Report of the DOE Panel on Low Activation Materials for Fusion Applications

DOE
Office of Fusion Energy
Panel on Low Activation Materials

June 1983

Published by

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed Copy: _____

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Report of the DOE Panel on
Low Activation Materials for Fusion Applications

UCLA/PPG--728

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DEB4 014341

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June 1983

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Executive Summary

Lower activation materials for fusion reactors are technically possible, may be important to the public acceptance of fusion energy, and should be a main goal of the fusion program. Actual levels of radioactivation in a reactor will depend on the material itself and on its alloying constituents and impurity content. The equilibrium activation level and post-shutdown decay rates affect three primary areas: long term waste material disposal; reactor maintainability, specifically, the prospects for limited hands-on or contact maintenance; and reactor safety. Goals relating to each of these three areas are proposed and used to develop four particular categories which classify both reactors and materials.

It is recommended that as a minimum, one goal of the fusion program should be a Reference Reactor which: 1) meets Class C requirements of the Code of Federal Regulations, 10CFR61, for near surface disposal of radioactive waste; 2) permits limited hands-on maintenance outside the reactor shield within 2 days of shutdown; and 3) meets all requirements for engineered reactor safety. A higher level goal could lead to a Low Activation Reactor which would meet Class B requirements for waste disposal in 10CFR61 and the same criteria for maintenance and safety as the Reference Reactor. A Very Low Activation Reactor would meet Class A requirements in 10CFR61, would permit limited hands-on maintenance behind the reactor blanket, and would meet criteria for both engineered and intrinsic reactor safety. A fourth classification, the Standard Reactor, is one which will meet requirements for engineered safety and may meet requirements for limited contact maintenance outside the reactor shield but does not meet the minimum requirements for near surface burial of waste (Class C) as presently provided for in federal regulations. A reactor constructed of

Type 316 Stainless Steel will be a Standard Reactor. More generally, it is necessary to avoid the use of highly activating materials such as nickel, molybdenum or niobium, often even as low percentage alloying constituents.

Very Low Activation Reactors would have to be constructed almost entirely of ceramic materials, examples of which include graphite and silicon carbide. Selective use of metal alloys such as aluminum is possible. All materials, whether ceramic or metallic in a Very Low Activation Reactor must have an extremely low impurity content, lower in fact than is considered reasonably probable for practical engineering materials. Even then it is not possible to achieve limited hands-on maintenance within the plasma chamber.

With more reasonable impurity levels, use of these materials would lead to a reactor in the Low Activation class. Quality commercial vanadium and titanium alloys are examples of metal alloys that can also potentially lead to a Low Activation Reactor. A definitive judgment on the engineering practicality of such reactors, especially when using ceramics, could not be reached but we note that essentially all components must be constructed of these materials.

Reference Reactors can be achieved with metal alloys provided care is taken to control the elemental composition of the alloy and its impurity content. Elemental tailoring of stainless or ferritic steel to avoid the use of natural nickel, molybdenum, or niobium is an example. A more speculative alternative is isotopically tailored molybdenum or nickel for use as low percentage alloying constituents. Both in the report and in extensive appendices, technical background material and a detailed discussion of the engineering issues associated with the use of lower activation materials are given.

Panel conclusions and recommendations are:

1. Quantitative definitions and goals are required in the areas of waste material disposal, reactor maintenance, and safety to guide fusion and materials development toward a product with advantageous radioactivation characteristics. The Panel has developed such goals in relation to waste management and maintenance. We have proceeded on the assumption that any fusion reactor must also meet criteria or standards for engineered safety. However, we have not established such standards.

The Panel recommends that the minimum goal for the fusion program should be a Reference Reactor which: a) meets requirements for Class C waste material disposal; b) permits limited hands-on maintenance outside the magnet's shield within two days of shutdown; and c) meets all requirements for engineered safety. We also recommend the adoption of the classification scheme proposed for reactor systems so it can be used in the evaluation of fusion reactor materials.

2. The waste management and maintenance goals for the Reference Reactor appear technically reasonable to achieve. The Panel concludes that the goals relating to waste management and safety may be important to the public acceptance of fusion power and are therefore important to the fusion program.

3. The activation characteristics of a material should be a primary consideration in the development of a fusion reactor material. The Panel recommends that the fusion program increase the research and development activities on materials that would meet the goals established for the Reference Reactor and the Low Activation Reactor. It should examine the role of elementally tailored structural alloys and assess the feasibility of limited isotopic tailoring. The goal in both cases is to develop materials

that meet at least the requirements for Class C waste disposal.

4. For the low activation ceramic materials, the Panel recommends that an assessment be made to determine the practical levels of impurities that can be achieved in engineering materials. Included as part of this assessment should be an economic tradeoff between the level of impurities in a material and the degree of contact maintenance that would be allowed. Such a study must include all the key reactor systems and the design interactions and constraints among these systems. The engineering feasibility of using low-activation materials for all of the components that will see a high neutron flux, including plasma heating systems and the various reactor diagnostic devices, must be assessed. If these assessments are positive, an in-depth reactor design study should be undertaken to develop a total system design for a low-activation commercial fusion power reactor. This study should be broad enough to include integration of all reactor systems and should be sufficiently detailed to permit an assessment of the system's engineering and economic practicality.

5. Further study is required to evaluate the relationship between the choice of a low activation structural material and other design selections or constraints (e.g., the coolant selection, the breeder selection, or the selection of operating parameters). Together with this, better understanding and quantification of the safety and the related cost-risk-benefit aspects of low activation reactor designs is needed. There is a strong relationship between material selections, design choices, and safety. The importance of a material's activation characteristics, afterheat, temperature capability, thermal capacity, and chemical release mechanisms relative to the safety goal must be studied. The Panel recommends that the DOE separately address this area with an eye toward developing safety goals for the

I. INTRODUCTION

In February, 1982, the Office of Fusion Energy, DOE, through its Division of Development and Technology, established a Panel to examine materials with attractive radioactivation characteristics for applications in fusion power reactors. Since February, the Panel has met together and in subgroups numerous times. Input from knowledgeable people was elicited via a two day workshop held at UCLA in April, 1982. The agenda, titles of talks, and speakers are given in Appendix II. We present here a synopsis of the Panel's findings based upon both external information provided to us and upon the work and deliberations of the Panel itself. Conclusions and recommendations follow. Background technical information brought together by the Panel is relegated to Appendices III and IV.

II. SYNOPSIS OF PANEL CONSIDERATIONS

Radioactivity in a fusion reactor is not an inherent product of the fusion reaction itself but is the result of neutron interactions with the materials from which the reactor is built. In principle, induced radioactivity levels can be held very low. Tritium, with a half-life of 12.35 years, is produced by neutron reactions with lithium or lithium-bearing compounds, is inherent to a D-T fusion reactor, and has not been the focus of the Panel's deliberations. Rather, the Panel has concentrated its concern with the neutron activation of the reactor structural materials. We have considered the question of "attractive activation characteristics" and issues related to the engineering practicality of "low activation" materials.

A. Goals of the Fusion Program as Related to Materials Activation

The Panel finds that the term "low activation material" is generally imprecisely used and that development of a "low activation fusion reactor" is a widely held but qualitative goal of the fusion program. The Panel believes that a more quantitative definition of the fusion program's goals regarding the neutron activation levels of materials in a fusion reactor is needed. The radioactivation levels of materials in a reactor influence three areas: 1. radioactive waste disposal or waste management; 2. reactor maintenance; and 3. reactor safety characteristics. We have examined this triad of areas and examined quantitative goals that might be applied to each one. However, we have been only partially successful and this is reflected in our recommendations.

The triad represented in Fig. 1 relates to three issues: I. long term management of activated reactor materials; II. hands-on or "contact" reactor maintenance (within a reasonably short time after shutdown);

Figure 1. The three areas strongly influenced by neutron activation of fusion reactor materials.

III. reactor safety in the case of a severe accident. The primary incentives for consideration of reactor safety and long-term waste management relate to environmental impacts whereas incentives influencing contact maintenance considerations relate primarily to economics. The quantitative measures suggested for these goals are summarized in Table 1 and their justification is given in Appendix III. For completeness, a summary is included in Appendix III of calculated radioactivity levels, by element, as a function of time after a reactor has been shut down following two years of continuous operation at a neutron wall loading of 1.5 MW/m^2 . In Appendix IV, an extended discussion is given of engineering practicality associated with the use of low activation materials in a fusion reactor.

The classifications of nuclear waste, as outlined in the guidelines of 10CFR Part 61, are summarized in Table 2. This guidance is for health and safety of the public. Waste classifications A, B, and C are based on the specific activity of various radionuclides in the waste. The allowable activity limits and restrictions on disposal increase from Class A to Class C waste. All three classes are regarded as low-level wastes, and 10CFR61 is not intended to cover the higher levels of activated structures that will be produced, for example, in alloys containing niobium and molybdenum, in service in a fusion reactor. The guidelines are appropriate to the evaluation of materials developed for reasons of their low level or rapid decay of radioactivity and can be used to judge the potential of materials for simple, inexpensive near-surface disposal.

The minimum goal for waste management for improvement beyond "conventional" alloys should be to identify materials that can be disposed of by shallow land burial (under the 10CFR61 regulations, Federal Register, Vol. 47, No. 248, Monday, Dec. 27, 1982, pp 57446-57482), and which decay to an

Table 1
Quantitative Definition of Goals Related To
Material Activation Levels in
Fusion Reactors

<u>Goal</u>	<u>Quantitative Definition</u>
I. <u>Waste Management</u>	Shallow land burial(a) of all materials. The materials must meet at least the requirements of Class C Waste Classification in the Code of Federal Regulations, 10CFR61.
II. <u>Contact Maintenance</u>	Limited contact maintenance allowed everywhere in the reactor in a reasonably short time after shutdown.(b) A more selective version of this goal is to achieve limited contact maintenance in a reasonably short time after shutdown for components located <u>outside</u> the blanket.(c)
III. <u>Reactor Safety</u>	Fusion reactors must meet whatever criteria are established for engineered reactor safety. A quantitative definition of one or more reactor safety goals as they may relate solely to the activation of materials has not been developed by the Panel. The issue is complicated by the inter-relationship between a material's activation characteristics, its mechanical and physical properties, and the type of accident itself.(d)

a) This depends strongly on the specific nuclides but generally requires the radioactivity to be $\leq 1 \text{ Ci/m}^3$. See federal regulation 10CFR61 and Table 2.

b) Federal regulation 10CFR20 limits a worker's radiation exposure to 1250 mrem during any 3 month period. This limit imposes a practical upper bound of about 1000 mrem/hr for limited access. For planned, routine maintenance, a still lower limit of about 10 mrem/hr would be needed. By "reasonably short time," we mean a time short enough that limited contact maintenance becomes economically advantageous relative to remote maintenance. The Panel believes that this time will be less than 14 days, although the actual dividing line will depend on the details of design and cost.

c) For this more selective version of the maintenance goal, we again mean a time short enough that limited contact maintenance is economically advantageous relative to remote maintenance. The Panel believes this time will be less than 2 days, though the actual time will depend upon details of design and cost.

d) The Panel did consider a definition such as "In the case of a mechanistically credible accident leading to the release of radioactivity, the maximum dose at the site boundary ($\sim 2 \text{ km}$) should be less than 25 rem, implying that there would be no prompt somatic effects." However, the Panel recommends that the DOE arrange to separately address this issue.

Table 2

NUCLEAR WASTE CLASSIFICATION AND STORAGE UNDER 10 CFR 61 RULES

Waste Class	Definition	Disposal
Class A Segregated Waste	Decays to acceptable levels during site occupancy.*	Segregated, Minimum requirements
Class B Stable Waste	Stabilized and decays to levels which do not pose a danger to public health and safety in 100 y.*	Covered to reduce surface radiation to a few percent of natural background.
Class C Intruder Waste	Does not decay to safe levels in 100 y. Decays to acceptably safe level in 500 y.*	≥ 5 meters below surface with natural or engineered barriers.
Waste which does not meet Class C Intruder Waste definition	Does not qualify for near surface disposal - proposed disposal methods are considered on case-by-case basis.	

*10CFR61 defines "acceptable level" to mean that inadvertent entry into the waste, with continuous occupancy, would result in less than 500 mrem yearly dose. Natural background radiation gives an average yearly dose of about 100 mrem.

acceptably safe level within 500 years after reactor shutdown (Class C waste). The Panel would hope that fusion can actually meet the criteria established for Class B material disposal, and that the time between reactor shutdown and the placement of the waste at the disposal site should not exceed approximately a plant lifetime.

In the safety area, the minimum goal must be for the reactor to meet engineered safety standards. The Panel did not develop specific quantitative goals for reasons given in Table 1. Intrinsic safety features that would allow passive response to accident situations are superior to engineered safety features requiring active response. The Panel finds that developing a goal for fusion safety vis-a-vis materials activation is complicated by the fact that the consequences of an accident will depend not only on the activation levels for materials but also on their physical and mechanical properties, the specific design, the combination of materials used, the state of components at the time of an accident, the course of events during an accident, and so on. For this reason, the Panel recommends that the DOE consider separately addressing this issue in the near future.

Finally, the maintenance goal is to achieve limited contact maintenance on components everywhere in the reactor, and particularly inside the magnet shield, within a reasonably short time after reactor shutdown. The goal of contact maintenance requires that radioactivity from all reactor components, e.g., the structure, breeder, shield, diagnostics, etc., be considered. In the past, this goal has been one of the aims of studies on the application of very low activation materials (e.g., aluminum alloys and silicon carbide). The Panel finds solely on the basis of activation of impurities in the structure that this goal cannot be met with practical

structural materials. However, a more selective goal of contact maintenance on components outside the blanket may be achievable. The Panel finds this more selective goal regarding contact maintenance to be an important factor in reactor design and it should, therefore, be considered in the selection and development of materials. Limited contact maintenance outside the magnet shield appears to be achievable with proper shield design, regardless of the structural material.

If these criteria are applied to fusion reactor structural materials, the conclusions summarized in Table 3 are reached. Impurity-free SiC could be disposed of as unrestricted waste, high purity V-Cr-Ti alloys as Class A waste, and manganese-stabilized austenitic steel as Class B waste after 30 years. However, in all of these cases, the impurities will dominate the long-term radioactivity. For example, to meet classifications A, B, or C after operating for 9 MW-y/m^2 , a first wall structural material would have to meet the limits given in Table 4 for some common impurities which lead to long-lived radionuclides. Meeting these concentrations limits in large quantities of structural materials has not been demonstrated for all elements. Several of the limits are presently exceeded in today's commercial materials. If a material does not meet the proposed Class A, B, or C guidelines, the Nuclear Regulatory Commission must approve provisions for disposal on a case-by-case basis.

The ultimate disposal of highly activated structural materials (for example, conventional stainless steels) are not covered by existing regulations. New rules will be required and long-term, safe storage will be necessary. While some storage techniques have been suggested, new techniques and new rules can be anticipated by the time they are needed for fusion systems.

Table 3

**Expected Maintenance and Waste Management Potential of
Several Materials Considered for Use in Fusion Reactor
First Wall and Blanket Structures**

Materials	Condition ^a	Maintenance	Waste Management ^c
SiC or C	Impurity-free High purity Quality commercial	Full contact ^{b-1} Limited contact ^{b-2} Semi-remote ^{b-3}	Unrestricted waste Class A Class B
Al + Mg, Si	Impurity-free High purity Quality commercial	Limited contact ^{b-2} Limited contact ^{b-2} Semi-remote ^{b-3}	Class A Class A Class B
V + Cr, Ti	Impurity-free High purity Quality commercial	Semi-remote ^{b-3} Semi-remote ^{b-3} Semi-remote ^{b-3}	Class A Class A Class B
Mn-stainless steel	Impurity-free	Semi-remote ^{b-3}	Class B, after 30 yr(d)
[Ni, Mo, Nb-free grades]	Quality commercial	Semi remote ^{b-3}	Class B, after 30 yr(d)
304 stainless steel	Impurity-free	Semi-remote ^{b-3}	Long term
[Mo, Nb-free grades]	Quality commercial	Semi-remote ^{b-3}	Long term
Ferritic stainless steel [Fe, Cr+1% Mo]	Impurity-free Quality commercial	Semi-remote ^{b-3} Semi-remote ^{b-3}	Long term Long term
316 stainless steel [grades with Mo, Nb]	Impurity-free Quality commercial	Semi-remote ^{b-3} Semi-remote ^{b-3}	Long term Long term

- a "High purity": assumed to be ≤ 10 at. ppm total of Fe, Ni, Cu, and Mo.
"Quality commercial": assumed to be ≤ 100 at. ppm total of the same elements.
Niobium may be important, but is not considered.
- b-1 "Full Contact" means that contact maintenance is possible everywhere in the reactor, that is, there is unlimited access.
- b-2 "Limited Contact" means that access to the components outside the blanket for limited hands-on maintenance is possible but access is not possible for contact maintenance of the first wall and inner blanket.
- b-3 "Semi-remote" means that contact or limited hands-on maintenance is not allowed inside the magnet's shield. However, limited hands-on maintenance outside the magnet's shield is possible with proper shield design.
- c Waste classifications are according to limits set by 10 CFR 61, for a time 10 years after shutdown, following operation to a first wall exposure of 9 MW-yr/m^2 .
- d Mn-stainless steels would require 30 years on-site storage before transfer to Class B disposal.

Table 4

Examples of Initial Concentration Level Restrictions^(a)
 10 CFR61 Waste Disposal Rules (Dec. 27, 1982)
 10 years after shutdown, 9 MW-y/m² exposure

Element	Limiting Radionuclide	Initial Concentration Limit ^(b)		
		Class A	Class B	Class C
N	¹⁴ C	365	---*	3650
O	¹⁴ C	250,000	--	>10 ⁶
Al	²⁶ Al	>10 ⁶	>10 ⁶	>10 ⁶
Co	⁶³ Co	30	>10 ⁶	>10 ⁶
Cu	⁶³ Ni	12	240	2400
Fe	⁵⁵ Fe	350	>10 ⁶	>10 ⁶
Ni	⁶³ Ni	100	2000	20000
Mn	⁵⁴ Mn	5000	>10 ⁶	>10 ⁶
Mo	⁹⁴ Nb	365	--	3650
Nb	⁹⁴ Nb	0.1	--	1
Zr	⁹⁰ Sr	400	>10 ⁶	>10 ⁶
Si	³¹ Si	>10 ⁶	>10 ⁶	>10 ⁶
Mg	²⁴ Na	>10 ⁶	>10 ⁶	>10 ⁶
V	⁴⁹ V	>10 ⁶	>10 ⁶	>10 ⁶
Ti	⁴⁵ Ca	>10 ⁶	>10 ⁶	>10 ⁶
Cr	⁴⁹ V	>10 ⁶	>10 ⁶	>10 ⁶

(a) these limits apply to the first wall region.

(b) atom parts per million based on assumed atom density of base materials of $8 \times 10^{22} \text{ cm}^{-3}$.

* the symbol -- signifies that storage in this classification is not defined.

The relationship between the selection of a structural material and the ability to achieve contact maintenance is summarized in Table 3. Only selected impurity-free materials offer the possibility of meeting the goal of contact maintenance everywhere in the reactor within 14 days of shut-down. Even with optimistic assumptions regarding the attainable purity of large volumes of these structural materials, it will not be possible to achieve contact maintenance in the plasma chamber after extended, high-power operation. In addition, contact maintenance would require that all other components in the high flux region be constructed of impurity-free low-activation materials. Although this consideration of contact maintenance necessitates the evaluation of a complete reactor design, attainment of the required material purity is not considered feasible. On the other hand, several materials (see Table 3) with practical impurity levels, both ceramics and metals, appear to have the potential to meet the more selective goal of limited contact maintenance allowed everywhere outside the blanket after extended high-power operation.

A classification scheme for reactor systems has been developed and is summarized in Table 5. A reactor system that meets the waste disposal criterion for Class A waste, permits limited hands-on maintenance outside the reactor blanket, meets all requirements for engineered reactor safety, and has the properties for intrinsic safety, leads to classification as a "Very-Low-Activation" Reactor. Only high-purity materials for which the induced radioactivity decays by a factor of at least 10^6 within two days after shutdown (e.g., pure SiC or C) can be used in a reactor which would meet this goal.

Reactor systems that can meet the Class B waste disposal criterion, permit limited hands-on maintenance behind the reactor blanket, meet the requirements for engineered reactor safety, and have some features of

Table 5

Categories for Fusion Reactors and Materials Based Upon Criteria
Relating to Waste Management, Maintenance, and Reactor Safety

Reactor and Materials	Waste Material Management (I)	Contact Maintenance (II)	Reactor Safety (III)
Very Low Activation	Reactor materials meet criteria for Class A waste disposal in 10CFR61.	Limited hands-on maintenance permitted behind the blanket within 2 days of reactor shutdown.	Meets requirements for engineered reactor safety. Has main characteristics for intrinsic safety.*
Low Activation	Reactor materials meet criteria for Class B waste disposal in 10CFR61.	Limited hands-on maintenance permitted outside the blanket or outside the shield within 2 days of reactor shutdown.	Meets requirements for engineered reactor safety. Has some characteristics for intrinsic safety.
Reference Activation	Reactor materials meet criteria for Class C waste disposal in 10CFR61.	Limited hands-on maintenance permitted outside the shield within 2 days of reactor shutdown.	Meets requirements for engineered reactor safety.
Standard Activation	Reactor materials do not meet criteria for shallow land disposal of radioactive waste given in 10CFR61.	No special requirement.	Meets requirements for engineered reactor safety.

* "Intrinsic safety" means no active safety features are necessary. The reactor would meet safety requirements following postulated severe but mechanistically possible accidents, without the need for active safety features.

intrinsic safety, are classified as "low activation" reactors. Ceramic materials have properties consistent with intrinsic safety and it appears that vanadium-chromium-titanium alloys may have distinctive safety advantages based upon the preliminary safety analysis work discussed in Appendix III.

Systems that meet the Class C waste disposal criterion, permit limited hands-on maintenance only outside the activation shield (we refer to this as "semi-remote"), and meet the requirements for engineered safety are defined as a Reference Reactor. Such systems would use materials that do not contain Ni, Cu, Nb, and Mo or have strictly controlled impurity levels of these high activation elements. Examples of materials lending to reactors falling in this category include manganese-stabilized austenitic stainless steels, elementally tailored ferritic stainless steels and possibly isotopically tailored stainless steels. The technical feasibility of producing materials of sufficient purity must be demonstrated and the economic tradeoffs associated with the use of high purity materials requires further study.

B. Functional Performance Requirements and Engineering Practicality

Given the desirability of designing for low levels of induced radioactivity, the question becomes "Can the perceived advantages be attained in a credible engineering system?" Therefore, it is important to review some of the design implications or limitations which appear to influence the practicality of achieving the low activation goals in a fusion reactor. An extended discussion of these issues is given in Appendix IV.

Preliminary assessments of the requirements for contact maintenance lead to three issues which control the intrinsic practicality of attaining this goal: (1) all components in the high neutron flux region must be

constructed of these low activation materials; (2) the concentration of impurities which form radioactive nuclides must be maintained at extremely low levels in all materials inside the plasma chamber, in the first wall and in the front portions of the blanket; and (3) joining methods must be adopted which avoid the introduction of radiologically unacceptable materials. The classes of components that are generic to a magnetically confined fusion reactor include: (1) high heat flux components such as a limiter or divertor; (2) the first wall; (3) the blanket system including the breeder, structure and possibly a neutron multiplier; (4) auxiliary equipment in the high flux region such as rf wave guide launchers, diagnostics and direct energy conversion hardware; (5) the shield; and (6) the magnet system. It is not clear at the present time whether all of these components can be designed to satisfy the specified operating criteria if they are fabricated entirely from materials with very-low activation characteristics. As in the case of the structural material, impurity-free material must be used for all components in the high flux regions.

Contact maintenance is primarily an economic issue. Any economic impacts related to material cost, reactor cost, different component lifetime, or altered performance parameters that are associated with the use of very low activation materials must be compared with economic impacts due to maintenance simplification associated with the use of very low activation materials.

Extensive use of materials leading to a low and reference activation reactor, e.g., high purity C, SiC, Al-Mg-Si alloys, V-Cr-Ti alloys or modified austenitic or ferritic stainless steels, to substantially reduce the long-term waste management requirements for fusion reactor structural

materials appears to be feasible. Although it may not be possible to construct every reactor component from this class of materials, design concepts that incorporate these materials into the major components appear credible. Since in most cases, the data base for these types of materials is very limited, a more extensive materials development program will be required. Further study is also required to evaluate more comprehensively the impact such designs would have on limiting concept selection (e.g., choice of coolant and breeding material) and operating criteria (such as wall load limits or lifetime).

C. Low Activation Materials in Near-Term, Unshielded Reactor Experiments

Both the US and Japan have considered the importance of activation in near-term tokamaks that will be used for a few D-T shots. The conclusions on acceptable materials are quite different, reflecting the assumptions for required maintenance.

The assumption in both TFTR and the Japanese R-project is that remote maintenance technology will not be needed for limited D-T operation of the reactor. The TFTR team assumes that entrance to the reactor hall within one day of shutdown is required in order to accomplish simple repairs and restore device operation. This means that even short-lived activation products will not have decayed appreciably and this places a strict limit on the number of D-T shots that will be allowed. This will require work in moderate activity fields and requires the elimination of aluminum and the use of steels in all zones near the plasma chamber to keep shutdown activity to reasonable levels. The equilibrium activation level from aluminum is less than 20% of that from steel but approaches equilibrium much faster because of the short (15 hr) ^{24}Na half-life compared to the 2.7 year half-

life for ^{55}Fe . Thus, for low neutron fluences (exposure times of less than a year) and very short times after shutdown (1 day), steel will actually give a lower dose rate. The Japanese team would not enter the reactor vault until two weeks after shutdown and, based on this, specify only aluminum alloys to permit the activity to decay greatly prior to vault entry. In this case, more extensive repairs are possible because of the lower dose rate, and the number of D-T shots allowed is much larger.

The Panel finds that it will be essential to think carefully and sensibly through conflicting requirements that are usually specific to a design. Materials such as nickel, manganese, molybdenum, and copper should be avoided for components which are likely to need repair in near-term D-T devices. The Panel finds it unlikely that there will be a general or overall use of low-activation materials in near-term machines.

Appendix I

Department of Energy
Washington, D.C. 20545

FEB 16 1982

Professor Robert W. Conn
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Dear Bob,

I would like to confirm with this letter our previous conversation regarding materials with attractive activation characteristics and the need to examine the application they might fulfill in fusion power reactors. In this context I would like to propose that you serve as chairman of a panel that would pursue this issue. The charter under which the panel would function is enclosed. Other members that have agreed to participate on the panel are:

Robert Gold	Westinghouse
Dale Smith	Argonne National Laboratory
John Davis	McDonnell Douglas
Roy Little	Princeton Plasma Physics Laboratory
Ken Schultz	General Atomic
Everett Bloom	Oak Ridge National Laboratory

As a preface to the deliberation of the panel, I would like to suggest a few guidelines concerning the context in which the charter needs to be considered.

A number of individual materials which are inefficiently activated by neutron bombardment or which readily decay to tolerable levels of radioactivity have come to be known as low activation materials. The extensive use of such materials in a reactor is perceived to accrue benefits through reducing the levels and longevity of activation of a fusion power reactor thereby improving maintenance capabilities, reducing radiation exposure to operating personnel, increasing safety, reducing capital cost, improving access, reliability and availability, and decreasing waste management requirements. Preliminary studies that have been conducted to date reinforce many of the intuitive deductions, but do not constitute definitive analyses that can identify exactly how the most significant benefits will result from the use of low activation materials. Consequently, the total utility of such an approach has not been completely scoped.

Since low activation materials hold to themselves an attractive prize, some criteria or standards of judgment that accurately reflect the harsh reality of system engineering need to be developed as a basis for considering continued pursuit of such a concept. Two major points need to be considered in establishing such criteria.

The first point, which will significantly impact the understanding of the second point, is the need to consider whether low activation materials, when used to fabricate a fusion power reactor, would be adequate in performing the functions desired of them. This particular point has yet to be addressed in detail when considering the role low activation materials can fulfill in fusion power reactors. Although a material may have very attractive characteristics from an activation viewpoint, if its mechanical, physical or chemical characteristics cannot fit within the design constraint envelope of a reactor, then its usefulness is suspect. This point is the principal focus of the panel's task as described in the enclosed charter.

The second is their true utility. A fusion power reactor will be a complex system of many subsystems, components and elements. Each of these will be fabricated from materials with special characteristics. Will it be possible to build enough of the subsystems, components and elements of such materials so that the perceived benefits will be realized? If only a moderate portion of the system is made of such materials, would the cost of development be justified by the limited benefits to be realized? This point must be included in the panel's work to provide a context in which to address the detailed questions raised in the charter.

The benefits that could be realized from low activation materials might be significant. However, these benefits can only be realized if the materials can perform the functions desired and they can be utilized to a reasonable extent throughout the system. We are asking for the panel's help in achieving a better picture of the feasibility and utility of low activation materials. Please let me know if you will accept the chairmanship of the panel.

Sincerely,

Robert J. Dowling
Director
Division of Development and Technology
Office of Fusion Energy
Office of Energy Research

Enclosure

cc:

R. Gold, WEC
D. Smith, ANL
J. Davis, McDonnell Douglas
R. Little, PPPL
K. Schultz, GA
E. Bloom, ORNL

APPENDIX II

LOW ACTIVATION MATERIALS
MEETING

(Held at UCLA, April 13-14, 1982.)

OPEN SESSIONS

Tuesday, April 13 (3564 Ackerman Union)

1:00 - 1:15	Opening Remarks (R. W. Conn)
1:15 - 3:15	General Atomic Presentations
1:15 - 1:40	Low Activation Fusion Rationale (G. Hopkins)
1:40 - 2:25	Ceramic and Aluminum Materials Applications to Low Activation Fusion (T. Gulden, P. Trester)
2:25 - 2:45	Design Studies with Low Activation Material (G. Hopkins)
2:45 - 3:15	Low Activation Superconducting Magnets (J. Purcell)
3:15 - 3:30	Coffee Break
3:30 - 4:15	Prospects for Low Activation Aluminum Structures (J. Fillo, J. Powell - BNL)
4:15 - 5:15	LLNL presentations
4:15 - 4:35	The Need for Low Activation (C. Henning)
4:35 - 4:55	Waste Disposal Considerations (C. Maninger)
4:55 - 5:15	Candidate Low Activation Materials (E. Dalder)
5:15 -	Discussion

Wednesday, April 14 (3564 Ackerman Union)

9:00 - 10:00	The Estimation of Benefits of Low Activation Materials in Reducing Reactor Accidents and Waste Management Hazards: Methods and Findings (J. Holdren - UC-Berkeley)
10:00 - 10:45	Safety Perspective of Low Activation Materials (S. Cohn, J. Crocker, EG&G)

10:45 - 11:00	Coffee Break
11:00 - 11:30	Overview of Fusion Reactor Alloy Development Program (E. Bloom, ORNL)
11:30 - 12:00	Neutron Activation Analyses for the STARFIRE Design (D. Smith, ANL)
12:00 - 12:30	Radioactive Material Considerations in Evaluation of Environmental Impact (F.W. Wiffen, ORNL)
12:30 - 1:30	Discussion

APPENDIX III
LOW ACTIVATION: DESIRABILITY, QUANTITATIVE EVALUATION,
AND RELATION TO GOALS FOR THE FUSION PROGRAM

III.1. Desirability

- A. Maintenance, Repair and Component Replacement
- B. Safety
- C. Waste Management
- D. Summary

III.2. Quantitative Evaluation

- A. Design Alternatives
- B. Activation Levels
 - Activation by Element
 - Baseline STARFIRE Design
 - Low Activation STARFIRE Design
 - Activation with Vanadium

III.3. Relation of Goals to Activation

- A. Access for Maintenance
 - STARFIRE
 - FED
- B. Safety Considerations
- C. Waste Management

References

fusion program. It may then be possible to more clearly establish the relationship between materials choices, activation levels, and reactor safety.

APPENDIX III

Low Activation: Desirability, Quantitative Evaluation, and Relation to Goals for the Fusion Program

Fusion is a nuclear reaction and involves the release of nuclear radiation and the potential for radioactivity. Radioactivity in a fusion reactor is not an inherent product of the fusion reaction itself but the result of neutron interactions with the materials from which the reactor is built. Radiation after shutdown can severely impact maintenance. Radioactive materials are hazardous if released and can result in safety concerns. If the radioactivity is long-lived, a waste management concern occurs. In this section, the desirability of minimizing radioactivity in fusion reactors is discussed, the quantities of radioactivity associated with different fusion design alternatives are compared, and the relationship between radioactivity and the goals of the fusion program is explored. The radioactivity from different materials can differ by factors of more than 10^6 , and trace impurities can thus dominate fusion activation characteristics. We have assumed a very low total impurity content of 1 appm of undesired, high activation material will be present. This high purity may not be attainable and is included for illustration only.

III.1. Desirability

The fundamental disadvantages associated with nuclear power are a direct consequence of the presence of radioactivity. It is clearly desirable to minimize radioactivity in fusion reactors by use of low activation materials. To achieve this, however, will require research and development programs to understand the system design requirements and limitations of low activation

materials and to attempt the needed low activation materials development. The central issue to the Low Activation Materials Panel deliberations and report is the question of whether perceived advantages of low activation concepts are attainable and, if they are, what are the costs associated with realizing them in practical engineering systems. These costs must then be carefully weighed as part of a cost-risk-benefit assessment.

A. Maintenance, Repair, and Component Replacement

All of the components within a fusion power plant will need to be designed with the capability for some degree of maintenance, repair, or replacement. The problems with activation revolve around the degree of personnel access achievable. Unforeseen fault diagnosis and repair is especially difficult to do entirely remotely, and is time consuming. The downtime required for repair and maintenance is a critical factor in cost of power from a power reactor and the cost of experiments for test reactors. The early fusion reactors can be expected to have the most frequent unforeseen faults and thus, could benefit most from reduction in activation. A few unplanned difficult outages in a high activation reactor could severely burden and delay the entire fusion power program. Extensive use of low activation materials could greatly reduce this kind of maintenance problem for fusion.

B. Safety

The safety concerns in fusion, to a large measure, are attributable to the radioactivity generated by activation. Tritium in the fuel cycle must also be considered from the safety aspect, but is generally found to be

a small component of the overall risk. The primary source of radioactivity is in the first wall and blanket structures surrounding the plasma.

The probabilistic risk approach provides a direct way to compare risk for differing activation levels. The biological risks from radioactivity and radioactive materials may be quantitatively assessed from a probabilistic approach described by

$$\begin{aligned} \text{Risk factor} &= \text{quantity of radioactivity} \\ &\times \text{probability of release and ingestion.} \end{aligned}$$

The radioactive inventory for a fusion reactor with steel structures is about a factor of 10 less than fission, which eases the safety concerns by at least a factor of 10. Low activation fusion, on the other hand, can give activation levels up to a factor of one million smaller within days after shutdown. In addition, radioactivity is a well-known physical quantity, whereas achievement of acceptable risk through reduction of the "probability of release," the other variable, involves a significant level of uncertainty.

One of the main consequences of the radioactivity generated in fusion is the potential melting of structures because of the afterheat generated in decay. Reduction of decay heat has a multiplicative effect on the risk factor. Not only is the risk factor reduced linearly through reduction of radioactivity, but in addition, the probability of release is reduced at the same time.

The public perception of nuclear safety is an issue that must soon be faced for fusion. The large reduction of risk through a direct reduction of

radioactivity by low activation materials should provide a positive impetus to pursue fusion as an energy source.

C. Waste Management

Waste management of the long half-life radioactive waste materials from a fusion plant appears to be technically manageable. The political problems associated with waste management over a time scale of many human generations, however, are less easily resolved. Low activation materials can reduce the major problems associated with waste management. All the intermediate and long half-life isotopic concentrations can potentially be reduced to levels requiring only shallow land burial for disposal. On-site disposal at the power plant may be a reality, avoiding handling and shipping problems.

D. Summary

In summary, the use of low activation material for fusion reactors would be highly desirable; however, the feasibility and cost of achieving this are presently unknown. Ultimately, extensive use of low activation materials in the high flux regions (first wall/blanket/ shield) could reduce the problems associated with radioactivity that presently plague fission reactors. Reduced biological dose rates could facilitate maintenance. Reduced hazard inventories could reduce the consequences of accidents. Reduced radioactivity levels in the long term could greatly simplify waste management considerations.

III.2. Quantitative Evaluation

To quantitatively assess the benefits of using reduced activation materials in fusion reactors, the various design alternatives must be explored and the activation levels associated with these must be quantified.

A. Design Alternatives

Several investigations have been conducted to explore the activation characteristics of various alternative materials in a fusion reactor neutron environment (Refs. 1-4). The conclusion of these studies is that materials selection can produce significant differences in activation levels and decay times. Conventional materials, primarily iron- and nickel-based alloys, result in activation levels about one order of magnitude less than those of the fission products associated with a fission reactor, and with times to decay to innocuous levels on the order of 1000 years. By chemically or isotopically tailoring these alloys, long-lived products may be avoided, resulting in materials with low activity levels after about 100 years. Less conventional construction materials such as vanadium and titanium can offer further reduction of about a factor of 5 in activation at shutdown and the potential for decay times of years instead of centuries. Aluminum alloys and several structural ceramics offer still further reductions and decay times as short as days. Impurities can significantly impact the activation.

Several fusion reactor conceptual design studies have been done using these alternative structural materials. The STARFIRE design (Ref. 5) is typical of designs using conventional structural steels and is the

latest, most complete tokamak reactor design. The substitution of tailored steels is expected to make little difference in the physical design of the reactor but could impact the activation decay characteristics (Ref. 6). The use of vanadium or titanium will similarly not be expected to significantly affect the physical design, but will result in a much different metallurgical environment because of the fabrication and chemical compatibility characteristics of these reactive alloys. The use of the low activation materials requires different design approaches to accommodate, for example, the low temperature limitations of aluminum alloys (Refs. 7 and 8), or the brittle nature of ceramics (Ref. 8). The activation characteristics of these four design alternatives are discussed below.

B. Activation Levels

Different elements, and the isotopes within those elements, exhibit different nuclear behavior when bombarded by fusion neutrons. This results in different activation products, activation levels, and decay times.

Activation by Element. The level of activation that occurs in a fusion reactor will depend upon the neutron flux and spectrum, the length of exposure, and the elements that are activated. An analysis in Ref. 4 used a neutron spectrum for a natural enrichment lithium oxide breeder blanket at a wall load of 1.5 MW/m^2 for two years to calculate the radioactivity in the first wall/blanket region for various elements that could be used in fusion systems. Current fusion reactor designs use higher wall loads and longer exposure times. Higher wall load will result in linearly proportional higher activation levels for all materials. Longer exposure times will

result in higher activation levels for the long-lived radioactive products. The resulting activity levels and the decay of these after shutdown are shown in Figs 1a and 1b. The activation levels at shutdown vary by about a factor of 5 around the mid-range value of about $2 \text{ Ci/W}_{\text{th}}$. A very large difference in the residual activity begins to occur after shutdown. Those elements with the lowest shutdown activity also have the shortest decay half-lives and the activity drops rapidly.

Table 1 summarizes the major radionuclides generated in various elements involved in the fusion reactor design.

The post-shutdown radioactive inventories and most important radionuclides induced in the first wall after exposure to 1.5 MW/m^2 for two years are summarized in Table 2 for various elements.

The actual levels of activation that will be found in a specific reactor design will depend upon the elements that are used in the materials of which it is made, upon the design specifications, and upon the operating history. The total radioactivity level for a typical 3000 MW(th) tokamak fusion power reactor was calculated using various alternative reactor structural materials. The results are summarized in Fig. 2. The total activity of a 3000 MW(th) LMFBR is shown for comparison. This shows that significant differences in the activation levels can be achieved by selection of the materials from which the reactor is constructed. The use of low activation materials will yield about an order of magnitude lower activity at shutdown than will conventional materials. This advantage increases to over a factor of 10^6 two weeks after shutdown. At these levels, impurities in the low activity materials will dominate the radioactivity levels.

Fig. 1a

Fig. 1b

Fig. 1. Post-shutdown radioactivity for various elements after exposure in the first wall region to a wall load of 1.5 MW/m² for two years.

TABLE 1
CHARACTERISTICS OF MAJOR INDUCED RADIONUCLIDES IN POTENTIAL ELEMENTS FOR FUSION REACTOR STRUCTURE

Natural Element		Neutron Induced Radionuclides				
Element	Natural Isotopes and Abundance (%)	Major Induced Radionuclide	Half-Life; Decay Mode; Gamma-Ray Emission	MPC ($\mu\text{Ci/cc}$)		Major Transmutations
				Air	Water	
Al	^{27}Al (100)	^{24}Na	15 h; β^- ; γ	5×10^{-9}	3×10^{-5}	$^{27}\text{Al}(n,\alpha)$
		^{26}Al	7.4×10^5 y; β^+ ; γ	(a)	(a)	$^{27}\text{Al}(n,2n)$
		^{27}Mg	9.5 min; β^- ; γ	(a)	(a)	$^{27}\text{Al}(n,p)$
C	^{12}C (98.9)	^{14}C	5730 y; β^- ; no γ	1×10^{-7}	8×10^{-4}	$^{13}\text{C}(n,\gamma)$
	^{13}C (1.1)	^{10}Be	2.5×10^6 y; β^- ; no γ	(a)	(a)	$^{13}\text{C}(n,\alpha)$
	^{59}Co (100)	^{58}Co	71.3 d; β^+ ; γ	2×10^{-9}	9×10^{-5}	$^{59}\text{Co}(n,2n)$
Co		^{59}Fe	45 d; β^- ; γ	2×10^{-9}	5×10^{-5}	$^{59}\text{Co}(n,p)$
		^{60}Co	5.27 y; β^- ; γ	3×10^{-10}	3×10^{-5}	$^{59}\text{Co}(n,\gamma)$
Cu	^{63}Cu (69.2)	^{60}Co	5.27 y; β^- ; γ	3×10^{-10}	3×10^{-5}	$^{63}\text{Cu}(n,\alpha)$
	^{65}Cu (31.8)	^{63}Ni	92 y; β^- ; no γ	2×10^{-9}	3×10^{-5}	$^{63}\text{Cu}(n,p)$
		^{64}Cu	12.8 h; β^- and β^+ ; γ	4×10^{-8}	2×10^{-4}	$^{63}\text{Cu}(n,\gamma)$; $^{65}\text{Cu}(n,2n)$
Cr	^{50}Cr (4.35)	^{49}V	330 d; EC; no γ	(a)	(a)	$^{50}\text{Cr}(n,2n)$ $^{49}\text{Cr} \xrightarrow{\beta^+} 42 \text{ min}$
	^{52}Cr (83.8)	^{51}Cr	27.8 d; EC; γ	8×10^{-8}	2×10^{-3}	$^{50}\text{Cr}(n,\gamma)$; $^{52}\text{Cr}(n,2n)$
	^{53}Cr (9.5)	^{52}V	3.8 min; β^- ; γ	(a)	(a)	$^{52}\text{Cr}(n,p)$
	^{54}Cr (2.4)					

TABLE 1 (Continued)

Natural Element		Neutron Induced Radionuclides				
Element	Natural Isotopes and Abundance (%)	Major Induced Radionuclide	Half-Life; Decay Mode; Gamma-Ray Emission	MPC ($\mu\text{Ci/cc}$)		Major Transmutations
				Air	Water	
Fe	^{54}Fe (5.8)	^{53}Mn	2×10^6 y; EC; no γ	*	*	$^{54}\text{Fe}(n,2n)$ $^{53}\text{Fe} \xrightarrow{\beta^+} \text{8.5 min.}$
	^{56}Fe (91.8)	^{54}Mn	303 d; EC; γ	1×10^{-9}	1×10^{-4}	$^{56}\text{Fe}(n,p)$
	^{57}Fe (2.1)	^{55}Fe	2.7 y; EC; no γ	3×10^{-8}	8×10^{-4}	$^{54}\text{Fe}(n,\gamma); ^{56}\text{Fe}(n,2n)$
	^{58}Fe (0.3)	^{56}Mn	2.6 h; β^- ; γ	2×10^{-8}	1×10^{-4}	$^{56}\text{Fe}(n,p)$
Hg	^{200}Hg (78.6)	^{200}Au	15 h; β^- ; γ	5×10^{-9}	3×10^{-5}	$^{200}\text{Hg}(n,p)$
	^{201}Hg (10.1)	^{201}Au	1 min; β^- ; γ	*	*	$^{201}\text{Hg}(n,p)$
	^{202}Hg (11.3)					
Mn	^{55}Mn (100)	^{54}Mn	303 d; EC; γ	1×10^{-9}	1×10^{-4}	$^{55}\text{Mn}(n,2n)$
		^{56}Mn	2.6 h; β^- ; γ	2×10^{-8}	1×10^{-4}	$^{55}\text{Mn}(n,\gamma)$
Ho	^{92}Ho (15.86)	^{92m}Nb	10.2 d; IT; γ	*	*	$^{92}\text{Ho}(n,p)$
	^{94}Ho (9.12)	^{93m}Nb	13.6 y; IT; γ	4×10^{-9}	4×10^{-4}	$^{93}\text{Ho} \xrightarrow{\beta^-} \text{~1000 y}$
	^{95}Ho (15.7)	^{93}Ho	~ 1000 y; EC; γ	*	*	$^{92}\text{Ho}(n,\gamma); ^{94}\text{Ho}(n,2n)$
	^{96}Ho (16.5)	^{94}Nb	2×10^4 y; β^- ; γ	*	*	$^{94}\text{Ho}(n,p)$
	^{97}Ho (9.45)	^{95}Nb	35 d; β^- ; γ	3×10^{-9}	1×10^{-4}	$^{95}\text{Ho}(n,p)$
	^{98}Ho (23.75)	^{99m}Tc	6 h; IT; γ	5×10^{-7}	3×10^{-3}	$^{99}\text{Ho} \xrightarrow{\beta^-} \text{67 h}$
	^{100}Ho (9.62)	^{99}Tc	2.1×10^5 y; β^- ; no γ	2×10^{-9}	2×10^{-4}	$^{99}\text{Ho} \xrightarrow{\beta^-} \text{67 h}$
		^{99}Ho	67 h; β^- ; γ	7×10^{-9}	4×10^{-5}	$^{98}\text{Ho}(n,\gamma)$

TABLE 1 (Continued)

Natural Element		Neutron Induced Radionuclides				
Element	Natural Isotopes and Abundance (%)	Major Induced Radionuclide	Half-Life; Decay Mode; Gamma-Ray Emission	MPC ($\mu\text{Ci/cc}$)		Major Transmutations
				Air	Water	
N	^{14}N (99.6)	^{14}C	5730 y; β^- ; no γ	1×10^{-7}	8×10^{-4}	$^{14}\text{N}(n,p)$
	^{15}N (0.4)	^{16}N	7.1 s; β^- ; γ	(a)	(a)	$^{15}\text{N}(n,\gamma)$
	^{93}Nb (100)	^{90}Y	64 h; β^- ; γ	3×10^{-9}	2×10^{-5}	$^{93}\text{Nb}(n,\alpha)$
Nb		^{92m}Nb	10.2 d; IT; γ	(a)	(a)	$^{93}\text{Nb}(n,2n)$
		^{92}Nb	>350 y; γ	(a)	(a)	$^{93}\text{Nb}(n,2n)$
		^{93}Zr	1.5×10^6 y; β^- ; γ	4×10^{-9}	8×10^{-4}	$^{93}\text{Nb}(n,p)$
		^{94}Nb	2×10^4 y; β^- ; γ	(a)	(a)	$^{93}\text{Nb}(n,\gamma)$
Ni	^{58}Ni (68.3)	^{55}Fe	2.7 y; EC; no γ	3×10^{-8}	8×10^{-4}	$^{58}\text{Ni}(n,\alpha)$
	^{60}Ni (26.1)	^{57}Co	270 d; EC; γ	6×10^{-9}	4×10^{-4}	$^{58}\text{Ni}(n,d)$
	^{61}Ni (1.1)	^{58}Co	71 d; EC; β^- ; γ	2×10^{-9}	9×10^{-5}	$^{58}\text{Ni}(n,p)$
	^{62}Ni (3.6)	^{59}Ni	8×10^4 y; EC; no γ	2×10^{-9}	2×10^{-4}	$^{58}\text{Ni}(n,\gamma)$; $^{60}\text{Ni}(n,2n)$
	^{64}Ni (0.9)	^{60m}Co	0.5 min; IT; β^- ; γ	(a)	(a)	$^{60}\text{Ni}(n,p)$
		^{60}Co	5.27 y; β^- ; γ	3×10^{-10}	3×10^{-5}	$^{60}\text{Ni}(n,p)$
		^{63}Ni	92 y; β^- ; no γ	2×10^{-9}	3×10^{-5}	$^{62}\text{Ni}(n,\gamma)$; $^{64}\text{Ni}(n,2n)$
Si	^{28}Si (92.2)	^{27}Mg	9.5 min; β^- ; γ	(a)	(a)	$^{30}\text{Si}(n,\alpha)$
	^{29}Si (4.7)	^{28}Al	2.3 min.; β^- ; γ	(a)	(a)	$^{28}\text{Si}(n,p)$
	^{30}Si (3.1)	^{29}Al	6.6 min; β^- ; γ	(a)	(a)	$^{29}\text{Si}(n,p)$
		^{31}Si	2.6 h; β^- ; γ	3×10^{-8}	2×10^{-4}	$^{30}\text{Si}(n,\gamma)$

TABLE 1 (Continued)

Natural Element		Neutron Induced Radionuclides				
Element	Natural Isotopes and Abundance (%)	Major Induced Radionuclide	Half-Life; Decay Mode; Gamma-Ray Emission	MPC ($\mu\text{Ci/cc}$)		Major Transmutations
				Air	Water	
Ti	^{46}Ti (8.25)	^{45}Ca	165 d; β^- ; γ	1×10^{-9}	9×10^{-6}	$^{48}\text{Ti}(n, \alpha)$
	^{47}Ti (7.45)	^{46}Sc	84 d; β^- ; γ	8×10^{-10}	4×10^{-5}	$^{46}\text{Ti}(n, p)$
	^{48}Ti (73.7)	^{47}Sc	3.4 d; β^- ; γ	2×10^{-8}	9×10^{-5}	$^{47}\text{Ti}(n, p); ^{50}\text{Ti}(n, \alpha) ^{47}\text{Ca} \xrightarrow{4.5 \text{ d}} \beta^-$
	^{49}Ti (5.4)	^{48}Sc	1.8 d; β^- ; γ	5×10^{-9}	3×10^{-5}	$^{48}\text{Ti}(n, p)$
	^{50}Ti (5.2)					
V	^{50}V (99.7)	^{48}Sc	1.8 d; β^- ; γ	5×10^{-9}	3×10^{-5}	$^{51}\text{V}(n, \alpha)$
	^{51}V (0.3)	^{49}V	330 d; EC; no γ	*	*	$^{50}\text{V}(n, 2n)$
		^{51}Ti	5.6 min; β^- ; γ	*	*	$^{51}\text{V}(n, p)$
W	^{180}W (0.14)	^{181}W	140 d; EC; γ	4×10^{-9}	3×10^{-4}	$^{180}\text{W}(n, \gamma); ^{182}\text{W}(n, 2n)$
	^{182}W (26.4)	^{185}W	75 d; β^- ; no γ	4×10^{-9}	1×10^{-4}	$^{184}\text{W}(n, \gamma); ^{186}\text{W}(n, 2n)$
	^{183}W (14.4)	^{187}W	1 d; β^- ; γ	1×10^{-8}	6×10^{-5}	$^{186}\text{W}(n, \gamma)$
	^{184}W (30.6)					
	^{186}W (28.4)					

TABLE 1 (Continued)

Natural Element		Neutron Induced Radionuclides				
Element	Natural Isotopes and Abundance (%)	Major Induced Radionuclide	Half-Life; Decay Mode; Gamma-Ray Emission	MPC ($\mu\text{Ci/cc}$)		Major Transmutations
				Air	Water	
Zn	^{64}Zn (48.6)	^{63}Zn	38.4 min; β^+ ; γ	*	*	$^{64}\text{Zn}(n,2n)$
	^{66}Zn (27.9)					
	^{67}Zn (4.1)	^{64}Cu	12.8 h; β^- , β^+ ; γ	4×10^{-8}	2×10^{-4}	$^{64}\text{Zn}(n,p)$
	^{68}Zn (18.8)	^{65}Zn	244 d; β^+ ; γ	2×10^{-9}	1×10^{-4}	$^{64}\text{Zn}(n,\gamma)$; $^{66}\text{Zn}(n,2n)$
	^{70}Zn (0.62)					
Zr	^{90}Zr (51.5)	^{89}Zr	78.5 h; β^+ ; γ	*	*	$^{90}\text{Zr}(n,2n)$
	^{91}Zr (11.2)	^{90}Sr	28.1 y; β^- ; no γ	3×10^{-11}	3×10^{-7}	$^{92}\text{Zr}(n,^3\text{He})$
	^{92}Zr (17.1)	^{90}Y	64 h; β^- ; γ	3×10^{-9}	2×10^{-5}	$^{90}\text{Zr}(n,p)$; $^{90}\text{Sr} \xrightarrow[28 \text{ y}]{\beta^-}$
	^{94}Zr (17.4)	^{91}Y	58.8 d; β^- ; γ	1×10^{-9}	3×10^{-5}	$^{91}\text{Zr}(n,p)$
	^{96}Zr (2.8)	^{93}Zr	1.5×10^6 y; β^- ; γ	4×10^{-9}	8×10^{-4}	$^{92}\text{Zr}(n,\gamma)$; $^{94}\text{Zr}(n,2n)$
		^{95}Zr	63 d; β^- ; γ	1×10^{-9}	6×10^{-5}	$^{94}\text{Zr}(n,\gamma)$; $^{96}\text{Zr}(n,2n)$
		^{95}Nb	35 d; β^- ; γ	3×10^{-9}	1×10^{-4}	$^{95}\text{Zr} \xrightarrow[65 \text{ d}]{\beta^-}$

(a) Not listed in Appendix B of 10CFR20. Its maximum permissible concentrations may be taken as 1×10^{-10} $\mu\text{Ci/cc}$ (air) and 3×10^{-6} $\mu\text{Ci/cc}$ (water) if its half-life is greater than 2 hours, and 3×10^{-8} $\mu\text{Ci/cc}$ (air) if its half-life is less than 2 hours.

EC - electron capture.

IT - internal transition.

TABLE 2
POST SHUTDOWN RADIOACTIVITY (Ci/cc) AND MOST CONTRIBUTING RADIONUCLIDES
IN POTENTIAL ELEMENTS FOR FUSION REACTOR STRUCTURE
(Two years operation at 1.5 MW/m²)

Natural Element		Time After Shutdown								
		1 Min.	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
Al	(a)	35	18	6.4	2.9×10^{-5}	2.9×10^{-5}	2.9×10^{-5}	2.9×10^{-5}	2.9×10^{-5}	2.9×10^{-5}
	(b)	²⁴ Na (55) (15 h) ²⁷ Mg (41) (9.5 min)	²⁴ Na (99)	²⁴ Na (-100)	²⁶ Al (100) (7.4 × 10 ⁵ y)	²⁶ Al	²⁶ Al	²⁶ Al	²⁶ Al	²⁶ Al
C	(a)	5.9×10^{-10}	5.9×10^{-10}	5.9×10^{-10}	5.9×10^{-10}	5.9×10^{-10}	5.9×10^{-10}	5.8×10^{-10}	5.2×10^{-10}	3.8×10^{-12}
	(b)	¹⁴ C (100) (5730 y)	¹⁴ C	¹⁴ C	¹⁴ C	¹⁴ C	¹⁴ C	¹⁴ C	¹⁴ C	¹⁴ C
Co	(a)	109	408	404	299	12	5.6×10^{-1}	3.8×10^{-6}	~ 0.0	
	(b)	⁵⁸ Co (86) (71.3 d) ⁵⁹ Fe (13) (45 d)	⁵⁸ Co (86)	⁵⁸ Co (86)	⁵⁸ Co (88)	⁵⁸ Co (83)				
Cu	(a)	432	409	121	9.5	4.3	2.0	5.1×10^{-1}	5.8×10^{-4}	2.0×10^{-33}
	(b)	⁶⁴ Cu (99) (12.8 h) ⁶⁰ Co (1) (5.27 y)	⁶⁴ Cu (99)	⁶⁴ Cu (96)	⁶⁰ Co (77)	⁶⁰ Co (75)	⁶³ Ni (51)	⁶³ Ni (100)	⁶³ Ni (100)	⁶³ Ni (100)

TABLE 2 (Continued)

Natural Element		Time After Shutdown								
		1 Min.	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
Cr	(a)	182	144	141	69.2	1.0	1.0×10^{-3}	~ 0.0		
	(b)	⁵¹ Cr (73) (27.8 d) ⁵² V (26) (3.8 min)	⁵¹ Cr (98) ⁴⁹ V (2) (330 d)	⁵¹ Cr (98) ⁴⁹ V (2)	⁵¹ Cr (97) ⁴⁹ V (3)	⁴⁹ V (99) ⁵¹ Cr (1)	⁴⁹ V (100)			
Fe	(a)	183	165	114	109	79.4	6.7	2.7×10^{-6}	2.7×10^{-6}	2.7×10^{-6}
	(b)	⁵⁵ Fe (53) (2.7 y) ⁵⁶ Mn (37) (2.6 h)	⁵⁵ Fe (59) ⁵⁶ Mn (31)	⁵⁵ Fe (85) ⁵⁴ Mn (11) (312 d)	⁵⁵ Fe (87) ⁵⁴ Mn (11)	⁵⁵ Fe (100)	⁵³ Mn (100) (2 × 10 ⁶ y)	⁵³ Mn (100)	⁵³ Mn (100)	⁵³ Mn (100)
Hg	(a)	46	41	14	1.4×10^{-13}	~ 0.0				
	(b)	²⁴ Hg (93) (15 h) ²⁵ Hg (1) (1 min)	²⁴ Hg (100)	²⁴ Hg (109)	²⁴ Hg (100)					

TABLE 2 (Continued)

Natural Element		Time After Shutdown								
		1 Minute	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
Hn	(a)	543	462	315	295	136	7.0×10^{-2}	8.4×10^{-35}	~0.0	
	(b)	⁵⁴ Hn (58) (312 d) ⁵⁶ Hn (35) (2.6 h)	⁵⁴ Hn (68) ⁵⁶ Hn (32)	⁵⁴ Hn (100)	⁵⁴ Hn (100)	⁵⁴ Hn (100)	⁵⁴ Hn (100)	⁵⁴ Hn (100)		
Ho	(a)	139	116	93.2	1.9	$9. \times 10^{-2}$	8.0×10^{-2}	1.0×10^{-1}	5.5×10^{-2}	2.9×10^{-4}
	(b)	⁹⁹ Ho (39) (67 h) ^{99m} Tc (39) (6 h)	⁹⁹ Ho (38) ^{99m} Tc (38)	⁹⁹ Ho (44) ^{99m} Tc (49)	⁹⁵ Nb (58) (35 d) ^{92m} Nb (20) (10.2 d)	⁹³ Ho (65) (3000 y) ⁹⁵ Nb (19)	⁹³ Ho (73) ^{93m} Nb (27) (13.6 y)	⁹³ Ho (54) ^{93m} Nb (46)	⁹³ Ho (54) ^{93m} Nb (46)	⁹⁹ Tc (43) (2.1×10^5 y) ⁹³ Ho (20) ^{93m} Nb (18) ⁹⁴ Nb (19) (2×10^4 y)
N	(a)	2.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	6.6×10^{-3}
	(b)	¹⁴ C (100) (5730 y)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)
Nb	(a)	160	160	149	20.3	0.2	0.2	0.2	0.2	0.2
	(b)	^{92m} Nb (98) (10.2 d) ⁹⁰ Y (2) (64 h)	^{92m} Nb (98) ⁹⁰ Y (2)	^{92m} Nb (98) ⁹⁰ Y (2)	^{92m} Nb (100)	⁹⁴ Nb (100) (2×10^4 y)	⁹⁴ Nb (100)	⁹⁴ Nb (100)	⁹⁴ Nb (100)	⁹⁴ Nb (100)

TABLE 2 (Continued)

Natural Element		Time After Shutdown								
		1 Minute	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
Ni	(a)	374	337	329	263	66	6.1	4.3×10^{-2}	1.6×10^{-4}	1.1×10^{-4}
	(b)	⁵⁸ Co (58) (71 d) ⁵⁷ Co (16) (270 d) ^{60m} Co (9) (10.5 min) ⁵⁵ Fe (8) (2. y)	⁵⁸ Co (65) ⁵⁷ Co (18) ⁵⁵ Fe (9)	⁵⁸ Co (66) ⁵⁷ Co (18) ⁵⁵ Fe (9)	⁵⁸ Co (62) ⁵⁷ Co (21) ⁵⁵ Fe (11)	⁵⁷ Co (36) ⁵⁵ Fe (35) ⁶⁰ Co (20) (5.27 y)	⁶⁰ Co (64) ⁵⁵ Fe (34)	⁶³ Ni (>99) (100 y)	⁵⁹ Ni (70) (8 × 10 ⁴ y) ⁶³ Ni (30)	⁵⁹ Ni (100)
O	(a)	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	2.8×10^{-5}	9.5×10^{-6}
	(b)	¹⁴ C (100) (5730 y)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)	¹⁴ C (100)
Pb	(a)	4.5	4.3	2.8	2.5×10^{-2}	6.5×10^{-3}	5.5×10^{-3}	3.3×10^{-4}	3.2×10^{-6}	3.2×10^{-6}
	(b)	²⁰³ Pb (86) (52.1 h) ²⁰⁹ Pb (13) (3.3 h) ²⁰³ Hg (0.6) (46.9 d)	²⁰³ Pb (88) ²⁰⁹ Pb (11) ²⁰³ Hg (0.7)	²⁰³ Pb (99) ²⁰³ Hg (1)	²⁰³ Hg (73) ²⁰⁴ Tl (3) (3.8 y) ²¹⁰ Pb (8) (22.3 y) ²¹⁰ Bi (8) (5.01 d) ²¹⁰ Po (8) (138.4 d)	²¹⁰ Pb (28) ²¹⁰ Bi (28) ²¹⁰ Po (28) ²⁰⁴ Tl (13) ²⁰³ Hg (3)	²¹⁰ Pb (33) ²¹⁰ Bi (33) ²¹⁰ Po (33)	²¹⁰ Pb (33) ²¹⁰ Bi (33) ²¹⁰ Po (33)	²⁰⁵ Pb (100) (1.4 × 10 ⁷ y)	²⁰⁵ Pb (100)

TABLE 2 (Continued)

Natural Element		Time After Shutdown								
		1 Minute	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
SI	(a)	102	1.6×10^{-2}	1.8×10^{-5}	1.8×10^{-30}	~0.0				
	(b)	²⁸ Al (97) (2.3 min) ²⁹ Al (1) (6.6 min)	³¹ Si (53) (2.6 h) ²⁷ Hg (32) (9.5 min)	³¹ Si (100)	³¹ Si (100)					
TI	(a)	55	53	43	15	2.1	1.6×10^{-6}	~0.0		
	(b)	⁴⁸ Sc (40) (1.8 d) ⁴⁷ Sc (22) (3.4 d) ⁴⁶ Sc (20) (84 d)	⁴⁸ Sc (41) ⁴⁷ Sc (23) ⁴⁶ Sc (21)	⁴⁸ Sc (35) ⁴⁶ Sc (25) ⁴⁷ Sc (23)	⁴⁶ Sc (57) ⁴⁵ Ca (42) (163 d)	⁴⁵ Ca (73) ⁴⁶ Sc (27)	⁴⁵ Ca (100)			
V	(a)	31	9.0	6.4	6.2×10^{-1}	3.1×10^{-4}	3.1×10^{-4}	~0.0		
	(b)	⁵¹ Ti (73) (5.8 min) ⁴⁸ Sc (27) (1.8 d)	⁴⁸ Sc (91) ⁴⁹ V (7) (330 d)	⁴⁸ Sc (88) ⁴⁹ V (10)	⁴⁹ V (100)	⁴⁹ V (100)	⁴⁹ V (100)			
W	(a)	421	418	364	249	26.3	1.7×10^{-6}	~0.0		
	(b)	¹⁸⁵ W (45) (75 d) ¹⁸¹ W (29) (140 d) ¹⁸⁷ W (26) (1 d)	¹⁸⁵ W (46) ¹⁸¹ W (29) ¹⁸⁷ W (25)	¹⁸⁵ W (52) ¹⁸¹ W (33) ¹⁸⁷ W (15)	¹⁸⁵ W (58) ¹⁸¹ W (42)	¹⁸¹ W (75) ¹⁸⁵ W (25)	¹⁸¹ W (100)			

TABLE 2 (Continued)

Natural Element		Time After Shutdown								
		1 Minute	1 Hour	1 Day	1 Month	1 Year	10 Years	10 ² Years	10 ³ Years	10 ⁴ Years
Zn	(a)	73	53	18	6.4	2.5	2.3 ×	10 ⁻⁴	1.0 × 10 ⁻⁴⁴	~ 0.0
	(b)	⁶⁴ Cu (51) (12.8 h) ⁶³ Zn (37) (38.4 min)	⁶⁴ Cu (67) ⁶³ Zn (18)	⁶⁴ Cu (58) ⁶⁵ Zn (30) (244 d)	⁶⁵ Zn (100)	⁶⁵ Zn (100)	⁶⁵ Zn (100)	⁶⁵ Zn (100)		
Zr	(a)	142	133	112	23.3	8.9 × 10 ⁻⁴	7.2 × 10 ⁻⁴	1.4 × 10 ⁻⁴	7.1 × 10 ⁻⁵	7.1 × 10 ⁻⁵
	(b)	⁸⁹ Zr (70) (78.5 h) ⁹⁵ Nb (9) (35 d) ⁹⁵ Zr (9) (65 d)	⁸⁹ Zr (74) ⁹⁵ Nb (10) ⁹⁵ Zr (10)	⁸⁹ Zr (71) ⁹⁵ Nb (12) ⁹⁵ Zr (12)	⁹⁵ Nb (53) ⁹⁵ Zr (41)	⁹⁵ Nb (67) ⁹⁵ Zr (41)	⁹⁰ Y (45) (64 h) ⁹⁰ Sr (45) (28.1 y) ⁹³ Zr (10) (1.5 × 10 ⁵ y)	⁹³ Zr (50) ⁹⁰ Sr (25) ⁹⁰ Y (25)	⁹³ Zr (100)	⁹³ Zr (100)

(a) Activity, Ci/cc of pure element following exposure at 1.5 MW/m² for 2 years.

(b) Most contributing radionuclides (percent of Ci/cc contribution, %).

Figure 2. Radioactivity for fusion and fission power reactors [3000 MW(th)]

Fission - Liquid metal fast breeder reactor (LMFBR)

Fusion - Tokamak first wall and blanket structures after two year's exposure at 1.5 MW/m².

The activation characteristics of reactor designs using alternate structural materials are described below.

Baseline STARFIRE Design. The STARFIRE baseline fusion reactor design (as described in Ref. 5) employs the stainless steel prime candidate alloy (PCA), Be or Zr_5Pb_3 neutron multiplier, $LiAlO_2$ solid tritium breeder, and a graphite reflector as the major blanket materials. It is water cooled and produces its own tritium for refueling. Material utilization was a very important concern in the STARFIRE design. The recyclability was studied for the structural and shielding materials and a guideline was set up to recycle as much as possible of the shielding materials within one human generation, i.e., 30 years. Based upon these guidelines, a three region shield was designed for the STARFIRE fusion reactor: a titanium alloy structured titanium hydride and boron carbide high flux shield, a Fe 1422 steel and boron carbide medium flux shield, and a Fe1422 steel low flux shield.

The baseline STARFIRE outboard blanket and shield design was modeled by one-dimensional neutronic analysis (Refs. 5 and 8). The induced radioactivity, associated afterheat, and biological hazard potential are depicted as a function of time after shutdown in Figs. 3, 4, and 5. Also shown are values for a low activation design which is discussed later. These results were calculated assuming five full-power years of operation at 3.6 MW/m^2 wall loading.

At shutdown, the activation level of the baseline STARFIRE design is a few curies per watt thermal which is typical of any D-T fusion reactor activation. However, it lasts for about one year at this level

Fig. 3. Post-shutdown radioactive inventories for the STARFIRE baseline and low activation designs.*

Fig. 4. Post-shutdown decay heat levels for the STARFIRE baseline and low activation designs.*

Fig. 5. Post-shutdown biological hazard potentials for the STARFIRE baseline and low activation designs.*

*After five full-power years of operation at 3.6 MW/m².
One appm iron assumed impurity in the low activation design.

without much decrease. At 10 years after shutdown, it is about 2 orders of magnitude lower than at shutdown. The radioactivity at 100 years after shutdown drops down to about 10^{-4} Ci/watt thermal. The afterheat and biological hazard potential are basically quantities derived from the radioactivity and are very similar to it.

Activation with Vanadium Alloy. The quantities of radioactive material expected to be generated for the STARFIRE reactor with a structure of vanadium-base alloy were calculated in order to provide a basis for comparison. The calculations were based on the shutdown radioactivity concentration given for V-20Ti in Ref. 3, assuming that the spatial distribution would be the same as for the baseline STARFIRE design, and would decrease in time with the proper decay characteristics for the vanadium alloy constituents. With these assumptions, the total activity at shutdown is 1.4 Ci/W, decreasing to 0.046 Ci/W 1 month after shutdown, to 0.015 Ci/W after 1 year of decay, and less than 3×10^{-9} Ci/W after approximately 30 years. These latter levels do not include impurity activation and they would be expected to dominate in this time frame based upon the results of the low activation STARFIRE design.

Low Activation STARFIRE. The five major components of the STARFIRE reactor design were modified to incorporate aluminum alloys and ceramics in an assessment of the benefits of low activation materials (Ref. 8). The components modified were the limiter, first wall, blanket and shield, and the toroidal field magnets. The STARFIRE (Ref. 5) austenitic stainless steel (PCA) panel first wall was replaced by an aluminum alloy water-cooled tubular first wall. A water-cooled aluminum alloy limiter was also used.

Because of the temperature limitations of aluminum, the energy from these components cannot be recovered at useful temperatures and the plant efficiency slipped from 34% to 30%. The circumferentially oriented pressurized-water PCA tubes used for cooling the tritium breeder were replaced by radially oriented ceramic (SiC) helium coolant tubes. The Zr_5Pb_3 neutron multiplier and $LiAlO_2$ breeder were replaced by Li_2O breeder. The PCA structure in the blanket (including the reflector) was replaced by a SiC structure with water-cooled aluminum supports. The highly effective STARFIRE shield was replaced by a less effective low activation Al + SiC + B_4C shield (water cooled). In the toroidal field magnets, more radiation tolerant insulation must be used and the copper and 304 stainless steel materials were replaced with aluminum and aluminum alloys. Subsequent investigations have shown that in order to achieve adequate shielding and acceptable tritium breeding in the very closely confined inboard region, it is necessary to use a composite toroidal field coil (steel structure in the outer region, aluminum structure in the inner region). An all-aluminum coil design would be too bulky. In addition, a removable tungsten insert is employed in the inboard shield to provide adequate magnet protection. Removal of the tungsten insert is necessary to provide low activation characteristics in the inboard region.

The radioactivity, afterheat, and biological hazard potential (BHP) resulting from neutron irradiation of the reactor materials for the low activation as well as the baseline STARFIRE designs are shown in Figs. 3, 4, and 5 as a function of time after shutdown. Note that an impurity level

of 1 appm iron in all low activation materials, SiC, Li₂O, B₄C and aluminum, was assumed and included in all calculations for the low activation design. As shown in Fig. 3, a factor of 3 reduction in radioactivity level is found at shutdown with the use of low activation materials in the low activation design. The radioactivity decreases dramatically shortly after shutdown for the low activation design. About one day after shutdown, it falls quickly to six orders of magnitude lower than at shutdown and is primarily dominated by the iron impurity present in the low activation materials. This activity level continues for about one year and then drops by another order of magnitude to the level that is controlled by the radioactive aluminum isotope ²⁶Al at times more than ten years after shutdown.

The post-shutdown decay heat levels for the baseline and low activation designs are shown in Fig. 4. They follow the trend shown for the radioactivity. The afterheat levels are about the same for these two designs at shutdown, however, within a few days after shutdown, the after-heat level of the low activation design has fallen by up to 6 orders of magnitude.

Figure 5 shows the postshutdown biological hazard potentials for these two designs. The advantage of a low activation design resulting in a very low biological hazard potential over a conventional metal alloy structured design is clear from these data. At shutdown, the BHP is about one order of magnitude lower for the low activation design than for the baseline design. Within a few days after shutdown, it is about five orders of magnitude lower.

The total quantity of radioactive material in the low activation STARFIRE design has been computed assuming that the component lifetime characteristics remain the same as in the baseline STARFIRE design, and thus the waste volumes generated remain approximately the same. A shutdown activity of 2800 MCi in a volume of 2940 m³ has been calculated for the low activation STARFIRE design. One month after shutdown, the total activity in the low activation design has dropped to 7500 Ci, approximately five to six orders of magnitude below the baseline STARFIRE design. The activity level in this time frame is dominated by the impurities. One year after shutdown, the activity level decreases to 3900 Ci, and 30 years after shutdown, it is reduced to 510 Ci.

III.3. Relation of Goals to Activation

The degree of success a fusion reactor design has in achieving each of the triad of goals identified in this report depends on the activation characteristics of the materials used. The three goals form a hierarchy of maintenance, safety, and waste management in that designs and materials that result in improved maintenance aspects may also benefit safety and waste management, but the converse is not necessarily true. Maintenance in the plasma chamber is the most difficult goal to achieve. The time frame of concern must begin within two weeks after shutdown so any activated materials with half-life longer than a few days will impact the maintenance dose rate. Further, in the intense neutron flux found in the fusion reactor first wall and blanket region, even 1 ppm of high activation material (e.g., iron) will result in a dose rate that precludes contact maintenance inside the plasma chamber.

The safety goal is somewhat more amenable to impact by design and material selection because it can be approached via several paths. The hazard potential and hazard lifetime can be reduced by the use of low activation and short half-life materials. The fractions of these materials that can credibly be released in the course of a postulated accident can be reduced by using materials that have a low level of afterheat, or materials that have high temperature capability. Aluminum, because of its high afterheat at shutdown and its low melting point, may cause concerns in this area. The probability of release may be controlled by appropriate use of engineered safety features.

The waste management goal is to achieve at least Class C permanent storage within one plant lifetime after shutdown. As a result the materials choices are much less constrained than for the other two goals.

A. Access for Maintenance

The biological dose rate in the various regions of a fusion reactor after shutdown will depend on the level and length of neutron exposure, on the materials of which the reactor is made, and on the time since shutdown. The dose rate is directly related to the level of activation. From Fig. 1, the activation level for reactors made of any material is about the same at shutdown. This activation results in a dose rate inside the plasma chamber on the order of 10^6 rem/hr. For the low activation design, the dose rate falls to about 7 rem/hr 10 days after shutdown.

Since higher activation materials would give a plasma chamber dose rate of about 10^6 rem/hr up to a year after shutdown, if these materials are

present as impurities, a plasma chamber dose rate of a few rem/hr will be produced for every atom part per million (appm) that is present. Federal Regulation 10CFR20 limits the radiation exposure a worker may receive to 1250 mrem during any 3-month period. Although use of personnel shielding may allow longer periods of access, this limit imposes a practical upper limit of about 1000 mrem/hr for limited contact maintenance. For planned routine maintenance, a still lower limit would be valid. This places a severe limitation on the level of impurities that could be tolerated in low activation materials without precluding access for maintenance. It should be noted that the neutron flux level drops quickly through the blanket and shield and much higher impurity levels would be allowed in these regions. Total impurity levels slightly below 100 appm have been achieved by Alcoa (Ref. 9) for aluminum alloys and slightly below 10 appm have been achieved by Norton (Ref. 4) for silicon carbide. It has not been demonstrated that these levels can be achieved on a commercial scale. The question of what level of impurities can be allowed and what level can be achieved at what cost is an area where further work is clearly needed.

STARFIRE. Post-shutdown biological dose rates are presented in Table 3 for both baseline STARFIRE (Ref. 5) and low activation (Ref. 8) designs at several locations:

1. In the plasma chamber.
2. At the plenum behind the blanket.
3. Behind the shield in front of the superconducting magnets.

Table 3. Post-Shutdown Dose Rates (mrem/hr) (Five Years Continuous Operation at 3.6 MW/m²)

Time After Shutdown	Behind Shield		Behind Blanket		Inside Plasma Chamber	
	STARFIRE Baseline Design	Low Activation Design ^(b)	STARFIRE Baseline Design	Low Activation Design	STARFIRE Baseline Design	Low Activation Design
1 day	3×10^{-2}	<0.1	2.5×10^6	20.8	$\sim 10^9$	7.1×10^3
2 weeks	3×10^{-3}	< 10^{-3}	2.4×10^6	20.6	$\sim 10^9$	7.0×10^3
1 year	1.7×10^{-3}	< 10^{-3}	1.5×10^6	15.9	$\sim 10^9$	5.3×10^3
10 years	1.5×10^{-4}	< 10^{-4}	1.4×10^5	1.4	$\sim 10^8$	4.6×10^2
1000 years	1.7×10^{-11}	< 10^{-11}	3.6×10^{-2}	7.6×10^{-7}	~ 10	2.6×10^{-4}

(a) Reference 4.

(b) The biological dose rates shown for the low activation design are primarily due to one atom part per million iron impurity in all materials.

For the baseline STARFIRE design, the biological dose rates behind the shield 1 day after shutdown are lower than the limits for continuous working contact (<2.5 mrem/hr). For the low activation design, the post-shutdown biological dose rate in front of the S/C magnet is higher than that in the baseline STARFIRE design, because of the incorporation of the SiC/B₄C low activation shield materials replacing relatively more efficient neutron attenuating materials. For both designs the area behind the shield is accessible for contact maintenance.

In the plenum region behind the blanket, the dose rates are about 2.4×10^3 rem/hr and 21 mrem/hr, respectively, for the baseline and low activation designs. In the plasma region, the baseline STARFIRE design shows a biological dose rate of about 10^6 rem/hr. It is only about 7 rem/hr for the low activation design due to the activation resulting from aluminum and impurity iron. Contact maintenance of this zone is not allowed in either design.

FED. Figure 6 shows the biological dose rate in the plasma chamber two weeks after shutdown for an FED/INTOR type reactor using a low activation aluminum alloy first wall and shield structure. The dose rate is given as a function of continuous operating time at an average wall loading of 0.4 MW/m^2 . Note that the biological dose rate resulting from the aluminum alloy structure is primarily due to the induced radionuclides from the impurity elements such as iron. The operating times needed for the biological dose rate one day after shutdown to reach a given limit depends upon the purity of the aluminum alloy. For a high purity alloy such as Al-6063 with

Fig. 6
LOW ACTIVATION FED/INTOR DESIGN
POST SHUTDOWN DOSE RATE

TWO WEEKS AFTER SHUTDOWN

Aluminum Alloy Al-6063

10 appm iron, the FED could operate continuously for 20 full power days before the post-shutdown dose rate in the plasma chamber exceeded 100 mrem/hr, a realistic upper bound for limited contact maintenance. At locations outside the plasma region, the biological dose rate should be reduced considerably.

B. Safety Considerations

The major potential hazard in a fusion system is the radioactivity produced as a result of neutron capture in structural materials (Refs. 10 through 12). Other hazards include tritium, and liquid metals for systems containing these materials, but the hazard represented by the activation product inventory was found to dominate safety concerns. The available stored energy and potential pathways which could result in a release of the hazard were also evaluated in Refs. 10 through 12. The major release mechanisms were identified as liquid metal fires and the inability to adequately remove decay heat.

References 11 and 12 calculated the radiological consequences of hypothetical accidents of fusion reactor concepts incorporating several different structural materials -- stainless steel, molybdenum-base, niobium-base, and vanadium-base alloys. The results of the calculations are strongly dependent on the assumptions made in the analysis, e.g., material thermal responses, volatilities, release fractions, etc. Although the assumptions are subject to engineering debate, the results do permit a number of observations and conclusions. First, a source of hazard and the mechanism for its release are present in a fusion reactor. Second, as presented in Ref. 12, the computed dose at the site boundary can vary by many

orders of magnitude, depending upon the activation characteristics of the structural materials and the release fractions used. The release fractions are a strong function of the assumed accident scenario and the thermal, mechanical and chemical properties of the materials. The dose figures shown in Table 4 are reproduced from Ref. 12. Reference 12 also considered the case of a vanadium alloy structure with helium cooling and a nonbreeding blanket for a D-D cycle reactor. The critical dose at the 2 km site boundary was 4 rem/GWe due to tritium and 10 rem/GWe due to activation products. The Panel, however, does not agree that this design is plausible.

Table 4. Accidental Release: Critical Dose (rem/GWe) at 2 km.

Reactor	Release Fraction	Critical Dose (rem/GWe)
Fission (PWR)(a):	5% to 70% of main fission products	6000
Fusion I:	500 megacuries tritium (as oxide)	400
	20% of stainless-steel activation products	4000
Fusion II:	50 megacuries tritium (as oxide)	40
	1% of niobium activation products	500

(a) PWR-1 (from WASH-1400), is the worst release considered in the Rasmussen Report; Fusion I-II represent first-, and second-generation machines, as follows. I: liquid-lithium coolant, stainless-steel structure, D-T fuel cycle, high tritium inventory. II: same but niobium structure and moderate tritium inventory.

Similar accident consequence analysis has not yet been done for designs using aluminum and SiC. Materials with low activation characteristics provide other safety-related benefits in addition to the lower worst-case, site-boundary radiological dose. Low activation levels translate into lower integrated decay heat levels, reducing the available stored energy with which to mechanistically effect damage. Temperature rise rates and times to melting or decomposition after shutdown may be calculated. Table 5 shows adiabatic meltdown times from temperature rise rates from Fig. 7, assuming no post-shutdown cooling. The integrated decay heat of SiC is insufficient to cause failure while aluminum will melt in 17 minutes, steel in 2 hours, and vanadium in 11 hours. The decay of the radioactivity provides a limit to the energy available and the cooling cutoff time in Table 5 shows the time after which no further cooling is needed to prevent melting. This is 0 for SiC, 1 day for vanadium, 7 days for aluminum, and 30 years for steel. The rapid decay of the activity also lowers the effective lifetime of the hazard and thus results in lower integrated dose. The assumption of adiabatic conditions is one way to approach the safety issue but may not be appropriate or valid for events occurring over periods of hours and involving materials with melting temperatures over 1000°C.

Fusion's potential for safety is a major component of its attractiveness as a long-term energy source. The level of radioactivity associated with fusion power plays a central role in the technical aspects, as well as the public and political perceptions, of fusion's safety. The goal of

Table 5. Post-Shutdown Heating Characteristics (1.5 MW/m² Wall Loading; Two Years Operation)

	First Wall Material				
	SiC	Al-Alloy	316SS	Ti-Alloy	V-Alloy
Adiabatic meltdown time	∞	17 min	2 hr	3 hr	11 hr
Post-shutdown cooling cutoff time	0	7 days	30 yr	1 yr	1 day
Afterheat at shutdown (W/cm ³)	0.9	1.1	0.6	0.4	0.2
Melting point (°C)	2600(a)	616	1420	1649	1890
Operating temperature (°C)	1000	150	400	400	400
Specific heat, C _p (J/kg°C)	1286	963	460	565	502
Density (g/cm ³)	3.2	2.7	7.8	4.4	6.0

(a) Decomposition.

Fig. 7. Integrated decay heat for the first wall of various blankets, as a function of time after shutdown (Ref. 4).

minimizing the level of radioactivity induced in the reactor's structural material is thus synonymous with the goal of safe fusion power.

C. Waste Management

Proposed Nuclear Regulatory Commission Regulatory Guide 10CFR61 classifies radioactive waste into three categories of eligibility for shallow land burial. Each classification prescribes upper limits on the concentration of specific radionuclides. In addition to these maximum activity limits, each class has prescribed waste stability/burial depth requirements as follows:

Class A (Segregated Waste)	Decays to acceptable levels during site occupancy.*
Class B (Stable Waste)	Stabilized and decays to levels which do not pose a danger to public health and safety in 100 y.*
Class C (Intruder Waste)	Does not decay to safe levels in 100 y. Decays to acceptably safe level in 500 y.*

Waste forms that exceed the radionuclide concentration limits of Class C, or that do not meet the packaging requirements, do not qualify for shallow land burial under 10CFR61 and must be considered on a case by case basis.

*10CFR61 defines "acceptable level" to mean that inadvertent entry into the waste, with continuous occupancy, would result in less than 500 mrem yearly dose. Natural background radiation gives an average yearly dose of about 100 mrem.

An assessment of the disposal classifications of the STARFIRE reactor first wall/blanket radioactive wastes and those of the low activation STARFIRE has been performed (Ref. 13). Some of the detailed results are presented in Tables 6 and 7. Assuming packaging of the wastes in casks according to the transportation requirements of 49CFR100 and 10CFR71, the classification of the radioactive waste shown on Table 7 was determined.

Thus, low activation materials permit shallow land burial of all of the generated radioactive first wall/blanket waste. The conventional STARFIRE design generates 2 to 3 times the quantity (mass and number of casks) of waste and the PCA first wall does not qualify for shallow land disposal under 10CFR61. Low activation materials would simultaneously lower the active cooling requirements of the radioactive waste. The decrease in afterheat levels with low activation materials range from 2 to 6 orders of magnitude lower in the time frame of 1 to 30 years (Ref. 4).

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Table 6. A Comparison of Post-Shutdown Radioactivity Concentrations in First Wall(a)

Post-Shutdown Time (y)	Activity (MCi/m ³)			
	PCA(b)	V-15Cr-5Ti(b)	Al6063(c)	SiC(d)
0	3.8 (2)(e)	1.7 (2)	1.1 (2)	2.1 (1)
1	1.4 (2)	1.2 (0)	4.0 (-4)	1.1 (-4)
10	1.2 (1)	1.7 (-3)	7.1 (-5)	9.1 (-6)
100	4.0 (-2)	2.6 (-5)	7.0 (-5)	1.4 (-9)

(a) Reference 13.

(b) ANL evaluation - with typical commercial level impurities.

(c) General Atomic evaluation - with impurities of Fe, Cu, Mn, and Zr ~1 to 4 wppm each.

(d) General Atomic evaluation - with 1 appm Fe impurity.

(e) Read as 3.8×10^2 .

Table 7. Waste Storage Requirements.
Quantities per year during normal operation(a)

	Mass (MT)	Number of Casks	Disposal Classification
STARFIRE			
PCA	71	48	Exceeds 10CFR61 limits
Zr ₅ Pb ₃	55	90	C
LiAlO ₂	100	375	A
Graphite	27	115	A
Low Activation STARFIRE			
Al-6063	3	12	A
SiC + Li ₂ O	141	123	A
Graphite	28	115	A

(a) References 8 and 13.

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APPENDIX IV

Engineering Practicality, Low Activation Materials, and the Data Base

Given the desirability of designing for low levels of induced radioactivity, the question becomes "Can the perceived advantages be attained in a credible engineering system?" The purpose of this section is to review some of the design implications or limitations which appear to influence the practicality of achieving low activation in a fusion reactor. To illustrate the variety and scope of applications, the functional requirements and performance criteria of the major reactor components are described. Pertinent comments and caveats are offered regarding specific design approaches which will have to be adopted when using the various types of low activation materials considered here. In a final section, we discuss in general terms the data base, as it exists and as it is required, for low activation materials.

IV.1. Design Implications

Potential benefits derived from the use of very-low or low-activation materials in a fusion reactor include the possibility of hands-on maintenance, a reduction in waste management requirements, and improved reactor safety. However, the design implications associated with the use of the limited number of low-activation materials in a viable reactor design are significant. In each subsection to follow, we address these implications sequentially for each category of benefits.

A. Contact Maintenance

The requirements for contact maintenance are the most restrictive. Very-low activation materials which have potential to permit hands-on maintenance are carbon (graphite), and SiC. Preliminary assessments of the requirements for hands-on maintenance have identified three practicality

issues: 1) all components in the radiation environment must be constructed of very-low-activation materials; 2) impurities must be maintained at very low levels; and 3) joining (e.g., by brazing) of components must be accomplished using only similarly low activation materials.

The classes of components which are generic to most magnetically confined fusion reactor concepts are listed in Table IV-1. To permit hands-on maintenance, all components inboard of the shield, viz., limiters, divertors, first wall, blanket, and certain auxiliary equipment such as rf waveguides or neutral beam lines, must be constructed of very-low-activation materials. It is probable that the shield would also have to be constructed of these same materials. Design studies to date have not addressed the full impact of constructing each of these components or subsystems totally of this limited choice of low activation materials. A limited design study (described briefly in Appendix III) did investigate the substitution of very low activation materials for the limiter, first wall, blanket, shield, and magnets of the STARFIRE commercial tokamak reactor design.

Table IV-1

Classes of Major Components for a Magnetically Confined
Fusion Reactor

High Heat Flux Components

- First Wall
- Auxiliary Equipment - High Neutron Flux Region
- Blanket System
- Shield
- Magnets
- Auxiliary Equipment - Low Neutron Flux Region
- Non-Reactor Systems

Classes are arranged in order of location moving radially away from the neutron source (plasma).

Several neutronics studies have been performed to evaluate the influence of impurities in C, SiC, and Al on residual radioactivity. Results indicate that 1 appm Fe in a first wall/blanket structure (C, Al, or SiC) will produce about a 7 rem/hr gamma-ray field in the plasma chamber for the period between two weeks and one year after shutdown. This radiation level precludes contact maintenance in the plasma chamber.

The neutron flux is attenuated by many orders of magnitude across the blanket and shield, allowing a corresponding increase in the level of high activation impurities that can be tolerated. The range is thus extended to tens of parts per million at the back of the blanket to several percent in the shield to 100% exterior to the shield.

The impact of joining processes for SiC and C must also be considered in more detail. Brazing is most often suggested for the bonding of these materials but most conventional braze materials consist of elements that will produce some residual radioactivity. Silicon brazing is presently used for joining siliconized SiC components. Graphite parts may be joined mechanically or by use of carbonaceous cements. Thus, low activation joining techniques are available. However, demonstration for fusion applications is needed.

B. Waste Management

For the case of very-low-activation materials, the residual activation will correspond directly to the concentration of impurities. Hence, acceptable impurity concentration limits can be specified for various waste management scenarios. If special components must be constructed of materials having unfavorable activation characteristics, these components can relatively easily be isolated from the bulk low-activity material. Therefore, significant benefits can be realized even if modest amounts of conventional materials are used in the reactor. Separation of braze or bond materials that have higher residual radioactivity levels would be more difficult but may also be achievable.

C. Safety

The safety concerns in fusion are attributable in large measure to the radioactivity generated by activation. The primary source of radioactivity resides in the first wall and blanket structure and in specialized high heat flux components. The levels of radioactivity are thus dependent upon the materials used for components in these regions of high neutron and heat flux. The relative impact on safety depends not only on the amount of

residual radioactivity in the system but also on the probability of release. Therefore, materials having higher melting and vaporization temperatures should provide a safety advantage. This factor is particularly significant for aluminum and will tend to compromise some of the intrinsic advantages of this metal. In general, the relative safety of different reactor concepts cannot be accurately evaluated until complete designs are developed.

D. Operating Performance and Lifetime

In-depth studies are required to fully evaluate the impact of using low-activation materials on the operating performance and/or lifetime of a fusion reactor. This involves a thorough assessment of the total available data base for materials exposed to severe radiation, thermal, stress, and chemical environments. A compatible combination must be developed which integrates the specified materials into a functional reactor system. This has not been done in a comprehensive, self-consistent reactor design using low activation materials.

IV.2. Functional Requirements and Performance Criteria

The magnetic confinement fusion program in the United States is currently focused primarily on D-T-Li fueled tokamak and tandem mirror reactor concepts. Although the physics of these two fusion devices are quite different, the materials and technology aspects, when considered in generic terms, are quite similar. The functional requirements and performance criteria are evaluated in terms of the operating environment for the major reactor components or subsystems; these are summarized in the following subsections.

A. High Heat Flux Components

Components or subsystems in this category include limiters, divertors,

target plates, first wall armor, and beam dumps. These components serve as the first solid material interface with the fusion plasma and must accommodate the heat flux and particle flux associated with this interface under both normal and off-normal conditions. In addition, certain of these components provide protection to the reactor first wall and blanket systems in the event of extreme off-normal conditions such as plasma disruptions and unintended neutral beam impingements.

Because they interface directly with the plasma, the high heat flux components must satisfy the coupled requirements of adequate lifetime and performance capability without serving as a source of plasma contamination. The major performance criteria for these components are listed below. These criteria are separated into three broad groupings, depending upon whether they are primarily of concern because of surface characteristics, bulk materials properties, or operational/maintenance/safety issues.

Surface Characteristics. 1) Erosion by energetic plasma particles (D, T, He) must neither compromise the integrity of the component nor provide a source of unacceptable plasma contamination. 2) The components must accommodate very high surface heat fluxes due to the energetic particles and electromagnetic radiation emanating from the plasma volume. These conditions cause high thermal stresses which, for some designs, may be cyclic. 3) The materials used for these components must be compatible with attainment and maintenance of a high quality vacuum environment ($\sim 10^{-8}$ torr). 4) The components should be capable of recovering from such off-normal events as plasma disruptions without necessitating major repairs or replacement.

Bulk Mechanical and Chemical Properties. 1) Structures must be capable of accommodating the cumulative primary and secondary stresses and loads

imposed by gravitational, thermal, and magnetic forces. 2) The response to high energy neutrons (energies up to 14 MeV) must not lead to excessive dimensional instability (swelling), loss of ductility or toughness, or changes in critical thermal or physical properties. 3) Hydrogen retention and permeation characteristics must be acceptable and consistent with the recovery/reprocessing of tritium. 4) Actively cooled components (e.g., limiters) must demonstrate adequate corrosion resistance to avoid stress corrosion or unacceptable radioactive mass transfer.

Operational, Maintenance and Safety Concerns. 1) Manufacturability must be consistent with both the functional and topological requirements of the application. 2) Component design and materials selection must be compatible with demonstrated NDE/NDT techniques. 3) Materials selections should acknowledge such features as safety and activation which influence the overall environmental acceptability of the reactor.

B. First Wall

The first wall is the inner surface of the reaction chamber. Depending upon the specific design and the deployment and location of armor, etc., the first wall may have to accommodate the heat and particle fluxes associated with direct plasma interfacing. In conjunction with the limiter, the first wall defines the plasma volume and topology. Moreover, in conjunction with the blanket and shield, the first wall provides the vacuum boundary for the plasma reaction chamber.

The performance criteria for the first wall are in most respects identical with those previously listed for the high heat flux components. Differences are primarily of degree. For example, radiation-induced swelling or changes in physical properties may be equally severe for a piece of armor or a first wall. However, most conceptual designs assume that many

of the high heat flux components can be replaced more frequently without severely disturbing the utility of the reactor; this is unlikely for the first wall system.

C. Auxiliary Equipment - High Neutron Flux Regions

Included in this category are components such as rf antennae or waveguide launchers, and neutral beam line hardware used for auxiliary plasma heating. Certain plasma diagnostic and direct energy recovery subsystems may also belong in this class. The functional requirements associated with these components are generally defined for a specific reactor design and depend on the approach adopted for heating and monitoring the plasma. Their common grouping here reflects the fact that each must articulate closely with the plasma reaction volume in a way that precludes significant neutron shielding.

Performance criteria for the various components considered in this category are intimately related to their functional design requirements. The major consideration which can be noted here is that the cumulative effects of neutron irradiation on these components or subsystems must not compromise their reliability or serviceability. This is particularly important for the larger components such as neutral beam lines or rf waveguide launchers which cannot be easily replaced or serviced.

D. Blanket System

The primary functions of the blanket system are to convert the neutron energy into sensible heat, provide for the efficient recovery of this heat, and breed sufficient tritium for the fuel cycle. All blanket concepts require lithium or a lithium-bearing compound for tritium breeding, a circulating coolant for heat removal, and structural material to contain and support the blanket system. In some design concepts, the same

material, e.g., liquid lithium, may be used as both a breeder and coolant. Some concepts require a neutron multiplier to provide for adequate tritium production. In several concepts, tritium is recovered from the recirculating coolant or liquid metal breeder, whereas a separate tritium processing fluid is utilized for tritium recovery in most solid breeder concepts. Reflectors or moderators have been proposed in some blanket designs to improve breeding performance or to reduce the lithium inventory. Blanket concepts which utilize water cooling may require tritium barriers to minimize tritium permeation into the coolant. All concepts require a compatible combination of materials that can be integrated into a functional design capable of satisfying the performance criteria. The primary performance criteria for the blanket system are defined below.

Tritium Breeding Performance. The net tritium breeding ratio for the entire blanket system must be sufficient to fuel the reactor. This typically requires a breeding ratio of ≥ 1.05 to account for decay losses and to provide an adequate doubling time.

Tritium Recovery. Tritium recovery methods should be adequate to maintain tritium concentrations in the blanket to $\lesssim 1$ kg. Higher tritium inventories begin to impact negatively on the tritium breeding requirement because of the decay losses and on the associated safety concerns. In the case of solid breeders such as Li_2O , higher tritium retention may affect the phase equilibria, i.e., $\text{Li}_2\text{O} - \text{LiOT}$.

Energy Conversion/Recovery. In conjunction with the first wall (and possibly the high heat flux components), the blanket must provide for conversion of the kinetic energy of the fusion products into sensible heat. The blanket system must also provide for recovery of the heat in a form that will result in conversion efficiencies $\geq 30\%$; higher efficiencies are

obviously desirable.

Acceptable Lifetime. Recent design studies indicate that first wall/blanket lifetimes greater than about $10 \text{ MW}\cdot\text{y}/\text{m}^2$ are necessary to satisfy most economic and maintenance goals for the structural materials.

E. Shield

The primary function of the shield is to protect the superconducting magnets from excessive nuclear heating and radiation damage. In addition to the bulk shield, special localized shielding around penetrations is generally required. The magnet shielding also serves as a major part of the biological shielding requirements. Since the shield is one of the most massive components and thus a major cost item, material cost is an important criterion for the shield design. This cost criterion must be considered together with the overall cost implications of shield size.

F. Magnets

Although the size, configuration, and perhaps operating characteristics, may vary with confinement approach or with specific reactor design, all of the magnetically confined reactor concepts depend critically on magnetic and electric fields for plasma confinement. The magnets required must reliably create steady state magnetic fields and transient electric fields to excite plasma currents in such a way as to effect plasma confinement. Magnetic fields may also be required to shape and control the plasma size and location.

Performance criteria for the magnet systems are directly related to the specific functions each must provide. For a particular reactor design they are typically specified in terms of the fields they must produce, and from this are derived such features as ampere-turns, etc. The choice between superconducting and conventional field coils is usually resolved on the basis of proximity of the coils to the plasma or to other regions of

high neutron activity such as the blanket and on requirements for auxiliary power. This reflects the fact that the major threats to magnet performance are related to the instantaneous and cumulative effects of neutron and ionizing radiation on the magnet materials. These effects are in turn controlled by the amount of shielding which can be provided. For either of these types of coils, key performance issues are: 1) radiation damage must not change the resistivity of conventional conductors or the critical properties of superconducting materials (J_c , T_c , or H_{c2}) to the extent they cannot satisfy their functional requirements; 2) the resistivity of the stabilizing material (typically Cu or Al) in superconducting field coils must not change to the extent their utility is compromised; 3) mechanical and electrical insulating properties of organic and/or inorganic insulators incorporated within the magnetic field coils must not change within well defined, acceptable limits; 4) nuclear heating must be acceptable and compatible with all features of the magnetic field coil power and cooling systems.

G. Auxiliary Equipment - Low Neutron Flux Regions

Included in this category are reactor support systems such as vacuum pumps, beam lines and rf waveguides, fueling systems, heat transfer systems including the intermediate heat exchangers and steam generators, and the tritium processing systems. The functional requirements associated with these components are dependent on the specific reactor concept and design. For this evaluation it is important to recognize the existence of these systems, which are large mass components in close proximity of the reactor, and therefore, are exposed to low levels of neutron radiation or are subject to deposition of activated material transported from the high flux regions.

H. Non-Reactor Systems

Several non-reactor systems outside the magnet shield but in close proximity to the reactor will also be exposed to low levels of radiation and must be considered in terms of low activation benefits and the potential for hands-on maintenance. The functional requirements can presently be given only in terms of the generic description. These systems include the reactor building and support equipment, the reactor building atmosphere, and special reactor maintenance equipment.

IV.3. Design Approaches Using Low Activation Materials

Achieving the goal of reduced activation for fusion reactors requires the use of special materials with low activation nuclear characteristics. To accommodate the mechanical, chemical, and thermal characteristics of these materials may require special design approaches. The following subsections present a brief synopsis of several of the key properties or characteristics of the various materials which can be considered for inclusion in very-low or low-activation fusion reactor designs.

A. Ceramic Materials - Carbon and Silicon Carbide

Silicon carbide and carbon offer very low activation and high temperature operation in fusion. They are, however, brittle ceramic materials and require special consideration in design to permit their use in complex engineering systems. A survey of several of the more important characteristics or properties which will influence their utility in fusion structural applications are:

- The ceramic material property, or brittleness, refers to a complete lack of ductility of the material. Elasticity is present, with elastic limits in the range of 0.1 to 1%.
- Stress limits for compressive loads are about five times those for

tensile loads; thus, most failures are due to tensile stresses.

- Fracture in ceramics results from rapid crack propagation with crack initiation occurring at flaws either on the surface, or in the body of the material.
- Early failures, described as failure rate versus tensile loading, show a broad statistical distribution (i.e., the Weibull distribution) which gives a small but finite failure rate at low stress levels.
- Proof testing eliminates the weaker components and provides a failure rate for the survivors with a low probability of failure below the proof test level, analogous to similar failure descriptions for metals.
- Low tensile stress designs are particularly important for ceramics since allowable stress limits are generally below those appropriate for high strength metals.

Present-day materials appear to provide a suitable combination of properties so that conceptual designs can be made for the major components in a fusion reactor blanket and first wall region. The materials, design methodology, and technology are relatively new so that an extensive base of experience in similar structural applications does not yet exist. This is perhaps the largest factor in establishing confidence in the applicability of ceramics to low activation fusion. Newer materials such as SiC fibers may offer use in composites which might alter the character of ceramic material behavior, particularly fracture behavior and failure modes.

B. Aluminum Alloys

Several types of Al alloys, particularly those containing Mg and Si, are low activation materials provided impurity levels can be maintained in

the very low ppm range (e.g., 1 ppm Fe). Activation about two weeks after shutdown is dominated by these impurities.

Preliminary data on the mechanical properties of high purity Al alloys indicates that there is very little change from their commercial counterparts. This is significant in that it implies that the existing design and fabrication technology can be directly applied. The attractive design features of aluminum alloys include: relatively low material cost (although this may be less true for ultra-high purity alloys), excellent fabricability and weldability, immunity to stress-corrosion cracking in aqueous environments, a broad data base, good ductility and toughness (125°C to -269°C).

The maximum operating temperature of 125°C arises because of long-term creep limitations. This requires special techniques for handling the higher temperature coolants desirable for efficient energy conversion. These techniques include insulation of the structural wall on the hot side and integral cooling of the walls. These are useful for the blanket where high heat fluxes through the structure are not required.

The first wall, limiters, and other in-vessel components have a high surface heat flux requiring heat transport through the wall to a coolant. The high thermal conductivity of aluminum helps in keeping temperatures low, but the 125°C maximum temperature limitation precludes use of the heat in an efficient way in energy conversion cycles. This is perhaps the most severe restriction for aluminum alloy in the fusion reactor plant.

C. Vanadium Alloys

Vanadium alloys are representative of a group of materials which can be considered as low or reference activation structural materials. By this

rather broad classification is meant a material which offers moderate biological hazard potential, decaying by approximately 6 orders of magnitude within about 10 years after plant shutdown, low levels of long-term radioactivity, and good physical and mechanical properties that lead to advantages from a safety viewpoint. Vanadium and the elements commonly used as solutes in alloys based on vanadium, including Ti and Cr, satisfy these conditions. Hence, it is conceivable that actual construction quantities of these alloys could be obtained which would offer a high probability for realizing some of the low activation benefits.

For vanadium alloys, the benefits to be gained are primarily associated with safety and long term storage or possible reprocessing on some intermediate time scale (30-60 years). They clearly do not lend themselves to design approaches based on short-term contact maintenance operations. Therefore, benefits may be realized without the need for the total utilization of these materials. In order to realize these promised benefits, however, it will be essential that designers and materials engineers work together to ensure that a compatible and consistent reactor design is evolved. This design must provide clear recognition of the unique properties or limitations which are associated with the choice of a major structural material.

For vanadium-base alloys, a key factor which will influence reactor design is the readiness with which they react with oxygen and nitrogen, and the negative consequences which this contamination implies. Features of a credible fusion reactor design which utilizes vanadium alloys for major first wall and blanket structural applications will probably include:

- The use of a liquid metal as the coolant.

- The use of lithium or lead-lithium for tritium breeding.
(Liquid lithium or liquid lead-lithium can play the combined role of coolant and breeder.)
- Design of the reactor containment to guarantee the exclusion of air or other reactive gases from contact with vanadium in any region where metal temperatures might exceed about 300-350°C.

An integrated design approach making extensive use of vanadium alloys will also undoubtedly reflect their excellent thermophysical properties and good strength at elevated temperatures. It will also display features which reflect the need to design for limited component sizes, due to the handling and fabrication limits which exist in the refractory metals industry, and will have to provide credibly located and configured transition joints to other materials.

D. Elementally and Isotopically Tailored Steels

For reasons which have been discussed previously in this report, the use of specially tailored steels (tailored in terms of the alloyed elements selected or in the use of isotopic selection) may be of interest for fusion reactor designs offering lower activation levels than those based on conventional stainless steels. Several studies have been published in the recent literature (see Conn, et al., Nuclear Tech. 41 (1978) 389). These indicate that isotopic tailoring to remove certain problem isotopes of iron, nickel, and molybdenum can lead to dramatic improvements in the radioactivity and biological hazard potentials of stainless steels. These are the isotopes which undergo neutron reactions to produce long-lived radionuclides.

An especially interesting example of the potential benefits of elemental tailoring is the austenitic stainless steel, Tenelon. This steel

is basically nickel or molybdenum free, the austenite being stabilized by 14 wt. percent Mn and small additions of nitrogen. In its normal chemistry, Inconel offers approximately a three-orders-of-magnitude reduction in radioactivity compared to Type 316 stainless steel for a ten year decay, following first wall service. Moreover, if this steel is prepared by using isotopic selectivity to retain only ^{15}N and $^{56, 57, 58}\text{Fe}$ (i.e., removal of ^{14}N and ^{54}Fe) an additional three-orders-of-magnitude reduction can be effected. Closer examination of the various austenitic and ferritic steels will doubtless identify other areas for significant improvement. Another example worth mentioning is the substitution of V or W for Mo in ferritic steels.

For any of these tailored steels, careful consideration will have to be given to possible changes in metallurgical, chemical, or radiation stability which might result from compositional adjustments. This is not usually a problem when dealing strictly with isotopic selectivity, but care must be exercised if elemental concentrations are perturbed. From the standpoint of reactor design, subtle alterations in concentration of elements should not affect choices of coolants, breeding media, or fabrication approach. However, corrosion/compatibility can be significantly affected by certain elements, e.g., nitrogen. Properties such as fabricability are not expected to be sensitive to modest changes in elemental concentrations.

This general category of materials, like the vanadium-base alloys discussed in the previous section, provides advantages primarily in the areas of intermediate term reprocessing or long-term storage. They offer no potential for hands-on maintenance or repair.

IV.4. Materials Data Base

Only a limited judgment can be made regarding the adequacy of a materials data base for low activation materials. Design studies have attempted to define first wall design criteria by examining various modes of failure and the likelihood that these failures could occur. The four most important modes of failure are:

- Leaks are coolant penetration that leads to the introduction of impurities in the plasma. The mechanical properties that are usually important are crack growth rate, fatigue and creep rupture.
- Fracture is gross rupture of the wall that leads to the interruption of coolant flow, loss of vacuum, or flow of coolant into adjacent areas. In general, fracture is most likely to occur during an off-normal situation such as a plasma disruption which produces high loads in fractions of a second. The important mechanical properties are tensile and shear strength, ductility and fracture toughness, and creep-rupture.
- Deformation is structural deformation that occurs when the total allowable strain, as defined by structural symmetry or by a design code such as the ASME Nuclear Pressure Vessel code, is exceeded. Important mechanical properties are thermal creep and irradiation creep. However, the amount of swelling or irradiation creep that can be tolerated without causing problems has not been defined and is design dependent.
- Instability is general instability or buckling of structural components, local buckling, or wrinkling of structural members that can occur, for example, when structural stiffness is inadequate. Important mechanical properties are the modulus of elasticity and shear (rigidity).

Of these four modes of failure, "instability" is probably the least important since it can be avoided by providing adequate stiffness and applying an appropriate factor of safety. In general, leaks are found to be the most likely mode of failure. However, if the structural material is embrittled by irradiation or contamination, fracture will become an increasingly likely failure mode.

A list of properties important in the design of a first wall and blanket structure is presented in Table IV-2, along with the significant variables associated with each property. Depending upon the type of reactor in which this structure would be used (e.g., tokamak, mirror, EBT, etc.), and the specific design philosophy employed, this list may need to be expanded. Included in the table as examples are materials which fall into different classifications with respect to induced radioactivity and the triad of goals we have developed. The type-316 stainless steel is representative of a material with high short-term and long-term radioactivity when measured relative to the other materials listed in the table. The titanium and vanadium alloys represent materials that have short-term radioactivity levels (<1 year) similar to those for type 316 stainless steel but whose long-term radioactivity levels (>50 years) are much lower. Very high purity aluminum alloys and silicon carbide represent materials that have low short-term and long-term radioactivity levels. The long-term radioactivity levels of aluminum may be larger than the levels for either titanium or vanadium alloys but are still much below the levels of Type 316 stainless steel. The data base for 20% cold-worked Type 316 stainless steel remains inadequate to reliably design components to operate in a commercial fusion reactor. Of particular concern is the absence of secure knowledge relating to the effects of irradiated materials in a D-T fusion

Table IV-2. Extent of Material Data Base for First Wall/Blanket
(Numerical Values Indicate the Extent of the Data Base Relative to that for 316 S.S. In Percent)

IV-20

Property	Variables ⁽¹⁾	MATERIAL									
		20% CW-316 Stainless Steel		Titanium Alloy Ti-6Al-4V		Vanadium Alloy V-Cr-Ti		Aluminum Alloy 6061		Silicon Carbide	
		Unirrad.	Irrad ⁽²⁾	Unirrad.	Irrad	Unirrad	Irrad.	Unirrad	Irrad ⁽³⁾	Unirrad.	Irrad.
1. SHORT TIME PROPERTIES											
o TENSION											
- ULTIMATE TENSILE STRENGTH	T, σ_t	D ⁽⁴⁾	D	100	<10	10	5	100	<50	100	<10
- YIELD STRENGTH	T, σ_t	D	D	100	<10	10	5	100	<50	100	<10
- ELONGATION	T, ϵ_t	D	D	100	<10	10	5	100	<50	100	<10
- MODULUS OF ELASTICITY	T, E	D	NE	100	NE	5	NE	100	NE	100	<1
- POISSON'S RATIO	T, ν	D	NE	100	NE	5	NE	100	NE	>75	-
- STRESS-STRAIN CURVES	T, σ, ϵ_t	D	D	100	<5	10	<5	100	<25	>50	<1
- FRACTURE TOUGHNESS	T, K_{Ic}	D	L	100	<1	<1	<1	100	<25	>75	<5
o COMPRESSION											
- SHEAR STRENGTH ⁽⁵⁾	T, σ_s	D	D	100 ⁽⁶⁾	<10	5	5	100 ⁽⁶⁾	<5	<10	<10
- SHEAR MODULUS	T, G	D	NE	100 ⁽⁶⁾	NE	5	NE	100 ⁽⁶⁾	NE	<10	<10
2. TIME DEPENDENT PROPERTIES											
- CREEP RATE	T, σ, t	D	NA	100	NA	10	-	100	<1	>10	<1
- CREEP RUPTURE	T, σ, t	D	NA	100	NA	10	-	100	<1	>25	<1
- FATIGUE	T, σ, ϵ_t, n	T	T	>75	<1	10	<1	>75	<1	>5	<1
- FATIGUE CRACK GROWTH RATE	T, $\epsilon_t, \Delta k$	T	L	100	<1	<1	<1	>75	<1	>25	<1
- SWELLING RATE	T, ϵ_t, ϕ, σ	NA	D	NA	<10	NA	5	NA	<50	NA	5
- IRRADIATION CREEP-RATE	T, $\sigma, \epsilon_t, \phi, \sigma$	NA	D	NA	<5	NA	<1	NA	<5	NA	<5
- IRRADIATION CREEP-RUPTURE	T, $\sigma, \epsilon_t, \phi, \sigma$	NA	T	NA	<1	NA	<1	NA	<5	NA	<1
3. PHYSICAL PROPERTIES											
- COEFFICIENT OF THERMAL EXPANSION	T	D	NE	100	NE	>25	NE	100	NE	100	<50
- THERMAL CONDUCTIVITY	T	D	NE	100	NE	>25	NE	100	NE	100	<50
- SPECIFIC HEAT	T	D	NA	100	-	>25	NE	100	NE	100	<1
- DENSITY	T, ρ	D	D	100	<10	100	<5	100	<50	100	<5
- ELECTRICAL RESISTIVITY	T	D	NE	<50	NE	>25	NE	100	NE	>75	>50
- PHYSICAL SPUTTERING YIELD	H, D, T, He, Z [*]	T	-	<30	-	50	-	50	-	>75	-
- CHEMICAL SPUTTERING YIELD	H, D, T	T	NE	NA	-	NA	-	NA	-	>75	-
- HYDROGEN ISOTOPE DIFFUSIVITY	D, ϕ	T	L	>75	<1	50	<1	>75	<1	<25	<1

NOTES:

1. DEFINITION OF VARIABLES: T = TEMPERATURE, t = TIME, n = CYCLE NUMBER, p = PRESSURE, Z^{*} = SELF SPUTTERING, σ = STRESS, ϵ = STRAIN, ϕ = FLUX
 Δk = STRESS INTENSITY
2. IRRADIATION DATA BASE FROM FAST BREEDER REACTORS, WITHOUT REGARD TO ADEQUACY IN EVALUATING RESPONSE TO FUSION CONDITIONS
3. RANGE OF TEMPERATURES MAY NOT BE ADEQUATE
4. T = DATA BASE SUFFICIENT TO ESTABLISH TREND D = DATA BASE ADEQUATE FOR DESIGN BUT IS NOT DESIGN DATA BASE IN THE SENSE OF ASME CODE M-4.7.
 L = LIMITED OR NON-EXISTENT DATA
 NA = NOT APPLICABLE
 NE = NO SIGNIFICANT EFFECT OBSERVED
5. SHEAR STRENGTH BASED ON CALCULATIONS
6. SHEAR STRENGTH BASED ON MEASUREMENTS

neutron spectrum versus a fission reactor spectrum. Establishment of such a correlation can allow utilization of the large data base already developed for material service in fast breeder reactors. In almost all property categories, currently available irradiation data for 20% cold-worked 316 stainless steel is adequate to establish trends but is inadequate for design.

The data base relating to particular properties of the other materials on Table IV-2 has been evaluated in relation to the extent of our knowledge of that property for stainless steel. Specifically, we indicate by a percentage the size and quality of the data base compared to that for 20% cold-worked, Type 316 stainless steel. If the data base is as large or larger than that for the steel, we simply use 100%. Otherwise, specific numerical estimates are given. It is clear that the data base relating to properties of irradiated materials is sparse to non-existent, making definitive evaluations of engineering practicality impossible at this time. The unirradiated data base for the titanium alloy and the aluminum alloy is probably greater than that of stainless steel while that for vanadium alloys is much less. The data base for silicon carbide appears to lie somewhere between that for vanadium and that for stainless steel. The unirradiated data base for these materials has been established by testing commercially available alloys.

While the unirradiated data base is reasonably well developed, that for irradiated properties is limited except for Type 316 stainless steel. Most of the information that is available is either at low fluence or at temperatures outside the range of interest for fusion. As a result, available data is somewhat useful to establish trends but quite inadequate for use in design. If low-activation materials are to be used for the

first wall/blanket structure, much more information is needed, particularly regarding the effects of neutron irradiation on mechanical properties. While it is premature to develop design data, trend data is required to predict component lifetime in conceptual designs. The predicted lifetimes could then be compared to stainless steel to determine the cost-risk-benefit of low-activation materials.

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