LA-UR -80-2885

CONF-801011--57

TITLE: ENVIRONMENTAL AND SAFETY ENVELOPE ANALYSIS
FOR INERTIAL FUSION APPLICATIONS

AUTHOR(S): Joyce Gross Freiwald
John H. Pendergrass
Thurman G. Frank

MASTER

SUBMITTED TO: Fourth ANS Topical Meeting on the
Technology of Controlled Nuclear Fusion
King of Prussia, Pennsylvania,
October 14-17, 1980

University of California

DISTRIBUTION OF THIS DOCUMENT IS

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3

ENVIRONMENTAL AND SAFETY ENVELOPE ANALYSIS FOR INERTIAL FUSION APPLICATIONS[*]

Joyce Gross Freiwald, John H. Pendergrass, and Thurman G. Frank

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545

This paper describes an envelope analysis concept and a generic process flow model which together can be used to identify and isolate plant functions and provide for detailed mass- and energy-balance bookkeeping for environmental and safety studies. Los Alamos Scientific Laboratory's (LASL) two laser fusion power plant concepts were analyzed with this approach. Samples of the detailed tables of material flow rates into and out of an envelope are presented in this paper. The tritium and lithium inventories and air activation were identified as having important potential environmental problems and safety risks.

The purposes of this paper are to describe an envelope analysis concept for use in environmental and safety studies and to provide a bookkeeping scheme to integrate environmental and safety research in the development of a technology. These concepts have been applied to two laser fusion power plant designs to show how they can be used. Samples of the detailed results have been selected and presented in this paper.

Background

Typically, detailed environmental and safety analyses of new technologies are not performed until designs are finalized. Two examples are the light water reactor and the liquid metal fast breeder reactor. This is basically because there is very little funding for environmental and safety research, the designs are not sufficiently defined for specific analyses, and verified evaluation methodologies have not existed. This postponement has caused expensive redesign, licensing and construction delays, and a lowering of the plant capacity. However, if potential hazards and licensing problems could be identified early enough, they could be solved at lower cost, and inappropriate design approaches could be eliminated. Each generation of experiments should be instrumented to provide environmental and safety data to be used as design criteria for later generations of experiments. This inherently minimizes environmental impact by safety design throughout the research, development, and demonstration process. A data base successfully developed through design iterations would facilitate both the preparation of environmental impact statements and the licensing process.

As the technology development program for laser fusion evolves over the next 20 years or more, studies on specific aspects will be parcelled out to different organizations, and there will be a continual changeover in people doing the environmental and safety analysis. Therefore, a *logical, uniform, and simple bookkeeping scheme is needed to integrate the environmental and safety research and the resulting data.*

Envelope Analysis Concept

Envelope analysis can provide a simple, logical, uniform, and universally applicable framework to guide research and to integrate study results. This approach identifies and isolates plant functions, provides for detailed mass- and energy-balance bookkeeping, and outlines a nested envelope containment scheme. Los Alamos Scientific Laboratory's two laser fusion power plant concepts, the wetted wall and the magnetically protected wall reactors, were analyzed using this approach (see Figs. 1 and 2, respectively). Each envelope is conceived as a boundary around a system's components. Thus, in Fig. 1, envelope A contains the reactor itself, envelope B contains the pipe chase area, envelope C contains the lithium cleanup equipment, and envelope D contains the laser hall. All of these envelopes, along with five others are

---

[*] Work performed under the auspices of the U.S. Department of Energy.

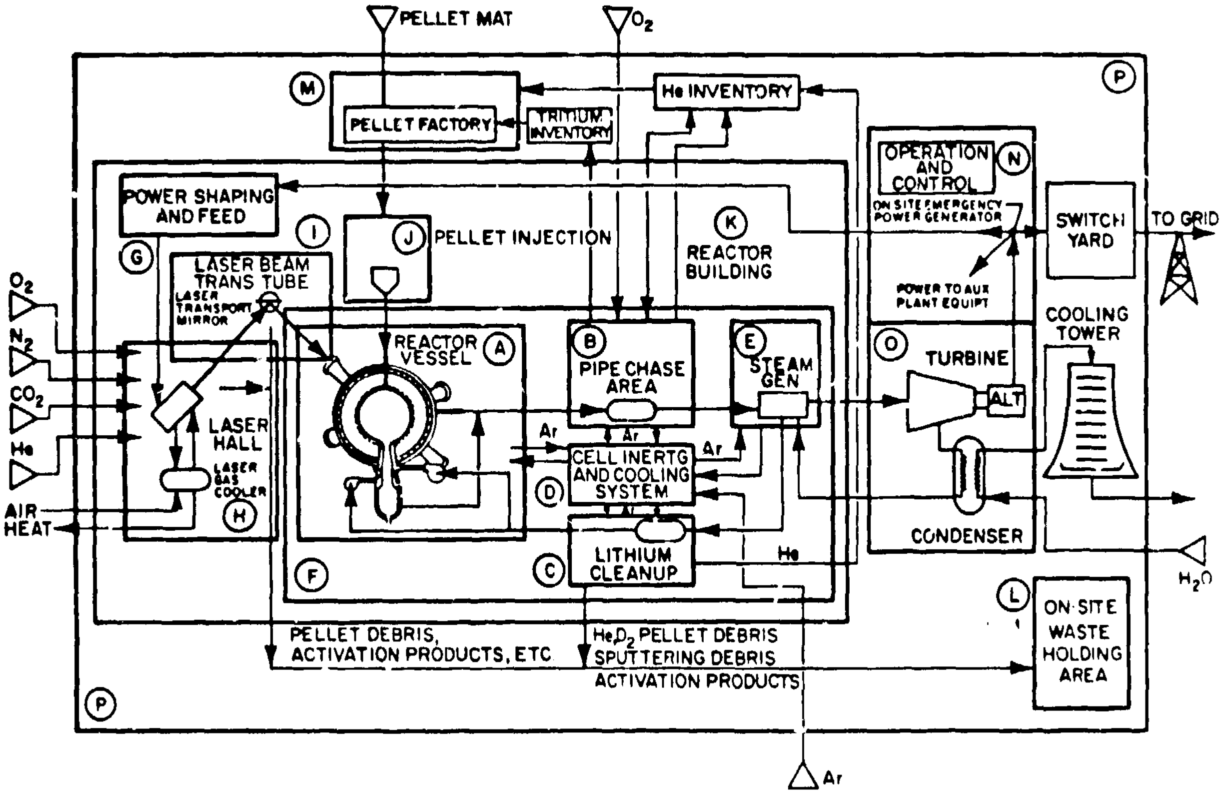

Fig. 1. Environmental envelopes for LASL's laser fusion power plant concept - wetted wall design.

contained within a larger envelope, K, the reactor building. Separate envelopes contain the pellet factory, M, waste handling, L, the operations and control building, N, the turbine hall, O, etc. All these envelopes are contained within the largest envelope, P, for the plant site itself. Typically, envelopes enclosing the least conventional equipment will require resolution of the greatest number of environmental and safety questions. For example, envelopes A through J inside the reactor building are deepest inside the plant and represent the least conventional technologies. Clearly, all unnecessary passage of materials between envelopes should be minimized. If the results of such studies are fed back into design and safety system criteria, there is less probability of adverse impacts outside the larger containing envelopes (for example, the reactor building, K, and then the site itself, P).

Quantifying the material and energy flows inside an envelope will facilitate assessment of how much material passes from this envelope to another. It will also allow for estimation of possible routine releases to the environment. As a result, the relative importance of each environmental and safety aspect can be evaluated.

Thus, envelope analysis during the research, development, and demonstration of an energy technology (such as an inertial fusion power plant) can (1) provide a bookkeeping scheme for research program planning and (2) facilitate the licensing process through design iterations.

Process Elements

The envelope analysis approach can also be used to study the entire fusion fuel cycle as well as the distinct plant elements. The fusion fuel cycle can be viewed as a series of processes. For each process, there are input requirements of money, materials and resources, labor, and energy, as shown in Fig. 3. There are basically three phases of a facility's lifetime: construction, operation, and decommissioning. The operational phase has four subsets of startup, routine operation, routine maintenance, and accidents that should be considered in an environmental and safety study. Each of these phases generate process wastes or effluents that must be handled and/or treated and disposed of. Figure 3 illustrates a framework for collecting data on money, materials and resources, people, and energy needs, and the effluents for each phase of a facility's lifetime, as well as on the environmental and safety aspects.

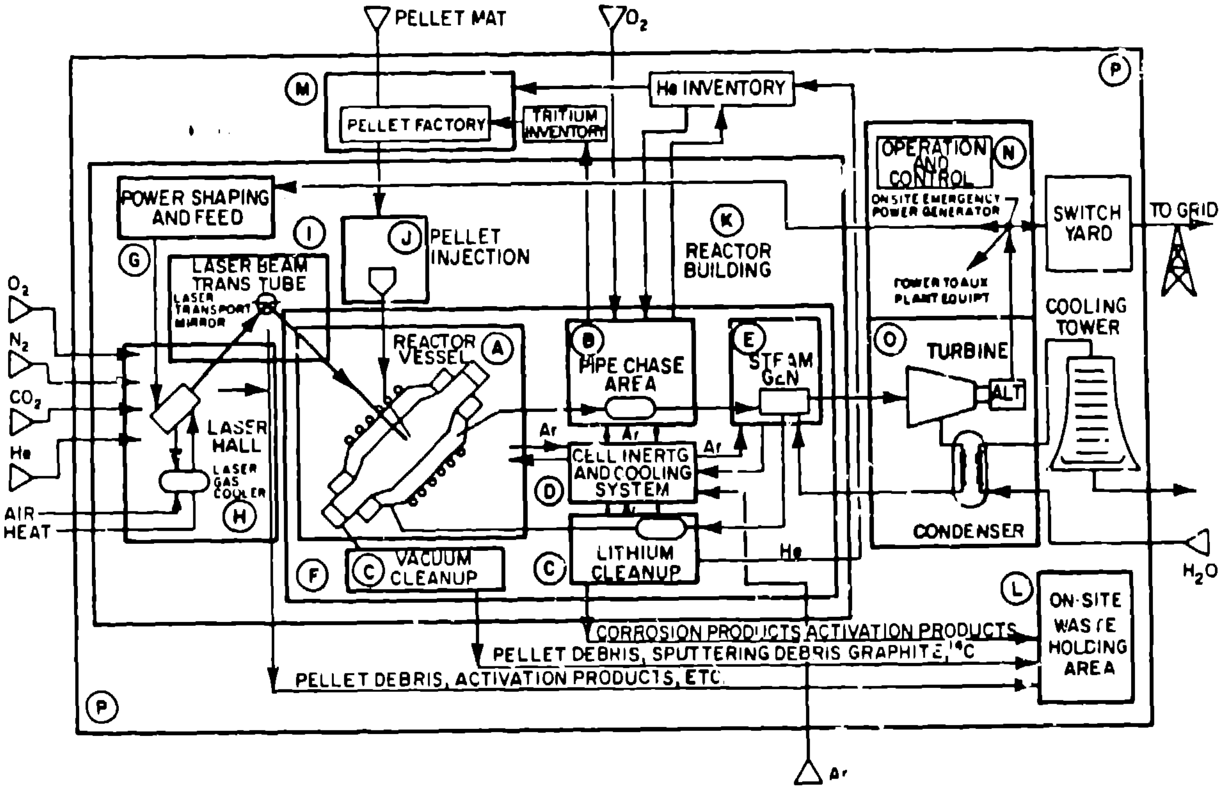

Fig. 2. Environmental envelopes for LASL's laser fusion power plant concept - magnetically protected wall design.

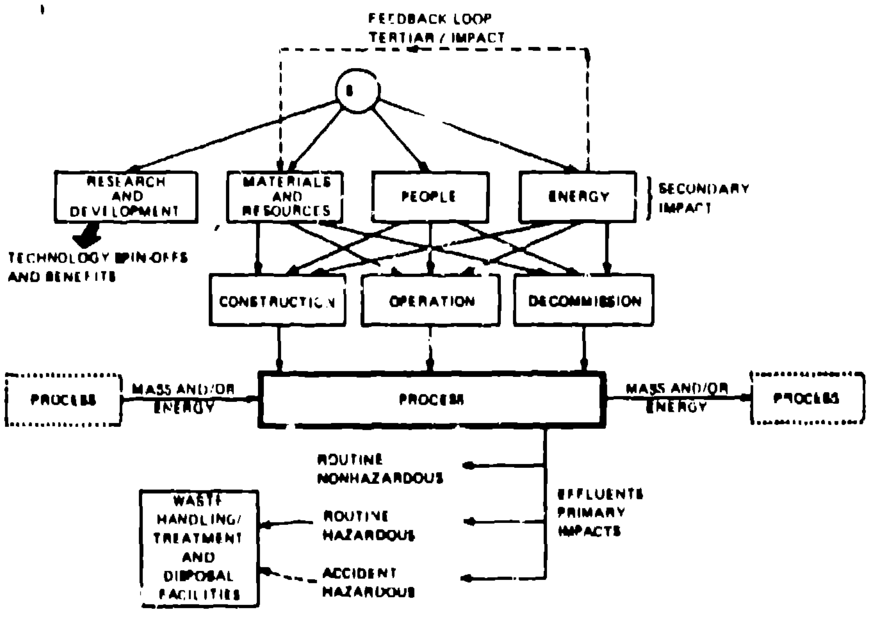

Fig. 3. A framework for collecting data on money, materials and resources, labor, and energy needs, and the effluents, for each phase of a facilitiy's lifetime, as well as the environmental and safety aspects.

TABLE I

MASS- AND ENERGY-FLOWS FOR ENVELOPE A

3000-MWt-PLANT, 20 WETTED-WALL REACTORS, EACH 150 MWt

INPUTS				INTERNAL PRODUCTION		OUTPUTS				
Mass	Energy	Source	Flow Rate	Mass	Energy	Mass	Energy	Flow Rate	Destination	Flag Items
	Laser beam	I Laser transport tubes	1 Hz/reactor		Neutrons		Neutrons	5.3×10^{19} n/s	I Laser transport tubes	Structural activation.
								5.3×10^{19} n/s	J Pellet injection	Neutron damage
					X Rays					
Pellet (D,T, structure)		J Pellet injection	1 Pellet/s/reactor	Pellet debris, D_2	Heat: 150 MJ/reactor pulse	Pellet debris, D_2			C Lithium cleanup system	Main Li stream through the pipeway & steam generator will contain pellet debris.
Ar or He		J Pellet injection	Nominal							If pneumatic
Ar	55°F	D CICS[a]	2300 kg/s, 2% leak, -370°F Δtemp	Neutron activation products of cover gases		Argon	120°F (~3% neutron energy from vessel)	2300 kg/s	D CICS	Argon separation
Ar impurities		External	<0.01%[b]			Tritium			D CICS	Tritium inventory, barriers & recovery technologies.
Air in-leakage		External	11.56 m³/day[c]			^{14}C		0.16 Ci/yr	D CICS	^{14}C production, inventory, migration, and removal.
						$^{13,16}N$		Nominal	D CICS	
						^{41}Ar		50 kCi/yr	D CICS	Possibly ^{37}S and ^{39}K as stable decay products.
Li	600°F low 785°F high	C Li cleanup & makeup	8800 kg/s for 3000 MWt plant, 300°F Δtemp	Neutron activation products of Li coolant	900°F low 1085°F high	Lithium	900°F low 1085°F high 2.56×10^9/Btu/hr/loop (8 loops)	8800 kg/s	B Pipeways	Large inventory ~9.6×10^5 kg/power plant. Lithium cleanup system.
						^{8}Li		Essentially 0	B Pipeways	0.9 s half-life
						^{38}Cl		30 kCi	B Pipeways	37.2 min half-life
						Li activation products		30 kCi	B Pipeways	
						Tritium		0.62 kg at 1 ppm in Li	B Pipeways	~7 MCi
						Helium		Uncalculated	B Pipeways	T_2 removal from helium.
Li impurities		External	~0.007%	Li Corrosion products		^{14}C, ^{56}Mn, [illegible]		Uncalculated	B Pipeways	Corrosion products and their activities.
	Electricity	G Turbine hall								

---

[a] CICS is the Cell Inerting and Cooling System.

[b] See Table III for argon impurities.

[c] See Table IV for potential sources of air activation products.

TABLE II
MASS- AND ENERGY-FLOWS FOR ENVELOPE A
5600-MWt-PLANT, 4 MAGNETICALLY PROTECTED WALL REACTORS, EACH 1400 MWt[1]

INPUTS				INTERNAL PRODUCTION		OUTPUTS				
Mass	Energy	Source	Flow Rate	Mass	Energy	Mass	Energy	Flow Rate	Destination	Flag Items
	Laser beam	I Laser transport tubes	10 MW/reactor		Neutrons		Neutrons	2.5×10^{21} n/s	I Laser transport tubes	Structural activation.
								2.5×10^{21} n/s	J Pellet injection	Neutron damage
					X Rays					
					Steady state magnetic field		Steady state magnetic field			
Pellet (D,T, structure)		J Pellet injection	10 Pellet/s/reactor	Pellet debris, D_2	Heat: 137 MJ/reactor pulse	Pellet debris, D_2			C Vaccum & Cleanup	
Ar or He		J Pellet injection	Nominal							If pneumatic
Ar	55°F	D CICS[a]	2300 kg/s, 2% leak, -370°F Δ temp	Neutron activation products of cover gases		Argon	120°F (~3% neutron energy from vessel)	2300 kg/s <1000 SCFM	D CICS	Argon separation
Ar impurities		External	<0.01%[b]			Tritium			D CICS	Tritium inventory, barriers & recovery technologies.
Air in-leakage		External	7.86 m³/day[c]			^{14}C		0.16 Ci/yr	D CICS	^{14}C production, inventory, migration, and removal.
						^{13,16}N		Nominal	D CICS	
						^{41}Ar		50 kCi/yr	D CICS	Possibly ^{37}S and ^{39}K as stable decay products.
Li	600°F low 745°F high	C Li cleanup & makeup	4400 kg/s for 3000 MWt plant, 300°F Δ temp	Neutron activation products of Li coolant	900°F low 1085°F high	Lithium	900°F low 1085°F high 4.78×10^{9}/Btu/hr/loop (4 loops)	4400 kg/s	B Pipeways	Large inventory ~2.05×10^{6} kg/power plant. Lithium cleanup system.
						^{8}Li		Essentially 0	B Pipeways	0.9 s half-life
						^{38}Cl		30 kCi	B Pipeways	37.2 min half-life
						Li activation products		30 kCi	B Pipeways	
						Tritium		0.62 kg at 1 ppm in Li	B Pipeways	~7 MCi
						Helium		Uncalculated	B Pipeways	T_2 removal from helium.
Li impurities		External	~0.007%	Li Corrosion products		^{14}C, ^{56}Mn, ^{93,94}Nb, ^{60}Co		Uncalculated	B Pipeways	Corrosion products and their activities.
Li		C Li cleanup	Same as above	Same as above		Same as above	900°F low 1085°F high	Uncalculated	B Pipeways	
				D_2		D_2			B Pipeways	
				Pellet debris		Pellet debris			B Pipeways	
	Electricity	O Turbine hall								

---

[a] CICS is the Cell Inerting and Cooling System.

[b] See Table III for argon impurities.

[c] See Table IV for potential sources of air activation products.

Sample Results

Early environmental and safety studies will focus mainly on generic items for routine operation and accident potentials. As laser fusion reactor designs are firmed up, more detailed aspects of the other four cases can be evaluated. For a routine-operation analysis, we prepared tables of material flow rates into and out of each envelope. Tables I and II show input of materials and energy, production or conversion of materials and energy, and output of materials and energy for envelope A, the reactor cell, of two laser fusion power plant design concepts. Flag items (the right-hand column for each table) are environmental or safety aspects that need further definition or research. As indicated above, some of these items might be addressed, at least in part, through instrumentation in present or future generations of experiments.

For the purposes of an environmental and safety analysis, the inputs are the same with both reactor concepts but vary in quantities. In reference to outputs, the design of the reactor cell has four purposes: (1) to assure that the radiation dose to the rest of the plant and to the general environment will be at acceptable levels, (2) to withstand any lithium spills and sprays, (3) to maintain an inert atmosphere, and (4) to contain tritium leakage.

Detailed Discussion

Calculational results as shown in the tables also indicate that air activation may be a significant consideration. As one of the areas containing liquid lithium, the reactor cell surrounding the reactor vessel would have an inert atmosphere of argon. The argon atmosphere will also minimize generation of air activation products in the reactor cell. There are four potential sources of impurities in the argon atmosphere. The different grades of argon commercially available vary in the percentage of impurities, as shown in Table III, but they all contain some traces of oxygen, nitrogen, and carbon. The comparison of these trace concentrations with those from air in-leakage is yet unknown because the in-plant purification systems have not yet been designed in detail.

A second source of air activation products would be from air leakage into the reactor cell. Low-leakage containment vessels for fission reactors have an air leakage of 0.1% per day,[3] although in principle the argon could be maintained on a zero-leakage basis. It has been estimated that the normal in-leakage for the reactor cells will be 0.01% cell volume per day.[4] Tables I and II give the estimated volume of daily in-leakage at that rate. The main constituents of air are, of course, oxygen and nitrogen, followed by carbon dioxide and argon, with traces of krypton, neon, helium, hydrogen, and xenon. The proportion of in-leaking air pollutants such as CO, SO_x, NO_x, and methane vary widely with the site. Table IV shows the potential air activation products on the assumption that all the constituents leaked at the same rate, which would only happen in the case of structural cracks. Otherwise the gases would have to permeate the solid walls of concrete and the stainless steel liners. Nitrogen and hydrogen would then be much more likely to in-leak by permeation. Since no rare gas goes through any metal unless the gas is ionized, it is very unlikely that neon and xenon will leak in.[5] The argon in-leakage is of no concern obviously. A minute amount of krypton (less than 10^{-4} ppm) might be expected.

TABLE III

Argon Impurities[2]

	Commercial	Research
Argon	99.9+%	99.995%
Oxygen	0.002%	0.1 ppm
Hydrogen	0.002%	0.1 ppm
Nitrogen	0.001%	0.1 ppm
Carbon	0.003%	0.1 ppm CO
		0.1 ppm CH_4
Total Impurities	0.01%	5 ppm

The third source of activation products in the atmosphere of the cavity cell would be gas leakage from the reactor vessel and piping, which could conceivably include lithium, lithium impurities, helium, deuterium, and tritium.

A fourth source, gases from the body of the structural material, involves minute quantities and was not considered in this analysis.

Rough estimates indicate that ~2% of the neutron energy may leak into the reactor cell.[4] The air activation products to be expected are tritium, ^{13}N, ^{16}N, ^{14}C, and ^{41}Ar. Nitrogen-14 has a thermal radiative capture cross section to stable ^{15}N of 0.075 b. Nitrogen-15 has a thermal radiative cross section of 0.24 mb. From Table IV, nitrogen will be <0.008% by volume. Since the half-lives of ^{13}N and ^{16}N are 9.97 minutes and 7.10 seconds, respectively, they represent a negligible hazard.[6,7] On the other hand,

TABLE IV

Potential Sources of Air Activation Products
(m^3 for wetted wall design)

	Ar	N	H	O	CO_2	$^{39,41}K$	He	Neon	Xenon
Contribution from argon impurities[a]	115,000	0.11	0.11	0.11	0.11				
Contribution from in-leakage of air[b]	0.10	9.03	$5x10^{-6}$	2.42	0.005	$1x10^{-5}$	$5x10^{-5}$	$2x10^{-4}$	$1x10^{-6}$
Contribution from leakage from reactor vessel or piping[c]		$3x10^{-4}$ to $6x10^{-3}$		$1x10^{-3}$		$1x10^{-3}$			
Per cent by volume	99.990	0.008	-	0.002	-	-	-	-	-

---

[a] Assumes argon at 99.9995% purity (research grade commercially available).

[b] Assumes air in-leakage rate of 0.01% reactor cell volume per day. Assumes air constituents all leak at same rate; actually nitrogen and hydrogen are much more likely to leak in by permeation than are O, CO, CO_2.

[c] Also could include the following: Si, Ca, Na, Fe, Ni, Cr, Ta, F, Cl, ^{6}Li, ^{7}Li, and Nb.

$^{14}N(n,p)^{14}C$ has a thermal cross section of 1.81 b, and the resulting ^{14}C has a half life of 5730 years, so some researchers have identified ^{14}C as "the most significant activation product arising from activation of air...".[8] However, preliminary estimates indicate an annual production of 0.16 curie of ^{14}C for the wetted wall design, with a resultant global population dose of approximately 0.3 person-rem per year.[9] Further investigation of ^{14}C production is desirable.

Argon activation was estimated at 50 β kilocuries, where β is a correction coefficient accounting for detailed geometries of the reactor vessel and reactor cell. Argon-41 is an energetic beta and gamma emitter but, because argon is a rare gas, it is not readily taken up by living organisms and has an extremely small biological effect.[10] However, the ^{41}Ar clearly should be considered a potential reactor effluent.

Argon, with its impurities, would be circulated through the cell inerting and cooling system. There the impurities would be removed, minimizing the inventory that could be dispersed to the atmosphere in an accident. Assuming a 50 K difference in temperature and a 2% leakage of neutron energy, the flow rate for argon in the cell inerting and cooling system would be 2300 kg/s.

The target pellet is injected through (D), either by a pneumatic or an electromagnetic process. The electromagnetic process would operate with an internal vacuum and thus minimize contamination of the reactor cell's inert atmosphere. The pneumatic process would be operated in an inert atmosphere (helium), so again there would be no introduction of impurities into the reactor cell's atmosphere. As with the laser beam transport ducts, the neutron streaming into the pellet injection system is of concern.

Accident Analysis

Accident analysis requires assessment of the probability of failures leading to material exchange between envelopes and to potential hazardous releases to the environment. Some of the basic data for theoretical accident analysis is contained in Tables I and II. The tritium and lithium inventories were identified as having important potential environmental problems and safety risks. For the wetted wall design, the total lithium inventory would be 9.6 x 10^5 kg; and for the magnetically protected wall design, the total lithium inventory would be 20.5 x 10^5 kg. As a general conclusion, the greatest hazard is from the lithium, which represents a more serious chemical than radiological hazard. This problem has been theoretically addressed by the use of double-walled steam generator tubes, reactor cell linings, isolation valves, and argon atmospheres. The use of lithium in the primary heat exchange loop remains a focal point of discussion.

Summary

Using this envelope analysis approach, we have identified material and energy flows and have formulated a systematic approach for assessment and analysis. Flagged items needing further environmental and safety research include corrosion products and their activities; structural activation; handling of pellet debris; lithium cleanup systems; tritium inventories, barriers, and recovery technologies; and ^{14}C production, inventories, migration, and removal. For further studies, we recommend a five-phase cycle, including completion of theoretical mass- and energy-flow calculations, postulation and calculation of accident scenarios, assignment of priorities to scenarios according to predicted effects, design of experiments to gather data, and incorporation of results such as new subsystem designs in the next generation hardware. This approach should provide inherent safety and minimize environmental impact.

References

1. R. N. Cherdack, "Conceptual Designs and Cost Data Base for Laser Driven Fusion Power Plants," Burns and Roe, Oradell, NJ, unpublished report (June 1979).

2. Los Alamos Scientific Laboratory memorandum L5-75:48 to L. A. Booth from F. T. Finch on March 31, 1975, "Preliminary Survey of Potential LWR Radioactive Effluents During Normal Operations," p. 9.

3. J. D. Kaser, A. K. Postma, and D. J. Brandley, "Management of Nontritium Radioactive Wastes from Fusion Power Plants," Battelle-Pacific Northwest Laboratories report BNWL-2019 (September 1976) p. 35.

4. Cherdack, op. cit., p. 61.

5. F. J. Norton, "Permeation of Gases through Solids," J. of App. Phys. 28, 1 (January 1957) pp. 34-39.

6. Los Alamos Scientific Laboratory memorandum L5-77:2 to L. A. Booth from J. J. Devaney on February 3, 1977, "Radioactive Hazards from Laser Fusion Reactor Accidents or From Sabotage," p. 17.

7. R. G. Clark, "Safety Review of Conceptual Fusion Power Plants," Battelle-Pacific Northwest Laboratories report BNWL-2[illegible] (November 1976) p. 5.

8. J. P. Holdren, "Environmental Aspects and their Systems Implications," Proc. EPRI Executive Seminar on Fusion, San Francisco, October 11-13, 1977 (Nichols and Associates, Inc., Austin, Tex., 197[illegible]) Section 15, p. 17.

9. D. A. Baker and J. K. Soldat, "Methodology for Estimating Radiation Doses Due to Tritium and Radioactive Releases," Battelle-Pacific Northwest Laboratories report BNWL-2020 (September 1976) p. 13.

10. J. J. Devaney and J. H. Pendergrass, "The Expected Environmental Consequences and Hazards of Laser-Fusion Electric Generating Stations," Proc. Int. Conf. Health Effects of Energy Production, 1st, Ontario, Canada, September 12-14, 1979 (Atomic Energy of Canada, Ltd.), pp. 259-274.