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Actinide Partitioning-Transmutation Program Final Report: VI. Short-Term Risk Analysis of Reprocessing, Refabrication, and Transportation (Summary)

R. Fullwood

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With contributions by

Other SAI staff

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NUCLEAR FUEL AND WASTE PROGRAMS

Waste Management Analysis for Nuclear Fuel Cycles
(Activity No. AP 05 25 10 0; 189 No. ONL-WH01)

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GLOSSARY

2EHOH - 2-ethylhexanol, a partitioning agent

10CFR20 - Code of Federal Regulations, Title 10, Chapter 20

AGNS - Allied-Gulf Nuclear Services plant at Barnwell, South Carolina

CRAC - Consequences of Reactor Accidents Code

CMP - The bidentate extractant (dihexyl-N,N-diethylcarbamylmethylene phosphate); used with a diisopropylbenzene diluent

FFP - Fuel Fabrication Plant

FRP - Fuel Reprocessing Plant

GESMO - Generic Environmental Statement for Mixed Oxide Fuel - NUREG-0002

HAW - HA waste - fission product waste

HEPA - high-efficiency particulate absolute filters

HLW - high-level waste

MT - metric tonne; i.e., 1000 kg.

NFS - Nuclear Fuel Services plant at West Valley, New York

ORNL - Oak Ridge National Laboratory

PT - Partitioning-Transmutation cycle

Reference - comparison nuclear fuel cycle

TBP - tributyl phosphate

WTF - Waste Treatment Facility

ABSTRACT

The Chemical Technology Division of the Oak Ridge National Laboratory has prepared a set of documents that evaluate a Partitioning-Transmutation (PT) fuel cycle relative to a Reference cycle employing conventional fuel-material recovery methods. The PT cycle uses enhanced recovery methods so that most of the long-lived actinides are recycled to nuclear power plants and transmuted to shorter-lived materials, thereby reducing the waste toxicity.

This report compares the two fuel cycles on the basis of the short-term radiological and nonradiological risks they present to the public and to workers. The accidental radiological risk to the public is analyzed by estimating the probabilities of sets of accidents; the consequences are calculated using the CRAC code appropriately modified for the material composition. Routine radiological risks to the public are estimated from the calculated release amounts; the effects are calculated using the CRAC code. Radiological occupational risks are determined from prior experience, projected standards, and estimates of accident risk. Nonradiological risks are calculated from the number of personnel involved, historical experience, and epidemiological studies.

The result of this analysis is that the short-term risk of PT is 2.9 times greater than that of the Reference cycle, primarily due to the

larger amount of industry. This conclusion is strongly dominated by the nonradiological risk, which is about 150 times greater than the radiological risk. If the radiological risk is considered alone, the ratio of PT to Reference risk is 3, composed as follows: radiological operations affecting the public - 5, radiological operations affecting the workers - 1.7, and radiological accidents affecting the public - 1.4, all in the order of decreasing risk.

The absolute risk as estimated for the fuel cycle portions considered in this report is 0.91 fatality/GWe-year for the PT cycle and 0.34 fatality/GWe-year for the reference cycle. This should be compared with Inhaber's estimate of 1.5 for nuclear and 150 for coal.[1] All of the risks assumed here are associated with the production of one billion watts of electricity (GWe) per year. The present results, which encompass only a portion of a fuel cycle, are slightly higher than Inhaber, possibly as a result of using different data in estimating the health effects of nonradiological pollutants.

1.0 RESULTS AND QUALIFICATIONS

1.1 General Remarks

This report is concerned with the calculation of short-term harm that could result from two alternate nuclear fuel cycles: a Reference cycle utilizing conventional methods for fuel recovery and recycling, and a partitioning-transmutation (PT) cycle that uses enhanced recovery techniques for fuel and the other actinides. Following recovery, the PT cycle transmutes these materials to lighter and more rapidly decaying elements, thus reducing waste toxicity. To perform these comparisons, it is necessary to define the bases on which the comparisons are made.

Harm, meaning the results or consequences of an undesired event, is not in itself a sufficient measure because the effects depend on how frequently the harm is inflicted; thus this report uses the actuarial term "risk."

Risk used in this sense is the average rate at which society is harmed. If the harm is measured as fatalities in the affected population (as it is in this report), then risk is the number of fatalities per year from the cause under consideration. For continuous effects, this is readily understood. However, to apply this risk concept to accidents requires the time-averaging of the effects of individual accidents. Mathematically, this is the product of an effect times its frequency of occurrence, and overall risk is the sum of these products.

It must be emphasized that using fatality as a common denominator of effects has several deficiencies. Radiation generally does not cause immediate death; instead it changes the probability that an affected individual will die prematurely from cancer. Thus a latent cancer that becomes an active cancer results in less lifetime shortening than had an immediate fatality occurred. Furthermore, death from latent cancer occurs in years less productive to society, and possibly less enjoyable to the individual, than prime years. Latent cancer formation is practically the only way (except in extreme doses) that radiation affects humans; however, nonradiological accidents may result in both immediate or latent fatality as well as immediate or latent injury; hence a comparison based on fatalities is, by its nature, asymmetric between the accident types. In spite of these inadequacies, fatality is as close to a universal measure as any in current practice.

1.2 Relative Risk of the Reference and PT Cycles

Fortunately, many of the analysis deficiencies are avoided if the relative risks of two similar activities such as the Reference and PT cycles are compared. The short-term risk analyses presented here conclude that the PT cycle presents 2.9 times more risk than the Reference cycle*, and nonradiological risks are 150 to 170 times larger than radiological risks.

If radiological risks alone are considered, the risk of PT is about three times that of the Reference cycle. These relative comparisons are depicted in Figure 1.1, where the bar height is proportional to the

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*This is placed in perspective in the next section.

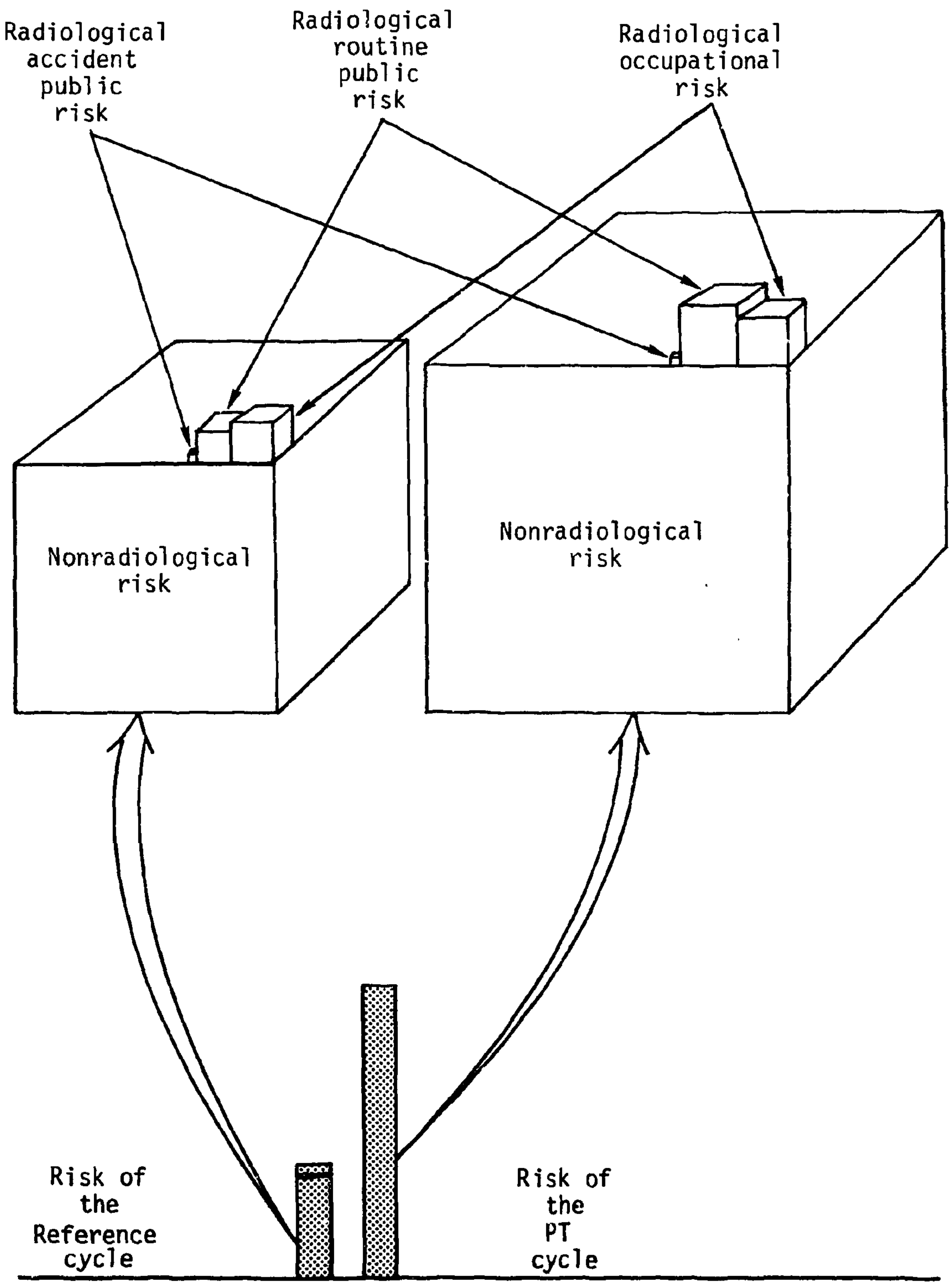

Figure 1.1. Depiction of the relative risks of the Reference and PT fuel cycles. (The volume of each cube is proportional to the designated risks; the height of each post is proportional to the overall risks.)

overall risk. Each of these bars is decomposed into nonradiological and radiological risk. The radiological risk is further decomposed into that from accidents affecting the public, normal plant emissions affecting the public, and occupational accidents and routine effects. The nonradiological risk results from routine emissions from fuel and diesel oil burning, chemical emissions, transportation, and industrial accidents.

1.3 Absolute Risk of the Reference and PT Cycles

The relative risks of two alternatives may be sufficient for comparing alternatives, but they give no insight into how much risk is presented by either alternative. Table 1.1 presents the risk associated with the portions of the two cycles considered to produce one billion watts of electricity in a year.* The risks presented do not include the whole cycle. For reference, Bethe[2] indicates that the total risk of nuclear power is about 1 fatality/GWe-year; however, the risk from a coal-burning plant with scrubbers far from a city is 7 fatalities/GWe-year, and the extreme case of a coal plant without scrubbers close to a city presents a risk of 74 fatalities/GWe-year. A major contribution to these fossil power risks comes from air pollution, which is also a major contributor to the risks analyzed here.

*The prefix "giga" is used to represent 10^9 which, in the U.S., is one billion. The methodology used plants and activities scaled to produce 75 GWe in LWR power plants running at full capacity. In fact, plants do not run at full capacity, but the fuel consumption is reduced accordingly.

Table 1.1. Summarized comparison of the fuel cycles (fatalities/GWe-year)

Risk types	Reference cycle	PT cycle	Ratio $\left(\frac{PT}{Reference}\right)$
Radiological occupational	1.2×10^{-3}	2×10^{-3}	1.7
Radiological routine - public	8×10^{-4}	4×10^{-3}	5
Radiological accident - public	5×10^{-7}	7×10^{-7}	1.4
Radiological subtotal	2×10^{-3}	6×10^{-3}	3
Nonradiological risk total	0.34	0.9	2.9

1.4 Facilities and Activities*

The major PT cycle operations are a fuel reprocessing plant (FRP) and associated waste treatment facility (FRP-WTF), fuel fabrication plant (FFP) and associated waste treatment facility (FFP-WTF), and the interconnecting transportation. The major Reference cycle operations are the same except for the omission of the two waste treatment facilities. Table 1.2 presents a breakdown of the risk by operation and by radiological or nonradiological risk. More detailed results are presented in Section 3.

The work presented here must be qualified as follows:

1. The fuel cycles analyzed are not complete fuel cycles. However, except for the power plants themselves, it is believed that the major accident risks of each cycle have been included. There are significant radiological risk contributors that have been excluded, specifically mining and milling; however, their contribution would be practically the same for both the Reference and PT fuel cycles.

2. Neither the Reference nor the PT cycle has ever been actually implemented; hence, experience cannot be directly used. The analysis must be synthesized using models of each cycle, with each model using pieces of information derived from related current experience.

*The Glossary defines unusual abbreviations.

Table 1.2. Summarized comparison of risks by operations (fatalities/GWe-year)

Operation	Radiological risk		Nonradiological risk	
	Reference cycle	PT cycle	Reference cycle	PT cycle
FRP	8×10^{-4}	1.9×10^{-3}	0.24	0.24
FRP-WTF	--	1.6×10^{-3}	--	0.4
FFP	6×10^{-4}	6×10^{-4}	1.1×10^{-2}	1.1×10^{-2}
FFP-WTF	--	8×10^{-4}	--	0.16
Transportation	8×10^{-5}	8.5×10^{-5}	9×10^{-2}	0.12

3. Each cycle is sampled as a snapshot in time at which each cycle is in fifth recycle. This is highly unrealistic because there would normally be admixtures of fuel from earlier recycles. Furthermore, the models are based on present projections, whereas, in fact, fifth-recycle plants would have experience derived from processing the earlier, less recycled and less radioactive fuel. This experience would modify the regulatory climate as well as design, construction, and operating techniques.

4. Detailed plans and operating procedures are lacking for the operations that were analyzed, and it was necessary to draw on similar facilities and procedures in current or past usage.

5. While the failure rates and accident rates used in this study are the best available, they were adapted from experience in past fuel cycle facilities and related activities and are not precisely for the equipment being modeled.

6. Because the methods used in this study are similar to those used by the Reactor Safety Study[3] and in recognition of the criticisms of this study that have been made, it is appropriate to quote the Lewis Committee Report:[4] "Despite its shortcomings, WASH-1400 provides the most complete single picture of accident probabilities associated with nuclear

reactors." The Lewis Committee went on to level several criticisms at WASH-1400 and, by inference, any study using similar methodology, such as this study. Some of their more significant criticisms and the responses by this study are as follows:

a. Peer Review - The acknowledgments to this report indicate the Peer Reviewers.

b. Data Base - In this report, the best available data are used with conservative error estimation to hopefully encompass the uncertainties and not mislead the reader as to the accuracy of the conclusions.

c. Executive Summary - The Abstract and Section 1.2 are intended as Executive Summaries which endeavor to concisely present the results of the effort without adopting any position of advocacy regarding either of the cycles.

d. Relative Risk - Both the Lewis Report[4] and the American Physical Society[5] endorsed WASH-1400 methods for relative risk comparisons but had reservations regarding these tools for absolute risk estimation. This study aims primarily at a relative comparison between two fuel cycles, and it is in this sense that the conclusions have the most validity, although results are expressed in absolute values.

e. Common Mode - The Lewis Report was highly critical of WASH-1400's use of the strong-weak coupling model for common modes, i.e., geometric mean of the independent and completely dependent failure rates. This study attempts to avoid this model by phenomenologically modeling the common modes.

7. This study consistently uses the Consequences of Reactor Accident Code (CRAC) to calculate population doses and health effects. CRAC was developed for WASH-1400 and has been thoroughly tested and reviewed. It was adapted to this work by the addition of isotopes present in the fuel cycles and by modification for the analysis of continuous releases.

8. There are cases, however, where CRAC has not been applied, such as in the estimation of routine occupational doses from past experience. For these cases the BEIR Report[6] results are approximated as 1×10^{-4} latent fatality/person-rem. It will be noted that this simple multiplier does not generally agree with the CRAC results.

9. This report models risk as the product of probability times consequences. There is no universal agreement on this definition of risk, nor is it one measure of

consequences of universal validity. One measure of consequence used here is latent cancer induction, which is taken to result in death in half the cases.[7] This is not directly comparable with chemically induced cancer because of differences in the latency period, nor is it comparable with an immediate fatality such as may result from an industrial or transportation accident in terms of life-shortening effects. Similarly, the consequences may be a disabling injury instead of death; however, Pochin[8] shows that, in terms of lost-time hours, death is the dominant effect. It therefore appears that fatality is about as close to a common denominator for routine and accident consequences for both radiological and nonradiological effects as can be found. It should also be noted that the same measure is applied to both fuel cycles so that the relative risk is generally correctly treated.

2.0 INTRODUCTION

2.1 Relationship of This Report to Other Reports in the Series

The Chemical Technology Division of Oak Ridge National Laboratory is evaluating the incentives for implementing a partitioning-transmutation nuclear fuel cycle. This program consists of two major phases. The first phase investigated the experimental, calculational, and conceptual studies concerning various specialized aspects of PT. This investigation involved experimental studies for reducing the actinide content of the wastes, calculational studies of the transmutation of the actinides, a study of the impact of PT on nuclear fuel cycle oper tions, and studies concerning the integration of partitioning into reprocessing and refabrication plant flowsheets.

The second phase involves evaluating the incentives for commercial implemention of PT. The principal tasks are:

1. Determine the total costs of implementing PT r the commercial nuclear fuel cycle.
2. Determine the short-term risks imposed by the additional handling of increased amounts of transuranic elements.
3. Determine the change in the long-term risks from a geologic radioactive waste repository with reduced actinide content.

This report and its supporting Appendices Report[9] present work performed in executing Task 2 - the short-term risk analysis. As such, this report is a condensation of Reference 9. It emphasizes the results but omits the detailed analysis used in obtaining these conclusions.

2.2 Description of the PT and Reference Cycles

2.2.1 Overview

The Reference nuclear power fuel cycle begins with the mining of the uranium. It continues through the steps of milling, conversion, enrichment, uranium fuel fabrication, consumption (in a nuclear power plant), reprocessing, mixed-oxide fuel fabrication, and waste disposal, with transportation interconnecting the geographically dispersed plants. A PT fuel cycle is similar in outline except that special actinide waste treatment facilities must be added to the fuel reprocessing and mixed-oxide fuel fabrication plants to greatly reduce the quantity of actinides reporting to the wastes. These actinides build up in the PT fuel cycle to a higher level than found in the Reference fuel cycle. Certain actinide isotopes are highly radioactive, some emit substantial amounts of decay heat, and others require substantial neutron shielding. The PT fuel poses additional requirements in the handling of fresh fuel at the power plant; compared with the Reference fuel, it could pose an increased risk in case of a nuclear power plant accident.

This study simplifies the cycle somewhat by not investigating the differences between the Reference and PT cycles that occur before and at the power plant. The work reported here does not address the differences in the waste repository risks or facility cost differences; these topics are addressed in companion reports.[10,11] It is believed, however, that the major public and occupation risk differences between the two cycles are encompassed in the reprocessing, fuel fabrication, and transportation steps considered here.* Figure 2.2.1 diagrams the steps in the Reference cycle, and Figure 2.2.2 shows the steps in the PT cycle that are being considered. The annual material mass or quantity for either of the two cycles to produce 75 gigawatt-year of electricity (GWe-year) is presented in reference 9. The comparison has been sized for this level of electricity production, but most comparisons presented here are based on the risk from the production of one gigawatt of electricity per year at the related site. The risks for arbitrary electric power levels may be found by linear scaling of these results.

2.2.2 Simplified Plant and Process Description

The previous section provides the framework of the interactions of the plants and transportation linkages of the two cycles. This section provides a very brief description of the plants and transportation with emphasis on safety-related aspects.

The discussion begins with the arrival of fuel at any one of the power plants. For the Reference cycle this will consist of 8.8 MT/charge of recycled fuel that is free of the higher actinides (e.g., curium). The reactor will also receive 17.9 MT/charge of slightly enriched uranium fuel. The PT cycle is the same except that the recycled fuel loaded into the reactor contains essentially all of the

*It will be noted that the omission of mining and milling removes a major routine radiological risk contributor from the risk total. This is justified on the basis that this risk is the same for both fuel cycles.

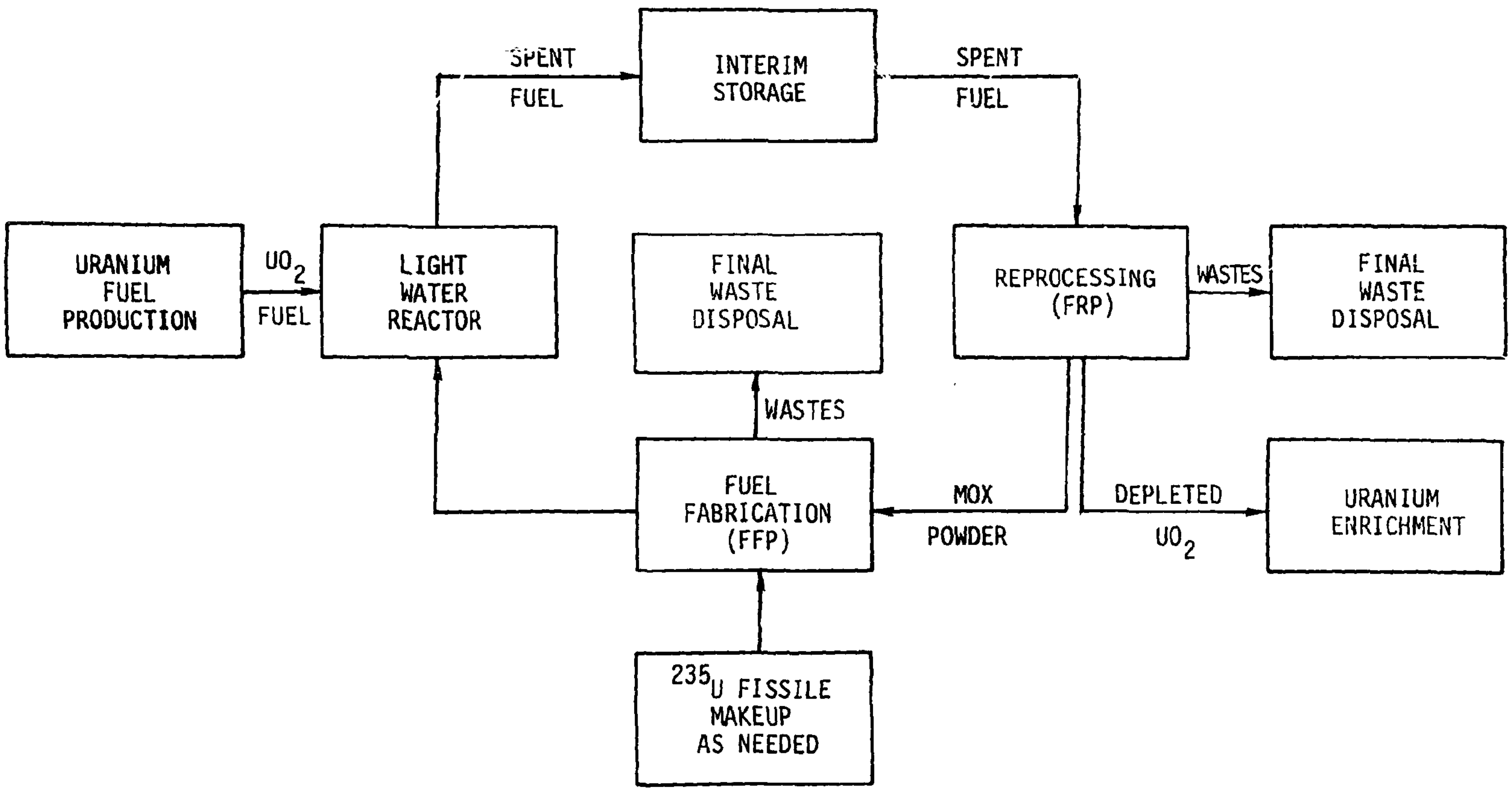

Figure 2.2.1. Reference fuel cycle (MOX recycle - LWR).

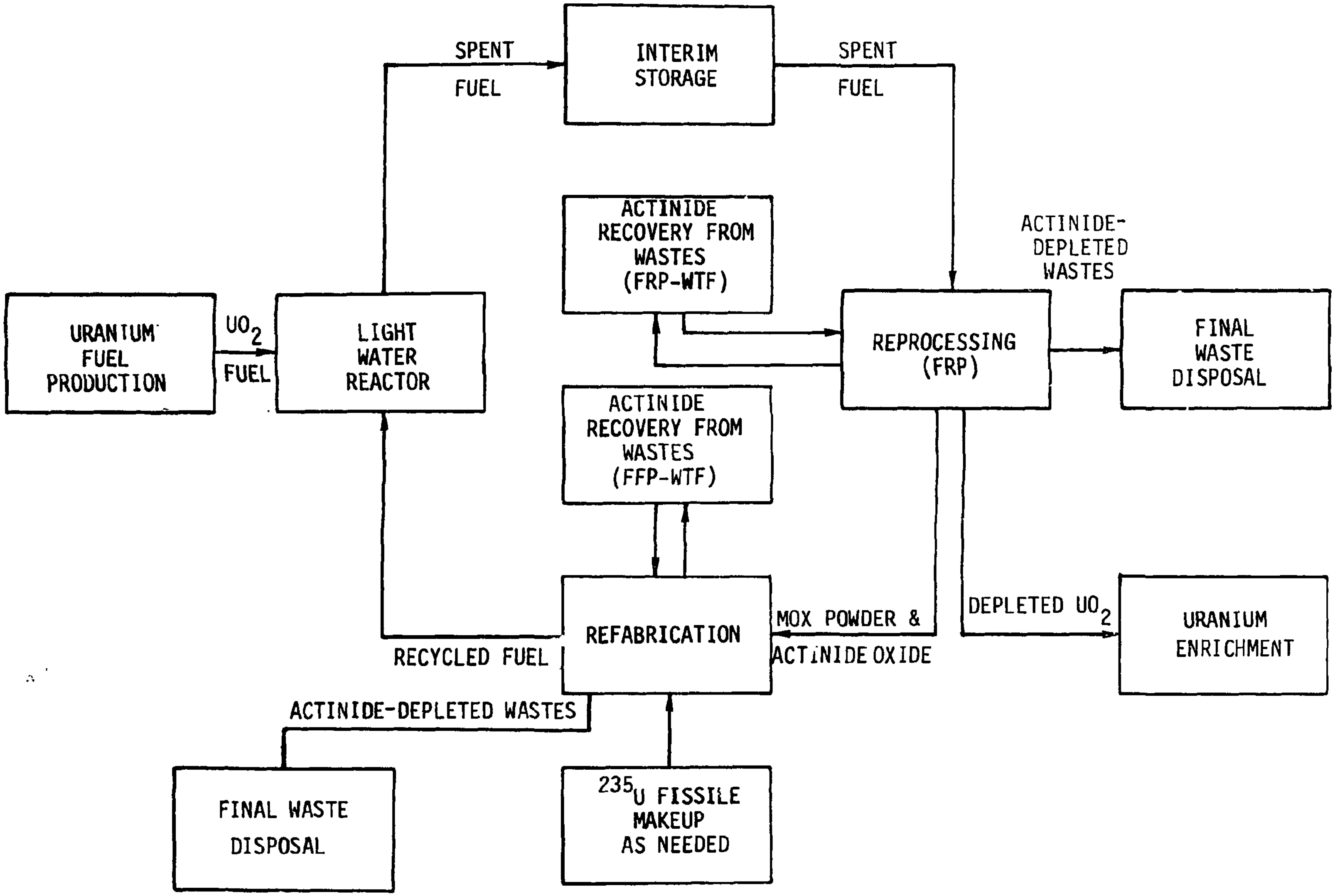

Fig. 2.2.2. Conceptual actinide partitioning and transmutation cycle.

actinides that were built up by neutron irradiation in previous irradiation cycles. After an assumed burning of 33,000 MWd/T, fuel is withdrawn. In the Reference cycle the fuel is discharged and shipped in conventional or slightly modified spent-fuel shipping containers. The discharged PT cycle fuel is separated according to that which was originally uranium fuel and that which was partitioned fuel. The original uranium fuel is shipped in a conventional spent-fuel shipping container, and the partitioned fuel is shipped in special ORNL-designed shipping casks. The ORNL-designed cask accomplishes neutron moderation using lithium hydride in combination with boron carbide for neutron absorption and inelastic scattering materials for high-energy degradation. In contrast, conventional casks use water as the moderator with neutron absorption recurring in the fuel, water, and structural materials. Gamma shielding is similarly accomplished using lead or uranium.

Because there are many descriptions of reprocessing and fuel fabrication plants available in the open literature, such will not be reported here. Descriptions of reprocessing are available in references 9, 12, and 13; coprocessing is discussed in reference 14 as well as in other periodical articles. A good discussion of the fabrication of MOX fuel is contained in reference 15, and a general overall discussion of PT flow sheets is contained in reference 16.

The PT cycle includes two plants in addition to the reprocessing and fuel fabrication plants, namely the companion waste treatment facilities (WTFs). The WTFs are similar, but the FRP-WTF is larger and more inclusive. Because the actinides reside in several waste forms, various methods must be applied to extract each of them. This results in a plant that is larger and more complex than a reprocessing plant. An overview of the processes follows.

The major waste streams from the FRP are (1) high-level liquid waste (e.g., the HAW); (2) salt waste, primarily from solvent recovery; (3) HEPA filters, which must be disassembled and low-temperature ashed; (4) incinerator wastes; and (5) cladding hulls, dissolver solids, and fuel assembly hardware.

The acidic high-level liquid waste is treated with CMP (bidentate) solvent extraction to remove the lanthanides and the actinides. The lanthanides are then separated from the actinides using cation exchange chromatography. The actinides are then sent to the FRP to be combined with the uranium, plutonium, and neptunium and later fabricated into new fuel elements. The actinide-depleted wastes are sent to the parent plant (FRP or FFP) for immobilization and offsite shipment.

Salt wastes arising from solvent recovery are treated with nitric acid and contacted with 2-ethylhexanol (2EHOH) to remove the solvent degradation products. The resulting aqueous raffinate is stripped of acidic organics and routed for TBP extraction of the actinides.

Incinerator wastes and ashed HEPA filters are subjected to boiling nitric and in situ-produced ceric acid leaching with gadolinium for nuclear reactivity control. The cerium leachate goes to TBP extraction for actinide removal.

The cladding hulls, dissolver solids, and fuel assembly hardware are subjected to a HNO_3 acid leach from which the actinides are removed by extraction with TBP.

The wastes from either cycle that must be transported to the Federal waste repository are the glassified high-level waste, the cladding hulls and fuel element hardware, and TRU-contaminated concrete wastes. These are transported, respectively, in a modified Reference spent-fuel cask, in a special ORNL-designed high-volume cask without neutron shielding, and in drums in an overpack, such as a "Super-Tiger." Non-TRU-contaminated wastes are sent to a licensed burial ground.

This completes the overview of the two cycles; further details may be found in Reference 9.

2.3 Methods Used in This Analysis

The general methods used in risk analysis are (1) system definition, (2) identification of risk-causing initiators, (3) probability of initiators and system degradation, and (4) consequences of initiators and system degradation. This outline is described in general terms to encompass routine and accident risks; however, the level of effort is generally much greater for accident risk analysis. For routine risk analysis, the probability is assumed to have a value of one and the consequences are estimated using laboratory or experimental data for the release fraction and the effectiveness of mitigation systems. The impacts on the public are assessed using diffusion models to estimate the amount of material reaching the public and experimental or epidemiological data to estimate the effect of hazardous material on people.

Accident risk analyses address observed and hypothetical events. The frequency of observed events can be approximated from experience; however, the frequency of hypothetical events must be estimated from the frequency of various occurrences which, if they occur in a certain pattern, can result in the hypothetical accident. The logic that specifies the pattern of events composing an accident is contained in a diagrammatic Boolean-logic device called a fault tree. Reference 9 contains the many fault trees that were used in modeling the accidents considered here.

The stages involved in an accident analysis, diagrammed in Figure 2.3.1, are essentially an amplification of the preceding remarks. Using the block identifying numbers in the figure, the analysis begins with the preparation of a Preliminary Hazards Analysis that draws on a data base of experience and physical knowledge (1A) to prepare a table of initiating events (1) and correlates these with failures of plant protection and confinement barriers. The set of circumstances that makes an accident possible are called event sequences (2), which draw on a knowledge of the plant and processes (2A). At this point, the flow bifurcates into calculations of the amounts of hazardous material (3) that could be released based on a data base (3A) and the probability (4) that the accident described by the event sequence occurs based on its supporting data base (4A). It is step 4, the probability

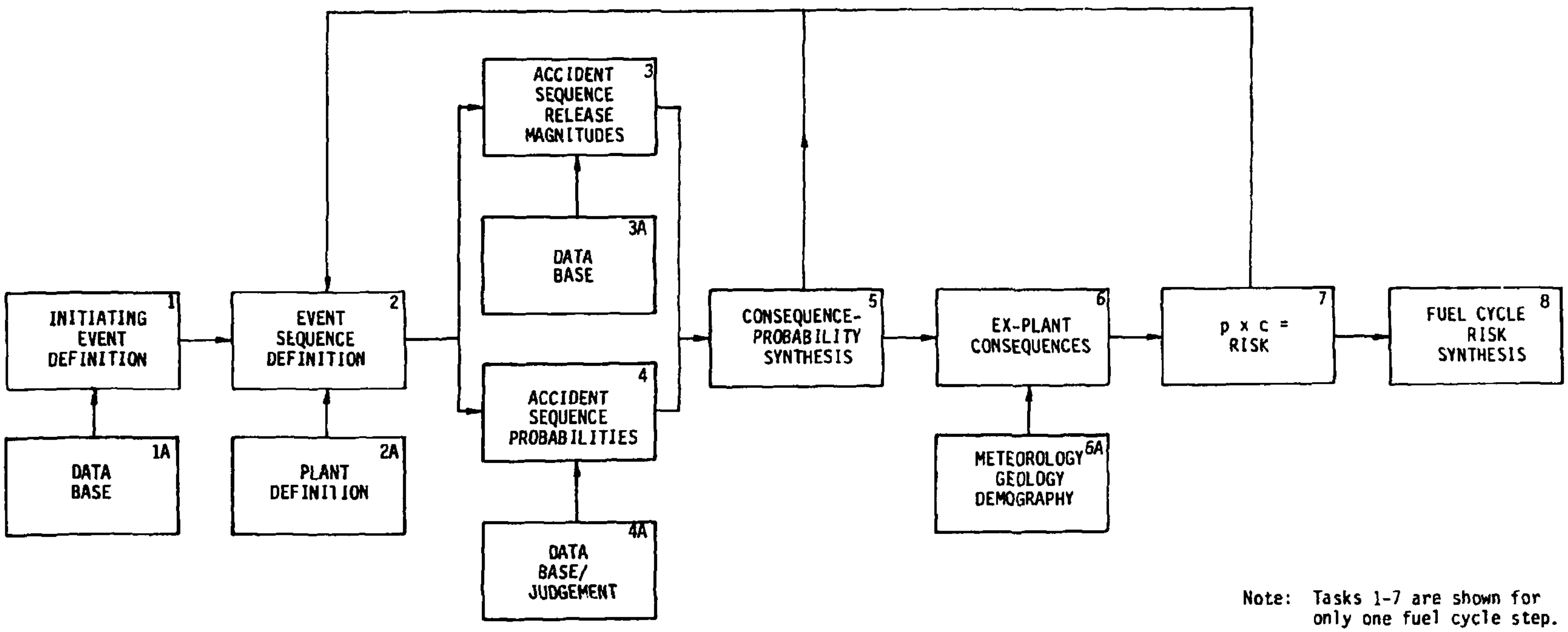

Fig. 2.3.1. Steps in constructing a probabilistic risk analysis.

estimation, that uses fault-tree analysis. The accident probabilities and consequences are brought together (5) for an iteration to examine possible interactions and common-mode effects. When this iteration settles down, the consequences outside of the plant (6) are calculated using site-dependent meteorology and demography data (6H). The probability-consequence number pairs are combined as a risk measure (7) to provide an overall measure of the fuel cycle risk (8).

The calculation of the accident consequences is performed with a modified version of the Consequences of Reactor Accident Code (CRAC), which was developed for the Reactor Safety Study but was modified extensively to perform fuel cycle accident and routine release calculations. CRAC uses a complex algorithm to predict health effects, depending on the chemical nature of the radioactive material and the organs that are primarily affected. CRAC was also modified to calculate the radiological effects of routine gaseous plant effluents. For those cases where CRAC could not be used, such as occupational risk, the conversion from dose to health effects (eventual cancer fatalities) used $1x10^4$ rem/cancer fatality, taken from data quoted in the BEIR report.[6] It should also be noted that the CRAC results predict latent cancers. However, during the latency period, an affected individual may die from other causes. To correct for this effect, a factor of 2 is used.[7]

3.0 RISKS FROM PLANTS AND FACILITIES

3.1 Radiological Accidents Affecting the Public

The general techniques that were applied to this investigation were outlined in the preceding section. The plant and process descriptions were thoroughly reviewed, as well as past history associated with similar processes. The results of this review were incorporated into Preliminary Hazard Analyses from which certain accidents were selected as risk dominators; other accidents, had they been included, would made an insignificant contribution to the numerical assessmen risk. The accidents that were selected as dominant risk contributors were analyzed using fault trees to determine the accident probabilities. The consequences of the accidents were determined using data on material mobility and release fraction. Credit was also applied if the material passed through the off-gas system and for the amount of material removed by the filtration system. Each accident was calculated separately on the condition of zero, one, or two failed HEPA filters. Appropriate filtration factors were used for each case, and the accident probability was adjusted for the probability of the accident occurring in combination with filter failure. Tables 3.1.1 and 3.1.2 summarize the radiological accidents for the two plants considered in the Reference cycle, and Tables 3.1.3 through 3.1.6 do the same for the four plants considered in the PT cycle. Each accident contains separate entries for the HEPA filter status in the order stated above. It will be noted that the risks are given on a per-plant-year basis. Since the plants are sized

Table 3.1.1. Probabilities, consequences, and risk for the Reference cycle FRP radiological accidents (Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
H_2 fire and explosion in HAF tank	-- 3×10^{-6} 8×10^{-11}	-- 3×10^{-4} 4	-- 9×10^{-4} 1.2×10^{1}	-- 1.1×10^{-6} 1.5×10^{-2}	-- 3×10^{-9} 1×10^{-9}	-- 3×10^{-12} 1.2×10^{-12}
Solvent fire in HA contractor	-- 2×10^{-6} 5×10^{-11}	-- 9×10^{-4} 15	-- 7×10^{-4} 1.1×10^{1}	-- 9×10^{-6} 1.5×10^{-1}	-- 1.4×10^{-9} 6×10^{-10}	-- 1.8×10^{-11} 7×10^{-12}
Red oil explosion in HLW concentrator	-- 4×10^{-8} 1×10^{-12}	-- 2×10^{-3} 30	-- 8×10^{-3} 1.1×10^{2}	-- 2×10^{-6} 3×10^{-2}	-- 4×10^{-10} 1.1×10^{-10}	-- 8×10^{-14} 3×10^{-14}
Explosion in HLW calciner	-- 2×10^{-7} 5×10^{-12}	-- 8×10^{-2} 1400	-- 2×10^{-1} 4×10^{3}	-- 8×10^{-5} 1.4	-- 5×10^{-8} 2×10^{-8}	-- 1.6×10^{-11} 7×10^{-12}
Red oil explosion in fuel product concentrator	-- 4×10^{-8} 1×10^{-12}	-- 9×10^{-4} 15	-- 6×10^{-4} 1.1×10^{1}	-- 9×10^{-6} 1.5×10^{-1}	-- 3×10^{-11} 1.1×10^{-11}	-- 4×10^{-13} 1.5×10^{-13}
Explosion in fuel product denitrator	-- 4×10^{-9} 1×10^{-13}	-- 1.7×10^{-2} 300	-- 1.2×10^{-2} 2×10^{2}	-- 1.7×10^{-4} 3	-- 5×10^{-11} 2×10^{-11}	-- 7×10^{-13} 3×10^{-13}
Criticality in process cell	2×10^{-5} -- --	9×10^{4} -- --	2 -- --	2×10^{-4} -- --	4×10^{-5} -- --	4×10^{-9} -- --
Failure of krypton cylinder	1.3×10^{-4} -- --	1×10^{6} -- --	4×10^{1} -- --	6×10^{-3} -- --	5×10^{-3} -- --	7×10^{-7} -- --
Hydrogen explosion in reductor	-- 9×10^{-6} 2×10^{-10}	-- 1.7×10^{-2} 300	-- 1.2×10^{-2} 2×10^{2}	-- 1.7×10^{-4} 3	-- 1.1×10^{-7} 4×10^{-8}	-- 1.5×10^{-9} 6×10^{-10}
Fuel assembly drop	1.2×10^{-3} -- --	1300 -- --	5×10^{-2} -- --	7×10^{-6} -- --	6×10^{-5} -- --	9×10^{-9} -- --
Hydrogen explosion in fuel product denitrator feed	-- 3×10^{-6} 8×10^{-11}	-- 1.7×10^{-2} 300	-- 1.2×10^{-2} 2×10^{2}	-- 1.7×10^{-4} 3	-- 4×10^{-8} 1.6×10^{-8}	-- 5×10^{-10} 2×10^{-10}
Total risk					5×10^{-3}	7×10^{-7}

Table 3.1.2. Probabilities, consequences, and risk for the Reference-cycle FFP radiological accidents
(Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
Air crash	1.5×10^{-9} -- --	1×10^{3} -- --	5×10^{2} -- --	8 -- --	8×10^{-7} -- --	1.1×10^{-8} -- --
H_2 explosion in ROR	5×10^{-3} 5×10^{-5} 1.5×10^{-9}	2×10^{-11} 1×10^{-7} 0.01	1.1×10^{-11} 5×10^{-8} 5×10^{-3}	1.6×10^{-13} 8×10^{-10} 8×10^{-5}	5×10^{-14} 3×10^{-12} 8×10^{-12}	8×10^{-16} 4×10^{-14} 1.2×10^{-13}
H_2 explosion in sintering	5×10^{-3} 5×10^{-5} 1.5×10^{-9}	7×10^{-10} 4×10^{-6} 0.4	4×10^{-10} 2×10^{-6} 0.2	5×10^{-12} 3×10^{-8} 3×10^{-3}	1.9×10^{-12} 1×10^{-10} 3×10^{-10}	3×10^{-14} 1.5×10^{-12} 5×10^{-12}
H_2 explosion in wet scrap	3×10^{-4} 3×10^{-6} 9×10^{-11}	2×10^{-11} 6×10^{-8} 6×10^{-4}	1.1×10^{-11} 3×10^{-8} 3×10^{-4}	1.6×10^{-13} 5×10^{-10} 5×10^{-6}	3×10^{-15} 9×10^{-14} 3×10^{-14}	5×10^{-17} 1.5×10^{-15} 5×10^{-16}
Criticality in wet scrap	6×10^{-5} -- --	9×10^{4} -- --	2 -- --	2×10^{-4} -- --	3×10^{-5} -- --	4×10^{-9} -- --
Powder shipping container spill	3×10^{-5} 3×10^{-7} 9×10^{-12}	2×10^{-11} 1×10^{-7} 0.01	1.1×10^{-11} 5×10^{-8} 5×10^{-3}	1.6×10^{-13} 8×10^{-10} 8×10^{-5}	3×10^{-6} 1.5×10^{-14} 5×10^{-14}	5×10^{-18} 2×10^{-16} 7×10^{-16}
Exothermic reaction in powder storage	1.5×10^{-6} 1.5×10^{-8} 5×10^{-13}	1×10^{-10} 5×10^{-7} 0.06	5×10^{-11} 3×10^{-7} 3×10^{-2}	8×10^{-13} 4×10^{-9} 5×10^{-4}	8×10^{-17} 5×10^{-15} 1.4×10^{-14}	1.2×10^{-18} 6×10^{-17} 2×10^{-16}
Total risk					3x10^- [illegible]	1.5×10^{-8}

Table 3.1.3. Probabilities, consequences, and risk for the PT-cycle FRP radiological accidents (Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
H_2 fire and explosion in HAF tank	-- $3x10^{-6}$ $8x10^{-11}$	-- $3x10^{-4}$ 5	-- $8x10^{-4}$ $1.4x10^{1}$	-- $1.2x10^{-6}$ $1.9x10^{-2}$	-- $3x10^{-9}$ $1.1x10^{-9}$	-- $4x10^{-12}$ $1.5x10^{-12}$
Solvent fire in HA contractor	-- $2x10^{-6}$ $5x10^{-11}$	-- $1x10^{-3}$ 16	-- $7x10^{-4}$ $1.2x10^{1}$	-- $9x10^{-6}$ $1.5x10^{-1}$	-- $1.5x10^{-9}$ $6x10^{-10}$	-- $1.9x10^{-11}$ $3x10^{-12}$
Red oil explosion in HLW concentrator	-- $4x10^{-8}$ $1x10^{-12}$	-- $2x10^{-3}$ 40	-- $7x10^{-3}$ $1.4x10^{2}$	-- $3x10^{-6}$ $6x10^{-2}$	-- $3x10^{-10}$ $1.4x10^{-10}$	-- $1.2x10^{-13}$ $6x10^{-14}$
Explosion in HLW calciner	-- $2x10^{-7}$ $5x10^{-12}$	-- $8x10^{-2}$ 1400	-- $3x10^{-1}$ $4x10^{3}$	-- $6x10^{-5}$ 11	-- $5x10^{-8}$ $2x10^{-8}$	-- $1.2x10^{-11}$ $6x10^{-12}$
Red oil explosion in fuel product concentrator	-- $4x10^{-8}$ $1x10^{-12}$	-- $1x10^{-3}$ 18	-- $5x10^{-4}$ 9	-- $7x10^{-6}$ $1.2x10^{-1}$	-- $2x10^{-11}$ $9x10^{-12}$	-- $3x10^{-13}$ $1.2x10^{-13}$
Explosion in fuel product denitrator	-- $4x10^{-9}$ $1x10^{-13}$	-- $2x10^{-2}$ 300	-- $3x10^{-1}$ $5x10^{2}$	-- $4x10^{-4}$ 7	-- $1.2x10^{-10}$ $5x10^{-11}$	-- $1.7x10^{-13}$ $7x10^{-13}$
Criticality in process cell	$2x10^{-5}$ -- --	$9x10^{4}$ -- --	2 -- --	$2x10^{-4}$ -- --	$4x10^{-5}$ -- --	$4x10^{-9}$ -- --
Failure of krypton cylinder	$1.3x10^{-4}$ -- --	$1x10^{6}$ -- --	40 -- --	$6x10^{-3}$ -- --	$5x10^{-3}$ -- --	$7x10^{-7}$ -- --
Hydrogen explosion in reductor	-- $9x10^{-6}$ $2x10^{-10}$	-- $1.5x10^{-2}$ 300	-- $1x10^{-2}$ $2x10^{2}$	-- $1.4x10^{-4}$ 3	-- $9x10^{-8}$ $4x10^{-8}$	-- $1.3x10^{-9}$ $6x10^{-10}$
Fuel assembly drop	$1.2x10^{-3}$ -- --	1300 -- --	$5x10^{-2}$ -- --	$7x10^{-6}$ -- --	$6x10^{-5}$ -- --	$9x10^{-9}$ -- --
Hydrogen explosion in fuel product denitrator feed	-- $3x10^{-6}$ $8x10^{-11}$	-- $1.5x10^{-2}$ 300	-- $1x10^{-2}$ $2x10^{2}$	-- $1.4x10^{-4}$ 3	-- $3x10^{-8}$ $1.6x10^{-8}$	-- $4x10^{-10}$ $2x10^{-10}$
Total risk					$5x10^{-3}$	$7x10^{-7}$

Table 3.1.4. Probabilities, consequences, and risk for the PT cycle FRP-WTF radiological accidents
(Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
Criticality in process cell	3×10^{-5} -- --	9×10^{4} -- --	2 -- --	2×10^{-4} -- --	6×10^{-5} -- --	8×10^{-9} -- --
Hydrogen explosion in actinide bearing vessel	a. 3×10^{-6} 9×10^{-11} b. 3×10^{-6} 9×10^{-11}	1×10^{-4} 2 3×10^{-4} 6	4×10^{-4} 6 9×10^{-5} 1.5	3×10^{-7} 5×10^{-2} 2×10^{-6} 3×10^{-2}	1×10^{-9} 5×10^{-10} 3×10^{-10} 1×10^{-10}	9×10^{-12} 5×10^{-12} 6×10^{-12} 2×10^{-12}
Hydrogen explosion in vessel vent system	8×10^{-4} 8×10^{-6} 2×10^{-10}	8×10^{-8} 8×10^{-4} 13	2×10^{-8} 2×10^{-4} 29	4×10^{-10} 4×10^{-6} 6×10^{-2}	2×10^{-11} 2×10^{-9} 6×10^{-10}	3×10^{-13} 3×10^{-11} 1×10^{-11}
Nitrated organic explosion in Am product concentrator	2×10^{-3} 2×10^{-5} 2×10^{-10}	2×10^{-8} 2×10^{-4} 3	5×10^{-9} 5×10^{-5} 0.9	1×10^{-10} 1×10^{-6} 1.6×10^{-2}	1×10^{-11} 1×10^{-9} 5×10^{-10}	2×10^{-13} 2×10^{-11} 1×10^{-11}
Red oil explosion in process concentrator	2×10^{-4} 2×10^{-6} 6×10^{-11}	3×10^{-8} 3×10^{-4} 4	9×10^{-9} 9×10^{-5} 1	1.8×10^{-10} 1.8×10^{-6} 2×10^{-2}	1.8×10^{-12} 1.8×10^{-10} 6×10^{-11}	3×10^{-14} 3×10^{-12} 1×10^{-12}
Resin explosion in CEC unit	4×10^{-4} 4×10^{-6} 1×10^{-10}	3×10^{-6} 3×10^{-2} 6×10^{2}	6×10^{-7} 6×10^{-3} 1×10^{2}	2×10^{-8} 2×10^{-4} 3	2×10^{-10} 2×10^{-9} 1×10^{-8}	8×10^{-12} 8×10^{-11} 3×10^{-10}
Facility solvent fire	2×10^{-4} 2×10^{-6} 6×10^{-11}	2×10^{-6} 2×10^{-2} 2×10^{2}	1.6×10^{-6} 1.6×10^{-2} 3×10^{2}	3×10^{-8} 2.5×10^{-4} 8	3×10^{-10} 3×10^{-8} 1.8×10^{-8}	6×10^{-12} 5×10^{-10} 5×10^{-10}
Solvent mist explosion	7×10^{-4} 7×10^{-6} 2×10^{-10}	8×10^{-8} 5×10^{-4} 9	9×10^{-8} 6×10^{-4} 11	1.4×10^{-9} 1×10^{-5} 0.2	6×10^{-12} 4×10^{-8} 2×10^{-9}	1×10^{-12} 1×10^{-11} 3×10^{-11}
Total risk					6×10^{-5}	8×10^{-9}

Table 3.1.5. Probabilities, consequences, and risk for the PT-cycle FFP radiological accidents (Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
Air crash	1.5×10^{-9} -- --	1.4×10^{3} -- --	1.1×10^{3} -- --	2×10^{1} -- --	1.6×10^{-6} -- --	3×10^{-8} -- --
H_2 explosion in ROR	5×10^{-3} 5×10^{-5} 1.5×10^{-9}	3×10^{-11} 2×10^{-7} 8×10^{-2}	3×10^{-11} 1.8×10^{-7} 1.8×10^{-2}	5×10^{-13} 4×10^{-9} 4×10^{-4}	1.4×10^{-13} 9×10^{-12} 3×10^{-11}	3×10^{-15} 2×10^{-13} 6×10^{-13}
H_2 explosion in sintering	5×10^{-3} 5×10^{-5} 1.5×10^{-9}	1×10^{-9} 5×10^{-6} 0.6	9×10^{-10} 4×10^{-6} 5.5×10^{-1}	1.8×10^{-4} 9×10^{-8} 1.1×10^{-2}	5×10^{-12} 2×10^{-10} 8×10^{-8}	9×10^{-14} 8×10^{-12} 1.7×10^{-8}
H_2 explosion in wet scrap	3×10^{-4} 3×10^{-6} 9×10^{-11}	3×10^{-11} 8×10^{-8} 8×10^{-4}	3×10^{-11} 7×10^{-8} 7×10^{-4}	5×10^{-13} 1.4×10^{-9} 1.4×10^{-5}	8×10^{-15} 2×10^{-13} 7×10^{-14}	1.6×10^{-15} 4×10^{-15} 1.5×10^{-15}
Criticality in wet scrap	6×10^{-5} 6×10^{-7} --	9×10^{4} 9×10^{4} --	5×10^{-1} 2 --	6×10^{-5} 2×10^{-4} --	3×10^{-5} 1.2×10^{-6} --	4×10^{-9} 1.2×10^{-10} --
Powder shipping container spill	3×10^{-5} 3×10^{-7} 9×10^{-12}	3×10^{-11} 1×10^{-7} 2×10^{-2}	3×10^{-11} 9×10^{-8} 1.8×10^{-2}	5×10^{-13} 1.8×10^{-9} 4×10^{-4}	8×10^{-16} 3×10^{-14} 1.6×10^{-13}	1.6×10^{-17} 5×10^{-16} 4×10^{-15}
Exothermic reaction in powder storage	3×10^{-5} 1.5×10^{-8} 4.5×10^{-13}	1×10^{-11} 7×10^{-7} 8×10^{-2}	9×10^{-12} 6×10^{-7} 7×10^{-2}	1.8×10^{-13} 1.3×10^{-8} 1.4×10^{-3}	3×10^{-16} 9×10^{-15} 3×10^{-14}	5×10^{-18} 2×10^{-16} 9×10^{-16}
Total risk					3×10^{-5}	5×10^{-8}

Table 3.1.6. Probabilities, consequences, and risk for the PT-cycle FFP-WTF radiological accidents
(Each accident is analyzed for zero, one, and two failed HEPA filters, in that order)

			Consequences		Risk (p x c)	
Description	Probability (/plant-yr)	Curie release to atmosphere	Total person-rem	Total latent cancer	Total person-rem / plant-yr	Total latent cancer / plant-yr
Criticality in process cell	3×10^{-5} -- --	9×10^{4} -- --	2 -- --	2×10^{-4} -- --	6×10^{-5} -- --	6×10^{-9} -- --
Hydrogen explosion in actinide-bearing vessel	3×10^{-4} 3×10^{-6} 9×10^{-11}	1×10^{-7} 1×10^{-4} 20	3×10^{-8} 3×10^{-5} 5	6×10^{-10} 6×10^{-7} 0.1	9×10^{-12} 9×10^{-11} 5×10^{-10}	1.8×10^{-13} 2×10^{-12} 9×10^{-11}
Hydrogen explosion in vessel vent system	8×10^{-4} 8×10^{-6} 2×10^{-10}	8×10^{-8} 8×10^{-5} 13	2×10^{-8} 2×10^{-5} 3	4×10^{-10} 4×10^{-7} 6×10^{-2}	1.6×10^{-11} 1.6×10^{-10} 6×10^{-10}	3×10^{-13} 3×10^{-12} 1.2×10^{-12}
Nitrated organic explosion in Am product concentrator	2×10^{-3} 2×10^{-5} 6×10^{-10}	1×10^{-7} 1×10^{-4} 20	3×10^{-8} 3×10^{-5} 5	6×10^{-10} 6×10^{-7} 0.1	6×10^{-11} 6×10^{-10} 3×10^{-9}	1.2×10^{-12} 1.2×10^{-11} 6×10^{-11}
Red oil explosion in process concentrator	2×10^{-4} 2×10^{-6} 6×10^{-11}	4×10^{-5} 4×10^{-5} 6	8×10^{-9} 8×10^{-6} 1.4	2×10^{-10} 2×10^{-7} 3×10^{-2}	1.6×10^{-12} 1.6×10^{-11} 8×10^{-11}	4×10^{-14} 4×10^{-13} 1.8×10^{-13}
Resin explosion in CEC unit	4×10^{-5} 3×10^{-7} 9×10^{-12}	8×10^{-6} 8×10^{-3} 1300	2×10^{-6} 2×10^{-3} 3×10^{2}	4×10^{-8} 2×10^{-5} 8	6×10^{-11} 6×10^{-10} 3×10^{-8}	1.2×10^{-12} 6×10^{-12} 5×10^{-11}
Facility solvent fire	2×10^{-4} 2×10^{-6} 6×10^{-11}	3×10^{-7} 3×10^{-3} 5×10^{2}	3×10^{-7} 2×10^{-3} 4×10^{2}	5×10^{-9} 5×10^{-5} 8	6×10^{-11} 4×10^{-9} 2×10^{-8}	1×10^{-12} 1×10^{-10} 5×10^{-10}
Solvent mist explosion	7×10^{-4} 7×10^{-6} 2×10^{-10}	1.5×10^{-8} 1.5×10^{-4} 35	1.6×10^{-8} 1.1×10^{-4} 30	3×10^{-10} 3×10^{-6} 0.4	1.1×10^{-11} 1.1×10^{-9} 6×10^{-8}	2×10^{-13} 2×10^{-11} 8×10^{-11}
Total risk					6×10^{-5}	6×10^{-9}

to support a 75-GWe nuclear electric power industry, the conversion to risk per GWe-year is done by dividing the plant-year risk by 75.

The tables show that the FFP, being primarily a dry fabrication facility, has associated with it distinctly different types of accidents (except for wet scrap recovery) than those associated with the FRP, FRP-WTF and FFP-WTF, which are chemical process plants. In these plants there are certain types of accidents whose release is unaffected by the HEPA filters; generally these are the high-risk accidents. In the FRP these are krypton storage cylinder failure, criticality, and fuel assembly drop. The results of these accidents may be modified in future plant designs by the "button-up" concept of confining everything, including gases to be cleaned up by the recovery system. This concept would result in trading public risk reduction for increased occupational risk. The other accidents could have severe effects except that they release particulates which are nearly completely caught by the filtration.

The analysis summarized in these tables does not credit any accident with forces capable of disrupting the filtration system (e.g., from explosive shock waves). Such accidents have been very carefully considered and are designed against by the use of filter separation, ducting lengths, and bends in the ducting to disperse shock waves and to provide barriers to missiles in the ducts. Hence the design is credited with achieving these objectives.

Besides the plants and processes, another major activity in a fuel cycle involves the transportation links for fresh fuel movement to the power plants, spent fuel movement from the power plants to reprocessing, powder movement between the FRP and the FFP, and waste movement from the FRP-FFP complex to the repository and disposal area. Transportation accidents were analyzed similarly to the plant accidents except for the following simplification.

Because of the many failed states that can be associated with each accident type, a system of categorization of accident severity was adopted that ranged from one to four. Each of these categories was associated with failure of barriers that prevent the dispersal of radioactivity to the public. Fault trees were constructed for each of the categories, and the fractional release of the various chemical species contained in the fuel or waste was calculated from the literature. These release quantities served as input source terms to the CRAC code, which was used similarly to its usage for the FRP-FFP complex of plants, except that the meteorology and demography were averaged over the transportation routes. After the risks associated with each accident category were calculated, they were summed to provide the risk of that transportation step.

Table 3.1.7 summarizes the risks associated with the six transportation steps considered for the two fuel cycles. It will be noted that the radiological public accident risks are the same for the two cycles because the transport of non-HLW (TRU-contaminated) wastes dominate and the quantities of this material, the modes of packaging, and the distances traveled for these wastes are the same for the two cycles. The reason that non-HLW dominates the accident risk is the assumed use of 55-gallon steel drums contained within an overpack. This type of packaging is not as accident resistant as casks. Another reason

Table 3.1.7. Summary of radiological public accident risks of transportation considered in the two fuel cycles

	Reference cycle		PT cycle	
Transportation step	p-rem/GWe	Latent cancer/ GWe-year	p-rem/GWe	Latent cancer/ GWe-year
Spent fuel	$3x10^{-5}$	$1x10^{-8}$	$4x10^{-5}$	$6x10^{-9}$
Powder	$3x10^{-12}$	$4x10^{-14}$	$4x10^{-12}$	$5x10^{-14}$
Fresh fuel	$8x10^{-7}$	$1.1x10^{-8}$	$4x10^{-7}$	$5x10^{-9}$
Cladding hulls	$1.6x10^{-4}$	$1.7x10^{-8}$	$1.7x10^{-4}$	$1.8x10^{-8}$
HLW	$1x10^{-5}$	$4x10^{-8}$	$8x10^{-6}$	$6x10^{-9}$
Non-HLW	$1.3x10^{-3}$	$9x10^{-7}$	$1.3x10^{-3}$	$1.3x10^{-6}$
Totals	$1.5x10^{-3}$	$1x10^{-6}$	$1.5x10^{-3}$	$1.3x10^{-6}$

for the higher risk of thi[illegible]s the health effects of the actinides, which also result in clad[illegible]ng hull accidents contributing the next highest risk. Regarding the r[illegible]ive cycle effects, it should be noted that the reduction of the actinides in the wastes going to the repository results in a slight reduction of PT HLW risks over that of the Reference HLW. Other effects between the two cycles are not so directly compared because of cask and transportation mix differences.

3.2 Radiological Accidents Affecting the Workers

The accidents treated in Section 3.1, besides affecting the public, can also affect the plant workers. In general, individual worker exposures will exceed public exposure because of the closeness to the accident. Accident probabilities were calculated by fault-tree analysis, and the results were presented in the previous section. The accident consequences could not be calculated using the CRAC code but were estimated from plant experience from similar types of accidents. These results are presented in Tables 3.2.1 through 3.2.4 for the four types of plants. Isotopic differences between the two cycles result in small differences in exposure, so that there is negligible distinction between the Reference and the PT cycles, except that the Reference cycle does not contain the two WTFs. In these calculations, the BEIR report[6] estimate of 10^{-4} fatality/man-rem exposure is used to estimate the plant health effects.

Table 3.2.1. Probabilities, consequences, and risks of the FRP radiological accidents affecting the workers

Description	Probability (/plant-yr)	Consequences: Accident person-rem	Consequences: Repair and recovery person-rem	Risk: Person-rem/plant-yr	Risk: Fatality/plant-yr
Dropped fuel assembly	1.2×10^{-3}	<3	--	4×10^{-3}	4×10^{-7}
Hydrogen fire and explosion in the HAF tank	3×10^{-4}	≤ 11	≤ 0.1	3×10^{-3}	3×10^{-7}
Solvent fire in the HA contactor	2×10^{-4}	≤ 11	--	2×10^{-3}	2×10^{-7}
Red oil explosion in HLW concentrator	4×10^{-6}	≤ 11	≤ 0.1	4×10^{-5}	4×10^{-9}
Explosion in the HLW calciner	2×10^{-5}	≤ 3	≤ 0.1	6×10^{-5}	6×10^{-9}
Red oil explosion in the fuel product concentrator	4×10^{-6}	<3	≤ 0.1	1.2×10^{-6}	1.2×10^{-10}
Explosion in the fuel product denitrator	4×10^{-7}	≤ 3	≤ 0.1	1.2×10^{-6}	1.2×10^{-10}
Criticality in a process cell	2×10^{-5}	--	≤ 0.05	1×10^{-6}	1×10^{-10}
Failure of a krypton storage cylinder	1.3×10^{-4}	--	≤ 0.05	7×10^{-6}	7×10^{-10}
Hydrogen explosion in uranium reductor	9×10^{-4}	<3	≤ 0.1	3×10^{-3}	3×10^{-7}
Hydrogen explosion in fuel product denitrator feed tank	3×10^{-4}	≤ 3	≤ 0.1	9×10^{-4}	9×10^{-7}
Total risk				1.3×10^{-2}	1.3×10^{-6}

Table 3.2.2. Probabilities, consequences, and risk of the FRP-WTF radiological accidents affecting the workers

Description	Probability (/plant-yr)	Consequences: Accident person-rem	Consequences: Repair and recovery person-rem	Risk: $\frac{\text{Person-rem}}{\text{plant-yr}}$	Risk: $\frac{\text{Fatality}}{\text{plant-yr}}$
Criticality in process cell	3×10^{-5}	≤0.05	--	2×10^{-7}	2×10^{-11}
Hydrogen explosion in actinide-bearing vessel	a. 3×10^{-4} b. 3×10^{-4}	≤0.1 ≤0.1	≤3 ≤3	1×10^{-3} 1×10^{-3}	1×10^{-7} 1×10^{-7}
Hydrogen explosion in vessel vent system	8×10^{-4}	≤0.1	≤3	2×10^{-3}	2×10^{-7}
Nitrated organic explosion in process concentrator	2×10^{-3}	≤0.1	≤3	6×10^{-3}	6×10^{-7}
Red oil explosion in process concentrator	2×10^{-4}	≤0.1	≤3	6×10^{-4}	6×10^{-8}
Resin explosion in CEC unit	4×10^{-4}	≤0.1	--	4×10^{-5}	4×10^{-9}
Facility fire	2×10^{-4}	≤0.1	--	2×10^{-5}	2×10^{-9}
Solvent mist explosion	7×10^{-4}	≤0.1	≤3	2×10^{-3}	2×10^{-7}
Total risk				1.3×10^{-2}	1.3×10^{-6}

Table 3.2.3. Probabilities, consequences, and risk of the FFP radiological accidents affecting the workers

		Consequences		Risk	
Description	Probability (/plant-yr)	Accident person-rem	Repair and recovery person-rem	Person-rem/plant-yr	Fatality/plant-yr
Air crash	1.5×10^{-9}	≤0.1	≤12	2×10^{-8}	2×10^{-12}
H_2 explosion in ROR	5×10^{-3}	≤0.1	≤3	2×10^{-2}	2×10^{-6}
H_2 explosion in sintering	5×10^{-3}	≤0.1	≤3	2×10^{-2}	2×10^{-6}
H_2 explosion in wet scrap	3×10^{-4}	≤0.1	≤3	1×10^{-3}	1×10^{-7}
Criticality in wet scrap	6×10^{-5}	≤0.05	--	3×10^{-6}	3×10^{-10}
Powder shipping container spill	3×10^{-5}	≤0.1	≤3	1×10^{-4}	1×10^{-8}
Exothermic reaction in powder storage	1.5×10^{6}	≤0.1	≤3	5×10^{-6}	5×10^{-10}
Total risk				4×10^{-2}	4×10^{-6}

Table 3.2.4. Probabilities, consequences, and risk of the FFP-WTF radiological accidents affecting the workers

		Consequences		Risk	
Description	Probability (/plant-yr)	Accident person-rem	Repair and recovery person-rem	$\frac{\text{Person-rem}}{\text{plant-yr}}$	$\frac{\text{Fatality}}{\text{plant-yr}}$
Criticality in process cell	$3x10^{-5}$	≤ 0.05	--	$2x10^{-7}$	$2x10^{-11}$
Hydrogen explosion in actinide-bearing vessel	$3x10^{-4}$	≤ 0.1	≤ 3	$9x10^{-4}$	$9x10^{-8}$
Hydrogen explosion in vessel vent system	$8x10^{-4}$	≤ 0.1	≤ 3	$2x10^{-4}$	$2x10^{-8}$
Nitrated organic explosion in process concentrator	$2x10^{-3}$	≤ 0.1	≤ 3	$6x10^{-3}$	$6x10^{-7}$
Red oil explosion in process concentrator	$2x10^{-4}$	≤ 0.1	--	$2x10^{-5}$	$2x10^{-9}$
Resin explosion in CEC unit	$4x10^{-5}$	≤ 0.1	--	$4x10^{-5}$	$4x10^{-9}$
Facility fire	$2x10^{-4}$	≤ 0.1	--	$2x10^{-5}$	$2x10^{-9}$
Solvent mist explosion	$7x10^{-4}$	≤ 0.1	≤ 3	$2x10^{-4}$	$2x10^{-8}$
Total risk				$7x10^{-3}$	$7x10^{-7}$

3.3 Nonradiological Accidents Affecting the Public

Nonradiological accidents affecting the public can only occur outside of the plant complex (i.e., in the supporting transportation). As a result, focus was placed on the transportation of the radioactive materials, to the exclusion of the transportation of the nonradioactive supply materials, to the plants. The nonradiological risk to the public from plant workers commuting to work has also been excluded. A justification for these exclusions is that similar activities and commuting would take place, regardless of the plants. With these omissions, the nonradiological public transportation risks are presented in Table 3.3.1.

3.4 Nonradiological Accidents Affecting the Workers

The effect of nonradiological accidents incurred by workers was obtained from estimates of the amount of labor involved in constructing, operating, and decommissioning the facilities. Using these manpower estimates and data from previous work experience, these nonradiological risks were estimated. Table 3.4.1 presents the estimated manpower involved in plant construction. Using data from Reference 17, the indicated conversion factors are obtained to determine the injuries and fatalities.

Table 3.4.2 uses the same reference data for plant-operating-experience accidents to determine the annual average estimated injury and fatality rates. The decommissioning risks are based on Reference 18

Table 3.3.1. Nonradiological risk from PT and Reference cycle transportation

Cycle	Mode	Distance	Trips/GWe	Risk (p x c) Fatalities/trip	Risk (p x c) Fatalities/GWe-yr
Reference	Spent fuel	1000	6	4×10^{-3}	2×10^{-2}
	Fresh fuel (MOX)	1000	2	4×10^{-3}	8×10^{-3}
	Fresh fuel (U)	1000	4	4×10^{-3}	1.6×10^{-2}
	Cladding hulls	2000	6	7×10^{-3}	4×10^{-2}
	HLW	2000	0.27	7×10^{-3}	1.9×10^{-3}
	Non-HLW	2000	16	1.8×10^{-4}	3×10^{-3}
Reference-cycle total nonradiological risk					0.09
PT	Spent fuel	1000	10	4×10^{-3}	4×10^{-2}
	Fresh fuel (MOX)	1000	3	4×10^{-3}	1.2×10^{-2}
	Fresh fuel (U)	1000	7	4×10^{-3}	3×10^{-2}
	Cladding hulls	2000	6	7×10^{-3}	4×10^{-2}
	HLW	2000	0.27	7×10^{-3}	1.9×10^{-3}
	Non-HLW	2000	16	1.8×10^{-4}	3×10^{-3}
PT-cycle total nonradiological risk					0.13

Table 3.4.1. *Nonradiological fatality and injury estimates in facility construction*

Facility	Assumed structure cost ($)	Manpower[a] (man-hours)	Lost-time injuries[b]	Fatalities[c]
FRP	$5x10^8$	$8x10^6$	39	0.3
FRP-WTF	$1x10^9$	$1.6x10^7$	84	0.7
FFP	$2x10^8$	$3.2x10^6$	14	0.1
FFP-WTF	$2x10^8$	$3.2x10^6$	16	0.2

[a] Based on $500/man-day.

[b] Based on a construction injury rate of $5x10^{-6}$ injury/man-hour.

[c] Based on a construction fatality rate of $4x10^{-8}$ fatality/man-hour.

Table 3.4.2. Annual injury and fatality rate in routine facility operation

Facility	Work force $\left(\frac{\text{million man-hours}}{\text{years}}\right)$	$\frac{\text{Injuries}}{\text{year}}$[a]	$\frac{\text{Fatalities}}{\text{year}}$[b]
FRP (Reference and PT)	0.62	1.3	0.014
FRP-WTF	0.64	1.3	0.015
FFP (Reference and PT)	0.62	1.3	0.014
FFP-WTF	0.14	0.3	0.003
Total		4.2	0.046

[a] Based on an AEC operations injury rate of 2.1 injuries/10^6 man-hours.

[b] Based on an AEC operations fatality rate of 0.023 fatality/10^6 man-hours.

results of 1.7 injuries and 9×10^{-3} fatality resulting from 142 man-years of labor to decommission an AGNS-type plant. These results were scaled to the facilities on the basis of the ratio of the volume of the facility under consideration to that of AGNS. These results are presented in Table 3.4.3.

It is necessary to incorporate the construction-type accidents that occur before and after the useful facility lifetime. This is done by adding the effects of the construction and decommissioning accidents to the effects of the facility lifetime accidents and dividing by the facility lifetime (40 years assumed). This summary is presented in Table 3.4.4.

3.5 Radiological Operations Affecting the Public

Plants must provide fresh air for workers and vent gases to the atmosphere. In spite of elaborate air-cleaning practices and equipment, small amounts of radioactive material are discharged into the atmosphere. The amount varies with chemical species. Using data from past experience with similar processes, estimates are made for the amounts of material which are anticipated to be discharged from each plant. After estimating the average continuous release quantities, these were used as source terms for CRAC suitably modified for routine release calculations.[9] Table 3.5.1 summarizes the effects of the quantity of material discharged in one year from each plant for each fuel cycle.

Table 3.4.3. Nonradiological risks associated with decommissioning

Facility	Lost-time injuries	Fatalities
FRP	5.1	2.7×10^{-2}
FRP-WTF	16	6×10^{-2}
FFP	1.7	9.1×10^{-3}
FFP-WTF	3.2	1.7×10^{-2}
Total	26	1.1×10^{-1}

Table 3.4.4. Facility lifetime-averaged injuries and fatalities[a]

Facility	Daily operation number of workers	Injuries/plant-year		Fatalities/plant-year	
		Reference	PT	Reference	PT
FRP	275	2.4	2.4	0.022	0.022
FRP-WTF	300	--	3.8	--	0.034
FFP	310	1.7	1.7	0.017	0.017
FFP-WTF	120	--	0.8	--	0.008
Totals		4.1	8.7	0.039	0.081

[a]Based on an assumed facility lifetime of 40 years.

Table 3.5.1. Routine annual radiological population dose and health effects among the public

Plant or cycle	Population dose (person-rem/plant-year)		Health effects (latent cancer/plant-year)	
	Reference	PT	Reference	PT
FRP	680	730	0.12	0.29
FRP-WTF	--	5.3	--	0.24
FFP	7×10^{-3}	1.7×10^{-2}	1.9×10^{-4}	6.8×10^{-4}
FFP-WTF	--	0.55	--	0.12
Totals	680	736	0.12	0.65

3.6 Radiological Operations Affecting the Workers

The radiological occupational risk was estimated as routine exposure, maintenance exposure, and abnormal occurrences. The routine exposure in the FRP was estimated from NFS experience, AGNS and GESMO estimates, and ALARA projections with anticipated stricter design criteria. Estimates for the other plants were based on capacity scaling to the one-third power. Estimates for maintenance exposure were based on past plant experience, anticipated ALARA considerations, and the assumption that no work would be undertaken in fields greater than 250 mrem/hr. The bases for the assumptions and details of the calculations are contained in Reference 19. Abnormal exposures are defined as individual exposures in excess of 10CFR20 limits. These were estimated from NFS experience with anticipated reductions due to more stringent requirements.

Table 3.6.1 summarizes these estimates for each of the plants. The estimates for the FRP and FFP are the same for both Reference and PT cycles.

3.7 Nonradiological Operations Affecting the Public

As stated in the previous section, these plants, like all plants, discharge air and gases to the atmosphere. In spite of scrubbers and other air-cleaning devices, small amounts of hazardous materials are discharged into the atmosphere. There are two main sources of these pollutants from these plants: the chemical processes themselves and the

Table 3.6.1. Annual radiological occupational population dose and health effects

Facility	Population dose (person-rem/plant-year)				
	Routine	*Maintenance*	*Abnormal*	Total population dose	Latent fatalities / plant year
FRP	220	220	10	450	4.5×10^{-4}
FRP-WTF	220	220	10	450	4.5×10^{-4}
FFP	230	230	10	470	4.7×10^{-4}
FFP-WTF	90	90	3	180	1.8×10^{-4}
Reference total				920	0.09
PT total				1600	0.16

auxiliary services, primarily the steam supply system, which is assumed to burn fuel oil. The use of electric boilers would eliminate this latter source at the plant, but, depending upon how the electricity is produced, this change would simply move the source to another location with a slight increase due to transmission line losses. Table 3.7.1 presents the annual health effects from the FRP based on AGNS estimates but scaled to allow for the larger size of the FRP. The health effects were estimated from epidemiological studies on SO_2 and its relationship to the other pollutants. Table 3.7.2 presents the results for the plants under consideration. No difference was determined in the nonradiological effects for the use of the FRP and the FFP in the Reference or PT fuel cycle. One economic death was estimated to result from disabilities lasting 6000 person-days or longer.

Table 3.7.1. Estimated annual health effects from FRP pollution

Pollutant	Mass discharged (lb)	Person-days of aggravated heart-lung disease symptoms	Premature deaths
CO	$3.7x10^4$	$3.7x10^4$	2.0
HC (incomplete combustion)[a]	$3.8x10^5$	$5.5x10^3$	0.3
NO_2	$6.2x10^5$	$2.4x10^4$	1.3
SO_2	$5.7x10^5$	$1.5x10^4$	0.8
Total		$8.1x10^4$	4.4

[a]Estimated from AGNS, using scaling for plant size. It includes burning, transport, and storage of heating oil.

Table 3.7.2. Summary effects (per plant-year) of gaseous nonradiological effluents

	Premature deaths		Economic deaths		Total deaths	
Plant	Reference	PT	Reference	PT	Reference	PT
FRP	4	4	14	14	18	18
FRP-WTF	--	7	--	21	--	28
FFP	0.2	0.2	0.6	0.6	0.8	0.8
FFP-WTF	--	3	--	9	12	12
Totals	4.2	14.2	14.6	44.6	18.6	58.8

4.0 SUMMARY

4.1 Risk Summary

The risks presented in Section 3 are assembled in Table 4.1.1. These risks include estimated population doses as well as estimated statistical deaths calculated on the assumption that half of the latent cancers will result in fatalities due to this cause.[7] The other modification of the data of Section 3 was the reduction to risk in terms of gigawatt-electric years by division of the per-plant-year risk by 75, which is the estimated electric power industry capacity that each of the cycles could support.

This table shows that the relative risk of the PT to the Reference cycle is an increase of 290%. This is primarily due to the increase in nonradiological effluents and secondarily to the transportation accidents associated with the greater amount of transportation in the PT cycle.

4.2 Sensitivity Analysis

These results and conclusions are based on many assumptions which could be modified, as a result of changes in plant designs and procedures, from those considered here. Furthermore, there may be errors in the data used to arrive at the conclusions of Table 4.1.1. Reference 9 includes a detailed sensitivity analysis; however, only the sensitivity of the major risk contributors is considered here. This

Table 4.1.1. Summarized risks for the Reference and PT fuel cycles

	Reference		PT		Risk ratio
	Person-rem / GWe-year	Fatalities / GWe-year	Person-rem / GWe-year	Fatalities / GWe-year	(Fatalities / GWe-year (PT)) / (Fatalities / GWe-year (Reference))
Nonradiological operations affecting the public		0.25		0.78	3.1
Nonradiological accidents affecting the public		0.09		0.13	1.4
Nonradiological accidents affecting the workers		5×10^{-4}		1.1×10^{-3}	2
Nonradiological subtotal		0.34		0.91	2.9
Radiological operations affecting the workers	12	1.2×10^{-3}	21	2×10^{-3}	1.7
Radiological operations affecting the public	9.2	8×10^{-4}	9.8	4×10^{-3}	5
Radiological accidents affecting the public	1.5×10^{-3}	5×10^{-7}	1.5×10^{-3}	7×10^{-7}	1.4
Radiological accidents affecting the workers	7×10^{-4}	7×10^{-8}	1×10^{-3}	1×10^{-7}	1.4
Radiological subtotal	21	2×10^{-3}	31	6×10^{-3}	3
Risk total		0.34		0.91	2.9

sensitivity is presented in Table 4.2.1 in terms of fractional change in risk or subtotal risk for a fractional change in risk contributor. For example, a change that modified the Reference Radiological Operations Risk Affecting the Public by 100% would affect the radiological subtotal risk by 40% and the overall Reference cycle risk by 0.19%.

4.3 Error Analysis

The errors associated with this analysis, summarized in Table 4.3.1, have been estimated on the basis of data sources. The errors are combined in quadrature, with each weighted according to its sensitivity to the final result. This procedure is the statistically correct one for propagating variances in a linear system when there is statistical independence of each risk contributor. Since this results in error factors of 90% and 140%, the risk is expected to be from 0.8 to 0.2 and 2.8 to 0.5 fatalities/GWe for the Reference and PT cycles, respectively. The ratio of risks could be uncertain in the range of 2.5 to 3.6, with a central value of 2.9. It should be noted that, in calculating the errors in the ratio, the dominating risks are nonradiological air pollution and traffic accidents. This ratio contains correlated errors because the same data were applied to both the Reference and PT assessments. Hence the error in the ratio was calculated with both numerator and denominator error correlated in the same direction.

In conclusion, the near-term risks of the PT cycle are about 290% greater than those of the Reference cycle for the production of the same amount of electric energy.

Table 4.2.1. Fractional change in total or subtotal risk for a fractional change in risk contributor

Risk contributor	Sensitivity to the subtotal risk: Reference	Sensitivity to the subtotal risk: PT	Sensitivity to the total risk: Reference	Sensitivity to the total risk: PT
Nonradiological operations affecting the public	0.8	0.9	0.8	0.9
Nonradiological accidents affecting the public	0.2	0 10	0.2	0.10
Nonradiological accidents affecting the workers	1.2×10^{-3}	9×10^{-4}	1.2×10^{-3}	9×10^{-4}
Radiological operations affecting the workers	0.6	0.3	3×10^{-3}	1.7×10^{-3}
Radiological operations affecting the public	0.4	0.7	1.9×10^{-3}	3×10^{-3}
Radiological accidents affecting the public	5×10^{-4}	3×10^{-4}	2×10^{-6}	1.3×10^{-6}
Radiological accident affecting the workers	4×10^{-5}	1.3×10^{-5}	1.7×10^{-7}	7×10^{-8}

Table 4.3.1. Estimated errors in the risk contributors and the estimated overall error

Risk contributor or overall risk	Estimated error factor[a]
Nonradiological operations affecting the public	2
Nonradiological accidents affecting the public	0.2
Nonradiological accidents affecting the workers	0.2
Radiological operations affecting the workers	0.5
Radiological operations affecting the public	2
Radiological accidents affecting the public	10
Radiological accidents affecting the workers	10
Reference cycle	2
PT cycle	2
Reference cycle radiological	0.9
PT cycle radiological	1.4

[a]Multiplier or divisor of the quoted value.

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