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DISPOSAL OF ACTIVATED FUSION WALL MATERIALS*

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We have used NRC's low level waste disposal regulation (10CFR61) to classify activated fusion reactor structural materials. The limits set by the NRC in 10CFR61 will require extremely expensive steels with degraded properties, even when the limits are adjusted to give credit for use of an expensive hot waste disposal facility. Both the expense and the poorer properties could have a negative impact on reactor safety, thus subverting the overall goals of the NRC family of regulations. Following this initial study, we have examined the methodology used by the NRC to set waste concentration limits. For a long-lived gamma emitter like ^{94}Nb , direct gamma dose to an intruding home builder dominates the limit setting process. Of all the tests applied to the waste, the controlling test which sets the lowest limit ignores all the engineered intrusion barriers which are themselves required by the same regulation. If even a small fraction of the barriers remain intact (an extremely likely event), the ^{94}Nb limit could be increased from the 0.2 Ci/m^3 in 10CFR61 to 1100 Ci/m^3 without exceeding the limits set for personnel exposure. Similarly, cautious application of the 10CFR61 methodology to other radioisotopes of interest to fusion designers will result in limits which are more in line with the unique nature of fusion energy.

1. INTRODUCTION

Magnetic (MCF) and inertial (ICF) fusion reactors will produce radioactive structural and other materials through neutron activation. A major goal of current design efforts is to assure occupational and public health and safety for fusion wastes at low cost. Thus, material selection is based on both technical performance and waste management considerations. It is likely that fusion wastes will be regulated under the same institutional conditions as for fission wastes. Thus, the NRC Regulation 10CFR Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste,"¹ is a logical starting point for examining the effects of materials selection on fusion waste management.

We believe that the fundamental bases for 10CFR61 are excellent and pertinent to fusion as well as fission wastes. However, some of the more detailed requirements, such as the

limits for concentrations of certain specific isotopes, seem to be unrealistic and inconsistent with the fundamental bases for 10CFR61, at least for fusion. Designers have much more freedom in controlling the character of wastes from fusion than for fission. Fusion waste contains few if any transuranics or actinides, and it has fewer high activity elements in the fission product region. Thus, fusion waste will be more completely characterized, and surrogate nuclides need not be used to set limits for a variety of other nuclides (in contrast to the 10CFR61 procedure for fission products). Hence, we believe that "literal" application of the concentration limits in Tables 1 and 2 of 10CFR61 is inappropriate for fusion waste and not suitable for guidance to fusion alloy developers.

The more fundamental procedures of 10CFR61 can be used to find explicit limits of waste concentrations. To this end, we used the

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INVERSI and INVERSW codes² (developed by NRC for 10CFR61) to determine the allowable concentrations of one nuclide, ⁹⁴Nb, in fusion reactor waste. We compare our results with the limit chosen by NRC and suggest that the NRC limit is overly conservative for fusion and inconsistent with the fundamental premises of 10CFR61. Our logic can be applied to all nuclides projected to be in fusion waste, including some nuclides not explicitly considered by 10CFR61.

2. SCENARIOS USED TO ESTABLISH CONCENTRATION LIMITS

In 10CFR61, several scenarios are used to insure the dose to an intruder or the general public is below set limits. These scenarios are described in Table 1. Each scenario considers dose through one or more pathways. These include direct gamma, air (inhalation of a dust cloud, deposition on garden plants, and gamma from the cloud), food and water. Six organs and the whole body are considered, and the most restrictive limit is used.

In some cases, the scenarios are modified. For example, if the waste is stable, an intruder at 100 years after dump closure is assumed to recognize the waste; this reduces his exposure time from 500 hours to 6 hours. Another example is the elimination of the wind/water (but not the intruder) erosion scenarios if the dump site is a "hot waste facility," the most expensive option in 10CFR61.

The INVERSI and INVERSW computer codes published in support of 10CFR61 can be used to determine the maximum concentration for each nuclide and scenario to limit the dose to both intruders and the public. We have applied these computer codes for one nuclide of interest to fusion wall designers, ⁹⁴Nb (Table 2). For long-lived nuclides like ⁹⁴Nb (20,000 year half-life), regular and layered

Table 1. 10CFR61 Scenarios

Scenario	Description
Intruder well	A well is dug within the dump boundary 100 years after closure. It is used by the intruder.
Boundary well	A well at the site boundary is used by a few individuals.
Population well	A well located 500 m downstream from the disposal site is used by about 100 people.
Intruder construction	An intruder digs a 3-m-deep foundation on the dump site for his house. The lower 1 m of the hole is assumed to be waste in some cases. The excavated earth is spread over a 25-m-radius circle around the house. A family garden is planted within the circle.
Intruder agriculture	After the intruder construction scenario is complete, commercial agriculture begins.
Erosion	Either intruders or wind/water erode the cover. Wind or runoff then transports the waste to population centers.
Accident--container	A container breaks during transportation to the dump.
Accident--fire	Flammable waste ignites at the dump during disposal operations.

waste is considered Class A and the hot waste facility is considered Class C due to its 5-m-thick intruder barrier. (The hot waste facility is described in more detail below.)

2.1 Implications of the limits

For ferritic steels in both ICF and MCF geometries, ⁹⁴Nb dominates the waste at 50 years

Table 2. Concentration Limits* (Ci/m³) for ⁹⁴Nb in Fusion Wall-Waste Disposed in a Hot Waste Facility

Scenario	Hot Waste Facility
Intruder well	4E8
Boundary well	5E12
Population well	7E17
Intruder construction	1.3
Intruder agriculture	1.1
Erosion-water	none
Erosion-wind	none
Intruder erosion-water	4E4
Intruder erosion-wind	1E8
Accident-container	1E7
Accident--fire	none
10CFR61 limit	0.2

*The water scenarios use the most conservative values of the retardation coefficient. All scenarios use waste characteristics suitable for fusion structures, and dump characteristics suitable for a hot waste facility. To allow duplication of our results, the following values of waste and dump indices are provided:

flam = 0, disp = 3, leach = 4,
chem = 0, stabl = 1, acces = 3,
IR = 2, ID = 2, IC = 3, IX = 1,
IE = 2, IS = 1, IL = 1, IG = 1,
IH = 0, ICL = 1, IPO = 2, III = 100.

after shutdown. This nuclide is produced from Nb (thermal neutron activation of natural ⁹³Nb) and Mo (fast neutron reactions on ⁹⁴Mo and ⁹⁵Mo which account for ~ 1/4 of natural Mo). If the 0.2 Ci/m³ limit on ⁹⁴Nb is applied, Nb must be limited to ~ 0.8 wppm for both ICF and MFE.^{3,4} The Mo limit would be ~ 60 wppm for MFE and ~ 700 wppm (0.07 wt.%) for ICF.^{3,4} If both Mo and Nb are present, the limits must be reduced proportionately, i.e.,

$$\frac{C_{Mo}}{L_{Mo}} + \frac{C_{Nb}}{L_{Nb}} < 1.0 \quad (1)$$

where C is the concentration and L is the limit.

These limits pose a problem for fusion wall designers. It appears to be difficult to produce any steel with Nb concentration below ~ 10 wppm. Further, steel designers would like the freedom to include up to 1 w/o Mo (10,000 wppm) in the steel to improve its structural properties. Although the Mo limit can be circumvented by isotopically removing the worst of the seven natural isotopes, there is only one natural isotope of Nb.

The conflict between design requirements and the 10CFR61 limits led us to examine the scenarios used to determine the limits. Table 2 shows that for a hot waste facility, the only significant scenarios are intruder construction and intruder agriculture.

3. WASTE CLASSIFICATION PROCEDURE FOR THE INTRUDER AGRICULTURE AND CONSTRUCTION SCENARIOS

Figure 1 presents the 10CFR61 Waste Classification Test Procedure appropriate to stable waste in the intruder scenarios. This procedure ascertains the maximum allowable concentrations (limits) in waste for nuclides of interest. Using the INVERSI code, we determined the limit for each of the tests depicted. The tests represent increasingly expensive treatments of the waste, and thus allow near-surface disposal of wastes with increasingly higher concentrations of the radioactive isotopes.

Before beginning the test procedure, we first must determine that the waste is physically stable and segregated from physically unstable waste. For fusion first walls, this classification is clearly true. The first test is the "Regular - Modified Test at IIC years," where IIC is the time after closure when institutional control of the dump site is lost and the site markings are assumed to be no longer recognizable. The regulation uses 100 years as

Fig. 1 Limit Setting Procedure for the Intruder Construction and Agriculture Scenarios.

the value of IIC. The test assumes that an inadvertent intruder begins to excavate a home foundation at the dump. After six hours of exposure, he recognizes that he is in waste rather than earth and terminates construction. The test result is the concentration of each isotope (in Ci/m^3) that will result in the maximum permissible dose to the intruder, 500 mR/yr.

The second test is the "Regular - Standard Test at 500 years." In this test, the waste is assumed to have decomposed and mixed with the surrounding earth. The intruder spends 500 hours in contact with the waste, not discerning that he is constructing his house in an old radioactive waste dump. The test assumes that the bottom 1 m of the 3-m-deep excavation is waste, even if thicker, engineered covers were installed at dump closure. It also gives no credit for layering the waste.

The third test, the "Layered - Modified Test at IIC years," again assumes that the home-builder spends six hours in the excavation before he notices that this is an old dump. However, the waste disposal site is different in that the highest activity waste has been placed at the bottom of the dump with the less active waste above it. This procedure results in the intruder being subjected to less radiation than in the "regular" (unlayered) case. Thus, the limit from this scenario will be higher than for the regular modified test

The "Hot Waste Facility Test at IIC years" assumes the waste is layered, grouted and enclosed in a concrete vault with at least five meters of "cover." The concrete vault has 1/3-m-thick concrete sides and bottom and a 1-m-thick concrete top. The cover is usually an engineered barrier of clay and other materials. A final meter of fill completes the

facility. The direct gamma pathway of the agricultural scenario (where the homebuilder pursues commercial agriculture on the site) is not considered in the hot waste facility test. For the direct gamma pathway of the construction scenario (where the homebuilder has a small family garden), a reduction factor of $(1/1200)^2$ is applied to account for shielding, and a factor of 1/100 is applied to account for grouting and reduced accessibility. The effective removal of the radioactive waste from the biosphere by the hot waste facility results in a limit which is higher than any of the other situations.

Finally, the "Regular Test at 1000 years" assumes that the dump has had sufficient degradation that it is indistinguishable from the surroundings. The direct gamma pathway has a reduction factor of 1/10 to account for dilution during decomposition. While the additional time may allow short half-lived material to decay, the test is difficult to meet for long-lived isotopes because of the lack of discovery (500 hours of exposure during excavation), coupled with ignoring the engineered cover, the concrete vault, and the layering of the waste.

The results of applying the various intruder tests to hot waste facility waste containing ^{94}Nb are shown in Table 3. As Fig. 1 shows, a hot waste facility must meet only the final two tests. For ^{94}Nb , the direct gamma exposure is the dominant pathway for both the construction and agricultural scenarios. The regular standard test at 1000 years sets the limits. This test assumes that waste identity is lost and the waste is within 2 m of the surface (so intruders building homes excavate it). For the hot waste facility, 1 m of earth, 5 m of engineered intruder barrier, 1 m of concrete cap, the lower activity layers and the grout filler all are ignored in this test. Since we have assumed a hot waste facility for fusion waste, the Table 3 limit of 1.1 Ci/m^3 ^{94}Nb would replace the 10CFR61 limit of 0.2 Ci/m^3 .

If as little as one meter of shielding remains intact at the time of discovery that a dump is being excavated, the dose will be more than three orders of magnitude less; i.e., the limit can be set three orders of magnitude higher, 1100 Ci/m^3 . With this limit, a steel containing 5% Mo and 0.4% Nb would be acceptable.

Table 3. Intruder Test Results (^{94}Nb limits in Ci/m^3)

Test	Construction			Agriculture			
	Direct Gamma	Air	Combined	Direct gamma	Air	Food	Combined
Regular modified, 100 years	103	2E8	103	none*	none*	none*	none*
Layered modified, 100 years	1.2E6	2E8	1.2E6	none*	none*	none*	none*
Regular standard, 500 years	1.2	2E6	1.2	1.0	6E6	1.0	1.0
Hot waste facility, 100 years	2E7	2E7	1E7	none*	none*	none*	none*
Regular standard, 1000 years	1.3	2E5	1.3	1.1	6E5	2E7	1.1

*No agriculture takes place due to discovery of the waste.

4. SUMMARY

The NRC has thoroughly researched pathways, dose limits, and many other aspects of low-level waste disposal. NRC integrated their research into a regulation that requires barriers against inadvertent intruders who might try to use the site if it loses its identity centuries after it is filled. However, in establishing limits on waste concentrations, they set aside their mandated intruder barriers, resulting in very low limits. If the concrete cap plus at least one of the five meters of cover remains, the limits can be at least seven orders of magnitude higher. Retaining four out of the seven orders of magnitude as a safety factor will protect intruders while giving design freedom to fusion reactor designers. Our proposed limit for ^{94}Nb , 1100 Ci/m^3 , still requires removal of 1 m of earth, and 4 m of engineered barrier, before an intruder would reach the NRC dose limit. Reference 2 demonstrates that natural erosion would not remove these layers during the time of interest (1000 years). If non-corrodible engraved signs were imbedded at various depths within the barrier, it is also unlikely that an intruder would penetrate to dangerous regions.

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