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WASTE MANAGEMENT PROCEDURES FOR FUSION- BASED CENTRAL POWER STATIONS

T.E. Botts and J.R. Powell

August 1977

DEPARTMENT OF NUCLEAR ENERGY

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ABSTRACT

Several early conceptual designs of fusion demonstration and commercial reactors are used in a discussion of radioactive waste streams, methods of handling these wastes, and their possible environmental effects. Comparisons are made between these waste streams and the fuel cycles of the light water reactor and the liquid metal fast breeder reactor.

Most radioactive waste in fusion reactors is generated through replacement of the inner blanket region. Because there is a high degree of uncertainty with regard to blanket lifetimes, there is some uncertainty concerning the activity levels that must be handled. However, in general, fusion reactors are expected to create larger physical amounts of radioactive waste with lower and shorter-lived activity than do fission plants. Material recycling of fusion blanket waste, for nuclear applications, seems feasible after a 100-yr holding time.

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CONTENTS

ABSTRACT.....	iii
TABLES.....	vi
FIGURES.....	ix
SUMMARY AND CONCLUSIONS.....	xi
I. Introduction.....	1
II. Source and Transportation Schemes.....	4
1. Source Terms.....	4
2. Transportation.....	5
3. Cost of Transportation.....	7
III. Decommissioning.....	10
IV. Isolation and Disposal.....	12
1. General Considerations.....	12
2. Ultimate Disposition of Fusion-Reactor-Activated Structural Waste.....	17
1. Introduction.....	17
2. Permanent, Ultimately Unguarded Disposal.....	17
3. Structural Material Recycle.....	18
ACKNOWLEDGMENTS.....	19
REFERENCES.....	19
APPENDIX A Sensitivity of Waste Source Terms to First-Wall Lifetime Integrated Neutron Load.....	20
APPENDIX B A Brief Comparison of LMFBR, LWR with Pu Recycle, and Fusion Fuel Cycles and Waste Streams.....	20
APPENDIX C Further Comparisons of Fusion and Fission Wastes and Fuel Cycles.....	22

TABLES

I-1. Annual Transport Mileage for Spent-Fuel or Blanket Waste for Various 10^6 -MW(e) Electrical Generating Systems.....	2
II-1. Annual Source Terms for Spent-Fuel and Solid Blanket Wastes.....	4
II-2. Characteristics of Spent-Fuel Casks Used in Modeling Solid High-Level Waste Management in Fusion Reactors.....	6
II-3. Shipment Activity and Afterheat for Three Tokamaks and a Reference LWR With a TN-12 Rail Cask Used for Shipping....	6
II-4. Annual Number of Shipments of High-Level Solid Waste per GW(e) for Candidate Fusion and Fission Power Reactors.....	7
II-5. Details of Fission Reactor Shipments to Fuel Reprocessing Facilities....	7
II-6. Estimated Annual Transport Costs and Activities per GW(e) for Spent-Fuel or High-Level Solid Waste Generated in Fusion Plants..	7
II-7. Estimated Costs To Ship and Bury Solid and Resinous Wastes Generated During One Year of Normal Reactor Operations.....	8
II-8. Accident Rates for Truck and Rail Accident Severity Categories.....	9
II-9. Accident Severity Categories.....	9
II-10. Annual Spent-Fuel or Blanket Structural Material Transport Mileage per 10^6 MW(e).....	9
II-11. Annual Frequency of Transportation Accidents of Different Severity per 10^6 MW(e) of Generating Capacity.....	10
III-1. Gulf Nuclear Fuels Corporation Preliminary Cost Estimates for 1100-MW(e) LWR Decommissioning.....	11
III-2. Itemized Costs To Entomb UWMAK-I.....	11
III-3. Itemized Costs To Decommission UWMAK-I by Complete Removal, With Cost Assumptions Similar to Those in Ref. 17.....	11
III-4. Itemized Costs To Decommission UWMAK-I by Complete Removal, Assuming Economies of Scale.....	12

TABLES

IV-1. Number of Barrels of Waste and Amount of Land Needed for Burial After One Year's Operation of a 10^6 -MW(e) Fusion Power System.....	14
IV-2. Volumes of Nongaseous Waste Created Annually by LWRs of 10^6 -MW(e) Generating Capacity.....	14
IV-3. Volumes of Solid Waste Generated Annually by 30.5 1500-MTHM/yr Fuel Reprocessing Plants Supporting LWRs of 10^6 -MW(e) Generating Capacity.....	14
IV-4. BHPs for Solid Structural Waste or Spent Fuel Shipped per Annum per GW(e).....	15
IV-5. Times Required for Fusion Reactor Structural Waste To Decay to Safe Levels	18
IV-6. Varied Conditions Considered in Dose Calculations of Radiation Received by a Worker Exposed to a 1-m Sphere of Decayed Fusion Reactor Blanket Waste.....	18
IV-7. Isolation Time Following Reactor Shutdown Required for Waste To Decay to a Level Such That a Worker Will Receive Annual Exposures of 5.0/0.5 R Under Conditions Described in Table IV-6.....	19
IV-8. Annual Worker Exposure After 100 Years of Waste Isolation.....	19
A-1. Annual Structural Waste Source Terms per GW(e) for First-Wall Lifetimes, Both As-Designed and Normalized to 10 MW yr/m ²	20
B-1. Biological Hazard Potentials for High-Level Wastes Generated During One Year of Mature Reactor Operation.....	21
B-2. Comparison of Estimated Annual Quantities of Radioactive Solid Wastes From an LWR and an LMFBR.....	21
C-1. Percent of U.S. Air and Groundwater Reserves Needed To Dilute the Annual Waste From Various 10^6 -MW(e) Nuclear Generating Systems to Their MPCs.....	22
C-2. BHPs of Indian Monazite Ore With and Without ThO ₂	22

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FIGURES

I-1. LWR Fuel Cycle With No Recycle.....	2
I-2. LWR Fuel Cycle, Including Pu Recycle, for MOX Fuels.....	2
I-3. Flow Diagram for a Generalized Waste Management Scheme for a Fusion Power Reactor.....	3
II-1. Exploded View of a Transnuclear TN-8 Shipping Cask.....	6
II-2. Trench Storage at INEL.....	8
IV-1. BHP (Water Dilution) as a Function of Time After Reactor Shutdown for Various Electrical Generating Schemes.....	16
IV-2. BHP (Air Dilution) as a Function of Time After Reactor Shutdown for Various Electrical Generating Schemes.....	16
IV-3. BHP Values (Water Dilution) Integrated Over Time Ranges of 1 to 10^7 and 1 to 10^9 Years After Reactor Shutdown.....	16
IV-4. BHP (Air Dilution) Integrated Over Time Ranges of 1 to 10^7 and 1 to 10^9 Years After Reactor Shutdown.....	16

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SUMMARY AND CONCLUSIONS

Fusion reactors, unlike fission reactors, do not generate radioactive waste products from nuclear reactions in the fuel. The actinides and long-lived fission products generated in fission reactors present formidable problems of handling and disposal. These are eliminated in fusion reactors. However, the fusion reactions that are easiest to achieve, those using DT or DD fuel, release high energy neutrons that cause nuclear reactions in the structures (blankets, ducts, shielding, etc.) surrounding the fusion plasma. Depending on the materials present in these structures, radioactive wastes may be produced that will require handling and disposal.

The characteristics of fusion radioactive wastes (total radioactive inventory, half-life, storage time, biologic hazard, volume), unlike those of fission reactors, will depend very strongly on the materials and details of particular fusion reactor designs.

This report examines possible waste management procedures for a range of conceptual fusion reactor designs that have been developed by various fusion research groups. These designs tend to reflect goals relating to reactor performance, such as high thermal efficiency and maximum resistance to radiation damage, and they rely as far as possible on materials and technology developed for fission reactors. So far, waste management issues have been addressed after the designs are complete, and their impact on the design of fusion reactors has been small.

Thus, the conclusions reached in this report should be regarded as only a first step in the evaluation of the characteristics of radioactive wastes from fusion reactors. Examination of a much broader range of fusion reactor designs is desirable, particularly with regard to assessing how waste management problems could be reduced by alternative reactor designs and materials. For example, there are no fusion reference designs using SiC, C, or Mg alloy structures. These materials can be made very pure at reasonable cost, and their use would essentially eliminate all radwaste handling and disposal problems. Laser-separated isotopes offer another alternative material for fusion reactor structures. Work at the University of Wisconsin indicates that selected separated isotopes are potentially cheap enough that activated

waste inventory levels can be greatly reduced, even though alloy compositions that normally would be highly activated are used.

This report examines fusion radwastes at all stages after they leave the reactor, that is, during on-site storage and processing, transportation, isolation and disposal, and reactor decommissioning; and the potential for recycling is considered. In general, fusion radwastes appear to present far fewer problems than fission radwastes.

1. For the range of conceptual fusion reactor designs investigated, radioactive waste from fission reactors [i.e., light water reactors (LWRs) and liquid metal fast breeder reactors (LMFBRs)] has a much higher biological hazard potential (BHP) than the radioactive waste from fusion reactors. This is especially true after a two-century holding time when almost all the radioactivity in the waste from fusion reactors has decayed away.

2. For some fusion reactor designs, a holding time of 200 years for reactor radwaste results in BHP/kW(t) values substantially below those for the ash from coal-fired power plants. Uranium and thorium are present in coal, and its ash is slightly radioactive.

3. From the point of view of waste management, aluminum is the most attractive of the possible structural materials for the fusion reactor designs considered. It can be permanently disposed of by direct burial after only a few years' storage. The long-lived ^{26}Al isotope present in the radwaste will not create a disposal problem because even if ^{26}Al does not equilibrate with the vast reservoir of natural Al in the earth, the activity in groundwater exposed to aluminum radwaste will be very small compared to the maximum permissible concentration (MPC) for ^{26}Al . Equilibration with natural Al seems likely and will reduce the activity of ^{26}Al in groundwater to levels many orders of magnitude lower than the MPC.

4. For the fusion reactors considered, molybdenum is the least attractive of the possible structural materials in terms of waste management.

5. Stainless steel is an intermediately attractive material for the designs considered. High levels of activity are present after reactor shutdown, but within a fairly tractable period of time (~ 100 yr) the activity decays to levels such that either

permanent below-grade disposal or recycling is possible.

6. Most structural materials considered for fusion reactors could be recycled after one or two centuries of isolation, which would make concrete-lined trenches, caves, and abandoned mines likely candidates for retrievable waste storage facilities. If the material is not recycled at this time, permanent direct burial could be carried out.

7. Fusion-reactor-activated structural waste will probably require on-site storage for at least one year to allow activity levels to decay sufficiently for casks built according to present spent-fuel cask technology to be used for fusion shipment. Shorter decay times may be used, but shipment sizes would then appear to be prohibitively small. If reactor entombment is ultimately to be carried out, the radioactive material could be stored within the secondary containment.

8. Current conceptual designs indicate that fusion reactors, dependent upon wall load, will generate a greater volume of radwaste from their replaceable blanket components than do fission reactors, because of spent-fuel storage and disposal.

9. An area of the order of one square mile per year will be needed for near-grade burial of blanket and low-level wastes for $10^6/\text{MW(e)}$ of fusion electrical generating power, according to first-generation fusion power reactor conceptual studies.

10. Because of the quantities of radioactive blanket material associated with fusion reactors, rail shipping is the mode of choice from economic and safety considerations.

11. Transport costs for wastes from fusion reactors appear to be two to six times greater than those for LWRs of similar electrical output if present-day costing schemes are used, but these costs are small compared to other reactor costs.

12. There appears to be very little difference in the volumes and activities of low-level solid and liquid wastes associated with fusion and fission plants.

13. Because of the high activity levels and large physical size of some conceptual designs for fusion reactors, their decommissioning costs will be quite large for complete removal schemes. Future designs, taking this problem into account, could reduce removal costs.

WASTE MANAGEMENT PROCEDURES FOR FUSION-BASED CENTRAL POWER STATIONS

I. INTRODUCTION

Waste management is presently one of the principal problems associated with fission power reactors. Although fusion reactors have no spent-fuel problem, other forms of radioactive waste will be generated during normal plant operation. An extensive body of literature and research addresses the waste management question as it relates to fission reactors. Recently, a few investigators^{1,2} have begun to consider what types of waste management problems will result from the operation of fusion power reactors and how fusion reactor rad-waste may be handled.

Comparisons between fusion and fission reactors are made, on the basis of existing reactors and conceptual designs where possible. Three existing light water reactors (LWRs) and a reference LWR fuel cycle³ provide fission reactor data. San Onofre I, Dresden II, and Oyster Creek, the three LWRs considered, were chosen because they represent different sites and have shipped spent fuel to a reprocessing facility. Five conceptual designs of fusion reactors provide data for a fusion power economy. UWMAK-I is considered to account for low wall loading, steel structure, and lithium cooling. The PPPL design includes PE-16 structure, higher wall loading, and molten-salt breeding material. The BNL minimum-activity blanket design shows low induced activity, aluminum structure, low wall loading, and helium cooling. UWMAK-III shows a higher wall loading, lithium and helium cooling, and tungsten zirconium molybdenum (TZM) structure. The ORNL demonstration reactor features higher wall loading, steel structure, and molten-salt cooling.

In comparing source terms from these reactors, it must be remembered that there are different lifetime goals for different design types. Therefore, while very little waste is generated by the 2000-MW(t) ORNL demonstration reactor (with an assumed electrical conversion efficiency of 0.35 for comparison), it is performing the function of a demonstration and experimental device, as opposed to the commercial function of the other designs considered. Furthermore, higher integrated wall loading is assumed by ORNL, leading directly to the generation of less activated structural waste.

In general, high-level waste in fission reactors is associated with spent fuel, whereas in fusion reactors activated structural material is the major source term. Material flow for a simple near-term LWR fuel cycle is presented in Figure I-1. A slightly more sophisticated fuel cycle, including Pu recycle, is shown in simplified form in Figure I-2. Finally, a general material-handling scheme for replaceable structural components in a fusion reactor is presented in detail in Figure I-3.

With the methods and assumptions given in Section II, the transportation requirements in miles traveled are calculated for these different fuel and material cycles and are presented in Table I-1. The mileage associated with intermediate steps is included. Only main stream high-level waste is considered. In general, both fusion and fission wastes appear to have similar transportation requirements. However, significantly lower biological hazards associated with fusion waste (Section IV) would imply a lesser risk for a similar number of miles traveled.

In this report the management of fusion reactor material is discussed in detail in order that estimates of throughput and inventories associated with waste management may be made. Workers at the University of Wisconsin have presented a scheme for their design, UWMAK-III, which is slightly different from the one set forth herein. Higher activity levels are present in stainless steels and PE-16 than in TZM, proposed for UWMAK-III. An operation is proposed that will be able to accept different levels of waste activity and volume to be generated by fusion reactors of different conceptual designs. Nearly all this waste is associated with replacement of at least part of the blanket throughout the reactor lifetime.

The management of activated structural material includes removal, storage, packaging, transportation, and isolation. After shutdown, it may be necessary to remove decay afterheat for some time before blanket replacement begins. When decay heat has fallen to an acceptable level, any liquids present must be drained out. In the event that some tritium breeding material or coolant remains, as would be the case for salts (e.g., Flibe) or liquid metals (Li or Na), this residue must be removed. *In situ* reaction with a wet inert gas will form hydrides, hydroxides, and oxides, which al-

lows for dismantling of the blanket without concern that any residual liquid metals or salts will react inadvertently. It may also be advisable to vacuum pump the blanket while heating it to remove some of the remaining tritium before dismantling begins. Removal of replaceable components may now be performed remotely.

Any remaining hydroxides, hydrides, or oxides may now be physically removed from the metal components. As some of the replaceable blanket components may be quite bulky, they will be cut up into sheets of manageable proportions (e.g., one to two meters on a side). On-site storage will follow to allow short-lived radioactivity to decay away before permanent disposition is made.

Permanent disposition of structural radwaste may be made on site or in a central waste repository. In either event, waste will first be crushed and placed in storage containers (e.g., 55-gal drums or concrete vaults up to two meters on a side). This waste may be fixed with styrene-

Figure I-1. LWR fuel cycle with no recycle.¹¹

Table I-1

Annual Transport Mileage for Spent-Fuel or Blanket Waste for Various 10⁶-MW(e) Electrical Generating Systems

Distances of all high-level shipments are included. An IF-300 cask is used for fusion shipments.

	Millions of miles	
	Truck	Train
LWR* - no Pu or U recycle	123	116
LWR* - U recycle	123	75.8
LWR* - U and Pu recycle	142	82.1
UWMAK-I	-	119
UWMAK-III	-	80
PPPL	-	22
BNL	-	65

*LWR data are taken from ref. 11.

Figure I-2. LWR fuel cycle, including Pu recycle, for mixed oxide fuels.¹¹

Figure I-3. Flow diagram for a generalized waste management scheme for a fusion power reactor.

amounts or activities for the demo plant are lacking.

II-2. Transportation

Each of the four candidate fusion power reactor designs proposes a waste management scheme for high-level waste produced during the reactor lifetime. UWMAK-I proposes two possible schemes.⁴ In the first case, solid waste is stored on site for an unspecified time before being shipped by rail to a waste repository in either compacted or uncompacted form. On-site burial is also proposed. For UWMAK-III² a blanket waste management scheme is presented in far greater detail than for any of the other conceptual designs considered. Removed material is stored for three years and cut into small pieces, and any remaining lithium is removed. Decontaminated material is then crushed, fixed in concrete, and shipped to an off-site disposal site with lead shielding. For the BNL design,⁹ aboveground on-site storage of waste is proposed. On-site storage is also proposed for solid waste in the PPPL design.⁵

Throughout this paper certain assumptions are made regarding UWMAK-III which set it apart from the other conceptual reactors. Blanket waste is comprised of nonmetallic (graphite) and metallic (TZM) components. Nonmetallic components are less highly radioactive and may be shipped immediately upon removal from the reactor. For purposes of comparison, an average mixture of metallic and nonmetallic wastes is treated as the source stream, neglecting the phase lag of the metallic stream. Furthermore, specific spent-fuel casks are used for shipping rather than the shipping schemes proposed for UWMAK-III.

The rejection of local waste storage facilities by communities, environmental groups, or governments could make long-term on-site storage untenable. In order to take this possibility into account, a situation is posited wherein several different sorts of spent-fuel casks are used to ship waste from the site to a repository 1000 miles away. Table II-2 lists the casks considered and their characteristics. Figure II-1 illustrates a representative shipping cask.

It is assumed that prior to shipment, first-wall and blanket materials are compacted. Therefore, weight, afterheat, or total activity will limit the amount of waste per shipment for existing casks. If all wastes are held on site one year, perhaps in

something like a spent-fuel storage tank, activity and afterheat appear to pose less serious problems. Table II-4 lists the number of shipments per year per gigawatt electric [GW(e)] for the eight reactors being considered. In this table, weight is taken as the shipment size limit and the most optimistic sets of data, giving the smallest number of shipments, are used.

If one assumes material densities of 6.8 g/cm³ for UWMAK-I compacted first-wall material¹⁰ and a 1-yr holding time, the total activity of a shipment in a TN-12 cask is 57.3 MCi. This compares (Table II-3) to a total activity of 35.5 MCi for a shipment of irradiated reference LWR fuel assemblies. Both shipments will have an appreciable quantity of tritium (3.17×10^3 Ci for a spent-fuel assembly shipment in a TN-12*), and there are no actinides present in fusion shipments. Shipments from a fusion reactor would, therefore, seem to present less of a hazard owing to their lower chemical toxicity.

In making a comparison of shipping requirements, one must keep in mind the following: it appears that fusion reactors will have to be larger than LWRs for economic considerations, and that different means of waste disposal may be appropriate for fusion waste. In general, radioisotopes present in fusion reactor waste have shorter half-lives than those in fission reactors. Two notable exceptions are ⁹²Nb ($T_{1/2} = 2 \times 10^7$ yr) and ²⁶Al ($T_{1/2} = 7 \times 10^5$ yr). However, ²⁶Al cannot leach into groundwater at a concentration greater than 10% of its MPC¹¹ even if the groundwater is saturated with ²⁶Al, and no dilution occurs because of the isotope exchange with the large reservoir of natural aluminum in the soil. Thus, such a long half-life appears to be but a slight hindrance to the use of aluminum and alloys of aluminum in minimum-activity controlled thermonuclear reactor (CTR) applications.

Reactor size affects the density of waste traffic along specific routes. Clearly, several smaller reactors (e.g., the Dresden reactor) are, in a gross manner of speaking, indistinguishable from a much larger reactor. However, if the density of high-level waste shipments past population centers were to become a significant issue, the indivisible nature of fusion reactors would tend to make their siting somewhat less flexible. Shipments that have

*Vacuum baking of first-wall material to limit residual tritium has been proposed.⁹

Figure II-1. Exploded view of a transnuclear TN-8 shipping cask.

Table II-2

Characteristics of Spent-Fuel Casks Used in Modeling Solid High-Level Waste Management in Fusion Reactors*

Cask type	No. of fuel rod assemblies that may be carried (PWR/BWR)	Shielding	Maximum heat removal, kW	Approx. wt (MT loaded)	No. available/ No. being built	Spent-fuel load wt, MT**
NFS-4 truck	1/2	Pb	11.5	24	6/0	0.669
NFS-5 truck	2/4	U	20.0	25	0/0	1.337
TN-8 overweight truck	3/0	Pb	36.5	36	0/2	2.006
TN-9 overweight truck	0/7	Pb	24.5	36	0/3	2.006
IF-300 rail	7/18	U	76.0	74	4/0	4.608
TN-12 rail	12/32	steel	~95.0	97	0/1	8.023

*Taken from ref. 23.

**PWR fuel rod assembly weights used are taken from ref. 3.

Table II-3

Shipment Activity and Afterheat for Four Tokamaks and a Reference LWR With a TN-12 Rail Cask Used for Shipping

	UWMAK-I*	UWMAK-III	RNL	PPPL	Reference LWR fuel assemblies ³
Short holding time (120 days for LWR)					
Shipment activity, MCi	81.8	0.32	0.12	80.2	35.5**
Shipment afterheat, kW	33.8	8.55×10^{-3}	—	281.0	157.0†
1-yr holding time					
Shipment activity, MCi	31.1	—	—	12.1	—
Shipment afterheat, kW	15.9	—	—	24.1	—

*An entire shipment of first-wall material compressed to 6.8 g/cm^3 is assumed as an extreme case.

**1.9 MCi/assembly and 18% assemblies per shipment are assumed.¹⁰

†8.4 kW/assembly and 18% assemblies per shipment are assumed.¹⁰

Table II-4

Annual Number of Shipments of High-Level Solid Waste per GW(e) for Candidate Fusion and Fission Power Reactors

For fusion reactors, a 1-yr on-site holding time is assumed and weight is the limiting factor in determining shipment size.

	NFS-4	NFS-5	TN-8 and -9	IF-300	TN-12
UWMAK-I	815	408	252	119	68
UWMAK-III	549	275	184	80	46
BNL*	446	223	149	65	38
PPPL	150	75	50	22	13
ORNL Demo **	10	5	4	2	1
Oyster Creek	146	73	42	17	10
Dresden II	146	73	42	17	10
San Onofre I	121	61	41	18	11

*For minimum activity, wastes are intermediate and low level.

**Only inner-blanket replacement is considered.

Table II-5

Details of Fission Reactor Shipments to Fuel Reprocessing Facilities

Reactor	Reprocessing facility
San Onofre I (truck)	GE Midwest Reprocessing Plant - Morris, IL
Dresden II (rail, IF-300)	GE Midwest Reprocessing Plant - Morris, IL
Oyster Creek (truck)	NFS - West Valley

been made from the three candidate fission reactors to fuel reprocessing plants have gone within 50 miles of the three largest population centers in the U.S. (Table II-5).

II-3. Cost of Transportation

To continue with the assumption that on-site waste storage may not be acceptable, a comparison of shipping costs for wastes from both fusion and fission power reactors is made. All waste is assumed to be solid or resinous at shipping time and is broken down into two categories. The first category is for high-level solid waste (e.g., spent first-wall material and spent-fuel elements). The second covers miscellaneous low-to-medium-level waste from many sources.

Table II-6

Estimated Annual Transport Costs and Activities per GW(e) for Spent-Fuel or High-Level Solid Waste Generated in Fusion Plants

A 1000-mile shipping distance is assumed in all cases.

	Millions of dollars				MCi/yr shipped
	I	II	III	IV	
UWMAK-I	4.45	5.85	7.78	8.30	230
UWMAK-III	2.99	3.94	5.23	5.30	0.130
BNL*	2.43 (0.267)	3.20 (-)	4.25 (-)	4.57 (-)	0.002
ORNL Demo	0.051	0.067	0.089	0.103	5.5
San Onofre I	0.50	0.66	0.87	0.90	630
Dresden II	0.66	0.87	1.16	1.23	630
Oyster Creek	0.66	0.87	1.16	1.23	620

I - 1000-mile truck shipment @ \$12/kg HM.¹⁷

II - 1000-mile rail shipment @ \$15.80/kg HM.¹⁷

III - 1000-mile truck shipment @ \$21/kg HM.¹²

IV - II + (\$18/mile) × (2000 miles/trip) × (No. of trips).¹³

*\$0.51/lb for intermediate-level waste and \$0.25/lb for low-level waste.

For high-level waste costs, it is assumed that all shipments cover a 1000-mile route and that all materials are carried in spent-fuel casks. In order to estimate costs, four costing schemes are used. The costs of truck shipments are calculated on the basis of the numbers in the Generic Environmental Statement on Mixed Oxide Fuels (GESMO),¹¹ and the requirements for fuel reprocessing and waste burial facilities are estimated.

Table II-6 shows calculated high-level solid waste shipping costs per reactor year per gigawatt electric. In general, fusion reactors appear to incur greater shipping expenses, of the order of one to five million dollars per year. The lower figure for the BNL blanket shows the cost reductions possible with low- and intermediate-level structural wastes. When compared to capital costs, such a difference may be minor.

Further comparisons are greatly complicated by the number of options available. Fusion wastes may be stored aboveground or in near-grade burial sites; or they may be recycled.⁵ Spent fuel may be thrown away, or chop-leached and the cladding thrown away, or recycled. Uranium may be

recycled, or uranium and plutonium may be recycled. Further consideration is needed to estimate the economic consequences and desirability of these different post-reactor stages of the fuel and material cycles.

Estimates of the remaining solid and resinous wastes generated for four of the candidate reactors are presented in Table II-7. UWMAK-I and

PPPL will each generate a few barrels ($\sim 200/\text{yr}$) of medium-level waste from coolant cleanup and extraction systems and from vacuum pumping system wastes. All other waste is low level. It is assumed that all waste is shipped by truck 1000 miles to a commercial burial ground and buried in some near-grade site. The greater cost for medium-level waste reflects the need for some remote

Table II-7

Estimated Costs To Ship and Bury Solid and Resinous Wastes
Generated During One Year of Normal Reactor Operation

	Activity, Ci/yr	No. of 55-gal drums/yr	Burial cost/yr @ \$1/ft ³	Burial cost/yr @ \$1/ft ³ /GW(e)
UWMAK-I ¹	6.1×10^6	2116	\$36,600*	\$24,000
UWMAK-III	1.8×10^5	1973	14,500	7,300
BNL ¹	23.4	1929	14,300	8,900
PPPL ¹	4.3×10^7	2111	31,600*	15,800
Oyster Creek ¹⁴	3576	1500	11,100	17,300

*Slightly less than 10% of solid waste is projected to be medium level. This waste is costed at \$115/bbl.

Figure II-2. Trench storage at INEL.

handling, smaller shipment sizes, and greater shielding during shipment. There appears to be no great difference in costs per unit electrical power between fusion and fission plants. Figure II-2 illustrates such a burial site.

Blanket structural material and spent-fuel shipments will total in the tens of millions of miles per year for each 10^6 MW(e) generated (Table II-10). Full shipments of 1000 miles each are assumed. Because of the distances being covered, there will exist the chance of shipping accidents. Table II-8 lists probabilities of rail and truck accidents presented in Wash 1238¹⁵ for accidents of different

Table II-8

Accident Rates for Truck
and Rail Accident Severity Categories¹⁵

Accident category	Severity	Accident rate per vehicle mile	
		Rail	Truck
1	minor	7.3×10^{-7}	1.3×10^{-6}
2	moderate	7.9×10^{-8}	3.0×10^{-7}
3	severe	1.5×10^{-9}	8.0×10^{-9}
4	extra severe	1.3×10^{-11}	8.0×10^{-13}
5	extreme	1.2×10^{-13}	2.0×10^{-14}

Table II-9

Accident Severity Categories¹⁵

Type-B packaging is required to withstand a 30-mph impact and a 30-min 1475°F fire, according to 10 CFR-71.

Vehicle speed at impact, mph	Fire duration,* hr	Accident category	Severity
0-50	0	1	minor
0-30	$< \frac{1}{2}$		
50-70	0	2	moderate
30-70	$< \frac{1}{2}$		
0-30	$\frac{1}{2}$ -1		
>70	0- $\frac{1}{2}$	3	severe
30-70	$\frac{1}{2}$ -1		
0-50	>1	4	extra severe
>70	$\frac{1}{2}$ -1		
50-70	>1	5	extreme
>70	>1		

*A fire is defined as exposure to 1475°F thermal radiation with an emissivity of 0.9.

degrees of severity, and definitions are given in Table II-9. While DOT and NRC standards for class-B packages apply to impacts of up to 30 mph, it is generally considered⁷ that radioactivity will be released only in unusual extra-severe and extreme accidents. Expected frequencies of various accidents (Table II-11) have been calculated. For all cases, the frequency of extra-severe and extreme accidents is less than 10^{-3} , or less than one accident per thousand system years.

The consequences of shipping accidents may be different for fission and fusion wastes. Fuel assemblies are not volatile, but they do contain cesium (68,000 Ci), tritium (170 Ci), krypton (2100 Ci), and xenon (60 Ci), which may be partly released in the event of a cladding failure. Furthermore, light metals, fission products, and transuranics, which are held as oxides and are chemically more stable, may be volatilized in the event of fire. Fusion waste is composed of light metals which may be volatilized by fire, but a significantly lower biological hazard potential (see Section IV) exists for the materials present.

If one includes Pu, and Pu and U, recycle distances traveled by radioactive waste will increase over the values given in Table II-11 for LWRs. In any event, similar probabilities are found for the most dangerous accidents. Therefore, risk involved in shipping is directly associated with the biological hazard potential of the shipments (see Section IV). As a result, fusion reactors with the lowest BHP [minimum activity (BNL) or UWMAK-III] should offer the least risk of serious radiological accident during waste shipment.

Table II-10

Annual Spent-Fuel or Blanket Structural Material
Transport Mileage per 10^6 MW(e)

	Millions of miles	
	All truck (NFS-5 cask)	All rail (TN-12 cask)
UWMAK-I	408	68
UWMAK-III	275	46
BNL	223	38
PPPL	75	13
ORNL Demo	5	1
LWR reference* Design ³	60	10

*All distances associated with fuel recycle are ignored.

Table II-11

Annual Frequency of Transportation Accidents of Different Severity per 10^6 MW(e) of Generating Capacity

Accident category:	Truck shipments/rail shipments				
	1	2	3	4	5
UWMAK-I	530.0/49.6	122.4/5.4	3.3/0.1	$3.3E-4/8.8E-4$	$8.2E-6/8.2E-6$
UWMAK-III	358.0/33.6	82.5/3.6	$2.2/6.9E-2$	$2.2E-4/6.0E-4$	$5.5E-6/5.5E-6$
BNL	290.0/27.7	66.9/3.0	$1.8/5.7E-2$	$1.8E-4/4.9E-4$	$4.5E-6/4.6E-6$
PPPL	97.5/9.5	22.5/1.0	$0.6/2.0E-2$	$6.0E-5/1.7E-4$	$1.5E-6/1.6E-6$
ORNL Demo	6.5/0.7	1.5/0.1	$4.0E-2/1.5E-3$	$4.0E-6/1.3E-5$	$1.0E-7/1.2E-7$
LWR reference design ³	78.0/7.3	18.0/0.8	$0.5/1.5E-2$	$4.8E-5/4.3E-4$	$1.2E-6/1.2E-6$

III. DECOMMISSIONING

At the end of a reactor's lifetime the nuclear island, including containment structures, heat transfer systems, and the steam system, will contain varying quantities of radioactive material. Final disposition of the reactor must, therefore, be accomplished in such a manner as to avoid the release of unduly high concentrations of various radionuclides. Both fusion and fission power reactors are candidates for decommissioning since they are expected to meet the relevant ERDA¹⁶ criteria: (1) the facility is radioactively contaminated to the extent that it cannot be occupied or dismantled without health physics controls, (2) the facility is in excess of any identified ERDA needs, and (3) the facility is clearly defined by site map coordinates. Entombment and complete removal are two methods of decommissioning considered.

On-site entombment would involve removal of penetrations to the containment level at which entombment is to occur and a complete sealing off of the facility at that containment level. Such a scheme would necessitate continued monitoring and surveillance of the site. Furthermore, the site would not be available for any other use. In favor of entombment as an option for plant decommissioning is the fact that spent-blanket structural material could be stored within the reactor building. If a reactor is sited such that on-site storage of spent-blanket waste is possible, the reactor building could also store this waste. On-site waste processing associated with a fusion reactor would still be present, but no transportation or separate burial site would be needed.

Complete removal would involve removing all reactor materials from the site, to some predeter-

mined depth, and making the site reusable to some degree. This process would generate more waste, both clean and contaminated, that would have to be transported, and would result in larger exposures to workers and the general public living along transport routes. However, in view of the numbers of LWRs and fusion reactors planned for this country, environmental considerations may make complete removal the preferred method. Roughly 3000 square miles per century would be committed to decommissioned sites for each 10^6 MW(e) generated annually.

Cost estimates are made based on the Gulf United Nuclear Fuels, Inc. study¹⁷ on decommissioning two 1100-MW(e) reactors, a boiling water reactor (BWR) and a pressurized water reactor (PWR), using both the methods mentioned previously. All costs are based on 1972 dollars. For LWRs it is assumed that all fuel is removed, and in fusion reactors the first wall is removed before decommissioning begins. No technological improvements over the removal of the Elk River Reactor (ERR) are assumed for LWRs. Because of the far greater amounts of structural concrete and building cladding in fusion reactors, such an assumption leads to pessimistically high costs. Therefore, fusion reactor costs are estimated on the basis of both ERR costs and an assumed increase in cost effectiveness of phases dealing with concrete and building cladding.

Table III-1 shows the grand total costs for 1100-MW(e) LWRs, taken from the Gulf United Nuclear Fuels Corporation study.¹⁷ Costs for both PWRs and BWRs are similar, with short-term expenditures for complete removal being roughly four times those of on-site entombment. As a comparison, the cost of complete removal from its site

of the Elk River Reactor, a 58-MW(t) BWR, is approximately \$6,200,000.¹⁸

For the present, only figures for the decommissioning of UWMAK-I will be presented. The reason for this is that UWMAK-I has a fairly well documented balance of plant and, as will be seen, great uncertainties regarding removal costs make further calculations unwarranted at this time.

Entombment costs are presented in Table III-2 along with a listing of the anticipated steps involved. Many of these steps are the same for both LWRs and fusion reactors. Furthermore, it will be noted that total costs are quite similar.

With a slightly different operating scheme to account for differences in hardware and levels of contamination, complete removal costs for

UWMAK-I are presented in Tables III-3 and III-4. Costs and process efficiencies used in estimating the removal cost of UWMAK-I in Table III-3 are based on dismantling experience gained at Elk River.¹⁷ Because of the very large amounts of concrete and steel cladding necessary for tritium containment and safe operation with large inventories of liquid metals, economies of scale may be applied to their removal, which will reduce such costs. Similar economies may be possible in the removal of the shield and magnets. Furthermore, since there will be no actinides within the nuclear island, shipping costs have probably been overestimated somewhat. Costs for painting contaminated surfaces to temporarily fix tritium are neglected as being insignificant to the total cost, al-

Table III-1

Gulf Nuclear Fuels Corporation¹⁷ Preliminary Cost Estimates for 1100-MW(e) LWR Decommissioning

All costs in 1972 dollars.

	On-site entombment	Complete removal
BWR	\$4,439,000	\$19,195,000
PWR	3,845,000	13,195,000

Table III-2

Itemized Costs to Entomb UWMAK-I

Steps involved	Cost
Calculate radioactive inventories*	\$ 116,000
Develop overall entombment concept*	50,000
Prepare and submit environmental statement*	175,000
Prepare and submit decommission plan*	75,000
Change license to possession only*	50,000
Prepare facility for entombment*	219,000
Remove exterior radioactive equipment and place in secondary containment	2,147,900
Seal secondary containment	399,900
Radiation protection equipment*	62,000
Shipping, disposal, and burial	178,100
Ground improvement and cleanup*	50,000
Subtotal cost	3,522,900
Fee @ 7%	246,600
Basic total	3,769,500
Contingency @ 25%	942,400
Grand total	\$4,711,900

*These figures are the same as those given in ref. 17 for an 1100-MW(e) LWR.

Table III-3

Itemized Costs to Decommission UWMAK-I by Complete Removal

Cost assumptions used are similar to those in ref. 17.

Steps involved	Cost
Calculate radioactive inventories*	\$ 116,000
Develop overall removal concept*	50,000
Prepare and submit environmental statement*	200,000
Change from operator to possession license*	50,000
Prepare facility for decommissioning	169,000
Remove equipment and piping from plant (including Li and Na floors)	9,758,000
Remove and prepare to ship outer blanket and reflector	13,904,600
Remove and prepare to ship shield, magnets, and primary containment cladding	16,258,600
Remove all remaining secondary containment and nonradioactive buildings	1,509,425,100
Ship all radioactive and nonradioactive material	139,438,400
Prepare and submit papers to terminate license*	50,000
Radiation protection equipment*	123,000
Ground improvement and cleanup*	50,000
Subtotal cost	1,689,692,000
Fee @ 7%	118,278,400
Basic total	1,807,970,400
Contingency @ 25%	451,992,600
Grand total	\$2,259,963,000

*These figures are the same as those given in ref. 17 for an 1100-MW(e) LWR.

though such measures may be essential for worker protection.

Taking these considerations into account, a revised estimate of the cost for complete removal of UWMAK-I is made, and an itemized accounting is given in Table III-4. Removal and shipping preparation costs for the shield, magnet, and primary containment cladding are decreased by a factor of 5 to attempt to account for economies of scale. A tenfold reduction in the cost of removing the remaining building cladding, a fourfold re-

Table III-4

**Itemized Costs to Decommission UWMAK-I
by Complete Removal**

It is assumed that economies of scale make certain steps more cost effective than would be the case for ERR or an 1100-MW(c) LWR.¹⁷

Steps involved	Cost
Calculate radioactive inventories*	\$ 116,000
Develop overall removal concept*	50,000
Prepare and submit environmental statement*	200,000
Change from operator to possession license*	50,000
Prepare facility for decommissioning*	169,000
Remove equipment and piping from plant (including Li and Na floors)*	9,758,000
Remove and prepare to ship outer blanket and reflector*	13,904,600
Remove and prepare to ship shield, magnets, and primary containment cladding**	3,778,000
Remove all remaining secondary containment and nonradioactive buildings†	71,782,500
Ship all radioactive and nonradioactive material††	31,782,500
Prepare and submit papers to terminate license*	50,000
Radiation protection equipment*	123,000
Ground improvement and cleanup*	50,000
Subtotal cost	130,095,900
Fee @ 7%	9,100,700
Basic total	139,202,600
Contingency @ 25%	34,800,700
Grand total	\$174,003,300

*These costs are the same as those in Table III-3.

**A fivefold increase in labor productivity is assumed.

† A fourfold decrease in cost of concrete removal and a tenfold decrease in cost of steel liner removal are assumed.

†† It is assumed that shield and magnets can be shipped as lower-level waste.

duction for removal of all remaining concrete, and a reduction by one level of radioactive shipping costs are used to attempt to model cost decreases expected because of the greater size of fusion power plants. Note that removal of the actual buildings is the single most expensive item.

Given the second set of assumptions for complete removal, the costs are still significantly greater than those for an LWR of similar generating capacity. Dismantling should be considerably cheaper for a minimum-activity fusion reactor. Greater physical size of the fusion plant is the main reason for this disparity. By entombing the plant for one or two hundred years tritium contamination, which is both unavoidable and difficult to remove, will be decreased greatly. The activity level of primary containment structures will decrease by roughly two orders of magnitude.¹⁹ After such a period of entombment, the structure could be entered and removed with less concern for radioactive releases and worker exposure.

After entombment for a period of time sufficient for background activity within the reactor building to decay to levels such that work could be accomplished with minimal worker protection, two options exist for use of the plant. First, the building could be dismantled by conventional means, e.g., with explosives, without concern for creating significant quantities of tritiated water or other mobile radioactive species. This would allow for lower removal costs. Second, the containment structure could be reused without the almost insurmountable problem of having to assemble a fusion nuclear island in a radiation environment. Such considerations argue for use of reactor materials less prone to transmuting to nuclei with long half-lives. Clearly, the problems of decommissioning fusion power plants, as they are currently envisaged, are quite different from those of LWRs, and costs for fusion reactors will be greatly reduced if these problems are taken into account at the design stage.

IV. ISOLATION AND DISPOSAL

IV.1. General Considerations

Final disposition of radioactive waste is one of the more serious problems facing the users of fission and first-generation (D-T, D-D, or D-³He reaction) fusion reactors. Various approaches to this problem are well documented elsewhere for fission

reactors.²⁰ Many of the techniques developed for the fission reactor industry may be applicable to the slightly different problems of fusion reactor waste isolation and disposal.

Because of the nature of fusion structural waste, isolation will probably be the preferred method of disposition. As stated previously, highly activated 300-series stainless steels, vanadium-titanium alloys, and possibly SAP or other aluminum-based alloys will be reusable after no more than a few centuries of isolation from the biosphere. Resource scarcity and energy costs may make the recycling of the large quantities of radioactive waste that would accompany a fusion economy an attractive proposition. Therefore, only techniques affording ease of retrieval are considered.

Prior to burial, steps must be taken to contain the stored material. Such containment would inhibit the leaching of radioisotopes from buried structural waste. Possible schemes to afford such protection with shielded or unshielded containers, with or without concrete fixing and stored above or below grade, are considered. Containers may be minimal for compacted structural waste if tritium and smearable radioactivity are removed or fixed. Waste may be placed in such containers prior to shipment from the reactor site if this aids handling.

Interim storage and burial ground methods similar to those used for fission reactor wastes will probably be appropriate for fusion waste, as the storage time for effective and complete removal of most isotopes by decay is less than 300 years. ⁶³Ni, ⁹²Nb, ⁹³Zr, ⁹³Mo, and ²⁶Al are all exceptions to this rule, however. ⁶³Ni is present in slight quantities in 316 SS; as stated earlier, ²⁶Al does not appear to present much of a storage problem in spite of its long half-life; and ⁹³Mo, while present in significant quantities in TZM, is present in small quantities in PE-16. Furthermore, because of the relative ease of retrieval and lower costs, the above schemes will be attractive when compared with such methods as deep geologic storage, geologic disposal, extraterrestrial disposal, and transmutation, although one or more of these methods will ultimately be necessary for the high-level fission wastes with their very long decay times.

Possible methods of material isolation and storage for fusion wastes are earth-covered above-ground storage, below-grade hole-in-ground or trench storage, or storage in a cave or abandoned mine. In above-grade earth-covered storage, used

at the Idaho Nuclear Engineering Laboratory (INEL) for low-level transuranic wastes,²¹ containers are placed on a sloping concrete or asphalt pad and covered with plywood and polyvinyl film, with about a meter of soil on top. Below-grade hole-in-ground and trench storage involve steel- or concrete-lined holes or trenches with a steel or concrete cover and an earth cover on top. Some form of water removal, either drain holes in the trench or a sump pump, is necessary. Storage in an abandoned mine or a cave involves setting waste in a geologically stable mine or cave and erecting suitable physical barriers to secure the area.

Advantages of above-grade earth-covered storage include: low cost for the actual site; ease of construction on most locations; and easy detection of leaks by monitoring of pad run-off water. Disadvantages to aboveground earth-covered storage include: greater vulnerability of such a site to floods and other extremes of weather; and increased costs of shielding. Hole-in-ground and trench storage are quite similar, but, if large quantities are to be stored, trenches cost less. The advantages of such storage methods are better shielding than for aboveground storage, and greater protection and containment as well. The primary disadvantage is the difficulty of monitoring run-off water which would require that a sump pump be kept operable for a period of two or three centuries. Caves and mines provide the best shielding, best weather protection, and greatest ease of securing a site when it is full, but geologic stability should be investigated. Most of the technology presently exists for all four of these methods of isolation, and a decision as to which is used may be based upon the geology and economics of a particular waste storage site.

One very basic difference between fission and fusion reactor wastes is that the above storage methods represent interim storage for fission waste and final disposition for fusion waste. This means that when fusion waste has decayed to the point that most concentrations of radioisotopes are below their MPCs, long-lived transuranics and ¹²⁹I are still near their original concentrations. Thus, while no final storage or disposal of fission waste has been implemented, existing storage techniques would be appropriate for final disposition of fusion wastes.

In all these cases, no account has been taken of afterheat removal. For UWMAK-I, the adiabatic rate of temperature rise is 2.4×10^{-3} K/sec for a

Table IV-1

Number of Barrels of Waste and Amount of Land Needed for Burial After One Year's Operation of a 10 ⁶ -MW(e) Fusion Power System				
	UWMAK-I	UWMAK-III	BNL	PPPL
No. of 55-gal drums of solid nonstructural waste/1000 GW(e)-yr (millions) [†]	1.41	0.99	1.12	1.06
No. of 55-gal drums of solid structural waste/1000 GW(e)-yr (millions)*	0.76	1.13	0.42	0.14
Total No. of 55-gal drums of waste/1000 GW(e)-yr (millions)	2.17	2.12	1.54	1.20
Area committed to burial (acres/yr)**	897	876	638	497

*Waste packed at 50% of its maximum compressive density.

**Trenches similar to those used at INEL: 3 m wide, 4 m deep, 275 m long, and 10 m apart, filled to 1 m from top and 1 m at bottom.

barrel of structural waste. In 20 years the rate is roughly 1% of that value. Either good conduction paths away from waste containers are maintained, or, temporarily (~20 yr), air- or water-cooled storage is maintained. Because of the large quantities of waste to be generated by a fusion-based economy, final isolation should be simple and inexpensive. Thus, heavily shielded aboveground facilities with active methods of cooling probably are not desirable.

Total waste generated by a 10⁶-MW(e) fusion economy based on the four-candidate power reactor designs is shown in Table IV-1. Trench burial is assumed. Trenches are 4 m deep, 3 m wide, and 275 m long, similar to those at INEL.²¹ A meter

of porous fill is placed below the containers and a meter of earth above for protection and shielding. For a 10⁶-MW(e) fusion-based generating system, roughly a square mile of land per year is needed for burial.

Tables IV-2 and IV-3 are abridged presentations of solid wastes associated with LWRs capable of generating 10⁶ MW(e) annually and the associated fuel reprocessing plants presented in ref. 3. It is assumed that all fuel is recycled and, therefore, that fuel reprocessing capacity must equal

Table IV-2

Volumes of Nongaseous Waste Created Annually by LWRs of 10 ⁶ -MW(e) Generating Capacity		
An equal number of BWRs using deep-bed demineralizers or powdered resin filter demineralizers for condensate cleanup are assumed.		
Waste type	Amount of waste, ³ m ³ /10 ⁶ MW(e)-yr	Amount of waste, millions of 55-gal drums/yr
Combustible β - γ	3.17×10^5	1.51
Noncombustible solid β - γ	5.15×10^4	0.25
Noncombustible liquid β - γ	1.55×10^5	0.74
Combustible β - γ (resin from)	1.60×10^3	-

Table IV-3

Volumes of Solid Waste Generated Annually
by 30.5 1500-MTHM/yr Fuel Reprocessing Plants³
Supporting LWRs of 10⁶-MW(e) Generating Capacity
An equilibrium situation with complete U and
Pu recycle is assumed.

Waste type	m ³ /55-gal bbl	
	TRU	Non-TRU
Combustible (uncompacted, noncombusted form)	4.58E4/2.18E5	3.70E4/1.32E5
Noncombustible solids	5.06E4/2.41E5	9.61E3/4.58E4
Slurries, sludges, and resins	4.76E2/2.27E3	4.76E3/2.27E4
Filters	7.32E3/3.49E4	4.76E2/2.27E3
Spent-fuel basin (combustible resins)*		1.83E1/8.71E1

*Each fuel reprocessing plant is assumed to hold 800 fuel assemblies like those in ref. 3.

Table IV-4

BHPs for Solid Structural Waste or Spent Fuel Shipped per Annum per GW(e)

	No: of yr after shutdown				Time-integrated BHP in air for 1 to 1000 yr after reactor shutdown, km ³ air/kW(t)-yr	Principal isotopes
	BHP, km ³ air/kW(t)		Specif. activity of waste, Ci/kW(t)			
	1	200	1	200		
UWMAK-I	32.8	7.39E-6	735	2.46E-4	1.39E+2	⁴⁹ V, ⁵⁴ Mn, ⁵⁵ Fe, ⁶⁰ Co, ⁵⁷ Ni
UWMAK-III	0.25	0.12	150	2.81	1.16E+2	⁹³ Mb, ^{93m} Nb
BNL	1.64E-4	5.23E-6	2.03E-2	4.90E-4	7.02E-3	²⁶ Al, ⁵⁵ Fe, ⁵⁴ Mn, ¹¹⁹ Sn
ORNL Demo	0.105E-3	2.2E-6	6.85	2.44E-6	4.61E+1	⁴⁹ V, ⁵⁴ Mn, ⁵⁵ Fe, ⁵⁷ Co, ⁶⁰ Co, ⁵⁷ Ni
PPPL	145.4	0.143	0.207E-4		8.12E+2	⁴⁹ V, ⁵⁴ Mn, ⁵⁵ Fe, ⁵⁷ Co, ⁶⁰ Co
Fast breeder reactor ²⁵	2999	214	518		1.58E+5	⁹⁰ Sr, ¹³⁷ Cs, ²²⁶ Ra, ** ²³⁹ Pu, and other isotopes
LWR spent fuel ^{3,*}	33.99	25.87	349		2.45E+4	⁹⁰ Sr, ¹³⁷ Cs, ²²⁶ Ra, ** ²³⁹ Pu, and other isotopes

*PWR, 3.2% enrichment, based on a recycle core loading of 70% UO₂ and 30% MOX fuel, 25,000 MWd/MTHM burnup, and 35 MW/MTHM specific power.

**²²⁶Ra becomes significant as an actinide decay product after ~10⁴ yr.

the rate at which spent fuel is removed. Fission reactor fuel reprocessing plant waste includes fission products, activated cladding, and actinides.

As a gross comparison, Table IV-4 presents biological hazard potentials for shipped structural waste or spent fuel per annum. (As all of these materials are fairly nonvolatile metals being shipped in similar casks, a similar but unspecified release factor may be assumed for all cases. Thus, it is possible, with some confidence, to compare BHPs for transported goods.) Clearly, fusion reactors present a much smaller radiological hazard if this form of comparison is used. If we integrate, with respect to time, the BHP of waste streams over some period of time after reactor shutdown, some measure of the risk associated with holding these materials is obtained. These values may be compared only with each other, and such a comparison is possible since one may posit similar release factors for all these materials. It may be noted as well that higher wall loadings tend to reduce the biological hazard potential of shipped structural waste for fusion reactors. Attempts to minimize induced structural activity will produce even lower biological hazard potentials.

BHP decreases with time as the various radioisotopes decay away. Figures IV-1 and IV-2 rep-

resent BHP(t) for MPCs in water and air, respectively. LMFBR actinides are taken to be 1% of all uranium and plutonium and all of the remaining actinides. Both water and air are considered as possible media for transport of stored or shipped radionuclides. As a comparison, the amount of uranium and thorium in the coal burned annually in a 1000-MW(e) coal-fired plant is included²² along with 10 kg of tritium. Except for the low MPC of ⁹³Mo, the predominant long-lived isotope in UWMAK-III, fusion BHPs are significantly lower than comparable fission BHPs. In some cases, e.g., UWMAK-I and BNL, the BHP equals or approaches that of coal.

Figures IV-3 and IV-4 show the time intervals from 1 yr after reactor shutdown to 10⁷ and 10⁹ yr for air and water MPCs. Here, a premium is placed on short half-lives, high MPCs, and low initial activities. LMFBR actinides, LWR spent fuel, and coal all contain very long-lived radioisotopes, which is reflected in the large integrated BHPs exhibited for these cases.

When to cut off integrated BHP, since some actinides have half-lives around the expected remaining lifetime of the sun, is a serious question. Values of 10⁷ and 10⁹ yr were chosen to represent the time when the fusion systems will have satu-

Figure IV-1. BHP (water dilution) as a function of time after reactor shutdown for various electrical generating schemes.

Figure IV-2. BHP (air dilution) as a function of time after reactor shutdown for various electrical generating schemes.

Figure IV-3. BHP (water dilution) integrated over time ranges of 1 to 10^7 and 1 to 10^9 years after reactor shutdown.

Figure IV-4. BHP (air dilution) integrated over time ranges of 1 to 10^7 and 1 to 10^9 years after reactor shutdown.

rated, and the time when it is believed the earth as we know it will no longer exist.

After two centuries of storage, LWR spent-fuel BHPs will have nearly reached their long-term values. ^{239}Pu , ^{240}Pu , ^{242}Pu , and ^{241}Am represent the most significant contributions to the BHP after this time. The plutonium isotopes have half-lives of 2.44×10^4 , 6540, and 3.87×10^5 yr, respectively. ^{241}Am has a half-life of 433 yr. ^{131}I has not entered into the present considerations as it decays to insignificant levels in 1 yr. Long-lived fission products ^{79}Se , ^{99}Tc , ^{137}Cs ; some isotopes of Sm; and fission products in general do not contribute significantly to the BHP of spent fuel. ^{137}Cs and ^{90}Sr have half-lives of 30.1 and 29 yr, respectively, and contribute significantly to 1-yr BHPs, but they decay such that they contribute less than 1% of the total BHP in 200 yr. Metallic assembly components do not contribute significantly to spent-fuel BHP at the times considered. Many of the long-lived isotopes in metallic assembly components, ^{14}C , ^{63}Ni , ^{93}Mo , and ^{99}Tc , are the same isotopes found in CTR waste. Of primary concern in spent fuel, however, as has often been stated, are the long-lived transuranics.

Blanket waste is quite different from spent fuel because of the absence of ^{90}Sr , ^{137}Cs , and transuranics. This results in lower initial BHPs and more rapid decay. One notable exception is ^{26}Al , whose contribution is quite small to begin with. ^{54}Mn , ^{44}V , ^{58}Co , ^{60}Co , ^{57}Ni , and ^{55}Fe make up 95% of the BHP at removal time for 316-SS-based designs (UWMAK-I and the ORNL Demo). In 200 yr, ^{63}Ni ($T_{1/2} = 100$ yr) becomes the dominant isotope. The same isotopes are dominant for the PPPL design, and ^{93}Mo also contributes to the long-lived radioactivity. For UWMAK-III, after 1 to 3 yr of cool down, only ^{93}Mo and $^{93\text{m}}\text{Nb}$ are significant. ^{93}Mo has a half-life of roughly 3000 yr. One year after shutdown ^{26}Al , ^{54}Mn , ^{55}Fe , and ^{119}Sn all contribute to the BHP, but after 200 yr only ^{26}Al remains. Because of its long half-life (7.3×10^5 yr), its BHP declines very sluggishly with time.

IV.2. Ultimate Disposition of Fusion-Reactor-Activated Structural Waste

IV.2.1 Introduction. At least two options appear to exist with regard to the ultimate disposition of fusion-reactor-activated structural waste. First, materials may be isolated until all radioisotopes

have decayed to an innocuous level. At such time, the material may be either left where it is or returned to industry. Economics and demand for materials used in fusion reactors will determine whether or not recycling is desirable. A second option is to recycle the material before all radioisotopes have decayed to such low levels. Recycled material could then be used for reactor, or other radiation environment, applications. The level of activity at which recycling is permitted is set to be such that the dose required by a full-time worker with only minimal protection would be acceptable. Such protection could include fume hoods with HEPA filters, but there would be no need for glovebox facilities or shielding.

IV.2.2 Permanent, Ultimately Unguarded Disposal. In the event that recycling of fusion reactor structural material should seem unattractive, some means of permanent disposal will probably have to be implemented. Since disposal cost increases with irretrievability,^{20,23} economic considerations tend to favor less extreme isolation schemes. It is assumed that loss through leaching by groundwater or some other mechanism acts to disperse any residual radioactivity at some time after maintenance of the storage site ceases.

Following lines similar to those in BNWL-2019,¹ one may use the time required for all isotopes to decay to concentrations below their respective MPCs as the time structural radwaste must be actively managed. After all radioisotopes have decayed to their MPCs, the remaining material may be left unattended. However, for below-grade storage, a naturally occurring element will tend to inhibit the diffusion of its radioisotopes leached from stored waste. In the case of ^{26}Al ($T_{1/2} = 7.3 \times 10^5$ yr), aluminum present in the earth's crust limits the maximum concentration at which it is found around waste from the BNL minimum-activity blanket to roughly 10% of its MPC. Furthermore, isotopes such as ^{63}Ni ($T_{1/2} = 100$ yr) must be ingested to be hazardous to life. This particular isotope is present in stainless steel (<10 Ci/m³) in quantities which suggest that if long pathways to water tables are provided, loss through leaching may not be a significant hazard.

Table IV-5 presents times that fusion waste must be managed before it may be ignored. Below-grade storage and some form of containment (e.g., concrete vaults or 55-gal drums) are assumed. If one assumes that ^{26}Al and ^{63}Ni will not be a

Table IV-5

Times Required for Fusion Reactor Structural Waste To Decay to Safe Levels			
No. of years/limiting isotope			
	All isotopes	Neglect ^{26}Al	Neglect ^{63}Ni for 316 SS
UWMAK-I	1783/ ^{63}Ni	-	163.9/ ^{60}Co
BNL	1.72E7/ ^{26}Al	50.1/ ^{55}Fe	-
PPPL	8.16E4/ ^{93}Mo	-	-
ORNL Demo	2205/ ^{63}Ni	-	186.0/ ^{60}Co

problem for the reasons stated, some candidate structural materials may be ignored after a relatively short time. Clearly, molybdenum- or nickel-based alloys must be held for longer times as they contain large inventories of compacted waste composed of fairly long-lived isotopes ($100 \leq T_{1/2} \leq 3000$ yr). Stainless steels, Si-Al-Mg alloys, and SAP may be left unattended after less than two centuries. Rigid control of material impurity levels must be maintained for such short holding times to be possible, however.

IV.2.3 Structural Material Recycle. Some chemical components of fusion reactor structural waste (e.g., chromium) may be sufficiently scarce or valuable to make material recycling attractive. One factor that will significantly influence the decision of whether to recycle or not is the cost, which is directly coupled to the level of remaining radioactivity. In order to estimate how long an isolation period is required for waste after reactor shutdown, the annual dose received by a worker near an unshielded 1-m sphere of waste material is calculated as a function of isolation time. It is assumed that fume hoods and air filters will be used to keep the amount of radioactive waste dispersed as small as possible. Only effects due to shielding and remote operation are eliminated in this scheme. Furthermore, it is assumed that all surface-bound tritium is removed before operations begin and all bulk-bound tritium is lost up the fume hood stack. The geometry is intended to approximate a milling operation. Fabrication operations would clearly be more realistically modeled by a slab geometry.

For three proposed reactor structural waste streams and two time schedules for the worker receiving the exposure, approximate times to decay to two maximum annual exposure levels are cal-

Table IV-6

Varied Conditions Considered in Dose Calculations of Radiation Received by a Worker Exposed to a 1-m Sphere of Decayed Fusion Reactor Blanket Waste

It is assumed that the worker spends far more time at a distance away from the sphere than near it and that for 10% of his 8-hr day he is fully shielded from the sphere.

Case No.	Close distance, m	Far distance, m	% of time* close to sphere	% of time* far from sphere
1	2	10	10	80
2	4	10	10	80
3	4	20	10	80
4	2	10	5	85
5	4	10	5	85
6	4	20	5	85

*8-hr work day, 260 work days/yr.

culated. Spheres of spent-blanket material 1 m in diameter are taken as the source of gamma emissions from UWMAK-I (316 SS), the PPPL reactor (PF-16), and the BNL blanket design (Al, Al_2O_3).

Limits for maximum allowable worker exposure are taken to be the currently accepted 5.0 R/yr²⁴ and one tenth of that value. Table IV-6 shows the cases considered for obtaining this exposure. It is assumed that most of the time the worker will be 10 to 20 m from the source for milling operations. Some time must be spent near the recycle feed material, and this is taken to be 5 to 10% of the working day. It is assumed that 10% of the working day is spent far away, or otherwise shielded, from the source.

For these sets of conditions, the times required for reactor waste to decay to acceptable levels and the expected annual worker exposures after a 100-yr holding time are presented in Tables IV-7 and IV-8. Clearly, present maximum worker exposure standards (5 R/yr) may be met after reasonable holding times (usually <50 yr) and 10% of that value of exposure (0.5 R/yr) may be met in, at most, 70 yr. For 100-yr holding times, no exposure greatly exceeds 10 mR/yr.

Very soon after shutdown (~ 1 yr), minimum-activity blanket materials may be recycled under the scheme proposed. Because of the long half-life of ^{26}Al ($T_{1/2} = 7.3 \times 10^5$ yr), an increase in the holding time has little or no impact on exposures.

Table IV-7

Isolation Time Following Reactor Shutdown Required for Waste To Decay to a Level Such That a Worker Will Receive Annual Exposures of 5.0/0.5 R Under Conditions Given in Table IV-6

Case No.	Years		
	UWMAK-I	PPPL	BNL
1	28/46	52/70	<1/<1
2	22/38	46/62	<1/<1
3	18/34	42/58	<1/<1
4	24/42	48/66	<1/<1
5	20/38	44/62	<1/<1
6	14/32	38/56	<1/<1

Table IV-8

Annual Worker Exposure After 100 Years of Waste Isolation

Case No.	R/yr		
	UWMAK-I	PPPL	BNL
1	3.23E-4	1.09E-2	8.87E-4
2	1.40E-4	4.72E-3	3.83E-4
3	8.08E-5	2.73E-3	2.22E-4
4	2.06E-4	6.96E-3	5.64E-4
5	1.14E-4	3.85E-3	3.12E-4
6	5.14E-5	1.74E-3	1.41E-4

Stainless steels, or nickel-based alloys, however, continue to become more manageable with time, for at least a century in the former case and ten centuries in the latter case. After such times, worker dose rates become secondary to both natural and man-made radioactivity.

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APPENDIX A

Sensitivity of Waste Source Terms to First-Wall Lifetime Integrated Neutron Load

As mentioned earlier, various fusion reactor conceptual designs assume different first-wall lifetimes. In order to investigate sensitivity to first-wall integrated loading three designs, UWMAK-I, ORNL Demo, and PPPL, have their first-wall lifetimes normalized to 10.0 MW yr/m². Annual volume and activity of waste and integrated BHPs are calculated and compared to as-designed values.

Table A-1 shows annual waste terms for the three candidate conceptual designs for both as-designed and normalized first-wall lifetimes. It is assumed that the lifetimes of all other components are changed by the same factor as that used for the first wall. Beyond a blanket lifetime of two years there is only a very slight buildup of activity in 316 SS⁴ or PE-16.⁵ Clearly, the Wisconsin and Princeton designs exhibit more similar blanket source terms under the imposition of a common first-wall lifetime neutron load.

At present, great uncertainties exist as to what is a reasonable estimate of first-wall lifetime loads for different candidate materials. Therefore, previous estimates of waste volume based upon a design group's first-wall lifetime may change as improved data on material behavior become available.

Because of the small change in integrated wall load, the specific activity of blanket structural waste changes only slightly from the values presented in Table II-1 for the PPPL and ORNL Demo designs. Little change is seen for UWMAK-I as well. After 2.5 MW yr/m², very little buildup in blanket activity is expected.¹⁹

APPENDIX B

A Brief Comparison of LMFBR, LWR with Pu Recycle, and Fusion Fuel Cycles and Waste Streams

In the body of this report, comparisons are made between waste streams of fusion devices and LWRs with no recycle. By the time fusion is ready for implementation, breeder reactors may be one of the major alternatives for central power generation. Therefore, a brief comparison is included in this appendix of LMFBR waste management, based on an extrapolation of the Clinch River Breeder Reactor (CRBR), and fusion waste management.

A basic difference between our discussion of the LMFBR and the LWR fuel cycles is that reprocessing and fuel fabrication are included for the LMFBR. A mature breeder reactor economy is assumed; a similar assumption is made for LWRs. As a result of fuel reprocessing, much of the actinide inventory is converted to shorter-lived, less toxic fission products.

Table A-1

Annual Structural Waste Source Terms per GW(e) for First-Wall Lifetimes,
Both As-Designed and Normalized to 10 MW yr/m²

	Design first-wall lifetime neutron load, MW yr/m ²	Annual structural waste at design wall lifetime/GW(e) (material/metric tons)	Annual structural waste for 10 MW yr/m ² first-wall lifetime (material/metric tons)
UWMAK-I*	2.5	SS/543	33/133.75
PPPL	10.5	PE-16/100.0	PE-16/105.0
ORNL Demo	10.5	SS/8.97	SS/9.42

*Complete blanket removal is assumed for UWMAK-I, while for ORNL Demo only the first 20 cm are changed.

Table B-1

Biological Hazard Potentials for High-Level Wastes
Generated During One Year of Mature Reactor Operation

	LMFBR (fission products, transplutronics, and 1% U + Pu)	LWR	UWMAK-I
BHP in air, km ³ /kW(t)			
at t = 1 yr	3.00E3	3.74E0	3.28E1
at t = 1000 yr	2.78E1	2.58E0	3.12E-8
Integrated BHP			
1 to 10 ⁷ yr	2.33E13	7.06E14	5.80E9
1 to 10 ⁹ yr	2.93E13	4.54E16	5.80E9
BHP in water, m ³ /kW(t)			
at t = 1 yr	9.42E7	1.46E4	4.50E5
at t = 1000 yr	5.22E4	6.00E2	1.04E-2
Integrated BHP			
1 to 10 ⁷ yr	1.50E17	9.41E16	6.68E13
1 to 10 ⁹ yr	2.62E17	6.05E18	6.68E13

Table B-2

Comparison of Estimated Annual Quantities of Radioactive Solid Wastes
From an LWR and an LMFBR*

Wastes	1000-MW(e) LWR with plutonium recycle	1000-MW(e) LMFBR
Produced at reactor site		
Medium and low level		
ft ³	8,000-12,000	1,000-2,000
No. of 55-gal drums	560-1,120	140-280
Burial ground, ft ²	800-1,600	200-400
Noble gases		
Cylinders	-	5
Produced at reprocessing plant site		
High-level solid		
ft ³	55	55
No. of 12-in.-diam × 10-ft-long containers	9	9
Spent-fuel storage tank space, ft ²	11	11
Cladding hulls		
ft ³	60	165
No. of 3.5-ft ³ containers	17	48
Repository** or burial space, ft ²	12	35
Medium- and low-level solid		
ft ³	600-4,000	5,000-10,000
No. of 55-gal drums	80-540	700-1,400
Burial ground, ft ²	100-800	1,000-2,000
Noble gases		
Cylinders		1
Produced at fabrication plant site		
Medium and low level, including Pu contaminated		
ft ³	10,000-30,000	10,000-30,000
No. of 55-gal drums	1,400-4,200	1,400-4,200
Repository** space, ft ²	2,000-6,000	2,000-6,000

*Taken from ref. 25.

**If required by future regulations.

Table B-1 presents biological hazard potentials for one year's high-level wastes from an LMFBR, LWR with plutonium recycle, and UWMak-I. LMFBR waste is composed primarily of fission products, transplutoniums, and 1% of the reprocessed uranium and plutonium. To provide a more direct comparison between an LWR and LMFBR, the LWR fuel cycle is now closed with regard to plutonium. UWMak-I is taken as a representative fusion plant.

BHP decreases with time most rapidly for fusion waste. LMFBR waste has the greatest near-term biological hazard potential. However, the presence of greater quantities of long-lived actinides means that LWR waste has a significantly greater long-term integrated biological hazard potential.

Table B-2 illustrates an abbreviated comparison of wastes created on site annually in the operation of an LWR with Pu recycle and an LMFBR.²⁴ LWRs generate four times as much low- and medium-level waste as a similar-sized LMFBR, and noble gases are neglected because of the relatively small quantities involved. LMFBR fuel reprocessing generates more cladding hulls and low- and medium-level waste than does the LWR. No differences are seen between the two reactor types in reprocessing high-level waste or low- and medium-level waste from fuel fabrication. Differences in volumes of low- and medium-level waste are not considered significant for the present comparison.

Greater distances imply higher accident probabilities. However, it seems unlikely that distances and probabilities would be increased by more than a factor of 2, and, therefore, they were not estimated. However, if fuel with short decay times is reprocessed, the consequences of any release of radioactivity will be more significant.

In conclusion, it appears that differences arising from the inclusion of LMFBRs are due to recycling operations. LMFBRs represent the greatest near-term biological hazard. Less than 1000 years (closer to 200) after reactor shutdown, fusion waste represents the least biological hazard.

APPENDIX C

Further Comparisons of Fusion and Fission Wastes and Fuel Cycles

Further evaluations and comparisons of fusion and fission reactor wastes may be made on the basis of the percentage of the United States air

Table C-1

Percent of U.S. Air and Groundwater Reserves Needed To Dilute the Annual Waste From Various 10⁶-MW(e) Nuclear Generating Systems to Their MPCs

	% U.S. air resource*	% U.S. groundwater**
UWMak-I	0.38	5.83-3
UWMak-III	682	286
BNL	2.92E-2	2.36E-2
PPPL	1700	87.1
ORNL Demo	0.11	1.67E-3
LMFBR (fission products)	1.22E+2	6.03E+3
LMFBR (actinides, 1%)	1.70E+6	2.0E+7

*Continental U.S. only - to an altitude of 30,000 ft.

**Continental U.S. only - to a depth of ½ mile (U.S. Geological Survey).

Table C-2

BHPs of Indian Monazite Ore With and Without ThO₂

	BHP (air), km ³ /kW(t)-yr	BHP (water), km ³ /kW(t)-yr
Total with ThO ₂	0.143	68.5
Total without ThO ₂	7.64E-3	1.00

and groundwater reserves needed to dilute the annual waste from a 10⁶-MW(e) economy to MPC levels. In order to estimate the possible effects of the front end of a uranium or thorium fuel cycle, BHP values for uranium and thorium ores are calculated in this appendix, as well.

In these calculations it is assumed that for 100 years no release is made, and after 100 years the waste is distributed evenly through all the air or groundwater considered. No attempt is made to associate these conditions with an accident scenario; such a situation is set up for comparison alone. Clearly, such dilution could not occur in the groundwater case in times of interest.

Table C-1 presents results for the above situations. Limitations imposed upon fusion waste results are the uncertainties due to sensitivities associated with variations in wall loading and to the lack of data at the time these early conceptual designs were made.

Clearly, for all cases fusion wastes require less dilution than fission wastes. Furthermore, after 100 years stainless steel becomes a very manageable material.

Mining of fuels is another activity with radiologic hazards. Fuel for fusion reactors includes, for a D-T cycle, deuterium from sea water, lithium, and possibly beryllium. Aside from the chemical toxicity of beryllium, which is not considered, no radioactivity is associated with these input streams other than naturally occurring background radiation from ^{40}K etc.

If one considers monazite ore, BHP may be obtained for the amount of ore that must be mined to supply the necessary ^{235}U to an LWR for one year. An enrichment of 3.2% is assumed. Ore com-

position is taken to be that of Indian monazite²⁶ (9.6% ThO_2 , 0.3% U_3O_8). If one neglects the thorium, the uranium composition is found to be similar to that of other uranium ores. Table C-2 presents the results of these calculations. If one considers that the vast majority of the ore stays in the ground (or in the background 0.1 ppb average uranium content of water) and that most of the mined ore is returned to the earth as tailings, these results show that although a significant amount of radioactivity is handled [$\sim 500 \text{ Ci/GW(e)-yr}$], most of it is not affected by these operations.