onsite. The period of time for which plutonium is stored has an important bearing on the type of storage that must be provided. Precautions must be taken to ensure safety when plutonium is handled and to ensure strict materials accountability when plutonium is transferred from point to point.

b. Effects on LWR Fuel Cycle Operations

(1) Materials Processed

Material requirements in the LWR fuel cycle that assumes reprocessing spent fuel and recycling only uranium differ from the base case that includes plutonium recycle.

Uranium feed demand in the year 2000 would require an increase of about 16% in mining and milling. Eight additional mine-mill complexes would produce an additional 11,000 MT of U_3O_8. Total U_3O_8 requirements through the year 2000 would be increased 135,000 MT U_3O_8 (13% of base case requirements).

Demand for uranium enrichment to meet domestic LWR requirements in the year 2000 would increase 19% (8 million SWU) and would require one additional isotopic enrichment plant. About one-half of the separative work in the year 2000 is assumed to meet foreign needs.

Although the total amount of fuel charged to the reactors is unchanged, the UO_2 fuel requirement in the year 2000 would increase by 2300 MTU to replace MOX fuel produced in the base case. The increased demand is assumed to be met by one additional UO_2 fuel fabrication plant and transfers from inventory.

The reprocessing load forecast for the year 2000 would be the same as for the base case. However, the plutonium processed would decrease approximately 17 MT because, with uranium recycle, the plutonium content of the spent fuel will be less than for the base case. The total amount of plutonium processed from spent fuel through the year 2000 would decrease about 170 MT to 1200 MT. All of this plutonium is assumed to be placed in storage. Transportation of fuel materials including PuO_2 to storage in the year 2000 is expected to decrease by about 1400 shipments (to

8500). Material flows projected for Alternative 6 are given in Appendix A, Tables A-1 through A-5.

(2) Use of Natural Resources

The industry in the year 2000, including nuclear reactors, will require about 760,000 acres of temporarily committed land and about 57,000 acres of permanently committed land under Alternative 6. The increase of about 4,000 acres of permanently committed land from the base case is attributed almost entirely to the increased number of mining and milling facilities.

Electrical energy requirements in the year 2000 are expected to increase 21 million MW-hr to 231 million MW-hr under Alternative 6. About two-thirds of the increase is attributed to the additional requirements for separative work, and the remainder of the increase results from higher throughput requirements in the mining, milling, and UF_6 conversion steps of the fuel cycle.

Consumption of natural gas will increase by 4.5 billion ft^3 to 39 billion in the year 2000. The increase is attributed to the increased process heat load in the milling conversion operations.

(3) Waste Management

The industry under Alternative 6 is expected to generate in the year 2000 about the same amount of concentrated high-level

liquid waste as in the base case, which will, within 5 years, be converted to the same amount (630 m^3) of dry solid. The dry solid must be shipped to a Federal repository by the year 2010. Production of transuranic wastes is expected to decrease about 19,000 m^3 because MOX plants would be eliminated. These wastes must be stored pending ultimate disposal. Radioactive waste from other fuel cycle operation (reactors, primarily) would be generated in about the same amount as for the base case. This waste will be buried at sites licensed to receive such wastes. Transportation of wastes associated with industry operations in the year 2000 is expected to decrease 700 shipments (to 4700).

(4) Effluents and Environmental Effects

(a) Radiological

Effluents and environmental effects of closing the LWR fuel cycle by reprocessing and then recycling only uranium differ as follows from the base case that includes plutonium recycle.

Releases of the radionuclides that result in nearly all of the worldwide or regional health effects from the back end of the fuel cycle are not changed significantly from the base case. These nuclides are ^{3}H, ^{85}Kr, ^{14}C, and ^{129}I. Releases of particulates containing transuranium nuclides are reduced because of the smaller amount of plutonium and other transuranics in the fuel being reprocessed and because there is no MOX fuel fabrication plant. The reduction results in 90,000 less man-rem bone dose and 3 fewer health effects (bone cancers).

A more significant radiological effect of this alternative is the increased release of ^{222}Rn from mining and milling and from mill tailings. This effect is directly proportional to the quantity of uranium mined and milled. The increase in ^{222}Rn release results in an estimated increase of about 190 health effects from operation through the year 2001.

(b) Non-radiological

Chemical releases from the back end of the fuel cycle are about the same as those for the base case. The biggest effect is from the 13% increase in the chemicals used and fuels burned to provide power for the increased front end activities of mining, milling, and enriching uranium.

(c) Occupational

Occupational exposure from back end operations is reduced by 11,000 man-rem [6 health effects (from 28 to 22)] by elimination of MOX plants; front end mining increases are estimated to result in 25 additional health effects (from 143 to 168) to miners from radiation exposure and 200 more (from 1400 to 1600) accidental mining deaths.

(5) Economic Considerations

The cost of fuel cycle operations needed to support the LWR industry under Alternative 6 through the year 2000 is expected to increase by 23 billions to 246 billions of 1977 dollars. Front end operations (mining, enrichment, and UO_2 fuel fabrication)

account for 84% of these costs. Back end operations (reprocessing and storage) account for the remainder.

(6) Safeguards Considerations

Safeguards measures which have been implemented and are under consideration are discussed in Section 10. In this section, the availability of plutonium arising from fuel cycle operations under Alternative 6 is described with reference to needs for safeguards.

In an LWR industry operating with recycle uranium and storage of plutonium (Alternative 6), bulk plutonium will be present at the reprocessing plant storage and load-out areas and would have to be safeguarded. Storage of the hundreds of tons to be recovered by the year 2000 would require considerable attention. Transportation of PuO_2 from the reprocessing plants to the central storage repository would be a potentially vulnerable activity that would require careful safeguarding.

Under Alternative 6, transportation of PuO_2 to the onsite fabrication plants and the availability of pure PuO_2 and PuO_2 mixed with UO_2 within fabrication plants during processing would be deferred. Similarly, the availability of PuO_2 mixed with UO_2 in fresh fuel assemblies in storage at the fabrication plant, in transit to power reactors, and in storage at reactor sites before loading would also be deferred. Thus, plutonium handling at transfer points and in unsecured areas would be greatly reduced for this alternative.

4. No Recycle (Alternative 7)

a. Description

Alternative 7 is the LWR fuel cycle in which spent fuel is stored before permanent disposal or possible subsequent reprocessing and recovery of the plutonium and uranium. The same level of reactor operation is assumed as for the base case. However, the only fuel material used would be virgin uranium.

Following irradiation for approximately three to four years, spent fuel assemblies would be discharged from the reactor and stored in basins, possibly for 3 to 4 years. The fuel assemblies would then be shipped to a central storage facility. Storage for the purposes of the following discussion is assumed to be beyond the year 2000.

b. Effects on LWR Fuel Cycle Operations

(1) Materials Processed

Material requirements in the LWR fuel cycle that assume no recycle differs as follows from the base case that includes recycle of plutonium and uranium.

Uranium feed demand in the year 2000 would require an increase of about 39% in mining and milling. Twenty-two additional mine-mill complexes would produce an additional 27,000 MT of U_3O_8. Total U_3O_8 requirements through the year 2000 would be increased 334,000 MT (32% of base case requirements).

Demand for uranium enrichment to meet domestic LWR requirements in the year 2000 would increase 20% (9 million SWU) and would

require one additional isotopic enrichment plant. About one-half of the separative work production in the year 2000 is assumed to meet foreign needs.

Although the total amount of fuel charged to the reactors is unchanged, the UO_2 fuel requirement in the year 2000 would increase by 2300 MTU to replace MOX fuel produced in the base case. The increased demand is assumed to be met by one additional UO_2 fuel fabrication plant and transfers from inventory. However, eliminating the spent fuel reprocessing step would eliminate the seven reprocessing facilities required under the base case and reduce total transportation in the year 2000 by 7600 shipments to 8700 shipments. The 10,500 MTU slated for reprocessing under the base case would be stored at irradiated fuel assembly storage facilities applicable for long-term storage. Material flows for Alternative 7 are given in Appendix A, Table A-1 through A-7.

(2) Use of Natural Resources

The industry in the year 2000 (including power plants) will require about 790,000 acres of land on a temporary basis and about 63,000 acres of permanently committed land under Alternative 7. The increase of about 10,000 acres of permanently committed land is attributed to the increased number of uranium mining and milling facilities.

The land committed to mining and milling operations, about 510,000 acres temporarily committed and about 39,000 acres permanently committed, represent about 64% and 62% of the industry

totals, respectively. Thus, mining and milling land requirements combined with the land needs of the nuclear reactors represent over 96% of the total land requirements of the industry. The facility for packaging and interim storage of spent fuel is expected to require about 1% of the temporarily committed land.

Annual electrical energy requirements are expected to increase 21 million MW-hr to 231 million MW-hr under Alternative 7. About two-thirds of the increase is attributed to the increase in separative work requirements in the enrichment facilities. The remainder of the increase is produced by the higher throughput requirements in the mining, milling, and UF_6 conversion steps of the fuel cycle.

Similarly, consumption of natural gas will be increased 13 billion ft^3 to 47 billion ft^3. The entire increase is attributed to the increased process heat load in the milling and conversion operations.

(3) Waste Management

Eliminating the fuel reprocessing step does away with the generation of high-level wastes and transuranic wastes, but the volume of radioactive wastes scheduled for burial at commercial burial grounds increases slightly.

There would be no reprocessing plants or mixed oxide fabrication plants and no concern for safeguarding purified plutonium.

There would be no immediate requirement for high-level waste management. However, spent fuel storage facilities and provisions for containing emissions from deteriorating fuel would be required. Eventually, packaging and disposal of the spent fuel assemblies would be required unless a decision was made to reprocess the spent fuel, in which case waste management facilities similar to those in the base case would be required.

(4) Effluents and Environmental Effects

(a) Radiological

Effluents and environmental effects of this alternative differ from the base case of plutonium and uranium recycle in the following manner.

Only very minor short-term radiological effects are estimated for interim storage of the irradiated fuel assemblies. These effects result from occasional fuel failures and the risk of low probability accidents. Therefore, almost all of the total 720 health effects estimated to result from reprocessing operations are prevented. However, if subsequent processing of the fuel is required, these effects are merely deferred.

About 32% more uranium is mined and milled than in the base case, resulting in an estimated additional 570 health effect (from 1790 to 2360) from the ^{222}Rn released from mining and milling and from mill tailings.

(b) Non-Radiological

Chemical (non-radiological) releases from the back end of the fuel cycle are eliminated, but these are exceeded by the increased need for chemicals and power for chemicals and power for the front end activities of mining, milling, and enriching uranium.

(c) Occupational

Occupational exposure from back end operations are eliminated (46,000 man-rem — an estimated 18 cancer cases and 10 genetic defects). Front end mining increases are estimated to result in 45 additional health effects (from 143 to 188) to miners from radiation exposure and 400 more accidental mining deaths (from 1400 to 1800).

(5) Economic Considerations

When the LWR industry is considered through the year 2000 for the no recycle case (Alternative 7), the total cost of fuel cycle operations, exclusive of reactors, increases 12 billion dollars to 235 billions. Front end operations (mining, enrichment, and UO_2 fuel fabrication) account for 98% of these costs. The cost of interim storage in basins, canning, shipping, and terminal storage accounts for the remainder. If a decision is made to retrieve and reprocess the spent fuel at some later date, additional costs will be incurred. However, the value of the recovered plutonium and uranium is expected to exceed the additional costs.

(6) Safeguards Considerations

Safeguards measures which have been implemented and are under consideration are discussed in Section 10. In this section, the availability of plutonium arising from throwaway fuel cycle (Alternative 7) is described with reference to needs for safeguards.

For this alternative, plutonium would be present only in a diluted form and would be entirely contained within irradiated fuel assemblies. Reprocessing plants and LWR mixed oxide fabrication plants would not be required before the year 2000. The spent fuel could be stored at existing storage basins or at a central repository. Transportation requirements from nuclear power plants to storage would be about the same in either case.

5. Alternative Technologies

Two fuel cycles that use the fissile content of spent fuel from light water reactors to provide additional electrical power but do not separate plutonium into a concentrated form are discussed below. These are coprocessing (processing spent LWR fuel to recover uranium and plutonium in a single fuel stream) and the tandem cycle (irradiating spent LWR fuel in heavy water reactors).

a. Coprocessing (Alternative 8)

(1) Description

Alternative 8 is the reprocessing of spent fuel, after decay for one year, without separation of plutonium from uranium. The fissile content of recovered U-Pu mixtures would be increased by the addition of enriched uranium; no recovered uranium would be returned to the gaseous diffusion plant. All recycled uranium would contain plutonium and, therefore, would be treated as mixed oxide fuel. As in the base case, the installed generating capacity of LWRs is projected to be 507 GWe in the year 2000.

At the reprocessing plant, fuel assemblies would be dissolved and chemically treated to produce two primary streams. One stream would contain all recovered uranium and plutonium that would serve as feed for the mixed oxide fuel fabrication plant. The other stream, containing high-level fission product waste, would be stored onsite as a liquid for up to five years, then solidified and transferred to a disposal site. In addition, an input stream of enriched uranium is added to the recovered U-Pu mixture to meet requirements on fissile content of the MOX plant feed.

Recovery and recycle of uranium and plutonium without separation leads to several changes in the fuel recycle facilities. The major process differences are:

- Fewer cycles of solvent extraction are required for recovery and decontamination from fission products. In the typical fuel reprocessing plant, U and Pu are coextracted and partitioned in the first solvent extraction cycle, followed by additional decontamination in separate cycles of solvent extraction and/or ion exchange. Coprocessing eliminates the need for partitioning; both products are decontaminated simultaneously so that duplicate equipment for separate products is eliminated.
- A facility for converting plutonium nitrate to plutonium oxide is eliminated. The plutonium is converted with the uranium in a thermal denitration step.
- The facility for converting UO_2 to UF_6 is eliminated.
- The capacity of the mixed oxide fuel fabrication facility must be over five times greater with coprocessing than with separate uranium and plutonium recycle.

Competing factors influence the choice of ^{235}U enrichment selected for addition to the recovered U-Pu mixture. Use of low enrichment minimizes separative work requirement while a higher enrichment reduces the fabrication cost of mixed oxide.

An upper limit of 20% ^{235}U is necessary to avoid the concern of proliferation and safeguards for the enriched uranium makeup

stream. The optimum value of ^{235}U enrichment depends on the mixed oxide fuel fabrication cost, which is not well known. At an assumed value of $200/kg for mixed oxide fabrication, a ^{235}U enrichment of 10 to 20% is best. For this analysis, 19.5% ^{235}U was used; this choice requires blending one part 19.5% ^{235}U to ten parts of recovered U-Pu mixture. The resulting increase in fuel inventory from reprocessing plants can be used effectively in a growing nuclear economy. About 15% more separative work is required when 19.5% ^{235}U is blended, compared to re-enrichment of the uranium stream when uranium and plutonium are separated and recycled independently.

(2) Effects on LWR Fuel Cycle Operations

(a) Materials Processed

Uranium feed requirements for the LWR fuel cycle that assumes coprocessing of spent fuel are the same as for the base case that includes separation and recycle of the uranium and plutonium. Process requirements that differ include:

- Demand for uranium enrichment to meet domestic LWR requirements through the year 2000 would increase 12% to 690 million SWU); this increase would require one additional isotopic enrichment plant.
- Although the total amount of fuel charged to the reactors is unchanged, the UO_2 fuel requirement peaks at about 5000 MTU per year. This capacity can be achieved by expanding the capacity

of the six existing UO_2 plants; the four new plants required in the base case are not needed.

- The reprocessing load forecast for the year 2000 is the same as for the base case. However, the annual MOX fuel fabrication capacity increases from the 2450 MTHM requirement of the base case to 10% more than the total reprocessing load, or 11,550 MTHM. The total amount of plutonium processed is the same as in the base case. Material requirements for Alternative 8 are summarized in Appendix A, Table A-8.

(b) Use of Natural Resources

The industry in the year 2000 will require slightly less land in temporary commitment than the base case (∿3000 acres difference) primarily because of fewer UO_2 fabrication plants. The permanent commitment of land will be unchanged. Other resource requirements are essentially unchanged.

(c) Waste Management

The industry under Alternative 8 is expected to generate in the year 2000 about the same amount of concentrated high-level liquid waste as in the base case, which will be converted within 5 years to the same amount (630 m^3) of dry solid. The dry solid must be shipped to a Federal repository by the year 2010. Production of transuranic wastes from MOX fuel fabrication plants is estimated to increase about 200% over the base case (to 40,000 m^3, after incineration or compaction). Radioactive waste from other

fuel cycle operations would be generated in about the same amount as for the base case. This waste will be buried at sites licensed to receive such wastes. Shipments of wastes associated with industry operations in the year 2000 is expected to increase by about 2600 (to 8000 shipments).

(d) Effluents and Environmental Effects

For Alternative 8 releases of radioactive materials and chemicals are assumed to be the same as for the base case. Although the capacity of MOX plants will be five times greater, the same amount of TRU alpha contamination will be released if off-gas control systems are comparable to the base case. Therefore, population health effects from back end and front end operations will be the same as the base case.

Occupational health effects from front end operations, miner cancers and accidental deaths will be the same as the base case. From back end operations, worker health effects and accidental deaths will be the same as the base case.

(e) Economic Considerations

The cost of fuel cycle operations needed to support the LWR industry under Alternative 8 through the year 2000 is expected to increase by 13 billions to 236 billions of 1977 dollars compared to the base case. The separative work cost increases $7 billion and fuel fabrication costs increase $11 billion. Chemical reprocessing costs decrease $4 billion and plutonium storage costs are eliminated ($0.3 billion).

(f) Safeguards Considerations

Safeguards measures which have been implemented and are under consideration are disucssed in Section 10. In this section, the availability of plutonium arising from coprocessing of uranium and plutonium (Alternative 8) is described with reference to needs for safeguards.

Under Alternative 8, plutonium would be available only in a diluted form, which would require diversion of about 100 times as much of the U-Pu mixture to obtain an equivalent quantity of Pu as from diversion of pure plutonium compounds. The diluted plutonium would be present at the reprocessing plant, the MOX fabrication facility, and in transportation to LWR power plants. Safeguards will be required for all phases of this part of the fuel cycle. Plutonium will be present in the irradiated assemblies as in the base case, only in a more dilute form. Targets for sabotage and Pu theft or diversion in transit and at fixed processing plants are discussed in detail in Section 10.

The ^{235}U used to re-enrich recovered U-Pu mixtures will not require safeguarding so long as the enrichment is kept below 20%.

b. Tandem Cycle (Alternative 9)

(1) Description

Alternative 9 is the refabrication of spent LWR fuel into fuel for a heavy water reactor (HWR) without chemical reprocessing. As in the base case, the installed generating capacity totals 507 GWe in the year 2000. This capacity is the sum of 380 GWe of of LWR power and 127 GWe of HWR power.

The tandem concept is calculated to extend the spent LWR fuel exposure by about 30%, thus depleting much of the residual fissile uranium and reducing the fissile plutonium by 20%. The value of fissile material remaining in the highly burned fuel may be less than the recovery cost, thus making chemical processing unattractive. Eliminating chemical reprocessing simplifies the safeguarding required to prevent diversion of plutonium for proliferation purposes.

Of the several ways of using spent LWR fuel in HWRs, the simplist and least expensive method in terms of fabrication costs would be to disassemble the fuel assemblies, cut off the end of the fuel rods, swage a zirconium tube around the fuel, and weld end caps in place. These fuel rods could then be assembled into 37 rod clusters to approximate the CANDU moderator-to-fuel ratio. Because these assemblies would be 2/3 as long as CANDU assemblies, a new HWR design would be required.

A second method would be to cut fuel rods into short sections (about 2 ft long) and reclad and bundle these short lengths. The ends of each LWR rod could be used in peripheral radial positions in a HWR, or they could be discarded. It would be difficult to guarantee that no rod ends were ever used in central channels of the core, where they would exceed specific power limits at full reactor power and necessitate a power derating.

Finally the LWR fuel could be disassembled as much as possible and the fuel pellets could be reground, homogenized, and reformed

into HWR pellets. This method has been used for this assessment because power reactor derating is minimized and the economics of the fuel cycle are most sensitive to reactor power.

In Alternative 9, spent LWR fuel is assumed to be refabricated into HWR fuel in a facility designed for 1500 MT/yr. The refabrication is expected to include the following steps.

- Removing Zircaloy cladding; disposing of hulls
- Pulverizing LWR fuel pellets
- Voloxidation (<500°C in oxidizing atmosphere); collecting and disposing of volatile effluents
- Reducing U_3O_8 to UO_2
- Grinding to produce sinterable UO_2
- Cold pressing (20,000 to 100,000 psi)
- Sintering (1600 to 1800°C in reducing atmosphere); collecting and disposing of volatile effluents
- Grinding pellets to final dimensions; disposing of scrap
- Inspecting and gaging pellets
- Encapsulating; loading pellets into rods, and welding
- Inspecting rods
- Assembling rods

Voloxidation is included to assist in removing gaseous fission products that could impair irradiation performance of the HWR fuel and also (in conjunction with the reduction step) as an aid in promoting sinterability of the UO_2 powder. Containment of fission gases released during rod unloading and pellet

fabrication, especially voloxidation, will require an off-gas treatment system similar to that assumed for model reprocessing plants.

The refabricated HWR-MOX fuel is assumed to be irradiated to about 9000 MWD th/MT in CANDU-type heavy water reactors. The model HWR is sized for the same power generation as model LWRs but is derated 15%, primarily because performance of refabricated fuel is expected to be poorer than performance of LWR fuel. Capital cost of the HWR is assumed to be 15% greater than model LWRs because of additions for hot fuel handling and different licensing requirements.

First cores in the HWR require 150 MTHM of fuel, and annual replacements require 76.5 MTHM. The spent fuel discharged from three model LWRs is assumed to fuel 1000 MWe of installed HWRs. The schedule for startup of model LWRs and equivalent 1000 MWe HWRs in Alternative 9 is given in Appendix A, Table A-9. Ten years are assumed to be needed to license and build the first HWRs.

(2) Effects on LWR Fuel Cycle Operations

(a) Materials Processed

Material requirements for the LWR fuel cycle that assumes recycle of spent LWR fuel into HWRs differ from the base case.

Uranium feed demand in the year 2000 is unchanged, however, the cumulative demand through the year 2000 would increase U_3O_8 requirements by 102,000 MT (10% of the base case requirements).

No additional mine-mill complexes are needed in the year 2000, however, earlier startup is required for some complexes.

Annual demand for uranium enrichment to meet domestic LWR requirements is forecast to peak in the year 1999 at 41 million SWU, 11% (~5 million SWU) less than required in the base case. The cumulative separative work demands through the year 2000 are unchanged from the base case, as is the number of enrichment plants required. However, the enrichment demand in Alternative 9 is greater in the early part of the study period.

The reduced separative work demand in the year 2000 is obtained at the cost of providing heavy water (D_2O) for the HWRs. About nine heavy water plants of 1000 MT/yr capacity would be required to bring HWRs on line according to the proposed building schedule (Table A-9).

The total amount of UO_2 fuel charged to LWRs is unchanged from the 165,000 MTU required for the base case. The annual requirement for UO_2 fuel fabrication peaks at 11,000 MTU compared to 12,300 MTU for the base case. One less UO_2 fabrication plant is required in the year 2000.

Chemical processing of spent LWR fuel to recover uranium and plutonium is eliminated in Alternative 9. However, 102,000 MTU of spent LWR fuel is refabricated into HWR-MOX fuel by the year 2000 (3.6 times as much MOX as fabricated in the base case). Eight refabrication plants are projected to meet the annual requirement of 11,500 MTHM of HWR fuel in the year 2000. Through

the year 2000, about 67,000 MTHM of spent HWR fuel would be stored awaiting final disposition. Projected material flows for Alternative 9 are given in Appendix A, Table A-10.

(b) Use of Natural Resources

The industry in the year 2000 will require about 8% more land in temporary commitment (60,000 additional acres) and permanent commitment (4,000 additional acres) than the base case. Most of this increase is associated with increased mining requirements. Other resource requirements are essentially unchanged.

(c) Waste Management

Eliminating fuel reprocessing does away with the generation of high-level wastes from reprocessing plants. However, high-level wastes would be generated at fuel refabrication plants (about 50,000 m^3 of incinerated and compacted waste in the year 2000). This waste must be shipped to a Federal repository. Very little high-level liquid waste would be generated. About 5000 shipments of waste are expected in the year 2000.

Spent fuel storage facilities and provisions for containing emission from deteriorating fuel would be required. The quantity of spent fuel to be stored in the tandem cycle is 25% less than in the throwaway case because fewer light water reactors are required (25% less in a mature industry). Eventually, packaging and disposal of the spent fuel assemblies would be needed.

(d) Effluents and Environmental Effects

Alternative 9 assumes that spent LWR fuel is fabricated into HWR fuel in refabrication facilities that are equipped with improved offgas controls. Releases of fission products from back end operations are reduced substantially compared to the base case. The release of radioactive effluents from CANDU-type heavy water reactors is expected to be small[7] and, except for tritium releases, the environmental effect of HWRs in the tandem cycle is assumed to be equal to that of the LWRs which they replace. The estimated annual release of tritium from a HWR is approximately four times as large as that from a reprocessing plant with improved offgas controls.*

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* The annual tritium release from a CANDU-type heavy water reactor was estimated as follows:

Bases

(1) D_2O loss rate assumed to be 100 g/hr for a 500-MWe CANDU reactor.[8]

(2) Tritium activity in D_2O assumed to be 40 Ci/l.

Calculation

Annual tritium loss from Model HWR

$$= 100 \text{ g } D_2O/\text{hr} \times \frac{40 \text{ Ci } T_2}{1100 \text{ g } D_2O} \times \frac{1000 \text{ MWe Model HWR}}{500 \text{ MWe Pickering Unit}}$$

$$\times 0.85 \text{ derating factor} \times 24 \text{ hr/day} \times 365 \text{ days/year}$$

$$\times 0.75 \text{ capacity factor} = 40{,}000 \text{ Ci } T_2/\text{yr}$$

In comparison to the base case, health effects from population exposures to radioactive effluents from the back end will be:

Cancer: Whole body - Decreased from 503 to 10 (50% fatal). (Population health effects from front end operations are increased from 1790 to 1960. An additional 70 health effects are expected from tritium released from HWRs)

Thyroid - No change at 20 (25% fatal)

Lung - Decreased from 15 to <1 (100% fatal)

Leukemia - Decreased from 92 to <1 (100% fatal)

Bone - No change at 3 (50% fatal)

Genetic effects - Decreased from 91 to 3

Occupational effects for Alternative 9 will be:

- From front end operations

  Miner cancers increased from 143 to 157
  Miner accidental deaths increased from 1400 to 1600

- From back end operations

  Worker health effects decreased from 28 to 22
  Worker accidental deaths decreased from 7 to 5

(e) Economic Considerations

The cost of fuel cycle operations needed to support the LWR-HWR industry under Alternative 9 through the year 2000 is expected to decrease from the base case by 11 billion (to 212 billion 1977 dollars); however, this savings is more than offset by an additional $55 billion in reactor charges resulting from cost premiums associated with construction and operation of HWRs.

(f) Safeguards Considerations

Safeguards measures which have been implemented and are under consideration are discussed in Section 10. In this section, the availability of plutonium arising from the tandem fuel cycle is described with reference to needs for safeguards.

In Alternative 9, plutonium would be available only in a diluted form and always homogeneously mixed with very large quantities of radioactive fission products. The same processing technology would be required to recover the plutonium in a form suitable for weapons as for the throwaway case. Safeguards will be required at the refabrication plant and during transportation of spent LWR fuel and refabricated HWR fuel. Safeguarding of spent HWR fuel past the year 2000 will be similar to that required for the throwaway case (Alternative 7) except that less fuel is involved.

C. FUEL CYCLE OPERATIONS FOR HIGHER AND LOWER PROJECTED NUMBERS OF REACTORS (600 AND 400 LWRs IN THE YEAR 2000)

1. Introduction

The effects on the fuel cycle industry of higher and lower growth rates of nuclear power (LWRs) than assumed for the base case have been examined to provide additional points of reference. The number of LWRs for the high and low growth schedule and the number of reprocessing and MOX fabrication facilities are compared with base case projections in Table 5.3 for the years 1985, 1990, 1995, and 2000. Reactor building schedules for the high and low schedules are given in Appendix A, Table A-9, and material flows are given in Appendix A, Tables A-11 and A-14.

2. Higher Projected Number of Reactors (600 LWRs in Year 2000)

a. Recover and Recycle Uranium and Plutonium (Alternative 10)

Overall effects of a higher nuclear growth rate will be commensurate with the increased number of LWRs. Table 5.3 shows the number of reactors and recycle facilities compared to the base case. Total mining requirements through the year 2000 would increase about 16% from 1.05×10^6 MT U_3O_8 to 1.21×10^6 MT U_3O_8. Land and power requirements would be increased proportionately.

The projected number of fuel cycle facilities which will constitute the industry in the year 2000, both with and without spent fuel recycle, are summarized in Table 5.4.

TABLE 5.3

Number of Reactors and Recycle Facilities for High and Low Nuclear Growth Projections

Calendar Year	High Projection			Low Projection			Base Case		
	No. of LWRs	No. of Plants[a]		No. of LWRs	No. of Plants[a]		No. of LWRs	No. of Plants[a]	
		Reprocessing	MOX		Reprocessing	MOX		Reprocessing	MOX
1985	172	1	1	136	1	1	156	1	1
1990	302	6	5	230	4	4	268	6	5
1995	459	7	7	332	6	6	399	7	7
2000	600	9	9	400	6	6	507	7	7

a. All reprocessing plants are rated at 1500 MTU/yr. Model MOX fabrication plants are collocated with reprocessing plants and rated for equivalent capacity.

TABLE 5.4

A Mature Industry of 600 LWRs in Year 2000

LWR Industry Components	*Number of Plants Without U or Pu Recycle*	*Number of Plants With U Recycle Only*	*Number of Plants With U and Pu Recycle*
Light Water Reactors	600	600	600
Fuel Reprocessing	-	9	9
Mixed Oxide Fuel Fabrication	-	-	9
Mine-Mill Complexes	84	68	57
UF_6 Conversion	7	6	5
Uranium Enrichment[a]	12	12	11
UO_2 Fuel Fabrication	12	12	10
Waste Management	1	1	1
Plutonium Storage	0	1	0

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a. Includes facilities for foreign demand assumed to be about 53 million SWU in the year 2000 (see Table A.4).

Effluents and environmental effects of the entire fuel cycle are proportional to the total amounts of uranium and plutonium processed. Based on the higher projection of LWRs, and the linear dose/effect assumption, increases in radiological effects from population exposure over the base case (through the year 2101) would be as follows:

Health Effects

Whole body	- Increased from 503 to 520 (50% fatal). Increased from 1790 to 2040 for the front end of the fuel cycle.
Thyroid	- Increased from 20 to 22 (25% fatal)
Lung	- Increased from 15 to 17 (100% fatal) for reprocessing.
Leukemia	- Increased from 91 to 92 (100% fatal)
Bone	- Increased from 3 to 4 (50% fatal)
Genetic defects	- Increased from 91 to 95

Occupational effects are proportional to the increased size of the industry. Effects of back end operations based on the linear dose/effect assumption are an additional 5 health effects (from 28 to 33 cancers and genetic effects). Front end operations result in 24 more latent cancers in miners (from 143 to 167) and 200 more accidental mining deaths (from 1400 to 1600).

Fuel cycle costs would increase because of generally increased activity. Under Alternative 10, the total fuel cycle cost for operations through the year 2000 would increase about 34 billions of 1977 dollars (relative to the base case).

Safeguards requirements are primarily determined by the type and quantity of plutonium operations. Under Alternative 10, total amount of plutonium processed through the year 2000 would be about 1480 MT (1000 MT fissile Pu). This value is 7% greater than the total amount of plutonium handled in the base case.

b. Recycle Uranium Only (Alternative 11)

The projected number of fuel cycle facilities which will constitute the industry in the year 2000 are shown in Table 5.4 for Alternative 11 (recycle of uranium only in an industry with 600 LWRs). Overall, effects are increased about 13% for this alternative over those for Alternative 10. This increase is primarily caused by increased mining activity (13% greater to 1.37×10^6 MT U_3O_8 versus 1.21×10^6 MT U_3O_8 for Alternative 10).

Compared to Alternative 10, the health effects for Alternative 11 are increased as follows:

Health Effects

From Front End Operations - Increased from 2040 to 2360.
From Back End Operations - No change.

Occupational

Front End Operations - Miner lung cancers increased from 167 to 188.
Miner accidental deaths from 1600 to 1800.

Back End Operations - No change.

Fuel cycle costs would also increase because of increased activity in front end operations. Total fuel cycle costs for Alternative 11 are calculated to be 284 billions of 1977 dollars, an increase of 10% from Alternative 10.

Although the reprocessing activity remains the same as in Alternative 10, the safeguards requirements will decrease slightly because the total amount of plutonium processed will decrease about 12%, and because the MOX production and distribution activities will be replaced by shipment and storage of the plutonium in one central repository.

c. No Recycle (Alternative 12)

The projected number of fuel cycle facilities which will constitute industry in the year 2000 are shown in Table 5.4 for Alternative 12 (throwaway fuel cycle in an industry with 600 LWRs). Front end operations would be increased compared to Alternative 10 to compensate for elimination of recycle activities. Total mining is increased 31% to 1.58×10^6 MT U_3O_8.

Compared to Alternative 10, total offsite health effects are almost unchanged because increased health effects (710) associated with front end operations are offset by decreased health effects (750) from elimination of back end operations.

Occupational exposures from back end operation are eliminated; increases in mining operations result in an additional 50 miner deaths (from 167 to 217) from radiation and 500 from mining accidents (from 1600 to 2100).

Fuel cycle costs for Alternative 12 would increase because the generally increased activity in front end activities outweighs the cost of the eliminated recycle operations. Compared to Alternative 10, total fuel cycle costs would increase 6% to 273 billions of 1977 dollars.

Safeguards requirements under Alternative 12 would be reduced from requirements for Alternative 10 because plutonium would be present only in diluted form and would be entirely contained within irradiated fuel assemblies.

3. Lower Projected Number of Reactors (400 LWRs in Year 2000)

a. Recover and Recycle Uranium and Plutonium (Alternative 13)

Overall effects of a smaller nuclear growth rate will be commensurate with the decreased number of LWRs. The number of reactors and recycle facilities for Alternative 13 (recycle of U and Pu in an industry containing 400 LWRs) are compared to the base case in Table 5.3. Total mining requirements through the year 2000 would decrease about 18% from the base case to 864,000 MT U_3O_8.

The projected number of fuel cycle facilities which will constitute the industry in the year 2000, both with and without spent fuel recycle, are summarized in Table 5.5.

Population dose and health effects for Alternative 13 are about the same as the base case because the projected reprocessing industry (including the AGNS plant operating with existing offgas controls) requires until 2002 (same as the base case) to complete processing of all fuel discharged through the year 2000. Radiological effects from population exposure compared to the base case would be:

Health Effects

Whole body	- Increased from 503 to 520 (50% fatal). Front end effects decreased from 1790 to 1470.
Thyroid	- Increased from 20 to 21 (25% fatal)
Lung	- Unchanged at 15 (100% fatal) for reprocessing.
Leukemia	- Unchanged at 92 (100% fatal)
Bone	- Unchanged at 3 (50% fatal)
Genetic effects	- Increased from 91 to 92

Occupational Effects

From Front End Operations	- Miner cancers decreased from 143 to 115 Miner accidental deaths decreased from 1400 to 1200
From Back End Operations	- Worker cancers and genetic effects decreased from 28 to 25

Fuel cycle costs would decrease because of decreased activity. Under Alternative 13, the total fuel cycle cost throuth the year 2000 would decrease about 40 billions of 1977 dollars (18% relative to the base case).

Safeguards requirements under Alternative 10 compared to the base case would decrease because total plutonium flow through the year 2000 would decrease about 14% to 1180 MT (802 MT fissile plutonium).

b. Recycle Uranium Only (Alternative 14)

The projected number of recycle facilities which will constitute the industry the year 2000 are shown in Table 5.5 for Alternative 14 (recycle of uranium only in an industry with 400 LWRs).

TABLE 5.5

A Mature Industry of 400 LWRs in the Year 2000

LWR Industry Components	*Number of Plants Without U or Pu Recycle*	*Number of Plants With U Recycle Only*	*Number of Plants With U and Pu Recycle*
Light Water Reactors	400	400	400
Fuel Reprocessing	-	6	6
Mixed Oxide Fuel Fabrication	-	-	6
Mine-Mill Complexes	56	45	38
UF_6 Conversion	5	4	4
Uranium Enrichment[a]	10	9	9
UO_2 Fuel Fabrication	9	9	8
Waste Management	1	1	1
Plutonium Storage	0	1	0

a. Includes facilities for foreign demand assumed to be about 53,000 MT SWU in the year 2000 (see Table A.4).

Overall effects are increased about 13% for this alternative from those for Alternative 13 primarily because of the greater mining activity (979,000 MT U_3O_8 versus 864,000 MT U_3O_8 for Alternative 13).

Compared to Alternative 13, the health effects for Alternative 14 are increased as follows:

Health Effects

From Front End Operations - Increased from 1470 to 1630

From Back End Operations - No change

Occupational Effects

From Front End Operations - Miner cancers increased from 115 to 130.

From Back End Operations - No change

Fuel cycle costs would also increase because of increased activity in front end activities. Total fuel cycle costs for Alternative 14 through the year 2000 are calculated to be 202 billions of 1977 dollars, an increase of 19 billions from Alternative 13.

Although reprocessing activity remains the same as in Alternative 13, the safeguards requirement would decrease slightly because the total plutonium flow would decrease about 12% to 1040 MT, and the MOX production and distribution activities would be replaced by shipment to and storage at a central repository.

c. No Recycle (Alternative 15)

The projected number of fuel cycle facilities which will constitute the industry in the year 2000 are shown in Table 5.5 for Alternative 15 (throwaway fuel cycle in an industry with 400 LWRs). Front end activities would be increased compared to Alternative 13 to compensate for elimination of recycle activities. Total mining is increased 33% to 1.15×10^6 MT U_3O_8.

Compared to Alternative 13, total population health effects are reduced about 10%. This reduction results from an increase of 490 effects from front end operations and a decrease of 740 effects from back end operations.

If back end operations are eliminated, occupational health effects are reduced by 25 and accidental deaths are reduced by 6 compared to Alternative 13. Increased front end operations cause 400 accidental deaths from accidents and 42 from cancers.

Fuel cycle costs for Alternative 15 would increase because the generally increased activity in front end operations outweighs the cost of the eliminated recycle operations. Compared to Alternative 13, total fuel cycle costs would increase about 9 billions of 1977 dollars to 193 billions.

Safeguards requirements under Alternative 15 would be reduced from requirements for Alternative 13 because plutonium would be present only in diluted form and would be entirely contained in irradiated fuel elements.

REFERENCES FOR SECTION 5

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6. SHORT-TERM USES AND LONG-TERM PRODUCTIVITY

This section compares the short-term and long-term environmental gains and losses of closing the LWR fuel cycle. For purposes of this discussion, short-term effects are those that occur during the period of construction and operation of reprocessing and recycle facilities through the year 2000. Long-term effects are those that extend past this period and into the indefinite future. Short-term effects are generally in terms of tradeoffs in cost, land use, and radiological impact on the environment. Long-term effects have to do with conservation of energy reserves, land use, and management of radioactive waste products.

The fundamental trade off associated with closing the LWR fuel cycle is that energy resources are conserved while the radioactive products of reactor irradiation may be made more susceptible to release or diversion.

A. SHORT-TERM EFFECTS

1. Gains

Through the year 2000, the major gain from recycling LWR fuel is that less uranium would have to be mined as fuel for LWRs. About 25% savings (330,000 tons) would be realized from uranium and plutonium recycle compared to the no recycle case. Because

mining contributes the second largest fraction (next to reactors) of the total cost of the fuel cycle, these savings result in overall LWR system cost savings by the year 2000.

Environmental effect reductions are also realized because of the reduced release of radon from mill tailings. These benefits are discussed further in Sections 5 and 9 of this environmental statement.

2. Losses

Through the year 2000, the major loss from recycling LWR fuel is that the radioactive products are processed in forms that are susceptible to accidental releases that could result in environmental effects and to thefts that could place fissionable materials in the possession of terrorists. These potential hazards are discussed in Sections 3 and 10 of this environmental statement, respectively.

Other losses associated with the reprocessing and recycle activities are the small environmental effects of unavoidable radioactive releases during normal operation and the use of land and expendable resources for construction of the facilities. Environmental effects from releases are discussed in Section 3, and the use of resources is discussed in Section 8 of this statement. The environmental effect of back-end fuel cycle operations through the year 2000 is estimated to be a commitment to the

worldwide, U.S., and local populations of about 720 health effects (statistical incidence of cancers and genetic defects estimated using EPA factors); including effects of long-lived radionuclides through year 2101.

B. LONG-TERM EFFECTS

1. Gains

The major long-term gain resulting from recycle of LWR fuels is the improved utilization of U.S. energy resources. A gain of about 50% in the useful energy from a given amount of uranium ore can be achieved by uranium and plutonium recycle in comparison with no recycle. Development of plutonium recycle technology could also provide the fuel needed for the orderly development of breeder reactors. The useful energy obtained from uranium could be increased by a factor of 50 or more by the large-scale use of breeders.

These savings in utilization of U.S. uranium resources would help maintain adequate energy supplies in the U.S. The uranium energy supply, along with coal, will be needed to maintain a reasonable standard of living and to move the U.S. toward energy independence.

2. Losses

The major long-term environmental loss resulting from recycle of LWR fuels is the commitment that must be made to care for the contaminated reprocessing and recycle facilities and the resulting radioactive wastes. Decommissioning studies are under way that should enable the long-term commitment to be recognized and addressed during design of the various facilities.

Long-term management of the long-lived radioactive waste material formed during reactor operation is required whether or not a recycle industry is established.

Other long-term losses that might result because of the LWR recycle industry would include the small but long-term contamination of the environment from unavoidable releases of long-lived radionuclides and a possible decreased emphasis on development of sources other than nuclear that will be needed to supply U.S. and worldwide energy needs in the future.

7. EFFECTS ON LAND-USE PLANS, POLICIES, AND CONTROLS

The proposed action of reprocessing and recycling uranium and plutonium to close the LWR fuel cycle does not conflict in general with Federal land use plans and policies. As part of the site specific environmental assessment for each proposed reprocessing or recycle plant, the relationship to Federal, state, and local plans, policies, and controls will be discussed.

Minimal environmental impact will be achieved for these facilities by requiring compliance with the Federal and State permit systems such as:

- National Environment Protection Act
- Federal Water Pollution Control Act
- National Historic Preservation Act
- Wild and Scenic Rivers Act
- State Pollution Control Authorities

8. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

Irreversible commitments involve changes set in motion by the proposed action which cannot be altered at some later time to restore the present order of environmental resources. Irretrievable commitments include the use or consumption of resources that are neither renewable nor recoverable for subsequent use. Resources of concern are: 1) material resources, including materials of construction, renewable resource material consumed in operation, and depletable resources consumed, and 2) nonmaterial resources, including a range of beneficial uses of the environment.

Resources that generally may be irreversibly committed by the construction and operation are: 1) biota destroyed in the vicinity; 2) construction materials that cannot be recovered and recycled with present technology; 3) materials that are rendered radioactive but cannot be decontaminated; 4) materials consumed or reduced to unrecoverable forms of waste, including consumed ^{235}U, ^{238}U, and plutonium; and 5) land areas rendered unfit for the preconstruction uses.

A. LAND

In general, land commitment is neither irretrievable nor irreversible. Land temporarily committed for front- and back-end facilities for the plutonium-uranium recycle case (base case) is

estimated at 711,000 acres through the year 2000 (Table 8.1). Of this land, about 53,000 acres is estimated to be permanently committed. This includes the areas covered by tailings from uranium mills which are assumed to be restricted. The back end of the cycle requires temporary land commitments of about 43,000 acres, with about 140 acres (including 30 acres for land burial of wastes containing less than 10 nCi/g of transuranium elements) permanently committed through the year 2000. Not included are Federal repository requirements for solidified high-level wastes, compacted cladding hulls, and other wastes containing more than 10 nCi/g of transuranium elements. The commitment of this land will be discussed in a subsequent environmental statement for long-term storage of wastes from reprocessing and recycle plants. Also not included are land requirements for decontamination and dismantling wastes from decommissioning operations. The selection of land to be irreversibly committed at facility sites depends on the mode of plant decommissioning (protective storage, entombment, or total dismantlement). Decommissioning mode is determined by the intended use of the site, the value of the property, and the salvage value of the structures.

Land commitments, both temporary and permanent, for storage of radioactive waste in commercial burial grounds are summarized in Table 8.2. Through the year 2001, wastes containing less than 10 nCi of transuranium elements per gram of waste (non-TRU wastes) are estimated to require about 1000 acres in temporary commitment

TABLE 8.1

Irreversible and Irretrievable Commitments of Resources with LWR Fuel Recycle (Base Case)

	Mining and Milling	*UF_6 Conversion*	*Enrichment*	*UO_2 Fuel Fabrication*	*MOX Fuel Fabrication*	*Reactor*	*Reprocessing*	*Transportation*	*Waste Management*	*Total*
Land (Acres)[a]										
Temporarily Committed	390,000	7000	15,000	7500	*b*	248,000	42,000		∿1000	711,000
Permanently Committed	29,000	70	-	-	-	23,000	110		500[c]	53,000
Energy[d]										
Elec. Energy (MW-hr x 10^3)	1,100	620	207,000	600	420		630			210,000
Fossil Fuel										
Equiv. Coal (MT x 10^3)[e]	240	140	45,500	130	90		140			46,200
Nat. Gas (SCF x 10^6)	26,000	7260		1120						34,400
Diesel Fuel (gal x 10^6)	24					240		6		270

a. Cumulative land requirements for fissile fuels discharged from reactor through year 2000; projections for the front end of the nuclear fuel cycle are based on data from References 1 and 2.

b. Assumed collocated on fuel reprocessing sites.

c. Commercial burial grounds, for wastes containing less than 10 nCi/g transuranium elements (non-TRU wastes) from operation of reactors, fuel reprocessing plants and uranium operations (conversion, enrichment, and fuel fabrication). Does not include wastes transported to Federal repositories and wastes generated by decommissioning operations.

d. Requirements for operations in the year 2000. Requirements are prorated from Reference 1 and relative throughputs.

e. Assumes 60% of electrical power supplied by fossil-fueled plants.

TABLE 8.2

Estimated Wastes Generated by LWR Pu-U Recycle

	Wastes from Process Operations through Year 2000[a]			*Ultimate Decommissioning*[b]		
	Commercial Burial Ground			*Commercial Burial Ground*		
	Volume, m^3	*Permanent Land Commitment, acres*	*Federal Repository*[c]*, m^3*	*Volume, m^3*	*Permanent Land Commitment, acres*	*Federal Repository*[c]*, m^3*
UF_6 Enrichment and UO_2 Fuel Fabrication	2×10^5	20	-	10^5	10	-
Reactors	4×10^6	400	-	6×10^6	600	-
FRPs				4×10^4	4	9×10^3
HLW	-		8000			
Cladding Hulls	-		8700			
Other TRU Wastes	-		7×10^5[d]			
Non TRU Wastes	3×10^5	30				
MOX	-		2×10^5[d]	1×10^4	1	2×10^4
Totals	5×10^6	500	9×10^5	6×10^6	600	3×10^4

a. Projections of volumes of high-level waste by the year 2000 from References 2 and 3 estimates.

b. Preliminary estimates of waste volumes generated during decommissioning by decontamination and dismantling based on Reference 2 estimates.

c. Land commitments for perpetual care of wastes in deep geological formations are not estimated because isolation methods and locations are not established.

d. Volumes reduced by incineration or compaction where practical.

and about 500 acres for permanent storage. About 7% of these wastes is generated in the back end of the fuel cycle. Ultimate decontamination and partial dismantling of the seven fuel processing plants and MOX fabrication plants (base case option) is estimated to require about 5 acres of permanent burial ground space for non-TRU wastes and about 110 acres for protective storage or entombment. Total dismantlement would require additional permanent burial ground space.

B. WATER

When water is withdrawn from wells or from surface waters and is not replaced within the immediate locality, it becomes unavailable for local consumers. However, the water is returned to the hydrologic system and is not irretrievably or irreversibly committed. The total volume of water discharged to the air, ground, or to surface water is estimated to be 5×10^{13} gal in the year 2000. About 90% of the demand is needed to cool reactors (evaporative loss from cooling towers).

C. FUELS

Consumption of uranium for plutonium-uranium recycle and other alternatives is discussed in Section 5 "Alternatives" and Section 9 "Cost-Benefit Analysis." The fissile uranium and plutonium consumed in the production of electrical power have no alternative large-scale use.

Electrical energy expended for the base case (complete fuel cycle, 507 reactors in the year 2000) is about 2.1×10^{8} MW-hr in the year 2000; about 98% of this energy is consumed during

enriching uranium by gaseous diffusion. This value is estimated to be less than 0.7% of the projected usage of electricity in the year 2000.[4] About 60% of the electricity is assumed to be supplied by fossil fueled plants which will consume 4.6×10^7 MT of coal or equivalent fuel. Natural gas consumed is about 3.4×10^{10} ft^3, primarily in milling operations and is about 0.1% of the projected usage in the year 2000.[4] Also about 2.7×10^8 gal of diesel fuel is consumed, which is less than 0.08% of the projected usage in the year 2000.[4] Table 8.1 indicates consumption of fossil fuels in various operations.

D. MATERIALS OF CONSTRUCTION

Construction materials are almost entirely of the depletable category of resources. Concrete and steel constitute the bulk of these materials, but numerous other mineral resources are incorporated in the physical plants. These construction materials are a small portion of the total construction materials used nationwide. Materials recovered during decommissioning and that are not contaminated with radioactivity may be salvaged.

E. MANPOWER

By the year 2000, an estimated 120,000 people will be working in the commercial nuclear fuel cycle industry. Closing the fuel cycle by recycling uranium and plutonium is expected to create ten to fifteen thousand new jobs in back end operations. These new jobs could have a favorable impact on the localities involved. However, about 5000 fewer workers would be needed in front end operations than required for the no-recycle case.[1]

REFERENCES FOR SECTION 8

1. *Environmental Survey of the Uranium Fuel Cycle.* Report WASH-1248, Energy Research and Development Administration (1974).
2. *Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle.* Report ERDA-74-43, Energy Research and Development Administration (1976).
3. *Generic Environmental Statement - Mixed Oxide Fuel.* Report NUREG-0002, Nuclear Regulatory Commission (August 1976).
4. E. Teller. *Energy - A Plan for Action.* Commission on Critical Choices for Americans, New York (1974).

9. COST-BENEFIT ANALYSIS

A. INTRODUCTION

ERDA is undertaking programs that are expected to lead to decisions regarding construction of facilities for closing the back end of the LWR fuel cycle. Recycle of uranium and plutonium in an industry with 507 LWRs in the year 2000 was described in Section 5 as the base case. The effects and benefits of such a recycle industry are compared in this section. A total of fifteen alternatives are also examined. In the first five alternatives of fuel recycle, the variables are the timing of reprocessing LWR fuel, the degree of control of radioactive off-gases from reprocessing, and the siting variations for the reprocessing plants. The next four alternatives describe unique fuel cycles - recycle of uranium only (plutonium stored for future use), no recycled uranium and plutonium (throwaway), coprocessing (recycle of the mixture of recovered uranium and plutonium), and the tandem fuel cycle (irradiated LWR fuel refabricated for use in HWR). The final six alternatives compare full recycle, uranium recycle only, and no recycle for a high nuclear schedule (600 GWe by the year 2000) and a low nuclear schedule (400 GWe by the year 2000).

In this section, the alternatives are compared on the basis of resource utilization, environmental effects, and fuel cycle

cost. In addition, conclusions are made on a suitable course of action. The primary effects for each alternative are given in Table 9.1, and are discussed in Sections 9 B-D.

TABLE 9.1

Summary Effects of Fuel Cycle Activities[a]

	Change from Base Case					
			Health Effects			
Fuel Cycle	*Uranium Consumption (thousands of MT (U_3O_8)*	*Permanent Land Commitment (thousands of acres)*	*Radiological Effects[b] (General Public)*	*(Occupational)*	*Accidental Deaths (Occupational)*	*Costs (Includes Deferred Costs) (Billions of 1977 Dollars)*
Base Case	(1047)	(53)	(2500)	(170)	(1400)	(225.8)
Recycle uranium and plutonium. 1 year fuel decay. 507 LWRs in CY-2000.						
Alternative						
1. Same as base case except 5 year fuel decay.	+118	+4	+400	+20	+200	-1.1
2. Same as base case except delay reprocessing 5 years.	+89	+2	-300	+10	+100	+1.2
3. Same as base case except eliminate earth cover over tailings piles and offgas controls from reprocessing plants built after 1985.	0	0	+4500	0	0	-1.2
4. Same as base case except retrofit AGNS reprocessing plant with offgas controls.	0	0	-600	0	0	+0.5
5a. Same as base case except locate reprocessing and MOX fabrication plants at different sites.	0	0	0	0	0	+0.2
5b. Same as base case except locate reprocessing plants to minimize transportation of spent fuel.	0	0	-1	0	-2	<0.2
5c. Same as base case except locate reprocessing plants near Federal repositories.	0	0	+3	0	+3	<0.2
6. Uranium recycle, plutonium stored. 507 LWRS in year 2000.	+135	+4	+200	+20	+200	+24.8
7. Throwaway 507 LWRs in year 2000.	+334	+10	-100	+20	+400	+17.7
8. Coprocess, Uranium and Plutonium recycled as mixture.	0	0	0	0	0	+16.3
9. Tandem fuel cycle. Irradiate spent LWR fuel in HWRs.	+104	+4	-400	+10	+200	+63.9
10. Same as base case except larger number of reactors (600 LWRs in year 2000).	(1212)	(62)	(2800)	(200)	(1600)	(260.0)
11. Same as Alternative 6 except larger number of reactors (600 LWRs in year 2000).[c]	+157	+5	+300	+10	+200	+30.0
12. Same as Alternative 7 except larger number of reactors (600 LWRs in year 2000).[c]	+372	+12	0	+20	+500	+23.3
13. Same as base case except smaller number of reactors (400 LWRs in year 2000).	(863)	(44)	(2200)	(140)	(1200)	(186.4)
14. Same as Alternative 6 except smaller number of reactors (400 LWRs in year 2000).[d]	+115	+3	+200	+20	+100	+20.8
15. Same as Alternative 7 except smaller number of reactors (400 LWRs in year 2000).[d]	+287	+6	-200	+20	+400	+13.2

a. Fuel cycle activities in support of LWR operations from year 1976 to year 2000. The full effect is shown (in parentheses) for the case of U, Pu recycle at each projected level of GWe. Differential effects within a given GWe projection are compared to U, Pu recycle for that projection.

b. Includes cancers and serious genetic effects resulting from radiation exposures to workers.

c. Compared to Alternative 10 as the base case.

d. Compared to Alternative 13 as the base case.

B. RESOURCE UTILIZATION

1. Uranium Requirements

The amount of uranium ore needed to supply fuel for nuclear power reactors depends on the rate of growth of the nuclear industry and on whether the back end of the fuel cycle is closed. For a given rate of nuclear power growth, the largest quantities of uranium ore are required to support a throwaway fuel cycle (Alternative 7). In a throwaway fuel cycle, the irradiated fuel is stored and not reprocessed. If irradiated fuel elements are reprocessed to recover the uranium as feed to the enrichment plants (enrichment of the recovered uranium is about 0.9% ^{235}U), 14% less natural uranium (0.7% ^{235}U) is required by the year 2000. If, in addition to uranium recycle, the plutonium is recovered and fabricated into fuel assemblies, ore requirements are reduced by an additional 10%.

The domestic resources of uranium ore available to support the nuclear industry are under intensive study, and forecasts of reserves are subject to change as exploration proceeds and as cost-of-energy increases allow exploitation of lower quality reserves. Table 9.2 suggests that present conventional domestic ore resources probably exceed 1.7 million tons of U_3O_8 with a possible high estimate of about 3 million tons. Use of non-conventional ore deposits such as shales (Table 9.3) probably involve both higher costs and larger environmental effects than conventional mining. Recovery of uranium from sea water has been

under study, but such a process is considerably more expensive than conventional mining.

TABLE 9.2

Reserves and Potential Resources (January 1, 1976[a]), tons U_3O_8

Class	*$10*	*$15*[b]	*$30*[b]
Reserves	270,000	430,000	640,000
Potential Resources[c]			
Probable	440,000	655,000	1,060,000
Possible	420,000	675,000	1,270,000
Speculative[d]	145,000	290,000	590,000

a. *Statistical Data of the Uranium Industry*. ERDA Report GJO-100(76), 1976.[1] *Reserves* constitute the known portion of resources, whereas *potential resources* are essentially estimates of additional resources which hopefully will be developed in the future. These estimates do not include approximately 140,00 tons of U_3O_8 that is expected to become available through the year 2000 as a byproduct of phosphate and copper production.

b. Includes lower cost resources; cost categories reflect estimated operating costs and capital cost not yet incurred. Profit and costs already incurred are not included. Cost categories represent ore grade, not selling price.

c. The three classes of potential are arranged in order of decreasing reliability from probable to speculative. Probable potential is in mineralized trends within existing mining districts and productive formations; possible potential is in productive provinces and productive formations; speculative is in new provinces or new formations.

d. The estimates of speculative potential, made solely on geologic inference for unexplored areas, are considerably less reliable than either probable or possible potential estimates which are in areas in which considerable exploration has occurred. Continuing extensive geological and geophysical investigation and drilling will be required to discover and to convert the potential into reserves.

TABLE 9.3

Total Uranium Resources[a]

Types of Uranium Deposit	*Concentration, ppm*	*Amount, millions of tons U_3O_8*
Conventional	700 - 2100	3[b]
Shale	60 - 80	5
Shale	25 - 60	8
Granite	10 - 20	8
Shale	10 - 25	200
Granite	4 - 10	1800
Seawater	.003	4000

a. ERDA-1535[2]

b. 1976 estimate, Table 9.2 excluding speculative resources

The comparison in Table 9.1 of the uranium ore requirements for a closed nuclear fuel cycle (base case) with the requirements for other options show that:

- Recycle of uranium and plutonium on a timely schedule significantly reduces uranium requirements compared to a throwaway fuel cycle through the year 2000. A throwaway fuel cycle would require about 30% additional U_3O_8 for LWR industries ranging from 400 to 600 reactors through the year 2000.

  Meeting the uranium requirements projected for the throwaway fuel cycle (Alternative 7) will consume about half of the expected domestic resources of conventional uranium; this is over twice the amount of uranium contained in the known domestic reserves. Decreased consumption of uranium is considered to be a significant benefit of the fuel cycle with recycle of uranium and plutonium because 1) more efficient use is made of a limited resource that is expected to provide a large share of our electrical needs, and 2) the effort required to discover and develop new ore bodies to meet projected demands will increase and become more expensive as uranium resources are consumed.

- A closed fuel cycle that features storing irradiated fuel for 5 years before reprocessing (Alternative 1) or a 5-year delay in closing the fuel cycle (Alternative 2) increases the demand for uranium by about 10% over the study period compared to the base case. However, the effect should be temporary. In

a continuing industry, the increased consumption resulting from delayed recycling will be offset by decreased consumption at a later date.

- Variations in extent of control technology for retention of offgases (Alternatives 3 and 4) and variations in siting of recycle facilities (Alternative 5) have no effect on the demand for uranium ore.
- Coprocessing of uranium and plutonium (Alternative 8) requires the same amount of uranium ore as the base case until year 2000. Added ore would be needed to support a static LWR reactor base after the year 2000 if coprocessing were used rather than the base case (recycle of uranium separate from plutonium). With a constant (or decreasing) number of LWRs, more recycled fuel is generated by coprocessing (recovered fuel plus added enriched uranium) than is needed to meet reactor demand.
- The tandem fuel cycle (Alternative 9) requires about 10% more uranium ore than the base case by year 2000. However the annual demand for ore from the combination of LWR and HWR equals that in the base case in year 2000 and will be less than the base case thereafter.
- Recycle of uranium only (Alternatives 6, 11, and 14) increases the demand for uranium ore by about 13% over the full recycle cases for LWR industries ranging from 400 to 600 reactors through the year 2000.

2. Other Resource Requirements

Of the other resource uses, only land requirements were found to differ significantly between the alternative fuel cycles. The largest requirements for land are associated with mining and milling operations (370 acres in temporary commitment per 1000 MT U_3O_8 produced; 360 acres per mine/mill complex plus an additional 7 acres permanently committed per 1000 MT U_3O_8 produced. The next largest land use is for reactor siting (490 acres for temporary commitment and 45 acres for permanent commitment, per reactor). Land requirements for mining and milling, for back-end operations, and for total use are compared in Table 9.4. Differences in uranium demand between the fuel cycle alternatives are directly reflected by corresponding changes in land requirement because land committed to mining and milling activities is greater than 50% of the total land commitment. Thus, in an industry with a given number of LWRs, land requirements decrease as the extent of recycle increases. However, land associated with mining and milling is not likely to be as valuable as land used in other fuel cycle activities.

The permanent commitment of land to mining and milling operations is associated primarily with isolation of tailings piles. This commitment might be reduced substantially by increasing the thickness of cover from 12 to 20 ft. At this thickness periodic monitoring may show that much of the land can be used for productive activity (such as grazing) that does not require excavation.[3]

TABLE 9.4

Land Requirements Through the Year 2000

Fuel Cycle	Land Requirements, thousands of acres					
	Temporary Commitment			Permanent Commitment		
	Mining and Milling	Back-End Activities	Total[a]	Mining and Milling	Back-End Activities	Total[a]
Base Case						
Recycle uranium and plutonium. 1 year fuel decay. 507 LWRs in year 2000.	390	43	711	29	<1	53
Alternative						
1. Same as base case except 5-yr fuel decay.	430	37	745	33	<1	57
2. Same as base case except delay reprocessing 5 years.	420	43	741	31	<1	55
3. Same as base case except eliminate earth cover over tailings piles and offgas controls from reprocessing plants built after year 1985.	390	43	711	29	<1	53
4. Same as base case except retrofit AGNS with offgas controls.	390	43	711	29	<1	53
5. Same as base case but with site variations.	390	43	711	29	<1	53
a. Locate reprocessing and MOX fabrication at different sites.						
b. Locate reprocessing plants to minimize transportation of spent fuel	390	43	711	29	<1	53
c. Locate reprocessing plants near Federal repositories.	390	43	711	29	<1	53
6. Uranium recycle, Pu stored. 507 LWRs in year 2000.	440	43	763	33	<1	57
7. Throwaway, 507 LWRs in year 2000.	510	1	792	39	<1	63
8. Coprocessing, 507 LWRs in year 2000.	390	43	708	29	<1	53
9. Tandem cycle, 507 GWe of LWRs and HWRs in year 2000.	430	49	769	32	<1	58
10. Same as base case except larger number of reactors (600 LWRs in year 2000).	450	55	829	34	<1	62
11. Same as Alternative 6 except larger number of reactors (600 LWRs in year 2000).	510	55	893	39	<1	67
12. Same as Alternative 7 except larger number of reactors (600 LWRs in year 2000).	590	1	921	46	<1	74
13. Same as base case except smaller number of reactors (400 LWRs in year 2000).	320	37	578	25	<1	44
14. Same as Alternative 6 except smaller number of reactors (400 LWRs in year 2000).	360	37	619	28	<1	47
15. Same as Alternative 7 except smaller number of reactors (400 LWRs in year 2000).	430	1	656	32	<1	50

a. Includes reactors.

C. ENVIRONMENTAL CONSIDERATIONS

The analyses of environmental effects of the base case (Section 3) and changes introduced by the alternatives to the base case (Section 5) lead to the conclusion that only the effects of radiological releases and occupational accidents show potentially significant differences that warrant inclusion in the cost-benefit analysis.

The population dose commitment to local, U.S., and world populations were calculated for the various alternatives in the same way as described in Section 3C2 for the base case of full recycle. Health effects (cancers and serious genetic effects) were estimated as described in Section 3C3 and 3C4. As discussed in Section 3C3, the health effects estimates are based on the linear, no-threshold dose-effect relationships derived by the Environmental Protection Agency from the BEIR report.[4] These estimated effects are expected to substantially over-estimate the actual effects but are used in this report to provide upper-limit health effects estimates. Health effects were also calculated using the Rasmussen central estimate of effects for comparison. The Rasmussen dose-effect factors, which are lower than the EPA estimates, recognize that both dose and dose rate are important considerations influencing the sematic effect of ionizing radiation. Effects of occupational exposure and occupational accidents were estimated as described in Section 3C4. The major effects of the alternative fuel cycles are summarized in Table 9.5A (using

EPA dose-effect factors) and 9.5B (using Rasmussen dose-effect factors) and compared with the base case in each power growth projection.

The population health effects expected from recycle of plutonium and uranium (base case) result from radiological release during reprocessing irradiated fuel and from mining and milling uranium. Most of these effects occur in the world population over a period of 100 years following the end of the study period (2001). As explained in Section 3C, the 100-year cutoff is arbitrary; effects of long-lived isotopes could persist well beyond this time. The incidence of estimated cancers and genetic defects are shown in Section 3C to be low compared to other causes. Statistical probabilities may overestimate health effects because of the assumed relationships between the effects and radiation dose.

The population health effects under Alternative 7 (no recycle) are comparable to the base case, primarily because effects of increased mining offset effects of deleted back end operations.

Delays in reprocessing activities as assumed in Alternative 1 (store spent fuel 5 years) and Alternative 2 (delay startup of reprocessing 5 years) have relatively little effect on total health effects (less than 15%). Most of the 600 additional health effects under Alternative 1 result from increased mining. However, about 180 health effects would result from increased processing of spent fuel in a plant with existing off-gas controls.

TABLE 9.5A

Estimated Health Effects of Fuel Cycle Alternatives[a] Using EPA Dose Effect Factors

	507 GWe										*600 GWe*			*400 GWe*		
	Base Case	*Alt. 1*	*Alt. 2*	*Alt. 3*	*Alt. 4*	*Alt. 5*	*Alt. 6*	*Alt. 7*	*Alt. 8*	*Alt. 9*	*Alt. 10*	*Alt. 11*	*Alt. 12*	*Alt. 13*	*Alt. 14*	*Alt. 15*
Population Health Effects[a]																
Back End	720	900	**630**	2470	170	720	720	0	720	40	750	750	0	740	740	0
Front End	1790	1960	1950	4610	1680	1790	1980	2360	1790	1960	2040	2360	2750	1470	1630	1960
Total	2500	2900	**2600**	7100	1900	2500	2700	2400	2500	2000	2800	3100	2800	2200	2400	2000
Occupational Health Effects[b]																
Back End	28	28	28	28	28	28	22	0	28	22	33	25	0	25	25	0
Front End	143	161	155	143	143	143	168	188	143	157	167	188	217	115	130	157
Total	170	190	180	170	170	170	190	190	170	180	200	210	220	140	160	160
Occupational Accidental Deaths																
Back End	7	7	7	7	7	7	5	0	7	5	8	6	0	6	4	0
Front End	1400	1600	1500	1400	1400	1400	1600	1800	1400	1600	1600	1800	2100	1200	1300	1600
Total	1400	1600	1500	1400	1400	1400	1600	1800	1400	1600	1600	1800	2100	1200	1300	1600
Total Population and Occupational Effects	4100	4700	**4300**	8700	3500	4100	4500	4400	4100	3900	4600	5100	5100	3500	3900	3800
Change from Base Case[c]		+600	**+200**	+4600	-600	0	+400	+300	0	-200	+Base	+1500	+500	Base	+400	+300

a. Effects of reactor operations are not included.

b. Calculated upper limit health effects, cancers and serious genetic effects. See text and Section 3C3 for a discussion of dose-effect factors and the probable overestimation of health effects.

c. Power reactor growth projections (400, 507, 600 GWe by 2000) are taken as base cases for comparisons.

d. Includes approximately 70 cancers expected from tritium release from HWRs.

TABLE 9.5B

Estimated Health Effects of Fuel Cycle Alternatives[a] Using Rasmussen (Central Estimate) Dose Effect Factors

	507 GWe										*600 GWe*			*400 GWe*		
	Base Case	*Alt. 1*	*Alt. 2*	*Alt. 3*	*Alt. 4*	*Alt. 5*	*Alt. 6*	*Alt. 7*	*Alt. 8*	*Alt. 9*	*Alt. 10*	*Alt. 11*	*Alt. 12*	*Alt. 13*	*Alt. 14*	*Alt. 15*
Population Health Effects[b]																
Back End	280	340	**250**	1120	70	280	280	0	280	**20**	290	290	0	290	290	0
Front End	680	740	740	1740	630	680	750	890	680	740	770	890	1040	550	620	740
Total	1000	1100	**1000**	2900	700	1000	1000	900	1000	800	1100	1200	1000	800	900	700
Occupational Health Effects[b]																
Back End	14	14	14	14	14	14	11	0	14	11	16	13	0	13	9	0
Front End	143	161	155	143	143	143	168	188	143	157	167	188	217	115	130	157
Total	160	180	170	160	160	160	180	190	160	170	180	200	220	130	140	160
Occupational Accidental Deaths																
Back End	7	7	7	7	7	7	5	0	7	5	8	6	0	6	4	0
Front End	1400	1600	1500	1400	1400	1400	1600	1800	1400	1600	1600	1800	2100	1200	1300	1600
Total	1400	1600	1500	1400	1400	1400	1600	1800	1400	1600	1600	1800	2100	1200	1300	1600
Total Population and Occupational Effects	2600	2900	**2700**	4500	2900	2600	2800	2900	2600	2600[d]	2900	3200	3300	2100	2300	2500
Change from Base Case[c]		+300	**+100**	+1900	-300	0	+200	+300	0	0	Base	+300	+400	Base	+200	+400

a. Effects of Reactor operation are not included.

b. Calculated central estimate health effects, cancers, and serious genetic effects. See test and Section 3C3 for a discussion of dose-effect factors and probable overestimation of health effects.

c. Power reactor growth projections (400, 507, 600 GWe by 2000) are taken as base cases for comparisons.

d. Includes approximately 18 cancers expected from tritium releases from HWRs.

Alternative 3 (no improved off-gas controls in plants built after 1985 or earth cover for mill tailings) would increase population health effects from 2500 to 7100 (Table 9.5A) compared to the base case. Whole body exposure would be increased from 1.3×10^6 man-rem to 5.3×10^6 man-rem. In the base case, improved controls are assumed for the six reprocessing and MOX plants started after 1985, but not for AGNS. Population health effects from front end operations would increase from 1790 to 4610 as a result of not covering mill tailings piles.

Alternative 4 considers the effects of retrofitting AGNS with the off-gas controls assumed to be available in 1985, and of additional earth cover (or equivalent) for mill tailings (20 ft vs. 12 ft). Population health effects would be 76% of the base case. Whole body exposure would be reduced from 1.3×10^6 man rem to 2.8×10^5 man-rem as a result of retrofitting AGNS with improved controls. Population health effects from front end operations would decrease from 1790 to 1680 as a result of additional cover for mill tailings piles.

Health effects estimated with recycle of uranium only (Alternative 6) would increase about 10% from the base case almost entirely because of increased mining.

Effects estimated for coprocessing (Alternative 8) would be unchanged because the levels of mining and reprocessing would be unchanged.

Health effects estimated for the tandem cycle would decrease about 5% from the base case primarily because refabrication,

which replaces reprocessing in the base case, is done entirely in facilities with improved off-gas controls.

The introduction of LWRs with a higher or lower growth rate projection is assessed in Alternatives 10-15. Comparison of alternatives within each projection shows the same changes relative to Pu-U recycle as in the 507-GWe case.

Site variations were found to have negligible impact on health effects.

The probability that actual health effects will be lower than the calculated values must be recognized when using the estimates in a cost-benefit assessment. They must also be compared with other causes of similar effects (see Section 3C), so that true cost-benefit comparisons can be made that do not result in unduly restrictive policies or unwarranted expenditures of resources or dollars.

It should be recognized that proceeding with reprocessing and recycling of LWR fuel may well result in increasing the number of installed nuclear power plants by the year 2000. This will consequently result in additional health effects in almost direct proportion to the increase in installed nuclear power. However, if this increase in nuclear power production results in a commensurate decrease in fossil fuel power production, the net environmental and health effects will decrease. A comparison of health effects from a nuclear and fossil-fuel generation is given in Section 2A.

D. ECONOMIC CONSIDERATIONS

1. Introduction

This section presents economic effects in FY-1977 dollars of the options for the back end of the nuclear fuel cycle. About 75% of the total cost of generating electricity from nuclear energy is for reactor capital and operating costs. The remaining 25% is for the fuel cycle, which includes uranium mining, milling, enrichment, spent fuel transportation, reprocessing, and waste management. In all cases except the tandem fuel cycle, reactor costs are constant for a given nuclear industry growth projection, and only the differences in fuel cycle costs need to be compared. Among the alternatives considered, the fuel costs account for about 6 mills/(kW-hr) of the total of about 25 mills/(kW-hr) for generation of electricity by nuclear power. A change of about 10 billion dollars (FY-1977 dollars) is required to change the cost of generated electricity (1976-2000) by 1%.

2. Cost Methods

a. General

Economic calculations for the period 1976-2000 were made for several modes of fuel cycle operations with the aid of a computer model of the fuel cycle (Figure 9-1). Estimates of the fueling requirements for LWRs (Table 2.3) and several nuclear power schedules (Table 9.6) are input data so that the annual flow of materials (ore, uranium, etc.) can be determined. Each processing step within the cycle is associated with a unit

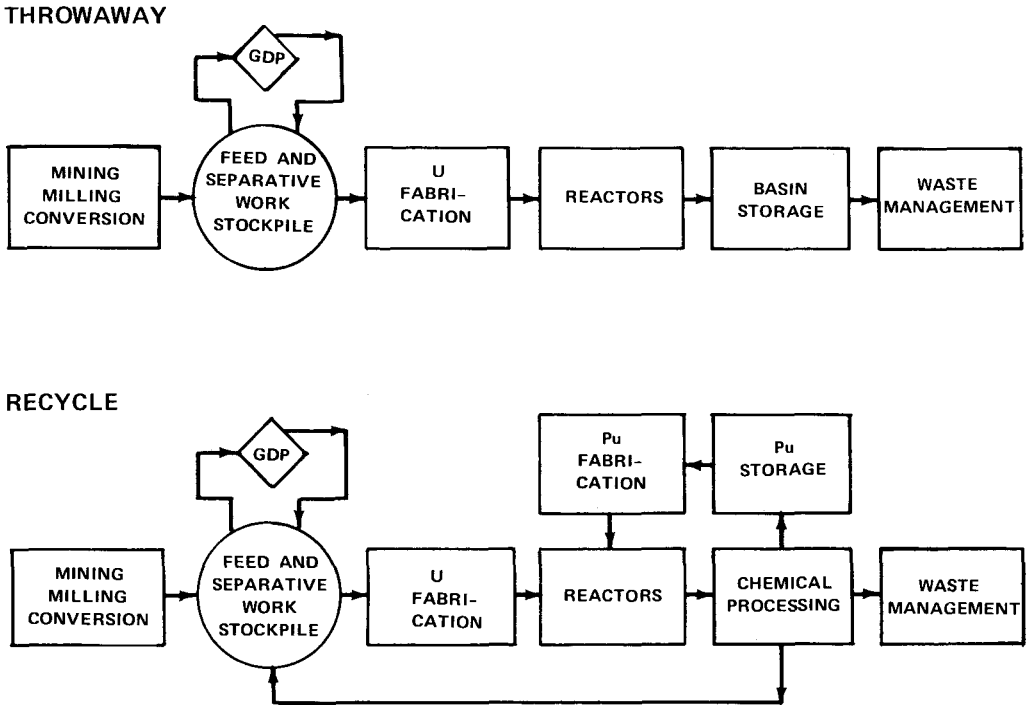

FIGURE 9.1. Cost Centers and Material Flows in Power Reactor Systems Model

TABLE 9.6

Nuclear Power Schedules

Projection	*Reactor Type*	*Total Capacity, GWe*				
		1980	*1985*	*1990*	*1995*	*2000*
Base	PWR	48	103	178	266	338
	BWR	22	53	90	133	169
Tandem	PWR	48	103	163	209	254
	BWR	22	53	85	106	126
	HWR[a]	0	0	20	84	127
High	PWR	51	114	201	306	400
	BWR	23	58	101	153	200
Low	PWR	45	90	153	221	267
	BWR	21	46	77	111	133

a. Equivalent number of 1000 MWe reactors.

processing cost, inventory requirement, and loss rate (the latter is typically 1%). A fixed charge rate (typically 25%) is applied to the estimated capital cost to compute working capital cost, taxes, profit, etc. The unit cost is based on the operating cost and the fixed charges. Lower fixed charge rates are used for LWR cost (15%) and enrichment capital cost. No interest charges are levied on uranium and plutonium in inventory.*

Key cost parameters used in the computer model are shown in Table 9.7. The cost base for Table 9.7 is FY-1977 dollars. Some of the unit costs (e.g. uranium fabrication) are defined in the current market place; others depend heavily on future developments. Costs without escalation were used because the primary purpose is to calculate cost differences between alternatives rather than optimum schedules (presumably all alternatives are equally affected by inflation and more-severe regulatory requirements). Even without inflation the price of uranium ore can be expected to increase as the resources are depleted, and a price schedule depending on consumption is used in the analysis. Other

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* Expenditures for a series of years can be adjusted to present value dollars by means of a discount factor that decreases each year at the selected discount rate. The comparison of discounted costs is judged preferable to applying interest charges in accounting for the cost-time relationship when comparing fuel cycles (throwaway vs recycle). Fuel purchase is an operating expense to be recovered while the fuel is irradiated. In a throwaway cycle, the fuel value decreases to zero during irradiation. Any interest charge on the uranium and plutonium should be based on the net value of the material after reprocessing. With recycle, the real value of the materials is accounted for in reduced ore and enrichment cost without interest charges.

TABLE 9.7

Cost Parameters (All costs in FY-1977 dollars)

Uranium Oxide Cost, \$/lb U_3O_8 (including conversion to UF_6). Linear interpolation between values shown.

Cumulative Amount Mined, Millions of tons U_3O_8	*Cost*
0	36
1	47
2	58
3	69

Enrichment Cost, \$/SWU	100
Uranium Fabrication, \$/kg	90
MOX Fabrication Penalty, \$/kg of Pu Fissile[a]	5000
Plutonium Storage, \$/yr/kg of Fissile Pu[b]	300
Separations Plant Cost, \$/kg U (1500 MTU/yr)[c]	
Designed to process irradiated fuel that has decayed one year	286
Designed to process irradiated fuel that has decayed five years	267
Designed to coprocess irradiated fuel	256
Waste Management Cost, \$/kg	25
Storage of Fuel Assemblies, \$/kg (throwaway fuel cycle)	90

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a. Cost is in addition to uranium fabrication cost in MOX assembly. For coprocessing (Alternative 8), a cost of \$200/kg HM was used.

b. For short storage times (less than permanent storage).

c. Includes \$6/kg for fuel shipping; 25% capital charge applied for commercial reprocessing.

processes, such as enrichment services, are forecast to increase significantly in the 1980s as new plants are built to augment the Gaseous Diffusion Plant, but new separations processes are likely to stabilize enrichment costs. Reprocessing costs estimated in the studies are uncertain because of lack of experience with licensed reprocessing facilities. Mining, enrichment, and reprocessing costs are the major contributors to the variable costs for closing the fuel cycle. Costs are accumulated through the study period for each fuel cycle cost center.

Major assumptions used in the cost calculations are listed in Table 9.8.

The calculations include corrections for isotopic changes in recycled materials. About half of the ^{236}U produced during LWR irradiation is recycled. The recycle stream to the enrichment plant is less than 15% of the virgin uranium feed needed to support the expanding power industry through 2000. A 1% increase in cost is required to allow for ^{235}U added to compensate for ^{236}U in the recycle stream. In addition, the fissile fraction of plutonium decreases with irradiation, and ^{242}Pu content increases. The fixed relationship that 1 g fissile plutonium displaces 0.8 g ^{235}U was used in the study. An additional 1% cost increase is included to compensate for increase in ^{242}Pu. For conservatism, the calculated amount of recovered plutonium was reduced 5% when computing the savings in mining and enrichment.

TABLE 9.8

Assumptions

1. Nuclear power schedule is not affected by option selected for the back end of the fuel cycle.

2. The required mining, separative work, and fuel fabrication for a fuel charge occurs one year before the fuel is charged to the LWR.

3. Tails assay at the enrichment plants is assumed to be 0.25% ^{235}U during the study.

4. Reprocessing plants operate at 40% capacity (year 1), 67% capacity (year 2), and 100% (1500 MTU/yr) during later years. AGNS startup is assumed in 1981, and subsequent plants starting in 1986. A maximum of one new plant per year is assumed to be built after 1985.[a]

5. Plutonium recycle starts in 1983.[b] Nominal plutonium content of LWR fuel us 6.6 Kg/MTU, and 7.5 Kg/MTU with plutonium recycle.

6. MOX plants are collocated at reprocessing plants, matched to reprocessing plant capacity, and operate at 50% full capacity in the first year of operation and 100% during later years.

7. Waste from reprocessing is transferred to geologic storage 10 years after reprocessing.

8. Discharged fuel is stored in water-cooled basins for 10 years before transfer to geologic storage (throwaway case).

9. The discount rate is assumed to be 10%.

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a. In Alternative 2, AGNS startup is delayed until 1986 and new plants until 1991. Two new plants per year are assumed to be built in Alternative 2.

b. With coprocessing (Alternative 8), all recycle starts in 1983.

b. Deferred Costs

The timing for the costs elements in the nuclear power cost model are intended to parallel current practice. Money is spent for mining and enrichment services before the fuel is irradiated in the reactor, but final disposal costs for wastes from reprocessing (for example) are not incurred until years after irradiation. Therefore, two tabulations of costs are shown for each alternative: the costs incurred through 2000 and the deferred costs. Deferred costs for recycle cases are incurred for reprocessing fuel left in inventories, fabricating plutonium into fuel, and for disposing of waste. Deferred credits for mining and enrichment are also accrued for the recycle of uranium and plutonium recovered in the deferred processing and fabrication operations. In the throwaway case, there are no credits, but there are delayed charges for storing fuel and terminal fuel storage. The summary table of differences (Table 9.9) includes the deferred costs.

c. Discounted Costs

The annual expenditures of the alternatives using the base reactor schedule were discounted to determine whether the timing of expenditures differed between fuel cycles. Discounting is especially meaningful in evaluating the effects of 5 years added decay for LWR fuel before reprocessing or delays in the reprocessing schedule. A discount rate of 10% was used to compute the present dollar value of the alternatives.

TABLE 9.9

Costs of Alternatives

Alternative	*Nuclear Reactor Capacity in Year 2000, GWe*	*Recycle of U*	*Pu*	*Fuel Decay before Reprocessing, yr*	*Difference in Cost[a] from Base During Study, Billions of FY-77 Dollars*
Base	507	Yes	Yes	1	-
1	507	Yes	Yes	5	-1.1 (-0.7)[b]
2	507	Yes	Yes	3-4	1.2 (1.4)[b]
3	Base case with no improvements in offgas treatment				-1.2[c]
4	Base case with retrofit of AGNS for offgas treatment				0.5
5a	Base case with separate sites for reprocessing and MOX fabrication				0.2
5b	Base case with reprocessing plants located to minimize transportation of spent fuel				<0.2
5c	Base case with reprocessing plants located near Federal repositories				<0.2
6	507	Yes	No	1	24.8
7	507	No	No	-	17.7
8	507	Yes	Yes	1	16.3
9	507	No	No	-	63.9
10	600	Yes	Yes	1	34.2 (0)[d]
11	600	Yes	No	1	64.2 (30.0)[d]
12	600	No	No	-	57.4 (23.2)[d]
13	400	Yes	Yes	1	-39.4 (0)[e]
14	400	Yes	No	1	-18.6 (20.8)[e]
15	400	No	No	-	-26.2 (13.2)[e]

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a. Includes deferred costs.

b. Includes estimate for ^{241}Pu decay.

c. Includes the option of not covering mill tailings piles.

d. Numbers in parentheses compare the cost of fuel cycle options with the high nuclear power schedule.

e. Numbers in parentheses compare the cost of fuel cycle options with the low nuclear power schedule.

3. Results

The costs of alternatives are compared in Table 9.9. Recycle of uranium and plutonium is calculated to be the least expensive option for the fuel cycle. Reprocessing is not cost justified if only the uranium is recycled to LWRs. The cost differences for either a 5-year fuel decay period before reprocessing or a 5-year delay in starting reprocessing are considered to be negligible as discussed later. Fuel cycle costs are itemized by processing step in Table 9.10 for the base case of recycle of uranium and plutonium (1 year decay), for 5-year fuel decay (Alternative 1), and for 5-year delay in starting reprocessing (Alternative 2). A similar comparison is given in Table 9.11 for the base case, recycle of uranium only (Alternative 6), no reprocessing or throwaway (Alternative 7), coprocessing (Alternative 8), and the tandem fuel cycle (Alternative 9).

a. Base Case

The base case and Alternatives 1-9 assume that 507 GWe of light water reactor capacity will be installed by the year 2000, and that no more LWRs will be built after 2000. Spent fuel from these reactors is reprocessed after at least one year of radioactive decay, and both the uranium and plutonium are recycled in the base case.

Fuel cycle costs for the base case are summarized in Table 9.9 and shown by cost center in Table 9.10. Calculated fuel cycle cost for the base case is approximately 226 billion dollars (Table 9.10).

TABLE 9.10

Fuel Cycle Costs, Billions of FY-1977 Dollars
(Base Schedule - 507 GWe by Year 2000
Alternatives 1 and 2

	1976-2000			*1976 - End of Study (Includes Deferred Costs and Credits*[a]		
	Base U Recycle Pu Recycle 1-Yr Decay	*Alternative 1* U Recycle Pu Recycle 5-Yr Decay	*Alternative 2* U Recycle Pu Recycle 5-Yr Delay	*Base* U Recycle Pu Recycle 1-Yr Decay	*Alternative 1* U Recycle Pu Recycle 5-Yr Decay	*Alternative 2* U Recycle Pu Recycle 5-Yr Delay
Mining	100.3	113.5	110.1	95.5	94.8	95.3
Separative Work	61.6	65.8	64.3	60.1	60.3	60.0
Uranium Fabrication	16.0	16.9	16.6	16.0	16.9	16.6
Fuel Storage	0.4	1.2	1.2	.4	1.6	1.4
Chemical Reprocessing	36.8	22.2	27.1	41.5	38.8	41.5
Pu Storage	.3	.2	.1	.4	.4	.3
MOX Fabrication	6.9	4.4	5.2	8.3	8.3	8.3
Terminal Waste	0.7	0.5	.2	3.6	3.6	3.6
Total	223.0	224.7	224.8	225.8	224.7	227.0
Difference from Uranium and Plutonium Recycle	-	+1.7	+1.8	-	-1.1	+1.2

a. Deferred costs are defined as costs required to complete processing, storage, and disposal of irradiated fuel discharged through year 2000. Credit for recovered uranium and plutonium is applied to reduce the mining and separative work costs incurred through the year 2000.

b. Effect of Fuel Decay (Alternative 1)

The effects of a 5-year fuel decay period before reprocessing are to decrease the reprocessing cost, defer the amount of recycle, and thus increase the amount of ore mined by the year 2000. The increase in cost by the year 2000 with delay is about $2 billion (1%). However, the deferred cost difference shown in Table 9.10 indicates a small (approximately 0.5%) cost advantage caused by lower reprocessing cost for the 5-year decay case.* However, a clearer definition of the alternatives is shown by discounting the costs. Discounted costs for the base case and Alternatives 1, 2, 6, 7, and 9 are shown in Table 9.12. With discounting, there is almost no difference in the present value of the cost of recycle with decay time.

With increased fuel decay, some of the fissile plutonium (^{241}Pu) decays to ^{241}Am, a nonfissile isotope. The loss of fissile plutonium resulting from the increased fuel decay is conservatively estimated** as 2% ($0.4 billion cost increase with 5 year decay).

c. Effect of Delay in Reprocessing (Alternative 2)

The effects of a 5-year delay in starting to reprocess LWR fuel are similar to those described for Alternatives 1, and the total cost through the year 2000 is nearly identical (Table 9.10).

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* The total mining costs (including deferred credits) for Alternatives 1 and 2 are less than the base case because the delayed credit for recycled uranium and plutonium is priced at a higher (future) ore price.

** Based on 12% ^{241}Pu in fissile plutonium discharged from LWRs and 3 years difference in the time that spent fuel is stored before reprocessing in the base case and Alternative 1.

TABLE 9.11

Fuel Cycle Costs, Billions of FY-1977 Dollars
(Base Schedule - 507 GWe by Year 2000)
Alternatives 6, 7, 8, and 9

	1976-2000					*1976 - End of Study (Includes Deferred Costs and Credits)*[a]				
	Base U Recycle Pu Recycle 1-Yr Decay	*Alternative 6 U Recycle*	*Alternative 7 Throwaway*	*Alternative 8 Coprocessing*	*Alternative 9 Tandem*	*Base U Recycle Pu Recycle 1-Yr Decay*	*Alternative 6 U Recycle*	*Alternative 7 Throwaway*	*Alternative 8 Coprocessing*	*Alternative 9 Tandem*
Mining	100.3	115.4	138.5	100.3	111.9	95.5	112.5	138.5	95.5	111.9
Separative Work	61.6	71.9	73.2	68.7	61.5	60.1	71.8	73.2	68.2	61.5
Uranium Fabrication - LWR	16.0	18.5	18.5	5.6	15.4	16.0	18.5	18.5	5.6	15.4
- HWR	-	-	-	-	21.2	-	-	-	-	26.1
Fuel Storage	0.4	0.4	2.1	0.4	2.0	.4	.4	3.6	0.4	4.3
Chemical Reprocessing	36.8	36.8	0	32.9	-	41.5	41.5	0	37.2	-
Pu Storage	.3	1.9	0	0	-	0.4	2.3	0	0	-
MOX Fabrication	6.9	0	0	27.9	-	8.3	0	0	31.6	-
Terminal Waste	0.7	0.7	2.7	0.7	0.1	3.6	3.6	9.7	3.6	8.4
Total	223.0	245.6	235.0	236.5	212.1	225.8	250.6	243.5	242.1	227.6
Incremental Electricity[b]	-	-	-	-	55.4	-	-	-	-	62.1
Difference from Base Case (U and Pu Recycle)	-	+22.6	+12.0	+13.5	+44.5	-	+24.8	+17.7	+16.3	+63.9

a. Deferred costs are defined as costs required to complete processing, storage, and disposal of irradiated fuel discharged through year 2000. Credit for recovered uranium and plutonium in irradiated fuel is applied to reduce the mining and separative work costs incurred through year 2000.

b. The cost of electricity in the base case and Alternatives 1-8 is the same (all LWR); in Alternative 9, the increment of higher cost from HWR operation is a cost associated with this fuel cycle.

TABLE 9.12

Discounted Fuel Cycle Costs, Billions of FY-1977 Dollars, 10% Discount Rate
(Base Schedule - 507 GWe)

	1976-2000					
	Uranium and Plutonium Recycle			*U Recycle*	*Throwaway*	*Tandem*[b]
	Base 1-Yr Decay	*Alternative 1 5-Yr Decay*[a]	*Alternative 2 5-Yr Delay*	*Alternative 6*	*Alternative 7*	*Alternative 9*
Discounted Total Fuel Cycle Cost	57.16	57.40	57.60	61.56	59.13	55.39
Difference from Base Case	-	0.24	0.44	4.40	1.97	6.60

	1976 - End of Study (Includes Deferred Costs)					
	Uranium and Plutonium Recycle			*U Recycle*	*Throwaway*	*Tandem*
	Base	*Alternative 1 5-Yr Decay*[a]	*Alternative 2 5-Yr Delay*	*Alternative 6*	*Alternative 7*	*Alternative 9*
Discounted Total Fuel Cycle Cost	57.31	57.33	57.67	61.65	59.63	56.24
Difference from Base Case	-	+.02	+0.36	4.34	2.32	7.95

a. Discounted costs include no correction for added ^{241}Pu decay with extended fuel decay.

b. The premium for generating electricity via HWR is included when compared to the base case.

With deferred costs, the cost of Alternative 2 exceeds the base case because of the additional requirement for storing irradiated fuel. With discounting, the cost becomes essentially equal to the base case (Table 9.12).

d. No Improvement in Offgas Treatment (Alternative 3)

The release of radioactive gases from fuel reprocessing and radon from tailings of uranium mining combine to increase the worldwide radiation exposure. In the base case, improved controls are assumed to be developed and included in reprocessing plants built after 1985 and for all mill tailings piles. In Alternative 3, it is assumed that no improvement in control of the radioactive gases is warranted or that effective removal is impractical to achieve.

An extensive program is underway to develop processes for controlling radioactive emissions from reprocessing plant offgases, but as yet the cost and effectiveness of such controls are uncertain.

In this Alternative, elimination of new and improved control technology that removes significant amounts of ^{85}Kr, ^{3}H, ^{14}C, ^{129}I, and particulates from the gaseous effluent of a new reprocessing plant is estimated to reduce capital costs about $40 million (undiscounted 1977 dollars) and to reduce annual costs $12 million. Total incremental savings is estimated to be about $1.2 billion (undiscounted 1977 dollars) if the six model reprocessing plants are constructed and operated with none of the improved control systems assumed for the base case. Cost estimates for inclusion of control technology in new plants were based on estimates given in References 5

and 6 escalated to 1977 dollars; to the sum of these estimates was added an allowance of $15 million for the premium required in the plant design to collect all the offgases for treatment and $10 million for uncertainties in the technology and for handling and storage of retained wastes. The capital cost estimates shown in Table 9.12 for the individual control steps contain the allowance prorated according to the expected first cost.

Eliminating the 12-ft cover of earth over the tailings piles is expected to save a total of $43 million (1977 dollars) based on costs given in Reference 3.

Total savings from eliminating offgas controls and earth cover (about $1.2 billion) would be about 1/2% of the fuel cycle costs for the base case. Annual costs were generated by the method described in Section 6 of Reference 5.

e. Retrofit AGNS for Control of Radioactive Effluent Gases (Alternative 4)

The cost to backfit AGNS is expected to be significantly higher than the cost for similar installations in new plants; however the additional cost is known with even less certainty than the cost of new construction. Retrofitting AGNS with the technologies shown in Table 9.13 is estimated at about $80 million (undiscounted 1977 dollars) capital, and $20 million annual costs. These estimates were escalated from preliminary estimates in References 5 and 6; a retrofit penalty of 100% was applied where retrofit estimates were incomplete. To the sum of these estimates

TABLE 9.13

Cost Estimates for Offgas Control Technology

Control Step	*Cost for Model Plant, Millions of 1977 Dollars*	
	Capital	*Annual*
Voloxidation (^{3}H control)	10	3
Selective Absorption (^{85}Kr control)	15	5
Catalytic Oxidation (^{14}C control)	5	1.5
Selective Absorption (I_2 control)	5	1.5
Sand Bed (TRU particulates)	5	1.5
Total	40	12.5

was added an allowance of $15 million for uncertainties in technology and for waste handling and storage. Total costs (capital and annual) for retrofitting AGNS is estimated to be $500 million (1977 dollars). Even at this cost, the economic benefit of recycling would not be significantly affected (though the economic impact on the AGNS facility would be major).

f. Separate Location of MOX Facilities (Alternative 5a)

A small cost penalty is estimated for locating plutonium fuel fabrication facilities separate from reprocessing plants. The capital cost of a stand-alone MOX plant is estimated to increase 10%, and the costs of shipping PuO_2 to the MOX plant would also be incurred. However, the total cost penalty would be less than $0.2 billion and would not significantly affect the advantages of recycle.

g. Location of Reprocessing Plants to Minimize Transportation of Spent Fuel (Alternative 5b)

The cost of shipping spent fuel is a very minor portion of the fuel cycle cost (less than 1%). Locating the reprocessing plants to reduce the fuel shipping distance would only partly reduce the shipping cost; the cost impact is estimated to be less than Alternative 5a and thus does not significantly affect the cost of recycle.

h. Location of Reprocessing Plants to Minimize Transportation of Waste (Alternative 5c)

The cost of shipping waste to terminal storage is estimated to be less than the fuel shipping cost (Alternative 5b). Locating the reprocessing plants to reduce the distance waste is shipped would have an insignificant effect on the cost of recycle.

i. Uranium Recycle Only (Alternative 6)

Prompt reprocessing (after one year) of spent fuel and recycle of uranium, but storage of recovered plutonium, results in a cost penalty of $25 billion compared to the base case (Table 9.11, Alternative 6).

j. Throwaway Fuel Cycle (Alternative 7)

Storage of spent fuel instead of fuel reprocessing is about $18 billion more expensive than the base case (Table 9.11), but is $7 billion less expensive than reprocessing the fuel and recycling only the uranium (Alternative 6).

k. Coprocessing (Alternative 8)

Recycle of a mixture of uranium and plutonium recovered from spent LWR fuel (Alternative 8) increases enrichment and fuel fabrication costs; mining demand remains unchanged (Table 9.11). The fuel cycle cost is about $16 billion more expensive than the base case and $1 billion less expensive than the throwaway option (Alternative 7).

l. Tandem Cycle (Alternative 9)

Fuel cycle costs for the tandem cycle (Alternative 9) are slightly more expensive (about $2 billion more) than the base case primarily because increased mining and fuel fabrication costs are largely offset by elimination of reprocessing. However, the significant premium for electricity generated in the HWRs increases the tandem cycle cost to over $60 billion more than the base case.

m. Effect of a Larger Nuclear Industry (Alternatives 10, 11, and 12)

With a nuclear capacity of 600 GWe installed by 2000, the options of recycle of uranium and plutonium (Alternative 10), recycle of uranium only (Alternative 11) and no reprocessing (throwaway, Alternative 12) were reanalyzed. The fuel cycle costs for these alternatives are listed in Table 9.14. The ranking by cost of the three alternatives is unchanged with a larger nuclear industry. As for the base schedule, Alternative 8 (uranium recycle) is the most expensive option; the throwaway option (Alternative 10) costs $23 billion more than recycle of uranium and plutonium.

n. Effect of a Smaller Nuclear Industry (Alternatives 13, 14, and 15)

With a nuclear capacity of 400 GWe installed by 2000, the options of recycle of uranium and plutonium (Alternative 13), recycle of uranium only (Alternative 14), and no reprocessing (Alternative 15) were reanalyzed. Fuel cycle costs for the

TABLE 9.14

Fuel Cycle Costs, Billions of FY-1977 Dollars
(High Schedule - 600 GWe by Year 2000)
Alternatives 10, 11, and 12

	1976-2000			*1976 - End of Study (Includes Deferred Costs)*		
	Alternative 10 Uranium and Plutonium Recycle	*Alternative 11 U Recycle*	*Alternative 12 Throwaway*	*Alternative 10 Uranium and Plutonium Recycle*	*Alternative 11 U Recycle*	*Alternative 12 Throwaway*
Mining	118.8	137.0	163.0	110.5	132.1	163.0
Separative Work	71.5	82.5	83.9	69.2	82.3	83.9
Uranium Fabrication	18.7	21.2	21.2	18.7	21.2	21.2
Fuel Storage	.6	.6	2.4	.7	.7	4.1
Chemical Reprocessing	39.5	39.5	0	46.9	46.9	0
Pu Storage	.3	2.1	0	.5	2.7	0
MOX Fabrication	7.4	0	0	9.4	0	0
Terminal Waste	.7	.7	2.9	4.1	4.1	11.0
Total	257.3	283.6	273.4	260.0	290.0	283.2
Difference from Uranium and Plutonium Recycle	-	+26.3	+16.1	-	+30.0	+23.2

a. Deferred costs are defined as costs required to complete processing, storage, and disposal for the fuel discharged through year 2000. Credit for recovered uranium and plutonium in recovered fuel is applied to reduce mining and separative work costs incurred through the year 2000.

alternatives are shown in Table 9.15. The ranking by cost of options remains unchanged, but recycle (Alternative 13) has a $13 billion cost advantage over Alternative 15, and a $21 billion cost advantage over Alternative 14.

4. Sensitivity Study

The costs for the major contributors to the fuel cycle costs were varied to determine if any parameter was especially relevant to the economic viability of a fuel cycle option. The results in Table 9.16 show that a combination of a 1) more expensive reprocessing cost, 2) low ore-price schedule, and 3) either a low separative work cost or a higher cost schedule for managing reprocessing wastes* would be required to offset the cost advantage indicated for reprocessing and recycle.

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* Assuming no change in spent-fuel disposal cost.

TABLE 9.15

Fuel Cycle Costs, Billions of FY-1977 Dollars
(Low Case - 400 GWe by Year 2000)
Alternatives 13, 14, and 15

	1976-2000			*1976 - End of Study (Includes Deferred Costs)*		
	Alternative 13 U Recycle Pu Recycle	*Alternative 14 U Recycle*	*Alternative 15 Throwaway*	*Alternative 13 U Recycle Pu Recycle*	*Alternative 14 U Recycle*	*Alternative 15 Throwaway*
Mining	80.6	92.9	111.8	76.7	90.7	111.8
Enrichment	51.3	60.1	61.1	50.2	60.0	61.1
Uranium Fabrication	13.1	15.3	15.3	13.1	15.3	15.3
Fuel Storage	.4	.4	1.9	.5	.5	3.1
Chemical Reprocessing	31.0	31.0	0	35.4	35.4	0
Plutonium Storage	.3	1.7	0	.3	2.2	0
MOX Fabrication	5.0	0	0	7.1	0	0
Terminal Waste	.6	.6	2.5	3.1	3.1	8.3
Total	183.3	202.0	192.6	186.4	207.2	199.6
Difference from Uranium and Plutonium Recycle	-	+18.7	+9.3	-	+20.8	+13.2

TABLE 9.16

Sensitivity Cost Studies for Base Reactor Schedule,
Billions of FY-1977 Dollars

	Cumulative Parameter Cost		*Total Cost Difference, Throwaway - Recycle*	
	2000	*Total[a] Study*	*2000*	*Total[a] Study*
A. Uranium Ore				
Base - Recycle	100.3	95.5	12.0	17.7
Throwaway	138.5	138.5		
High[b] - Recycle	107.0	101.6	16.9	23.2
Throwaway	150.1	150.1		
Low[c] - Recycle	93.7	89.4	7.0	12.2
Throwaway	126.9	126.9		
B. Separative Work				
Base - Recycle	61.6	60.1	12.0	17.7
Throwaway	73.2	73.2		
$125/SWU (High) - Recycle	77.0	75.1	15.0	21.1
Throwaway	91.6	91.6		
$75/SWU (Low) - Recycle	46.2	45.1	9.1	14.4
Throwaway	54.9	54.9		
C. Reprocessing				
Base	36.8	41.5	12.0	17.7
+25% Capital Charge	44.5	50.2	4.3	9.0
-25% Capital Charge	29.1	32.8	19.7	26.4
D. Reprocessing Waste Management Cost - Recycle				
Base - $25/kg	0.7	3.6	12.0	17.7
$50/kg	1.5	7.3	11.2	14.0
E. Spent Fuel Storage and Disposal Cost - Throwaway				
Base - $90/kg	4.9	13.4	12.0	17.7
Low - $60/kg	3.6	9.0	10.9	13.3
High - $200/kg	9.3	29.3	16.6	33.6

a. Includes deferred costs beyond the end of the study period.

b. The high ore price schedule assumes the price of ore increases $16/lb per million tons mined rather than $11/lb as shown in Table 9.7.

c. The low ore price schedule assumes the price of ore increases $6/lb per million tons mined rather than $11/lb as shown in Table 9.7.

E. BREEDER REACTOR CONSIDERATIONS

1. Introduction

The breeder option is completely dependent on a closed fuel cycle. Commercial application is based on LWR-generated plutonium for initial core loadings, and reprocessed breeder spent fuel is needed for system fuel reloads. Thus, both the extent and timing of a breeder commercial impact in the nuclear power sector are directly related to the policy decisions for LWR fuel reprocessing under consideration.

2. Impacts on Meeting the Liquid-Metal-Cooled Fast Breeder Reactor (LMFBR) Development and Program Requirements

LWR plutonium is needed in the breeder reactor program:

- To provide sufficient plutonium inventory to meet the operating and programmatic needs of the Fast Flux Test Facility (FFTF), the Clinch River Breeder Reactor Plant (CRBRP), and the Prototype Large Breeder Reactor (PLBR) until the Hot Pilot Plant (HPP) is operational in 1988.*
- To meet the program objective of demonstrating reactor performance and fuel cycle closure using prototypic LWR plutonium fuel with its higher 240-plutonium content.

Existing program requirements can be maintained with existing and future plutonium inventories without purchase from LWR reprocessing facilities until 1984. Operation of the FFTF and CRBRP

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* These facilities are described in ERDA 1535[2].

past 1985 and plans for fueling the PLBR cannot be continued until additional plutonium is made available either from an LWR reprocessing facility or from the HPP. This could delay the commercialization decision by as much as two to five years. Other options include:

- Continued operation of N-Reactor to produce fuel-grade plutonium and deferral of the advanced fuels programs could maintain operations in the FFTF and CRBRP for two to four years until the HPP becomes operational.
- The HPP could be expedited by four years so that LMFBR recycle plutonium would be available in 1984 when the fuel-grade plutonium inventories become depleted.
- Foreign plutonium could be purchased, weapons stockpile material could be used, and LWR fuels could be reprocessed in government facilities.

3. Impacts on Commercialization

The commercialization of the LMFBR is dependent on the use of LWR plutonium in its initial penetration and buildup phases. The present 1993 LMFBR commercialization date would require the initial fuel loading of 4.5 to 6.0 MT of fissile plutonium be available in 1991 which would require operation of a 1500 MT/yr LWR reprocessing plant no later than 1990. Following introduction of the first commercial plant, the rate of LMFBR penetration would be limited by the availability of LWR Pu from LWR reprocessing plants.

F. CONCLUSIONS

The different alternatives were assessed in terms of resource use, environmental, and economic costs and benefits. A summary of incremental changes is given in the following paragraphs, together with general conclusions resulting from this assessment.

1. Alternative 1 (5-year decay)

Alternative 1 results in no significant environmental benefits overall, although 25% of the back end cycle releases would be deferred until after the year 2000 because of delayed processing. Costs are about the same as the base case. Uranium resource requirements are about 13% higher through the year 2000 but eventually become the same as for the base case; more land would be required for fuel storage basins.

2. Alternative 2 (5-year delay)

Alternative 2 results in no significant environmental benefits overall, although 26% of the back end cycle releases would be deferred after the year 2000 because of delayed processing. Costs and ore requirements are about the same as the base case.

3. Alternative 3 (No Improved Offgas Controls for Reprocessing Plants and No Cover for Tailings Piles) and Alternative 4 (Retrofitting AGNS with Improved Controls in 1986)

Alternatives 3 and 4 should be evaluated on a cost-benefit basis when the technology for the various controls become available and when more accurate cost estimates can be made. A preliminary

comparison of cost and dose effects developed in this statement are given in Table 9.17 to indicate whether programs to develop offgas controls are warranted. Covering mill tailings piles is more cost-effective than controlling offgases from reprocessing plants.

TABLE 9.17

Preliminary Cost-Benefit Analysis

Alternative	*Action*	*Cost Change, millions of dollars*	*Equivalent Dose Change, millions of man-rem*[a]	*Cost/Dose Change, dollars/man-rem*
3	Omit offgas controls on new reprocessing plants	-1200	+4	300
	Eliminate 12-ft cover on mill tailings piles	-43	+4[b]	10
4	Add offgas controls to AGNS	500	-1	500
	Increase cover from 12 to 20 ft on tailings piles	22	-0.2[b]	150

a. Dose to world population for 100 years.

b. The "smeared lung" model used for calculating dose commitment from ^{222}Rn and its daughters results in significant dose to lungs, bone, and thyroid in addition to whole-body dose. Health effects are calculated separately for the whole body and each critical organ and are summed to give total health effects. The value of a health effect is **$1,400,000** based on $1000 per man-rem (whole body) and EPA's estimate of 700 health effects (400 cancers and 300 genetic effects) per 10^6 man-rem.

Appendix I to 10 CFR 50[7] contains an interim numerical guide for judging the practicality of an effluent treatment system for a power reactor. Appendix I indicates that the bound of practicality is about $1000 per man-rem reduction of whole-body dose considering exposure of the population within 50 miles of the reactor. If the interim guide for reactor effluent systems were applicable to the alternatives in Table 9.17, development of offgas controls for reprocessing plants is warranted. However, this conclusion is subject to these uncertainties:

- The guideline value of $1000 per man-rem may not be appropriate for releases from mill tailings and reprocessing plants with respect to long-term exposure of the world population.
- The control systems are not yet completely developed, the costs may be underestimated, and the effectiveness may be overestimated, especially for ^{14}C.

Regardless of cost-benefit ratios, if the Standards proposed by the Environmental Protection Agency relating to planned discharge from uranium fuel cycle facilities are adopted (40 CFR 190) reprocessing plants would be required to control gaseous radioactive effluents to the approximate degree assumed for model reprocessing plants with improved offgas controls in Section 2C (see discussion in Sections 3B, 3C, and 5).

4. Alternative 5a (Separate vs Collocated Site)

Alternative 5a has only minor penalties in environmental effects and costs. Of more significance would be safeguards requirements involved in shipping PuO_2.

5. Alternatives 5b and 5c (Siting Reprocessing Plants to Minimize Shipment of Spent Fuel or Radioactive Waste)

Alternatives 5b and 5c have minor environmental effects and negligible impact on cost.

6. Alternative 6 (Recycle U Only)

Alternative 6 results in significantly higher environmental effects and costs as compared to the base case.

7. Alternative 7 (No Recycle)

Alternative 7 results in reduced environmental effects from back end operations but increased effects from front end operations (an overall increase of 300 health effects and accidental deaths); it incurs about 8% higher costs. Additional U_3O_8 resources are also required that represent an increase of 30% above the base case. Because of the limited uranium available by conventional recovery techniques, this increase is considered significant.

8. Alternative 8 (Coprocessing)

Alternative 8 results in 7% higher costs. Environmental effects and uranium demand are unchanged. Safeguarding of plutonium to prevent diversion would be simplified.

9. Alternatives 9 (Tandem Fuel Cycle)

Alternative 9 results in similar environmental effects and resource requirements as the base case. However, with a 6% higher cost of nuclear power and many technical uncertainties, it is not considered to be a promising fuel cycle option.

10. Alternatives 10-15 (High and Low Nuclear Growth Rate Projections)

Comparison of alternatives within the high and low nuclear growth rate projections shows that resource usage, health effects, and economic costs retain the same ranking as in the base 507 GWe projection.

11. General

The assessments described in this report also lead to the following general conclusions regarding the significance of various effects when considering the differences between options:

a. Differences not significant
   - Electrical power, fossil fuel, and water
   - Manpower (employment opportunities)

b. Differences exist, but are not significant in context of other costs, uses, and effects
   - General public health effects (except Alternative 3)
   - Occupational accidental deaths
   - Land Use
   - Costs
   - High-level waste disposal options

c. Differences probably significant
   - Uranium resource utilization
   - Safeguards - arms limitation questions
   - Higher cost of tandem fuel cycle

d. Differences probably significant - outside of scope of this report
   - Effects on other energy sources
   - Detailed effects on breeder reactor development

In summary, based on resource use, environmental and economic analyses, this statement finds no technical reason to delay programs that will provide the information needed on costs, environmental effects, and other important factors needed for decision making concerning the back end of the LWR fuel cycle.

REFERENCES FOR SECTION 9

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2. *Environmental Statement, Liquid Metal Fast Breeder Reactor Program.* Report ERDA-1535, Energy Research and Development Administration, Washington, DC (1975).
3. *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "as Low as Practicable" Guide — Mining of Uranium Ores.* ERDA Report ORNL-TM-4903, Vol. 1, Oak Ridge National Laboratory, Oak Ridge, TN (1975).
4. *Radiological Effects of Ionizing Radiation.* BEIR Report. National Academy of Science, National Research Council, Washington, DC (1972).
5. *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "as Low as Practicable" Guide — Nuclear Fuel Reprocessing.* ERDA Report ORNL-TM-4901, Oak Ridge National Laboratory, Oak Ridge, TN (1975).
6. *Draft Supplement No. 1 to the Final Environmental Statement, Barnwell Nuclear Fuel Plant.* Report NUREG-0082, Supp 1 (Draft), U.S. Nuclear Regulatory Commission, Washington, DC (1976).

7. *US Code of Federal Regulations*, Title 10, Part 50, Appendix I. "Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low as is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents."

10. SAFEGUARDS

A. INTRODUCTION

This section describes the safeguards aspects of the proposed programs to close the LWR fuel cycle. The areas where safeguards considerations have a potential for affecting the general welfare and safety of the public are identified, and programs to mitigate the risk are described.

The analyses presented here closely parallel the evaluation of safeguards issues developed for the LMFBR and documented in the environmental statement for that program.[1] In addition, material from the Nuclear Regulatory Commission's review of the nuclear energy center concept[2] and information from ERDA's Division of Safeguards and Security are included. These programs, together with current methods and standards, provide a broad, generic base for design and implementation of safeguards throughout the LWR industry.

B. BACKGROUND

The fundamental objective of safeguards principles is the mitigation of risk to the public resulting from sabotage or malevolent use of special nuclear material (SNM). In this environmental statement, this objective applies primarily to the protection of plutonium during reprocessing and recycle of LWR fuels. That

the achievement of this safeguards objective is both possible and likely is demonstrated by several decades of successful worldwide experience in protecting nuclear weapons and their components, both in storage and in transit. Efforts to prevent incidents have been successful because of an effective safeguards program which has evolved to reflect current conditions and requirements. Furthermore, the tactical problems associated with the protection of U.S. weapons systems are similar in many ways to those associated with safeguarding the nuclear fuel cycle. Much of this methodology and hardware is directly applicable.

The safeguards-related risks associated with the nuclear fuel cycle may be viewed as the product of the probability of attempted theft or diversion of special nuclear materials (SNM) times the probability of success times the consequences of such acts to the public. Existing ERDA safeguards programs have components in each area. Current physical protection systems, which include information systems, access control systems, and incident response systems, serve to reduce the frequency of attempted thefts or diversions and the likelihood that such attempts would be successful. Special recovery technology and procedures, use-denial methods for despoiling special nuclear material, siting and transportation requirements, and sabotage-resistant equipment and facilities have been developed to reduce the likelihood that terrorists or other potential diverters of nuclear material could threaten society even if they successfully obtain material or gain access to vital

system components. The intent is to constantly improve these programs to force diverters to commit greater and greater resources with a) concomitant increases in the likelihood of detection, and hence nullification, by law enforcement agencies, and b) a poorer tradeoff against the expected return or the force required to attain the objective by conventional method. These components form a hierarchy of safeguards measures which may be expanded as necessary to achieve the objective of no significant increased public risk of death, injury, or property damage from nuclear fuel cycle activities.

The safeguards systems incorporated in future fuel cycle facilities and activities will be both heuristic and responsive. While the principles, objectives, and responsibilities of safeguards systems can be defined in detail, it is unrealistic and detrimental to restrict future development by defining the mechanical workings of systems to be instituted and installed over the next decade or more. These systems will be much more effective if allowed to evolve continuously in response to changing social and technical conditions. Safeguards improvements and refinements may be expected with time to reflect changes in threats, increased commercial use of SNM, and on-going ERDA safeguards research and development activities, and innovation by industry.

C. SAFEGUARDS ASPECTS OF THE LWR FUEL CYCLE

The projected LWR fuel cycle, including plutonium recycle, is illustrated in Figure 10.1. The fuel cycle materials important for safeguards considerations are listed in Table 10.1 in order of their potential use to a diverter.

For this statement, reprocessing is defined to start with transportation of the spent LWR fuels from the reactors to the reprocessing plant. The spent fuel elements are transported in massive shielded casks. They are treated at a reprocessing plant to separate the plutonium and uranium from the high-level wastes. The fission products are separated, solidified, and transported to high-level waste storage. The plutonium (including both plutonium produced in the LWR irradiations and any unexpended plutonium from the old loading) is either transported to storage or recycled directly to the fuel fabrication facility for recycle as PuO_2. Alternatively it might be coprecipitation with some of the recovered uranium. The unused uranium is separated as uranyl nitrate, uranium oxide, or uranium hexafluoride and is transported to the gaseous diffusion plant for re-enrichment. Alternatively it might be sent to storage or recycled directly to the fuel fabrication facility.

At the fuel fabrication facility, plutonium and uranium oxides, if not already mixed, are blended to form the bulk mixed-oxide feed and then pressed into pellets. Most of the uranium will come from the enrichment plant, where, under the assumed LWR

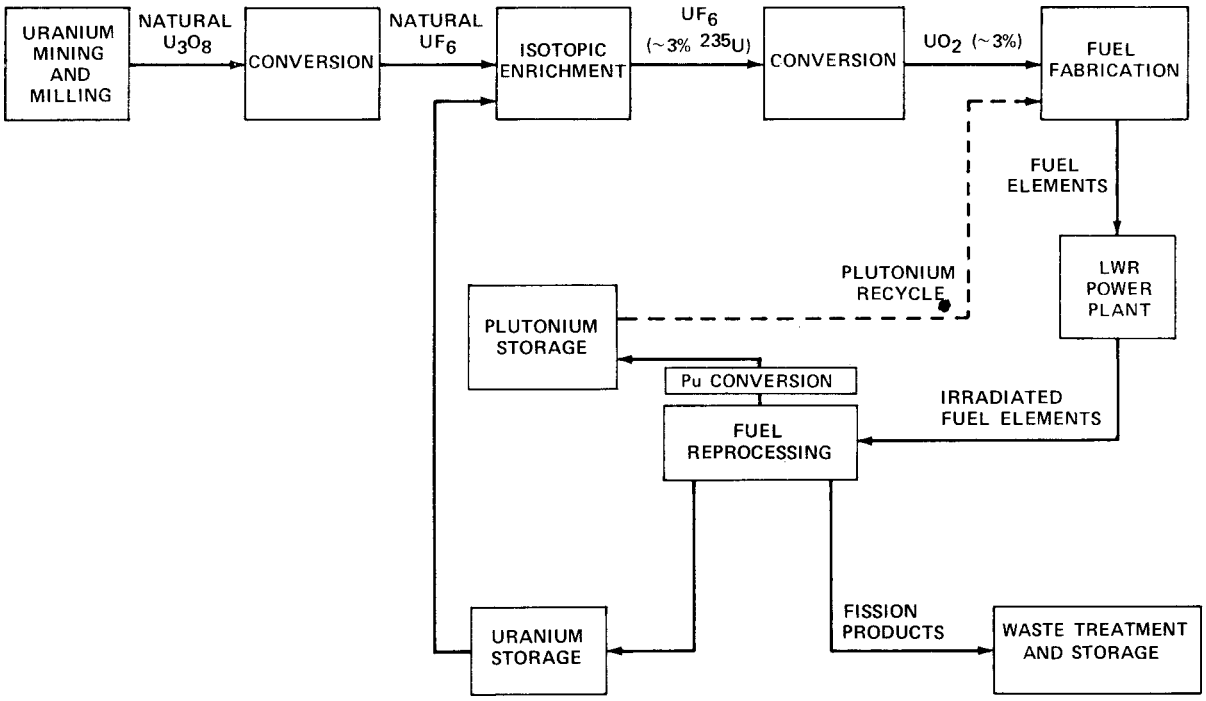

FIGURE 10.1. LWR Fuel Cycle

TABLE 10.1

Pertinent Materials Present in LWR Fuel Cycle

Material[a]	*Location in Fuel Cycle*[b]	*Processing Necessary*	*Approximate Mass Needed for 10 kg of Contained Pu*	*Other Difficulties*
PuO_2	Reprocessing output Plutonium storage Recycle fuel fabrication	None	12 kg	Toxicity Radioactivity
$Pu(NO_3)_4$	Reprocessing	Conversion to oxide	17 kg	Toxicity
$(Pu+U)O_2$	Recycle fuel fabrication	Dissolution and separation	350 to 1000 kg	Toxicity
Fuel element (prior to irradiation)	Recycle fuel fabrication Reactor input	Mechanical and chemical separation	1 PWR, 2 BWR assemblies (∿400 to 1000 kg)	Toxicity
Irradiated element	Reactor output Reprocessing input	Mechanical and chemical separation	1 PWR, 2 BWR assemblies (∿400 to 1000 kg)	Intense radioactivity, massive shielding

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a. Materials are listed in the order of attractiveness as a target for theft based on the amount of processing necessary to transform them into useful forms.

b. Including transportation between fuel cycle facilities where appropriate.

recycle, the feed will be a mixture of newly mined uranium and recycle uranium. The oxide fuel pellets are loaded into fuel pins, which in turn are assembled into complete fuel elements. The elements are then transported to the reactor for refueling.

The attractiveness of fuel materials as a target for theft will depend on the degree of processing necessary to transform the material into a useful form. Of the materials listed in Table 10.1, PuO_2 is the most suitable for use as a nuclear explosive. Although $Pu(NO_3)_4$ can sustain a fission reaction, it is not directly suitable for use in a nuclear explosive and would require chemical conversion to the oxide or metal. The mixed plutonium-uranium oxide fuel (bulk feed, pellets, pins, or elements) can also sustain a fission reaction. However, the amount of contained plutonium and the technical sophistication necessary to produce an explosion without separation would be much greater than if the plutonium were separated. Therefore, diverted mixed oxide materials would have to be processed to separate the plutonium. A possible alternative use of the plutonium to a terrorist or criminal group might be as a radiological contaminant and poison.

The enriched uranium supplied for the LWR fuel contains about 3% ^{235}U. This material is not usable as a nuclear explosive, nor does it constitute a serious radiological hazard. The recovered uranium from the reprocessing plant is at even lower enrichment. The spent fuel also is of little use as a fissionable

material before it is reprocessed, although sabotage might be attempted to disperse radioactivity from this fuel. Likewise the separated fission products (waste) contain essentially no fissionable materials, but could be a target for dispersion.

D. DEFINITION OF THE PROBLEM

The basic purpose of safeguards facilities and procedures is to counter premeditated violent acts or threats by individuals or groups against targets that may either be symbolically related to a public issue or have substantial intrinsic value in relation to the ultimate objectives or motives of the individual or group. Such acts or threats may arise from several sources, including psychotics, disgruntled employees, dissidents from labor-management disputes, criminals, or terrorists.

Attack by a terrorist group represents the most difficult situation to deal with because, to some degree, it embodies all of the attributes of other threats. In terms of capability and force size, it has the potential to engage local security forces on equal terms. Determination to succeed may be as strong as in the case of mentally unbalanced individuals. Organization and discipline may exceed that of all other threats. The terrorist threat is used as the basis for this discussion to cover all relevant aspects of the problem; assumptions include the possibility the terrorist groups may include facility employees with a high skill level and ready access to the particular nuclear facility.

Based on a survey[3] of terrorism and terrorist acts, the following trends were identified:

- The incidence of terrorism is increasing.
- More terrorist groups are operating in more areas than have been known to be operating simultaneously before.
- Terrorist groups are cooperating, both internally and internationally, to an unprecedented extent.
- Terrorist incidents increasingly involve interests of more than one country.
- The level of sophistication of weapons at the terrorists' disposal has increased.
- Terrorists are attacking targets of wider variety and greater complexity.
- The cost of terrorism, in damage or harm to individuals and property, is increasing.
- Terrorists are using more sophisticated means of gaining access to and escaping from their targets.
- With the exception of airplane hijacking, counter-terrorist measures have had little apparent effect on the proliferation of terrorist incidents.

There is no indication that terrorist groups have attained the level of sophistication necessary to obtain and employ special nuclear materials in acts of violence. However, there is no inherent reason why such sophistication could not be achieved; thus, the threat of terrorist activity must be considered possible, and

countermeasures must be devised. From historical data, neither the form of the threat nor the means used by the adversary can be predicted with much assurance. The safeguards system must be based on an assumption that the possibility of a serious threat exists, and the system must be designed to make its effectiveness as independent as practicable of the nature of the threat.

E. CONSEQUENCES OF SUCCESSFUL ACTS

Failure of safeguards implies a successful act of sabotage or the unauthorized acquisition of SNM by a person or group. If the act of sabotage extends into the public sector or if the SNM can successfully be exploited to create a nuclear explosion or dispersal of radioactive material, then an actual public risk can be defined.[4] Some of the major consequences associated with potential public risks are discussed below.

1. Nuclear Explosion

The debate on whether construction of a nuclear explosive device is easy revolves around matters of degree. The general agreement is that, even given the availability of the requisite nuclear material, the construction of an illicit explosive device still requires a high level and range of skills and resources.[5] The design and implementation of LWR fuel cycle safeguards systems will be conservatively based on the premise that making an illicit nuclear explosive device is within the range of skills and resources available to persons or groups operating outside the law.

The uranium and plutonium forms available in the LWR fuel cycle are far from ideal for the purpose of constructing a weapon, either in nuclear, i.e., isotopic, or chemical characteristics. Currently, isotopic adjustment is judged to be beyond the capabilities of any clandestine operation; however, new technology such as laser separation may eventually change this conclusion. Even chemical conversion of these materials to more efficient forms, while technically feasible, requires a sequence of time-consuming, careful operations; severe penalties (e.g., accidental criticality, plutonium ingestion) await the uninformed or inexperienced person or group. The fabrication and assembly of a workable weapon is complex and laden with many obstacles, any one of which could prevent the accomplishment of the adversary's first goal — the availability of a workable explosive device. The attempted detonation of even high-grade material is more likely to result in a low tonnage yield or a disassembling, non-nuclear, explosion than a substantial-yield explosion unless the fabrication and assembly have been carried out by highly-trained and experienced personnel. A weapon fabricated directly from raw fuel-cycle material will be still less likely to operate successfully. Considering the sequence of goals that must be attained by the adversary, the overall probability of any successful explosion of an illicit weapon is extremely low. The possibility that such a weapon would be in the multi-kiloton range is even more unlikely.

The destructiveness of any illicit nuclear explosion depends

on the circumstances at the time and place of its detonation as well as on its yield. The circumstances are a matter of choice for the adversary. This choice is affected by constraints such as logistics and target accessibility and will depend on his perception of how best to serve his purposes. The yield will depend on the characteristics of the nuclear material and the skills and resources of the adversary. The physical effects of a nuclear blast can be determined from the published literature. A summary of these physical effects is given by Willrich and Taylor.[5] The damage radii for various effects of nuclear explosions as functions of yield are shown in Table 10.2 (reproduced from Table 2-1 in that report[5]).

More graphic examples are given by Willrich and Taylor to illustrate the effects of nuclear explosions in a football stadium, a residential area, or a basement parking lot. For example, "An explosion (10-ton) in the center of a football stadium during a major game could lethally irradiate as many as 100,000 spectators." While the examples cited by Willrich and Taylor are speculative and are based on an assumption of complete success by the adversary, they do illustrate the extremely severe consequences of a nuclear explosion. However, for the reasons stated earlier, the probability that any of these events would actually take place, while not specifically quantifiable, is considered to be extremely low.

The adversary who has succeeded in fabricating a workable weapon, despite the obstacles cited above, faces further serious obstacles

TABLE 10.2

Damage Radii for Various Effects of Nuclear Explosions as Functions of Yield[a]

Yield (High Explosive Equivalent)	*Radius for Indicated Effect, meters*						
	500-rem Prompt Gamma Radiation	*500-rem Neutrons*	*Fallout (500-rem Total Dose)*[b]	*Severe Blast Damage (10 psi)*	*Moderate Blast Damage (3 psi)*	*Crater Radius (Surface Burst)*	*Crater Radius (Underground Burst)*
1 ton	45	120	30-100	33	65	3.4	6.7
10 tons	100	230	100-300	71	140	6.8	13.3
100 tons	300	450	300-1,000	150	300	13.6	26.5
1 kiloton	680	730	1,000-3,000	330	650	27	53
10 kilotons	1,150	1,050	3,000-10,000	710	1,400	54	104
100 kilotons	1,600	1,450	10,000-30,000	1,500	3,000	108	208
1 megaton	2,400	2,000	30,000-100,000	3,250	6,500	216	416

a. From Reference 5.

b. Assuming 1-hr exposure to fallout region, for yields less than 1 kiloton, increasing to 12 hr for 1 megaton with much larger fallout region.

if his goal is to cause a high number of casualties and great damage. The selection of appropriate emplacement areas is finite. The safeguards response capability, alerted by the theft or diversion, would have brought its search and recovery actions to bear; and law enforcement agencies would be watchful for suspicious actions, especially in congested urban areas, at public gatherings, at key governmental facilities, and in areas of technological vulnerability. Clearly, however, if a workable illicit device of even modest yield were cleverly placed and detonated, thousands of people could be killed and millions of dollars worth of property could be destroyed. **It is likewise true that equal damage and death could be created with more certainty and greater ease by non-nuclear methods. Such deaths would be immediate as opposed to delayed deaths by cancer. Also, terrorists have not shown the inclination to kill indiscriminately large numbers of innocent people.**

2. Radiological Weapons

The consequences of the use of radiological (dispersal) weapons are more speculative than the consequences of nuclear explosions because of the wider ranges of criminal intent, time span, and physiological responses that are involved. For example, the public risk factors range from zero in the case where the intent is to deny access to an empty facility by dispersing plutonium in it and then notifying the authorities, to significant when the same material is surreptitiously released in a fine particle form in, say, a large, occupied building. In the latter case, the critical path for exposure resulting from a plutonium dispersal

device would be inhalation and dose to the lung. There are some uncertainties connected with the specific dose-effect relationship, but the order of magnitude of the amount in the lung usually associated with short-term death is 10^{-3} to 10^{-2} g and with long-term death (from cancer) is 10^{-5} to 10^{-4} g. The dose received will be a function of concentration suspended in air, respiration rate, retention rate, and residence time. Other factors such as solubility will also have an effect, but they are not considered in this discussion of gross effects.

The area to be contaminated, the concentration in air, the particle size (affecting settling and resuspension rates and respiratory retention rates), and the residence time of the victims are more or less subject to the control of the adversary within the level of his skills and resources and within such constraints as logistics and target accessibility. Depending on the attacker's ability to transform the physical or chemical form of the material, plutonium could be prepared in liquid or solid form with coarse or fine particle size. It might be dispersed in corridors or ventilation systems, from moving vehicles, or by explosion or fire.

As an example, a large office building or roofed stadium 200 m long by 100 m wide by 50 m high will have an enclosed volume of 1,000,000 m^3. If a respiration rate of 20 ℓ/min and a retention rate of 10% is assumed, the plutonium concentration in air necessary to produce short-term death after a 5-min exposure would be 0.1 to 1 g/m^3 or 100 to 1000 kg suspended in air.[1] Because only a fraction of the total released is likely to be suspended, the

total amount required would be several times that amount. The corresponding amount for long-term death would be 1 to 10 kg in suspension. For residence times longer than 5 min, the quantity required would be proportionately smaller. If the purpose is to force evacuation of the building or costly decontamination with minimal injury to personnel, 1 g uniformly scattered on the 20,000 to 10,000 m^2 of floor area would be sufficient.

As in the case of nuclear explosion, the number of mechanisms by which the potential effects can be illustrated is very large. Willrich and Taylor[5] offer a qualitative discussion of some possibilities. They also indicate that the use of radiological weapons does not appear to be consistent with observed behavior of terrorists or extortionists.

3. Facility Sabotage

A fundamental effort in the design of nuclear facilities is to incorporate features and engineering concepts to provide public protection from internal accidents and the forces of natural phenomena. Such design efforts inherently provide a significant degree of protection against forced entry and acts of sabotage divorced from direct requirements for safety purposes. Thus, an examination of the inherent sabotage resistance that fuel cycle facilities can be expected to possess is pertinent. Although specific requirements that will apply to future facilities is one of the program elements to be developed as part of this program, currently available information related to existing and near-term

nuclear facilities is useful in indicating the inherent sabotage resistance probable in future facilities.

In fulfilling the requirements of 10 CFR 50[6] applicants for reprocessing facilities must provide construction and operating license applications from the Nuclear Regulatory Commission (NRC) and show evidence of meeting strict design criteria. The portions of the plants used for storing or processing plutonium must be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, and floods without impairing their capability to perform safety functions. Such design requirements result in massive structures that provide confinement for processing and storage facilities.

In fulfilling the requirements of 10 CFR 70,[7] applicants for mixed-oxide fuel fabrication and associated storage facilities must also provide construction and operating license applications from the NRC and show evidence of meeting strict design criteria. As described in the section on current licensing and safeguards activities, the function of NRC is to approve construction of the proposed structures, systems, and components only after determining that the design bases provide a reasonable assurance of protection against natural phenomena and the consequences of potential accidents.

The inherent design features in nuclear facilities supplement safeguards systems in protecting against sabotage. However, the consequences of potential acts of sabotage can be described. The probability of sabotage by nuclear bomb explosions is judged to be extremely low because it would be the product of many low-probability

events. Some of these are: the theft of the necessary quantity of SNM from the safeguarded fuel cycle; the evasion of recovery activities mounted by Federal and other authorities; the acquisition and application of the knowledge, skills, and resources necessary for processing and fabrication of an explosion device; the placement of the device in a safeguarded area; and detonation of the device. It is also considered highly improbable that the individual or group having such a device would choose to attempt sabotage of a nuclear fuel cycle facility, which will be locally protected and physically hardened, in preference to using the device as a threat against relatively unprotected targets such as urban areas. For these reasons, the probability that a nuclear bomb would be successfully used to sabotage a nuclear facility is considered to be so low that the event must be judged incredible.[1]

In contrast with nuclear bomb sabotage, sabotage attempts involving less potent damage initiators are considered credible. These would include relatively small quantities of chemical explosives or other devices that might be used to cause physical damage to key safety systems or equipment either inside or outside facility buildings and flammable or pyrophoric materials that might be used to initiate fires inside facility buildings. Also, without any devices except readily available hand tools, an individual or small group might attempt to put an operating nuclear fuel cycle facility into an increasingly unsafe condition by maladjustment of operating systems and protective interlocks.

The consequences of successful sabotage of fuel cycle facilities cannot be quantitatively estimated with certainty at this time, primarily because designs and operating procedures for some parts of the fuel cycle have not yet been developed in sufficient detail to permit meaningful analysis. However, available preliminary analyses of serious accidents in future facilities[1] are believed useful in indicating the general magnitude of the consequences of facility sabotage. For example, a general facility fire in a mixed oxide fabrication plant (which might be caused by a saboteur) would release about 0.013 g of plutonium oxide to the environment. Table 10.3 shows that an individual near the plant would receive a dose of about 0.2 rem (bone), and Table 10.4 indicates a 50-mile population dose of about 22 man-rem (bone) as the result of this release. As another example, Table 10.5 presents estimates of the releases associated with a serious leak of highly radioactive liquid within the reprocessing plant. For this accident (which also might be imagined as sabotage-initiated), Table 10.6 shows that an individual near the plant could receive a total body dose of 8×10^{-5} rem, and Table 10.7 shows a 50-mile population dose of 0.12 man-rem.

TABLE 10.3

Potential Doses to an Individual Resulting From Accidental Radionuclide Releases From a Fuel Fabrication Plant (Dose to an Individual 1000 m From the Stack)[a,d]

	Inhalation and Submersion in the Passing Cloud						
	Total-Body Dose			*Highest Reference Organ Dose*			
Accident Description	*Dose, rems*	*Significant Radionuclides*[b]	*% Dose From Significant Radionuclides*	*Dose, rems*	*Reference Organ*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*
Criticality Accident	3.4 E-3[c]	^{88}Kr	11	6.5 E-2	Thyroid	^{133}I	24
		^{134}I	60			^{134}I	26
		^{135}I	15			^{135}I	46
General Facility Fire	4.2 E-3	^{238}Pu	50	2 E-1	Bone	^{238}Pu	46
		^{239}Pu	11			^{239}Pu	10
		^{240}Pu	14			^{240}Pu	14
		^{241}Pu	25			^{241}Pu	29

a. Stack height = 100 m.

b. A significant radionuclide is one that contributes the largest dose to a reference organ.

c. 3.4 E-3 = 3.4×10^{-3}.

d. Reprinted from Reference 1.

TABLE 10.4

Potential Population Doses Resulting From Accidental Radionuclide Releases From a Fuel Fabrication Plant[c]

	Inhalation and Submersion in the Passing Cloud						
	Total-Body Dose			*Highest Reference Organ Dose*			
Accident Description	*Dose, man-rem*	*Significant Radionuclides*[a]	*% Dose From Significant Radionuclides*	*Dose, man-rem*	*Reference Organ*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*
Criticality Accident	3.3 E-1[b]	^{87}Kr ^{88}Kr ^{134}I	10 47 10	6.5 EO	Thyroid or Bone	^{133}I ^{134}I ^{135}I	28 5 53
General Facility Fire	5.1 E-1	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu	50 11 14 25	22 EO	Bone	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu	46 10 14 29

a. A critical radionuclide is one that contributes the largest dose to a reference organ.

b. 3.3 E-1 = 3.3×10^{-1}

c. Reprinted from Reference 1.

TABLE 10.5

Radionuclide Release Resulting From Leak in Vessel or Pipe Containing Highly Radioactive Material[a,c]

	Quantity Released, Ci	
Nuclide	*Degraded Filters*	*Normal Filters*
^{3}H	1.01 E-1[b]	1.01 E-1
^{89}Sr	2.35 E-4	6.52 E-6
^{90}Sr	1.68 E-3	4.67 E-5
^{90}Y	1.68 E-3	4.67 E-5
^{91}Y	5.90 E-4	1.64 E-5
^{95}Zr	1.64 E-3	4.57 E-5
^{95}Nb	3.50 E-3	9.71 E-5
^{103}Ru	1.50 E-4	4.16 E-6
^{106}Ru	2.48 E-2	6.88 E-4
^{110}Ag	1.41 E-5	3.93 E-7
^{125}Sb	7.31 E-4	2.03 E-5
^{127}Te	1.27 E-4	3.54 E-6
^{129}Te	1.51 E-6	4.20 E-8
^{129}I	3.92 E-6	3.92 E-6
^{131}I	3.10 E-12	3.10 E-12
^{134}Cs	7.49 E-4	2.11 E-5
^{137}Cs	4.46 E-3	1.24 E-4
^{141}Ce	2.68 E-5	7.46 E-7
^{144}Ce	1.86 E-2	5.18 E-4
^{147}Pm	9.75 E-3	2.71 E-4
^{154}Eu	5.18 E-5	1.44 E-6
^{155}Eu	1.36 E-3	3.78 E-5
^{234}U	5.97 E-9	1.66 E-10
^{235}U	9.50 E-11	2.64 E-12
^{236}U	2.96 E-10	8.24 E-12
^{238}U	1.03 E-8	2.87 E-10
^{238}Pu	6.80 E-4	1.89 E-5
^{239}Pu	1.39 E-4	3.85 E-6
^{240}Pu	1.89 E-4	5.24 E-6
^{241}Pu	2.05 E-2	5.71 E-4
^{241}Am	1.06 E-4	2.95 E-6
^{243}Am	1.95 E-6	5.41 E-8
^{242}Cm	6.23 E-4	1.73 E-5
^{244}Cm	5.18 E-5	1.44 E-6

a. Based on fission products associated with 1 kg heavy metal being made airborne as submicron particles.

b. 1.01 E-1 = 1.01×10^{-1}.

c. Reprinted from Reference 1.

TABLE 10.6

Potential Individual Doses Resulting From Accidental Radionuclide Releases[a,d]

	Inhalation and Submersion in the Passing Cloud						
	Total-Body Dose			*Highest Reference Organ Dose*			
Accident Description	*Dose, rems*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*	*Dose, rems*	*Reference Organ*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*
Fuel Element Rupture	1.4 E-6[b]	^{85}Kr ^{134}Cs ^{137}Cs	50 20 27	8.8 E-6	Lung	^{134}Cs ^{137}Cs	32 67
Leak of Vessel or Pipe[c]	8 E-5	^{238}Pu ^{240}Pu	43 13	3.1 E-3	Bone	^{238}Pu ^{240}Pu ^{241}Pu	43 14 28
Solvent Fire[c]	1.4 E-5	^{239}Pu ^{240}Pu ^{241}Pu	19 26 45	8.9 E-4	Bone	^{239}Pu ^{240}Pu ^{241}Pu	19 26 53
Nuclear Criticality (Other Vessels)	1.1 E-3	^{138}Xe ^{89}Kr ^{137}Xe	34 55 6	1.1 E-4	GI	^{138}Xe ^{89}Kr	65 33
Explosion in HLW	<1 E-6	^{241}Am ^{244}Cm	55 15	1.2 E-6	Bone	^{241}Am ^{242}Cm	48 14
Explosion (Pu)[c]	1.0 E-6	^{238}Pu ^{240}Pu ^{241}Pu	47 15 26	4.5 E-5	Bone	^{238}Pu ^{240}Pu ^{241}Pu	45 14 30
Explosion (I)[c]	<1 E-6	^{129}I	100	<1 E-6	Thyroid	^{129}I	100
^{85}Kr Storage	1.3 E-4	^{85}Kr	100				

a. Stack height = 100 m. The highest potential doses to an individual occurred at ∿1000 m from the stack.

b. 1.4 E-6 means 1.4 x 10^{-6}.

c. Calculations are for the degraded-filter case.

d. Reprinted from Reference 1.

TABLE 10.7

Potential Population Doses Resulting From Accidental Radionuclide Release[a,d]

	Inhalation and Submersion in the Passing Cloud						
	Total-Body Dose			*Highest Reference Organ Dose*			
Accident Description	*Dose, man-rem*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*	*Dose man-rem*	*Reference Organ*	*Significant Radionuclides*	*% Dose From Significant Radionuclides*
Fuel Element Rupture	2.9 E-3[c]	^{85}Kr ^{134}Cs ^{137}Cs	50 20 27	1.4 E-2	Lung	^{134}Cs ^{137}Cs	32 67
Leak of Vessel or Pipe[b]	1.2 E-1	^{238}Pu ^{240}Pu ^{241}Pu	43 13 24	4.8	Bone	^{238}Pu ^{240}Pu ^{241}Pu	43 14 28
Solvent Fire	2.1 E-2	^{239}Pu ^{240}Pu ^{241}Pu	19 26 45	8.6 E-1	Bone	^{239}Pu ^{240}Pu ^{241}Pu	19 26 53
Nuclear Criticality (Other Vessels)	2.2 E-1	^{138}Xe ^{89}Kr	45 55	1.1 E-1	GI	^{138}Xe ^{89}Kr	75 25
Explosion in HLW	1.0 E-4	^{241}Am ^{244}Cm	55 15	1.9 E-3	Bone	^{241}Am ^{242}Cm	48 14
Explosion (Pu)[b]	1.6 E-3	^{238}Pu ^{240}Pu ^{241}Pu	47 15 26	6.8 E-2	Bone	^{238}Pu ^{240}Pu ^{241}Pu	45 14 30
Explosion (I)[b]	<1 E-6	^{129}I	100	<1 E-6	Thyroid	^{129}I	100
^{85}Kr Storage	0.38	^{85}Kr	100				

a. Stack height = 100 m.

b. Calculations are for the degraded-filter case.

c. 2.9 E-3 = 2.9×10^{-3}.

d. Reprinted from Reference 1.

The above consequences are well within limits currently considered acceptable for credible accidental events. It is a considered judgment that acts of sabotage would produce results that would not be significantly greater than those associated with such accidents, and would, in most events, be less. Part of the effort associated with the development of fuel cycle facilities will be to do additional analytical studies to define more precisely the risks and consequences of sabotage involving mechanisms other than those related to general safety considerations.

4. Transport Sabotage

It is generally conceded that radioactive materials in transport are inherently more vulnerable to sabotage attack than when confined to more substantial process facilities. For this reason, early efforts in the field of safeguards were directed at the potential transportation hazards. Advanced means for protecting SNM are currently operational, and even more sophisticated safeguards methods are being developed by ERDA and are under study by both ERDA and NRC.

The packages currently approved or projected for shipping the various kinds of radioactive materials found in the LWR fuel cycle are described in Section 2C7 of this environmental statement. Information on the radioactive inventory and mode of transport of each shipment is also presented in that section. Through qualitative consideration of the hardness of the packages, the physical form of the products contained and the general characteristics of the vehicle, judgments can be made on the percentages of

radioactive inventories that might escape to the environment (outside the vehicle enclosure) as the result of sabotage attack with various kinds of damage-producing devices. The contained products are assumed to be unprotected (i.e., no physical protection is assumed other than that provided by the current-design package and the nonhardened vehicle). Table 10.8 presents a set of estimates made on this basis.

The percent release numbers given in the table are believed to be conservative (high) estimates of the amounts of material that might escape from the package and the vehicle. Where the possible release is estimated to range from zero to an upper value (e.g., 0-10%), the probability that material will be released in an attack is very low, because of factors such as:

- Package design (e.g., the outer container of PuO_2 packages may be penetrated, but the inner capsule containing the PuO_2 may be unaffected).
- Physical characteristics of the contained item (e.g., the fresh fuel outer and inner containers may be ruptured, but the fuel cladding may remain intact).
- Lack of knowledge and skill of the saboteur.

Most of the materials in transport are nonvolatile solids, which, should they escape to the environment, would be likely to produce localized contamination only. The exceptions are UF_6, which reacts with moisture to produce gaseous HF; spent fuel, which contains gaseous and volatile fission products; and the noble gases.

TABLE 10.8

Estimated Radioactivity Releases to Environment Resulting From Hypothetical Sabotage of Unprotected Shipping Packages (Current Design)[a]

Material in Package	*Mode of Transport*	*Inventory of Shipment, Ci*	*Inventory of Radioactivity Release, % of Inventory*	*Maximum Release, Ci*
UF_6	Truck	3	10-50	1.5
UO_2	Truck	102	0-5	5
PuO_2	Truck	67×10^5	0-1	0.7×10^5
Fresh Fuel	Truck	11×10^5	0-5	0.6×10^5
Spent Fuel	Rail	33×10^6	0-1	0.3×10^5
Alpha Waste	Rail	2.8×10^4	0-1	280
Low-Level Beta-gamma Waste	Truck	475	0-10	48
Tritium	Truck	3.2×10^4	0-5	1600
Alpha-beta Gamma Waste	Rail	500	0-1	5
Cladding Hulls	Rail	1.5×10^6	0-1	0.2×10^5
High-Level Waste	Rail	7.8×10^6	0-1	0.8×10^5
Noble Gases	Truck	9×10^5	0-20	1.8×10^5
Iodine	Truck	1	0-5	0.05

a. Reproduced from Reference 1.

In order to further evaluate the potential consequences of transport sabotage, each of the following examples assumes that the release is the maximum shown in Table 10.8.

a. Plutonium Dioxide

Table 10.8 indicates a maximum release of PuO_2 to the environment of 0.7×10^5 Ci. The amount of material involved would be about 6 kg. This would cause a serious contamination problem in the immediate vicinity. In addition, some of the material would become airborne. In order to estimate the effect of the airborne material, additional assumptions are necessary on area of contamination, wind velocity, and particle pickup. For this analysis, the contaminated area is assumed to be 30 m^2 and wind velocity is assumed to be 3 m/sec. For PuO_2 (assumed to be in the form of powder), respirable size particles would exist in a concentration of about 1 $\mu g/m^3$ in the air immediately above the contaminated area. For these conditions, there would be a downwind release of 0.3 g/hr, or about 3.5 Ci/hr.

The doses to man associated with this release can be estimated by methods given in Reference 1. For an assumed 1-hr release from the sabotage site, the maximum dose to an individual (50 m from the site) would be about 12 rem (whole body) and about 520 rem to the critical organ (bone). The corresponding 50-mile population doses would be about 10 man-rem (whole body) and 440 man-rem (bone).

b. Spent Fuel

Table 10.8 indicates a maximum sabotage-related release of 0.3×10^5 Ci from spent fuel transported by rail. A sabotage device was assumed to rupture all fuel assemblies and produce an opening in the cask large enough to permit all available gaseous and volatile fission products to escape quickly. If a fire accompanied the sabotage, additional volatilized fission products would escape until the fire was extinguished. Solid and nonvolatile radioactive materials ejected from the damaged cask would make up the remainder of the release.

The spent fuel cask incident involving release of gaseous and volatile fission products has been analyzed. Calculations[1] indicate that about 2120 Ci would be released without a fire, and 3080 Ci could be released with a 2-hr fire. The maximum individual dose calculated for this incident was 4.3 rems (short-time ground-level release with no fire for an individual 50 m from site). The highest population dose is 6.8 man-rems (2-hr elevated release with fire). Most (about 90%) of the postulated sabotage release would be solid and nonvolatile radioactive material. The ejection of this material from the damaged cask would seriously contaminate the rail car and nearby ground or facilities and cause local, high-intensity radiation fields. The area contaminated would probably be greater if the car were moving at the time of the attack. Individuals near the car might suffer severe exposure, particularly if they remained in the area.

F. CURRENT LICENSING AND SAFEGUARDS ACTIVITIES

1. Licensing Procedures

Title 10 of the *Code of Federal Regulations* (10 CFR 70) provides that no person shall receive title to own, acquire, deliver, receive, possess, use, transport, import, or export SNM without a license. The intent of the code is to establish Federal control over all SNM and its uses. A fundamental part of the licensing procedure is to assure the applicant's intent and capability to comply with safeguards requirements. Further, the regulation defines the relationship between NRC, which is responsible for licensing, regulations, and inspections, and the proposed licensee. The regulation includes 1) prelicensing evaluation of a license applicant's proposed nuclear activities including safeguards procedures, 2) issuance of a license to authorize approved activities subject to specific safeguards requirements, and 3) inspection and enforcement to ensure that applicable safeguards requirements are met by implementation of approved procedures.

The prelicensing review addresses information submitted by the applicant to NRC for approval, including the applicant's technical qualifications; a description of the process, equipment, and facilities to be used; the material control and accounting program, including measurement performance capability; and a physical security plan. The details of the material control and accounting program and the physical security plan are withheld from public disclosure as provided in 10 CFR 2.8.[8]

The prelicensing review includes considerations of other regulatory aspects of the facility design and operation. Full account is taken of the interrelated effects of safety requirements and of the inherent features of the facility that contribute to the protection afforded by the safeguards system. For example, the requirements that SNM be safely contained during normal operation, operational accidents, and earthquakes and tornadoes, as well as requirements for shielding and safe shutdown in the event of maloperation result in the incorporation of substantial physical containment structures, shutdown systems, and personnel access limitations that in themselves enhance safeguards.

Each licensee must confine possession and use of SNM to the purposes and locations authorized in the license and may transfer nuclear materials only to an authorized recipient. The licensee must also comply with the detailed accountability and physical protection requirements incorporated into the license in accordance with the regulations. The licensee is required to afford NRC opportunity at all reasonable times to inspect SNM and the premises and facilities where SNM is used, produced, or stored. In addition, each licensee is required to make available for inspection any relevant records and to perform or to permit NRC to perform any tests deemed necessary for the administration of Federal regulations.

2. Facility Protection

The safeguards procedures to be employed at future LWR fuel

cycle facilities will be based on extensive experience with commercial light-water reactors, enrichment and fabrication facilities for the present reactor industry, and government-owned, weapons-oriented facilities that encompass all of the types of industry considered in this statement. The current state of safeguards protection for the nuclear industry reflects this experience as shown by a series of regulations with an active safeguards posture. For example, regulations provide for a sabotage protection program to be designed by the licensee and approved by NRC. Regulatory Guides[9,10] have been published to assist the licensee in the development of an adequate program. The guide includes recommendations on control of material and personnel access to the plantsite, selection and training of plant operating personnel, monitoring of plant equipment, and design and arrangement of plant features. Some of the specific recommendations are: onsite armed guards; continuously-manned alarm stations; two independent communication links with law enforcement authorities; specifications for intrusion alarms, emergency exit alarms, and line supervisory systems; equipment testing; and protection of vital equipment through design features including automatic indication of inoperability.

This active program is also reflected in facility design regulations. Facilities that will process or contain SNM are designed to possess several inherent structural characteristics that would make intentional damage extremely difficult. In nuclear

installations, significant parts of the facility often are in the below-grade regions of the containment building, and the surrounding earth provides additional protection. Additional features that provide protection against acts of sabotage, incorporated into typical plant designs for normal safety reasons, include massive shields, physical separation of vital engineering safety features, and duplication of essential electrical and mechanical systems. These features, together with conventional industrial security measures such as fencing and guards, collectively provide a significant measure of protection against the occurrence or the effects of sabotage. Other requirements specify that vital equipment or SNM be located within areas protected by barriers, which, in turn, are within a fenced or walled, protected area. The space between the protected area fence and the inner barrier must be monitored to detect abnormal presence or activities. Guards and watchmen must be trained and equipped; access to protected and vital areas must be restricted; individuals authorized to enter such areas without escort must wear coded picture badges; and vehicles inside the protected area must be escorted. Persons and packages entering protected areas are searched (employees having official security clearance and packages other than hand-carried are searched at random). Before entry into a material access area, all packages are searched, and all persons, packages, and vehicles are searched upon leaving. A Regulatory Guide[11] has been issued on control of personnel access.

3. Material Control

In addition to physical protection, the maintenance of accountability records is a fundamental measure used in the safeguarding of nuclear materials and is applicable to all types of nuclear facilities. It includes preparation of detailed and current records on the form, quantity, and location of SNM and the completion of material balances based on physical inventories. In its general application, it includes various administrative and operational procedures directed at maintaining current knowledge of nuclear material quantity and locating and detecting any removal of such material from authorized locations. Methods include documented transfer of custodial responsibility, regular and frequent piece count by operating personnel, and analysis of correlated process information.

A specialized aspect of material accountability is "material balance" accounting in which statistical information is generated by which the accounting data can be evaluated. The sensitivity of this technique is limited by the accuracy of the measurements, and the timeliness is limited by the interval between physical inventory measurements.

Licensees authorized to possess at any one time more than one effective kilogram* in unsealed form are required to establish a measurement system and physical inventory procedures adequate 1) to assure that the uncertainty of the material balance is within prescribed limits, and 2) to calculate material balances based on physical inventories. These inventories are conducted for plutonium (except for plutonium containing 80% or more by weight of ^{238}Pu), for ^{233}U, and for uranium enriched to 20% or more in the isotope ^{235}U at bimonthly intervals, and at semiannual intervals for uranium enriched to less than 20% in the isotope ^{235}U. Inventories are also conducted for plutonium, ^{233}U, and highly enriched uranium in that portion of an irradiated fuel reprocessing plant from the dissolver to the first vessel outside the shielded portion of the process, and for plutonium containing 80% or more by weight of the isotope ^{238}Pu. Minimum standards have been stipulated for the quality of these material balances. Licensees authorized to possess from 350 g up to one effective kilogram of contained ^{235}U, ^{233}U, plutonium, or any combination thereof are required to conduct physical inventories at least annually.

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* "Effective kilograms of special nuclear material" means: 1) for plutonium and ^{233}U their weight in kilograms; 2) for uranium with an enrichment in the isotope ^{235}U of 0.01 (1%) and above, its element weight in kilograms multiplied by the square of its enrichment expressed as a decimal weight fraction; and 3) for uranium with an enrichment in the isotope ^{235}U below 0.01 (1%), by its element weight in kilograms multiplied by 0.0001.

4. Material in Transit

In addition to protecting SNM at specific facilities, safeguards regulations are also in force for material being moved between sites. At the present time, about 500 licensee shipments of SNM per year are regulated because the quantity and/or isotopic enrichment is of sufficient magnitude to be considered strategically important. The provisions of 10 CFR 73[12] include specific physical protection requirements that apply to licensees who ship 5 kg of ^{235}U (contained in uranium enriched to more than 20%), 2 kg of plutonium or ^{233}U, or a weighted combination of these.

Truck shipments involving these quantities of material must be escorted by two armed guards in a separate vehicle unless the licensee uses a truck or trailer specially designed to protect against theft or diversion. Truck shipments must be made directly from the shipper to the consignee with no loading or unloading of other cargo between these points. Additional measures include: 1) communication every 2 hr by radiotelephone on board the truck (where radiotelephone coverage is not available, conventional telephone calls must be made when there has been no communication for more than 5 hr); 2) marking of the top and sides of the truck with identifying letters or numbers; 3) use of preferential routing to avoid potential trouble areas; 4) continuous surveillance of truck transport, including the use of two persons on board; 5) preplanning shipments to ensure delivery at a time

when the receiver is available to accept the material; and 6) the use of locks and seals on vehicles and containers.

When rail transportation is used, the shipment must be escorted by two armed individuals in the shipment car or in an escort car of the train to keep the shipment cars under observation and to guard the shipment and check the car or container locks and seals when the train is stopped. Radiotelephone communication must be maintained with a licensee or his agent, backed up as needed by normal telephone communication at scheduled stops. All transfers must be monitored by armed personnel.

Regulation 10 CFR 73[12] prohibits licensee shipments aboard passenger aircraft of more than 20 g or 20 Ci, whichever is less, of plutonium or ^{233}U and shipments of more than 50 g of ^{235}U enriched to more than 20%. When cargo aircraft are used, the number of enroute transfers are to be minimized and are to be observed by armed monitoring personnel. Public law 94-79 bans shipments of plutonium by air transport.

Shipments by sea must be made on vessels making minimum ports of call; ship-to-shore contact must be made daily. No ship-to-ship transfers are permitted. Transfer to other transport modes must be monitored by armed guards. The shipment must be kept in a sealed compartment that must be monitored during transfer of other cargo.

Importers are required to protect shipments in accordance with the requirements outlined above from the time the shipments arrive in this country. Exports must be accompanied by escorts

(unarmed) from the last terminal in the U.S. to the point where the shipment is unloaded at a foreign terminal.

In addition to the current requirements, studies and development efforts are underway to reduce even further the risks associated with transportation of SNM. Items under development or consideration include:

- Use of specially designed vehicles with penetration-resistant cargo compartments and immobilization capability.
- Use of convoys with massive defensive forces and equipment.
- Transport by air from secure base to secure base.
- Combinations of the above.

5. Inspection and Enforcement

During operation of a licensed facility the NRC carries out a program of onsite inspection to assure continued effective implementation of safeguards regulations and programs. The strategy employed by the NRC during these inspections is directed at achieving its objectives on a systematic basis. The scope, frequency, and intensity of inspection are determined primarily by considering: 1) strategic value of the SNM, 2) the accessibility of the SNM, and 3) safety significance. Secondary but important modifying factors are: 1) prior inspection history of the facility, and 2) results of the NRC monitoring of facility reports, including shipper-receiver differences in SNM mass balances.

If items of noncompliance or deficiencies are found in the licensee's implementation of safeguards requirements, the licensee is instructed to take prompt corrective action and to inform the NRC of the results. The NRC has the authority to modify, suspend, or revoke licenses and to impose civil penalties on licensees for noncompliance with the terms and conditions of their license. Violators of the Atomic Energy Act or any regulation or order issued by the NRC may be guilty of a crime and, upon conviction, may be punished by fine or imprisonment or both as provided by law.

6. Response to Theft or Sabtoage

NRC procedures regarding licensed facilities provide for response to: 1) any suspected or actual theft of SNM or other material which could present a radiological hazard; 2) any threat of sabotage to a facility containing such materials; and 3) any threat involving the destructive use of such materials.

Licensees are required to inform the NRC promptly, and will normally inform local law enforcement agencies, in the event of a suspected or actual theft or of a threat of sabotage. If the threat arises outside nuclear facilities, the NRC may be informed by various sources such as local law enforcement agencies, other government agencies, or concerned citizens.

After being informed of any of the circumstances listed above, the NRC would promptly inform the FBI, which has statutory responsibility for investigating all such incidents. The NRC would support the FBI with specialized technical assistance, especially in connection with the recovery of stolen material. In addition, the NRC would undertake to determine whether there is a potential hazard of nuclear explosion or radiological danger. If a hazard is determined to exist, the various government organizations responsible for implementing the established Radiological Assistance Plan would be alerted or activated. This plan provides for advice and assistance in the areas of emergency evacuation and rescue, radiation monitoring, decontamination, and specialized emergency medical services where personnel are exposed to radiation.

The safeguards responsibilities of government-owned facilities, such as the Savannah River Plant, and shipment of government-owned SNM strategic quantities, are currently under ERDA jurisdiction. Plans for response to adversary action are operational on much the same basis as for licensed facilities. A diagram of the currently established activity and responsibility relationships in the event of a safeguards incident is shown in Figure 10.2.

A summary of current domestic and international safeguards responsibilities is shown in Figure 10.3. As shown in this summary, current plans for dealing with safeguards incidents extend

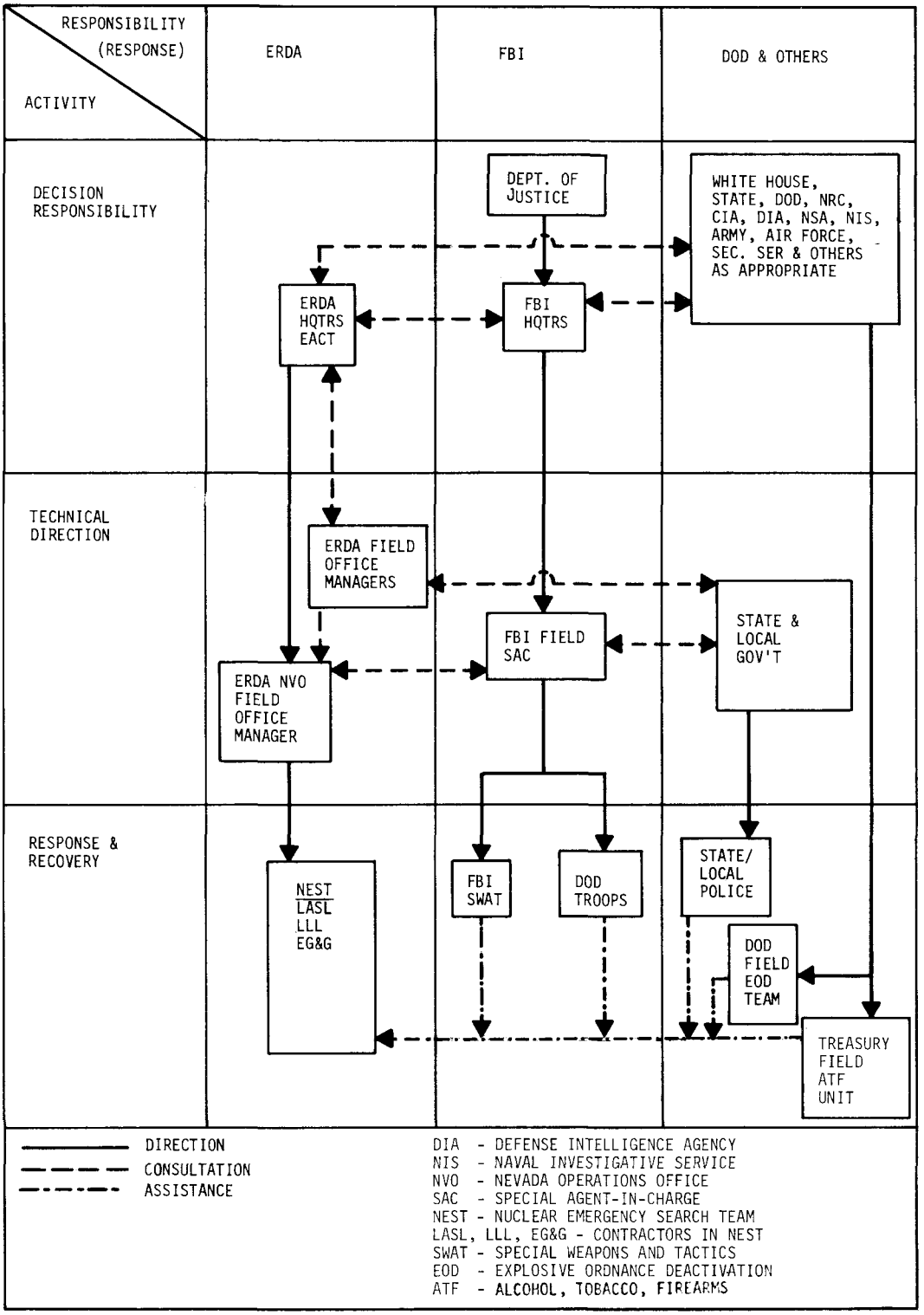


FIGURE 10.2. Safeguards Response to Adversary Action at Government Facilities

SAFEGUARDS RESPONSIBILITIES					
ACTS BY ADVERSARIES	DESIGN	RULE MAKING	OPERATIONS		
			DETECTION	RESPONSE	ASSURANCE
I. ACTS OUTSIDE THE U.S. [INTERNATIONAL SAFEGUARDS]					
A. BY FOREIGN GOVERNMENTS					
1. DIVERSION	IAEA, EURATOM	NPT, IAEA, EURATOM	IAEA INSPECTION OR EUROPEAN INTEL. COM.	STATE DEPT., U.N.	IAEA, INTEL. COM.
2. ILLEGAL USE			INTEL. COMMUNITY	STATE DEPT., DOD	
B. BY SUBNATIONAL GROUPS	IAEA, FORGN GOV	IAEA, FORGN GOV	IAEA, FORGN GOV, INTEL. COMMUNITY	FORGN GOV, STATE DEPT., DOD	IAEA, FORGN GOV
II. ACTS INSIDE THE U.S. [DOMESTIC SAFEGUARDS]					
A. PREPARATORY ACTIVITIES			FBI, PER. SECURITY	FBI	
B. NUCLEAR MATERIAL ACCESS AND ACQUISITION				INITIAL / COOPER. WITH / FINAL	
1. MATERIAL IN PRIVATE SECTOR	FACILITY	NRC	FACILITY	FAC / NRC / FBI	NRC
2. CERTAIN ERDA POWER RESEARCH FACILITIES	FACILITY	NRC	FACILITY	FAC / ERDA & NRC / FBI	NRC
3. MISC. MINOR GOVT FACILITIES	AGENCY, FACILITY	NRC	FACILITY	FAC / AGCY & NRC / FBI	NRC
4. DOD WEAPONS	DOD	DOD	DOD	DOD / / FBI	
5. ALL OTHER GOVT FACILITIES	CONTRACTOR	ERDA	FACILITY	FAC / ERDA / FBI	ERDA
C. UTILIZATION ACTIVITIES [RESPONSE AND RECOVERY]	ERDA (EACT)	AGENCIES	N/A	POLICE, FBI, WITH ERDA-EACT, NVO-NEST	NSC
D. POST-EVENT	EACT, IRAP, FPA	AGENCIES	N/A	CIVIL DEFENSE & DISASTER AGENCIES	NSC

IAEA INTERNATIONAL ATOMIC ENERGY AGENCY
EURATOM EUROPEAN ATOMIC ENERGY COMMUNITY
DOD DEPARTMENT OF DEFENSE
NRC NUCLEAR REGULATORY COMMISSION
FBI FEDERAL BUREAU OF INVESTIGATION
ERDA ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACTOR CONTRACTOR OPERATOR OF A GOVT-OWNED FACILITY
FAC, FACILITY MANAGEMENT OF A FACILITY
EACT EMERGENCY ACTION AND COORDINATING TEAM
IRAP INTERAGENCY RADIOLOGICAL ASSISTANCE PLAN
FPA FEDERAL PREPAREDNESS AGENCY
NSC NATIONAL SECURITY COUNCIL
NVO NEVADA OPERATIONS OFFICE, ERDA
NEST NUCLEAR EMERGENCY SEARCH TEAM
NPT NON-PROLIFERATION TREATY
PER. SECURITY ERDA PERSONNEL SECURITY PROGRAM

FIGURE 10.3. Overall Current Safeguards Responsibilities

to the international level and involve and coordinate foreign and international organizations and agencies with U.S. groups having safeguards responsibilities.

7. System Adequacy

The current overall safeguards system is designed to protect the public against the threats inherent in the theft or diversion of SNM or the sabotage of nuclear facilities. In general terms, the means used to accomplish this objective are to interpose barriers around SNM that are beyond the resources of the criminal or require more resources to overcome than would become available after successful penetration.

The judgement of the adequacy of the current safeguards program is necessarily subjective at the present time. Effectiveness evaluation tools currently are being applied and refined. Although hypothetical scenarios can be constructed for successful penetration of one or more barriers, the probability of successfully penetrating a number of successive barriers becomes very remote. The safeguards record of protecting the public against criminal acts involving SNM is favorable. It can certainly be questioned whether the safeguards program is the sole reason for this record, but it cannot be reasonably disputed that it has had a signficant effect.

Subsequent subsections describe programs to develop even more reliable and more effective safeguards measures. The development and implementation of these programs, together with even more sophisticated analyses of the threats to be countered, including those in transporting SNM, is an integral part of the program to develop a full complement of adequately safeguarded facilities for the LWR fuel cycle.

G. CURRENT SAFEGUARDS PROGRAM

The development of advanced safeguards methods is currently proceeding under the auspices of ERDA-Division of Safeguards and Security (DSS). Transportation and safeguards of government-owned fuel is the responsibility of ERDA Division of Military Applications (DMA). These programs are organized and funded independently of other research and development effort on the LWR fuel cycle, but they are closely aligned to efforts in that area by cooperation and consultation between DSS, the Division of Uranium Resources and Enrichment (URE), the Division of Waste Management, Production and Reprocessing (WPR), other agencies such as NRC, and appropriate contractors. An illustration of inter-agency and contractor coordination is the Safeguards Technical Advisory Committee composed of representatives from DSS, SR, RDD, URE, WPR, NRC, Brookhaven National Laboratory, Sandia Laboratories, and Los Alamos Scientific Laboratory. A primary objective of this committee is to provide guidance for the design and definition of research and development programs on safeguards to be funded and administered through DSS.

The DSS program has three distinct areas of responsibility:

- To prevent any possibility of major consequences (losses) to society caused by criminal acts involving nuclear materials.
- To support the U.S. defense program through the protection of classified information from unauthorized disclosure.
- To protect U.S. government property under ERDA control from theft, vandalism, or sabotage.

The DSS program objectives, indicative of expectations to be achieved by current tasks, are:

- To develop, assess, and assure the availability of cost effective safeguards systems for application to ERDA facilities and the commercial fuel cycle.
- To assist the International Atomic Energy Agency (IAEA) in its safeguards role in guarding against the proliferation of nuclear explosive devices and defining effective safeguards internal control and physical protection systems in conjunction with efforts of foregn countries for guarding against domestic threats to nuclear materials and facilities.
- To develop, assess, and assure implementation of effective physical protection and information control systems for the protection of classified information and ERDA property at ERDA, selected other U.S. government, and privately-owned facilities.

Determination of the adequacy of the safeguards program, in light of the program objectives, is made in terms of reducing the risk of societal consequences to levels commensurate with other hazards that are acceptable to the public.

Certain tasks are currently applicable to efforts in the LWR fuel cycle program described in this environmental statement. Later, as elements of the fuel cycle become operational, the operations-type efforts will become operative. At the present time, these tasks are defined to analyze and solve safeguards problems in both generic and specific terms. A summary of the objectives of these tasks is as follows:

1. Characterize Threat

The product of this task will be a continuation of efforts on identification and assessment of threats and the development of rational ways for dealing with them. Threats will be graded according to the attractiveness to an adversary of the various forms of nuclear materials and types of nuclear facilities. The final report on threat characterization is scheduled to be issued in FY-1977. Threat information will be updated biannually to reflect social, political, and economic changes.

2. Concept Development

Concept development is essential to assure that safeguards funds are allocated for maximum benefit and that possible trade-off alternatives are identified. Effectiveness evaluation techniques, which use both computers and systems analysis, are being developed for physical protection and internal control systems.

From this effort, data will be provided which allow evaluation of the adequacy of the safeguards concept, the hazards remaining, and the resultant consequences to be expected. Cost-effective comparison of these various safeguards concepts can then be obtained, and factual data can be provided to the regulatory agencies for development of safeguards requirements. The concept design structure used to identify needed technology, hardware, and systems is shown in Figure 10.4.

3. Technology, Hardware, and Systems Development Tests and Evaluation

This effort is directed toward development, test, and evaluation of new and/or improved:

- Physical protection.
- Material control and accountability.
- Recovery equipment.
- Instrumentation and techniques.

These mechanisms can then be applied in safeguards systems for specific types of facilities. The development of improved non-destructive analysis (NDA) mechanisms (under Material Control and Accountability Mechanisms) and recovery mechanisms are ongoing efforts.

4. System Design, Installation, Test, and Evaluation in Operating Environment

Following the development, test, and evaluation of the mechanisms discussed above, effort is directed toward the

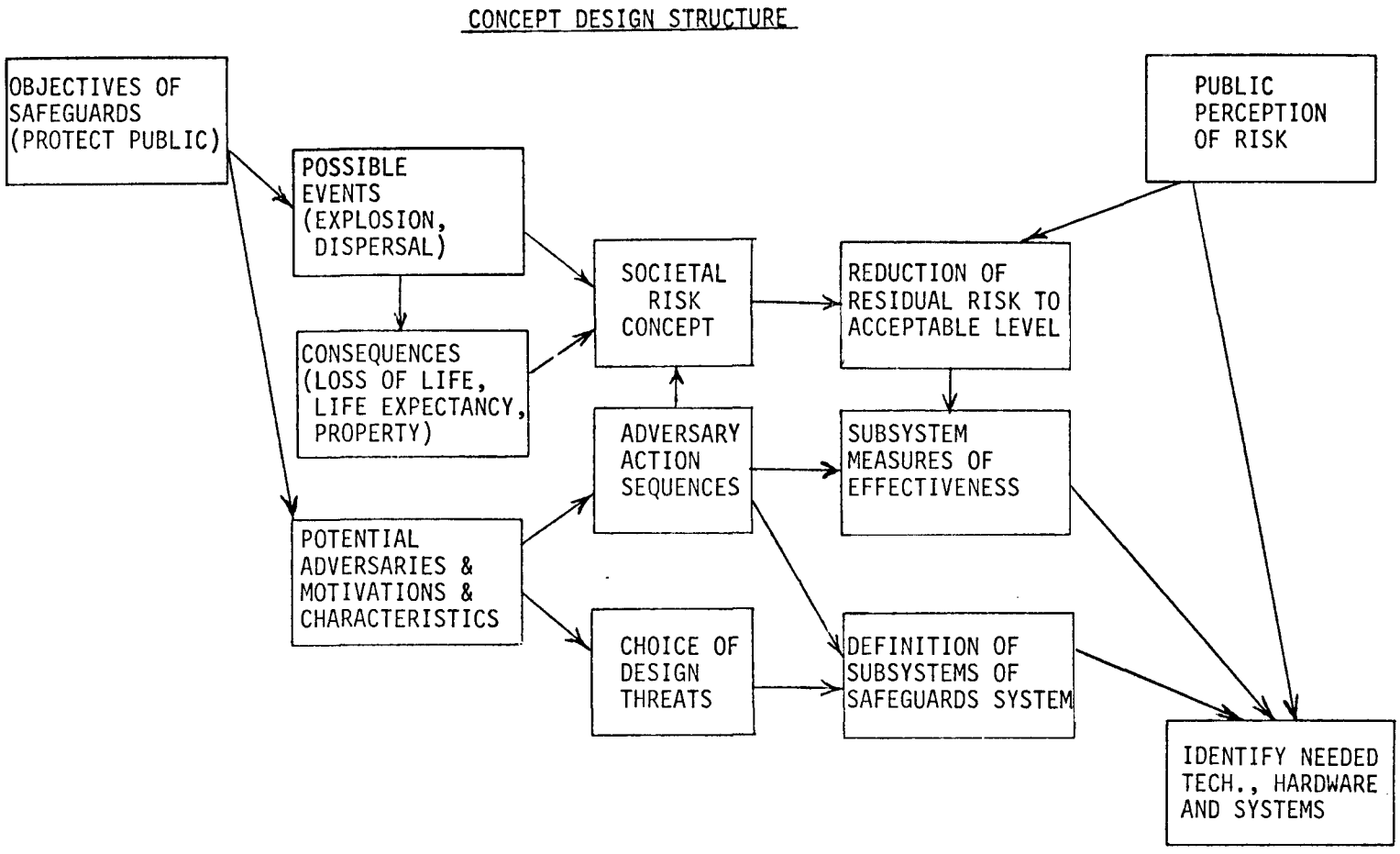


FIGURE 10.4. Task II Concept Design Structure

definition, development, acquisition, installation, and evaluation of prototype techniques and systems at selected sites representative of generic classes of facilities. In an operating environment, conceptual systems are then modified to adapt to real-world economic and operational constraints; these concepts will serve as working-model guidelines for the implementation of acceptable systems.

Concurrent with the general test and evaluation activities, safeguards systems are being developed for the five types of facilities involved in the ERDA program for LWR fuel cycle demonstrations. These are:

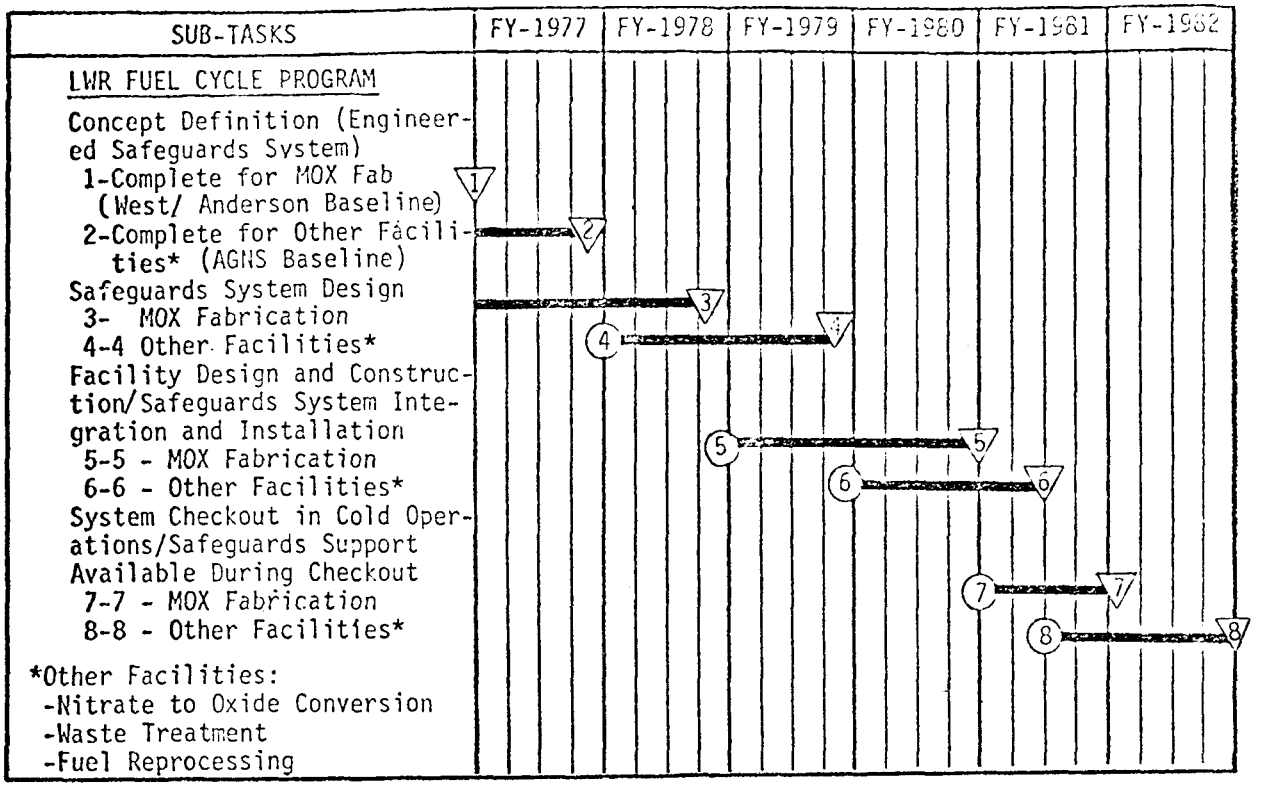
- Reprocessing.
- High-level waste solidification.
- Conversion of plutonium-nitrate to oxide.
- Mixed-oxide fuel fabrication.
- Recycled plutonium storage.

The characteristics of these facilities are different from the point of view of vulnerability to theft or sabotage; therefore, the development of safeguards measures applicable to each is scheduled as shown in Figure 10.5.

The first product of these four tasks is input into the regulatory process to satisfy the Division of Safeguards and Security program objective to develop, assess, and assure the availability of cost effective safeguards systems for application to the commercial fuel cycles. The second product is improved

TASK IV

INTEGRATED SYSTEM DESIGN (PLANT SPECIFIC)/INSTALLATION
AND TEST AND EVALUATION IN OPERATING ENVIRONMENT
SAFEGUARDS FOR LWR FUEL CYCLE PROGRAMS



○ - Begin Activity

▽ - End Activity

FIGURE 10.5. SAFEGUARDS SCHEDULE

ERDA facility safeguards, and the third product is the transfer to industry of the measures and protection technology developed in the ERDA program. Distinct considerations which contribute toward effective implementation of the results of these tasks are shown generically in Figure 10.6.

The development and demonstration of an integrated, safeguards system for a mixed-oxide fuel fabrication plant[13] is already underway (Figure 10.5); these plans can serve as an illustration and summary of how programs for other LWR fuel cycle facilities will be developed. The objective is the development of an Engineered Safeguards System (ESS) concept for a representative commercial mixed-oxide fuel fabrication facility. The conceptual design is intended to demonstrate that effective protection against a wide range of threats can be achieved without unreasonable impact on operation and initial cost of this facility. The threat spectrum included well-organized external attacks and covert diversion by employees in collusion.

The operational impact of the safeguards system on production rates, employee relations, and plant economics is a major concern. The system is being designed to interact closely with all aspects of plant operations but to minimize interference with plant operations and production processes unless unauthorized actions occur.

ESS is integrated closely with a reference plant physical layout. ESS consists of three separate interacting elements: a Personnel Control System (PCS), a Material Operations Control

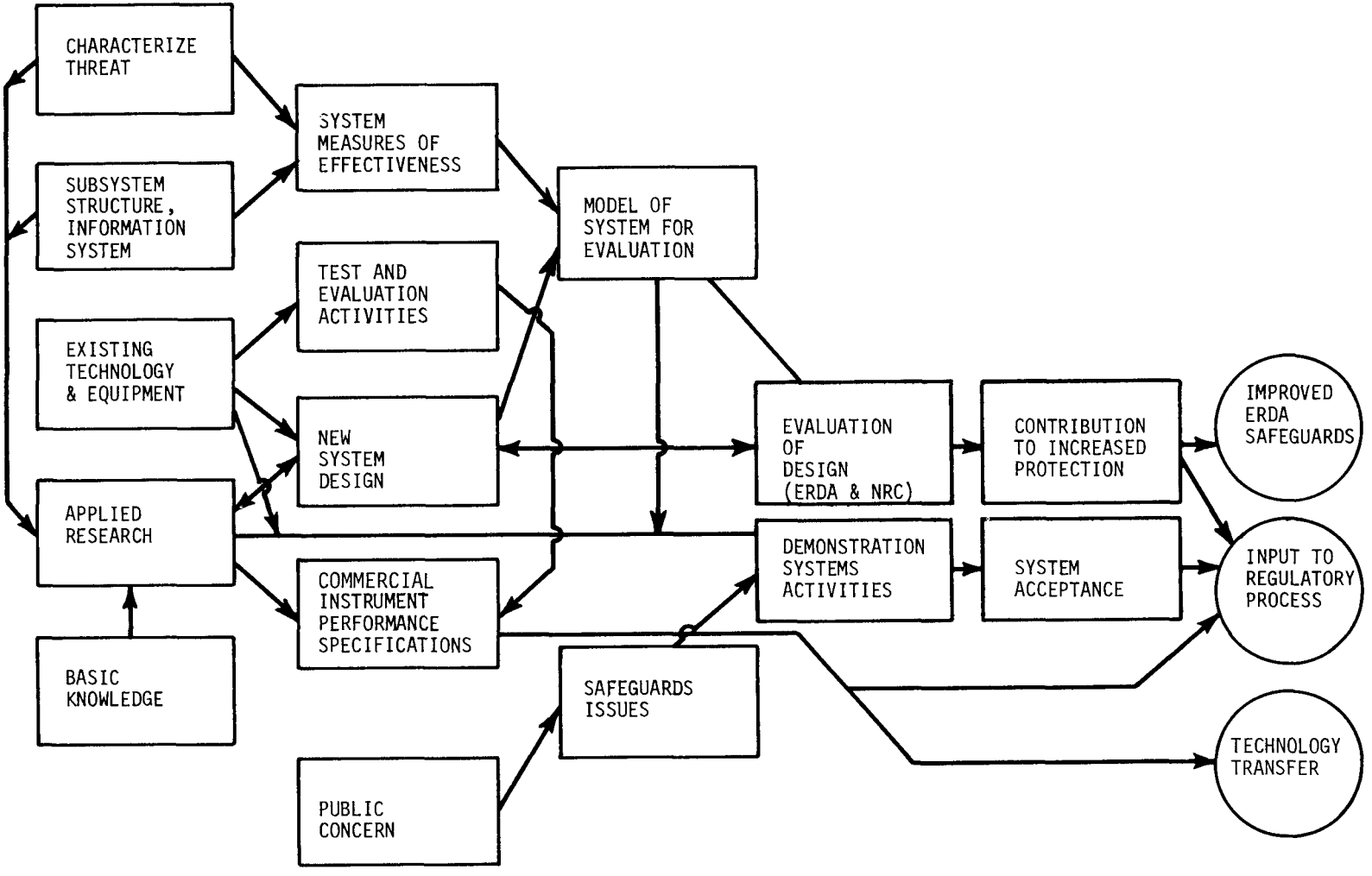


FIGURE 10.6. Implementation of Safeguards Program Results

System (MOCS), and a Material Measurement and Accountancy System (MMAS). The relationship between plant management and these protection elements for control of personnel and material operations and for monitoring of special nuclear materials is shown in Figure 10.7.

The PCS controls the admittance of personnel into and within the facility. Also, it provides response action in threat situations. It broadens the conventional security functions such as identification, portal control, barrier-intrusion detection, and response force action; these functions are integrated with the other elements in the system. Management defines admittance criteria for the PCS and receives information about plant security conditions.

The MOCS contributes to protection of material during various operations in which personnel access to SNM is involved. This protection is accomplished through centralized closed-loop control of each operation, which ensures that all steps follow a procedure authorized by management. Each sequential step in a procedure is monitored, and if an improper action is detected, the operation is stopped and appropriate response is initiated.

The MMAS provides on-line material measurements, supplies information on the location and status of SNM, computes material balances, and determines "material unaccounted for." The PC, MOC, and MMA systems include a common facility-wide protected information system for all three elements.

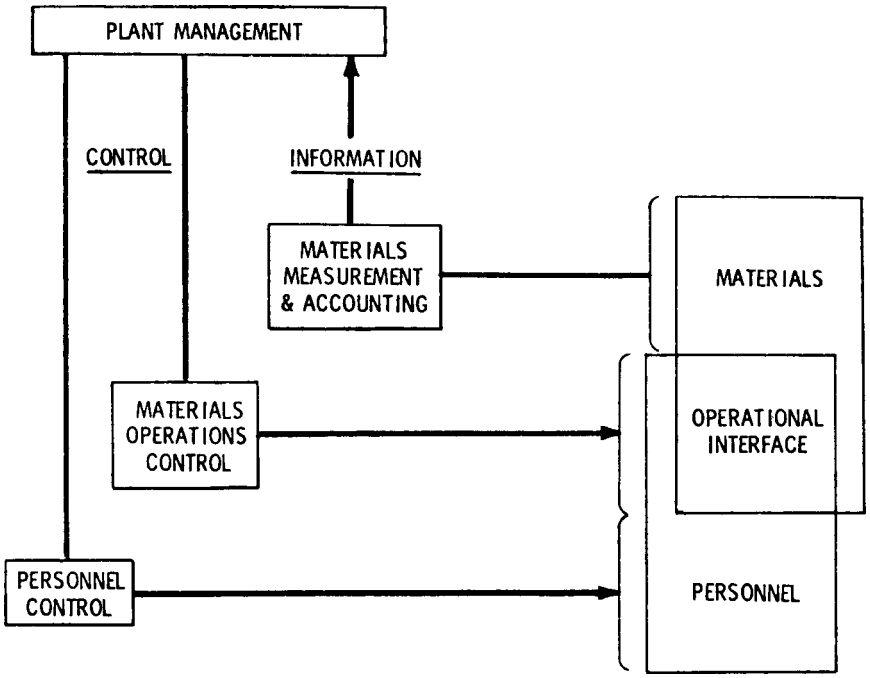


FIGURE 10.7. Generalized Safeguards Concept — Mixed-Oxide Fuel Fabrication Plant (Reprinted from Reference 13)

The development of the system concept is an iterative process of balancing the objectives of protection effectiveness with affordable economic and operational impact. The effectiveness of the system elements in contributing to the ESS concept will be analyzed by computer simulations of various adversary sequences using event-tree and dynamic modeling.

A complete safeguards concept for the mixed-oxide fuel fabrication facility will be defined in reports scheduled for issuance in FY 1977. These reports will include a cost-benefit analysis of the conceptual design. Performance requirements of the safeguards subsystems will be completed in FY 1978.

H. IMPACT OF NUCLEAR ENERGY CENTERS ON SAFEGUARDS

The Energy Reorganization Act of 1974, which created the Nuclear Regulatory Commission (NRC), authorized and directed the NRC to make a Nuclear Energy Center Site Survey (NECSS). The definition of a NECSS was broad: a center could include nuclear power plants, elements of the nuclear fuel cycle, or both. NRC was further directed to include a national survey to locate potential sites for centers, to report any conclusions and recommendations that it might have concerning the feasibility and practicality of nuclear energy centers, and to initiate future updates as might seem warranted.

The program of research, development, and demonstration described in this environmental statement will further define the

effects of collocating fuel cycle facilities. A primary impetus for collocation of fuel cycle facilities is the difference in safeguards considerations. The NECSS addressed this consideration and the results of that study,[2] summarized here, will provide input for the proposed design of joint ERDA/industry LWR fuel reprocessing and recycle demonstration projects.

A major conclusion of the NECSS was that nuclear energy centers, if they came into being, would extend a clustering trend already evident in siting of nuclear electric-generating facilities, with a number of installations with 2 to 4 units on one site already built, being built, or planned. Several utilities have indicated varying degress of interest in possible development of approximately 10-unit or larger power sites. Associated with the reactor units would be fuel cycle facilties. Of primary interest for NECSS purposes are the fuel cycle facilities that would be related to a program of recycling plutonium recovered from spent fuel into reactors. The NRC is presently considering whether large-scale recycle of plutonium may be permitted. The NECSS makes no judgment of the outcome of this consideration; it makes instead the assumption of plutonium recycle. The facilities in question would include reprocessing plants for spent fuel, fabrication plants for fuel which includes recovered plutonium for recycling into reactors, and facilities for radioactive waste disposal. Although much fewer units and a much smaller total investment would be involved than with the power plants, the projected fuel cycle facilities represent a major industry.

The NECSS also asserted that the safeguarding of plutonium was to be a primary motivation for consideration of the center concept for fuel cycle facilities. The implication is that the necessity to physically transfer plutonium in its most usable form through the public domain is obviated. A current obstacle to the implementation of this concept is the restrictions imposed by the Clayton Act expressly forbidding exclusive dealing or tying contracts. It is felt this could be acceptably overcome by appropriate Federal guidelines, price control, or a statutory exemption.

In summary, the NECSS findings with regards to safeguards questions were that some reduction in safeguards problems and costs can be achieved by the collocation of fuel cycle facilities; however, transportation safeguards considerations do not preclude dispersed siting.

Any step in the fuel cycle that can be eliminated is one less step to safeguard; as a corollary, any step that can be simplified or reduced in magnitude is likely to be easier and less costly to safeguard. Collocation, by eliminating some transportation links or shortening others, can thus have beneficial effects on safeguards. This is not to say, however, that collocation is necessary in order to achieve an adequate level of security. The analysis performed in the NRC study shows that transportation of SNM can be made secure with bearable costs. Consequently, from the safeguards point of view, dispersed siting is not precluded.

I. RELATED CONSIDERATIONS

Although not directly related to domestic safeguards problems, the implications and consequences of targeting fuel cycle facilities in the event of war and foreign safeguards threats are similar to our domestic questions and can be evaluated in much the same manner.

1. Acts of War

When discussing the vulnerability to acts of war of reactors and nuclear fuel cycle facilities, two issues must be treated: first, the likelihood of the facility being targeted in wartime, and, second, the consequences of a successful attack. Both of these issues are covered below.

To frame the discussion, three terms of reference are cited:

- The examination of vulnerability is made in terms of overt war between the U.S. and a potential aggressor.
- The examination is made in terms of vulnerability to nuclear weapons and excludes conventional attack. If the war is overt, attacks would likely be of intercontinental nature or from sea-based platforms (i.e., strategic attacks).
- The strategic attack would be of large scale, of necessity including massive attack on U.S. strategic retaliatory forces. While one may postulate a limited nuclear attack, including attack on U.S. nuclear fuel cycle facilities, such attack would not destroy U.S. retaliatory capability, and, therefore, is considered not likely.

In these terms of reference, the consequences of attack on nuclear fuel cycle facilities must be considered as part of a large hierarchy of events. The war situation that might give rise to postulated attacks on nuclear power facilities must be looked at as a whole. In the context of a massive attack on the forces and resources of United States, hundreds, if not thousands, of large-yield weapons would be used over widely-spread areas of the U.S., regardless of the existence of nuclear fuel cycle facilities. Many of these would be surface bursts, which maximize fallout. These attacks would create widespread havoc, and the effects of the weapons would have massive consequences in terms of casualties, facility destruction, and land contamination. Considering this outcome, the consequences of attacks on the nuclear facilities would clearly be a relatively small increment of the overall consequences. A general assessment of the implications and consequences of targeting fuel cycle facilities in war situations can, however, be made as follows:

- A foreign power may deliberately wish to produce casualties.
- The enemy may be primarily concerned with destruction of resources.

Several studies[1] have examined the vulnerability of nuclear facilities in these contexts. The probability of obtaining a militarily-useful increase in casualties or fallout by deliberately targeting the reactor for a single ground-burst weapon was too small to make it attractive for the enemy

planner. Also, multi-weapon attacks to raise the probability of success to an acceptable level would become prohibitively expensive as compared with other potential weapons uses, such as direct attacks on urban areas. These conclusions are sensitive to changes in delivery accuracies, and as accuracies improve, the numbers of weapons required would decrease.

Comparisons of the effects on the public of rupture of an operating reactor, and the nuclear weapon required to cause the rupture, indicate the fission product complement from the reactor would add a very small increment to the total population dosage. The study[1] considered the consequence of the reactor contents being added to the fallout from a 1-megaton fission weapon. With a 20-knot wind, the area of potentially lethal fallout (400-R isodose countour) to persons remaining unsheltered is increased by about 17% for a week's exposure and about 33% for a month's exposure. In terms of inflicting casualties, even if all core products were added to the weapon fallout, the enemy would gain only a marginally increased effect. While the products from the reactor have a much longer radioactive life than products of the weapon, they would not necessarily have the casualty effects that the enemy planner might be seeking. From the standpoint of the enemy planner, targeting of large urban areas can produce far more casualties for far fewer weapons and provide him the bonus of the probable destruction of soft industrial facilities in the area.

The possibility of an enemy attacking nuclear waste storage facilities to inflict casualties was also examined. Large amounts of high-level and noble gas wastes could accumulate in waste storage facilities by early in the 21st century. These would include wastes not only from LWRs, but also from other reactor fuel cycles as well. ERDA has investigated the vulnerability of radioactive waste storage facilities to nuclear attack using the Savannah River complex as a model.[1] At Savannah River, waste is stored at two tank farms about two miles apart, each containing about 15 tanks constructed of steel-lined concrete. Although the tanks have up to 10 ft of earth cover, they can be considered as surface targets because they would be cratered by a ground burst. Analysis showed that even with extremely large yields, multi-weapon attacks with reasonable accuracy would be needed for acceptable probabilities of success. A successful attack could release a very high level of long-lived radioactive waste. However, in the sense of near-term infliction of casualties, the radioactivity content of the waste is of the same magnitude range as that expected from high-yield weapons. Because waste storage facilities are generally sited in relatively remote areas, much of the immediate fallout would not likely add significantly to the casualties. Again, if the goal of the enemy planner is to inflict casualties, a direct attack on urban areas would be more remunerative. A similar logic would apply in weighing whether to attack fuel fabrication or fuel reprocessing facilities in order to inflict casualties.

The consequences to the U.S. of any possible attack must be viewed as part of a major nuclear strike. The additional effect from the attack on the nuclear facilities would be masked by the overall consequences of the required massive strategic attack. Given direct hits on the facilities, casualties would at worst be of the same range of magnitudes as those produced by the weapons themselves. When viewed in the context of large-scale strategic war, the additional fallout from the attacked facilities are unlikely to greatly increase casualties.

2. Diversion of Foreign Material

The threat of diversion exists in other countries as well as the U.S. The nature of the possible threat will vary considerably from country to country, depending on the size of the nuclear program and the type of nuclear facilities involved. However, nuclear materials and equipment supplied to other countries by the U.S. are provided under terms and conditions of agreements for cooperation which include safeguards procedures. The recipient governments provide written assurance, with regard to each import, that items will be subject to all the terms of the agreement including safeguards to assure the items are not diverted.

The various foreign countries engaged in nuclear programs have been made aware of U.S. concern about safeguarding nuclear materials to preclude diversions and the preventive steps that have been taken in the U.S. The U.S. is prepared to collaborate

closely in exchanging information, data, and experience in the area of physical security with a view to arriving at commonly agreed procedures to preclude diversion. As nuclear facilities are developed and placed into foreign commercial operation, the U.S. will use all available means to assure that security measures are significantly expanded and modified to accommodate the future material commitments. Thus, these security measures will be revised as the magnitude of the problem increases. While the protection of nuclear facilities and materials is a sovereign national responsibility that only the countries themselves have the authority and responsibility to dictate, the U.S. can influence the security measures to be employed by demonstrating a posture with emphasis on strong and effective safeguards precautions.

The International Atomic Energy Agency (IAEA) has published a series of recommendations for physical protection of nuclear facilities to assist the various countries in establishing the programs. The IAEA also administers an international safeguards and control system (involving records, reports, and inspections of nuclear material) to verify the Non-Proliferation Treaty and has been looked to by the U.S. to apply its safeguards to U.S. supplied materials and equipment.

The U.S. has urged and will continue to press for the expansion and modification of foreign nation security measures through our bilateral contacts and through the IAEA. These

measures include physical security to preclude diversion. The U.S. will give particular attention to future requests for supplies of highly enriched uranium and plutonium for power reactor use to assure that adequate safeguards including physical protection are in effect. The U.S. will continue to propose the adoption of international standards to be observed by all nations engaged in nuclear activities.

J. CONCLUSIONS

The problems of safeguards currently exist in connection with nuclear military programs and the active commercial ventures associated with the production of nuclear power. These problems are recognized and positive measures are in force to reduce the public risk to an acceptable level. These measures include facility design requirements, personnel security checks, various systems of interposed barriers and material accounting guides. These are promulgated by direct government supervision, stringent and exacting licensing regulations, and an inspection program. The program has been, to date, demonstrably successful.

The development of even more effective safeguards methods is in progress. The ERDA safeguards research and development program is coordinated with programs to develop LWR fuel cycle facilities as to need and timeliness. The objective is to provide cost-effective safeguards design criteria and recommendations to the commercial nuclear industry that can be incorporated in the demonstration programs described in this environmental statement.

ERDA has concluded that the objectives of the safeguards program can be maintained in the proposed demonstration programs. Although the development and implementation of safeguards methods and procedures will be a continuing process, there is no reason at present to infer or suppose that the final complement of systems will be either prohibitively expensive or entail a disruptive societal effect. Thus, with full recognition of the need to provide adequate protection against theft or diversion of SNM or sabotage of facilities involving nuclear materials, it is concluded that there is no safeguards-related reason to delay the development of LWR fuel cycle facilities to demonstrate reprocessing, including plutonium conversion and storage, mixed oxide fuel fabrication, and waste management functions.

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APPENDIX A

SUPPLEMENTARY TABLES

TABLE A-1

Reprocessing Schedule - Base Case

[ERDA-OPA 1975 Low Projection (507 LWRs, Pu and U Recycle)]

Calendar Year	Fuel Discharged, MTU	Cumulative Inventory 1-yr Cooled, MTU	Separations						
			Number of Plants		Production, MTU/yr	Inventory Unprocessed, MTU	Cumulative Uranium Processed MTU	Fissile Pu Processed, MT	
			New Startup	Operating				Annual	Cumulative
1976	937	1,623[a]		0	0	1,623	0	0	0
77	1,111	2,560		0	0	2,560	0	0	0
78	1,310	3,671		0	0	3,671	0	0	0
79	1,455	4,981		0	0	4,981	0	0	0
80	1,591	6,436		0	0	6,436	0	0	0
81	1,797	8,027	AGNS[b]	1	600	7,427	600	4.0	4.0
82	2,059	9,824		1	1,000	8,224	1,600	6.6	10.6
83	2,583	11,883		1	1,500	8,780	3,100	9.9	20.5
84	3,024	14,466		1	1,500	9,866	4,600	9.9	30.4
85	3,493	17,490		1	1,500	11,390	6,100	9.9	40.3
86	4,029	20,983	1	2	2,100	12,783	8,200	13.9	54.2
87	4,625	25,012	1	3	3,100	13,712	11,300	20.5	74.7
88	5,193	29,637	1	4	4,600	13,737	15,900	30.4	105.1
89	5,727	34,830	1	5	6,100	12,830	22,000	40.3	145.4
90	6,310	40,557	1	6	7,600	10,957	29,600	50.2	195.6
91	6,901	46,867		6	8,500	8,767	38,100	63.7	259.3
92	7,541	53,768		6	9,000	6,668	47,100	67.5	326.8
93	8,233	61,309		6	9,000	5,209	56,100	67.5	394.3
94	8,874	69,542	1	7	9,600	3,842	65,700	72.0	466.3
95	9,566	78,416		7	10,000	2,716	75,700	75.0	541.3
96	10,257	87,982		7	10,500	1,782	86,200	78.8	620.1
97	10,895	98,239		7	10,500	1,539	96,700	78.8	698.9
98	11,483	109,134		7	10,500	1,934	107,200	78.8	777.7
99	12,018	120,617		7	10,500	2,917	117,700	78.8	856.5
2000	12,529	132,635		7	10,500	4,435	128,200	78.8	935.3
2001	N.A.	145,164		7	10,500	6,464	138,700	78.8	1014.1
2002	N.A.	N.A.		7	6,464	0	145,164	48.5	1062.6

a. Spent fuel discharged prior to CY-1976.

b. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in first year, 67% in second year, and 100% thereafter.

TABLE A-2

U_3O_8 Production Schedule

[ERDA-OPA 1975 Low Projection (507 LWRs)]

Calendar Year	U_3O_8 Production, MT			Number of Mine-Mill Complexes[a]								
				Throwaway			U Recycle Only			U, Pu Recycle		
	Throwaway	U Recycle Only	U, Pu Recycle	Operating	New	Retired	Operating	New	Retired	Operating	New	Retired
1976	11,743	11,743	11,743	15	0	0	15	0	0	15	0	0
77	12,253	12,253	12,253	15	0	0	15	0	0	15	0	0
78	13,199	13,199	13,199	15	0	0	15	0	0	15	0	0
79	15,811	15,811	15,811	15	0	0	15	0	0	15	0	0
80	22,331	22,331	22,331	16	1	0	16	1	0	16	1	0
81	25,138	24,126	24,126	18	2	0	18	2	0	18	2	0
82	27,086	25,519	24,735	20	2	0	19	1	0	19	1	0
83	31,051	28,471	26,947	23	3	0	21	2	0	21	2	0
84	35,637	33,173	31,685	26	3	0	24	3	0	23	2	0
85	40,988	38,547	37,053	30	4	0	28	4	0	26	3	0
86	44,709	41,582	39,293	33	3	0	30	2	0	29	3	0
87	48,225	43,407	39,530	36	3	0	32	2	0	29	0	0
88	53,211	45,912	40,451	39	3	0	34	2	0	30	1	0
89	57,916	48,169	41,085	43	4	0	35	1	0	30	0	0
90	63,184	50,909	42,247	46	3	0	37	2	0	31	1	0
91	68,991	55,848	46,676	50	4	0	41	4	0	34	3	0
92	73,086	59,102	49,905	54	4	0	44	3	0	37	3	0
93	78,999	65,011	55,813	58	4	0	48	4	0	41	4	0
94	84,133	69,258	59,292	62	4	0	51	3	0	44	3	0
95	88,290	72,737	61,927	65	4	1	53	3	1	46	3	1
96	92,283	76,165	65,311	68	4	1	56	4	1	48	3	1
97	95,713	79,697	68.878	70	3	1	59	4	1	51	4	1
98	99,376	83,460	72,642	73	4	1	61	3	1	53	3	1
99	102,644	86,788	75,963	75	3	1	63	3	1	55	3	1
2000	95,328	79,174	68,364	72	0	3	58	0	5	50	0	5
Total	1,381,325	1,182,392	1,047,260									

a. Number of mine-mill complexes capable of producing 1360 MT U_3O_8 per year for 20 years.

TABLE A-3

UF_6 Production

[ERDA-OPA 1975 Low Projection (507 LWRs)]

Calendar Year	Throwaway			U Recycle Only			U, Pu Recycle		
	Number of Plants			Number of Plants			Number of Plants		
	New Startups[a]	Operating	Production, 1000 MTU	New Startups[a]	Operating	Production, 1000 MTU	New Startups[a]	Operating	Production, 1000 MTU
1976		2	9.9		2	9.9		2	9.9
77		2	10.3		2	10.3		2	10.3
78		2	11.1		2	11.1		2	11.1
79		2	13.3		2	13.3		2	13.3
80		2	17.5		2	17.5		2	17.5
81		2	21.0		2	21.0		2	21.0
82		2	21.0		2	21.0		2	21.0
83	1	3	28.5		2	21.0		2	21.0
84		3	36.0	1	3	28.5	1	3	28.5
85		3	36.0		3	36.0		3	36.0
86		3	36.0		3	36.0		3	36.0
87		3	36.0		3	36.0		3	36.0
88	1	4	43.5		3	36.0		3	36.0
89		4	51.0		3	36.0		3	36.0
90		4	51.0	1	4	43.5		3	36.0
91	1	5	58.5		4	51.0		3	36.0
92		5	66.0		4	51.0	1	4	43.5
93		5	66.0	1	5	58.5		4	51.0
94		5	66.0		5	66.0		4	51.0
95	1	6	73.5		5	66.0		4	51.0
96		6	81.0		5	66.0		4	51.0
97		6	81.0		5	66.0		4	51.0
98		6	81.0		5	66.0	1	5	58.5
99		6	81.0		5	66.0		5	66.0
2000		6	81.0		5	66.0		5	66.0

a. New plants of 15,000 MTU/yr capacity operate at 50% capacity in first year. Two existing plants assumed to be upgraded as shown.

TABLE A-4

Enrichment Schedule

[ERDA-OPA 1975 Low Projection (507 LWRs)]

Calendar Year	Enrichment Demand, 1000 MT SWU: Domestic Throw-away	Domestic U Recycle	Domestic U, Pu Recycle	Assumed Foreign Demand	Total Domestic plus Foreign plus Increment[a]: Throw-away	U Recycle	U, Pu Recycle	Enrichment Production: Throwaway No. of Plants	Throwaway Million SWU	U Recycle No. of Plants	U Recycle Million SWU	U, Pu Recycle No. of Plants	U, Pu Recycle Million SWU	Cumulative Inventory, Million SWU: Throw-away	U Recycle	U, Pu Recycle
1976	6.1	6.1	6.1	5.1	12.0	12.0	12.0	3[b]	16	3[b]	16	3[b]	16	19.0	19.0	19.0
77	6.5	6.5	6.5	6.4	13.1	13.1	13.1	3	18	3	18	3	18	23.9	23.9	23.9
78	7.0	7.0	7.0	7.7	14.9	14.9	14.9	3	20	3	20	3	20	29.0	29.0	29.0
79	8.3	8.3	8.3	8.6	17.1	17.1	17.1	3	22	3	22	3	22	33.9	33.9	33.9
80	10.5	10.5	10.5	9.4	20.2	20.2	20.2	3	23	3	23	3	23	36.7	36.7	36.7
81	12.8	12.8	12.6	9.2	22.2	22.2	22.0	3	23	3	23	3	23	37.5	37.5	37.7
82	14.0	13.9	13.3	8.9	23.0	22.9	22.2	3	23	3	23	3	23	37.5	37.6	38.5
83	16.1	15.7	14.6	10.2	26.6	26.2	25.1	3	24	3	24	3	24	34.9	35.4	37.4
84	18.5	18.2	17.1	11.4	30.3	29.9	28.8	3	24	3	24	3	24	28.6	29.5	32.6
85	21.3	21.5	19.9	13.0	34.7	35.0	33.3	4	37	4	37	3	28	30.9	31.5	27.3
86	23.5	23.4	21.6	14.6	38.5	38.3	35.5	4	37	4	37	4	37	29.4	30.2	28.8
87	25.5	25.1	22.1	17.1	43.0	42.6	39.5	4	37	4	37	4	37	23.4	24.6	26.3
88	28.1	27.4	23.2	19.6	48.2	47.5	43.2	5	46	5	46	4	37	21.2	23.1	20.1
89	30.7	29.7	24.2	19.4	50.2	49.3	43.7	5	46	5	46	5	46	17.0	19.8	22.4
90	33.5	32.6	25.4	19.2	53.0	52.1	44.9	6	55	6	55	5	46	19.0	22.7	23.5
91	36.5	35.3	28.5	20.6	57.5	56.3	49.4	6	55	6	55	5	46	16.5	21.4	20.1
92	38.9	37.8	30.9	22.0	61.3	60.2	53.3	7	64	7	64	6	55	19.2	25.2	21.8
93	42.0	41.0	34.1	26.2	68.8	67.9	60.9	7	64	7	64	6	55	14.4	21.3	15.9
94	44.8	43.7	36.3	30.3	75.7	74.7	68.3	8	73	8	73	7	64	11.7	19.6	11.6
95	47.2	45.9	37.9	33.0	80.7	79.4	71.2	9	82	9	82	8	73	13.0	22.2	13.4
96	49.4	48.5	40.3	35.7	85.6	84.7	76.6	9	82	9	82	9	82	10.4	19.5	18.8
97	51.4	50.5	42.3	39.5	91.5	90.6	82.3	10	91	10	91	9	82	9.9	19.9	18.5
98	53.3	52.5	43.6	43.3	97.2	96.3	87.4	11	100	10	91	10	91	12.7	14.6	22.1
99	55.1	54.5	46.3	48.2	103.9	103.4	95.2	11	100	11	100	10	91	8.8	11.2	17.9
2000	52.0	51.4	43.2	53.0	105.2	104.6	96.4	11	100	11	100	10	91	3.6	6.6	12.5
Total	733.0	718.9	615.8	531.7	1274.4	1261.4	1156.5		1262		1253		1154			

a. "Increment" included for process holdup is defined as follows: Increment = 0.1 x [(Domestic + Foreign Demand) year i - (Domestic + Foreign Demand) year i-1]

b. Production from three existing gaseous diffusion plants to 28 million SWU as projected in CONF-750209 (Reference 4, Section 2B). Additional plants (9 million SWU) added as shown.

TABLE A-5

Fuel Fabrication Schedule

[ERDA-OPA 1975 Low Projection (507 LWRs)]

Calendar Year	Reactor Requirement, MTHM	Throwaway and U Recycle Only — UO_2 Fuel Fabrication, MTU			U, Pu Recycle — MOX Fabrication, MTHM		UO_2 Fuel Fabrication, MTU		
		No. of Plants	Annual Production	Cumulative Inventory	No. of Plants	Annual Production	No. of Plants	Annual Production	Cumulative Inventory
1976	1,554	6[a]	1,800	246	0	0	6[a]	1,800	246
77	1,812	6	1,800	234	0	0	6	1,800	234
78	1,826	6	2,000	408	0	0	6	2,000	408
79	1,943	6	2,400	865	0	0	6	2,400	865
80	2,385	6	2,800	1,280	0	0	6	2,800	1,280
81	2,794	6	3,500	1,986	0	0	6	3,500	1,986
82	3,991	6	4,200	2,195	0	0	6	4,200	2,195
83	4,220	6	4,800	2,775	1[b]	175	6	4,800	2,940
84	4,793	6	5,500	3,482	1	350	6	5,300	3,780
85	5,466	6	6,300	4,316	1	350	6	5,800	4,440
86	6,299	7	7,050	5,067	1	350	6	6,300	4,780
87	6,802	7	7,800	6,065	2	525	6	6,300	4,770
88	7,235	7	7,800	6,630	3	875	6	6,300	4,670
89	7,946	8	8,550	7,234	4	1,225	7	7,050	4,940
90	8,636	8	9,300	7,898	5	1,575	7	7,800	5,600
91	9,405	9	10,050	8,543	6	1,925	8	8,550	6,570
92	10,266	9	10,800	9,077	6	2,100	8	9,300	7,600
93	10,794	10	11,550	9,833	6	2,100	9	10,050	8,840
94	11,655	10	12,300	10,478	6	2,100	9	10,800	9,980
95	12,377	11	13,050	11,151	7	2,275	9	10,800	10,570
96	12,905	11	13,800	12,046	7	2,450	9	10,800	10,790
97	13,419	11	13,800	12,427	7	2,450	9	10,800	10,500
98	13,842	11	13,800	12,385	7	2,450	10	11,550	10,540
99	14,328	11	13,800	11,857	7	2,450	10	12,300	10,840
2000	14,746	11	13,800	10,911	7	2,450	10	12,300	10,710
Total	191,439		202,350			28,175[c]		175,400	

a. Capacity of six existing UO_2 fuel fabrication plants expanded to 6300 MTU/yr and new 1500 MTU/yr plants added as shown. New plants operate at 50% capacity in first year. UO_2 fuel charged to reactor is generally fabricated the year preceding charging.

b. MOX plants of 350 MTHM/yr capacity (3% fissile Pu) operate at 50% capacity in first year. MOX fuel is assumed to be charged into reactors the year of fabrication; however, 5% of production is retained in pipelines until after the year 2000.

c. An additional 5160 MT of MOX containing plutonium recovered from fuel discharged through the year 2000 is charged to reactors after the year 2000.

TABLE A-6

Uranium-Plutonium Recycle with 5-Year Cooling (507 LWRs)

Calendar Year	*U_3O_8 Production, MT*	*Total Enrichment Production, Million SWU*	*UO_2 Fabrication, MT*	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
				(1623)[a]			
1976	11,743	16	1,800	937			
77	12,253	18	1,800	1,111			
78	13,199	20	2,000	1,310			
79	15,811	22	2,400	1,455			
1980	22,331	23	2,800	1,591			
81	24,126	23	3,500	1,797	600 AGNS[d]	4.0	
82	24,737	23	4,200	2,059	1,000	6.6	
83	26,947	24	4,800	2,583	1,500	9.9	175[e]
84	31,685	24	5,500	3,024	1,500	9.9	350
1985	37,053	37[b]	6,300	3,493	1,500	9.9	350
86	40,860	37	6,300[c]	4,029	1,500	9.9	350
87	42,577	37	7,050[c]	4,625	2,100[d]	13.9	350
88	46,143	46[b]	7,800	5,193	2,500	16.5	525[e]
89	50,026	46	7,800	5,727	3,000	19.8	700
1990	53,491	55[b]	8,550[c]	6,310	3,600[d]	23.8	700
91	58,332	55	9,300	6,901	4,000	26.4	875[e]
92	61,586	64[b]	10,050[c]	7,541	4,500	29.7	1,050
93	65,706	64	10,800	8,233	5,100[d]	33.7	1,050
94	69,444	64	10,800	8,874	5,500	41.3	1,225[e]
1995	72,753	73[b]	10,800	9,566	6,000	45.0	1,400
96	75,508	73	11,550[c]	10,257	6,600[d]	49.3	1,400
97	77,536	82[b]	12,300	10,895	7,000	52.5	1,575[e]
98	78,661	91	12,300	11,483	8,100[d]	60.8	1,750
99	80,503	91	12,300	12,018	8,500	63.8	1,925[e]
2000	72,421	91	12,300	12,529	9,000	67.5	2,100
01	NA	NA	NA	NA	9,600[d]	72.0	NA
02	NA	NA	NA	NA	10,000	75.0	NA
03	NA	NA	NA	NA	10,500	78.8	NA
04	NA	NA	NA	NA	10,500	78.8	NA
05	NA	NA	NA	NA	10,500	78.8	NA
06	NA	NA	NA	NA	10,500	78.8	NA
07	NA	NA	NA	NA	464	2.3	NA
Total	1,165,430	1,199	185,100	145,164	145,164	1,059.0	17,850[f]

a. Spent fuel discharged before CY-1976.

b. Indicates year of startup of new enrichment plants (9 million SWU/yr).

c. Indicates year of startup of new UO_2 fabrication plants (1500 MTU/yr). Plants operate at 50% capacity in the first year and at 100% thereafter.

d. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in the first year, at 67% in the second year, and at 100% thereafter.

e. Indicates year of startup of MOX plants. Plants operate at 50% capacity in the first year and at 100% thereafter (capacity equivalent to associated separations plant). 5% of MOX production is retained in pipelines.

f. An additional 15,480 MT of MOX containing plutonium recovered from fuel discharged through the year 2000 is charged to reactors after the year 2000.

TABLE A-7

Uranium-Plutonium Recycle with 5-Year Delay in Reprocessing (507 LWRs)

Calendar Year	*U_3O_8 Production, MT*	*Total Enrichment Production, Million SWU*	*UO_2 Fabrication, MT*	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
				(1623)[a]			
1976	11,743	16	1,800	937			
77	12,253	18	1,800	1,111			
78	13,199	20	2,000	1,310			
79	15,811	22	2,400	1,455			
1980	22,331	23	2,800	1,591			
81	25,138	23	3,500	1,797			
82	27,076	23	4,200	2,059			
83	31,051	24	4,800	2,583			
84	35,637	24	5,500	3,024			
1985	40,988	37[b]	6,300	3,493			
86	43,048	37	7,050[c]	4,029	600 AGNS[d]	4.0	
87	44,992	37	7,800	4,625	1,000	6.6	175[e]
88	49,487	46[b]	7,800	5,193	1,500	9.9	350
89	54,302	46	8,550	5,727	1,500	9.9	350
1990	58,679	55[b]	9,300	6,310	1,500	9.9	350
91	61,676	55	9,300	6,901	2,700[d]	17.8	525[e]
92	59,963	55	9,300	7,541	4,700[d]	31.0	875[e]
93	58,457	64[b]	10,050[c]	8,233	7,700[d]	50.8	1,400[e]
94	58,224	64	10,800	8,874	9,500	62.7	2,100[e]
1995	60,674	73[b]	10,800	9,566	10,500	69.3	2,450
96	65,309	73	10,800	10,257	10,500	78.8	2,450
97	68,847	82[b]	10,800	10,895	10,500	78.8	2,450
98	72,613	82	10,800	11,483	10,500	78.8	2,450
99	75,950	91[b]	11,550[c]	12,018	10,500	78.8	2,450
2000	68,365	91	12,300	12,529	10,500	78.8	2,450
01	NA	NA	NA	NA	10,500	78.8	NA
02	NA	NA	NA	NA	10,500	78.8	NA
03	NA	NA	NA	NA	10,500	78.8	NA
04	NA	NA	NA	NA	10,500	78.8	NA
05	NA	NA	NA	NA	9,464	71	NA
Total	1,135,823	1,181	182,100	145,164	145,164	1,052	20,830[f]

a. Spent fuel discharged before CY-1976.
b. Indicates year of startup of new enrichment plants (9 million SWU/yr).
c. Indicates year of startup of new UO_2 fabrication plants (1500 MTU/yr). Plants operate at 50% capacity in the first year and at 100% thereafter.
d. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in the first year, at 67% in the second year, and at 100% thereafter.
e. Indicates year of startup of MOX plants. Plants operate at 50% capacity in the first year and at 100% thereafter (capacity equivalent to associated separations plant). Five percent of MOX production retained in pipelines.
f. An additional 12,500 MT of MOX containing plutonium recovered from fuel discharged through the year 2000 is charged to reactors after the year 2000.

TABLE A-8

Material Requirements Through The Year 2000 with Coprocessing Fuel Cycle

	Coprocessing	*Base Case*
U_3O_8 Production (1000 MT)	1047	1047
Enrichment Production (million SWU)	690	616
UO_2 Fabrication (1000 MTU)	61	175
Spent Fuel Discharge (1000 MTU)	145	145
Chemical Processing (1000 MTU)	128[a]	128[a]
MOX Production (1000 MTHM)	140	28

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a. An additional 17,000 MTU of spent fuel discharged through the year 2000 are processed after the year 2000.

TABLE A-9

Nuclear Reactor Schedules[a]

Calendar Year	Base Case			Tandem Cycle				Low Schedule			High Schedule		
	PWR	BWR	Total	PWR	BWR	HWR	Total	PWR	BWR	Total	PWR	BWR	Total
1976	26	17	43	26	17	-	43	25	17	42	27	18	45
77	33	18	51	33	18	-	51	30	17	47	33	18	51
78	39	18	57	39	18	-	57	35	17	52	39	18	57
79	43	19	62	43	19	-	62	40	19	59	44	20	64
1980	48	22	70	48	22	-	70	45	21	66	51	23	74
81	54	26	80	54	26	-	80	53	26	79	55	27	82
82	66	34	100	66	34	-	100	59	30	89	72	37	109
83	77	40	117	77	40	-	117	68	36	104	85	44	129
84	88	47	135	88	47	-	135	76	40	116	99	52	151
1985	103	53	156	103	53	-	156	90	46	136	114	58	172
86	117	62	179	117	62	-	179	105	56	161	128	67	195
87	131	70	201	130	69	2	201	118	63	181	142	76	218
88	146	76	222	141	75	6	222	129	67	196	161	84	245
89	163	82	245	153	80	12	245	142	72	214	182	91	273
1990	178	90	268	163	85	20	268	153	77	230	201	101	302
91	195	98	293	173	90	30	293	165	83	248	222	111	333
92	213	107	320	183	95	42	320	179	90	269	242	122	364
93	230	115	345	191	98	56	345	193	96	289	264	132	396
94	248	124	372	200	102	70	372	206	103	309	285	143	428
1995	266	133	399	209	106	84	399	221	111	332	306	153	459
96	283		424	218	110	96	424	234	116	350	326	163	489
97	298	149	447	227	114	106	447	243	122	365	345	173	518
98	312	156	468	236	118	114	468	252	126	378	365	182	547
99	325	163	488	245	122	121	488	260	130	390	382	192	574
2000	338	169	507	254	126	127	507	267	133	400	400	200	600
01	334	165	499	250	122	127	499	263	129	392	396	196	592

a. Equivalent number of 1000 MWe reactors. In this statement, model LWRs are rated at 1000 MWe, whereas the model HWR is rated at 850 MWe.

TABLE A-10

Tandem Fuel Cycle

Calendar Year	U_3O_8 Production MT	Total Enrichment Production, Million SWU	Fuel Fabrication LWR MTU	Fuel Fabrication HWR MTHM	Annual Charge to LWR MT	Annual Charge to HWR MT	Annual Discharge LWR MT	Annual Discharge HWR MT
							(1623)[a]	
1976	11,743	16	1,800		1,554		937	
77	12,253	18	1,800		1,812		1,111	
78	13,199	20	2,000		1,826		1,310	
79	15,811	22	2,400		1,943		1,455	
1980	22,331	23	2,800		2,385		1,591	
81	25,138	23	3,500		2,794		1,797	
82	27,086	23	4,200		3,991		2,059	
83	31,051	24	4,800		4,220		2,583	
84	35,637	24	5,500		4,793		3,024	
1985	40,988	37[b]	6,300		5,466		3,493	
86	43,764	37	7,050	750[d]	6,299		4,029	
87	46,236	37	7,800	1,500	6,611	353	4,625	
88	49,490	46[b]	7,800	1,500	6,886	886	5,140	180
89	51,933	46	7,800	2,250[d]	7,293	1,599	5,574	540
1990	54,846	55[b]	7,800	3,000	7,601	2,492	6,006	1,080
91	57,763	55	7,800	4,500[d,d]	8,008	3,564	6,387	1,800
92	58,581	55	8,550[c]	6,750[d]	8,404	4,818	6,770	2,700
93	61,774	55	9,300	7,500	8,426	6,250	7,152	3,780
94	64,190	64[b]	9,300	8,250[d]	8,921	7,510	7,430	5,040
1995	66,574	64	9,300	9,750[d]	9,262	8,770	7,761	6,300
96	69,036	73[b]	9,300	10,500	9,614	9,678	8,091	7,560
97	71,472	73	10,050[c]	10,500	9,966	10,404	8,423	8,640
98	73,984	82[b]	10,800	11,250[d]	10,307	10,951	8,755	9,540
99	76,441	91[b]	10,800	12,000	10,659	11,949	9,086	10,259
2000	67,958	91	10,800	12,000	11,011	11,429	9,418	10,890
Total	1,149,279	1154	169,350	102,000[e]	160,055	90,653[e]	125,630	68,309

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a. Spent fuel discharged before 1976.

b. Indicates year of startup of new enrichment plants (9 million SWU/yr).

c. Indicates year of startup of new UO_2 fabrication plants (1500 MTU/yr). New plants operate at 50% capacity in first year and 100% thereafter.

d. Indicates year of startup of HWR fuel fabrication plants (1500 MTU/yr). New plants operate at 50% capacity in first year and 100% thereafter.

e. An additional 22,400 MT of HWR fuel are fabricated and charged into HWRs after the year 2000 from LWR fuel discharged through the year 2000.

TABLE A-11

Front-End Operations (600 LWRs)

Calendar Year	U_3O_8 Production, MT			Enrichment Production (Total), Million SWU			UO_2 Fuel Fabrication, MTU	
	Throwaway	U Recycle	U, Pu Recycle	Throwaway	U Recycle	U, Pu Recycle	U Throwaway & Recycle	U, Pu Recycle
1976	11,024	11,024	11,024	16	16	16	1,800	1,800
77	12,314	12,314	12,314	18	18	18	1,800	1,800
78	14,237	14,237	14,237	20	20	20	2,000	2,000
79	17,007	17,007	17,007	22	22	22	2,400	2,400
1980	22,173	22,173	22,173	23	23	23	3,000	3,000
81	28,964	27,933	27,933	23	23	23	3,700	3,700
82	30,108	28,628	27,744	23	23	23	4,500	4,500
83	35,191	32,851	30,798	24	24	24	5,300	5,300
84	38,612	36,170	34,430	24	24	24	5,800	5,800
1985	44,072	41,654	39,925	37[a]	37[a]	28	7,050[b]	7,050[b]
86	48,393	45,330	42,837	37	37	37[a]	7,800	7,800
87	54,412	49,652	45,346	46[a]	46[a]	46[a]	8,550[b]	7,800
88	59,824	52,579	46,466	55[a]	46	46	9,300	8,550[b]
89	66,132	56,282	48,553	55	55[a]	46	10,050[b]	9,300
1990	72,516	60,184	50,719	64[a]	64[a]	55[a]	10,800	10,050[b]
91	78,601	65,403	55,334	64	64	55	11,550[b]	10,800
92	84,827	70,825	60,793	73[a]	73[a]	64[a]	12,300	10,800
93	91,142	76,210	65,392	73	73	64	13,050[b]	11,550[b]
94	96,679	81,087	69,501	82[a]	82[a]	73[a]	14,550[b]	12,300
1995	102,248	85,888	74,388	91[a]	82	82[a]	15,300	12,300
96	107,601	90,619	78,439	91	91[a]	82	15,300	12,300
97	113,044	95,481	82,492	100[a]	100[a]	91[a]	15,300	12,300
98	117,922	99,593	86,695	100	100	91	15,300	12,300
99	122,380	103,081	89,396	109[a]	109[a]	100[a]	15,300	12,300
2000	114,382	92,505	77,987	109	109	100	15,300	12,300
Total	1,583,805	1,368,440	1,211,923	1,379	1,361	1,253	227,100	200,100

a. Indicates year of startup of new enrichment plants (9 million SWU/yr).
b. Indicates year of startup of new UO_2 fabrication plants (1500 MTU/yr). Plants operate at 50% capacity in the first year and at 100% thereafter.

TABLE A-12

Back-End Operations (600 LWRs, Pu and U Recycle)

Calendar Year	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production U,Pu Recycle, MTHM*
	(1623)[a]			
1976	937			
77	1,164			
78	1,310			
79	1,455			
1980	1,644			
81	1,899	600 AGNS[b]	4.0	
82	2,114	1,000	6.6	
83	2,817	1,500	9.9	175[c]
84	3,336	1,500	9.9	350
1985	3,908	1,500	9.9	350
86	4,442	2,100[b]	13.9	350
87	5,036	3,100[b]	20.5	525[c]
88	5,631	4,600[b]	30.4	875[c]
89	6,321	6,100[b]	40.3	1,225[c]
1990	7,032	7,600[b]	50.2	1,575[c]
91	7,778	8,500	63.8	1,925[c]
92	8,572	9,000	67.5	2,100
93	9,370	9,600[b]	72.0	2,100
94	10,189	10,000	75.0	2,275[c]
1995	11,009	10,500	78.8	2,450
96	11,802	11,100[b]	83.3	2,450
97	12,569	11,500	86.3	2,625[c]
98	13,312	12,000	90.0	2,800
99	14,050	12,600[b]	94.5	2,800
2000	14,743	13,000	97.5	2,975[c]
01	NA	13,500	101.3	NA
02	NA	13,163	98.8	NA
Total	164,063	164,063	1,204	29,925[d]

a. Spent fuel discharged before CY-1976.
b. Indicates year of startup for AGNS, and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in the first year, at 67% in the second year, and at 100% thereafter.
c. Indicates year of startup of MOX plants. Plants operate at 50% capacity in first year and at 100% thereafter (capacity equivalent to associated separations plant). Five percent of MOX production is retained in pipelines.
d. An additional 7910 MT of MOX containing plutonium recovered from fuel discharged through the year 2000 is charged to reactors after the year 2000.

TABLE A-13

Front-End Operations (400 LWRs)

Calendar Year	U_3O_8 Production, MT			Enrichment Production, Million SWU			UO_2 Fuel Fabrication, MTU	
	Throwaway	U Recycle	U, Pu Recycle	Throwaway	U Recycle	U, Pu Recycle	U Throwaway & Recycle	U, Pu Recycle
1976	10,091	10,091	10,091	16	16	16	1,800	1,800
77	11,122	11,122	11,122	18	18	18	1,800	1,800
78	13,292	13,292	13,292	20	20	20	2,000	2,000
79	14,562	14,562	14,562	22	22	22	2,400	2,400
1980	23,071	23,071	23,071	23	23	23	2,400	2,400
81	19,823	18,813	18,813	23	23	23	2,800	2,800
82	24,383	22,795	22,003	23	23	23	3,500	3,500
83	25,481	23,108	21,572	24	24	24	4,200	4,200
84	31,729	29,298	27,806	24	24	24	4,800	4,800
1985	38,204	35,241	33,735	28	28	28	5,300	5,300
86	40,144	36,900	34,653	28	28	28	5,800	5,300
87	41,479	36,501	32,682	37[a]	37[a]	37[a]	6,300	5,300
88	46,018	28,634	33,222	37	37	37	6,300	5,300
89	48,522	39,840	33,600	46[a]	46[a]	37	7,050[b]	5,800
1990	52,686	43,086	36,865	46	46	46[a]	7,800	6,300
91	57,567	47,516	40,616	55[a]	55[a]	46	8,550[b]	7,050[b]
92	60,924	50,184	42,498	55	55	46[a]	9,300	7,800
93	64,972	53,341	45,604	64[a]	64[a]	55[a]	9,300	7,800
94	70,281	57,722	49,248	64	64	55	10,050[b]	8,550[b]
1995	71,945	58,782	49,495	73[a]	73[a]	64[a]	10,800	9,300
96	74,415	60,495	51,313	73	73	64	10,800	9,300
97	76,148	62,436	53,237	82[a]	82[a]	73[a]	10,800	9,300
98	78,292	64,703	55,482	82	82	73	10,800	9,300
99	79,583	66,041	56,813	91[a]	82	82[a]	10,800	9,300
2000	75,586	61,458	52,234	91	91[a]	82	10,800	9,300
Total	1,150,320	979,032	863,627	1,145	1,136	1,046	166,250	146,000

a. Indicates year of startup of new enrichment plants (9 million SWU/yr).
b. Indicates year of startup of new UO_2 fabrication plants (1500 MTU/yr). Plants operate at 50% capacity in the first year, and at 100% thereafter.

TABLE A-14

Back-End Operations (400 LWRs, Pu and U Recycle)

Calendar Year	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production U,Pu Recycle, MTHM*
	(1623)[a]			
1976	937			
77	1,087			
78	1,208			
79	1,330			
1980	1,517			
81	1,696	600 AGNS[b]	4.0	
82	2,035	1,000	6.6	
83	2,296	1,500	9.9	175[c]
84	2,687	1,500	9.9	350
1985	2,997	1,500[b]	9.9	350
86	3,511	2,100[b]	13.9	350
87	4,162	3,100[b]	20.5	525[c]
88	4,677	4,600[b]	30.3	875[c]
89	5,056	5,500	36.3	1,225[c]
1990	5,511	6,000[b]	39.6	1,400
91	5,917	6,600[b]	49.5	1,400
92	6,379	7,000	52.5	1,575[c]
93	6,918	7,500[b]	56.3	1,750
94	7,429	8,100[b]	60.8	1,750
1995	7,944	8,500	63.8	1,925[c]
96	8,534	9,000	67.5	2,100
97	8,989	9,000	67.5	2,100
98	9,375	9,000	67.5	2,100
99	9,702	9,000	67.5	2,100
2000	10,095	9,000	67.5	2100
01	NA	9,000	67.5	NA
02	NA	4,512	33.8	NA
Total	123,612	123,612	903	24,150[d]

a. Spent fuel discharged before CY-1976.

b. Indicates year of startup of AGNS, and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in the first year, at 67% in the second year, and at 100% thereafter.

c. Indicates year of startup of MOX plants. Plants operate at 50% capacity in the first year and at 100% thereafter (capacity equivalent to associated separations plant). Five percent of MOX production is retained in pipelines.

d. An additional 4120 MT of MOX containing plutonium recovered from fuel discharged through the year 2000 is charged to reactors after the year 2000.

APPENDIX B
ASSUMPTIONS AND MODELS USED TO ASSESS ENVIRONMENTAL EFFECTS

A. METEOROLOGY

1. Releases from Normal Operations

The meteorological assumptions used to calculate dilution, dispersion, and deposition of radionuclides expected to be released during routine operation of the fuel recycle industry were adapted from those developed for the LMFBR program environmental statement.[1] The LMFBR meteorological model was based on data taken from 18 stations in the continental United States and is described briefly below; Appendix II-1 of Reference 1 should be consulted for further details.

The 18-station data include the joint frequency of wind speed and atmospheric stability category, which is independent of wind direction. They were averaged to obtain mean joint wind-speed stability categories in a typical 22.5° sector. The total frequencies for Pasquill stability categories and average wind speeds are shown in Table B.1.

The LMFBR calculations included downwind average ground-level concentrations using the Gaussian plume model (derived by Roberts[2] and described by Sutton[3]), with dispersion patterns developed by Pasquill[4] and Gifford,[5] plume rise using the Holland equation,[6] and plume depletion by the Chamberlain[7] method.

A deposition velocity of 0.01 m/sec was used for radioiodine and particulates. Values of calculated sector-averaged dispersion (not weighted by frequency of wind direction) resulting from these calculations are given in Table II-I-2 of Reference 1. Also, in the LMFBR calculations, the $\overline{\chi}/Q$ (average concentration per unit source, sec/m^3) values described above were combined with a nonuniform wind rose determined by averaging data from 70 U.S. locations. In this report, a uniform wind rose is assumed, and the $\overline{\chi}/Q$ values from LMFBR Table II-I-2 for 100-m stack height were divided by 16 (uniform 22.5° sectors) and plotted in Figure B.1. Curves for both an undepleted plume and a plume depleted by surface deposition are shown. The average χ/Q at the site boundary (1.5 miles - 2.4 km) is about 5×10^{-8} sec/m^3. To calculate the maximum dose to an individual, a maximum-to-average χ/Q ratio of 2.0 is assumed, and 1×10^{-7} sec/m^3 is used in subsequent calculations. The average value of 5×10^{-8} sec/m^3 is used to calculate annual average site boundary concentrations of nonradioactive pollutants. The integrated average χ/Q in the area between the perimeter and a circle 50 miles (80 km) distant from the center of the site is estimated to be 4×10^{-9} sec/m^3 for the undepleted plume and 2×10^{-9} sec/m^3 for the depleted plume.

Deposition within the 50-mile radius (7850 square miles or 2×10^4 km^2) is estimated to be about one-third of that released from the stack. Calculations of the effects of deposited nuclides include the assumption that one-third of the iodine and

TABLE B.1

Average Single Sector Frequencies[1]

	Pasquill Category			
	A & B	*C*	*D*	*E & F*
Total Frequency	0.17	0.14	0.29	0.39
Average Wind Speed, m/sec	3.5	4.1	4.4	4.0

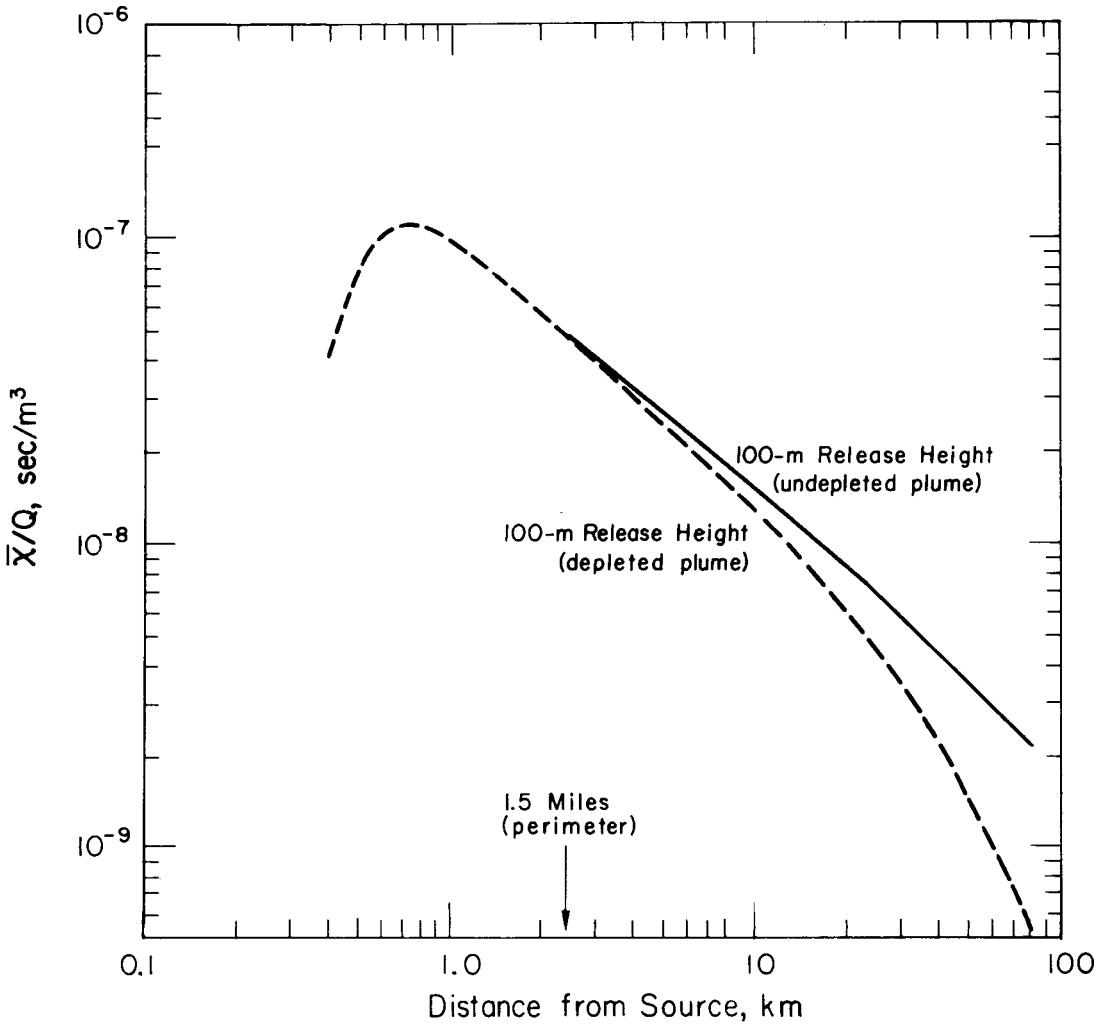

FIGURE B.1 Average χ/Q Values as a Function of Distance

particulates is deposited in the 50-mile radius and the remaining 2/3 is deposited in the eastern U.S. (see section on U.S. dose assumptions in this appendix).

2. Releases from Unlikely Accidents

The meteorological dispersing conditions during short-term releases from accidents (Section 3B2) are taken from Regulatory Guide 1.3.[8] The χ/Q value for a 100-m release height, 0-8 hours release time, and the closest offsite location (2400 m) is about 1×10^{-5} sec/m^3.

B. LOCAL DOSE

1. Maximum Individual Dose

The maximum dose commitment to an individual from one year's releases is calculated using the models described in the next section, 50-Mile Radius Population Dose. The models include a meteorological dispersion factor that results in concentrations twice as high as those for average conditions at the same distance. The ratio of maximum individual air concentrations to the value used for the 50-mile population average is 25:1 for undepleted plume and 50:1 for depleted plume. No other assumptions, such as increased local diet, etc., to optimize the maximum dose were made.

2. 50-Mile Radius Population Dose

The population within a 50-mile radius surrounding each fuel recycle site is assumed to average one million persons, uniformly distributed. This model is then readily adapted to actual

situations for site-specific assessments. The dose commitment from one year's releases is calculated using the models described under each nuclide or pathway.

The population dose from each site is also calculated for each year's releases occurring from startup through year 2001 for the base case (actually including some processing in year 2002 to complete the processing of fuel discharged from the reactors through year 2000). The reprocessing periods for alternate cases are shown in Appendix A. These doses were summed for the years of operation for each plant. The effects of long-lived nuclides persisting in the environment are included through the year 2101 for the base case and for 100 years after the end of reprocessing for alternate cases; details are given in the discussion of specific nuclides. The population surrounding the plants is assumed to increase in proportion to U.S. growth after year 2000 (Figure B.2), to reach 1.3 million in year 2030, and then remain constant.

Calculational results are tabulated in Section E of this appendix.

3. Uptake-Dose Models

a. Tritium

The local annual whole body dose rate from the release of tritium (assumed to be 100% tritiated water, HTO) is estimated using the approach given in the model described in ORNL-4992,[9] Chapter Two.

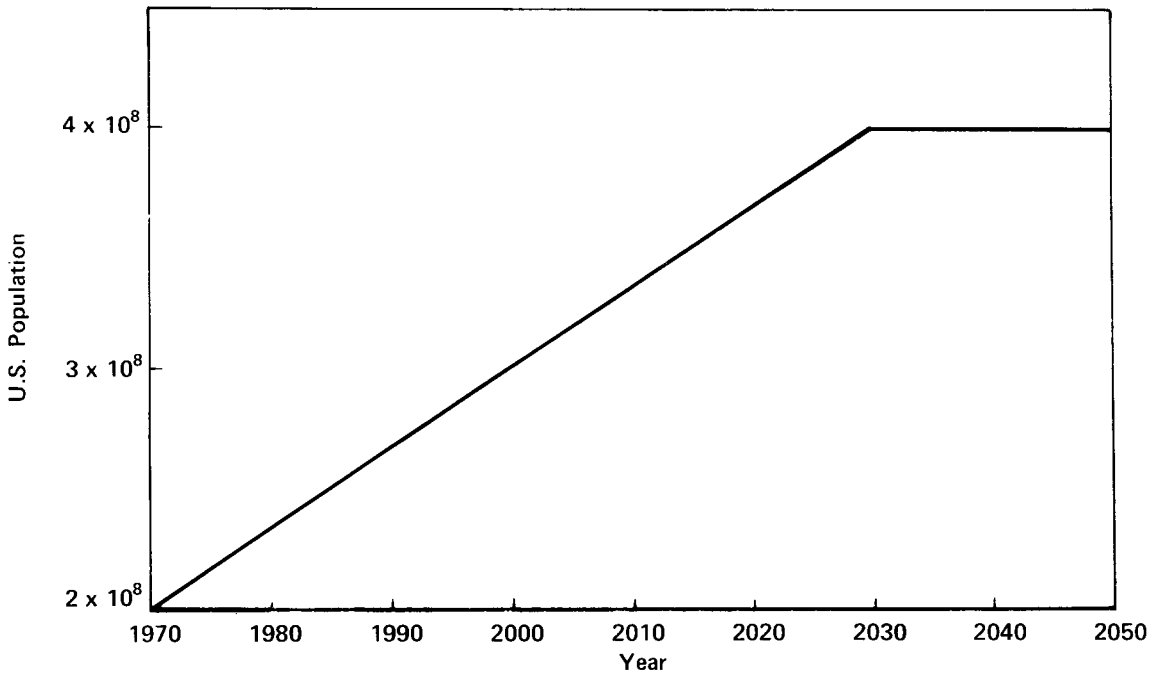

FIGURE B.2 Projected Total U.S. Population[10]

The ORNL model assumes that the water in man's diet reaches the same specific activity as atmospheric moisture. An average daily intake of 1300 g H_2O in food and 1200 g H_2O as drinking water is assumed; however, the drinking water is assumed to be diluted 100-fold to allow for drinking water sources (ground water) that would not be in equilibrium with atmospheric moisture. A dose conversion factor for foodstuffs and drinking water pathways of 52 rem/yr per Ci/m^3 (H_2O) was used in the calculations. This factor is based on the same parameters as the atmospheric factor described below.

In addition to the ORNL model for dietary intake of tritium, the dose from inhalation and skin absorption resulting from exposure to the annual average tritium atmospheric concentrations was

calculated. The dose conversion factor used at SRL was modified for use in these calculations. This factor is documented in Reference 11 for the active man breathing rate; this was corrected for the normal breathing rate.[12] The SRL factor incorporates a quality factor of 1.7 and assumes a 12-day biological half-life; a quality factor of 1.0 was assumed for these calculations, the dose conversion factor used was then 1.8×10^9 mrem/yr per Ci/m^3.

The dose to the local population from worldwide tritium recycling (described under "Worldwide Dose") is calculated for the reprocessing period and 100 years thereafter and added to the doses described above for "first-pass" exposure.

b. Carbon-14

The local annual dose rates from the release of ^{14}C (assumed to be available to the biosphere as CO_2) is estimated using the model described in ORNL-4992,[9] Chapter Two. The ORNL model assumes that the specific activity (^{14}C/total C) in human tissues is equal to the average steady-state value in the atmosphere. About 99% of the resulting dose is caused by the ingestion (dietary) exposure mode.[9] The ORNL dose-rate factors for the most significant organ doses are 1.28×10^{12} mrem/yr per Ci/m^3, total body, and 2.22×10^{12} mrem/yr per Ci/m^3, red marrow. Local dose from recycled ^{14}C is calculated for the reprocessing period and 100 years thereafter, and is added to the doses for "first-pass" exposure.

c. Krypton-85

NCRP Report No. 44[13] includes the dose conversion factors for ^{85}Kr exposure used in this statement. These are 1.5×10^7 mrem/yr per Ci/m^3, total body, and 3.1×10^7 mrem/yr per Ci/m^3, lung, for the most significant organ doses. Skin dose is about 120 times the whole body dose,[13] but is not included in this assessment because of the very low frequency of severe health effects from skin doses. Local dose from recycled ^{85}Kr is calculated for the reprocessing period and 100 years thereafter, and is added to the dose for "first-pass" exposure.

d. Iodine-129

The uptake-dose model used for ^{129}I calculations was developed by Soldat.[14] Soldat calculates ^{129}I doses to the thyroids of individuals at 1, 4, and 14 years of age, as well as doses to adults from dietary pathways. Table B.2, taken from Reference 14, shows the dietary habits assumed and dose conversion factors for the four age groups. The sum of the adult dose factors (5.94×10^{15} mrem/yr per Ci/m^3) is used to calculate maximum individual and population doses. Buildup of ^{129}I in the soil is assumed to contribute an additional 1% per year to the dose from milk and leafy vegetable pathways (Table B.2) and is included in the calculation of doses from the full reprocessing and recycling industry. One-third of the ^{129}I released is assumed to be deposited within the 50-mile radii of the 8 reprocessing plants.

TABLE B.2

Thyroid Doses From Unit Concentration of ^{129}I in Air [14]

	mrem/yr per pCi/m³[a]			
Exposure Pathway	*1 yr*	*4 yr*	*14 yr*	*Adult*
Inhalation[b]	21	11	18	39
Milk Consumption[c]	5800	2400	2000	3100
Leafy Vegetable Consumption[d]	0	510	730	1500
Beef Consumption[e]	0	320	500	1300

---

a. Maximum dose rate after equilibrium is reached between thyroid and intake rate. Soil-root pathway would add an additional ∿1.3% (per year of accumulation) to the milk pathway and ∿1.0% (per year of accumulation) to the vegetable pathway.

b. Inhalation rates are 5.6, 7.0, 13.5, and 20 m^3/day for the 1, 4, 14, and adult ages, respectively.

c. One liter per day of fresh milk from cow grazing on contaminated pasture 12 months per year.

d. Leafy vegetable consumption was assumed to be 0, 32, 54, and 72 kg/yr for the 1, 4, 14, and adult ages, respectively.

e. Beef consumption was assumed to be 0, 25, 45, and 80 kg/yr for the 1, 4, 14, and adult ages, respectively.

Because of its long half-life (1.6×10^7 years), ^{129}I will persist in the environment and potentially expose the population long after it has been released to the environment. For this assessment, the effects of ^{129}I released through the end of reprocessing (the year 2001 for the base case) are estimated for an additional 100 years. The EPA in its analysis of the fuel cycle[10] used this 100-year cutoff. The EPA also recognized that effects from ^{129}I releases could impose additional health risks for future generations if the ^{129}I remains in the biosphere beyond the 100 years. Although only the fraction of ^{129}I available through the soil-root pathway is assumed to contribute to population dose in the 100-year period following reprocessing, the man-rem thyroid dose is approximately equal to the dose in the period of continuing ^{129}I release.

e. Other Nuclides and Pathways

In addition to the dose calculations for ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I described above, the contributions of other nuclides released from the FRP-MOX plants are calculated with the models and dose conversion factors described in ORNL-4992.[9]

(1) External Exposure to Gamma-Emitters Deposited on the Ground

Tables in ORNL-4992,[9] Chapter Three, give the annual dose rate and the accumulated dose to individuals from continuous deposition of radionuclides at a rate of one $\mu Ci/(cm^2\text{-hr})$. The ground is modeled

as a plane surface with a uniform distribution of activity. The exposed individual is represented by a point receptor one meter above the ground. The tabulated dose rates and doses take into account radioactive decay and the buildup of radioactive daughter products after deposition; no environmental removal processes are included. Conversion factors to obtain dose rates at the end of a given period and total doses integrated over a given period for the nuclides that proved to be significant for this pathway of exposure to man are given in Table B.3 for one year and twenty years of releases.

The $\overline{\chi}/Q$ for a depleted plume is used to calculate ground deposition, together with a deposition velocity of 0.01 m/sec. Exposure to deposited nuclides was assumed to continue for a 100-year period following reprocessing; radioactive decay was the only removal factor included in the calculations.

TABLE B.3

Dose Rate and Integrated Dose Conversion Factors from Deposited Radionuclides[9]

	Dose Rate, mrem/yr per μCi/(cm²-hr)		*Total Dose, mrem per μCi/(cm²-hr)*	
Nuclide	*1 yr*	*20 yr*	*1 yr*	*20 yr*
^{129}I	1.16×10^{9}	2.31×10^{10}	5.78×10^{8}	2.31×10^{11}
^{134}Cs	1.79×10^{10}	6.2×10^{10}	9.47×10^{9}	1.07×10^{12}
^{137}Cs	7.24×10^{9}	1.17×10^{11}	3.63×10^{9}	1.26×10^{12}

(2) Inhalation

Exposure to the radioactive releases from fuel recycle sites via the inhalation pathway was calculated for the nuclides not previously considered in nuclide-specific models. The $\overline{\chi}/Q$ for an undepleted plume was used in this calculation, and resuspension was not included. When the undepleted plume concentration is used, the estimate of dose is more conservative than a depleted plume concentration plus a resuspension factor. The contribution of long-term resuspension should be evaluated in site-specific environmental assessments. Breathing rate is assumed to be 20 m^3/day. Dose conversion factors, taken from ORNL-4992,[9] result in 50-year dose commitments. The ORNL models for nuclide uptake, retentions, and distribution in the body are for the most part based on ICRP models,[12,15] including the ICRP-2 lung model. Dose factors for the more significant nuclides in the inhalation pathway are given in Table B.4.

Doses calculated by the inhalation pathway for the TRU actinides assume soluble forms for doses to all organs except lung; insoluble forms are assumed in calculating lung dose, thus introducing an over-estimation of dose depending on the soluble-insoluble fractions.

(3) Foodstuffs

The ORNL-4992 models for uptake in man of radionuclides via the dietary pathway are used in this assessment. The models use the "TERMOD" computer code which estimates uptakes through consumption of milk, beef, and plants contaminated directly by deposited radionuclides as well as by uptake from the soil.

TABLE B.4

50-yr Dose Conversion Factors for Inhalation of Radionuclides, rem/μCi Inhaled[9]

Nuclide	*Whole Body*	*Bone*	*Lung*	*Liver*	*Kidneys*
^{90}Sr	0.222	11.1	1.2	-	-
^{144}Ce	0.065	1.2	1.0	0.49	0.30
^{238}Pu	143.5	5705	188.5	816.4	608.7
^{239}Pu	159.2	6559	177.2	896.2	676.4
^{240}Pu	159.0	6551	177.2	896.2	676.4
^{241}Pu	2.55	124	0.165	6.41	12.1
^{242}Cm	3.38	50.9	40.5	51.9	15.4
^{244}Cm	74.5	1256	64.7	541.9	347.6

The code is described in Chapter Two of ORNL-4992.

The depleted plume $\overline{\chi}/Q$ values and a deposition velocity of 0.01 m/sec were used in the calculation. The ORNL model assumes the following foodstuff consumption rate: above-surface food - 0.25 kg/day, milk - 1.0 liter/day, and beef - 0.3 kg/day. Direct deposition on vegetation is assumed to be the more significant route to man than the soil-root pathway. The TERMOD model also assumes a 4% per year movement from the root zone to an unavailable soil sink. For these reasons, the foodstuff pathway is not included in dose estimates for the 100-year period following reprocessing, when direct deposition of releases during the study period has ceased. The validity of this assumption, the significance of resuspension as a means of continuing direct deposition, the movement of radionuclides in various soils, and the effect of agricultural practices on this movement should be evaluated in site-specific assessments.

Dose conversion factors taken from ORNL-4992 for nuclides that are significant in the foodstuffs pathway are listed in Table B.5.

(4) Direct External Exposure

Calculations using the ORNL-4992 model and dose conversion factors show that doses from external exposure to the radionuclides dispersed in the atmosphere surrounding the fuel recycle sites can be neglected when compared to other dose pathways.

TABLE B.5

50-yr Dose Commitment Factors for Ingestion of Radionuclides, rem/μCi Ingested[9]

Nuclide	*Total Body*	*Bone*	*Muscle*	*Liver*	*Kidney*	*Spleen*
^{90}Sr	0.166	8.31	-	-	-	-
^{134}Cs	0.075	0.05	0.13	0.14	0.04	0.10
^{137}Cs	0.043	0.08	0.08	0.11	0.04	0.09
^{238}Pu	0.017	0.68	-	0.10	0.07	-
^{239}Pu	0.019	0.79	-	0.11	0.08	-
^{240}Pu	0.019	0.79	-	0.11	0.08	-
^{241}Pu	-	0.015	-	-	-	-
^{241}Am	0.05	0.82	-	0.29	0.41	-
^{242}Cm	-	0.02	-	0.02	-	-
^{244}Cm	0.03	0.50	-	0.02	0.14	-

C. UNITED STATES DOSE

1. Atmospheric Concentrations and Population Distribution

Releases from fuel recycle plants are assumed to expose the population of the eastern U.S. in addition to the local populations included in the 50-mile radius population. The U.S. exposure was calculated for the nuclides described in subsequent sections for the releases from the base case reprocessing and recycling industry during the reprocessing period (1981-2001 for the base case). Effects of long-lived nuclides were assessed for an additional 100 years (ending in year 2101 for the base case). The NOAA[16] population-weighted concentration estimated for ^{85}Kr dispersal over the U.S. (and part of Canada) is 2.5×10^{-10} (person-Ci)/m^3 (1970 population; 1 curie annual release from the midwestern U.S.). This value is used in subsequent sections, together with annual releases, dose conversion factors, and population corrected to the appropriate year (Figure B.2), to estimate doses to the eastern U.S. population (assumed to be 80% of total U.S. population). Calculational results are tabulated in Section E of this appendix.

2. Tritium

The NOAA population-concentration estimate was combined with the ORNL-4992 tritium uptake models and dose conversion factors described for local dose estimates. The ORNL models include the assumption that tritium in foodstuff water and surface drinking water supplies is in equilibrium with tritium in atmospheric water. Global recycling is included in proportion to the fraction of the world population in the U.S.

3. Carbon-14

The dose to the eastern U.S. population is calculated as above for tritium, using the NOAA estimates and ORNL-4992 uptake and dose calculational models. The uptake model includes the assumption that the $^{14}C/C$ ratio in the body reaches rapid equilibrium with the atmospheric ratio. U.S. dose from global recycling is also included.

4. Krypton-85

^{85}Kr doses to the eastern U.S. population are calculated using the NOAA estimates for "first pass" exposures and NCRP-44 dose conversion factors. Global recycling is also included.

5. Iodine-129

^{129}I is assumed to be completely deposited in the eastern U.S. Two-thirds of the annual release is assumed to be deposited outside the 50-mile radius zones in the eastern U.S. Doses are calculated by combining the NOAA projection with the uptake-dose models proposed by Soldat[14] described for the local population dose estimates.

6. Other Nuclides

The NOAA projections are combined with the ORNL models and dose conversion factors described in the local dose section. Two-thirds of the particulate releases are assumed to be distributed over the eastern U.S.

D. WORLDWIDE DOSE

1. Population Growth

The world population is assumed to grow from a 1970 value of 3.56×10^9 at a rate of 1.9%/yr.[10] Distribution of specific nuclides on a global basis is discussed below under each nuclide. Dose calculations include the direct effects from the reprocessing period and persistent effects for 100 years after. Results are tabulated in Section E of this appendix.

2. Tritium

The worldwide dose due to tritium exposure is estimated by diluting the tritium oxide released into the atmosphere (2×10^{18} m^3 air) and the circulating waters[10] (1.4×10^{16} m^3, H_2O) of the Northern Hemisphere (the circulating waters include the oceans to 75 m depth). The tritium is assumed to reach equilibrium between atmospheric water and the circulating waters. Dose calculations include inhalation and skin absorption of tritium in the atmospheric moisture. A dose conversion factor of 1.8×10^6 rem/yr per Ci/m^3 is used. Also included is the dose estimated by assuming that man's body water reaches the same tritium concentrations as the circulating waters. A dose conversion factor of 52 rem/yr per Ci/m^3 (H_2O) is used (see Local Dose for discussion of these factors). The buildup of ^3H is calculated using the input values from Section 3, corrected for radioactive decay. After the reprocessing period, the available tritium is reduced by radioactive decay. The doses are summed over the reprocessing period and 100 years thereafter.

The Northern Hemisphere's population (80% of the world population) is assumed to be exposed to the resulting concentrations. The U.S. population contribution is subtracted and added to the U.S. dose values.

3. Carbon-14

The worldwide dose from ^{14}C is estimated by the technique used by Hayes and MacMurdo,[17] which was based on earlier UNSCEAR estimations.[18] The stratosphere, troposphere, and ocean surface are considered a single reservoir (I) that exchanges with the deep ocean. The removal rate of ^{14}C to the deep ocean is given by the expression[18] $0.96\ e^{-0.0209\ t} + 0.04\ e^{-0.000125\ t}$ The buildup of ^{14}C from the reprocessing industry is calculated with the input values from Section 3 and the removal rate given above for the reprocessing period. Doses were calculated using the curies available in Reservoir I and the dose conversion factor 1.15×10^{-10} (rem/Ci in Reservoir I) derived from the Hayes-MacMurdo paper. For the 100-year period following reprocessing, the curies available in Reservoir I was depleted using the exponential expression above, and doses to the steadily increasing population were estimated. The doses for the entire period are then summed to represent the total effects of closing the fuel cycle. The Seuss effect (dilution of ^{14}C by CO_2 released from fuel-burning operations) is neglected because it is not of sufficient magnitude relative to the uncertainties in the ^{14}C assumptions to warrant inclusion.

The U.S. population contribution is subtracted and added to the U.S. dose values.

4. Krypton-85

The worldwide dose from ^{85}Kr is estimated by diluting the releases into the world's atmosphere (4×10^{18} m^3).[10] The concentrations are calculated using release data from Section 3, corrected for radioactive decay. Doses for the reprocessing period (buildup) and 100 years thereafter (decreasing ^{85}Kr dose as a result of radioactive decay) are summed to estimate the effects of the fuel reprocessing industry.

The fraction of the worldwide dose occurring in the U.S. is subtracted and added to the U.S. dose.

E. RESULTS OF DOSE CALCULATIONS (BASE CASE)

Maximum individual doses and those to a 50-mile-radius population for individual FRP-MOX sites are given in Tables 3.4 and 3.5. Doses to the local, U.S., and worldwide populations from the 1981-2001 reprocessing and MOX fabrication industry for the base case are summarized in Table 3.22 and given in more detail in the tables below. Effects are calculated through the year 2101.

TABLE B.6

Tritium Population Dose, whole-body man-rem

Pathway	*Local*	*U.S. (Less Local)*	*World (Less U.S.)*	*Total*
First Pass 1981-2001	2.4×10^{4}	6.4×10^{4}	-	8.8×10^{4}
Worldwide Recycle 1981-2001	9.6×10^{-1}	2.6×10^{2}	4.5×10^{3}	4.8×10^{3}
2002-2101	2.3×10^{0}	6.2×10^{2}	1.1×10^{4}	1.2×10^{4}
Total	2.4×10^{4}	6.5×10^{4}	1.6×10^{4}	1.1×10^{5}

TABLE B.7

Carbon-14 Population Dose, whole-body man-rem[a]

Pathway	*Local*	*U.S. (Less Local)*	*World (Less U.S.)*	*Total*
First Pass 1981-2001	2.4×10^{3}	6.4×10^{3}	-	9.0×10^{3}
Worldwide Recycle 1981-2001	1.8×10^{1}	4.7×10^{3}	8.3×10^{4}	8.8×10^{4}
2002-2101	1.8×10^{2}	4.8×10^{4}	8.5×10^{5}	9.0×10^{5}
Total	2.6×10^{3}	5.9×10^{4}	9.3×10^{5}	9.9×10^{5}

a. For dose to red marrow, multiply by 1.73.[9]
For gonadal dose, muptiply by 0.39.[9]

TABLE B.8

Krypton-85 Population Dose, whole-body man-rem[a]

Pathway	*Local*	*U.S. (Less Local)*	*World (Less U.S.)*	*Total*
First Pass 1981-2001	5.6×10^{2}	1.5×10^{3}	-	2.1×10^{3}
Worldwide Recycle 1981-2001	9.0×10^{0}	2.4×10^{3}	4.2×10^{4}	4.4×10^{4}
2002-2101	1.9×10^{1}	5.1×10^{3}	8.9×10^{4}	1.4×10^{4}
Total	5.9×10^{2}	9.0×10^{3}	1.3×10^{5}	1.4×10^{5}

a. For lung dose, multiply by 2.07.[13]
For gonadal dose, multiply by 0.74.[13]

TABLE B.9

Iodine-129 Population Dose, thyroid man-rem

Pathway	*Local*	*U.S. (Less Local)*	*Total*
Inhalation and Foodstuff 1981-2001	3.4×10^{4}	1.2×10^{5}	1.5×10^{5}
Foodstuff via Soil Deposits 2001-2101	4.0×10^{4}	1.4×10^{5}	1.8×10^{5}
Total	7.4×10^{4}	2.6×10^{5}	3.3×10^{5}

TABLE B.10

Population Dose from Ground-Deposited Nuclides, whole-body man-rem

Period	*Local*	*U.S. (Less Local)*	*Total*
1981-2001	5.3×10^2	1.5×10^3	2.0×10^3
2002-2101	2.9×10^3	1.2×10^4	1.5×10^4
Total	3.4×10^3	1.4×10^4	1.7×10^4

TABLE B.11

Inhalation Population Dose,[a] man-rem (1981-2001)

Organ	*Local*	*U.S. (Less Local)*	*Total*
Whole Body	7.3×10^2	2.1×10^3	2.8×10^3
Bone	2.4×10^4	6.8×10^4	9.2×10^4

a. Due to nuclides other than ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.

TABLE B.12

Foodstuff Population Dose,[a] man-rem (1981-2001)

Organ	*Pathway*	*Local*	*U.S. (Less Local)*	*Total*
Whole Body	Above Surface Food	7.0×10^1	2.4×10^2	3.1×10^2
	Milk	7.0×10^1	2.4×10^2	3.1×10^2
	Beef	8.0×10^0	2.8×10^1	3.6×10^1
		1.5×10^2	5.1×10^2	6.6×10^2
Bone	Above Surface Food	1.3×10^3	4.6×10^3	5.9×10^3
	Milk	3.6×10^2	1.3×10^3	1.7×10^3
	Beef	5.3×10^1	1.9×10^2	2.4×10^2
		1.7×10^3	6.1×10^3	7.8×10^3

a. Due to nuclides other than ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.

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