



# **Minimizing Radioactivity and Other Features of Elemental and Isotopic Tailoring of Materials for Fusion Reactors**

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**May 1978**

**UWFDM-305**

Nuc. Tech. 41, 389 (1978).

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Materials for Fusion Reactors**

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May 19, 1978

Published in Nuclear Technology, 41 (1978) 389.

UWFDM-305

### Abstract

The levels of induced radioactivity in fusion devices can be controlled by appropriate selection of elements in a structural alloy and, in principle, by the selection of specific isotopes of a particular element. Three general rules are developed by which long term induced radioactivity can be minimized. These rules are then applied to two specific alloy systems, stainless steels and the molybdenum alloy, TZM. A particular steel, Tenelon, containing neither Ni nor Mo, is especially attractive. It is found that the principles of both elemental substitution and isotopic tailoring can reduce the long term radioactivity levels by orders of magnitude compared to normal 316 stainless steel.

A comparison of long term activity levels in systems like the LMFBR, fusion with standard structural alloys, and fusion with steel alloys designed for low activity show quantitatively the potential advantage of fusion in this area. The influence of isotopic tailoring on gas production rates is also discussed. The calculations on radioactivity indicate that with proper attention to the choice of materials and isotopes, long term radioactivity in fusion devices can be made so low as to either eliminate concern over long term storage or allow recycling within a few human generations.

## I. Introduction

Long-term radioactivity is not inherent to nuclear fusion reactors but the use of deuterium and tritium as fuels will mean the production of neutrons and the generation of neutron induced radioactivity in the reactor structural materials. The level of induced activity will of course depend on the structural materials employed. Many studies have been carried out to determine the long term levels of induced radioactivity and afterheat for specific conceptual fusion reactor designs<sup>(1-5)</sup> and Vogelsang<sup>(6)</sup> has recently given a comprehensive overview of past work in this area. Comparative studies have shown the relative advantages certain materials may have for minimizing long-term activity levels. Aluminum,<sup>(7)</sup> vanadium,<sup>(8)</sup> and recently titanium<sup>(9)</sup> alloys have been shown to be particularly advantageous from this point of view. Yet there may be other compelling reasons for choosing an alloy. Stainless steels are the most widely characterized and most commonly used structural material and are perhaps the most likely material to be used for the first reactors. Characteristics such as strength, resistance to radiation damage, the allowable operating temperature range, the value of particular nuclear cross sections (like  $(n,2n)$  and  $(n,\gamma)$ ), and the availability of an industrial production capacity are among the many items one must consider in ultimately selecting a reactor structural alloy. An important question is whether one can in principle control the long term levels of neutron induced radioactivity without severely limiting the choice of the reactor structural material. If this is possible, it would permit a wider range of alloys to be used and allow other factors to weigh more heavily in making the final materials choice.

In this paper, we will show that the levels of induced radioactivity in fusion devices can be controlled by the appropriate selection of elements in a structural alloy and, in principle, by the selection of specific isotopes of a particular element. The former process involves elemental substitution while the latter process involves what is referred to as isotopic tailoring. The general principles involved in selecting specific isotopes to minimize long term induced radioactivity will be developed and applied to two important alloy types, stainless steels and molybdenum alloys. The impact can be very great in reducing both the long-term radioactivity levels and the level of radioactivity and afterheat at reactor shutdown. It is also clear that these principles can be applied for other interesting alloy systems such as the nickel based alloys and the zirconium alloy, zircaloy. Also, isotopic tailoring will influence neutron induced gas production rates and this is briefly discussed.

The general rules for applying isotopic tailoring and elemental substitution are given in Section II. Illustrative calculations to indicate the theoretical impact of this idea are given in Section III along with results using potentially practical levels of isotopic purity. A comparison is presented between radioactivity and biological hazard potential for the liquid metal fast breeder reactor and typical fusion systems. A brief discussion is given in Section IV on the connection between isotopic tailoring and gas production rates in structural materials. The last section contains a summary with comments on the potential economics of isotopic tailoring.

## II. General Rules To Minimize Induced Radioactivity By Isotopic Tailoring

The radioactivity levels in a fusion reactor at long times after shutdown will depend on the nuclear transmutations that take place in the reactor while it operates at a specified flux level for a particular period of time. Methods now exist to calculate the radioactivity and afterheat levels given the appropriate nuclear data<sup>(6)</sup> and, in this paper, we use the radioactivity code, DKR, written by Sung and Vogelsang<sup>(10)</sup>. The program utilizes ENDF/B-IV data as well as cross sections provided by Pearlstein from the THRESH code<sup>(11)</sup>. The neutron flux used throughout is that associated with the blanket of the UWMAK-I conceptual tokamak reactor design,<sup>(12,13)</sup> a natural lithium cooled blanket with 316 stainless steel as the first wall and blanket structure.

The first step in minimizing the long term activity is to determine the specific isotopes contributing to that activity. In Fig. 1, the radioactivity following shutdown after two years of operation at a 14.1 MeV neutron wall loading of  $1.25 \text{ MW/m}^2$  is shown as a function of time for five different structural materials<sup>(6)</sup>. For times after shutdown greater than 100 years, the molybdenum alloy, TZM, shows the highest activity levels followed by 316 stainless steel. The activity level of the aluminum alloy, Al-2024, saturates at about  $10^{-7} \text{ Ci/W(th)}$  whereas the vanadium alloy, V-20Ti, shows essentially no activity at times greater than 10 years after shutdown. Therefore, let us consider stainless steels and molybdenum alloys as candidates for isotopic tailoring.

The percentage contribution of various isotopes to the induced radioactivity is shown in Fig. 2 as a function of the time after shutdown following two years of operation at  $1.25 \text{ MW/m}^2$ . For times greater than 100 years, the major contributing isotopes are  $^{63}\text{Ni}$  ( $t_{1/2} = 92 \text{ y}$ ),  $^{93}\text{Mo}$  ( $t_{1/2} = 10^4 \text{ y}$ ),  $^{59}\text{Ni}$  ( $t_{1/2} = 8 \times 10^4 \text{ y}$ ),  $^{99}\text{Tc}$  ( $t_{1/2} = 2.1 \times 10^5 \text{ y}$ ), and  $^{53}\text{Mn}$  ( $t_{1/2} = 1.9 \times 10^6 \text{ y}$ ). A similar plot is shown in Fig. 3 for an operating time of 10 years at a wall loading of  $5 \text{ MW/m}^2$ . Essentially all the same nuclides occur except that the higher operating flux level and longer operating time have allowed a somewhat larger relative amount of  $^{94}\text{Nb}$  ( $t_{1/2} = 2 \times 10^4 \text{ y}$ ) to build up. Fig. 4 shows the effect of flux level and operating time on the radioactive decay after shutdown. The differences are small at shutdown and become somewhat larger at very long times. Secondary reactions and burnup mean that the activity levels are not linearly related to the flux level or the exposure time.

An examination of the origin of these nuclides shows that except for  $^{94}\text{Nb}$  they are all produced directly or indirectly by  $(n,2n)$  or  $(n,\gamma)$  reactions on stable, neighboring nuclei in the periodic table. This point is developed more clearly in Table 1. We first list the nominal composition by element of 316 stainless steel and then list the natural isotopic make-up of the most important alloying elements. Finally, in Table 2 we list the reactions leading to the major long-term activities. Note that even  $^{53}\text{Mn}$  and  $^{99}\text{Tc}$  actually follow from the decay of the nuclide produced as a result of an  $(n,2n)$  or  $(n,\gamma)$  reaction.

These results suggest the first major rule to apply to minimize long term activity: Examine the sequence of isotopes occurring for a given element involved in the production of long term radioactivity and select one or more isotopes from the middle of a contiguous set. This principle



is most simply illustrated by example. Nickel is important as an alloying element in steels and as the primary element in nickel-based alloys like Inconel.<sup>(14)</sup> The naturally occurring isotopes are  $^{58}\text{Ni}$ ,  $^{60}\text{Ni}$ ,  $^{61}\text{Ni}$ ,  $^{62}\text{Ni}$  and  $^{64}\text{Ni}$ . Since  $^{59}\text{Ni}$  and  $^{63}\text{Ni}$  are produced by  $(n,2n)$  and  $(n,\gamma)$  reactions on their respective stable neighboring isotopes, one should select  $^{61}\text{Ni}$  to isotopically tailor the nickel to be used in an alloy to minimize induced radioactivity.

Molybdenum consists of nine stable isotopes of which seven are contiguous from  $^{93}\text{Mo}$  to  $^{98}\text{Mo}$ . Molybdenum is important as an alloying element and as the primary constituent of molybdenum alloys, particularly TZM, which has the composition, 99.4% Mo, 0.5% Ti, 0.08% Zr, and 0.01% C. Fig. 5 is a plot of the percentage contribution of various isotopes versus the induced radioactivity as a function of time after shutdown for a UWMAK-I blanket when TZM is used as the structure and the reactor is considered to have operated at  $5 \text{ MW/m}^2$  for 2 years before shutdown. Long term contributions to the radioactivity come from  $^{93}\text{Mo}$ ,  $^{93\text{m}}\text{Nb}$  and  $^{99}\text{Tc}$ . The suggestion is that the optimum procedure to minimize induced radioactivity is to select  $^{96}\text{Mo}$  and  $^{97}\text{Mo}$ . This example suggests the second general rule: Examine the contiguous set of stable nuclides for isotopes that can be produced by other nuclear reactions such as  $(n,p)$ ,  $(n,n'p)$ ,  $(n,\alpha)$ , and  $(n,n'\alpha)$ . Eliminate those nuclides for which such reactions lead to long term induced radioactivities.

The third rule is to consider elemental substitution in alloys to eliminate elements that produce undesirable radioactivities. For example, Mn occurs as 100%  $^{55}\text{Mn}$  but its use does not result in any serious long term radioactivities. Mn can be used to substitute for Ni in austenitic stainless steels, and the alloy, Tenelon, has been developed with a high Mn content (about 14%) and with no Ni or Mo.<sup>(14)</sup>

It is clear that isotopic tailoring or elemental substitution will not be applicable if an element is essential and consists entirely of a single nuclide. Important elements that fall in this category include  $^{27}\text{Al}$ ,  $^{93}\text{Nb}$ , and  $^{55}\text{Mn}$ . In aluminum alloys, the reaction  $^{27}\text{Al}(n,2n)$  produces  $^{26}\text{Al}$  which has a half-life of  $7.4 \times 10^5$  y. The constant level in Fig. 1 at about  $10^{-7}$  Ci/W(th) for the alloy Al-2024 is due to  $^{26}\text{Al}$ . Fortunately, the manganese needed for use in steels does not produce long lived activities when bombarded by neutrons. The long lived  $^{53}\text{Mn}$  ( $t_{1/2} = 1.9 \times 10^6$  y) isotope shown in Fig. 2 is produced from the  $\beta$ -decay of  $^{53}\text{Fe}$ . The  $^{53}\text{Fe}$  comes from an  $(n,2n)$  reaction on the stable isotope,  $^{54}\text{Fe}$ . Production of  $^{53}\text{Mn}$  from  $^{55}\text{Mn}$  would require successive  $(n,2n)$  reactions which is highly improbable.

### III. Applications of Isotopic Tailoring and Elemental Substitution

The general rules described in section II can be applied to specific cases to assess their effectiveness in generating a reduction in the levels of long term induced radioactivity. We first consider the theoretical impact these rules can have and then consider the effects of practical limits to isotope selectivity. We shall concentrate on elements in steels and molybdenum alloys as specific examples but we point out again that the notions have general applicability.

#### a. Theoretical Limits

The nominal composition of 316 stainless steel is given in Table 1. The main isotopes contributing to the long term radioactivity come from neutron reactions on Ni and Mo. Application of rules 1 and 2 as given in Section II suggests utilizing the isotopes  $^{61}\text{Ni}$  and  $^{97}\text{Mo}$  for these alloying elements in steel. A complete isotopic tailoring would utilize  $^{57}\text{Fe}$ ,  $^{61}\text{Ni}$ ,  $^{97}\text{Mo}$ , and  $^{53}\text{Cr}$ . Tailoring of Ni and Mo only is interesting because it would require purification only of minority elements in the alloy and, as we will discuss in the next section, this permits a larger price to be paid for such selectivity.

Fig. 6 shows the radioactive decay as a function of time following two years exposure at  $1.25 \text{ MW/m}^2$ . The decay for normal 316 stainless steel is given as a reference. Clearly, isotopic tailoring has an enormous impact in lowering the levels of long term radioactivity. The level of activity at 100 years after shutdown is already below the  $10^6$  year level in normal steel. This is found even though isotopic tailoring is used only on Ni and Mo. The constant level at  $10^{-9} \text{ Ci/W(th)}$  at times greater than 100 years is due to  $^{53}\text{Mn}$ . This is produced by an  $(n,2n)$  reaction on  $^{54}\text{Fe}$  and the subsequent  $\beta$ -decay of  $^{53}\text{Fe}$ . Thus, isotopic tailoring on iron and the use of  $^{57}\text{Fe}$  alone would cause the

radioactivity to drop to insignificant levels after about 100 years. Of course, 100% isotopic selectivity is not possible. The effect of using potentially practical selectivity levels will be discussed shortly, but these theoretical levels are important for reference.

The molybdenum alloy, TZM, was discussed in section II and it was noted that selecting  $^{96}\text{Mo}$  and  $^{97}\text{Mo}$  or  $^{97}\text{Mo}$  alone could substantially reduce the long term activity (see Fig. 5). The theoretical effect on the long term radioactivity is shown in Fig. 7. The impact here is even greater than in the case of steel. One sees that there is essentially no radioactivity at times greater than 10 years after shutdown. Further, the radioactivity level at shutdown after 2 years of operation is more than an order of magnitude below the level of TZM with natural molybdenum. A similar reduction is found in the afterheat levels shown in Fig. 8. This can be very important from a safety viewpoint since a loss of flow or coolant accident would not be as difficult to handle, although the situation for fusion is already reasonable from this point of view.<sup>(6)</sup>

Where metallurgically feasible, elemental substitution can be as effective as isotopic tailoring and would be inherently less costly. An interesting example is the substitution of manganese for nickel in austenitic stainless steel.<sup>(14)</sup> The 200 series steels contain from 1/2 to 1/3 the amount of Ni compared with the 300 series. Perhaps a theoretical limit is provided by the alloy, Tenelon, developed by the U. S. Steel Corporation. The nominal composition of Tenelon is given in Table 1 and one notes that the alloy contains neither nickel nor molybdenum. Nitrogen is present and application of rule 1 shows that the long term radioactivity is dominated by  $^{14}\text{C}$  ( $t_{1/2} = 5.73 \times 10^3 \text{ y}$ ) produced by the reaction  $^{14}\text{N}(n,p)^{14}\text{C}$  and Mn produced indirectly from  $^{54}\text{Fe}$ .

Nitrogen occurs naturally as 99.635%  $^{14}\text{N}$  and 0.365%  $^{15}\text{N}$ . Therefore, substituting  $^{15}\text{N}$  for the nitrogen required in the alloy will minimize  $^{14}\text{C}$  production.  $^{14}\text{C}$  is not entirely eliminated in this way because it can be produced by (n,n'p) and (n,d) reactions on  $^{15}\text{N}$ . No data exists for the  $^{15}\text{N}(n,n'p)^{14}\text{C}$  reaction and little data is available on the  $^{15}\text{N}(n,d)^{14}\text{C}$  reaction.<sup>(15)</sup> One measurement<sup>(16)</sup> for the latter reaction gives a cross section of about 15 mb at 14.1 MeV but there is no data at lower energies. No data on these reactions is included in the ENDF/B-IV data files which were used in our calculations. With this caveat, the results of radioactivity calculations for Tenelon and Tenelon with isotopically tailored nitrogen and iron are given in Fig. 9. The case of normal Tenelon compared to normal 316 stainless steel shows that elemental substitution has produced a 1000-fold decrease in the radioactivity at 50 years after shutdown. Isotopic tailoring of nitrogen would only reduce the activity level to that caused by  $^{53}\text{Mn}$ , or one more factor of 10. Isotopic tailoring of both nitrogen and iron (by removing  $^{54}\text{Fe}$  to eliminate the  $^{53}\text{Mn}$  production) leads to the final curve shown on Fig. 9. Activity levels have dropped below  $10^{-12}$  Ci/W(th) at times greater than 100 years after shutdown.

#### b. Results With Potentially Practical Selectivity Levels

Achieving 100% isotopic selectivity is not possible but isotope separation processes, particularly those based on using lasers<sup>(17)</sup> and utilizing a multistage process, can potentially achieve purity levels of 0.99999 or more. Here, we will assume that selectivity levels of 0.99 and 0.9995 can be achieved and examine the consequences for long-term radioactivity levels.

Fig. 10 contains results for various isotopic tailoring levels on 316 stainless steel. Basically, the radioactivity level at 50 years after reactor

shutdown drops by the same factor as the selectivity which is possible. Thus, if a selectivity of 0.99 is possible on  $^{61}\text{Ni}$  and  $^{97}\text{Mo}$ , then the radioactivity at 50 years decreases by a factor of 100. The results for 0.9995 selectivity on the isotopes listed on the figure produce a reduction in the radioactivity level at 50 years after shutdown of a factor of 5000. Beyond 50 years, the radioactivity level remains about a factor of  $10^3$  below the level without isotopic tailoring.

Isotopic selectivity of 0.9995 on  $^{15}\text{N}$  and  $^{52}\text{Fe}$ ,  $^{57}\text{Fe}$ , and  $^{58}\text{Fe}$  for use in Tenelon yields the result shown in Fig. 11. The activity level in tailored Tenelon at 100 years after shutdown is a million times less than the activity which would occur in normal 316 stainless steel.

#### c. BHP Levels and Comparisons With an LMFBR

A comparison of induced radioactivity levels in fission reactors with fusion reactors employing isotopic tailoring is another measure of the potential improvements which can be gained by isotope selection. Häfele et al.<sup>(18)</sup> have recently considered this question using the plutonium fueled liquid metal fast breeder reactor (LMFBR) as typical of advanced fission systems and the UWMAK-I conceptual tokamak reactor<sup>(2)</sup> as representative of fusion. The curves in Fig. 12 illustrate this comparison. In terms of  $\text{Ci/W(th)}$ , the curves without isotopic tailoring that describe fission and fusion differ by no more than a factor of 100. It should be pointed out that Häfele et al. assume reprocessing removes 99% of the Pu isotopes after 200 days for reinsertion into the reactor. Nevertheless, the LMFBR curve remains dominated by the actinide contribution for times less than  $10^5$  years. The fission products dominate at longer times.

The use of isotopic tailoring on 316 stainless steel in a fusion reactor greatly increases the relative advantage of fusion for times greater than 50 years and the use of isotopically tailored Tenelon steel would lower the radioactivity levels by a factor of  $10^8$  below the fission product level in an LMFBR at 100 years after shutdown.

Another important issue is the radioactivity level which would be considered acceptably low. U. S. Federal Regulatory Guidelines<sup>(19)</sup> give maximum permissible concentrations for air and water for all radionuclides, and a commonly used measure of hazard potential is the biological hazard potential, or BHP. The BHP is defined as

$$\text{BHP} = \frac{\text{Ci/kW(th)}}{\text{MPC (Ci/km}^3\text{)}} ,$$

and a BHP value exists for both air and water, depending on the maximum permissible concentration (MPC) value used. The  $(\text{BHP})_A$  for air gives the number of  $\text{km}^3$  of air required to dilute the specified amount of radioactivity such that the air would meet federal guidelines. A similar explanation holds for the  $(\text{BHP})_W$  for water. Solid radioactive material such as the structural material from a fusion reactor is likely to be compacted and stored underground, and the most useful measure of acceptability is probably the  $(\text{BHP})_W$ . On the other hand, the level at which a material can be recycled is more likely to depend upon the  $(\text{BHP})_A$  value since this can then be applied to industrial situations where some fraction of the material might be vaporized. Both situations are complicated by the need to know the fraction of material that is likely to enter the water or air by corrosion or other mechanisms and by the lack of MPC values for important isotopes. A specific example of the latter problem is  $^{53}\text{Mn}$ , which decays by electron capture without emitting a gamma ray, i.e., to the ground state of  $^{53}\text{Cr}$ . Since no MPC value is listed, application of

U. S. federal rules requires the use of a very low  $(MPC)_W$  value,  $3000 \text{ Ci/km}^3$ . Yet  $^{54}\text{Mn}$ , which decays by electron capture but is accompanied by a 0.835 MeV gamma, has an  $(MPC)_W$  value of  $10^5 \text{ Ci/km}^3$  and  $^{51}\text{V}$ , which results from decay of  $^{51}\text{Cr}$ , emits a 320 keV gamma and has a listed  $(MPC)_W$  value of  $2 \times 10^6 \text{ Ci/km}^3$ . We use an  $(MPC)_W$  value of  $3 \times 10^6 \text{ Ci/km}^3$  and an  $(MPC)_A$  value of  $100 \text{ Ci/km}^3$  for  $^{53}\text{Mn}$  in the work to be reported. A second example is the production of  $^{92}\text{Nb}$  by  $(n,p)$  reactions on  $^{92}\text{Mo}$ .  $^{92}\text{Nb}$  can be produced in either a metastable state,  $^{92m}\text{Nb}$  ( $t_{1/2} = 10.16 \text{ d}$ ), or the ground state  $^{92g}\text{Nb}$  ( $t_{1/2} = 3.7 \times 10^6 \text{ y}$ ).<sup>(20)</sup> The branching ratio to each of these states from the  $(n,p)$  reaction is not known. It is known<sup>(20)</sup> that for the reaction  $^{93}\text{Nb}(n,2n)^{92}\text{Nb}$ , the metastable state is produced about 66% of the time. For the reaction,  $(n,p)$ , the branching ratio should be larger to the ground state and we have used 50%. No MPC values are listed for either  $^{92m}\text{Nb}$  or  $^{92g}\text{Nb}$ . Comparison of other isotopes with similar properties, such as  $^{95}\text{Nb}$  or  $^{93}\text{Zr}$  ( $t_{1/2} = 1.5 \times 10^6 \text{ y}$ ), suggests that we use an  $(MPC)_W$  value of  $10^5 \text{ Ci/km}^3$  and an  $(MPC)_A$  value of  $350 \text{ Ci/km}^3$  (see ref. 4). We have used these values in the calculations we report.

The  $(BHP)_A$  and  $(BHP)_W$  levels are given in Figs. 13 and 14, respectively, as a function of time after shutdown for the LMFBR and fusion reactors with normal and isotopically tailored stainless steels. Again, since the LMFBR curve is dominated by the actinides or fission products, isotopic tailoring on the structure in the reactor core would have little effect on the overall activity level. The  $(BHP)_W$  level for isotopically tailored Tenelon falls to about  $10^{-13} \text{ km}^3/\text{kW(th)}$  after about 100 years. The level for the first wall alone is  $3.3 \times 10^{-14} \text{ km}^3/\text{kW(th)}$ . The UWMAK-I conceptual reactor is designed to generate 5000 MW(th) which means that to meet federal guidelines, the entire



first wall would have to be dissolved in just  $150 \text{ m}^3$  of water. Corrosion rates and solubility limits make it impossible to dissolve this much material. Thus, it appears this level of activity would be so low that the stored material would require no further attention after 50-100 years.

The  $(\text{BHP})_A$  levels are relevant if one considers the possible need to recycle the materials. For isotopically tailored Tenelon steel, the  $(\text{BHP})_A$  level of the blanket structure is just  $10^{-9} \text{ km}^3/\text{kW(th)}$  after 50 years. This is eleven orders of magnitude below the comparable level in the LMFBR and seven orders of magnitude below the fusion activity level when normal 316 stainless steel is used. An arbitrary but high level in air can be obtained by assuming 1% of the recycled blanket material is somehow vaporized during reprocessing. The volume of air required to dilute this amount of material to a safe level is  $5 \times 10^4 \text{ m}^3$ , a reasonable volume. Thus, recycling might also be feasible after a 50-100 year delay time for such a fusion reactor structural material.

These calculations, while admittedly simple, do indicate that with proper attention to the choice of materials and isotopes in a fusion reactor structure, one can potentially achieve radioactivity levels so low as to either eliminate concern over long term storage or allow recycling within a few human generations.

#### IV. Isotopic Tailoring and Gas Producing Nuclear Reactions

An area other than radioactivity affected by isotopic tailoring is the production of gases, particularly H and He, by neutron induced nuclear reactions such as  $(n,p)$ ,  $(n,n'p)$ ,  $(n,\alpha)$ , and  $(n,n'\alpha)$ . In a first wall of SS-316, these rates are on the order of 500-600 appm/yr of hydrogen and 150-200 appm/yr of helium per  $\text{MW/m}^2$  of neutron wall loading.<sup>(21)</sup> An examination of the nuclear systematics for these reactions<sup>(22-24)</sup> shows that charged particle production cross sections for a given element decrease with increasing atomic weight. Conversely, neutron producing reactions such as  $(n,2n)$  increase with increasing atomic weight since the nucleus is becoming neutron rich. Since gas production adversely affects materials performance while neutron multiplication aids tritium breeding, the simple rule here would be to use the heaviest isotope of a given element. This is not necessarily consistent with the rules for minimizing radioactivity but the effect should be kept in mind.

As an example, consider the influence of isotopic tailoring on gas production in the nickel based alloy, PE-16. The composition and neutronic behavior of this alloy has been discussed by Mills, et al.<sup>(25)</sup> and by Abdou and Conn.<sup>(21)</sup> If  $^{61}\text{Ni}$  is used in place of the natural Ni, the hydrogen production rate due to  $(n,p)$  reactions<sup>(21)</sup> drops from 688 to 348 appm/yr per  $\text{MW/m}^2$  of neutron wall loading, or by 50%. The helium production rate decreases less, by 20%, from 200 to 160 appm/yr per  $\text{MW/m}^2$ . Consideration of other metal alloys shows similarly that reductions of a factor of 2 or perhaps 3 can be expected in gas production rates. Larger factors are obtained only in quite special cases.

## V. Summary and Comments

Elemental substitution and isotopic tailoring can strongly influence the long term radioactivity level of neutron-irradiated materials used in fusion reactors. Orders of magnitude reductions are possible by isotopically tailoring stainless steel-316, the first wall material used in many conceptual fusion reactor designs. Calculations of BHP levels in air and water show similar reductions, and a comparison with the LMFBR system indicates the relative advantages of fusion in this area.

The ultimate practical utility of isotopic tailoring will be determined by economic considerations beyond the scope of this paper. For example, the cost of disposal of the radioactive material will have to be weighed against the isotopic purification costs. Additional considerations must be given to safety factors. For example, in case of emergency loss of coolant, the temperature rise could be reduced in isotopically tailored materials because of the lower level of afterheat at shutdown.

The costs of isotopic separation using present day gas-dynamic schemes can be estimated to be greater than  $\$10^7$ /tonne, a value that is probably prohibitively expensive. New separation techniques will reduce this cost in the future. A very promising technique, laser isotope separation, may make the cost of separation become very practical.

Although we have not treated the details of the cost of isotopic tailoring, we do consider the cost to be an extremely important factor. Indeed, the use of isotopically tailored materials in fusion reactors will be determined by a comparison of their cost to their benefits (reduced storage times, increased safety, etc.). Our calculations show that the benefits from isotopic tailoring of the materials in fusion reactors are unequivocally very important. A good cost comparison is yet to be performed.

Table 1Nominal Composition of 316 Stainless Steel<sup>(14)</sup>

(Weight Percent)

<u>Fe</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Mn</u>	<u>Si</u>	<u>P</u>	<u>S</u>	<u>C</u>
64.89	11.33	18.13	1.45	2.02	1.92	0.08	0.052	0.08

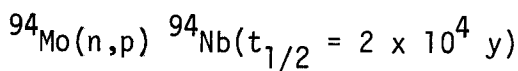
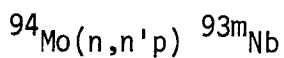
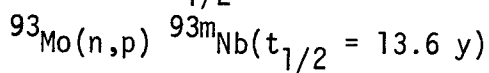
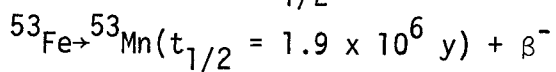
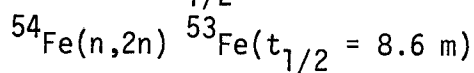
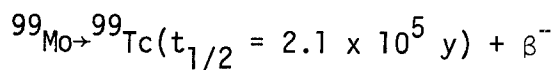
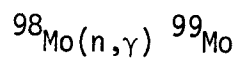
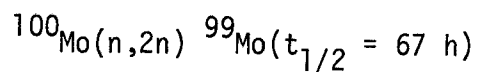
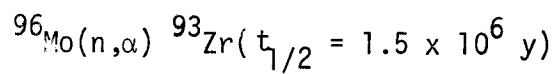
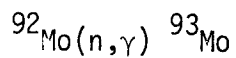
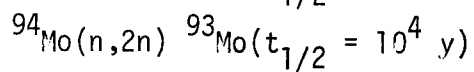
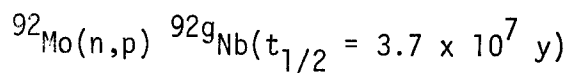
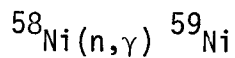
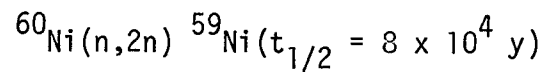
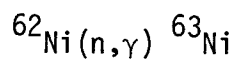
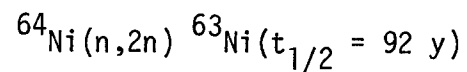
Nominal Composition of the Stainless Steel, Tenelon<sup>(14)</sup>

69.0	-	17.0	-	14.5	0.3	0.045	0.03	0.08
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Isotopic Makeup of Key Alloying Elements

(Percent of Natural Abundance)

Iron	$^{54}\text{Fe}(5.84\%)$ , $^{56}\text{Fe}(91.68\%)$ , $^{57}\text{Fe}(2.17\%)$ , $^{58}\text{Fe}(0.31\%)$
Nickel	$^{58}\text{Ni}(67.76\%)$ , $^{60}\text{Ni}(26.6\%)$ , $^{61}\text{Ni}(1.25\%)$ , $^{62}\text{Ni}(3.66\%)$ , $^{64}\text{Ni}(1.16\%)$
Chromium	$^{50}\text{Cr}(4.31\%)$ , $^{52}\text{Cr}(83.76\%)$ , $^{53}\text{Cr}(9.55\%)$ , $^{54}\text{Cr}(2.38\%)$
Molybdenum	$^{92}\text{Mo}(15.8\%)$ , $^{94}\text{Mo}(9.12\%)$ , $^{95}\text{Mo}(15.7\%)$ , $^{96}\text{Mo}(16.5\%)$ , $^{97}\text{Mo}(9.45\%)$ , $^{98}\text{Mo}(23.75\%)$ , $^{100}\text{Mo}(9.62\%)$
Manganese	$^{55}\text{Mn}(100\%)$

Table 2Reactions Leading to Major Long Term Radioactivitiesin Stainless Steels

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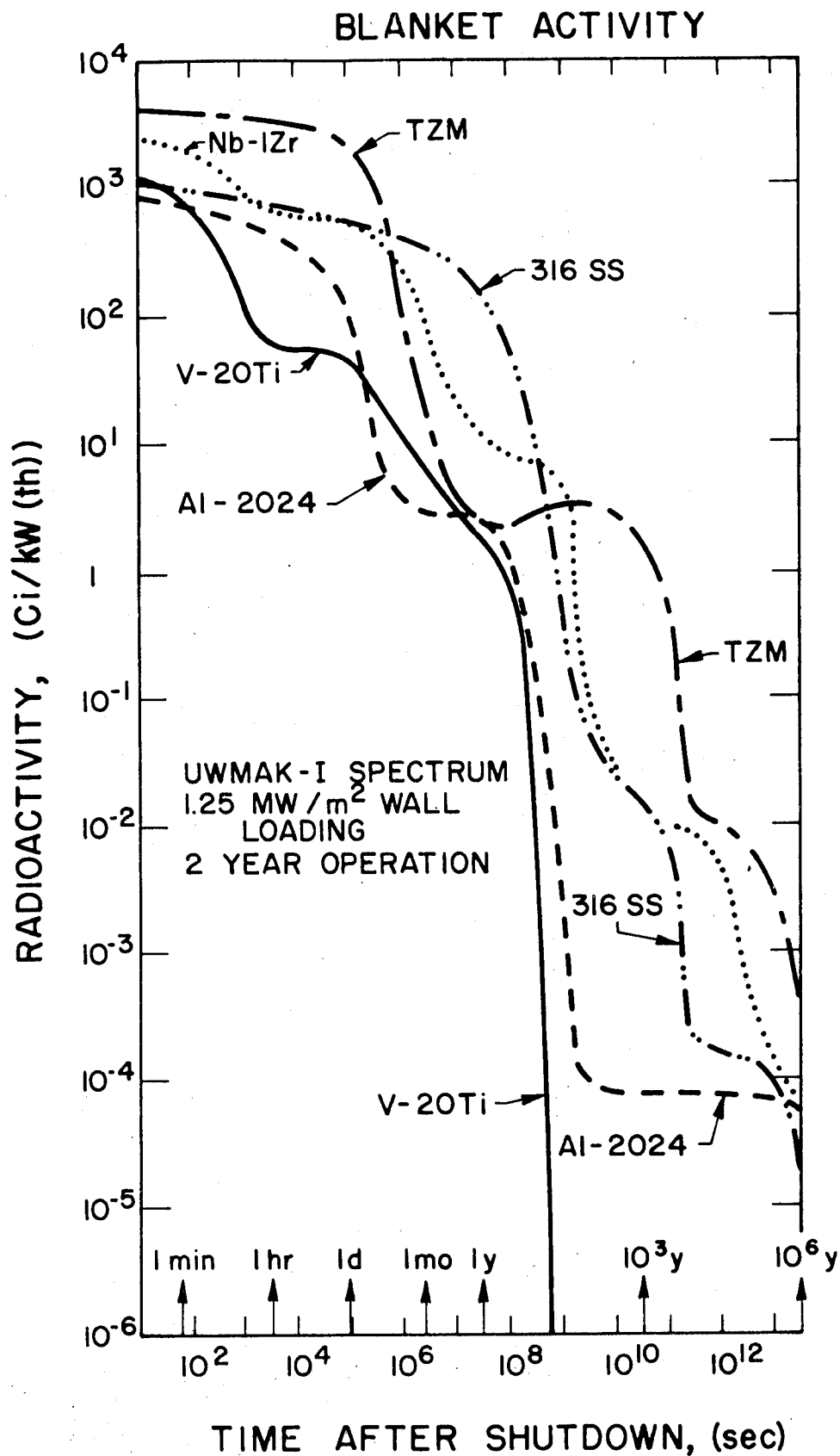


Figure 1 - Blanket Activity Levels After Shutdown for Five Different Structural Alloys Using the Neutron Spectrum from UWMAK-I.(2)



Figure 2 - Relative Contribution of Selected Isotopes to the Radioactivity of a 316 SS UWMAK-I First Wall Following 2 Years of Operation at a 1.25 MW/m<sup>2</sup> Wall Loading.

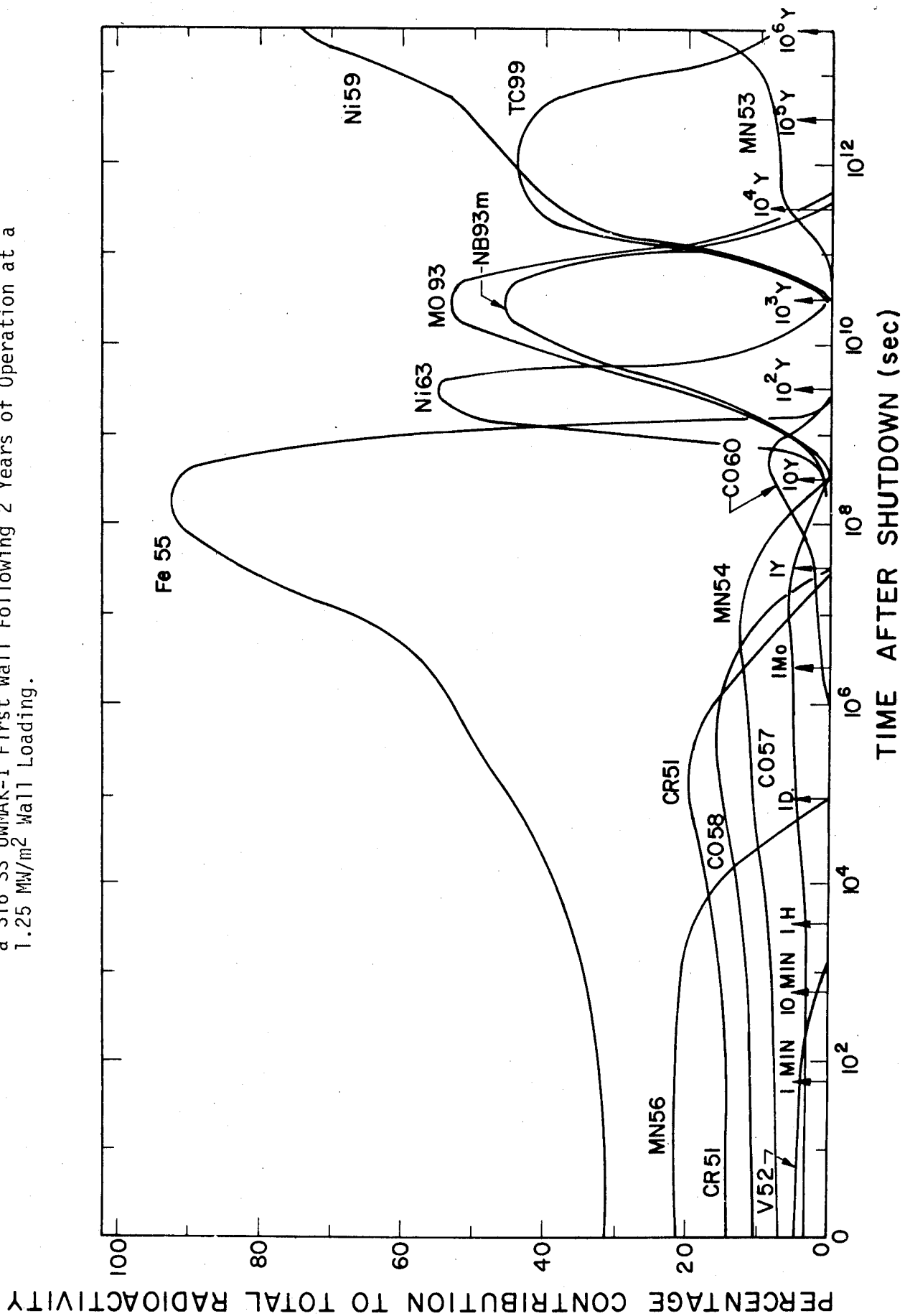


Figure 3 - Relative Contribution of Selected Isotopes to the Radioactivity of a 316 SS UWMAK-I First Wall Following 10 Years of Operation at a 5.0 MW/m<sup>2</sup> Wall Loading.

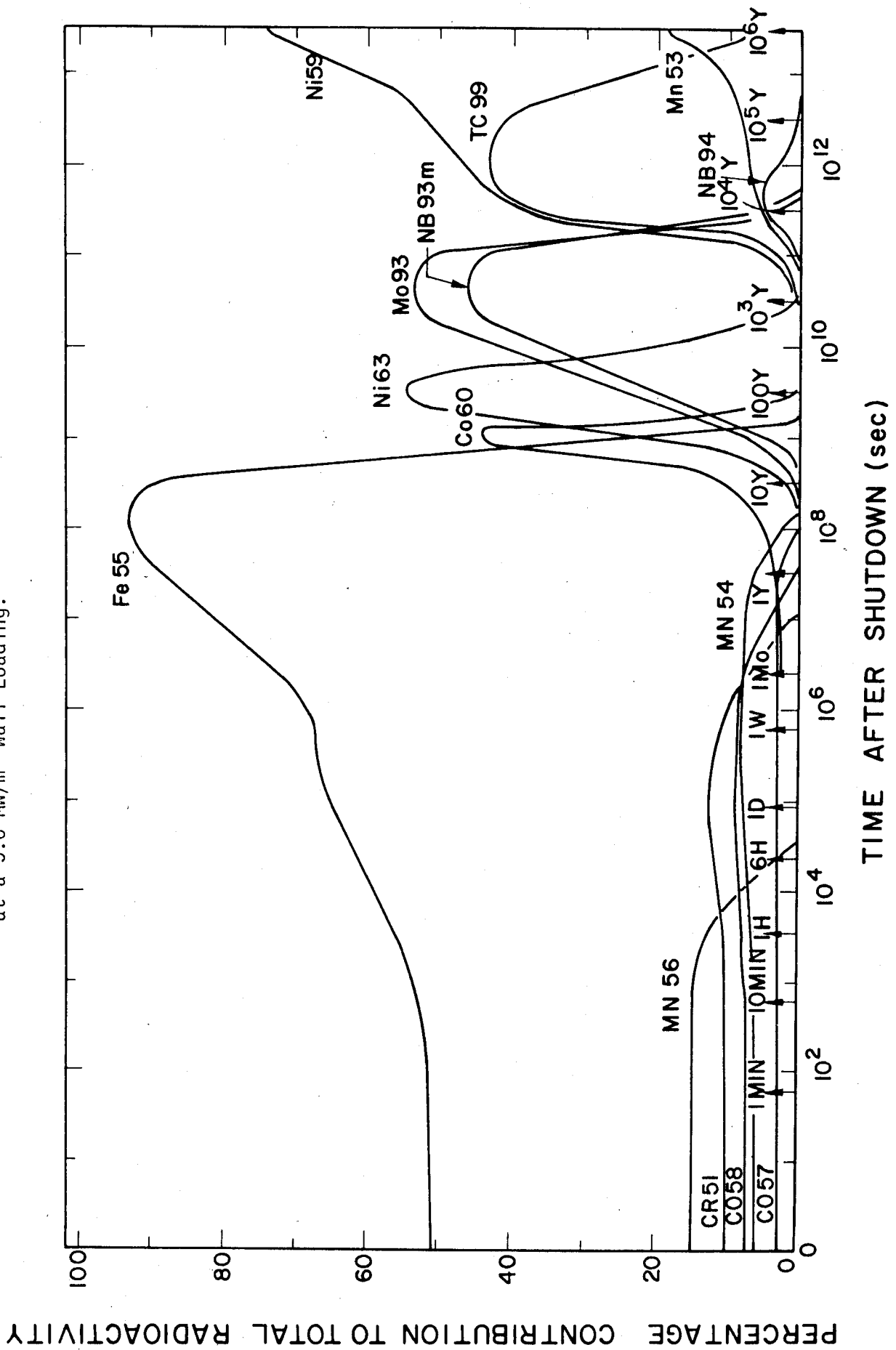
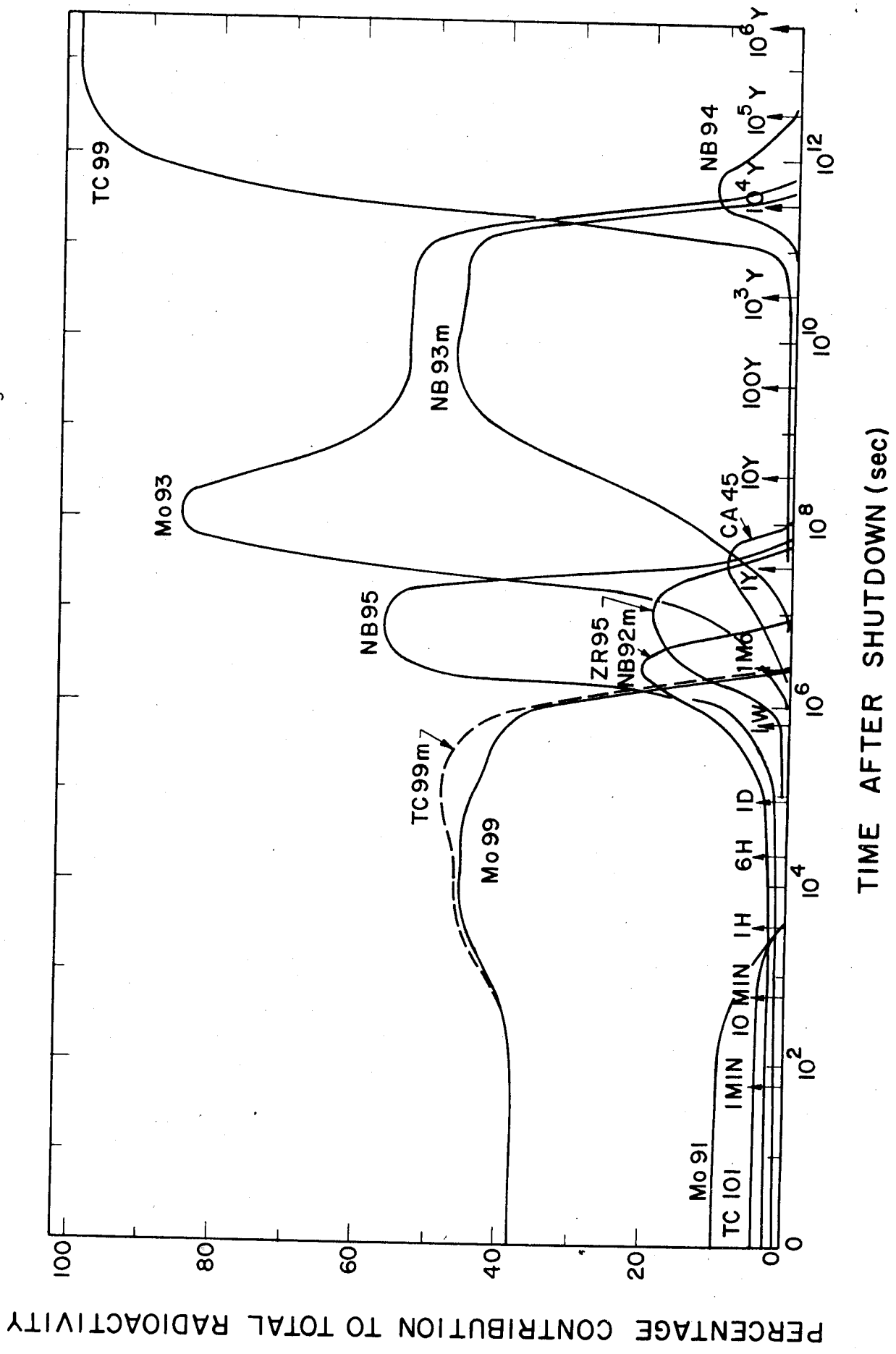


Figure 5 - Relative Contribution of Selected Isotopes to the Radioactivity of a T2M First Wall Following 2 Years of Operation at a 5.0 MW/m<sup>2</sup> Wall Loading.



# FIRST WALL RADIOACTIVITY IN SELECTED 316 SS ALLOYS

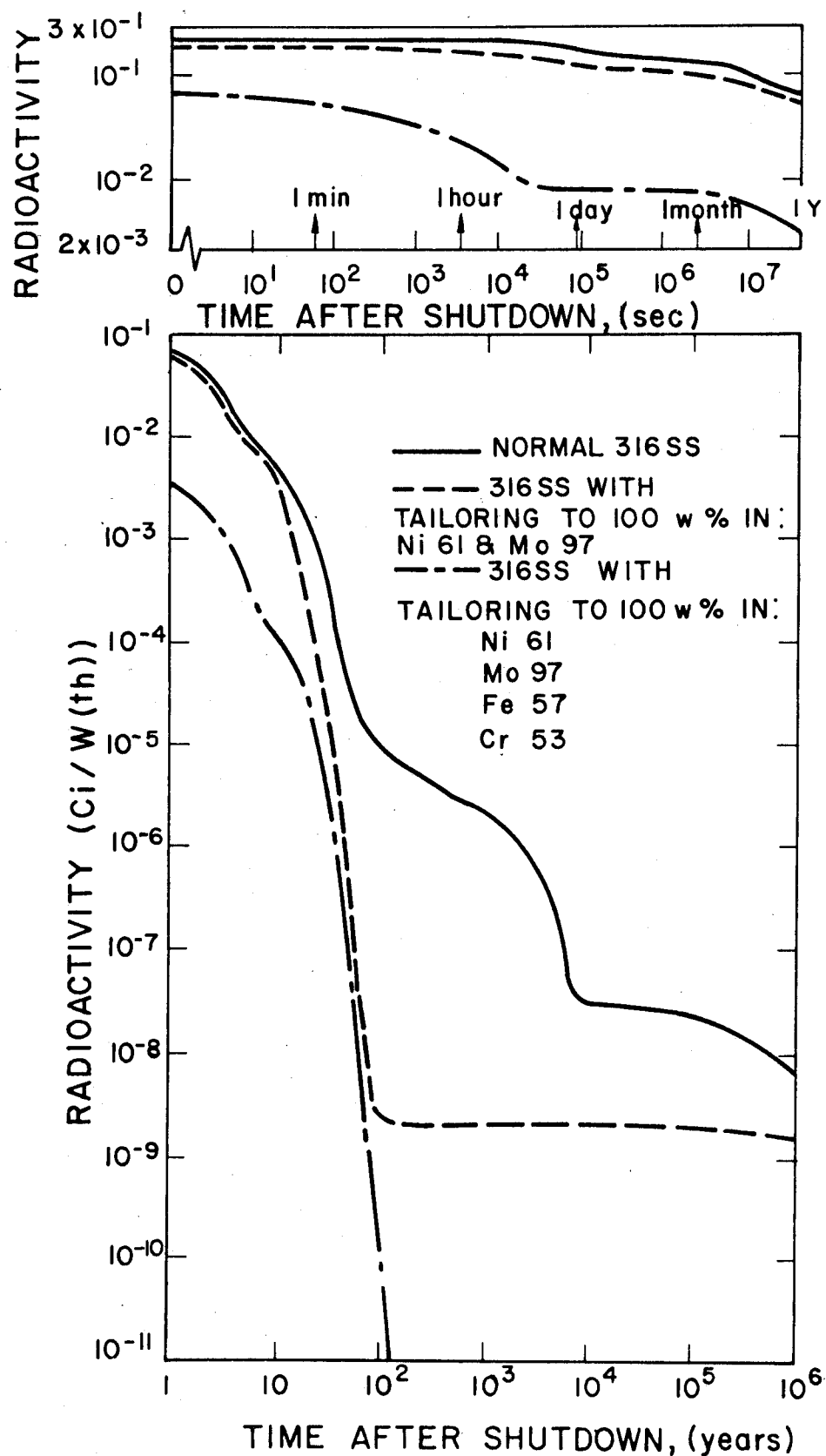


Figure 6 - Radioactivity After Shutdown in Normal and in 100% Isotopically Tailored 316 SS First Walls Following a 2 Year -  $1.25 \text{ MW/m}^2$  Operation.

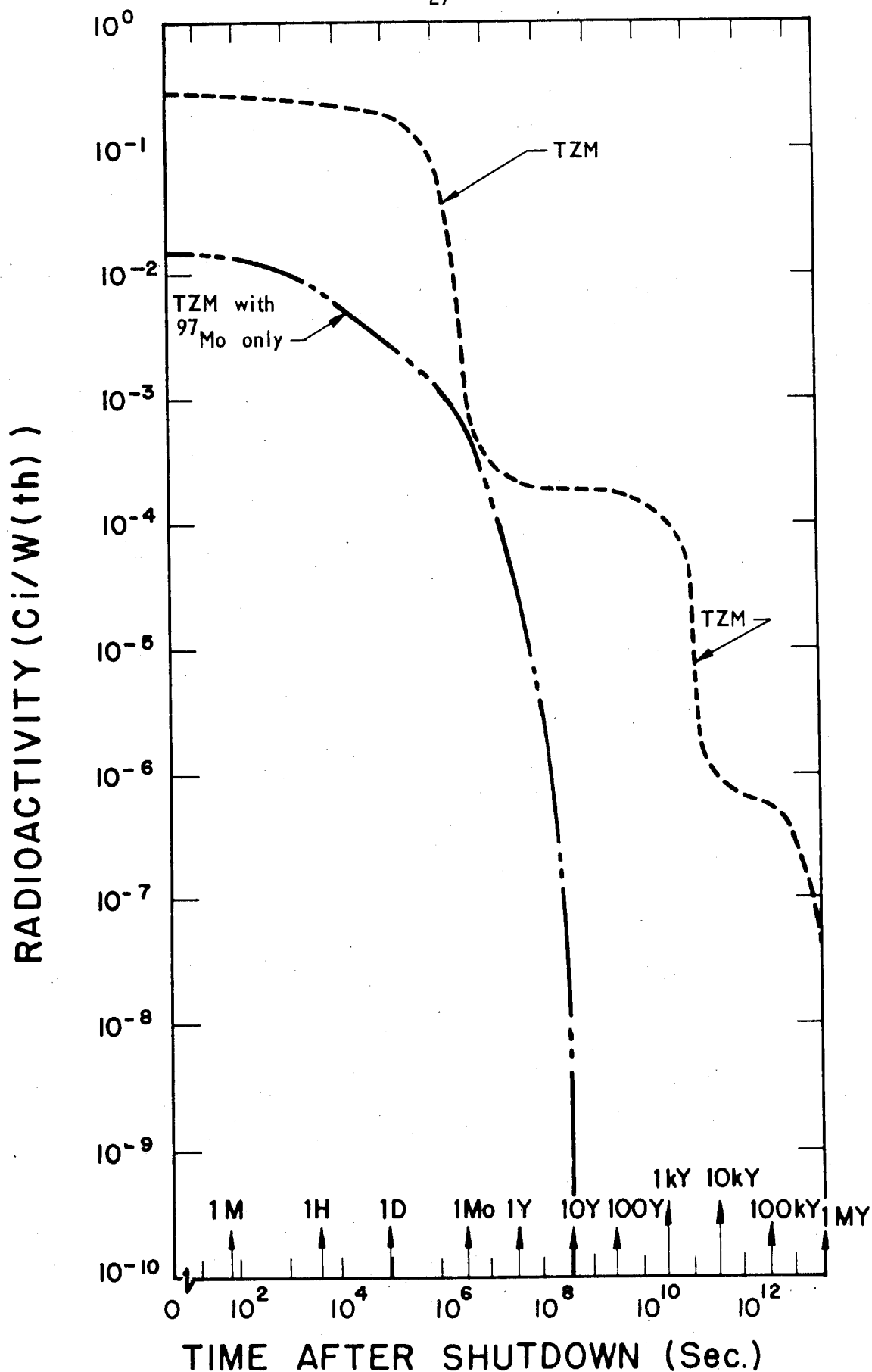


Figure 7 - Radioactivity Levels After Shutdown in Normal and in 100% Theoretically Tailored TZM First Walls Operated for 2 Years of a  $1.25 \text{ MW/m}^2$  Wall Loading. The Molybdenum constituent of TZM in the tailored case is 100%  $^{97}\text{Mo}$ .

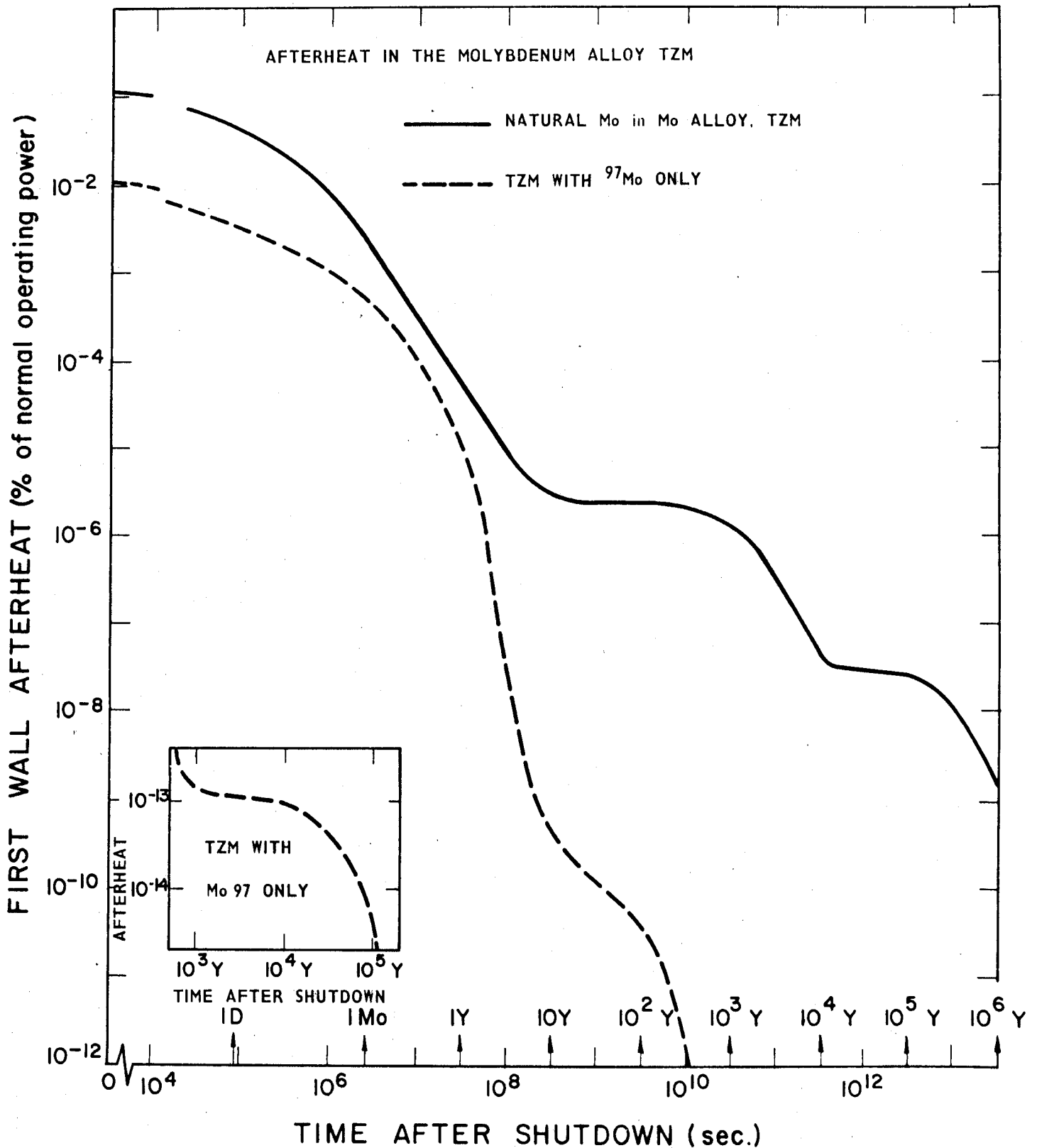


Figure 8 - UWMAK-I Afterheat for Normal TZM and for TZM Tailored in Mo to 100%  $^{97}\text{Mo}$  - 2 Year Operation,  $1.25 \text{ MW/m}^2$  Wall Loading.

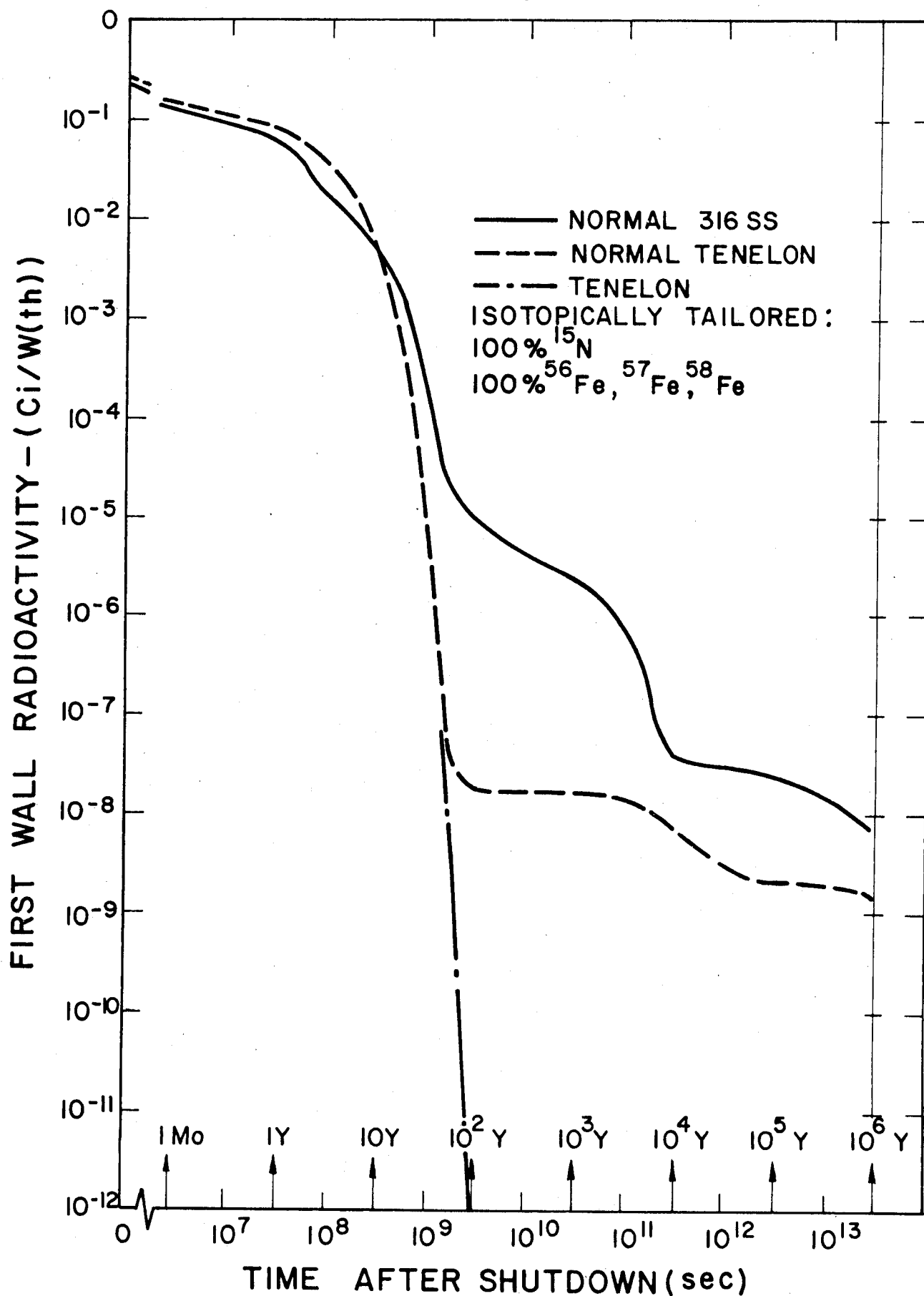


Figure 9 - Activity Levels After Shutdown in First Walls Composed of 316 SS, Normal Tenelon and Tenelon Tailored in N and Fe - 2 Year Operation - 1.25 MW/m<sup>2</sup> Wall Loading.

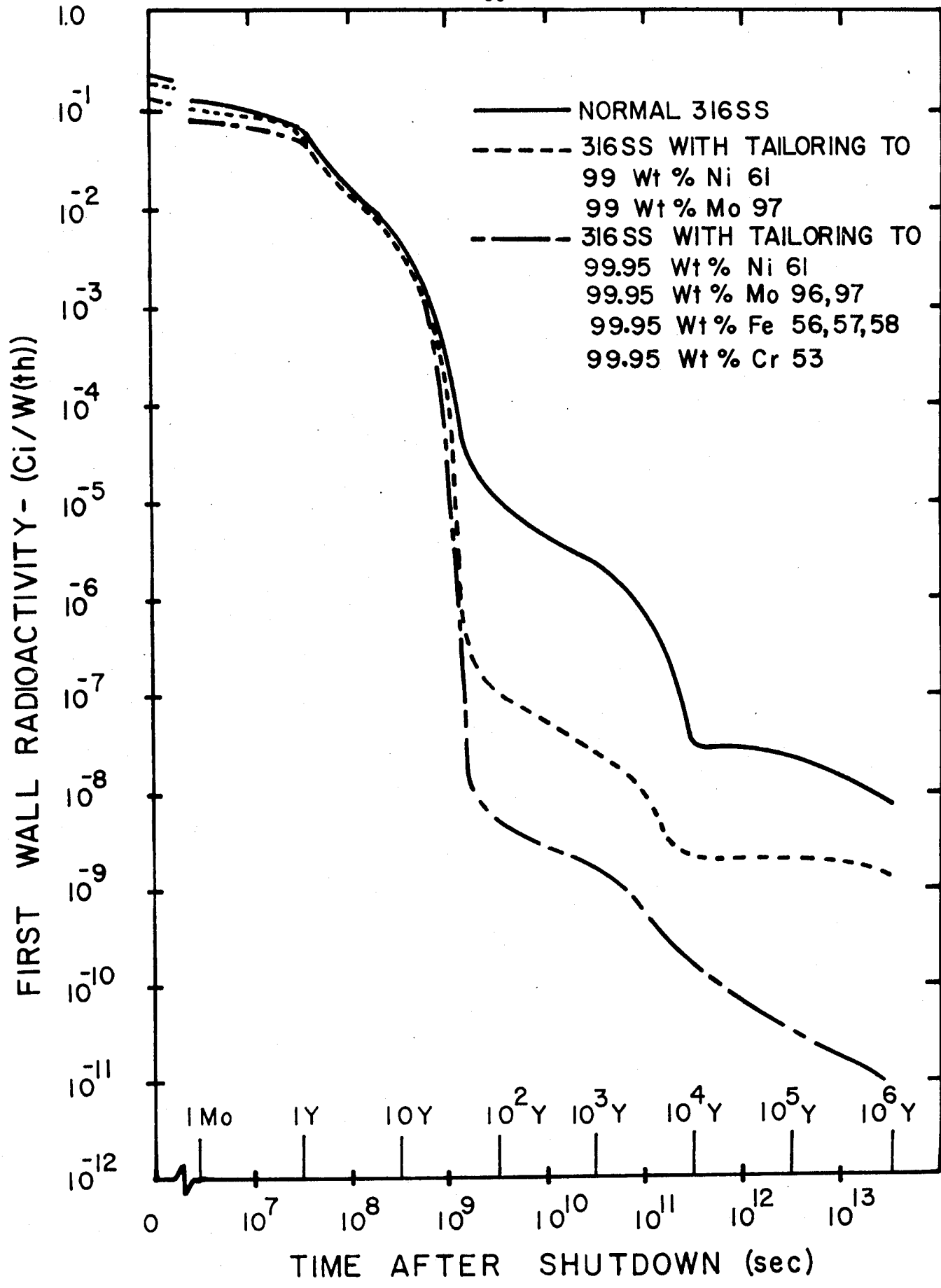


Figure 10 - Radioactivity After Shutdown for 316 SS First Walls Isotopically Tailored at Different Selectivity Levels - 1.25 MW/m<sup>2</sup> Wall Loading - 2 Year Operation.



FIRST WALL RADIOACTIVITY - (Ci/W(th))

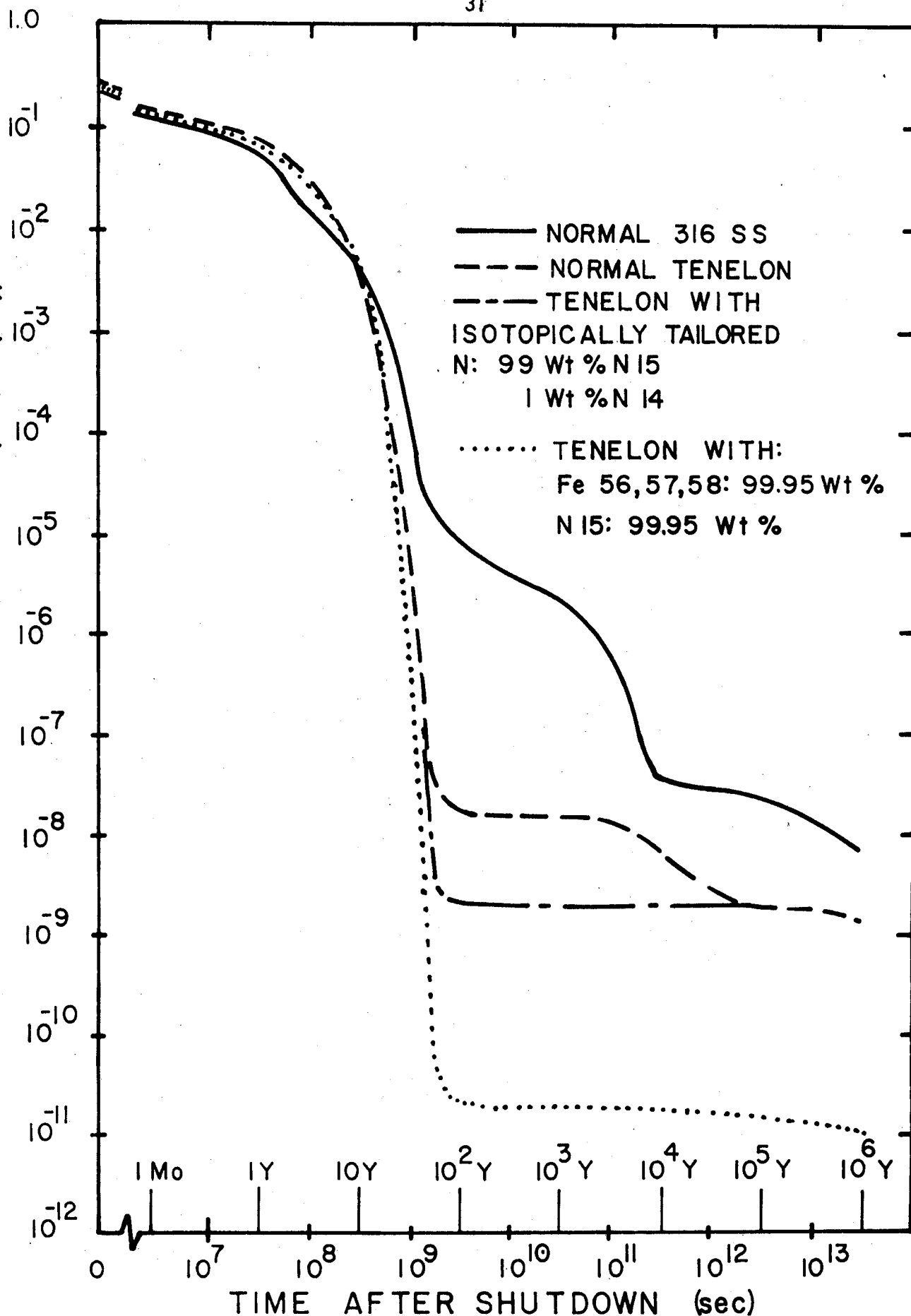


Figure 11 - Radioactivity After Shutdown for Tenelon First Walls Tailored at Different Selectivity Levels - 1.25 MW/m<sup>2</sup> Wall Loading & 2 Year Operation.

# COMPARISON OF RADIOACTIVE INVENTORY FOR FUSION & FISSION SYSTEMS

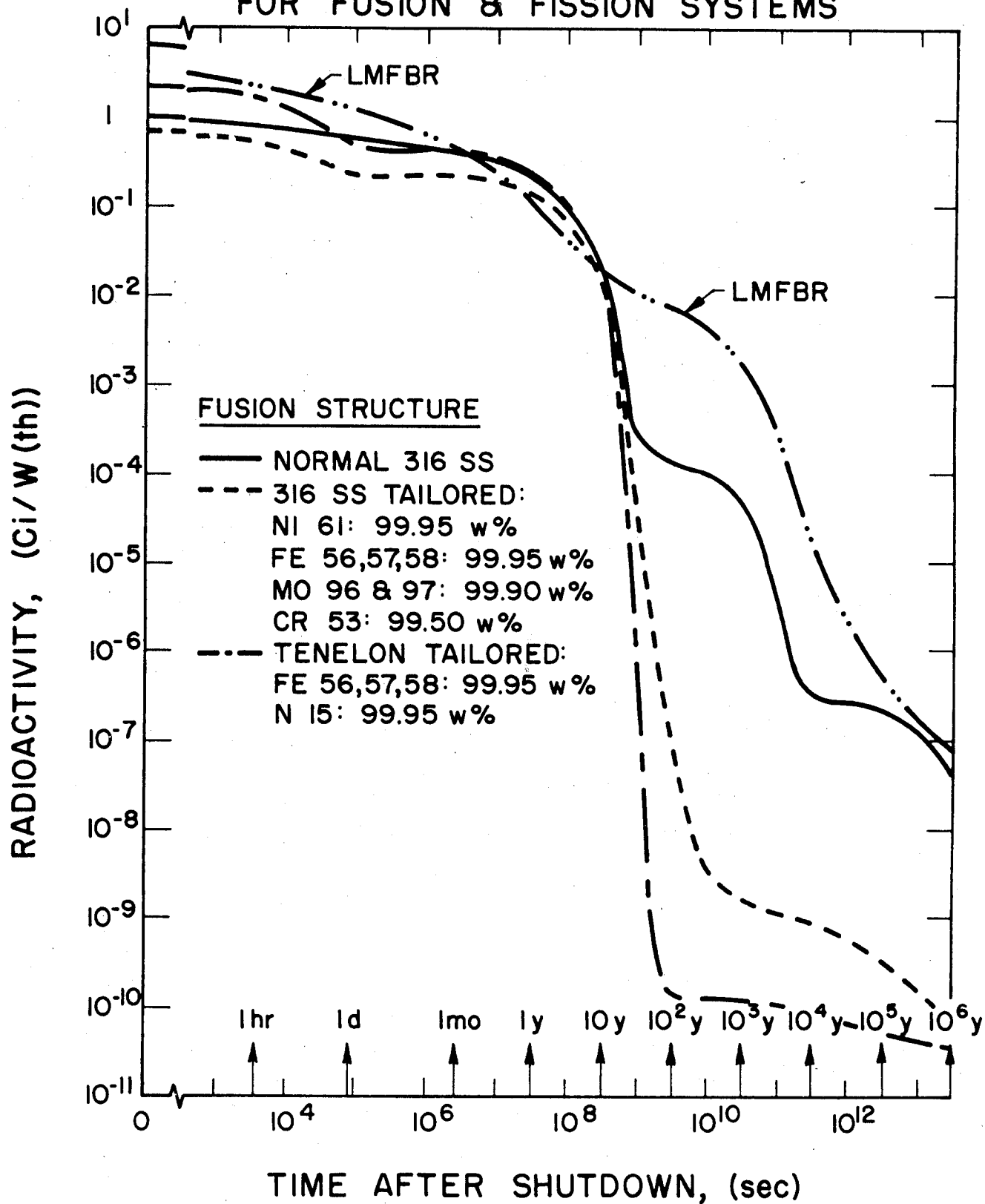


Figure 12 - Radioactivity Inventory Following Shutdown of a Fast Breeder Reactor System as Compared to that of Normal and Tailored UWMAK-I Stainless Steel Outer Blankets.

# COMPARISON OF BIOLOGICAL HAZARD POTENTIAL IN WATER (BHP<sub>WATER</sub>) FOR FISSION & FUSION SYSTEMS

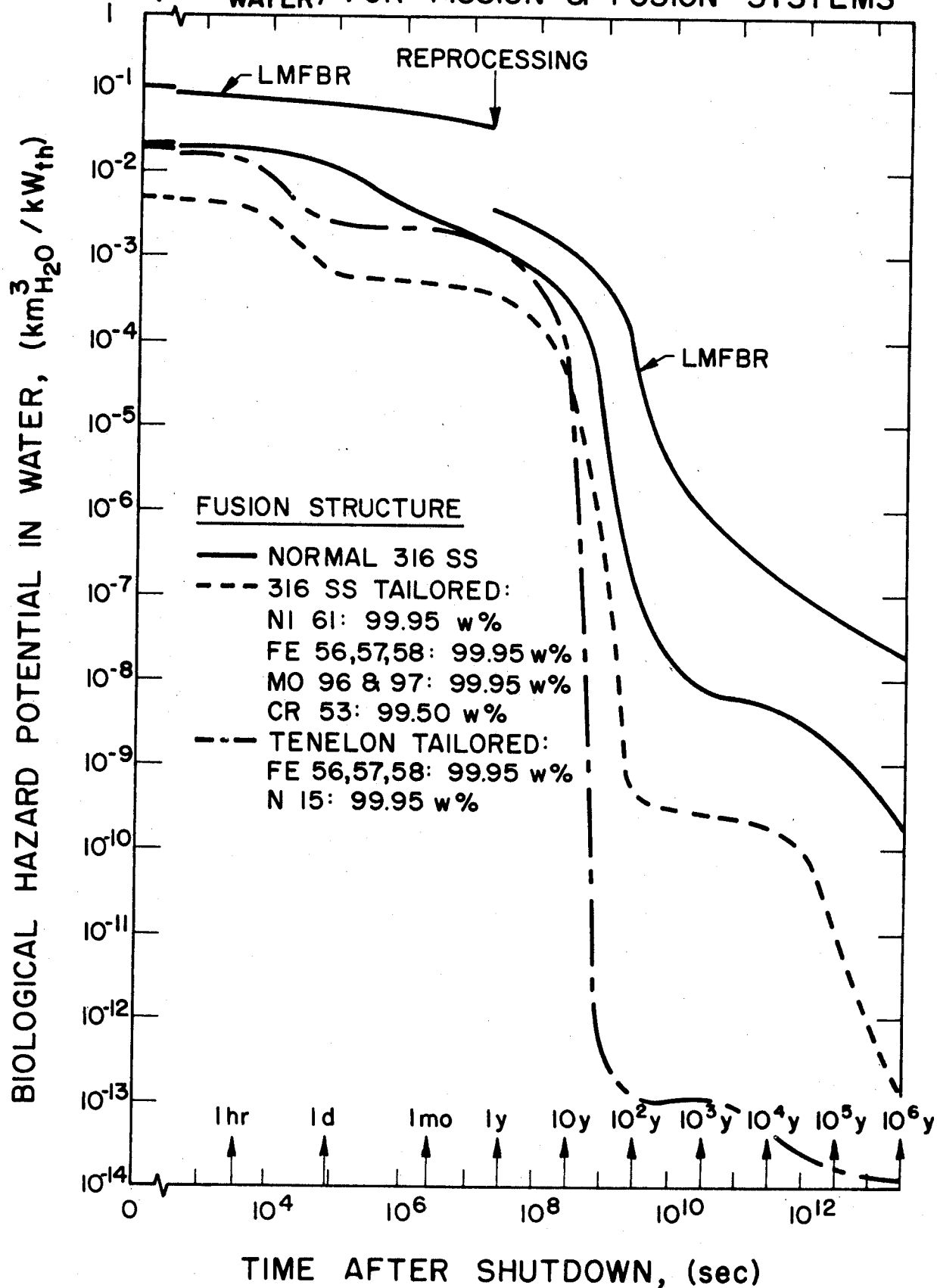


Figure 13 - Biological Hazard Potential in Water Following Shutdown of Fast Breeder Reactor and UWMAK-I Fusion Reactor (Normal and Tailored Stainless Steel Blankets) Systems.

# COMPARISON OF BIOLOGICAL HAZARD POTENTIAL IN AIR (BHP<sub>AIR</sub>) FOR FISSION & FUSION SYSTEMS

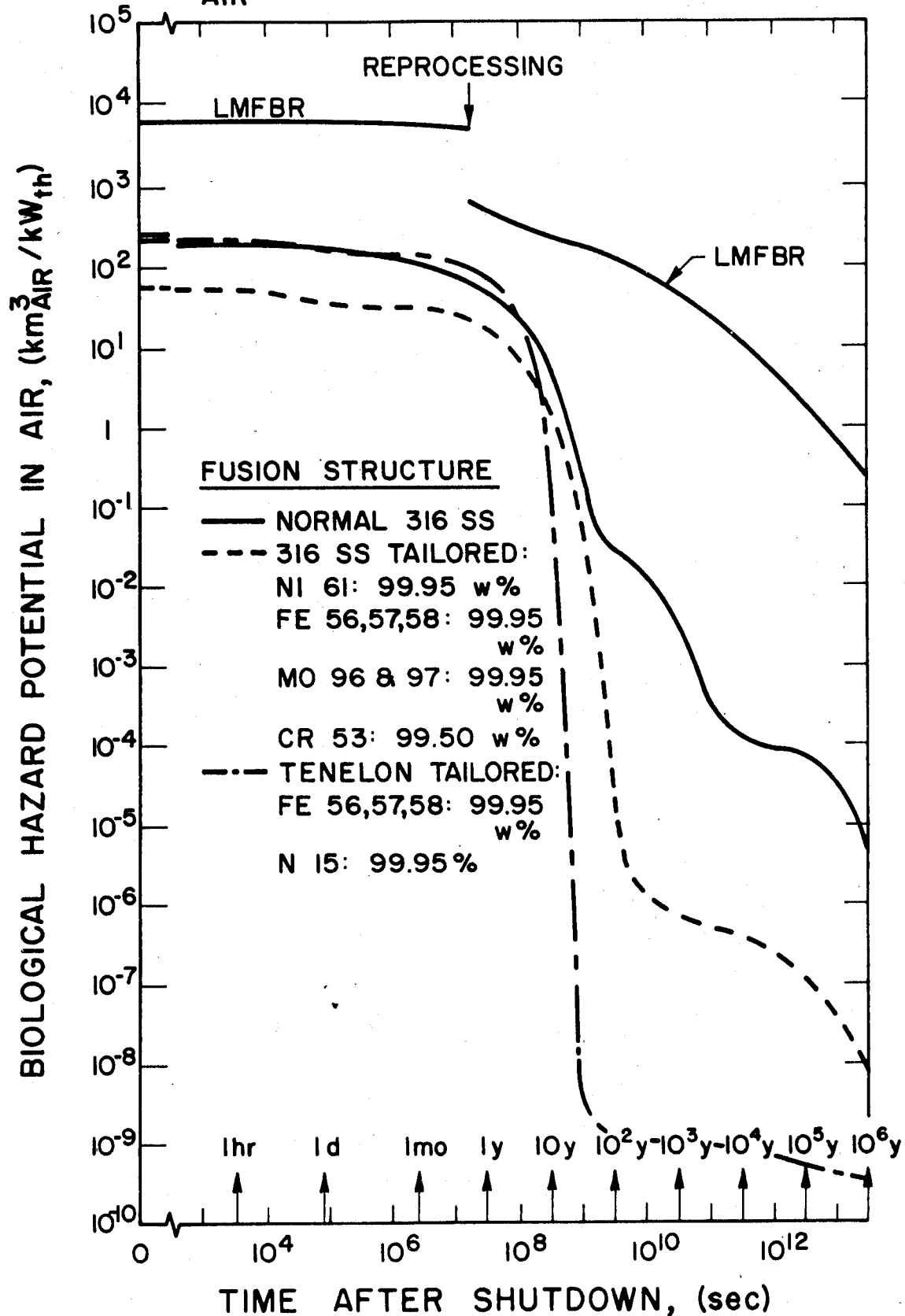


Figure 14 - Biological Hazard Potential in Air Following Shutdown of Fast Breeder Reactor and UWMAK-I Fusion Reactor (Normal and Tailored Stainless Steel Blankets) Systems.