Safety Assessment of the Protective Gases Used in IFE Chambers

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ABSTRACT

Using xenon as a fill gas in IFE chambers results in generating a large amount of radioactive xenon, iodine, and cesium isotopes. The cesium isotopes, ^{134}Cs and ^{136}Cs, and the iodine isotope, ^{126}I, would produce a high level of off-site dose (62.13 rem) at the plant site boundary if they were released entirely to the environment during an accident. The xenon gas is pumped out of the chamber (recycled) during operation to remove unburned T_2 and D_2. Removing the Cs and I isotopes from the Xe gas during this recycling process will reduce the Cs and I inventories inside the chamber to negligible values. This process limited the off-site dose caused by the accidental release of Xe from the chamber of the SOMBRERO power plant to 29.9 mrem, which is less than the 1 rem no-evacuation limit. Using krypton, argon or neon as fill gases will result in producing lower levels of off-site dose than xenon.

I. INTRODUCTION

One of the critical issues associated with the design of a dry wall Inertial Fusion Energy (IFE) power plant is the selection of the protective gas that fills the target chamber. The target chamber fill gas absorbs the target generated X-rays and ions, and re-radiates the energy to the target chamber first wall over a time long compared to the thermal response time of the wall. The first wall surface temperature can then be kept to a low enough peak value that vaporization does not occur. In this paper, we present results from the latest update of the safety assessment of the SOMBRERO study, where we have chosen xenon as the primary candidate for target chamber gas fill. Xenon was selected because it has a high cross-section for stopping X-rays as well as energetic ions, and it is chemically inert in its neutral state. We also examined the possibility of using krypton, argon, and neon as additional candidate fill gases in the SOMBRERO chamber.

SOMBRERO is a conceptual design study of a 1000 MW_e KrF laser driven IFE power plant utilizing direct drive targets with near symmetric illumination. The plant is directly driven with 60 beams from a KrF laser, where the beams are situated in a near symmetrical configuration. The laser energy is 3.4 MJ, the gain is 118 and the rep-rate is 6.7 Hz. The chamber structure is a C/C composite and the breeding/cooling material is a granular compound of Li_2O flowing through the chamber by gravity.

II. FILL GAS PARAMETERS

In the original SOMBRERO study[1] (completed in 1992), a 6.5-meter radius graphite target chamber was protected by 0.5 torr of xenon. Here, the unit torr is used as a measure of density and is the pressure that the gas would have if it were at 300 °K. In more standard units the Xe density is 1.77×10^{16} atoms/cm^3. This fill gas was not optimized, but it was found to be sufficient. That is, it was low enough in density that the laser beam did not break down and frictional heating on the target during injection did not heat the target excessively. In the mean time, the density was high enough to stop the target debris ions and re-radiate the energy to the wall over a sufficiently long time. Since 1992 the expected operating conditions for direct-drive laser fusion have substantially changed. The changes are reflected in Table 1, where the conditions are compared between 1992 and 2000 for the SOMBRERO target and for the current Naval Research Laboratory (NRL) target design. The SOMBRERO target is a 200 μm thick plastic ablator around a 450 μm thick cryogenic solid DT shell. The outer radius of the SOMBRERO target is 3 mm. The Naval Research Laboratory target has only a 1 μm thick plastic layer and 300 Å of gold surrounding a plastic foam layer that is filled with cryogenic DT ice. This filled foam sits atop a pure cryogenic solid DT layer.

One substantial change is the temperature that the target's cryogenic DT fuel is cooled to prior to injection into the target chamber. In the past few years it has been learned that if the fuel is cooled to less than 18 degrees, unacceptable non-uniformities grow in the solid fuel. This is only 1.7 °K below the triple point for DT. Also, when the fuel is heated from 18 to 18.5 °K a thermal stress limit may be reached. The two target designs are substantially different in their vulnerability to thermal damage. The NRL target design, with only a 1 μm thick plastic layer and 300 Å of gold as thermal protection, is much more

susceptible to thermal damage. In any case, the allowed heating of the target during injection is greatly reduced. Since part of the thermal load on the target is frictional heating with the fill gas, this puts an upper limit on the allowed gas density. In addition, differences in the target output lead to variation in the gas parameters required to protect the first wall. For the SOMBRERO target, a gas density of 0.5 torr is required to avoid vaporization of the first wall. For the NRL target, the lower target yield and differences in the spectra lower the requirement to 0.15 torr. If the first wall temperature were decreased or the chamber radius increased, the gas density would be lower yet. Therefore, there is a considerable range possible for the required gas density in dry-wall chambers like SOMBRERO. In this paper, we used the high gas pressure of 0.5 torr as our reference case. The results presented could be scaled down for lower fill gas pressures.

Table 1. Laser Target Parameters.

Parameter	SOMBRERO (1992)	SOMBRERO (2000)	NRL (2000)
Initial Fuel Temp. (°K)	4	18	18
Allowed Fuel ΔT (°K)	15.7	0.5–1.7	0.5–1.7
Target Yield (MJ)	400	400	170

III. CALCULATION APPROACH

Neutronics calculations are performed using the ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system.[2] A spherical geometry is utilized with the target represented by an isotropic point source in the center of the chamber. The source emits neutrons and gamma photons with energy spectra determined from target neutronics calculations for a generic target.[3] The neutron flux obtained from the neutron transport calculations is used in the activation calculations. The activation calculations are performed using the computer code DKR-PULSAR2.0[4] with the FENDL-2 activation cross section library.[5]

Using the DKR-PULSAR2.0 code allows for appropriate modeling of the pulse sequence in IFE chambers. To accurately calculate the radioactive gas inventory inside the chamber, a detailed pulse sequence was used in the activation calculations. The pulse sequence used in the activation calculations is shown in Fig. 1. In order to achieve 75% availability during the plant 40 year lifetime, the plant is assumed to shut down for a period of 5 days following every 25 days of operation for routine maintenance. The plant is also assumed to shut down for the last 40 days of each calendar year for an annual extended maintenance. During the 25 days of operation, the calculation used 14.47 million pulses with each pulse assuming neutron burn time of 1 μs and 150 ms of dwell time between pulses. The calculated activities are used to calculate the early off-site doses following the release of the radioactive gases during an accident. The calculated early dose values are based on a separate set of calculations[6] performed using the MACCS2 code for radionuclide release at ground level for a one-km site boundary. In addition, these calculations assumed conservative weather conditions of stability class F and wind speed of 1 m/s.

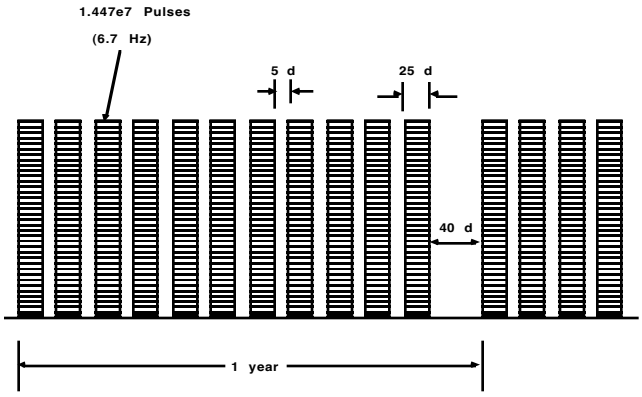

Fig. 1. Pulse Sequence Used in Activation Calculation.

IV. RADIOLOGICAL INVENTORIES

Next to the IFE power plant target, the chamber fill gas is exposed to the highest neutron flux. The level of radioactivity induced in the gas is not only dependent on the type of gas used, but also on the time spent by the gas inside the chamber as well as any on-line recycling process the gas might go through. During the recycling process, some of the highly radioactive products generated in the fill gas could be removed and hence reduce the overall hazard posed by the release of the gas during an accident. The recycling process is possible due to the fact that the proposed fill gases have very low boiling temperatures in comparison to the radioactive products generated in these gases during shots. For example, xenon and krypton remain in their gaseous forms at temperatures above -107 and -152 °C, respectively.

The calculated radioactive inventory of the fill gas is sensitive to the operation schedule used in the analysis as many of the important radionuclides may decay during the proposed plant maintenance periods. Similarly, the amount of time spent by the gas outside the chamber during the on-line recycling process will also have an impact on the final calculated inventory. However, in this case the time spent by radioisotopes present in the gas outside the chamber will have two opposing effects on

their final levels of radioactivity. On the one hand, production of some of the nuclides (produced by direct neutron transmutation of their parent atoms) will stop. On the other hand, the same nuclides will not suffer any destruction due to the absence of direct neutron transmutation. However, since a different amount of the same radionuclides will continue to be produced inside the chamber during the on-line recycling process, the net effect on the final levels of radioactivity varies depending on the type of nuclide. The total amount of radioactivity (inside and outside the chamber) generated by nuclides with high neutron destruction rates will increase as some of these nuclides benefit form spending time outside the chamber. Other nuclides may not fair as well.

A. Activation of Xenon Gas

In the SOMBRERO study, xenon was selected as the preferred chamber fill gas. Activation of the xenon gas resulted in generating a large amount of radioactive xenon, iodine, and cesium isotopes. The two cesium isotopes, ^{134}Cs and ^{136}Cs, as well as the iodine isotope, ^{126}I, produce a high level of off-site dose at the plant site boundary if they are released to the environment during an accident. Depending on the residence time of the Xe gas in the chamber, the off-site early dose at the site boundary due to the Cs and I isotopes could be as high as 62.13 rem. The ^{134}Cs ($T_{1/2}$ = 2.065 y) radioisotope is mostly produced by the two reactions: ^{134}Xe(n,2n)^{133}Xe(β-)^{133}Cs(n,γ)^{134}Cs, and ^{132}Xe(n,γ)^{133}Xe(β-)^{133}Cs(n,γ)^{134}Cs. The ^{136}Cs ($T_{1/2}$ = 13.16 d) radioisotope is mostly produced by the ^{136}Xe(n,2n)^{135}Xe(β-)^{135}Cs(n,γ)^{136}Cs reaction. In the mean time, ^{126}I ($T_{1/2}$ = 13 d) is mostly induced by the ^{124}Xe(n,γ)^{125}Xe(n,p)^{125}I(n,γ)^{126}I, and ^{126}Xe(n,d)^{125}I(n,γ)^{126}I reactions. Collecting the Cs and I gases during the on-line recycling of the Xe gas could reduce the off-site dose to well below the 1 rem limit set for public evacuation during an accident. An extended discussion of the fill gas recycling process is included in the next section.

As shown in Fig. 2, an accident resulting in the release of the recycled xenon gas present inside the chamber will result in an early dose at the site boundary of less than 100 mrem. The level of the early dose is dependent on the residence time of the gas inside the chamber. The figure shows that a 100% gas residence time (an impractical upper limit) results in an off-site dose of 96.4 mrem. On the other hand, a 1% gas residence time (lower limit) produces an early dose of only 1.6 mrem. In SOMBRERO, we estimated that the Xe gas spends 15 s inside that chamber and 60 s in the closed vacuum loop outside the chamber. In this case, with only 20% gas residence time, the early dose caused by the release of the recycled Xe gas present in the chamber at any time is only 29.9 mrem. The dose is dominated by the xenon isotopes, ^{127}Xe ($T_{1/2}$ = 36.4 d), ^{133}Xe ($T_{1/2}$ = 5.243 d), and ^{135}Xe ($T_{1/2}$ = 9.1 h).

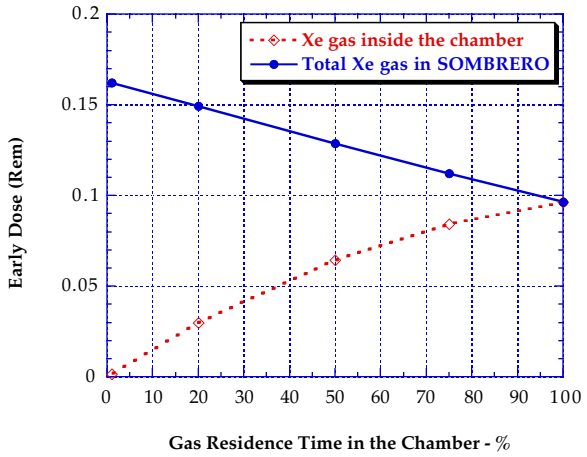

Fig. 2. Early Dose at Site Boundary due to the Release of Recycled Xenon Gas (Excluding Cs and I).

In the same figure, we plotted (solid line) the off-site dose due to the hypothetical release of all of the Xe gas present in the plant (chamber and vacuum loop). In order to account for the radioactivity of radionuclides outside the chamber, we had to make some assumptions. For example, if the gas residence time is only 1%, then the closed vacuum loop will hold 99 times the same amount of Xe present inside the chamber at any time. The 1% gas in the chamber is only exposed to neutrons during the 15 s it spends inside the chamber and then spends the following 1485 s in the vacuum loop (with no neutron exposure) before being pumped back into the chamber and so on. A gas residence time of 100% indicates that all of the Xe gas is present in the chamber all the time (an impractical upper limit). As shown in the figure, the lower the gas residence time, the higher the off-site dose during an accident. A 1% gas residence time yields an early dose of 162 mrem if the total amount of recycled Xe present in SOMBRERO is released. As explained before, this is caused by the fact that the ^{127}Xe, and to a lesser extent, the ^{135}Xe isotopes benefited from escaping the increased destruction associated with higher gas residence time inside the chamber. Once again, our reference case of 20% gas residence time yields an early dose of 149.5 mrem in the case of a release involving the total inventory of recycled Xe.

B. Activation of Other Fill Gas Candidates

Krypton, argon and neon are also considered as possible candidates for use as chamber fill gases in IFE power plants. Figure 3 shows a comparison between the early dose caused by the total release (from chamber and vacuum loop) of non-recycled Xe and Kr gases. The Kr gas used in the analysis also has a gas pressure of 0.5 torr.

The early dose due to the release of the non-recycled Kr gas is 7.96 rem for the upper limit of 100% gas residence time and it drops to 3.27 rem for the 1% gas residence time. For 20% gas residence time, the Kr early dose is 5.25 rem and hence needs to go through the recycling process to reduce the hazard it poses during an accident. The high dose is caused by the bromine isotope ^{82}Br ($T_{1/2}$ = 1.471 d), and the rubidium isotopes, ^{84}Rb ($T_{1/2}$ = 32.9 d) and ^{86}Rb ($T_{1/2}$ = 18.65 d). Since Br and Rb have boiling temperatures of 59 and 686 °C, respectively, they will not condense inside the chamber. These isotopes could then be collected during the recycling of the Kr gas and stored outside the chamber. Unlike the Xe isotopes, the Cs, I, Br, and Rb isotopes did not benefit from escaping the destruction associated with higher gas residence time by spending time in the vacuum loop outside the chamber.

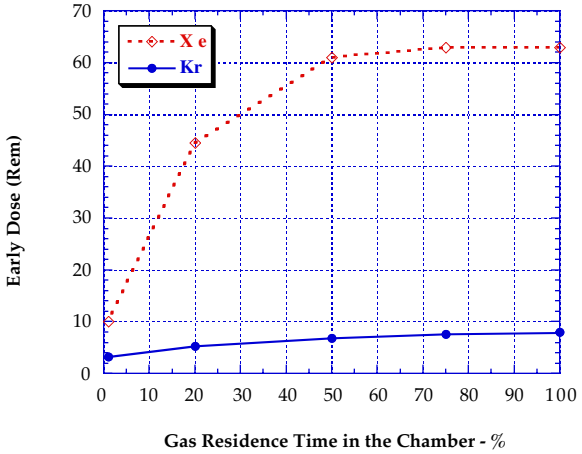

Fig. 3. Early Dose at Site Boundary due to the Release of the Total Inventory of the Non-recycled Xe and Kr.

The ^{82}Br isotope is produced by the ^{82}Kr(n,p)^{82}Br reaction. The ^{84}Rb and ^{86}Rb isotopes are mostly due to the multi-step reactions, ^{84}Kr(n,γ)^{85m}Kr(β-)^{85}Rb(n,2n)^{84}Rb, and ^{84}Kr(n,γ)^{85m}Kr(β-)^{85}Rb(n,γ)^{86}Rb, respectively. Figure 4 shows that collecting the Br and Rb gases during the on-line recycling of the Kr gas could reduce the off-site dose to far below the 1 rem no-evacuation limit. Similar to Xe gas, the level of the dose from recycled Kr is also dependent on the residence time of the gas inside the chamber. During an accident involving the release of the recycled Kr from the chamber only, a 100% gas residence time results in an early dose of 45.2 mrem. On the other hand, a 1% gas residence time produces an early dose of only 0.74 mrem. The reference case 20% gas residence time resulted in an early dose of 13 mrem. The dose is dominated by the krypton isotopes, ^{85m}Kr ($T_{1/2}$ = 4.48 h), and ^{79}Kr ($T_{1/2}$ = 1.455 d). As shown in the figure, if the total inventory of recycled Kr (from chamber and vacuum loop) is released, the lower the gas residence time, the higher the off-site dose during an accident. A 1% gas residence time produces an early dose of 74 mrem. This is caused by the fact that the ^{85m}Kr and ^{79}Kr isotopes benefited from avoiding the increased destruction associated with a higher gas residence time in the chamber. The 20% gas residence time yields an early dose of 64.9 mrem.

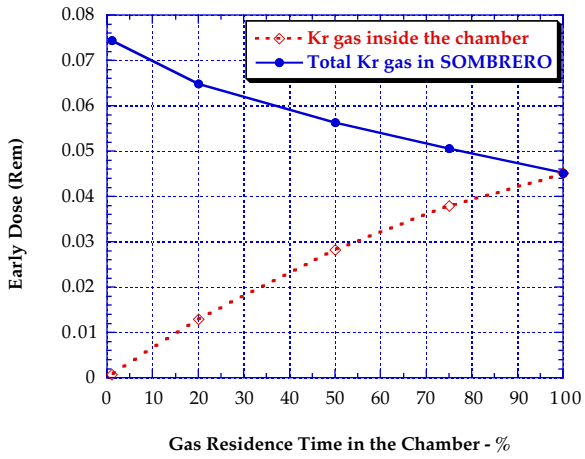

Fig. 4. Early Dose at Site Boundary due to the Release of Recycled Krypton Gas (Excluding Br and Rb).

Finally, we also calculated early dose rates caused by the release of argon and neon fill gases at 0.5 torr. Unlike the Xe and Kr gases, Ar and Ne do not need to be recycled as they produce early doses that are far below the 1 rem no-evacuation limit. Based on a 20% gas residence time, an accident resulting in the release of the non-recycled Ar and Ne present in the chamber at any time, will result in off-site doses at the site boundary of 19.5 and 1.26 mrem, respectively. In the meantime, a total release of the non-recycled Ar and Ne inventories present in SOMBRERO will result in off-site doses of 97.5 and 6.3 mrem, respectively. In the case of the argon gas, the dose is dominated by the ^{35}S ($T_{1/2}$ = 87.2 d), and ^{38}Cl ($T_{1/2}$ = 37.2 min) isotopes. On the other hand, ^{18}F ($T_{1/2}$ = 1.83 h) is the major source of off-site dose if neon is used as a fill gas.

V. FILL GAS RECYCLING

An IFE power plant must be pumped during operation in order to remove unburned T_2 and D_2. In the process, the fill gas is also evacuated, as well as gas species that are transmuted from the fill gas during the reaction. Following shots, the pumping capacity required in the SOMBRERO chamber is determined by two important considerations: the time required to pump down the system to the operating pressure and the rate at which the gases are blown out of the chamber following each shot. The pumping speed must be at least equal to the blowout rate while at the same time it must be capable of evacuating the system in a reasonable time. As the gases are blown out of the chamber, recycled gases from the

closed vacuum loop immediately replace them. The three components that need evacuation are the chamber, the shield enclosure and the beam handling building. The total volume is equal to 9.27×10^5 m^3. A pumping speed of 3.78×10^5 l/s would evacuate the building in 5 hours and 1.89×10^5 l/s in 10 hours. The final choice depends on the pump capacity needed to operate the chamber on a steady state basis. The best location for the vacuum system is with the intake at the bottom of the shield building. To determine the capacity needed to pump the chamber during operation, we estimate the amount of gases that are blown out through the beam ports after each shot. The parameters of the gas conditions after a shot are taken from the SOMBRERO final report.[1] The peak pressure on the chamber wall after a shot is 0.012 MPa and lasts only 90 μs. The chamber gas at that time is in the viscous regime. The conductance of the 60 beam ports of 30 cm diameter at a rep-rate of 6.7 Hz is 2.94×10^4 l/s which is equal to 656 g/s, or ~ 7.0% of the total gas in the chamber. It also means that approximately 1% of the gases in the chamber are exhausted every shot.

In the case of the xenon gas, both cesium and iodine have boiling temperatures much lower than the first wall temperature in the chamber (670 and 184 °C, respectively). Thus it is safe to assume that these species will not condense in the chamber but ultimately find their way into the shield building. There are two ways to handle these gases. One way is to maintain the temperature of the shield building walls at a low temperature (< 100 °C) and let them condense on the walls. In this case, a periodic heating of the walls with the beam ports in the shield building closed off, will permit the collection of the Cs and I in the vacuum system. The other way is to keep the building wall above the condensation temperature of Cs and I and let these species get pumped out along with the Xe. The second option is more desirable since it keeps the radioactive components of these materials securely in the vacuum system. If the wall is cooled, the pumping capacity needed is 2.21×10^4 l/s, but if the wall is maintained hot, it is 5.17×10^4 l/s. In either case, the pumping capacity is a small fraction of that needed to evacuate the building in a reasonable time.

VI. SUMMARY

In IFE power plants, the target chamber fill gas absorbs the target generated X-rays and ions, and re-radiates the energy to the target chamber first wall over the longest possible time, while allowing for the simultaneous propagation of the laser beams to the target. In the SOMBRERO study, using xenon as a fill gas resulted in generating a large amount of radioactive xenon, iodine and cesium isotopes. The isotopes, ^{134}Cs and ^{136}Cs, and ^{126}I produce a high dose at the plant site boundary of 62.13 rem if released during an accident. However, since both Cs and I have boiling temperatures much lower than the first wall temperature in the chamber, they could be pumped out of the chamber along with the Xe, where they could be collected and stored. This will reduce the off-site dose caused by the release of the recycled xenon gas present in the chamber to 29.9 mrem. If krypton is used as a fill gas, radioactive Br and Rb could be pumped out of the chamber as well and removed before recycling the Kr back to the chamber. In such a case, the release of recycled Kr gas from the chamber will produce an early dose of 13 mrem. If the Br and Rb are not collected, a release of accumulated inventory of these isotopes could produce an off-site dose of 7.96 rem. Using argon and neon as fill gas will produce much lower levels of potential off-site doses, eliminating the need for collecting any of their radioactive products during operation. An accident resulting in the release of non-recycled Ar and Ne will result in off-site doses at the site boundary of 19.5 and 1.26 mrem, respectively.

ACKNOWLEDGEMENT

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