CONF-771203--4

PREPRINT UCRL- 80387

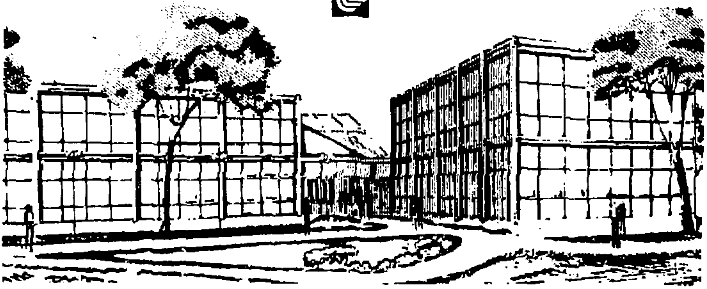
Lawrence Livermore Laboratory

A WASTE MANAGEMENT STRATEGY FOR NUCLEAR FUSION POWER SYSTEMS FROM A REGULATORY PERSPECTIVE

R. A. Heckman

December 6, 1977

This paper was prepared for submission to the
Miami International Conference on Alternative Energy Sources
December 5-7, 1977 Miami, Florida



MASTER

A WASTE MANAGEMENT STRATEGY FOR NUCLEAR FUSION POWER SYSTEMS FROM A REGULATORY PERSPECTIVE*

R. A. Heckman
Lawrence Livermore Laboratory
Livermore, California U.S.A.

ABSTRACT

A waste management strategy for future nuclear fusion power systems is developed using existing regulatory methodology. The first step is the development of a reference fuel cycle. Next, the waste streams from such a facility are identified. Then a waste management system is defined to safety handle and dispose of these wastes. The future regulator must identify the decisions necessary to establish waste management performance criteria. The data base and methodologies necessary to make these decisions must then be developed. Safe management of nuclear fusion wastes is not only a technological challenge, but encompasses significant social, political, and ethical questions as well.

INTRODUCTION

In this paper we develop a waste management strategy for future nuclear fusion power systems using an existing regulatory methodology. A probabilistic consequences analysis methodology is currently under development [1], [2] to provide a technical basis for promulgating performance based criteria for nuclear wastes from fission power systems [3]. Following our current approach, we will first develop a generic fuel cycle for a class of future commercial nuclear fusion power systems using deuterium an tritium as fuels in the reaction.

$$D + T \rightarrow {}^{4}He\ (3.5MeV) + n\ (14.1MeV) \qquad (1)$$

We further assume that deuterium will be obtained from ordinary water. Tritium would be bred from lithium by neutron capture by using a lithium blanket surrounding the plasma. The capture reactions are

$$ {}^{6}Li + n \rightarrow T + {}^{4}He + 4.8MeV \qquad (2)$$

---

*Work performed under the auspices of the Department of Energy under contract Number W-7405-Eng-48.

and

$$^{7}\mathrm{Li} + n \rightarrow \mathrm{T} + {}^{4}\mathrm{He} + n - 2.5\mathrm{MeV} \qquad (3)$$

Having developed the baseline or reference fuel cycle, we may identify the various radioactive waste streams from such a facility. We can define a waste management system to safely handle and dispose of these wastes. For a regulator, the identification of the decisions [4] to establish waste management performance criteria and the development of the data base and methodologies necessary to make these decisions are of prime importance to the success of any waste management program. For a regulator, the starting point in the decision making process is to determine: what decisions must be made; when must they be made; who will make them; what supporting data will be needed; and finally, what are the legal and procedural constraints. "What" and "when" can be derived by consulting industry and government schedules. The regulator must consider what is necessary to protect the public health and safety and the environment. Other considerations are the detailed decisions faced by the regulatory staff in their licensing reviews; and finally, what are the decisions the industry must make in designing waste management facilities that could be affected by regulatory positions.

In any case we must recognize managing nuclear fusion wastes is not only a technical challenge [5], but encompasses significant social [6], [7], political [8], and ethical [9] questions as well. However, we can expect regulations that wil be structured to require conformance with a fixed set of minimum acceptable performance standards (technical, social, and environmental) [4] for fusion-related waste management activities while providing for flexibility in technological approach.

Reference Fusion Fuel Cycle

We have chosen a reference or base line fuel cycle [10] based on composite generic design of a magnetically confined type of fusion reactor [11]. Table I summarizes net power characteristics and calculated neutron fluences at the initial containment wall for several magnetic-confinement schemes. A large number of nuclear reactions is possible for the 14MeV neutrons and structural materials contained in the reference designs mentioned above. Table 2 [12] summarizes calculations of radionuclide density in the containment wall of different CTR designs as a function of time. We would not expect an inertially confined type of fusion system to have a significantly different waste management system; only the details of waste quantities and types of radionuclides are expected. Our reference design envisions DT fuel injected into a magnetically confined plasma and surrounded with a lithium blanket.

The lithium is extracted from the blanket, heat transferred to an energy conversion system, and tritium recovered. Figure 1 is a schematic layout of the reference facility. For simplicity, the lithium is shown without a secondary loop in the energy recovery section. In the plasma exhaust purification system, unspent tritium is also recovered, as well as deuterium. The recovered tritium and deuterium are recycled back to the main fuel preparation unit, where additional deuterium is added. Excess tritium is hydrided into a solid metal matrix, much as titanium tritide, and processed for shipment as byproduct fuel material. Steam is generated in the power recovery section of the plant and drives a turbine to produce electrical power. An active tritium containment system is envisioned utilizing both a hermetically sealed reactor hall shell and a continuous catalytic oxidizer-molecular sieve adsorber tritium cleanup sytem [13].

Radioactive Waste Streams

Waste streams from a nuclear fusion power plant fall into two general categories: Those resulting from normal day to day operations; and neutron activation of structural materials that have a definite operating life determined by radiation damage effects. Gaseous wastes are expected from permeation and diffusion of tritium through the structural walls of the CTR reactor and blanket components. A reactor hall containment system should be able to limit these gaseous releases to less than 1Ci/d [13]. Additional gaseous wastes are expected from the main fuel preparation unit as well as the plasma exhaust purification system.

Liquid and gaseous wastes are anticipated for various operations in the energy conversion system, principally tritium. The tritium extraction and tritide preparation unit will produce three types of waste - liquid, gaseous, and solid - but again, primarily tritium and corrosion products from activated structural wall materials by the lithium. We have made rough estimates of the three waste forms associated with different operations in our reference fuel cycle. These estimates are summarized in Tables 3, 4, and 5. The values presented in these tables are consistent with previously reported work [14] Table 6 summarizes the principal long lived structural activation products [5], [16], [19].

By inspection of the previous Tables 1 through 6 we see, obviously, that the majority of the longer-lived radionuclides are associated with the structural components of the reactor, i.e., the inner wall of the reactor chamber and the magnetic field conductors, their supports and insulators. It is interesting to note that for a UWMAK-I, with a two year operational lifetime, the inner blanket structural components contribute 500 metric tons of solid wastes; and the outer blanket structural components contribute an additional 1,240 metric tons of solid waste [14]. A dose calculation for the radiation field outside the shield in a UWMAK-I for times after shutdown is given in Table 7 [16]. We see, therefore, that direct access removal of these components is not feasible because of the radiatio fields involved. The assumption is of course, that we cannot wait for decay because of economic reasons. The problem is further complicated by direct tritium contamination of the metals by permeation. Obviously, a remote handling operation of some sort will be necessary to remove and package for transportation the expended wall components. The mechanical configurations and sheer size and weight of these spent chamber walls will produce major decontamination and decommissioning problems and issues for the regulator.

Waste Management System

We can now define a waste management system that will allow a comparison of the relative risk between alternatives in a fusion fuel cycle operation. Figure 2 is a representation of a hierarchical system analysis structure for modeling a fusion power waste management system. This approach allows us to conduct a probabilistic consequences analysis. Note that in Figure 2, time flows from left to right and functional detail flows from top to bottom. With this model we can derive an expected value, i.e., probability that an event will occur times the consequences of that event for a radiological risk/impact performance measure. Normalizing this expected value of risk to an amount of electric power generated is a useful indicator of risk/benefit, i.e., person REM/MWe-yr. In addition, for a given scenario, the concentration of a radionuclide in air or water could be predicted at various probabilities of occurence.

Again referring to Figure 2, the waste management system is defined as follows. All wastes will be treated and packaged for disposal. There will be an interim storage step at the power plant site. A transportation step follows, which takes the packaged radioactivity to the final disposal site. The disposal process reguires a handling and storage operation at this final site. The material will be buried, or otherwise isolated, and a post-burial future history phase is entered. The specific activity of this material is such that shallow land burial would probably be allowed.

Intrusion by the near-surface ground water, or in hydrologic terms, an unconfined near-surface acquifer, would represent the most probable radionuclide transport mechanism into the biosphere. Our waste management system model provides for a quantitative analysis of the radioactivity release source term. The environmental model takes these source terms and uses them as input to the radionuclide migration model and the surface water use model, shown in Figure 4. The human water use model is indicated schematically in Figure 5. To better illustrate the system analysis methodology, let us follow the event tree for the transportation element. Referring to Figure 2, we arrive at the transportation system block. If we allow mixed mode transportation there is a probability that a fraction of the radioactivity will be transported by truck. We follow then down the right element of the transportation tree, labeled TRUCK. Now moving on to Figure 3, detailed event tree for truck transportation accidents, there will be a conditional probability of an accident. To illustrate further the methodology, let us follow the middle event tree. Given the accident, there is the conditional probability of a fire. Whether the accident scene is in a urban or rural setting will effect the demographical factors and, therefore, the consequences. Given the fire, there is a conditional probability that the fire severity will compromise the shipping cask integrity. Given the cask failure, there is a probability distribution function that expresses the degree of failure as a function of fire severity and intensity. There will be an associated release function for airborne dispersibility also as a function of the same fire severity and intensity. The expected value of the release is obtained by folding together the probability distribution function and the release function and then multiplying by the event tree conditional probabilities. Besides arriving at radiological exposures by deterministic methods for fixed scenarios and fixed future histories, a probabilistic risk analysis can also be performed.

Summary

It seems most likely that by the time nuclear fusion power systems are commercially feasible that radiation exposures allowable to the general public will be further reduced so that nearly all radioactivity must be confined within the containment shell (reactor hall) surrounding the total power plant system. In the parlance of the regulator, an objective performance measure for the acceptable risk associated with the production of power from nuclear fusion will be defined and generally accepted by our society, at levels below those currently allowed [17]. A review of the currently available neutronic code predictions of the radionuclides produced in proposed fusion reactor concepts shows several important points. First, the induced activities in the structural components have half-lives of significent duration, and have specific activities approaching those found in existing light water fission power reactors. Thus, wastes from fusion power systems may require isolation from the biosphere for times approaching those periods nominally asociated with the fission products from fission power systems (not to be confused with transuranium radionuclides produced by neutron capture). As a potential user of nuclear fusion power systems, Ashworth [18] may be underestimating the regulatory issues and the public perception of what is an acceptable risk for a high technology energy system. The final point being that occupational exposures may become the dominant societal risk associated with nuclear fusion power because of tritium exposures during normal maintenance operations and whole body exposures, as well as tritium impacts, during reactor chamber decontamination and decommissioning.

In conclusion, we have presented a possible methodology for analyzing the societal consequences of operation of a nuclear fusion power waste management system that is based on current methodology.

References

1. R. A. Heckman and T. Holdsworth, "Development of Performance Criteria for Solidified High-Level Waste," UCID in press, December 1977.
2. J. J. Cohen et al, "Determination of Performace Criteria for High-Level Solidified Nuclear Waste," NUREG 0279, February 1977.
3. R. A. Heckman, J. Miskel, and R. Borg, "Management and Storage of Commercial Power Reactor Wastes," ERDA 76-162, July 1976.
4. W. P. Bishop, J. Malaro, and W. Hewitt, "NRC and Nuclear Waste: The Process for Decisions IAEA Waste Management Conference Proceedings, July 1977."
5. J. W. Bartlett et al, report coordinators, "Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle," ERDA 76-43, Volumes 1 through 5, May 1976.
6. C. Hohenemser, R. Kaspersen, and R. Kates, "The Distrust of Nuclear Power," Science Volume 196, Page 2851, April 1977.
7. Paul Slovic, "Judgment, Choice, and Societal Risk Taking," K. R. Hammond (editor), "Judgement and Choice in Public Policy Decisions," AAAS Symposium Volume, Fall 1977, in press.
8. NRC Staff, "State Workshops for Review of High-Level Waste Repository Site Suitability Criteria," NUREG 0354, November 1977.
9. M.N. Maxey, "A Bioethical Perspective on Acceptable Risk Criteria for Nuclear Waste Management," UCRL 52320, July 1977.
10. A. B. Johnson, Jr. and T. J. Kabele, "Tritium Containment in Fusion Reactors," CONF-760935 Part 4, September 21-23, 1976.
11. C. E. Easterly, K. E. Shank, and R. L. Shoup, "Radiological and Environmental Aspects of Fusion Power," Nuclear Safety, Volume 18, Page 2, March-April, 1977.
12. R. W. Conn, T. Y. Sung, and M. A. Abdou, "Comparative Study of Radioactivity and Afterheat in Several Fusion Reactor Blanket Designs," Nuclear Technology, Volume 26, 1975.
13. T. R. Galloway, "Tritium Control in a Mirror Fusion Central Station," CONF-760935, Part 4, September 21-23, 1976.
14. J. D. Kaser et al, "Fusion Reactor Waste Management," CONF-760935, Part 4, September 21-23, 1976
15. W. F. Vogelsang et al, "Transmutation, Radioactivity, and Afterheat in a Deuterium-Tritium Tokamak Fusion Reactor," Nuclear Technology, Volume 22, Page 379, 1974.

16. W. F. Vogelsang, "Radioactivity and Associated Problems in Thermonuclear Reactors," CONF-760935, Part 4, September, 21-23, 1976.

17. J. J. Cohen et al (editor), "Determination of Acceptable Risk Criteria for Nuclear Waste Management Progress Report for FY77 Work," UCID in press, October 1977.

18. C. P. Ashworth, "A User's Perspective on Fusion-Part II," AAAS Annual Conference, Denver, Colorado, February 1977.

TABLE I

Performance Parameters of Various CTR Designs [11]

Reactor Design	Total Power Mw_t	Net Power Mw_e	14MeV Wall Load Mw/m^2	14MeV Neutron Current n/cm^2 sec	Total Flux n/cm^2 sec	Total Fluence at Replacement n/cm^2	Replacement time yrs.
Tokamaks							
Oak Ridge	1000	520	0.44	1.95×10^{13}	1.48×10^{14}	3×10^{22} †	10
Princeton	5300	2000	1.76	7.8×10^{13}	8.65×10^{14}	1×10^{23} ††	5
U of Wash.	4700	1500	1.25	5.5×10^{13}	4×10^{14}	3×10^{22}	2
Theta Pinch Argonne-Los Alamos	12000	4100*	6.66**	2.97×10^{14}	2.71×10^{15}	8.5×10^{22}/yr	2
Mirror (Yin-Yang) Livermore	400	200	1.6 av 1.9 pk	7.1×10^{13}	5.2×10^{14}	?	NA
Reference Reactor (this paper)	2500	1000	1.0	4×10^{13}	3×10^{14}	2.5×10^{22}	2

* duty cycle dependent
** 3 - sec reactor cycle
100% plant load factor
† 60% plant load factor
†† 75% plant load factor

TABLE II [12]

Radionuclide Density in the First Containment Wall for Various CTR Designs as a Function of Time

	Time After Shutdown									
	1.7 hr		2 years		20 years		200 years		2000 years	
Tokamak Design (first-wall material)	Dominant Isotopes	Radioactivity, dis/(sec)(cm^3)	Dominant Isotopes	Radioactivity, dis/(sec)(cm^3)	Dominant Isotopes	Radioactivity, dis/(sec)(cm^3)	Dominant Isotopes	Radioactivity, dis/(sec)(cm^3)	Dominant Isotopes	Radioactivity, dis/(sec)(cm^3)
UWMAK-I	^{55}Fe	0.964×10^{12}	^{55}Fe	0.570×10^{12}	^{55}Fe	0.594×10^{10}	^{63}Ni	0.369×10^{8}	^{59}Ni	0.169×10^{6}
(type 316 stainless	^{51}Cr	0.420×10^{12}	^{54}Mn	0.449×10^{11}	^{60}Co	0.160×10^{10}			^{53}Mn	0.253×10^{5}
steel)	^{54}Mn	0.223×10^{12}	^{57}Co	0.151×10^{11}	^{63}Ni	0.134×10^{9}				
	^{57}Co	0.697×10^{11}	^{60}Co	0.173×10^{11}						
	^{60}Co	0.222×10^{11}								
	^{58}Co	0.316×10^{12}								
	^{56}Mn	0.401×10^{12}								
ORNL	^{92m}Nb	0.678×10^{13}	^{93m}Nb	0.903×10^{10}	^{93m}Nb	0.378×10^{10}	^{94}Nb	0.174×10^{9}	^{94}Nb	0.164×10^{9}
(Nb-1%Zr)	^{90}Y	0.915×10^{11}	^{94}Nb	0.175×10^{9}	^{94}Nb	0.175×10^{9}				
	^{95m}Nb	0.729×10^{11}								
PPPL	^{55}Fe	0.103×10^{12}	^{55}Fe	0.618×10^{11}	^{55}Fe	0.645×10^{9}	^{63}Ni	0.199×10^{8}	^{59}Ni ^{53}Mn	0.812×10^{4} 0.186×10^{4}
(PE-16)	^{51}Cr	0.646×10^{11}	^{54}Mn	0.193×10^{10}	^{60}Co	0.937×10^{9}				
	^{54}Mn	0.957×10^{10}	^{57}Co	0.802×10^{10}	^{63}Ni	0.725×10^{8}				
	^{57}Co	0.476×10^{11}	^{60}Co	0.901×10^{10}						
	^{60}Co	0.116×10^{11}								
	^{58}Co	0.161×10^{12}								
	^{57}Ni	0.948×10^{10}								
BNL* (Al)	^{24}Na	0.567×10^{12}	^{26}Al	0.184×10^{6}	^{26}Al	0.184×10^{6}	^{26}Al	0.164×10^{6}	^{36}Al	0.184×10^{6}

*BNL = Brookhaven National Laboratory.

TABLE III

Summary of Solid Waste Quantities Estimates From Reference Fuel Cycle

Waste Description	Source	Quantity	Ci/yr	Equivalent Packaged Shipping Containers 55 gal. drums
Zirconium Foil	Impurity Traps	10^5 kg/yr	5×10^6	80
Li_2O	T_2 Extraction System	10^3 kg/yr	2×10^5	3
Yttrium Foil	T_2 Extraction System	10^3 kg/yr	10^3	3
Titanium Foil	Tritide Prep System	10^5 kg/yr	10^6	75
Charcoal	Exhaust Purification	10^5 kg/yr	10^6	120
Misc. Solids	Liquid Waste Immobilization Energy Conversion System	10^5 kg/yr	10^2	200

TABLE IV

Summary of Liquid Waste Quantity Estimates
from Reference Fuel Cycle

Waste Description	Source	Quantity	Ci/yr	Disposition
Liquid Waste	Energy Conversion System (turbine & pump seal leakage) (condensor blowdown etc.)	10^4 kg/yr	10^2	Immobilize in Concrete
Laundry Waste Water	Clothing Laundry	5×10^5 kg/yr	<1	Released to Environment

TABLE V

Summary of Gaseous Waste Quantity Estimates From Reference Fuel Cycle

Waste Description	Source	Activity Release	Disposition
Activation Products	Leaked Air	^{41}Ar ~0	
		$^{13}N_2$ ~0	
		^{14}C 30 Ci/yr	As CO_2 Trapped in Exhaust Purification
Tritium	Permeation Through Energy Conversion System Walls	150 Ci/day	Into Reactor Hall Containment System
Tritium	Exhaust Purification System Walls	20 Ci/day	Into Reactor Hall Containment System
Tritium	Main Fuel Prep System Walls	30 Ci/day	Into Reactor Hall Containment System
Tritium	Permeation Through Blanket Wall	100 Ci/day	Into Reactor Hall Containment System
Tritium	Reactor Hall Containment System Effluent	<1 Ci/day	Into Environment

TABLE VI [15] [16] [19]

Structural Activation Products for Reference Design

Based on 316 Stainless Steel
(but accounting for impurities)

Activation Product	Half-Life
$^{49}\mathrm{V}$	330 days
$^{51}\mathrm{Cr}$	27.8 days
$^{53}\mathrm{Mn}$	$1.9\mathrm{x}10^{6}$ years
$^{54}\mathrm{Mn}$	303 days
$^{55}\mathrm{Fe}$	2.6 years
$^{59}\mathrm{Fe}$	45.6 days
$^{57}\mathrm{Co}$	27.0 days
$^{58}\mathrm{Co}$	71.3 years
$^{60}\mathrm{Co}$	5.263 years
$^{59}\mathrm{Ni}$	$8\mathrm{x}10^{4}$ years
$^{63}\mathrm{Ni}$	92 years
$^{91}\mathrm{Nb}$	10^{4} years
$^{93}\mathrm{Mo}$	> 100 years
$^{99}\mathrm{Tc}$	$2.12\mathrm{x}10^{5}$ years

TABLE VII [16]

Calculated Dose Rate Outside the Shield in a UWMAK-I For
Times After Shutdown
1.25 MW/m^2 Wall Loading

Time After Shutdown	Dose Rate mREM/hr
0	4072.0
1 hour	3068.0
1 day	1165.0
1 week	1084.0
1 month	870.2
1 year	167.5

Natural Background ~100 mREM/yr.

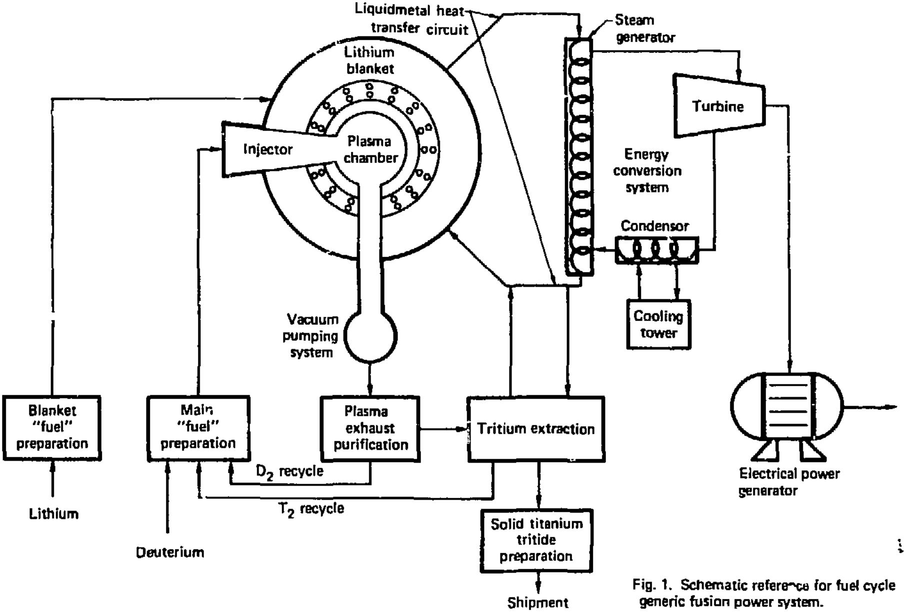


Fig. 1. Schematic reference for fuel cycle generic fusion power system.

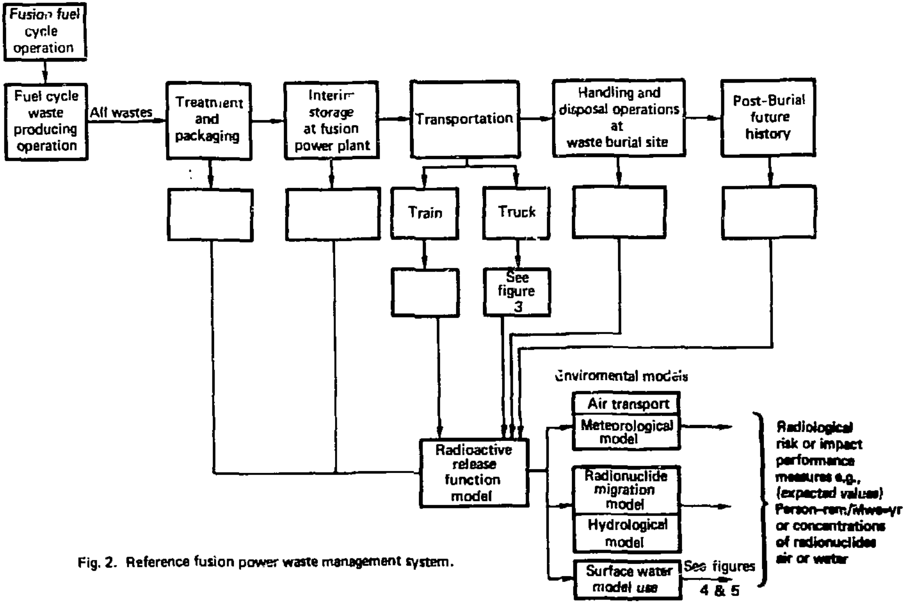


Fig. 2. Reference fusion power waste management system.

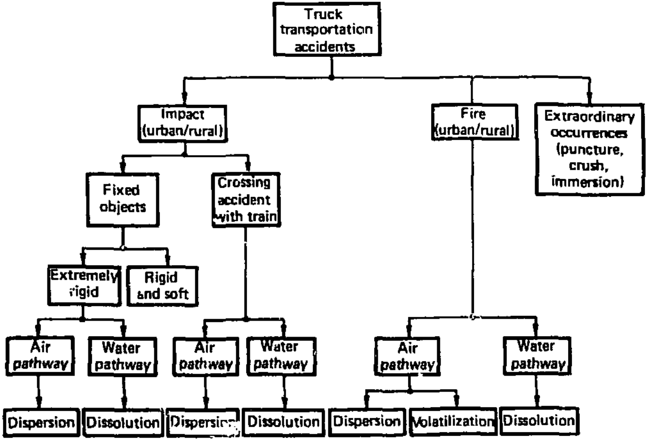


Fig. 3. Detailed event tree for truck transportation accidents.

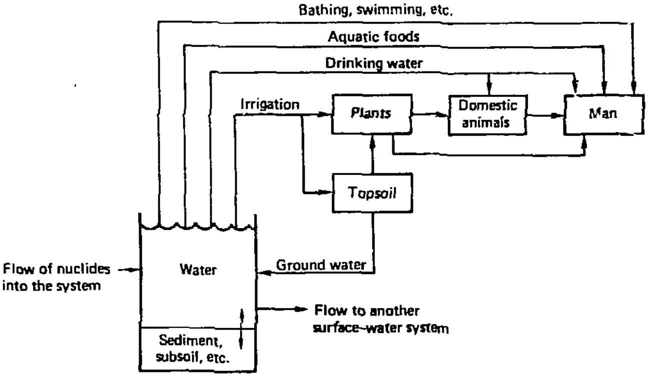


Fig. 4. Model for surface water system.

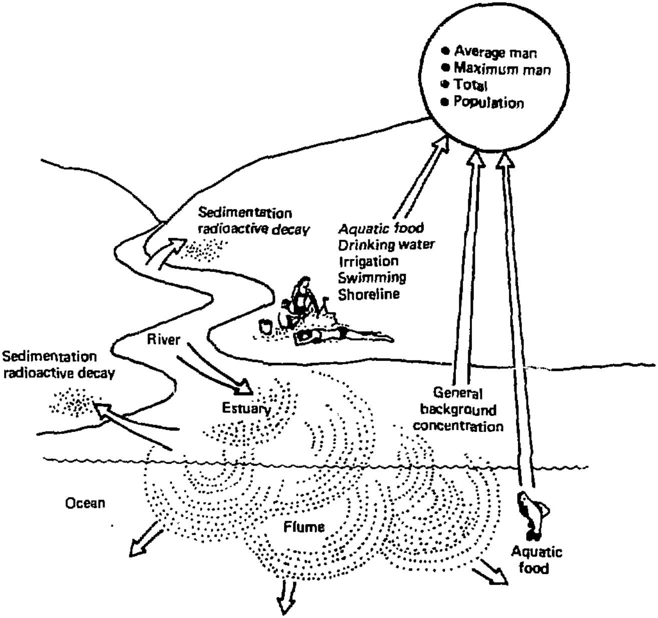


Fig. 5 Human water usage model.