Reduced Activation Stainless Steels for Fusion Reactors

G.L. Kulcinski

January 1992

UWFDM-895

Presented at the US-USSR Workshop on D-^{3}He Reactor Studies, 25 September – 2 October 1991, Moscow

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Reduced Activation Stainless Steels for Fusion Reactors

G.L. Kulcinski, M.E. Sawan and H.Y. Khater

Fusion Technology Institute
University of Wisconsin-Madison
1500 Johnson Drive
Madison, Wisconsin 53706

January 1992

UWFDM-895

Presented at the US-USSR Workshop on D-^{3}He Reactor Studies, 25 September - 2 October 1991, Moscow.

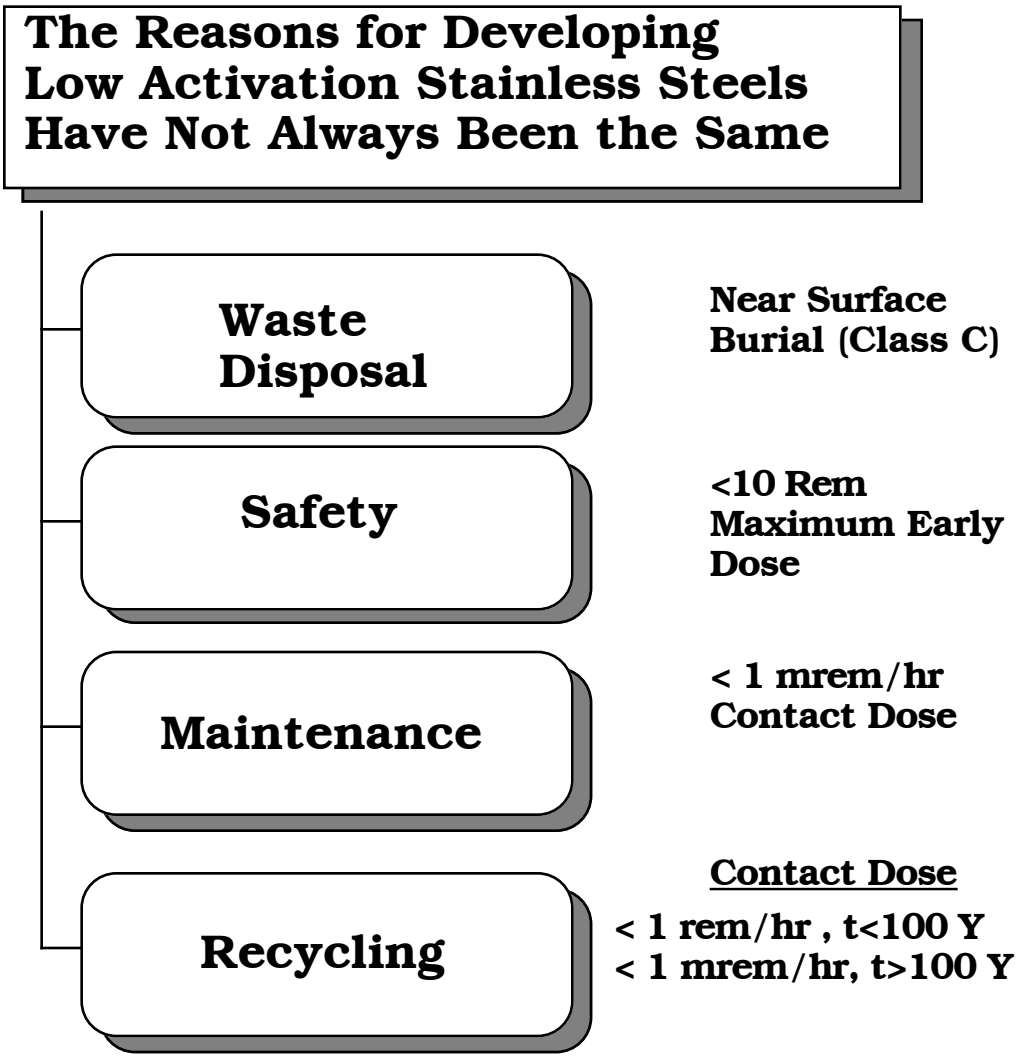
I. Introduction

One of the major reasons for developing the fusion option over that of fission is the widely held belief that the level and impact of radioactivity produced per kWh is considerably less than that in fusion. However, because there are 4 times as many neutrons released per kWh from a DT fusion plasma compared to a fission reactor, and because those 14 MeV neutrons can induce different, and sometimes longer lived, radioisotopes, the fact is that the levels of radioactivity in fusion plants are sometimes actually the same order of magnitude as in fission plants at shutdown![1,2] While the radioactivity level at shutdown is at least as important for afterheat and safety, most of the attention in the literature has been focused on the long lived radioactivity and waste disposal problems. It has been shown that fusion reactor structural materials, such as stainless steels, can have long lived radioactivity levels of 10 to 100 times less than those generated in fission reactors on an equivalent energy output basis.[1-3] There have been recent attempts to increase that margin by substituting alloying elements that produce less long lived radioactivity[4-6] and this paper summarizes some of the benefits and problems which result from that activity.

II. Reasons For Developing Low Activation Stainless Steels

There have been at least 4 motivations for the research in this area and they have not always been consistent (see Figure 1). The most prominent has been the desire to allow near surface burial, followed by the improvement in safety of the reactor, increased maintainability, and most recently, to allow recycling of irradiated components. A detailed discussion of each one of these reasons is beyond the scope of this short review but the main arguments for each will emerge in the following sections.

Figure 1



The arguments for and against developing low activation steels still need to be debated and a list of pros and cons is given in Table 1. For example, while it would certainly be beneficial, from both a cost as well as a public relations standpoint, to dispose of spent reactor components in a near surface waste burial facility, the replacement of the alloying elements which generate the long lived isotopes usually aggravates the short term radioactivity. If the short term activity increases, then the afterheat increases as does the activity that could be released in the event of an accident.

Table 1

Why Develop Low Activation Stainless Steels?

For	Against
Reduce long term radiation level to allow near surface burial	Usually aggravates the short term afterheat problem
Reduce long term waste disposal costs	Cost of developing and qualifying new low activation alloy can be substantial
Reduce exposure to workers if alloy is recycled	May increase short term radiation levels and increase radiation levels during maintenance
Makes fusion more attractive to environmentalists and politicians	Time involved in developing and qualifying low activation materials may delay the implementation of fusion

Similarly, the reduction of long lived isotopes may result in lower waste disposal costs, but the cost of developing, testing and qualifying a new alloy system in a nuclear environment will be substantial. Such a materials development program may take 10 to 20 years, extending the duration and cost of the R & D phase.

The reduction of exposure to workers in recycling plants by reducing long lived isotopes is desirable but is the corresponding increase in short term activity worth the increased risk to both workers and the public in the event of an accident? The higher short term activity also will increase the radiation levels in the maintenance areas and one could be trading lower exposure to one segment of the working population for increased exposure to workers of another segment.

The question of public relations is hard to quantify but it is clear that the benefits of lower long lived radioactivity (as perceived by the public) are presently being enjoyed by the fusion community. However, if the need to develop entirely new alloys, including all the testing and quality assurance that is necessary for nuclear grade systems, requires too much time (and money), then the public might just opt for a quicker solution to our future problems.

In any case, further debate on these topics, and others, will certainly be necessary before we commit to multi-billion dollar materials development programs.

III. How Are the Waste Limits Presently Defined?

Table 2 shows how the U.S. waste burial classes are defined. The key parameters include: the time period to decay to acceptable level, whether or not the radioactive material meets the minimum waste form and stability requirements, whether an "intruder barrier" has to be provided, and the burial depth of the waste material. Class A waste is the most benign in the U.S. system and is clearly the most most desirable from cost and the time of surveillance required. Class C is also a big improvement over the deep geological systems that we now are trying (without much success) to build for fission wastes. Unmodified stainless steels in use today would probably have to be treated as deep geologic waste if they were used in DT systems (the use of the D^3He fuel cycle would change that conclusion). The cost of deep burial for fission materials is now estimated at ≈ $440/kg, roughly 10 times the initial fabricated cost of the component itself.

Table 2

Current Definitions of U.S. Waste Burial Classes

Radwaste Class	Period From Decay to Acceptable Level	Meets Minimum Waste Form Requirement	Meets Stability Requirement	Provides an Intruder Barrier	Depth of Burial
A	<<100 y	Yes	No	No	<<5 m
B	<100 y	Yes	Yes	No	<5 m
C	<500 y	Yes	Yes	Yes	>5 m
Deep Burial	>500 y	Yes	Yes	Yes	Deep Geologic Burial Site

IV. Representative Reduced Activation Steels

Table 3 lists the major alloying and important impurities in 4 steels considered for fusion applications. Included are 2 austenitic steels (PCA, a slightly modified form of 316 SS and Tenelon, a high manganese steel) and 2 ferritic steels (HT-9 and modified HT-9). The main difference in the austenitic steels is the increase in the Mn content and a reduction in the Ni, Mo and Nb. The ferritic steels were modified by reducing the Ni, Nb and Mo and adding W.

Table 3.

Elemental Composition of Normal and Reduced Activation Steels

	Concentration in Wt. %			
Element	PCA	Tenelon	HT-9	MHT-9
B	0.005	0.001	0.01	0.001
C	0.005	0.15	0.2	0.15
N	0.01	0.005	0.05	0.001
O		0.007	0.01	0.007
Al	0.03	0.008	0.01	0.008
Si	0.5	0.2	0.35	0.2
P	0.01	0.13	0.02	0.013
S	0.005	0.004	0.02	0.004
Ti	0.3	0.003	0.09	0.1
V	0.1	0.002	0.3	0.3
Cr	14.0	15.0	12.0	11.0
Mn	2.0	15.0	0.55	0.53
Fe	64.88	69.4	85.0	85.2
Co	0.03	0.005	0.02	0.005
Ni	16.0	0.006	0.5	0.006
Cu	0.02	0.003	0.09	0.003
Zr	0.005	0.001	0.001	0.001
Nb	0.03	0.00011	0.0011	0.00011
Mo	2.0	0.00027	1.0	0.00027
Ag	0.0001	0.00009	0.0001	0.00009
Sn	0.005	0.003	0.003	0.003
Ta	0.01	0.0004	0.001	0.0004
W	0.05	0.01	0.5	2.50
Pb	0.001	0.0005	0.001	0.0005
Bi	0.001	0.0002	0.001	0.0002

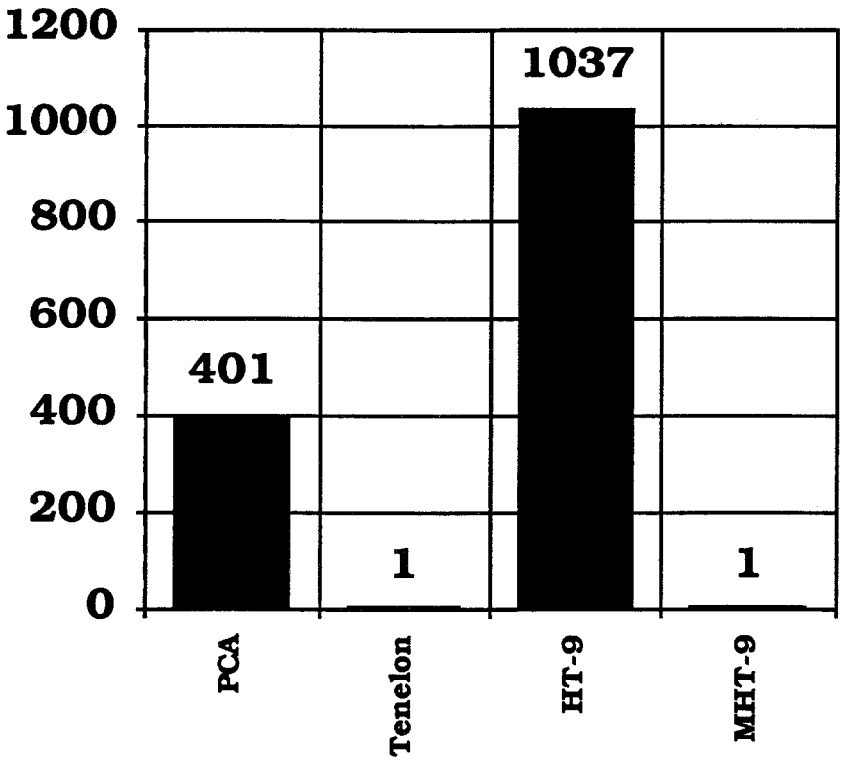


Figure 2. The relative waste disposal rating can be greatly reduced in stainless steels by elemental substitution.

V. Effect of Alloying Modifications on Long Lived Radioactivity

The effect of alloying elements on the relative Waste Disposal Ratings (WDR) of steels is given in Figure 2. The first thing one notices is that the reduction in Ni, Mo, and Nb (shown in Table 3) drops the relative WDR by a factor of 400 in austenitic steels and by over 1000 in ferritic steels.

The specific effect of each major element in PCA is shown in Figure 3. For example, even though Mo is only 2% of the composition of PCA, it contributes over 55% of the long lived activity for Class C burial. An even more dramatic effect can be seen with respect to Nb. The Nb impurity amounts to only 100 ppm by weight and yet this small amount of Nb contributes over 40% to the Class C waste limit in PCA. When the alloying changes are made, the Nb then becomes the dominating element even though it would be present at ≈1 ppm by weight. A similar effect in HT-9 is shown in Figure 4 where reducing the Mo content to 0.00027% drops its contribution to a few percent and even at ≈1 ppm by weight, Nb contributes over 95% to the Class C rating.

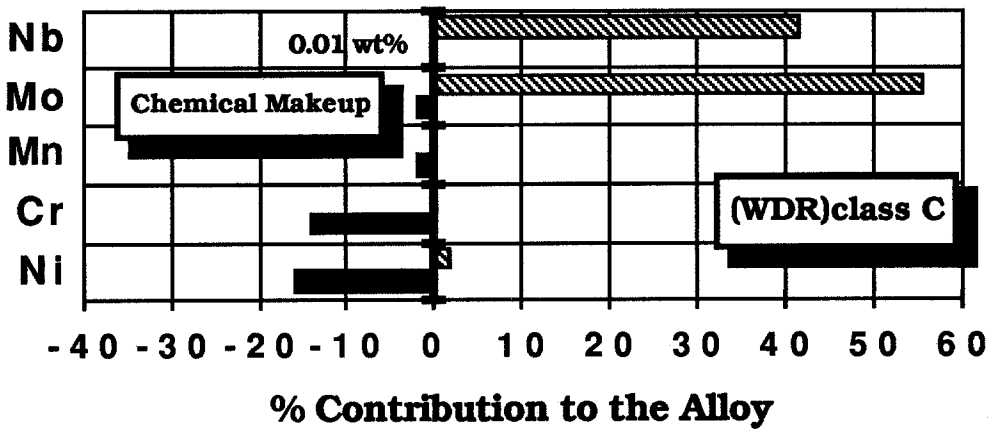


Figure 3. The Mo alloying element and the Nb impurity produce essentially all the long lived radioactivity in PCA austenitic steel.

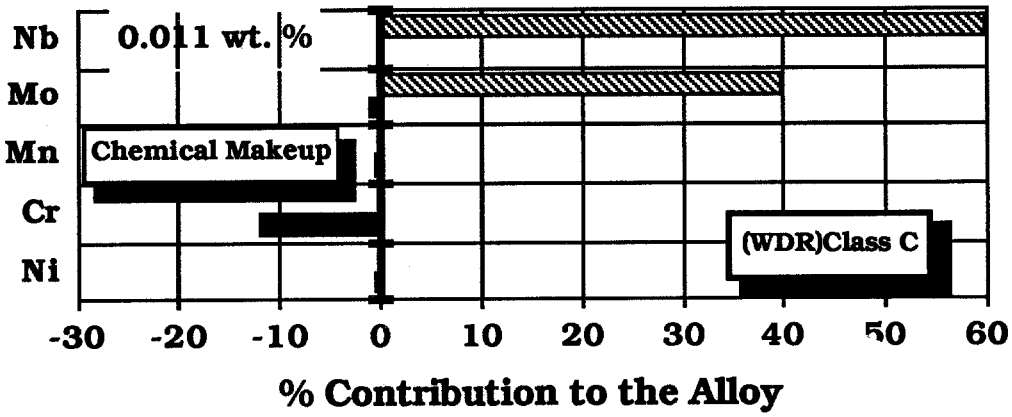


Figure 4. Mo and Nb produce essentially all the long lived radioactivity in HT-9 ferritic steel.

VI. Effect of Alloying Modifications on Afterheat

Another important feature of the alloy modifications is the increased short term radioactivity in high Mn austenitic steels. The relative levels of afterheat are compared in Figure 5 normalized to the afterheat in HT-9. It is obvious that the alloying changes in the ferritic systems have essentially no effect but that the addition of Mn in austenitic alloys more than doubles the afterheat level in a system which was already higher than ferritic alloys.

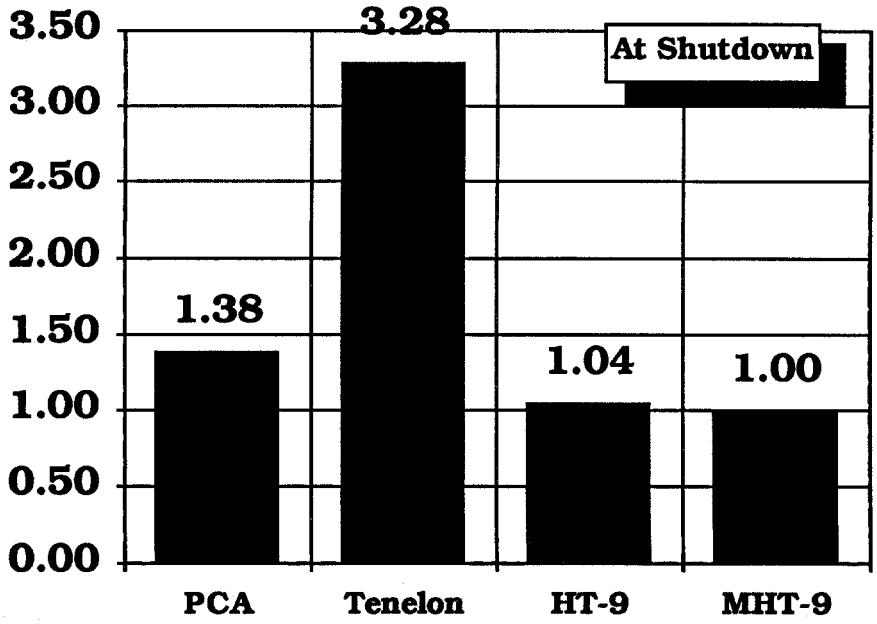


Figure 5. The relative afterheat in low activation alloys is increased in austenitic but unchanged in ferritic steels.

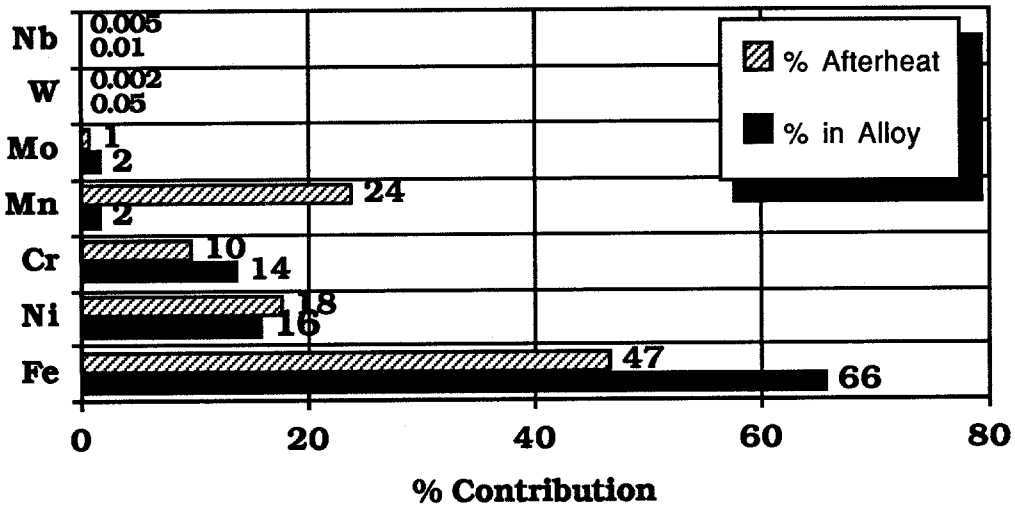


Figure 6. The manganese in PCA contributes more than 10 times to the afterheat than it does to the overall composition.

The specific reason for the change in afterheat in Tenelon is given in Figure 6. Here the percent contribution to the afterheat is compared to the percent contribution to the chemical composition for the 4 alloys. It is clear that even with only 2% Mn in PCA, that element contributes ≈ 10 times more to the afterheat than its composition level would indicate. In the reduced activation alloy, Tenelon, the Mn contributes 75% to the afterheat even though it is present in only 15% (Figure 7).

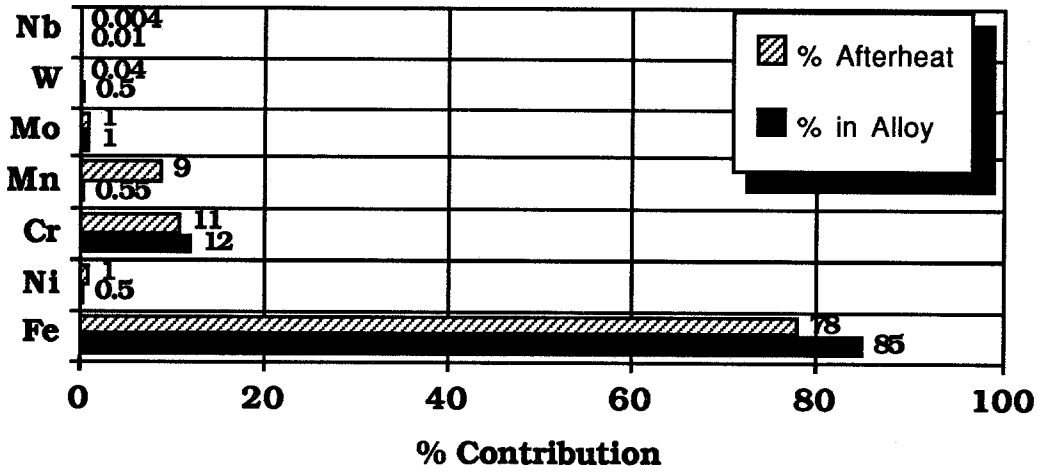


Figure 7. The manganese in HT-9 contributes more than 16 times to the afterheat than it does to the overall composition.

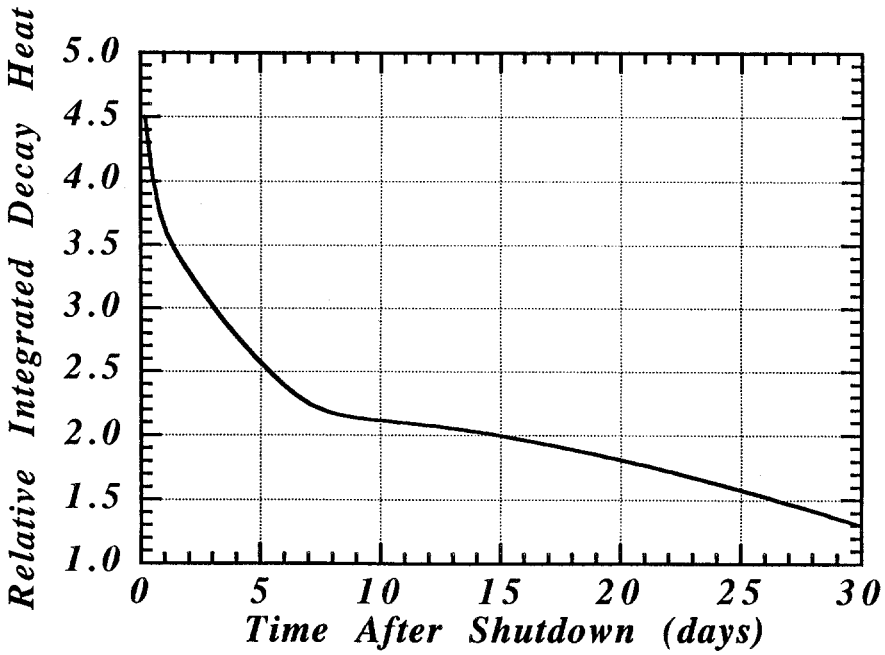


Figure 8. In spite of the short term afterheat released from high Mn steels, the total integrated energy released from Tenelon (high Mn) and 'normal' 316 stainless steels is about the same.

Even though the integrated afterheat from Tenelon is more than twice that of PCA, the actual afterheat within a few days of an accident might be as high as 4.5 times that of PCA (Figure 8).

Disposing of such afterheat in this short period is a problem as well as the fact that the radioactive elements responsible for this afterheat, Mn, have a particularly high vapor pressure

compared to the rest of the steel components (Figure 9). Such a high vapor pressure could be a safety hazard for the public in the event that primary containment were to fail. Obviously, the specific effect on the safety and general operation of a DT power plant must be examined in more detail before one could determine the degree of benefit obtained by using a high Mn, reduced activation alloy.

VII. The "Everything Goes Deep" Philosophy

At the recent IEA Workshop on Low Activation Material held in Culham, England[2], the following philosophy was proposed:

> "Shallow land burial is impractical and politically unsound. This is true in many European countries at present and will probably be true in the U.S. soon. It should be dropped from consideration in the definition of criteria for low activation materials."

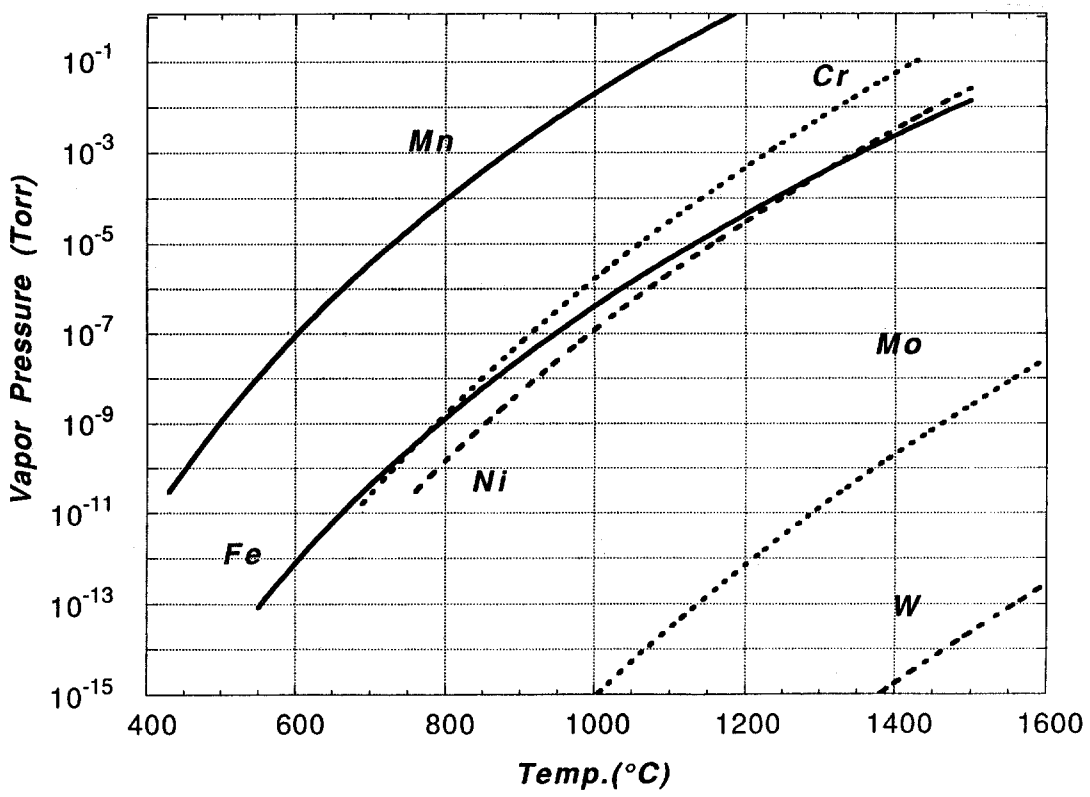


Figure 9. Manganese is the most volatile radioactive alloying element in stainless steel.

The implication of this philosophy is that if deep geological disposal replaces shallow land burial, then there is a greatly reduced benefit of low activation materials over conventional materials. If this philosophy were to be adopted, that is, even if the alloys are slightly radioactive, they must be buried in deep geological waste burial facilities, then one must ask why develop reduced (in the long term sense) activation alloys at all?

VIII. Effect of Advanced Fusion Fuels

One way to alleviate the waste disposal problems while at the same time reduce the radiation damage to the structural alloys is to use an advanced fuel cycle like D^3He. Only the side DD reactions contribute to the neutron flux and that can be kept to as low as 1-5% depending on the $^3He/D$ ratio and the magnetic configuration. The reduction in WDR possible with this fuel is shown in Figure 10. For the same net electrical power output, we can see that the relative WDR in HT-9 is reduced by a factor of over 10. Very often this level of reduction can make the difference between deep geologic or Class C burial, or even Class A vs. Class C.

IX. Conclusions

It is clear that all else being equal, one should strive to use materials in fusion power plants that have the least amount of long lived radioactivity. However, when the solution to long lived radioactivity requires elements that aggravate the short term afterheat problem, then the advantages of low activation steels become less clear. Furthermore, the use of elements with short half lives may increase the short and medium term risk to maintenance workers, or those involved in recycling. One solution to this problem is to use a fuel cycle that greatly reduces the total number of neutrons released per kWh_e of net electricity produced. Such a fuel cycle exists in the D^3He system and this may allow the materials community to use "off the shelf" alloys while still retaining low afterheat and low levels of long lived radiation.

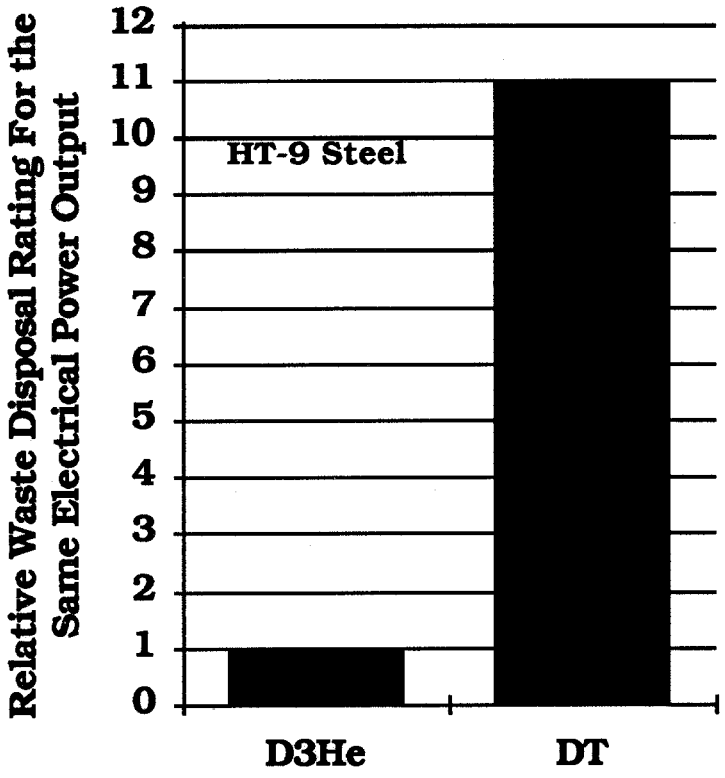


Figure 10. The use of the D^3He fuel cycle can reduce the WDR of HT-9 by more than an order of magnitude for the same electrical energy output.

Acknowledgements

The author wishes to acknowledge helpful discussions with Dr. Frank Garner, Dr. Everette Bloom, and Dr. F. W. Wiffen. Several members of the Wisconsin Fusion Technology Institute provided helpful data in the area of radioactive inventories and safety implications. Financial support for this work was provided by the Grainger Foundation.

References

1. W. Haefele, J.P. Holdren, G. Kessler, and G.L. Kulcinski, "Fusion and Fast Breeder Reactors," Intern. Inst. Appl. Syst. Analysis, A-2361 Laxenberg, Austria (1977).
2. Proceedings of the IEA Workshop on Low Activation Materials, Culham, England, April 8-12, 1991.
3. R.W. Conn et al., "Lower Activation Materials and Magnetic Fusion Reactors," Nucl. Technol./Fusion, 5, 291 (1984).
4. J.P. Holdren and Steve Fetter, "Contribution of Activation Products to Fusion Accident Risk: Part II. Effects of Alternate Materials and Designs," Fusion Technology, 4, 599 (1983).
5. R.C. Maninger and D.W. Doren, "Issues in Radioactive Waste Management,"IEEE Trans., Nucl. Sci., NS-30, 571 (1983).
6. N.M. Ghoniem, et al., p. 201 in "Development of a Low Activation V Steel for Fusion Applications," Proc. Conf. on Ferritic Alloys for Use in Nuclear Energy Technologies," Published by AIME, Warrendale, PA (1983).