

THE RADIOLOGICAL HAZARDS OF MAGNETIC FUSION REACTORS

SAFETY/ENVIRONMENTAL
ASPECTS

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The hope that fusion reactors will have fewer radiological hazards than competing fission technologies is an important rationale for fusion research. Estimates of the radiological hazard due to reactor accidents, occupational exposures, and waste disposal of reference fusion and fission designs; the Mirror Advanced Reactor Study (MARS); and a liquid-metal fast breeder reactor (LMFBR) indicate that fusion may enjoy substantial quantitative advantages over fission but that such advantages are neither sure to be achieved nor necessarily sufficient for fusion to be perceived as qualitatively superior to fission. The possibility of achieving maximum reductions of hazard is explored by analyzing the effects of relatively minor modifications of the MARS design, using completely

different structural or breeder/coolant materials, and changing the fusion fuel cycle. Minor modifications, such as elemental tailoring of structural and coolant materials, result in reductions of one to two orders of magnitude in each class of hazard. Using different reactor materials, such as vanadium alloy or high-purity silicon carbide blanket structure, can result in even greater reductions. Other combinations, such as a molybdenum alloy structure cooled by liquid lithium, can be as hazardous as an LMFBR. Using the only other promising fuel cycle, catalyzed deuterium-deuterium, accident hazards can be reduced one to two orders of magnitude and waste disposal hazards by a factor of 4.

INTRODUCTION

In the face of declining public enthusiasm for fusion energy, it is important that researchers keep sight of the ultimate justification for their work. This rationale is, I believe, that fusion may turn out to be the least costly way to produce electricity, where costs are understood to have environmental, as well as economic, components. The difficulty and complexity inherent in the fusion process make it unlikely that fusion reactors will be more economical than their fission counterparts unless they can achieve safety and environmental advantages that can be translated into substantial cost savings. Because the environmental costs of fusion are much more amenable to reduction

than those of fission, safety-related cost reductions or public-acceptance advantages gained by sufficiently reducing these costs may be the best, and perhaps only, way that fusion can come out ahead. Logan¹ has suggested many ways that inherent safety can contribute to the overall competitiveness of fusion reactors.

While there is little doubt that fusion reactors can have some *quantitative* environmental advantage over fission, it is difficult to imagine how such cost reductions or acceptance advantages can materialize unless the radiological hazards of fusion are *qualitatively* different from those of fission. In other words, fusion technologies should substantially avoid the criticisms most often levied at fission reactors: that the costs and risks associated with reactor accidents, decommissioning, and radioactive waste disposal are too great.

Past analyses of fusion's radiological hazards have used indexes of hazard that are not very illuminating and sometimes misleading,² have characterized too

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narrow a range of hazards (e.g., accidents only), or, in the case of accidents, have not treated release fractions properly.³⁻⁵ This paper presents the results of a more sophisticated and comprehensive analysis of the radiological hazards from fusion reactor accidents, occupational exposures, and waste disposal; and it explores how these hazards depend on various aspects of reactor design, such as changes in reactor materials and fuel cycle. Note, however, that two important radiological hazards—routine releases of tritium and the contribution of reactor technologies to the spread of nuclear or radiological weapons—are not considered here.

The present analysis is based on quantitative estimates of hazard indexes made using a calculational scheme developed by the author, which is described in detail in Refs. 6 and 7. Indexes calculated include the number of prompt deaths and injuries and latent cancer deaths following an accident, the contact dose rate of reactor components, and the dose to an inadvertent intruder into a waste disposal site.

ANALYSIS OF THE REFERENCE FUSION REACTOR DESIGN

The Mirror Advanced Reactor Study⁸ (MARS) was chosen as the reference fusion reactor design because it is one of the latest and most advanced studies available and because it attempts to address many of the safety concerns raised by earlier studies. Although MARS represents only one of several magnetic confinement schemes, magnetic fusion reactors based on other confinement schemes, such as tokamaks, will have roughly equal radiological hazards if they are constructed from the same materials and operated at the same power level for the same amount of time.⁹

From 2600 MW of fusion energy, MARS generates 1200 MW of electricity using a high-efficiency blanket. The blanket is composed of a tube region and a beam region; both are made of HT-9 ferritic steel and use liquid lithium-lead (17Li-83Pb) as the coolant and tritium-breeding material. Radionuclide inventories are calculated at the end of the blanket lifetime, which is 3.6 full-power years. The blanket is surrounded by a water-cooled steel (Fe-1422) reflector. All materials are assumed to be manufactured from high-purity, electrolytically refined elements. The material compositions and major parameters of the MARS design are given in Table I.

Accident Hazard

The severe accident sequence examined here is a blanket loss-of-coolant flow with a failure to immediately quench the fusion reaction. The reflector is assumed to simultaneously experience a loss-of-coolant accident (LOCA). (With the MARS design, LOCAs

and loss-of-coolant-flow accidents are about equally severe, although the latter are easier to model and can result in a greater fraction of volatilized coolant material.) The plasma continues to heat the blanket structure and stagnant coolant until the flux of vaporized structural material into the plasma is sufficient to quench the reaction through excessive plasma radiation losses. After the reaction is quenched the tube-zone temperature drops rapidly, but the structure continues to be heated by the decay of radionuclides (afterheat) in the structure and coolant.

Thermal energy transfer between reactor components during the accident is modeled by a fairly detailed heat transfer model. Natural coolant convection is neglected. Under average assumptions about emissivities, specific heats, etc., the calculated tube zone temperature rises to 1600 K after 3 h, and remains at or near this temperature for ~5 h. During this time the containment structure is assumed to be breached, with volatile oxides escaping from the tube region into the environment. The lithium-lead coolant is assumed to leak from the blanket and undergo oxidation and chemical reaction with hot water sprayed from the reflector.

The tube region release fractions resulting under these conditions were estimated from the results of experiments performed at EG&G Idaho, Inc., on the elemental volatility of HT-9 in air¹⁴ and are given in Table II. Although these release fractions are uncertain by at least one order of magnitude, they are well-supported by the available evidence and do not represent the greatest release imaginable. (It is worth noting that the release fractions postulated during fission reactor accidents have often been criticized as overly pessimistic but are still the basis for prudent public policy decisions.) The most important element is manganese, of which 1% of the tube zone inventory is assumed to escape. In addition, 100% of the vulnerable tritium inventory (50 g as HTO) is released, as well as 10% of the mercury and silver, 3% of the thallium, and 1% of the lead from the lithium-lead coolant. These estimates are based on the vapor pressure at 1600 K of the oxides most likely to form. Corrosion product releases from the coolant were also considered but are insignificant compared to activation product releases.

The results of the accident hazard analysis for this release are given in Table III. For the least favorable meteorological conditions examined, the maximum critical dose^a at the site boundary is 370 rem. No early fatalities and only four early illnesses result. For average weather conditions, the maximum critical dose is 20 rem, which is less than the emergency guideline of 25 rem set by the Nuclear Regulatory Commission (NRC). Approximately 500 late cancer fatalities are

^aThe critical dose is the whole-body dose in the first week plus half the dose in the next 3 weeks. It is used to determine the number of early deaths and illnesses.

TABLE I
Material Compositions* and Reactor Configurations

HT-9:	Density = 7.78 g/cm ³ 0.20% carbon, 0.004% nitrogen, 0.25% silicon, 0.0003% potassium, 0.3% vanadium, 11.5% chromium, 0.5% manganese, 85.24% iron, 0.5% nickel, 0.003% copper, 0.0003% arsenic, 0.002% niobium, 1.0% molybdenum, 0.0002% barium, 0.5% tungsten, 0.0002% bismuth (Ref. 10)
Modified HT-9:	Same as HT-9, except 85.72% iron, 0.0025% nickel, 0.02% molybdenum, 1.0% tungsten
PCA:	Density = 7.97 g/cm ³ 0.001% boron, 0.05% carbon, 0.01% nitrogen, 0.03% aluminum, 0.5% silicon, 0.01% phosphorus, 0.005% sulfur, 0.3% titanium, 0.04% vanadium, 14.0% chromium, 1.8% manganese, 65.12% iron, 0.03% cobalt, 16.0% nickel, 0.02% copper, 0.02% arsenic, 0.02% zirconium, 0.03% niobium, 2.0% molybdenum, 0.01% tantalum (Ref. 4)
TZM:	Density = 10.2 g/cm ³ 0.01% carbon, 0.005% oxygen, 0.50% titanium, 0.02% iron, 0.01% nickel, 0.08% zirconium, 99.38% molybdenum (Ref. 4)
V-15 Cr-5 Ti:	Density = 6.1 g/cm ³ 0.02% carbon, 0.05% nitrogen, 0.05% oxygen, 0.004% aluminum, 0.03% silicon, 0.01% phosphorus, 5.0% titanium, 79.8% vanadium, 15.0% chromium, 0.01% iron, 0.001% nickel, 0.0025% niobium, 0.008% molybdenum, 0.003% tantalum, 0.0075% tungsten (Ref. 4)
Al-6061:	Density = 2.7 g/cm ³ 1.0% magnesium, 98.4% aluminum, 0.6% silicon, 0.002% copper (Ref. 11)
SiC:	Density = 3.21 g/cm ³ 30% carbon, 70% silicon; impurities (atomic parts per million): 0.045 sodium, 0.06 potassium, 0.02 manganese, 0.35 chromium, 1.0 iron, 0.2 cobalt, 0.002 arsenic, 0.003 antimony, 0.01 tungsten, 3×10^{-5} gold, 0.08 tantalum (Ref. 12)
17Li-83Pb:	Density = 9.71 g/cm ³ 0.531% ⁶ Li, 0.0688% ⁷ Li, 0.00018% sodium, 0.00012% potassium, 0.00018% calcium, 0.0002% copper, 0.001% silver, 0.0003% antimony, 0.004% bismuth, 99.401% lead (Ref. 10)
Modified 17Li-83Pb:	Same as 17Li-83Pb, except 0.00001% silver [0.1 weight parts per million (wppm)]
Lithium:	Density = 0.51 g/cm ³ 7.5% ⁶ Li, 92.4% ⁷ Li, 0.001% carbon, 0.005% nitrogen, 0.03% sodium, 0.008% silicon, 0.004% chlorine, 0.02% potassium, 0.03% calcium, 0.0003% vanadium, 0.0002% chromium, 0.001% iron (Ref. 13)
Li ₂ O:	Density = 2.0 g/cm ³ 3.5% ⁶ Li, 42.9% ⁷ Li, 0.0004% carbon, 0.002% nitrogen, 53.5% oxygen, 0.01% sodium, 0.004% silicon, 0.002% chlorine, 0.01% potassium, 0.01% calcium, 0.0001% vanadium, 0.0001% chromium, 0.0004% iron (Ref. 13)
LiAlO ₂ :	Density = 2.04 g/cm ³ 6.2% ⁶ Li, 4.1% ⁷ Li, 0.001% beryllium, 0.001% boron, 48.5% oxygen, 0.005% sodium, 40.8% aluminum, 0.05% phosphorus, 0.01% chlorine, 0.05% potassium, 0.003% calcium, 0.003% titanium, 0.003% vanadium, 0.003% chromium, 0.001% manganese, 0.003% iron, 0.003% cobalt, 0.002% nickel, 0.001% copper, 0.05% zinc, 0.05% arsenic, 0.10% strontium, 0.01% zirconium, 0.003% molybdenum, 0.001% silver, 0.01% cadmium, 0.03% tin, 0.01% antimony, 0.01% barium, 0.001% lead, 0.001% bismuth (Ref. 13)
5Zr-3Pb:	Density = 8.9 g/cm ³ 0.00012% copper, 42.322% zirconium, 0.0006% silver, 57.678% lead, 0.0023% bismuth (Ref. 10)

*Unless otherwise indicated, elemental compositions given in percent by weight.

(Continued)

TABLE I (Continued)

Beryllium:	Density = 1.85 g/cm ³ Impurities (wppm): 3 lithium, 2 boron, 1000 carbon, 300 nitrogen, 800 magnesium, 900 aluminum, 600 silicon, 200 calcium, 100 chromium, 150 manganese, 600 iron, 5 cobalt, 300 nickel, 100 copper, 200 zinc, 20 molybdenum, 2 cadmium, 20 lead (Ref. 13)
MARS:	Mirror reactor, length = 130 m, plasma radius = 0.49 m; neutron wall loading: 4.3 MW/m ² ; tube zone radius = 0.60 m, composition (vol%): 7.1 HT-9, 73.7 17Li-83Pb; beam zone radius = 0.80 m, composition: 14.4 HT-9, 85.0 17Li-83Pb; Fe-1422 reflector radius = 1.01 m; shield radius = 1.44 m; magnet radius = 1.92 m (Ref. 8)
MARS with solid breeder:	First-wall thickness = 0.01 m, composition (vol%): 50 HT-9, 25 H ₂ O; neutron multiplier thickness = 0.05 m, composition: 100 5Zr-3Pb or 70 beryllium; second-wall thickness = 0.01 m, composition: 35 HT-9, 17 H ₂ O; tritium breeder thickness = 0.30 m, composition: 80 LiAlO ₂ or Li ₂ O, 10 HT-9, 5 H ₂ O, 5 helium; reflector and shield as in reference MARS
Cat-D:	Mirror reactor, length = 215 m, plasma radius = 1.10 m; neutron wall loading: 0.32 MW/m ² ; first-wall radius = 1.40 m, composition (vol%): 50 HT-9, 25 H ₂ O; blanket radius = 1.41 m, composition: 80 carbon, 8 HT-9, 2 H ₂ O; shield radius = 1.85 m; magnet radius = 1.92 m

caused by the release, assuming a uniform population density of 100/km².

Two isotopes of manganese, ⁵⁴Mn and ⁵⁶Mn, which are produced from neutron activation of iron and manganese in the HT-9 tube zone structure, contribute 47% of the critical dose and 87% of the chronic dose.^b Activation products of lead in the lithium-lead coolant, ²⁰²Tl, ²⁰⁴Tl, ²⁰³Pb, and ²⁰⁹Pb, contribute 43% of the critical dose and 6% of the chronic dose. The tritium released contributes only 1% of the critical dose and a much smaller percentage of the chronic dose. Other activation products of HT-9 contribute the remainder of the dose.

Occupational Hazards

The primary factor affecting the ease with which a reactor can be maintained or decommissioned is the dose rate to a worker in contact with reactor components. If the dose rate is <2.5 mrem/h, workers can have unlimited, unshielded access to the component. Materials with a contact dose rate below this limit could also be recycled for later use; for very expensive materials (such as isotopically tailored metals), recycling may have substantial economic incentives. Components with dose rates much higher than the limit must be manipulated remotely, which is time-consuming and costly.

^bThe chronic dose is the 50-yr whole-body dose, including chronic exposure to ground-deposited radionuclides (assuming no evacuation). It is used to estimate the number of late cancer fatalities.

Unfortunately, the contact dose rates of all major blanket components out to the shield are orders of magnitude above this limit, even 30 yr after shutdown, as shown in Table IV. (Dose rates at earlier times are not shown, since they are far too great to represent a meaningful basis for comparison.) The dose rate after 30 yr in the tube and beam regions and the reflector is almost entirely due to ⁶⁰Co, while that of the lithium-lead coolant is due to ^{108m}Ag.

Waste Disposal Hazards

In considering standards for the near-surface disposal of low-level radioactive wastes, the NRC developed a measure called the "intruder dose"¹⁵ to calculate the maximum dose that could be absorbed by a person inadvertently building a house on a waste disposal site after the period of institutional control ends. Waste streams are deemed appropriate for shallow burial if the intruder dose is less than the maximum permissible dose of 0.5 rem/yr.

The results of the hazard analysis for the reference MARS design are given in Table V, assuming that the blanket is compacted to normal density before disposal¹⁶ and is disposed of as class "C" waste (corresponding to the highest radionuclide concentrations allowed). In this case, the intruder dose from the tube and beam regions are factors of 40 and 15 higher than the maximum permissible dose. A single radionuclide, ⁹⁴Nb, is the major contributor to the dose. While the reflector is suitable for class C disposal, the intruder dose of the lithium-lead coolant is a factor of 2 greater than the limit, with ^{108m}Ag the main contributor.

TABLE II
Release Fractions of Tube Zone Structural Materials

Element	Fraction of Tube Zone Inventory Released					
	HT-9	PCA	TZM	V-15 Cr-5 Ti	Al-6061	SiC
Nickel ^a	0.0003	0.003	0.1	0.008	0.001	10 ⁻⁶
Nitrogen ^b	1.0	1.0	1.0	1.0	1.0	10 ⁻⁶
Sodium ^c	0.03	0.05	0.1	0.02	0.1	0.001
Magnesium ^d	0.1	0.15	1.0	0.06	0.1	0.001
Scandium ^e	0.0003	0.001	0.1	0.008	---	10 ⁻⁶
Molybdenum ^f	0.03	0.05	1.0	0.02	---	0.001
Chromium ^g	0.001	0.01	1.0	0.004	0.01	10 ⁻⁵
Manganese ^h	0.01	0.015	1.0	0.006	0.01	10 ⁻⁴
Iron	0.0001	0.003	0.1	0.008	0.001	10 ⁻⁶
Zirconium	0.0001	0.001	0.1	0.008	0.001	10 ⁻⁶
Tungsten	0.003	0.003	1.0	0.006	---	10 ⁻⁵

^aIncludes beryllium, aluminum, silicon, titanium, nickel, niobium, and tantalum.

^bIncludes nitrogen, carbon, and argon.

^cIncludes sodium, phosphorus, and potassium.

^dIncludes magnesium, calcium, strontium, and rhenium.

^eIncludes scandium and yttrium.

^fIncludes vanadium and molybdenum.

^gIncludes chromium, cobalt, and copper.

^hIncludes manganese, arsenic, and technetium.

TABLE III
Accident Hazards of Reference Fusion
and Fission Designs*

	Reference MARS	Modified MARS	Reference LMFBR
Inventory (MCi)	1400	1400	4 400
Released (MCi)	11.6	0.79	580
Maximum dose (rem)			
Critical	370	12	27 000
50-yr	680	22	630 000
Early deaths	0	0	210
Early illnesses	4	0	480
Cancer deaths	500	15	12 000

*The maximum dose and early deaths and illnesses are estimated assuming a ground level release with no plume rise under Pasquill stability class "F" conditions, 1 m/s wind speed, and an inversion layer at 250 m. Cancer deaths estimated assuming a 20-m release height, 20-m plume rise, class "D" stability, 5 m/s wind speed, and an inversion layer at 1000 m. In both cases the site boundary is at 300 m and the release duration is 5 h.

COMPARISON WITH FISSION

Since the breeder fission reactor is fusion's natural competitor, it is appropriate to attempt a direct comparison of the two. The reference fission reactor

TABLE IV
Occupational Hazards of Reference Fusion
and Fission Designs

	Contact Dose Rate 30 yr After Shutdown (mrem/h)		
	Reference MARS	Modified MARS	Reference LMFBR
Tube zone	86 000	860	---
Reflector	63 000	420	---
Lithium-lead	250	2.5	---
HLW	---	---	28 000 000
SMW	---	---	135 000
SCW	---	---	18 000

examined here is the German liquid-metal fast breeder reactor (LMFBR) SNR-300, for which an extensive risk analysis has already been performed.¹⁷ To facilitate comparison with the MARS reactor, the electrical output is scaled from 280 to 1000 MW.

The results of the accident analysis given in Table III indicate that, for the most severe accident under worst-case weather conditions, 210 early deaths and 480 early illnesses would result (assuming, as before, a uniform population density of 100/km²). Under average conditions, the number of cancer deaths

TABLE V
Waste Disposal Hazards of Reference Fusion and Fission Designs

	Reference MARS	Modified MARS	Reference LMFBR
Intruder dose (rem)			
Tube zone	21	0.50	---
Beam zone	8.9	0.21	---
Reflector	0.0034	0.0005	---
Lithium-lead	1.0	0.01	---
HLW	---	---	340 000
SMW	---	---	11
SCW	---	---	0.28
Intruder hazard potential (IHP) ^a (m ³)			
Tube zone	2000	46	---
Beam zone	2100	50	---
Reflector	3.6	0.53	---
Lithium-lead	2700	27	---
HLW	---	---	6 800 000
SMW	---	---	2 200
SCW	---	---	900
Total IHP (m ³)	6800	120	6 800 000

^aThe IHP is defined as the intruder dose of a reactor component multiplied by its volume and divided by the maximum permissible dose (0.5 rem), summed for all the components in the reactor. The life-cycle volumes (m³) assumed are as follows: tube zone, 46.5; beam zone, 120.0; reflector, 531.1; lithium-lead, 1354; HLW, 10.0; SMW, 100; and SCW, 1600.

would be ~12 000, which is in good agreement with the predictions of the German risk analysis.¹⁷ Thus, the accident hazard of the LMFBR is at least 20 times greater than that of the MARS reactor.

Occupational and waste disposal hazards are more difficult to compare, since the main source of hazard in the fission reactor is the relatively compact reactor core. Although the hazard of the LMFBR core is thousands of times greater than the MARS blanket, the core is more manageable to shield, transport, and dispose of. Furthermore, comparisons of waste disposal hazard cannot be based on near-surface disposal, since the high-level wastes (HLW) produced by the LMFBR cannot be disposed of in this fashion.

Nevertheless, readers can compare the hazard indexes given in Tables IV and V and reach their own conclusion about relative hazard. Thirty years after shutdown, notice that the solid material waste (SMW) from the LMFBR (fuel cladding and channels) has roughly the same contact dose rate and waste disposal hazard as the MARS tube region, while the hazards of the HLW are very much greater than any fusion reactor component. The sodium coolant waste (SCW) from the LMFBR, on the other hand, has a contact dose rate 80 times higher and a waste disposal hazard three times lower than the lithium-lead of MARS.

Overall, the radiological hazards of the reference fusion reactor appear to be considerably less than those of the reference fission reactor. But there are many considerations that diminish the value of these

quantitative advantages; for example, what meaning does accident hazard have without an associated probability? It could turn out that the overall accident risk of fusion is greater than fission if the probability of an accident is substantially higher. In the case of occupational hazards, the contact dose rate from fusion components, while in some cases less than those of corresponding fission components, is still far too great to allow hands-on maintenance or recycling. In the case of waste disposal, the greatest hazard from fission is posed by a small volume of HLW; if deep geological burial of HLW results in little radiological hazard and small economic penalties, then the much larger volume of low-level fusion wastes might prove relatively more burdensome. From this viewpoint, fusion's advantages seem to slip away. Numerous cancer deaths and large off-site doses are still possible in an accident, and the public may not view these hazards as qualitatively different from those associated with fission.

But the MARS design is not the only way to build a fusion reactor. While the radionuclide inventories of a fission reactor are more or less fixed by the laws of nature, those of a fusion reactor are design-dependent. Except for tritium, radionuclides in the MARS reactor are created by neutron activation of the structural and coolant materials. Since the types of radionuclides produced are dependent on the composition of the material, it is possible, at least in principle, to reduce radiological hazards by simply choosing materials that

produce less-hazardous radionuclides. The following sections explore these possibilities.

CHANGES IN REACTOR MATERIALS

Major changes in reactor materials often change the whole design of the fusion reactor: operating temperatures, breeding ratios, structural design, etc. It is more practical to study first the effects of relatively minor changes that would not affect reactor performance in any obvious way. Key insights into hazard reduction can be gained by noting how the major radionuclide contributors to each class of hazard are produced.

Minor Changes in the Reference MARS Design

Accident Hazards

In the case of the MARS accident hazards, the major contributors to dose are ^{54}Mn and ^{56}Mn , which are produced mainly from naturally occurring isotopes of iron, ^{54}Fe and ^{56}Fe . Iron is the primary ingredient of all steels, so no elemental modification is possible; and isotopic tailoring is not an option either, since the natural abundance of ^{56}Fe is 92%. In the case of the blanket coolant, the major contributors are activation products of lead, which also cannot be eliminated or isotopically tailored so as to significantly reduce accident hazards.

If radionuclide inventories cannot be altered, the only way to lower accident hazards (other than diminishing the probability of an accident, which is not considered here) is by reducing the release fraction, which is primarily determined by the maximum temperature reached during an accident. In the accident sequence examined above, the main sources of blanket heating are plasma heating and afterheat. Plasma heating of uncooled structures can be minimized by using a passive safety device, such as that described by Logan¹ that quenches the reaction at temperatures just above the normal operating temperature. Incorporating a passive quench mechanism would lower the maximum blanket temperatures by ~ 100 K.

Even more important is minimizing the afterheat deposited in the blanket. Although reductions could be achieved by altering the tube zone geometry or emissivity, or by incorporating emergency passive cooling, most of the heating is due to the decay of radionuclides in the reflector, not the blanket structure or coolant. The afterheat in the reflector during the first several hours is dominated completely by ^{56}Mn , which in this case is produced mostly from reactions with manganese in Fe-1422. If HT-9, which contains 28 times less manganese than Fe-1422 (0.5% versus 14%), is used as the reflector material, the short-term afterheat is reduced by one order of magnitude, and the maximum temperature of the blanket during the postulated accident falls by another 500 K.

At this temperature (1000 K) the release fraction of all elements except iron and nickel fall by factors of 30 to 150. The release fraction of manganese is 33 times less, which, as Table III indicates, leads to corresponding decreases in the accident hazard. The maximum critical dose for unfavorable weather conditions is now 12 rem, which is below the NRC emergency guideline and results in no early deaths or illnesses, and the number of late cancer fatalities is only ~ 15 .

Occupational Hazards

Short-term occupational hazards are so great that there is no hope of significant reductions through minor changes in the reference design. It was noted above that the long-term hazards of HT-9 are due to ^{60}Co , which is mostly produced from reactions with naturally occurring ^{60}Ni . Since nickel is not an essential alloying ingredient of HT-9, reducing its concentration from 0.5 to 0.0025% (25 wppm) lowers the contact dose rate 30 yr after shutdown by a factor of 100; eliminating nickel completely results in a reduction of another factor of 2. Although nickel could be eliminated from the reflector and shields by substituting modified HT-9 for Fe-1422, ^{60}Co production from reactions with iron isotopes in the softer neutron spectrum of these regions permits little reduction in the hazard.

The long-term contact dose rate of the lithium-lead coolant is due almost entirely to ^{108m}Ag produced from silver impurities in the lead, which are present at 10 wppm in the reference design. For silver concentrations >1 weight part per billion (wppb), the contact dose rate after 30 yr is roughly proportional to the concentration of silver, so that reducing silver to 0.1 wppm would result in a dose rate of 2.5 mrem/h, which would permit unlimited unshielded access and easy recycling. Such purity levels are probably achievable.

Waste Disposal Hazards

As noted above, all of the blanket materials in the reference design are too radioactive to permit near-surface disposal. The intruder dose from the tube and beam regions is due to three radionuclides: ^{94}Nb , ^{93}Mo , and ^{99}Tc . These are all activation products of molybdenum, which is an essential component of HT-9 (but just 1% by weight). Although these activation products could be reduced by clever isotopic tailoring of this relatively small amount of molybdenum, a much cheaper and simpler solution would be to find an acceptable substitute.

There are several elements that might be substituted for molybdenum in HT-9, including vanadium, titanium, tantalum, and tungsten.¹⁸ Indeed, the Blanket Comparison and Selection Study¹³ included calculations for a modified HT-9 in which tungsten was substituted for molybdenum, and samples of such a

material have already been produced.¹⁹ Fortunately, activation products of tungsten do not contribute significantly to any of the hazards considered in this paper. If molybdenum concentrations are reduced to 0.02%, the intruder dose drops to 0.5 rem and the modified tube-zone HT-9 would be appropriate for near-surface disposal.

The intruder dose from the lithium-lead coolant is due to ^{108m}Ag , the reduction of which has already been discussed in connection with long-term occupational hazards. In this case, the concentration of silver impurity only need be reduced by a factor of 2 for the coolant to qualify for near-surface disposal.

In summary, one can go a long way toward reducing the radiological hazards of the reference MARS design by making relatively simple changes: substituting HT-9 for Fe-1422 in the reflector and shields, incorporating a passive plasma quench mechanism, and reducing the concentrations of nickel and molybdenum in HT-9 and silver in lithium-lead. Such modifications decrease accident hazards by a factor of >30 and long-term occupational and waste disposal hazards by a factor of up to 100 compared to the reference design. Most important, these reductions allow fusion to obtain significant qualitative advantages: maximum off-site doses less than the NRC emergency guideline, recycling of the lithium-lead coolant, and near-surface disposal of all major reactor components.

Changes in Structural Materials

As mentioned earlier, neutron activation is entirely dependent on the material being irradiated, and, in principle, one could simply select a material that generates few hazardous radionuclides. But reactor materials must have additional attributes, such as strength, stability, and compatibility; and many times these requirements are at odds with the goal of low activation. In this paper, only those structural materials that have received considerable attention in previous reactor design studies will be examined; these are stainless

steel [primary candidate alloy (PCA)], molybdenum alloy [titanium-zirconium-molybdenum (TZM)], vanadium alloy (V-15 Cr-5 Ti), aluminum alloy (Al-6061), and high-purity silicon-carbide (SiC). The composition of these materials is given in Table I. Dozens of other materials have also received attention, but the seven materials analyzed here (including the reference and modified HT-9) cover a range sufficiently broad so that one can get a good idea of what can be achieved through changes in structural materials.

To accommodate many of these materials, the MARS design would have to changed rather substantially; walls may be thicker or thinner, operating temperatures higher or lower, and a different breeder/coolant required. Rather than develop a complete design for each material, the present analysis is based on substituting each material on an equal volume basis in the tube and beam zone of the reference MARS design. While this approach has obvious shortcomings, it has the advantage of simplifying the analysis and allowing one to isolate the effects of changing structural materials on radiological hazards. In other words, although some of the combinations considered here are impractical, the relative ranking of materials thus obtained will give a very good idea of the potential of each material for reducing radiological hazards.

The accident hazard of each alternate material was estimated for the same accident sequence described above for the reference design; no passive quench mechanism and Fe-1422 reflector and shields are assumed. The release fractions of elements from PCA, V-15 Cr-5 Ti, and TZM were estimated from experiments similar to those for HT-9 (Refs. 20, 21, and 22) while those from Al-6061 and SiC were estimated from the vapor pressure of the oxides most likely to be formed. The release fractions thus derived are presented in Table II.

Table VI presents the results of the analysis; note that the dose from tritium and the lithium-lead coolant are not included. For worst-case weather conditions, the maximum off-site critical dose ranges from

TABLE VI
Accident Hazards of Alternate Structural Materials*

	PCA	TZM	V-15 Cr-5 Ti	Al-6061	SiC
Inventory (MCi)	940	1 340	340	340	340
Released (MCi)	9.8	1 260	4.8	30	0.003
Maximum dose (rem)					
Critical	550	42 000	110	3000	0.014
50-yr	2200	44 000	180	3000	0.015
Early illnesses	10	550	0	94	0
Early deaths	0	270	0	29	0
Cancer deaths	1400	1 700	22	110	0

*See footnotes, Table II.

0.014 to 42 000 rem and the number of late cancer fatalities ranges from 0 to 1700, with SiC the best material and TZM the worst in every hazard index. The PCA is 1.5 to 3 and TZM is 3 to 100 times worse than HT-9, while V-15 Cr-5 Ti is 3 to 20 and SiC is 30 000 times better. Al-6061 is 4 to 8 times worse in acute but 5 times better in chronic indexes of accident hazard.

The contact dose rate 30 yr after shutdown for the alternate materials is given in Table VII. Note that even the least radioactive materials, SiC and V-15 Cr-5 Ti, are ~2 orders of magnitude higher than that required for recycling and unlimited contact. Only PCA is worse than the reference HT-9.

The results of the waste disposal hazard analysis are also given in Table VII. In this case, PCA and Al-6061 are both ~3 times worse than the reference HT-9, while TZM is more than a factor of 100 worse. On the other hand, V-15 Cr-5 Ti is over 10 times better, and SiC more than a factor of 10 000 better than HT-9.

In summary, SiC is the clear winner of the comparison, being orders of magnitude better than any other material examined. Also, V-15 Cr-5 Ti is better than the reference HT-9 by roughly a factor of 10 overall. The PCA and TZM are worse than HT-9 by

factors of ~3 and 100, respectively. Al-6061, while a factor of 5 better than HT-9 in chronic accident and long-term occupational hazard, is worse in acute accident and waste disposal hazard by a factor of 10.

It should be noted that, just as in the case of HT-9, minor changes in the composition of these materials can make large differences in radiological hazard. For example, the long-term occupational and waste disposal hazards of V-15 Cr-5 Ti are dominated by ^{60}Co and ^{94}Nb , which are activation products of impurities whose concentrations can be reduced. The PCA is quite similar to HT-9, and the same strategies used to reduce HT-9's hazard can also be employed here. In the case of SiC, radiological hazards are essentially dominated by impurities in every case. The exceptions are TZM and Al-6061, whose most hazardous radionuclides are produced from the primary constituents of the materials, molybdenum and aluminum.

Changes in Breeder/Coolant Materials

Changes in breeder and coolant materials must be considered together, since the choice of tritium breeding material often determines the coolant. The single most important factor influencing this decision is the phase of the breeder at operating temperatures; if the breeder is liquid, the reactor design is simplified greatly by using the breeder as the coolant material as well, as in the MARS design. If the breeder is solid, a fluid must be chosen as the coolant. Please note once again that routine releases of tritium were not considered here and that such considerations may change the overall ranking of breeder materials.

Liquid Breeders

Aside from ^{17}Li - ^{83}Pb , lithium metal is the only other liquid breeding material considered in major reactor design studies. Flibe (LiF - BeF_2) has been mentioned, but it has not been considered here. If Flibe can breed sufficient tritium without a neutron multiplier, it may be a very attractive material.

The solubility of tritium in lithium is much greater than in ^{17}Li - ^{83}Pb , resulting in a larger tritium inventory. The total vulnerable tritium inventory using lithium coolant would be ~900 g^4 , or ~18 times greater than that of the reference accident considered above. The activation products of lithium and its associated impurities are much less hazardous than those of lithium-lead; while lithium is also quite corrosive, the solubility of corrosion products is much less in lithium. These factors result in significantly smaller activation product inventories for lithium, with the corresponding reductions in occupational and waste disposal hazard indicated in Table VII.

The main problem with lithium is its capacity for violent exothermic chemical reactions with many potential reactor materials, including oxygen, carbon dioxide, water, and concrete.²³ While some of these

TABLE VII
Occupational and Waste Disposal Hazards
of Alternate Reactor Materials

Material	30-yr Contact Dose Rate (mrem/h)	Intruder Dose (rem)
Tube Zone Structure		
HT-9	86 000	21
Modified HT-9	430	0.0043
PCA	3 000 000	64
TZM	40 000	2600
V-15 Cr-5 Ti	300	1.7
Al-6061	10 000	71
SiC	110	0.0013
Liquid Breeder		
^{17}Li - ^{83}Pb	250	0.99
Modified ^{17}Li - ^{83}Pb	2.5	0.00052
Lithium	0.37	0.00011
Solid Breeder		
Li_2O	0.20	0.00005
LiAlO_2	12 000	4.1
5Zr-3Pb	800	4.2
Beryllium	100 000	0.082

materials can be eliminated from the reactor design, in an accident situation air (and perhaps water) cannot. The reaction of interest with air is



where Q , the heat of reaction, is equal to -76.0 kcal/mol Li at 298 K (Ref. 24). The lithium in an entire reactor would represent 20 000 GJ of stored energy, which is sufficient to vaporize more than 400 tons of ice.

Many authors have debated the likelihood of this energy being released and the maximum temperatures that could be achieved by the reaction.^{3,25,26} Although the calculated adiabatic flame temperature is 2400 K, the maximum temperature achieved in experiments and analytical modeling has been nearly 1000 K less than this. The experiments, however, were performed with modest amounts of lithium, small exposed surface areas, and extremely low flow rates of normal humidity air. Still, it seems likely that the maximum temperature obtainable in a real fire is not substantially greater than 1600 K, which is the maximum temperature in the reference accident due to afterheat.

Thus, while lithium fires may not raise structural temperatures much above those resulting from afterheat, lithium represents a liability that cannot be undone through clever design or elemental tailoring. As long as lithium is present in a reactor in large quantities, the possibility exists for a catastrophic accident. Furthermore, the probability of an accident involving lithium is likely to be greater than the reference accident. While not shown in Table VII, the greater inventory of tritium in lithium and the higher release fractions likely in a lithium fire make the accident hazards of lithium at least as great as, and probably greater than, those of lithium-lead.

Solid Breeders

Of the many solid breeding compounds that have been suggested over the years, Li_2O and LiAlO_2 have received the most attention. The most recent reactor design study to consider solid breeders, STARFIRE (Ref. 27), chose LiAlO_2 over Li_2O due to the high tritium inventory and potential corrosion problems of the latter. Based mostly on theoretical arguments, STARFIRE calculated a breeder tritium inventory of ~ 10 kg for LiAlO_2 and over 100 kg for Li_2O . For comparison, 1 kg of tritium released as HTO can cause an off-site critical whole-body dose of 75 rem under adverse meteorological conditions. Since the release of tritium and activation products from the 17Li-83Pb breeder of the reference MARS design resulted in a dose of 180 rem, it is unlikely that an alternate breeder with a vulnerable tritium inventory >1 kg could have any accident hazard advantages, especially given the volatility of tritium. Although Piet⁴ suggests that only 10 to 20% of the tritium

inventory is vulnerable to release, it should be assumed that the high temperatures of a severe accident would drive most of the soluble tritium out of the breeder.

Tritium inventories of solid breeders may, however, be significantly smaller than the STARFIRE work indicates. A recent study at GA Technologies²⁸ (GA) based on the use of Li_2O microspheres as a fluid breeder/coolant calculated a total breeder tritium inventory of 6 kg. Furthermore, recent experimental work²⁹ has lowered these estimates considerably; using new data, the GA group calculated a tritium inventory of only 100 g for LiAlO_2 (Ref. 30). It should be noted, however, that these inventories were calculated for a high-temperature blanket; more conventional blankets would have substantially higher tritium inventories.

Compared with liquid breeders, the activation products of solid breeders are not vulnerable to release, since they are usually behind the first wall and encapsulated in structural materials. While this makes little difference in the case of Li_2O , since the activation of the material and its impurities is negligible compared to 17Li-83Pb, activation products of aluminum in LiAlO_2 could make a rather large contribution to accident hazards if it were not for the difficulty of exposing a large fraction of the breeder to oxidation and volatilization. While the coolants typically used with solid breeders, water and helium, are much more prone to release, they contain very few activation or corrosion products compared to lithium or lithium-lead. The maximum off-site critical dose from a complete coolant release (activation and corrosion products) would be only 0.3 rem for water and much less for helium.

Solid breeders can make indirect contributions to accident hazards by generating afterheat that is deposited in the first wall. This is not important in the case of Li_2O , whose afterheat is more than a factor of 10 less than lithium-lead. The afterheat generated by LiAlO_2 , on the other hand, is three orders of magnitude greater than that of lithium-lead and could be the main cause of first-wall heating and release during a LOCA. Even more important, the tritium breeding ratio of LiAlO_2 is so low that a neutron multiplier is required. The two multiplier materials considered by STARFIRE were beryllium and 5Zr-3Pb. Although beryllium is the more efficient multiplier and generates the least radioactivity, world resources may be insufficient to sustain a large fusion economy.²⁷ But the afterheat generated by 5Zr-3Pb is even larger than that of LiAlO_2 and would present severe problems during a LOCA; in fact, the adiabatic temperature rise of the first wall is over four times that of the reference MARS design.

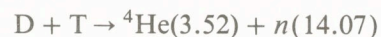
As one might have expected from the analysis of lithium coolant and aluminum alloy presented above, Table VII shows that the occupational and waste disposal hazards of Li_2O are quite low, while those of

LiAlO_2 are high. Note once again that the hazards cannot be reduced by isotopic tailoring, since ^{27}Al is the only naturally occurring isotope of aluminum. If ^{57}Zr - ^{210}Pb is chosen as the multiplier material, the comparison becomes even less favorable.

In briefest summary, to have advantages over lithium-lead coolant with regard to accident hazards, the vulnerable tritium inventory of a solid breeder must be <1 kg. While it appears that this may be possible for LiAlO_2 (depending on the details of the reactor configuration), it is unclear whether the tritium inventory of Li_2O can be made acceptably low. Solid breeders usually require a coolant such as water or helium, and while these coolants are not nearly as corrosive or prone to neutron activation as most liquid coolants, the probability and consequences of a LOCA may be much greater, since it could occur much more quickly and completely. Finally, LiAlO_2 suffers from high afterheat levels and waste disposal hazards, and the neutron multipliers required for its use have many problems of their own. Beryllium is scarce and has a very high long-term contact dose rate, and ^{57}Zr - ^{210}Pb greatly increases accident and waste disposal hazards.

CHANGES IN FUEL CYCLE: CATALYZED DEUTERIUM-DEUTERIUM (CAT-D)

The main sources of radiological hazard discussed above are a direct result of the deuterium-tritium (D-T) fuel cycle, which requires large amounts of tritium and produces copious high-energy neutrons. Although D-T is by far the easiest fuel to ignite, there are other possible fuel cycles that do not require radioactive fuels and that produce fewer neutrons. The most commonly discussed advanced fuel cycle is the Cat-D fuel cycle, which has the following primary reactions:



The numbers in parentheses are the particle energies in mega-electron-volts. There are also secondary reactions of p with tritium, tritium with tritium, tritium with ${}^3\text{He}$, and ${}^3\text{He}$ with ${}^3\text{He}$, but these are relatively unimportant for the purposes of this discussion. The first two reactions occur with roughly equal probability. In the Cat-D fuel cycle, the tritium and ${}^3\text{He}$ reaction products are recycled and burned completely according to the last two reactions. Note that Cat-D, like D-T, produces a substantial fraction of its energy in the form of neutrons: For every six deuterium nuclei consumed, one 14.07-MeV and one 2.45-MeV neutrons are produced, accounting for 38% of the total energy of 43.23 MeV. In contrast, neutrons account for 80% of the D-T reaction energy.

One could reduce the neutron energy fraction by storing tritium, which decays to ${}^3\text{He}$, but a substantial fraction (20 to 50%) would burn in the plasma in any case. In addition, the long half-life of tritium (12 yr) would lead to very large tritium inventories in storage. The reaction of deuterium with ${}^3\text{He}$ produces no neutrons, but there is no natural source of ${}^3\text{He}$ and no way to breed it except with deuterium-deuterium (D-D) reactions or the decay of tritium; and even if there were, it would still be neutron-producing D-D and D-T secondary reactions. There are many D- ${}^6\text{Li}$ reactions, but these have lower reaction rates and would still produce copious neutrons through both primary and secondary reactions. Finally, the p - ${}^{11}\text{B}$ reaction produces no neutrons at all, but ignition of this fuel appears impossible unless new physics concepts are discovered.³¹ In short, Cat-D is the most appropriate advanced fuel cycle for the present analysis.

The main disadvantage of Cat-D (or any other advanced fuel cycle) is the low reaction rate compared to D-T, which corresponds to a larger plasma volume for the same electrical output. For a given plasma pressure and temperature, the fusion power density of Cat-D is roughly two orders of magnitude lower than for D-T, although the fusion charged-particle power density is only a factor of 12 smaller.^c But low power density can also result in several advantages, such as longer blanket lifetimes and reduced specific afterheat. The main advantage of Cat-D is the elimination of tritium breeding so that no lithium compound is required in the blanket. The tritium inventory is greatly reduced (and therefore the consequences of routine and accidental releases of tritium), and the dangers posed by chemical reactions with lithium compounds are eliminated. In addition, the blanket is simplified and can be designed to maximize energy multiplication.

The Cat-D reactor partially compensates for its low power density by increasing the thermal efficiency and neutron multiplication of the blanket and by increasing the fraction of the power generated by charged particles, thereby raising the overall efficiency of power conversion. The efficiency of a Cat-D reactor is typically $\sim 50\%$ greater than that of the D-T reactor.

There have been several reactor design studies based on the Cat-D fuel cycle³²⁻³⁴ that explored the advantages and disadvantages of Cat-D compared to D-T. Each of these studies concluded that while the Cat-D reactor appears safer than a corresponding D-T reactor, it is also more costly. The cost disadvantage varies widely between reports; however, the WILD-CAT study³³ estimated that Cat-D is twice as costly,

^cIf the plasma density of a reactor is limited by neutron wall loading instead of plasma pressure (which is not now thought to be the case), the power density of Cat-D compares much more favorably to D-T, but the advantages of Cat-D with respect to lower specific afterheat would then disappear.

while a recent report done by Science Applications International³⁴ (SAI) indicated an only slightly greater cost of electricity. Neither report estimated the economic benefits of lower accident, occupational, and waste disposal hazards, which would make Cat-D somewhat more attractive. For the purposes of this paper, it is sufficient to say that Cat-D may be economically competitive with D-T, depending on details that cannot be accurately assessed at this time.

To estimate the radiological hazards of Cat-D relative to D-T, a modified version of the SAI tandem mirror design³⁴ is used. The plasma radius is kept the same, but the halo, blanket, and shield thicknesses are reduced so that the inside magnet radius is 2.25 m, which is 0.4 m greater than the MARS design. The central cell length is shortened from 300 to 215 m to reduce the net electrical output from 1997 to 1200 MW. The major parameters of the reference Cat-D design are summarized in Table I.

Accident Hazards

As in the case of D-T, a Cat-D reactor has several sources of radioactivity: tritium, structural activation, and coolant activation and corrosion products. The tritium inventory is greatly diminished, however, since only the tritium in the plasma must be processed and since the burnup fraction can be made fairly large. Reference 34 estimates a Cat-D vulnerable tritium inventory 200 times less than that of the MARS design, which makes the contribution of tritium to Cat-D accident hazards truly negligible. The maximum off-site dose from a release of 100% of the vulnerable tritium is only 30 mrem—about the same as a chest X ray.

As before, structural and coolant radioactivities were calculated using the codes and data described in Refs. 6 and 7. The total radioactivity vulnerable to release in the Cat-D reactor (tritium + first wall + coolant) is half that of the reference MARS design. The effect of afterheat on first-wall temperatures following a LOCA depends only on the specific afterheat as a function of space and time and the geometry of the blanket. The reference Cat-D blanket model uses a large volume fraction of graphite that efficiently moderates neutrons and greatly reduces the afterheat in the reflector/shields. Although the reflector is the main source of activity in the MARS design, there is no reason that a similar effect could not be achieved in a D-T reactor (albeit at some loss of efficiency); in fact, many D-T designs use graphite reflectors. The Cat-D blanket designs are more flexible than their D-T counterparts, but there is no *a priori* reason for assuming that Cat-D blankets are safer for a given specific afterheat.

But the specific afterheat is not equal, since the Cat-D inventory of short-lived radionuclides is smaller and the volume in which they are contained is greater.

The specific afterheat of a Cat-D design will be ~3 times lower than a D-T design due to the decreased neutron power and 2 times lower due to the larger volume of blanket structural material, for an overall factor of 6. Actual calculations for the reference Cat-D and D-T blankets indicate that this reasoning is correct for the entire blanket but not for the first wall, for which the ratio of specific afterheats is <2.5. This is due primarily to differences in geometry; the MARS tube zone is not a typical first wall, since most of the material is shielded from the neutron flux. If we consider only the first surfaces in both designs, we find that the ratio of the specific afterheats is ~4. The departure from the scaling laws may be due to differences in the spectrum of incident or backscattered neutrons. In general, the specific afterheat of Cat-D first-wall structures is 2 to 6 times less than those in a D-T reactor.

One could construct an elaborate heat transfer model for the Cat-D blanket model, calculate the temperature response of the first wall to various accident scenarios, and compare the results with those obtained in the same way for the reference MARS design. But this study aims for conclusions that are broader than those based on a point design—that depend, for example, only on the essential differences between Cat-D and D-T. In a LOCA, the essential difference between Cat-D and D-T is the lower specific afterheat. To first order, the temperature increase of a reactor component scales as the fourth root of the specific afterheat. Using the ratio of specific afterheats given above, this corresponds to a maximum first-wall temperature 100 to 300 K less than the reference MARS design. This in turn corresponds to a decrease in the release fraction of manganese (the largest contributor to HT-9 accident hazard) of a factor of 3 to 15.

By what overall factor are the accident hazards of Cat-D less than those of D-T? The inventories of radionuclides contributing most heavily to chronic effects are a factor of ~1 or 2 smaller for Cat-D; combining this with the decrease in release fractions gives an overall decrease of a factor of 6 to 30. For acute effects, also note that roughly half of the reference D-T accident hazard is due to activation products of lithium-lead, which are absent from the Cat-D blanket, giving an overall decrease of a factor of 12 to 60. From these general arguments we can therefore state that the accident hazards of Cat-D are 6 to 60 times less than those associated with D-T, depending on the type of hazard index and details of the designs.

Occupational Hazards

The results of the occupational hazard analysis for the Cat-D blanket are given in Table VIII. As pointed out previously, very large differences in the contact dose rate are required to produce meaningful changes in occupational hazard and its associated economic

TABLE VIII

Cat-D Occupational and Waste Disposal Hazards

Material	30-yr Contact Dose Rate (mrem/h)	Intruder Dose (rem)	IHP ^a (m ³)
First wall	220 000	30	520
Blanket	29 000 000	71	1100
Reflector	330	0.0002	0.19
Coolant	---	6.1×10^{-7}	2.4×10^{-4}

^aLife-cycle volumes (m³) are: first wall, 9.5; blanket, 77.5; reflector, 554; and coolant, 200.

penalties, and the differences between Cat-D and D-T are much too small to be significant. Although the dose rate in the reflector/shield is much smaller for Cat-D, this is mainly due to the large volume fraction of graphite in the blanket model and does not represent an essential difference between the two fuel cycles.

Waste Disposal Hazards

One might suppose that the total waste disposal hazards for a given material are simply proportional to the total neutron energy fluence, and the results presented in Table VIII are in good agreement with this reasoning. The overall hazards of Cat-D are four times less than D-T, with ~40% of this difference due to the absence of lithium-lead. It is especially important to note that Cat-D's advantage depends on using a low activation material such as graphite in the blanket; if the blanket is solid HT-9, for example, then the relative hazards of Cat-D and D-T would be reversed. It is the inherent flexibility of the Cat-D blanket that allows low activation materials to be more easily accommodated than is the case in D-T reactors.

Except in the case of occupational hazard, Cat-D has distinct if not overwhelming advantages over the D-T fuel cycle. The largest difference is in accident hazards, where lower activation product inventories combined with lower specific afterheat reduce the hazard indexes by an order of magnitude or more. Accidental (and probably routine) release of tritium is reduced to an insignificant problem. The overall waste-disposal hazard of Cat-D is four times less than D-T, although the intruder dose of the first wall and blanket is similar; the advantage lies mostly in a smaller volume of waste (due to the longer blanket lifetime) and the absence of the lithium-lead breeder/coolant.

It is difficult to judge if these advantages in radiological hazard are sufficient to overcome the technological and economic barriers of Cat-D, especially considering that similar or greater reductions in hazard can be accomplished by modifying D-T reactors. One radiological hazard not examined here—routine

releases of tritium—may influence this decision considerably, since Cat-D has the potential for tritium releases orders of magnitude lower than D-T. If tritium breeding turns out to be especially difficult, costly, or hazardous, then Cat-D may provide an acceptable solution.

CONCLUSIONS AND RECOMMENDATIONS

As indicated by the analysis of the reference MARS and LMFBR designs, fusion appears to have substantial radiological advantages over fission. For equal electrical outputs and meteorological conditions, the accident hazards of the LMFBR are 25 times greater than the MARS design; the occupational and waste disposal hazards are up to 1000 times greater.

It has been argued that the hazards of fusion must be qualitatively less than those of fission in order to gain safety-related cost reductions or public-acceptance advantages essential to fusion's future competitiveness. The comparison performed here shows that while fusion has quantitative advantages of one to three orders of magnitude, these may not automatically translate into a qualitative difference. But while the radiological hazards of fission are more or less fixed by the laws of nature, those of fusion are tied to design choices.

Large reductions in hazard can be achieved by reducing nickel impurities and substituting tungsten for molybdenum in HT-9, reducing silver impurities in lithium-lead, substituting HT-9 for Fe-1422 in the reflector and shields, and incorporating a passive plasma quench mechanism. These relatively minor modifications lead to a factor of 30 reduction in accident hazards, long-term occupational hazards 100 times smaller, and a 60-fold reduction in waste disposal hazard.

The possibility of achieving similar or greater reductions through the use of alternate reactor materials is also explored. Of the structural materials examined, V-15 Cr-5 Ti and SiC are a factor of 10 and 10 000 better overall compared to (unmodified) HT-9. The PCA and TZM were worse in every category of hazard, while Al-6061 has both advantages and disadvantages. Like HT-9, V-15 Cr-5 Ti and SiC can also be modified to reduce long-term occupational and waste disposal hazards, while Al-6061 cannot. In the case of alternate breeder/coolant materials, only Li₂O has the potential to be better than lithium-lead, and this depends on keeping the vulnerable tritium inventory <1 kg. Liquid lithium is also very clean, but the danger of violent chemical reactions with water and air increases accident hazards significantly. Using LiAlO₂ increases nearly every hazard index, especially if 5Zr-3Pb is chosen as the neutron multiplier. Routine releases of tritium, which were not considered in this study, may have a profound effect on the relative hazard of breeder materials.

At the most fundamental level, the radiological hazards of fusion are determined by the choice of fuel cycle. The hazards of D-T, for example, are due to tritium and production of energetic neutrons that activate reactor materials. The most commonly discussed alternative to D-T is the Cat-D fuel cycle, which uses only deuterium for fuel and also burns the tritium and ^3He generated as products of the D-D reactions.

Lower neutron fluxes and larger blanket volumes combine to give a significantly lower specific activity and afterheat for reactors based on the Cat-D fuel cycle. The accident hazards of Cat-D are at least one order of magnitude less than D-T; occupational hazards remain unchanged, and the waste disposal hazards are reduced by a factor of 4. Although similar or greater decreases in hazard can be accomplished by changing materials used in a D-T reactor, problems with tritium breeding and recovery would be eliminated.

The accuracy of the preceding analysis could be increased substantially by improvements in the required data. Using the results of Chen et al.,³⁵ I have noted whether the production of each radionuclide is predicted uniformly by different activation codes. In more than half of the cases there is not good agreement. Especially important are ^{26}Al , ^{48}Sc , ^{54}Mn , ^{60}Co , ^{59}Ni , ^{94}Nb , ^{99}Tc , ^{182}Ta , ^{203}Hg , ^{202}Tl , ^{204}Tl , and ^{210}Po . In addition, Ref. 35 does not contain results for the following important radionuclides: ^{27}Mg , ^{32}Si , ^{99}Mo , ^{108m}Ag , and ^{182}Hg . The discrepancies in radionuclide inventories are probably due to differences in cross-section data, not computational methods. Until these differences are resolved, accurately evaluating radiological hazards will be impossible.

Evaluating accident hazards is impossible without experiments that measure the elemental volatility of materials under reactor conditions. The groundbreaking experiments done at EG&G Idaho, Inc., are especially valuable in this regard and should be continued. The most critical data needs are measuring the volatilization of scandium from V-15 Cr-5 Ti, sodium from Al-6061, and impurities from SiC. If possible, the experiments should be expanded to include the effects of irradiation, air flow, moisture, and the presence of lithium compounds.

The hazards of 17Li-83Pb are sensitive to three poorly known quantities: the specific heat, corrosion rates, and the concentration of silver. All these should be measured accurately, and strategies for reducing the last two should be explored.

More research should be performed on the alloys identified here as promising, particularly modified HT-9, V-15 Cr-5 Ti, and SiC. The possibility of substituting other elements for molybdenum in HT-9 should be given high priority. The tremendous potential benefits of using high-purity SiC in first-wall structures justify a much larger effort on ceramics for

blanket structures. The ease with which nickel, niobium, and molybdenum can be eliminated from all potential materials should be evaluated. Breeder materials should be identified that have vulnerable tritium inventories <1 kg, do not require neutron multipliers, and do not contain high activation materials. Although the cost of developing and certifying new materials is very large, these costs can be spread over hundreds or thousands of future reactors.

Finally, all fusion reactor designers should take proper account of radiological hazards and seek ways to reduce these hazards. This is of utmost importance, since fusion's most essential advantage over fission is the possibility that it will be more environmentally benign. This possibility certainly exists but is by no means assured. As was shown in this study, relatively minor changes in the reference MARS design resulted in very large reductions in the overall hazard; on the other hand, some designs, such as those using TZM and liquid lithium, are as bad as fission. Careful design is essential to lead fusion down the path toward public acceptance.

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