CONF-801011
Dist. Category UC-20

The Technology of Controlled Nuclear Fusion

Proceedings of the Fourth Topical Meeting

Volume I

October 14-17, 1980
King of Prussia, Pennsylvania

Published July 1981

Edited by: F. H. Tenney and C. C. Hopkins

Cosponsor by:
Delaware Valley Section and Controlled Nuclear
Division of the American Nuclear Society
Princeton Plasma Physics Laboratory
Electric Power Research Institute
and
U.S. Department of Energy
Office of Energy Research
Office of Fusion Energy
Division of Development and Technology
Washington, D.C. 20545

IMPORTANCE OF SHIELD DESIGN IN MINIMIZING RADIOACTIVE MATERIAL INVENTORY IN TOKAMAKS*

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Summary

An optimization study is carried out for the outboard bulk shielding of the STARFIRE reactor. The optimization criteria used include: (1) reactor accessibility shortly after shutdown; (2) minimization of high-level long-term induced activation; and (3) radiation protection of reactor components. It is shown that with a 1.1 m-thick shield, the biological dose inside the reactor room decreases to ∿ 1.5 mrem/hr within 24 hr after shutdown. It is also shown that more than 90% of the total mass of the radioactive material inventory in STARFIRE has a high potential for recycling within 30 - 50 yr after component replacement or reactor decommissioning.

Introduction

One of the major objectives of the STARFIRE study[1] is to develop a reactor design with favorable safety and environmental features. Neutron-induced activation in the component materials and tritium as the DT fuel are the primary source terms for environmental impact assessments. The most serious concern with regard to the activation is the production of radioisotopes with very long half-lives (> 50 - 100 year) in relatively large volumes of materials as this results in: (1) permanent radwaste storage requirements and (2) depletion of some resource-limited materials. Although the activation level of fusion reactors is expected to be substantially lower than fission reactors because of the absence of fission products and actinides, minimizing the long-lived radioactive products from future fusion reactors remains an important design criterion.

With regard to the material resource problem, it should be emphasized that in a mature fusion power economy, the continued use of materials without the ability to recycle would result in the serious depletion of some reactor construction materials. For example, the STARFIRE design requires approximately 100 metric tons (MT) of niobium for the superconducting magnets, resulting in a resource requirement of ∿ 8 x 10^3 MT for 10^5 MWe fusion economy (equilalent to ∿ 83 STARFIRE reactors). This figure is compared to an identified niobium resource in the United States of ∿ 1.4 x 10^5 MT and worldwide resource of ∿ 1.5 x 10^7 MT[2] indicating that ∿ 5.7% of the total U. S. resource would be required. Another example is the chromium resource of which the identified chromite ore in the U. S. is estimated to be ∿ 5.6 x 10^6 MT[3] and the chromium metal resource in the U. S. is only ∿ 4.1 x 10^5 MT. Under the same condition of 10^5 MWe fusion economy, approximately 1.1 x 10^5 metric tons of chromium which is ∿ 28% of the U. S. resource will be needed. If the primary shield material of Fe-14Mn-2Ni-2Cr (Fe1422) is replaced by more conventional iron-base alloys such as type 304 stainless steel (304 SS) and type 316 stainless steel (316 SS) the chromium requirement will be raised to ∿ 2.8 x 10^5 MT which is ∿ 69% of the total U. S. resource. In fact, this is one of the reasons that Fe1422 has been selected as the primary shield structural material, instead of 304 SS, in the STARFIRE design.

An important strategy for fusion reactor development, therefore, is to avoid generating any large inventories of high-level, long-term activation so that a majority of the reactor construction materials could be recycled on a reasonably short time-scale, e.g., within a human generation of ∿ 30 yr after component replacement or reactor decommissioning. Our analysis shows that more than 98% of the total radioactivity inventory in the STARFIRE design is confined to the first wall/blanket region which is less than 10% of the total reactor component volume (excluding reactor building). More than 90% of the total volume of the radioactive material inventory in STARFIRE, and in tokamak reactors in general, is therefore, present in reactor components external to the first wall and blanket such as the bulk and penetration shields, toroidal and poloidal magnets and auxiliary plasma heating system. This large volume contains ∿ 2% of the total activation whose specific radioactivity concentration is still high enough to be accounted for in the design consideration. This observation clearly indicates the importance of the shielding design, particularly the outboard bulk shielding

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*Work supported by the U.S. Department of Energy.

and penetration, in minimizing the total long-lived radioactive products in the system. This paper presents the tradeoffs as well as the analysis of the reference STARFIRE shielding design with a particular emphasis on the outboard bulk shield design. The particle transport calculations were performed using ANTSN,[4] DOT[5] and MORSE-CG[6] depending upon subsystems to be analyzed. With regard to the transport cross section library and the reaction response library, VITAMIN-C[7] and MACKLIB-IV[8] are used, respectively. Both of them are based on ENDF-B-IV.[9] The radioactivity calculations have been carried out by RACC[10] along with the associated activation/decay data libraries of RACCXLIB and RACCDLIB[11].

Prior to the final design selection, an extensive analysis on the shield optimization was carried out, focusing on four candidate shielding structural materials of Ti6Al4V, Al-2024, Type 304 stainless steel (304 SS), and Fe14Mn2Ni2Cr (Fe-1422).[12] The Fe-1422 alloy composition has much manganese and much less nickel and chrome than other typical austenitic steels. This alloy seems very attractive as a shield material because in addition to having as good radiation attenuation characteristics as the more conventional iron-base alloys, it offers two important advantages. First it tends to produce less long-term activation due primarily to the reduced nickel content. In addition, since isotope ^{56}Mn which is one of the major short-lived radioactive products associated with manganese activation, has a decay life of only ∿ 2.6 h,[13] the reactor room activation shortly after shutdown exhibits a rapid decay which is attractive from maintenance personnel access considerations. The second important advantage of using Fe-1422 in the shield is the significant reduction in the use of chromium. For example, the use of Fe-1422 in the shield reduces the chromium requirements by approximately 2000 metric tons compared to the case where Fe-1422 is replaced by Type 304 stainless steel. This is important to note that chromium resources in the United States are limited.

Figure 1 compares the three candidate materials of Fe-1422, Ti6Al4V, and Al-2024 in terms of the radiation attenuation characteristics. Shown for comparison is a dose response of an epoxy-base superconductor insulation material provisionally placed in the outboard shield. The excellent shielding properties of Fe-1422 are clear. It is found that, for a dose limit of 10^6 Gy/MW-yr/m^2, for instance, the reduction in the required shield thickness of Fe-1422 is ∿ 0.2 m (∿ 200 m^2 in volume) compared to Ti6Al4V and ∿ 0.4 m relative to Al-2024.

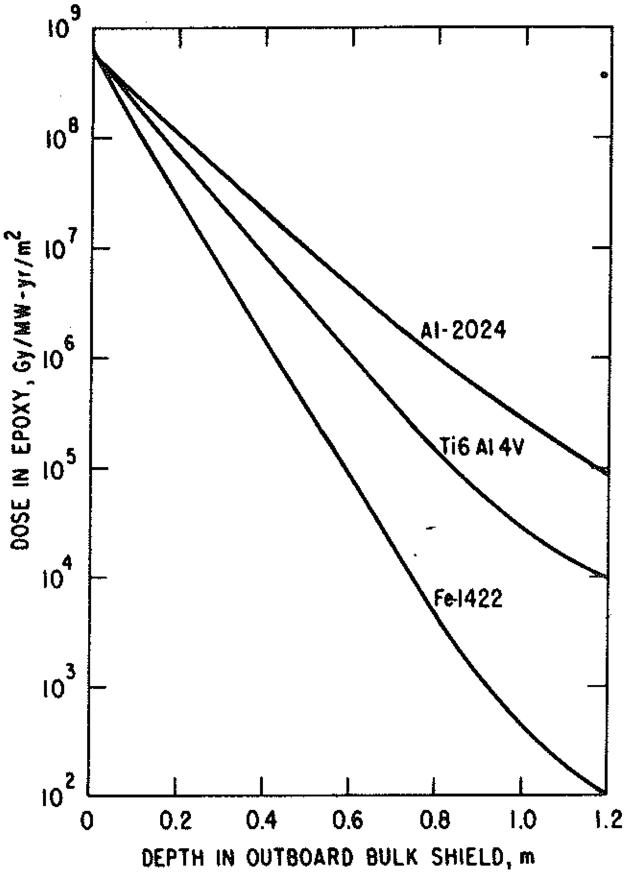

Fig. 1. A comparison of candidate shield materials on epoxy dose response.

Figure 2 shows the radioactivity concentrations in the first 0.1-m thick outboard shield for the three compositions as a function of time after shutdown following a reactor operation of an integral wall load of 18 MW/yr/m^2. Also shown in the figure is a specific radioactivity level of 10^{-7} MCi/m^3 below which materials are normally classified as low-level waste (LLW) that generally requires no special shield regarding the material handling. Due to the large amount of ^{55}Fe (decay half-life of 2.7 yr, EC decay with no gamma-ray) isotope production, the Fe-1422 shield exhibits a much higher radioactivity level up to 50 yr after shutdown than the Ti6Al4V and Al-2024 shields. The slow decrease in the Fe-1422 shield activation beyond that time period reflects the contribution from ^{63}Ni (100 yr, β^- decay/γ) isotope induced by the ^{62}Ni(n,γ) and ^{64}Ni(n,2n) reactions.

The Al-2024 shield activation shows a rapid decrease as the primary short-lived isotopes ^{24}Na (15 h, β^-/γ), ^{27}Mg (9.5 m, β^-/γ), and ^{28}Al (2.2 m, β^-/γ) decay. The major contribution up to ∿ 30 yr after shutdown comes from ^{54}Mn (312 d, EC/γ) and ^{55}Fe. Beyond 30 yr the most dominant isotope is ^{63}Ni which is produced in this case, mainly by the ^{63}Cu(n,p) reaction. It is of interest to see that the aluminum alloy exhibits a higher activation level than Fe-1422 after 30 yr because of the larger ^{63}Ni production rate caused by the less effective neutron flux attenuation. The steep decrease in the Ti6Al4V shield activation up to 10 yr after shutdown is very sub-

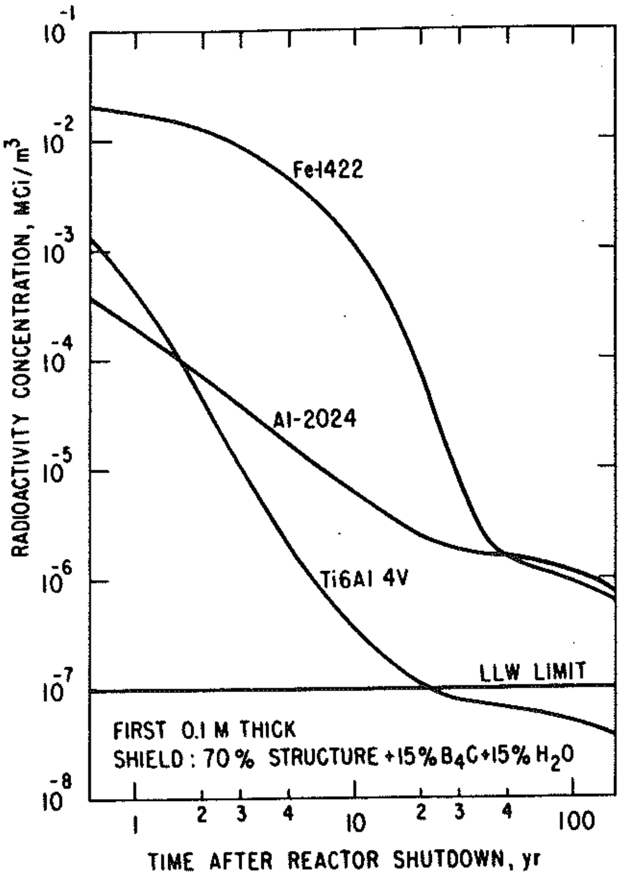

Fig. 2. A comparison of candidate shield materials on induced radioactivity.

stantial and due primarily to the fast decay of ^{24}Na, ^{45}Ca(165 d, β^-/γ), ^{46}Sc (84 d, β^-/γ), and ^{48}Sc (44 hr, β^-/γ). At times longer than 10 yr, the radioactivity in this shield is determined solely by the impurity activation products such as ^{63}Ni, ^{93m}Nb (13.6 yr, IT/γ), ^{93}Mo (3500 yr, EC/no γ), and ^{14}C (5700 yr, β^-/no γ).

With regard to the potential material recycling within one human generation, e.g., within 30 yr after component replacement or reactor decommissioning, Ti6Al4V seems to be the only candidate among those investigated that can be used in the high flux shield zone. The results of Figs. 1 and 2 suggest that the outboard bulk shield be divided into subregions using different shield structural materials by zone, in order to maximize the use of Fe-1422 without inducing any serious high-level activation. Figure 3 examines the spatial dependence of the specific radioactivity associated with the Fe-1422 shield. Clearly, in order for the Fe-1422 shield to be recyclable within 30 yr, it must be located at least 0.5 m behind the shield's inner surface.

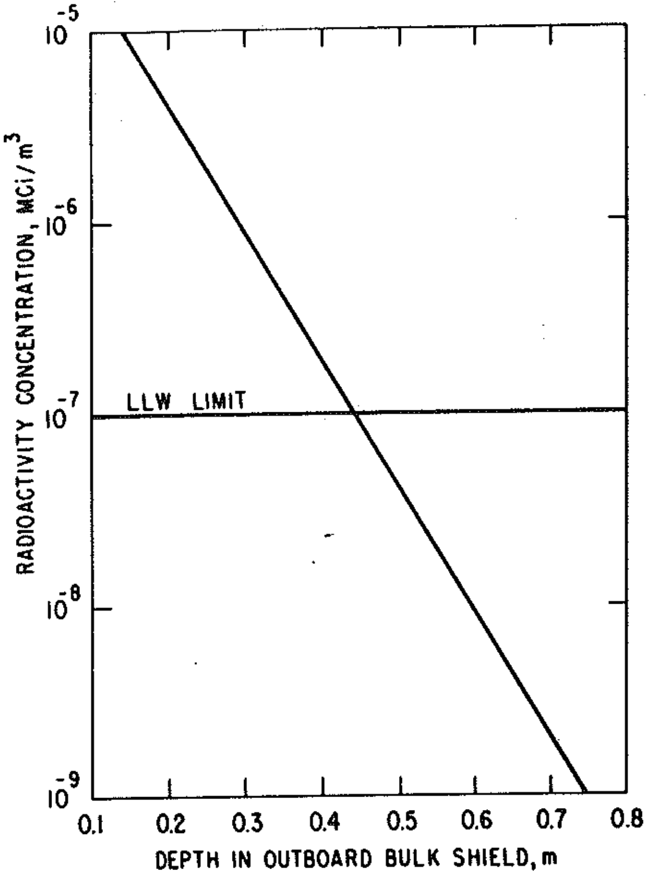

Fig. 3. Radioactivity concentration at 30 yr after reactor shutdown in a Fe14Mn2NiCr base shield.

The outboard bulk shield thickness used in the analysis is 1.2 m in the total thickness (including a 0.02-m shield jacket (vacuum boundary) at the front surface) and divided into three major shield zones of high flux shield (HFS, 0.5m), medium flux shield (MFS, 0.4 m), and low-flux shield (LFS, 0.28 m). The material compositions are as follows:

HFS: 5% Ti6Al4V + 65% TiH$_2$ + 15% B$_4$C + 15% H$_2$O

MFS: 70% Fe-1422 + 15% B$_4$C + 15% H$_2$O

LFS: 100% Fe-1422

Figure 4 shows the spatial and time dependence of contact biological dose of the outboard bulk shield system. During reactor operation, the biological dose inside the reactor building is ∿ 100 rem/hr which rules out any possibility of reactor accessibility. More than 90% of the total dose is attributable to neutrons. At reactor shutdown, the reactor room dose decreases to ∿ 100 mrem/h which is still too high to allow personnel access without protection, compared to the current NRC guideline[14] of 2.5 mrem/h for the occupational exposure limit (based on 40 h/wk-50 wk/yr work in a restricted area). The dose rate at this moment is dominated by the ^{56}Mn (2.6 h, β^-/γ) decay that emits the three major gamma rays of 0.85 MeV (intensity: 98.9%), 1.8 MeV (intensity relative to 0.85 MeV; 27.5%) and 2.1 MeV (relative intensity: 14.5%). The

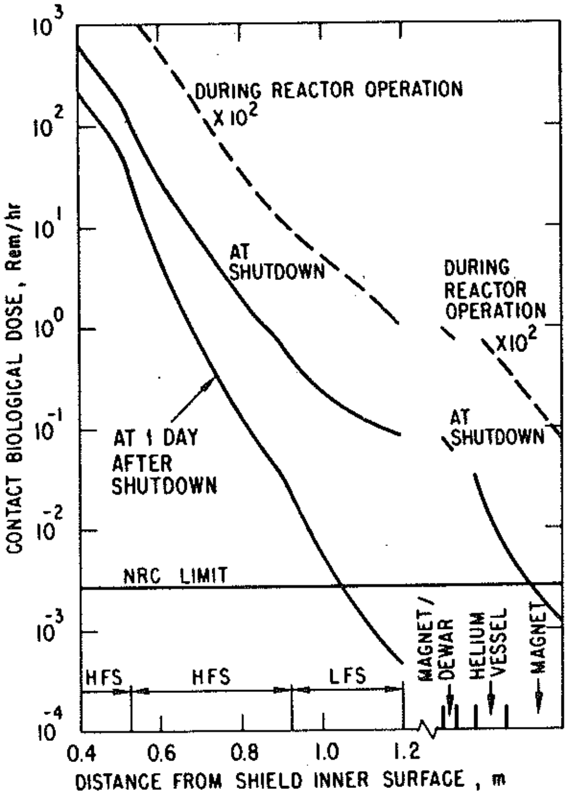

Fig. 4. Contact biological dose rate for the STARFIRE design.

second important gamma source (contributing to the total by ∿ 4%) is ^{54}Mn (312 d, EC/γ) emitting the 0.83-MeV (intensity: 100%) gamma ray. Due to the short half-life of ^{56}Mn and also to the relatively soft gamma spectrum, the reactor room dose decreases very rapidly following shutdown, resulting in ∿ 0.4 mrem/h at 24 h after shutdown. Again, the most dominant isotope in this time period is ^{54}Mn. Radioisotope ^{58}Co contributes to the total dose by less than 5% in the present case by virture of the substantial spectrum shifting and the less nickel content itself in the Fe-1422 shield. Although the STARFIRE plans call for fully remote maintenance, the dose rate of 0.4 mrem/h shows that personnel access into the reactor building with all shielding in place is premissible within one day after shutdown. This provides a degree of confidence in improving the plant availability factor, if desired, by allowing some maintenance tasks to be carried out in contact or semi-remote mode. Notice that when the shield thickness is reduced to 1.1 m, the dose rate at 24 h after shutdown is 1.5 mrem/h, which is still an acceptably low dose. Based on these results, the bulk shield thickness in the final reference design has been reduced to 1.1 m.

As already mentioned it is conceivable that material requirements for construction of a very large number of reactors would eventually pose resource availability and radwaste problems unless a capability of material recycling is established. Economic and technological considerations will ultimately determine the practicality of such material recycling. Decision on material recyclability for each piece of reactor components involves extremely difficult problems because of its dependence on many factors such as geometry of material, duration of cool-down, method of material handling, etc. There is presently no information on the "back-end" of the fusion material cycle that shows the relative economic, safety and technological merit of one material versus the other in respect to waste disposal and recycling. This lack of information forces the designer to use some judgment in material selection. In STARFIRE, a general guideline, based on the activation level after shutdown as disucssed below, was adopted as one of the primary criteria for material selection. The assumption here is that the lower the activation level of a material after shutdown is, the higher is its potential for economic recycling.

In general, radioactive waste can be defined by different waste categories, and various categories have been proposed. As a general qualitative classification of radwaste, Ref. 15 cites the following:

- High-level waste (HLW): requires cooling by forced convection, and heavy shielding during transportation
- Medium-level waste (MLW): shielding during transportation and handling is necessary but no cooling by forced convection. (the dose rate at the surface of drums used for disposal is greater than 200 mrem/hr.
- Low-level waste (LLW): No shielding, the dose rate is less than 200 mrem/hr.

Another definition for the waste categorization is given by D. Richter and W. Körner[16](*) and is also cited in Ref. 15 based on an evaluation of radwastes from fission nuclear power plants. The definition is presented in terms of both weight-base and volume-base radioactivity concentrations, i.e.,

HLW: > 10 Ci/ℓ (or Ci/kg)

MLW: $10^{-4} - 10$ Ci/ℓ (or Ci/kg)

LLW: $< 10^{-4}$ Ci/ℓ (or Ci/kg)

This classification seems useful for application to the material recycling potential. From the recycling considerations, the LLW category offers the best potential. This classification is simple

(*)According to Ref. 16, the radioactivity concentration between 10^{-4} and 10^{-5} Ci/ℓ(or Ci/kg) is not categorized. In the present analysis, this concentration interval is classified as LLW.

and useful as it is based on the curie level as the measure of radioactivity.

Table 1 classifies all reactor components according to the HLW, MLW and LLW categorizations defined above. It is noticed that most of the first wall/blanket components belong to either HLW or MLW at times of interest for recycling. A majority of the shield components can be categorized to LLW within 30 yr - 50 yr after shutdown and many of components external to the bulk shield appear to be recyclable at shutdown or in 1 yr at most. The only exception for such short-time recycling among those outside the shield is the inboard section of the TF-magnet, in particular, the high-field superconductors of Nb_3Sn. This is simply because of the relatively thin inboard bulk shield. Because of the fact that the reactor power is highly sensitive to the distance between the plasma center and the maximum field point in the inboard section of the magnets, the determination of the shield thickness as well as its composition can not be driven merely by activation considerations. It should be noted, however, that the volume of the high-field inboard magnet section is about 38 m^3 (excluding liquid helium) which is only ∿ 5% of the total TF-magnet volume. Consequently, from the material recycling consideration, the outboard section of the TF-magnets is of much more importance because of their large volume. It is remarkable that all activation levels of the outboard shield components where the largest shield volume is present (∿ 93% of 1500 m^3), decrease below the LLW limit within 30 yr at most. This was brought about by the shield optimization described earlier.

In summary, the STARFIRE reactor yields ∿ 1400 m^3 (∿ 7300 MT) of low recycling-potential and ∿ 4500 m^3 (∿ 25000 MT) of recyclable materials including the penetration subsystem shields at the end of its 30 yr plant life, based on the blanket sector replacement interval of 6 yr. The water coolant and the reactor building are eliminated from this evaluation. It should be noted that more than 60% of the 1400 m^3 low recycling-potential inventory consists of the medium level waste (order of ∿ 1 Ci/m^3) of $LiAlO_2$ containing only a single activation product of ^{26}Al. Approximately one third of the rest of the radwaste volume (∿ 40% in weight) is the Zr_5Pb_3 neutron multiplier having medium activation level of 100 Ci/m^3 beyond 50 yr after its decommissioning. The ultimate non-recycling high level radwaste discharged from the STARFIRE reactor over the 30 yr operation is ∿ 290 m^3 (∿ 2300 MT) contributed solely by the PCA steel structures.

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Table 1. Material Recyclability Classification Based on Component Radioactivity Concentrations

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----- H : HIGH   LEVEL WASTE : > 1.0E+01             KCI/M**3 -----
----- M : MEDIUM LEVEL WASTE :   1.0E-04 - 1.0E+01 KCI/M**3 -----
----- L : LOW    LEVEL WASTE : < 1.0E-04             KCI/M**3 -----
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TIME AFTER REACTOR SHUTDOWN

REACTOR COMPONENT		0	1YR	5YR	10YR	20YR	30YR	50YR	100YR	500YR	1000YR
1ST WALL	PCA	H	H	H	H	H	H	H	H	H	M
	H2O	H	L								
MULTIPLR	ZR5PB3	H	H	M	M	M	M	M	M	M	M
2ND WALL	PCA	H	H	H	H	H	H	H	H	M	M
	H2O	H	L								
IBLANKET	FCA	H	H	H	H	H	H	M	M	M	M
	LIALO2	H	M	M	M	M	M	M	M	M	M
	H2O	H	L								
OBLANKET	FCA	H	H	H	H	H	H	M	M	M	M
	LIALO2	H	M	M	M	M	M	M	M	M	M
	H2O	H	L								
REFLECTR	FCA	H	H	H	H	H	H	H	M	M	M
	GRAPHITE	L									
	H2O	M	L								
IBLK-JKT	PCA	H	H	H	H	H	M	M	M	M	M
OBLK-JKT	FCA	H	H	H	H	H	H	H	M	M	M
HEADER	FCA	H	H	H	H	H	H	H	M	M	M
	H2O	M	L								
ISLD-JK1	FE1422	H	H	H	H	M	M	M	M	M	M
OSLD-JKT	FE1422	H	H	H	H	M	M	M	M	M	M
ISHIELD1	FE1422	H	H	M	M	M	H	M	L		
	TUNGSTEN	H	M	M	M	M	L				
	H2O	M	L								
ISHIELD2	FE1422	M	M	M	M	M	M	L			
	B4C	M	L								
	H2O	M	L								
OSHIELD1	TI6AL4V	M	M	M	L						
	TIH2	M	M	M	L						
	B4C	M	L								
	H2O	M	L								
OSHIELD2	FE1422	M	M	M	M	L					
	B4C	M	L								
	H2O	M	L								
OSHIELD3	FE1422	M	L								
ISLD-JK2	FE1422	M	M	M	M	M	L				
AIR	CO2	L									
IMAG-DWR	FE1422	M	M	M	M	M	L				
OMAG-DWR	FE1422	M	L								
IMAG-HET	304SS	M	M	M	M	M	L				
OMAG-HET	304SS	L									
IMAGNET1	COPPER	M	M	M	M	L					
	304SS	M	M	M	M	L					
	NB3SN	M	M	M	M	M	M	L			
	G-10	L									
IMAGNET2	304SS	M	L								
	COPPER	M	L								
	NBTI	M	L								
	G-10	L									
IMAG-HE2	304SS	L									
OMAGNET1	304SS	L									
	COPPER	L									
	NB3SN	L									
	G-10	L									
OMAGNET2	COPPER	L									
	304SS	L									
	NBTI	L									
	G-10	L									
SUPT-CYL	G-10	L									
OH/EF	COPPER	L									
	304SS	L									
	NBTI	L									
	G-10	L									
BLDGHALL	CONCRETE	L									

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1ST WALL	FIRST WALL	MULTIPLR	NEUTRON MULTIPLIER
2ND WALL	SECOND WALL	IBLANKET	INBOARD BLANKET
OBLANKET	OUTBOARD BLANKET	REFLECTR	REFLECTOR
IBLK-JKT	INBOARD BLANKET JACKET	OBLT-JKT	OUTBOARD BLANKET JACKET
HEADER	COOLANT MANIFOLD HEADER	ISLD-JK1	INBOARD SHIELD JACKET 1
OSLD-JKT	OUTBOARD SHIELD JACKET	ISHIELD1	INBOARD SHIELD 1
ISHIELD2	INBOARD SHIELD 2	OSHIELD1	OUTBOARD SHIELD 1
OSHIELD2	OUTBOARD SHIELD 2	OSHIELD3	OUTBOARD SHIELD 3
ISLD-JK2	INBOARD SHIELD JACKET 2	AIR	REACTOR ROOM ATMOSPHERE
IMAG-DWR	INBOARD MAGNET DEWAR	OMAG-DWR	OUTBOARD MAGNET DEWAR
IMAG-HET	INBOARD MAGNET HELIUM VESSEL	OMAG-HET	OUTBOARD MAGNET HELIUM VESSEL
IMAGNET1	INBOARD HIGH FIELD MAGNET	IMAGNET2	INBOARD LOW FIELD MAGNET
IMAG-HE2	INBOARD MAGNET HE-VESSEL 2	OMAGNET1	OUTBOARD HIGH FIELD MAGNET
OMAGNET2	OUTBOARD LOW FIELD MAGNET	SUPT-CYL	SUPPORT CYLINDER
OH/EF	SUPER-CONDUCTING OH/EF COILS	BLDGHALL	REACTOR BUILDING