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UWFDM-1126

Presented at the IAEA Technical Committee Meeting on Physics and Technology of Inertial Fusion Energy Target and Chambers, Madrid, Spain, 7–9 June 2000.

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Abstract

A reassessment of the SOMBRERO laser driven fusion power plant that was designed in 1990-91 has been conducted. New information and analysis has confirmed most of the original design decisions except that the tritium inventory in the blanket may be larger than originally calculated. Possible methods of lowering the tritium inventory are described along with a discussion of the critical issues that still remain 10 years after the original design was completed.

1. Introduction

Since the publication of the SOMBRERO laser fusion power plant design study completed in 1991 and published in 1992[1], there has been new information and analyses concerning the response of the C-C composite material to the environment that exists in the target chamber and blanket region. The new information has been incorporated into a reassessment that covers five categories:

1) Thermal conductivity of irradiated C-C composites at high temperatures
2) Wall erosion due to vaporization at high temperatures
3) T_2 transport through the blanket walls
4) T_2 inventory in the C-C composite material
5) The useful lifetime of the C-C first wall resulting from high temperature neutron irradiation.

Generally, both the new information and subsequent analyses have confirmed the design conditions associated with the first three issues. On the other hand, it is apparent that based on new data generated between 1994-1998, there might be a higher T_2 inventory (≈1-2 kg) in the graphite structure. The potentially higher tritium inventory is not a "show-stopper" as there are engineering and/or materials solutions discussed later in the paper that can maintain the attractive features of the SOMBRERO design.

The issue of first wall lifetime (Item 5) remains just that – an issue. There is still ample evidence for the 2-3 FPY (full power years) lifetime that was projected in 1991. There is no doubt, however, that further experimental data is needed before one would make this a final design point.

2. Thermal Conductivity

The SOMBRERO first wall is composed of a 4D C-C composite cooled by flowing Li_2O on the backside (see Figure 1 for a cross section of the reactor and Figure 2 for a schematic of 3D and 4D weaves). One of the reasons a 4D weave was chosen is because it was expected to have a higher thermal conductivity than 3D weaves due to the higher density of fibers that can be oriented perpendicular to the first wall. When working with carbon, it is important to recognize that the thermal conductivity varies greatly with temperature, the type of graphite, and irradiation. Figure 3 [2-3] shows how high temperatures and the type of graphite influence the thermal conductivity. In addition, it is well known that neutron irradiation also can reduce the thermal conductivity.

The thermal conductivity of the first few microns of the first wall facing the target is particularly important for IFE (inertial fusion energy) chambers. This thin surface must accept energy fluxes of ≈ 10-20 J/cm^2 over a fraction of a ms and be able to operate at temperatures in excess of 2,000°C without significant evaporation. Beyond the first few microns, where the steady state temperature may range between 1,250 and 1,450°C, the graphite structure must

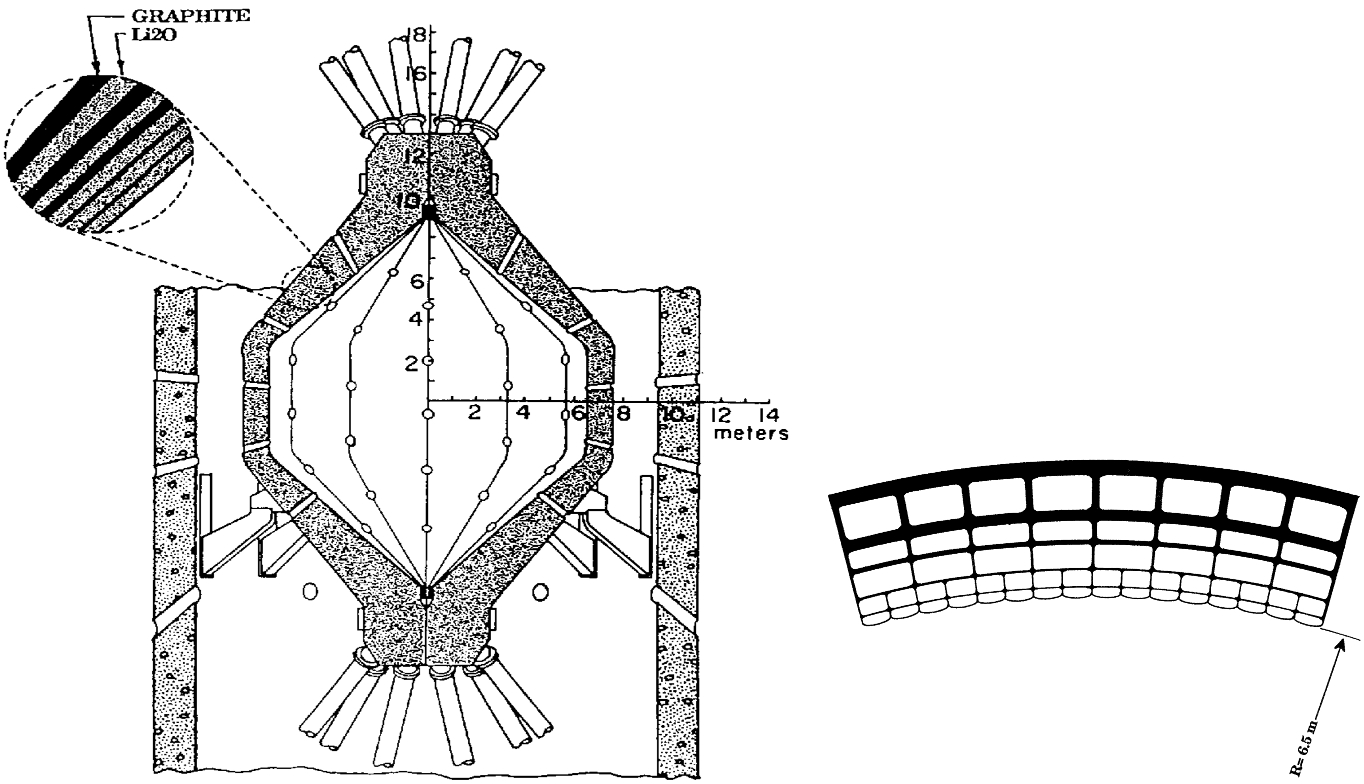

Figure 1. Schematic of the SOMBRERO chamber (left) and cross section of the blanket at the midplane (right).

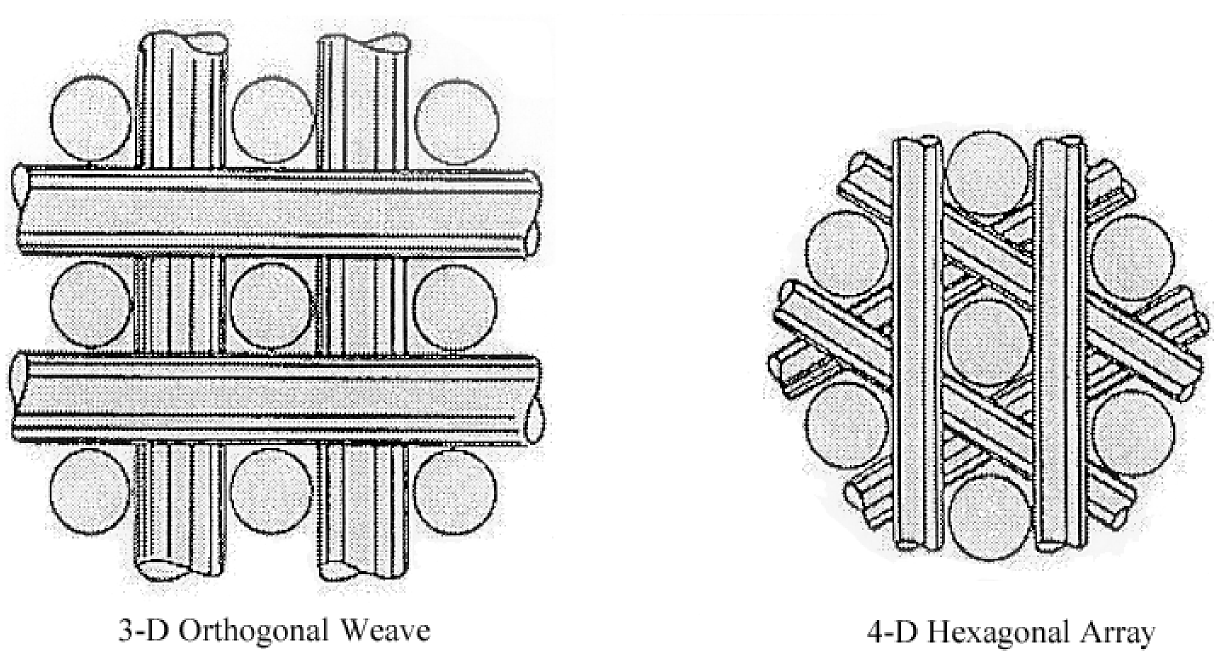

Figure 2. Example of woven graphite structures (courtesy of Mr. Leslie Cohen, Fiber Materials, Inc., Biddleford, Maine).

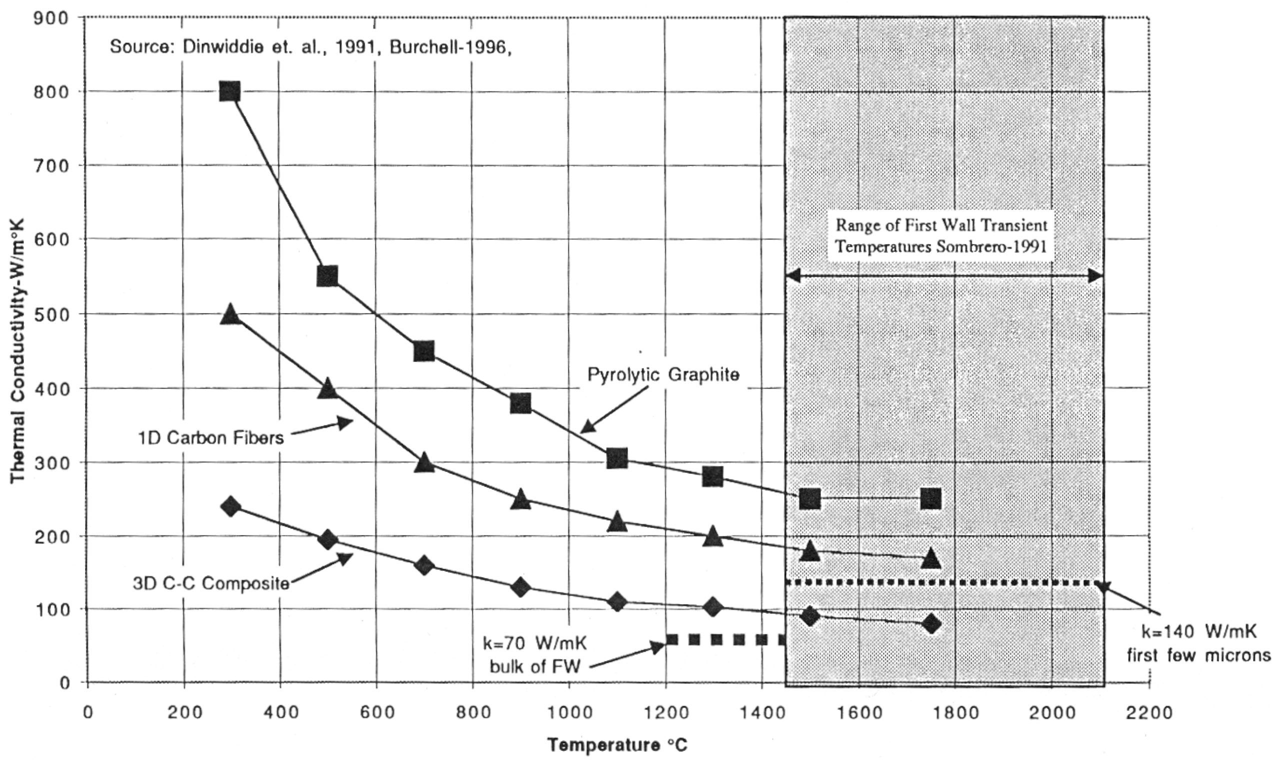

Figure 3. The thermal conductivity of pyrolytic graphite, carbon fibers, and C-C composites drops with increasing temperature.

continuously conduct heat to the back surface of the first wall where it is carried away by the Li_2O coolant. Therefore, two different thermal conductivities were used to calculate the SOMBRERO first wall temperature in order to reflect the different temperature regimes: 140 W/mK (for the ≈ 2,000°C region) and 70 W/mK for the rest of the first wall.

The value of 140 W/mK used for the first wall facing the target is slightly higher than the data shown in Figure 3 for 3D unirradiated composites in the 1,500 to 2,200°C temperature range. However, it should be consistent with the slightly higher thermal conductivity of a 4D weave. It will turn out that even if one had chosen 120 W/mK, the goal of "no significant evaporation" criteria of the SOMBRERO first wall would have been maintained.

The question of how neutron degradation of the thermal conductivity would affect the first wall must now be addressed. It has been known for some time that neutron irradiation reduces the thermal conductivity of carbon [3-4]. This effect is much more pronounced at low temperatures, a region where the irradiation induced defects can accumulate in the crystal structure. In 1990-91, it was assumed that if the temperature exceeded 2,000°C, most of the irradiation induced defects which degrade the thermal conductivity of carbon would be annealed out and the unirradiated value of thermal conductivity could be used. Recent work [4-6] has essentially confirmed that irradiation of carbon and C-C's above 1,000°C causes only a 10% or less reduction in the unirradiated thermal conductivity (see Figure 4). Extrapolation of the data in Figure 4 to ≈ 2,000°C would support the original assumption that the most appropriate value for k at this temperature would be essentially the unirradiated value. At the lower temperatures that might exist in the bulk of the first wall (≈ 1,200 to 1,500°C), the conservative value of 70 W/mK

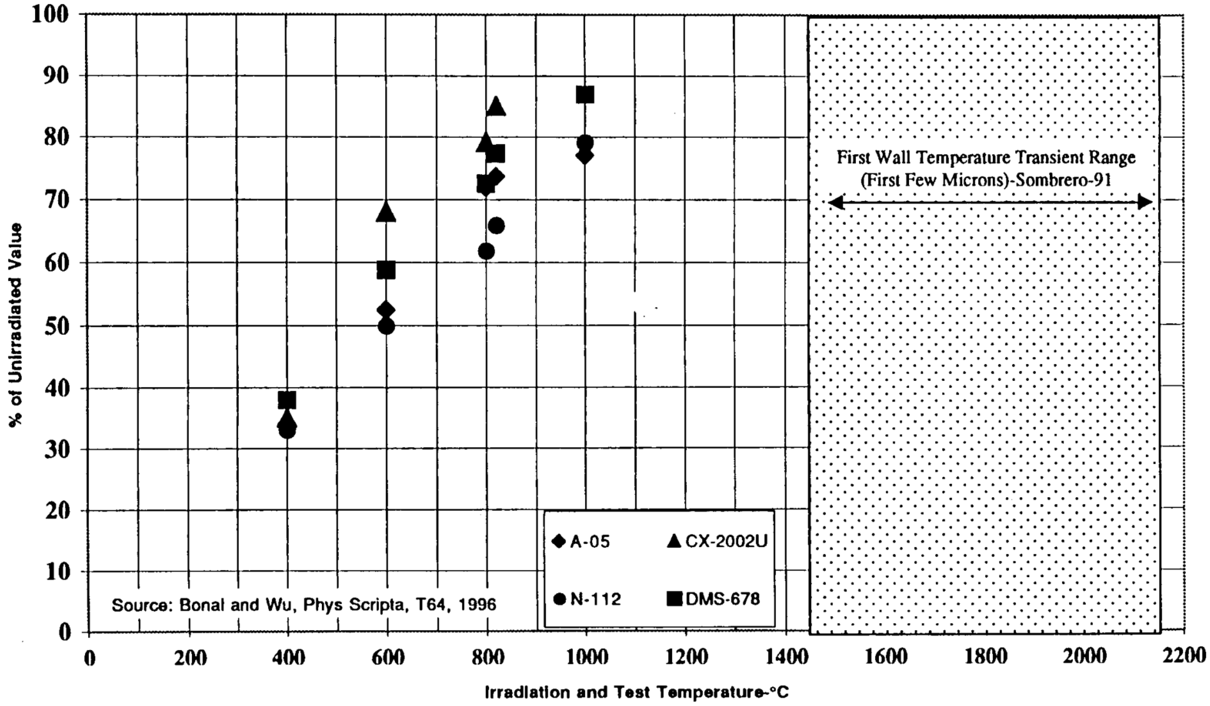

Figure 4. The neutron irradiated thermal conductivity of graphite at ≈1-2 dpa approaches the unirradiated value at high temperatures.

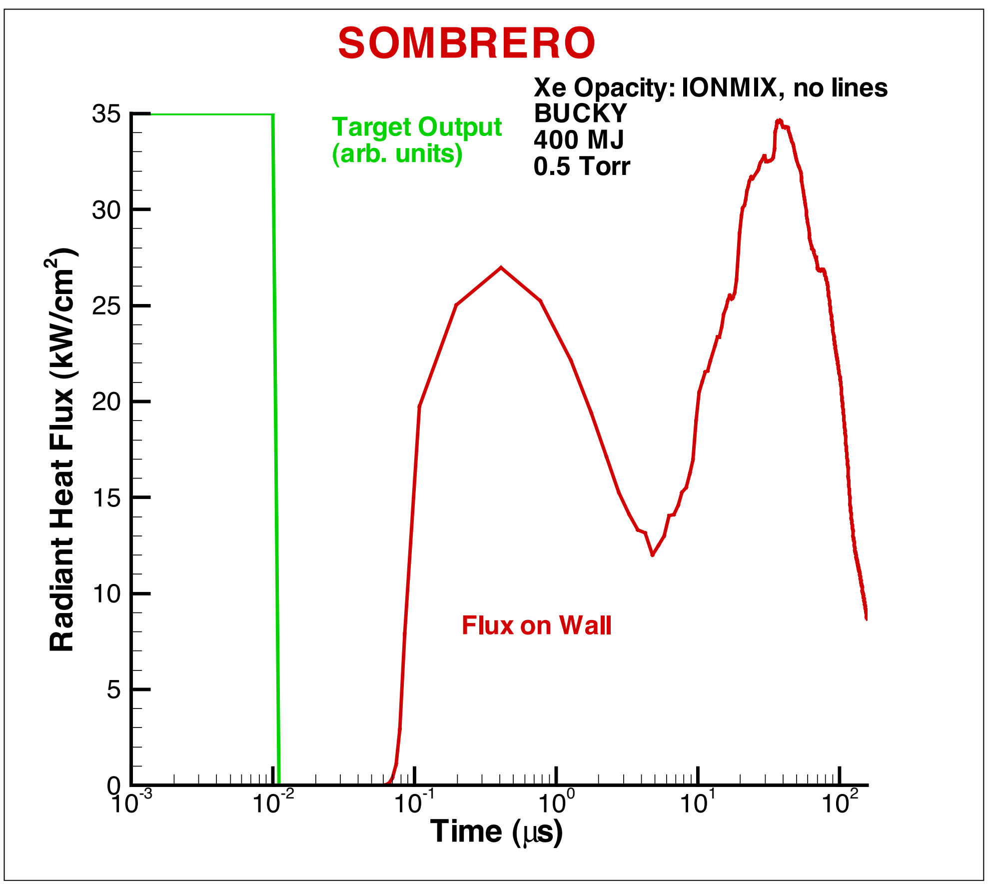

Figure 5. Radiant heat flux on the surface of the SOMBRERO target chamber wall. A 400 MJ yield, 0.5 torr xenon fill gas, and a 650 cm radius chamber has been assumed.

can be used because the thermal conductivity would probably be somewhat reduced from the unirradiated value.

Using the thermal conductivities of 140 and 70 W/mK, the peak and steady state temperatures in the SOMBRERO design have been calculated. The computer code used for these temperature calculations is BUCKY [7-8]. This code can include the time dependent energy flux to the first wall from the fireball (for example, see Figure 5) as well as temperature dependent thermal properties of graphite (including latent heat of vaporization). The peak first wall temperatures (for the heat flux depicted in Figure 5) are given in Figure 6 as a function of thermal conductivity for two different design assumptions:

1) The reference SOMBRERO heat flux of 15. 8 J/cm^2 for <0.1 ms
2) The heat flux for the reference SOMBRERO design if the first wall was moved from 6.5 m radius to 7.0 m (13.6 J/cm^2).

The peak temperatures (at 6.5 m) range from ≈2,170°C for the 140 W/mK conductivity value to ≈ 2,540°C at 50 W/mK. These time-dependent first wall temperatures were used as input to the thermal evaporation model of BUCKY to calculate the wall erosion rates.

3. Wall Erosion

The design philosophy in SOMBRERO was to avoid evaporation altogether by protecting the first wall with a dilute Xe gas in the chamber and by using a large chamber radius. The role of the Xe is to absorb and spread out the burst of thermonuclear energy from nanoseconds to a fraction of one ms at the first wall. The large radius is needed to reduce the power density at the first wall so that the temperature remains below that necessary to remove a monolayer of carbon.

The actual temperature of the first wall was calculated with the BUCKY code. This code includes deposition models for externally applied, x-ray, ion, and electron energy sources into a gas, plasma, liquid, or solid material. To model phase transitions in liquids or solids, the energy density profiles resulting from deposition, radiation transport and thermal conduction are compared with the sensible and latent heats required for phase transitions. When there is not enough energy density to overcome the sensible heat and latent heat, there is no phase transition, and in this case, vaporization. In the case where there is only sufficient energy density to remove less than a monolayer, the physical meaning is unclear. The approach in this paper is to ignore any vaporization that amounts to less than 1 Å removed per shot. In BUCKY calculations for SOMBRERO, the amount of carbon theoretically evaporated (in Å per shot) was calculated and plotted vs. the thermal conductivity in the first few microns (Figure 7). In these computer simulations, the thermal conductivity is assumed constant throughout the region examined (the first few microns). In the BUCKY calculations reported here, the product of mass density and heat capacity of graphite is held constant at 2 J/cm^3K. The fireball heat load in these calculations is approximately what was reported in the SOMBRERO documents (Figure 5). An x-ray flux that is a Gaussian (50 microseconds wide) is scaled to contain either 15.8 or 13.6 J/cm^2 with a 5 eV blackbody spectrum. As part of the NIF target chamber design effort [9], pulsed vaporization experiments were performed on the Nova, Helen, and Phebus lasers. Pulsed x-rays of variable fluences did vaporize measured amounts of various materials and the BUCKY code has been benchmarked to those experiments [10].

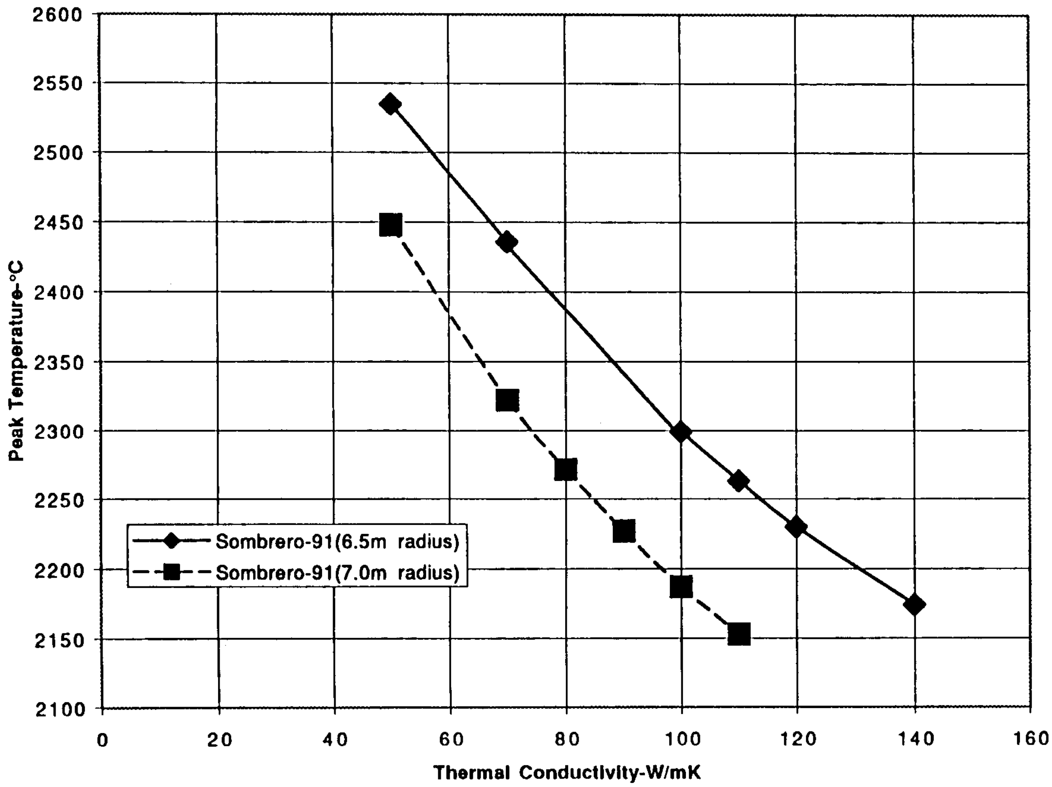

Figure 6. The peak first wall temperatures in SOMBRERO depend on the thermal conductivity of the first few microns.

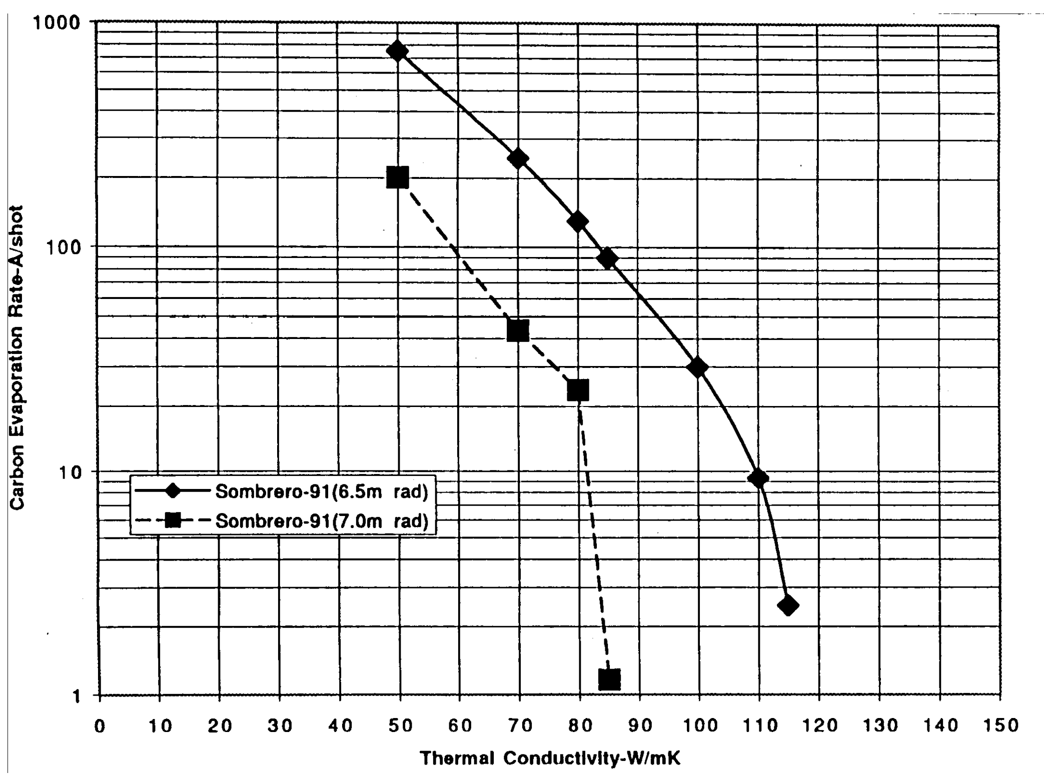

Figure 7. Once the evaporation is below a few Å per shot, there is essentially no erosion of the C-C first wall.

Fully integrated fireball/wall response simulations with BUCKY (using updated opacities) have been performed [11]. These calculations are not reported here because the fireball heat flux is substantially lower than what was reported in the SOMBRERO study. The BUCKY code has vastly improved high-density atomic physics compared to the now inactive CONRAD code, which was used in the original SOMBRERO calculations. The increased opacity of the Xe gas, as calculated with BUCKY, significantly reduces the energy flux that is re-radiated by the fireball. To avoid confusion, we have used the old heat fluxes for now and the new, much lower power loads will be reported in the future.

The amount of carbon evaporated per shot with the power loading shown in Figure 5 is graphically displayed in Figure 7. Note that for the SOMBRERO reference case [1], the evaporation per shot drops below 1 Å per shot for thermal conductivities above 115 W/mK. Above 85 W/mK, the evaporation drops to less than 1 Å if the first wall is moved back to 7 meters radius. Therefore, the original thermal conductivity estimate of 140 W/mK could be relaxed either in the reference design or in a slightly modified design and still avoid first wall evaporation.

In the worst case scenario, there are other methods of dealing with first wall erosion such as:

1) lowering the yield of the target and increasing the rep rate to > 6.7 Hz, or
2) increasing the Xe chamber gas pressure from 0.5 torr to ≈ 1 torr, or
3) coating the front surface with a high thermal conductivity graphite that has a k of >200 W/mK.

The conclusion of this work is that the design of the SOMBRERO first wall is still robust enough to satisfy erosion limits due to evaporation for any reasonable life of the first wall.

4. Tritium Transport

There is a concern that tritium permeation through the last wall section of the blanket could become a safety issue. The unburned D and T from the target will be thermalized in the Xe chamber gas to ≈ 0.1 to 0.2 eV. Some of this D and T will strike the first wall, diffuse through it and join the tritium released from the Li_2O in the blanket. The approach in the SOMBRERO design is to oxidize all of the hydrogen isotopes, e.g., to HTO (or T_2O) in the first coolant channel. The diffusivity of HTO (or T_2O) in materials is orders of magnitude lower than that of H_2, D_2, or T_2.

The oxidation of T_2 to HTO (or T_2O) is accomplished by adding a small amount of steam in the He coolant gas (a partial pressure of ≈ 64 Pa was used in the original SOMBRERO design) to extract the T_2 from the breeder Li_2O. The steam is also needed to prevent the reduction of Li_2O to Li vapor:

$$H_2O + 1/2\ T_2 \leftrightarrow HTO + 1/2\ H_2 .$$

This scheme is repeated in the second, third, etc., coolant channel (see Figure 1). Therefore, the "leakage" between channels is related to the diffusivity of HTO, not T_2.

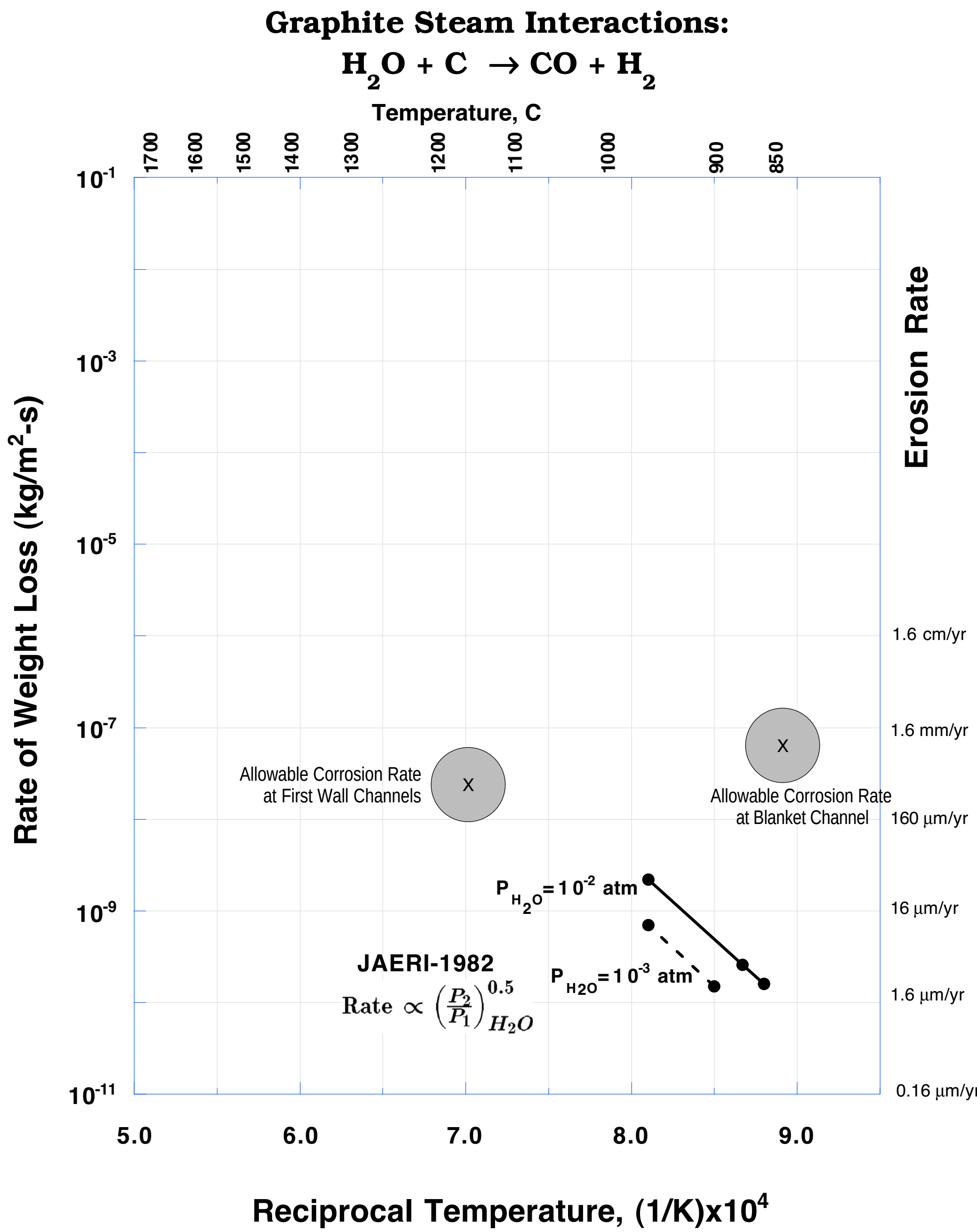

Figure 8. Basis for 1990 SOMBRERO analysis on carbon weight loss.

One might be tempted to ask whether the addition of a small amount of steam to the He coolant would result in erosion of the carbon walls. The original analyses conducted in 1990-1991 were based on experimental data from Hirooka and Imai [12] for the reaction rate of steam with neutron irradiated carbon. A summary of this data is given in Figure 8. The limits for erosion of the first wall and channel wall materials (10% reduction in thickness) have been placed on Figure 8 (note the limit is higher on the channel walls because they are thicker). It is shown that when the 10^{-2} atm steam pressure data from Hirooka and Imai [12] is scaled to 10^{-3} atm (100Pa) and extrapolated to the temperature of the carbon facing the first coolant stream, the erosion limit of a few hundred microns per year can be met.

Since the initial SOMBRERO design was finished, new data from Smolik et al. [13] on carbon weight loss in steam (Figure 9) has been discovered that confirms the original design

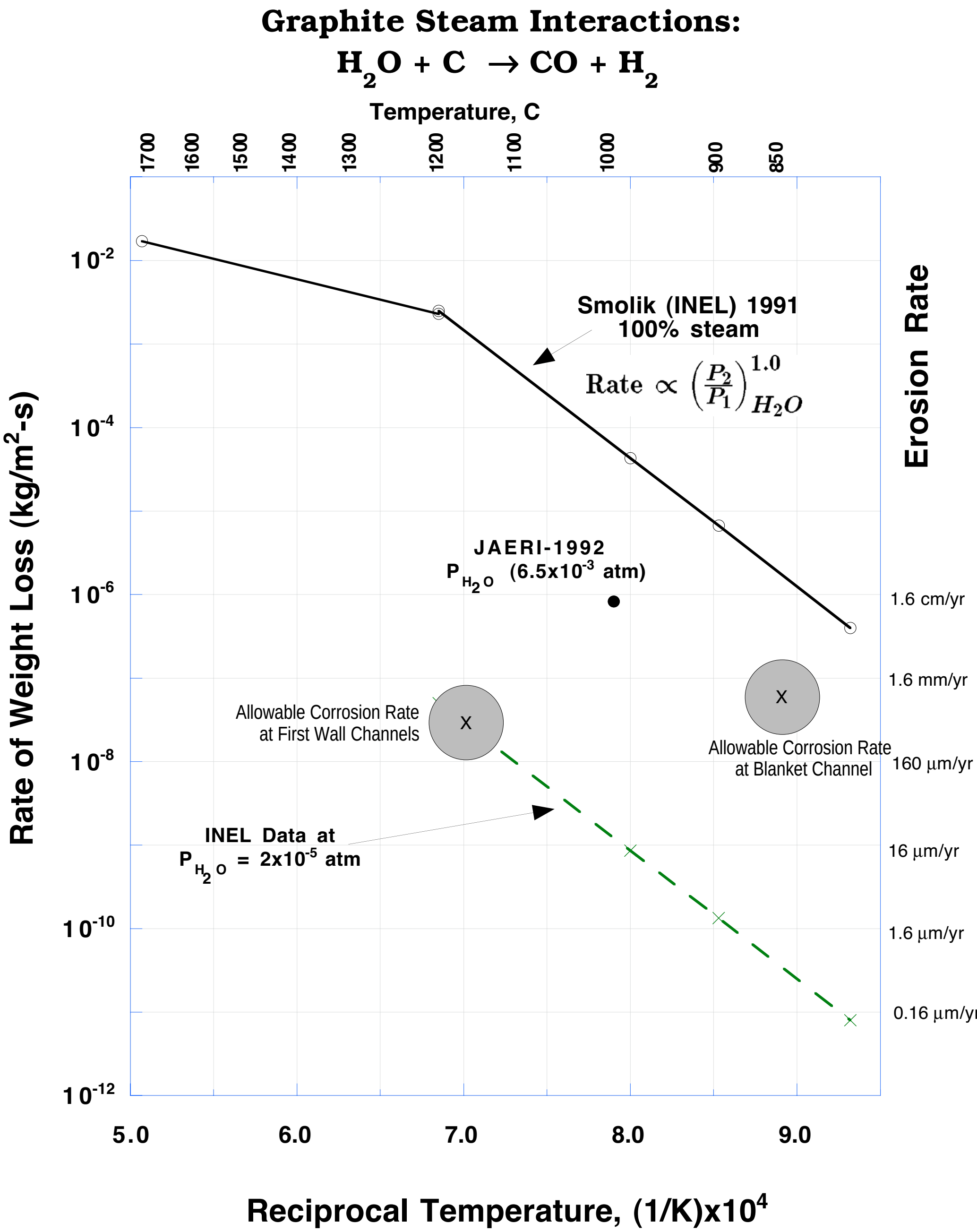

Figure 9. Effect of post-SOMBRERO information on carbon weight loss.

concept if an order of magnitude lower level of steam is used. Therefore, the steam partial pressure in the current design has been reduced to 2 Pa. Such a change results in an erosion rate of <0.3 mm/FPY from the blanket side of the first wall. This lower pressure steam can still convert all the tritium to HTO at the rate that it is bred in SOMBRERO.

Finally, if it is found that not all of the tritium is converted to HTO, then coatings such as B_4C, SiO_2, or thin diamond-like C tritium barriers could be used to reduce any T_2 leakage to very low levels. Therefore, it is not anticipated that there will be any environmental problems due to tritium leakage through the SOMBRERO blanket.

5. Tritium Inventory

There are four main locations where tritium is found in the SOMBRERO blanket: the first wall, the blanket structural walls, the He coolant, and the Li_2O. The tritium inventory in the Li_2O was calculated to be 162 g and that in the He coolant was calculated to be ≈ 5 g. Since there was no "free" tritium in the coolant channels, it was reasoned that there should have been little tritium absorbed and dissolved in the colder (≈ 800°C - 900°C) C-C composite walls. However, there would be free tritium in the reactor chamber and it could get absorbed in the hot first wall. During the time that the SOMBRERO study was done (1990-1991), the tritium inventory was assumed to be governed by the solubility relations existing in the literature of that time. Using the solubility expression of Causey et al. [14], along with the steady-state temperatures calculated for the first wall (1,200°C to 1,400°C), the absorbed tritium inventory in the 10 tonne first wall was calculated to be 10 grams.

Since the SOMBRERO report was written, new information about the effect of irradiation induced traps on tritium retention has become known. The main difference now is that the data of the mid-90's [15-16] shows that the hydrogen isotope inventory in C is closely associated with irradiation induced traps. It was found that the trap concentration saturates at levels of 100 - 1,000 appm and this level strongly depends on the material and the number of surviving defects. Tritium concentrations up to 2,000 appm (≈ 500 wppm) were measured [15] in N3M graphite irradiated at 10 dpa at 600°C. It was also found that irradiation at 875°C dropped the tritium retention by a factor of ≈ 10 (to ≈ 50 wppm) compared to irradiation at 600°C.

Since there will also be hydrogen in the coolant (from the steam) and the level of hydrogen is roughly equal to the amount of tritium, this would leave the tritium to fill only about 25 wppm of the lattice sites at 875°C. This totals ≈ 25 g/tonne of C. Since the dpa rate drops by more than an order of magnitude from the front to the back of the blanket and since most (> 90%) of the graphite is in the low irradiation zone, it is estimated that there might be ≈ 1 kg in the entire structure. That, of course, assumes that the tritium can diffuse into the graphite in the unoxidized form. The fact that the tritium in the blanket is converted to HTO will make less tritium atoms available for diffusion into the graphite.

The amount of tritium retained in the graphite will vary between different materials and it is quite possible that carbon with lower trap densities will be found in the future. If the tritium inventory in the blanket is determined by the solubility of tritium resulting from the reaction with carbon,

$$HTO + C \leftrightarrow CO + HT$$

then the inventory will be less. A recent analysis by Wittenberg [17] (using the data of Strehlow [18]) shows that this mechanism would result with about 1-2 kg of tritium dissolved in the carbon.

In conclusion, it is possible that based on the recent irradiation data reported since the SOMBRERO design was completed, the tritium inventory in the blanket could be in the 1-2 kg range. This level of tritium might be further reduced if coatings (such as boron carbide [19] or SiC [20]) could be found to reduce the diffusion of tritium into the graphite. Experiments on the

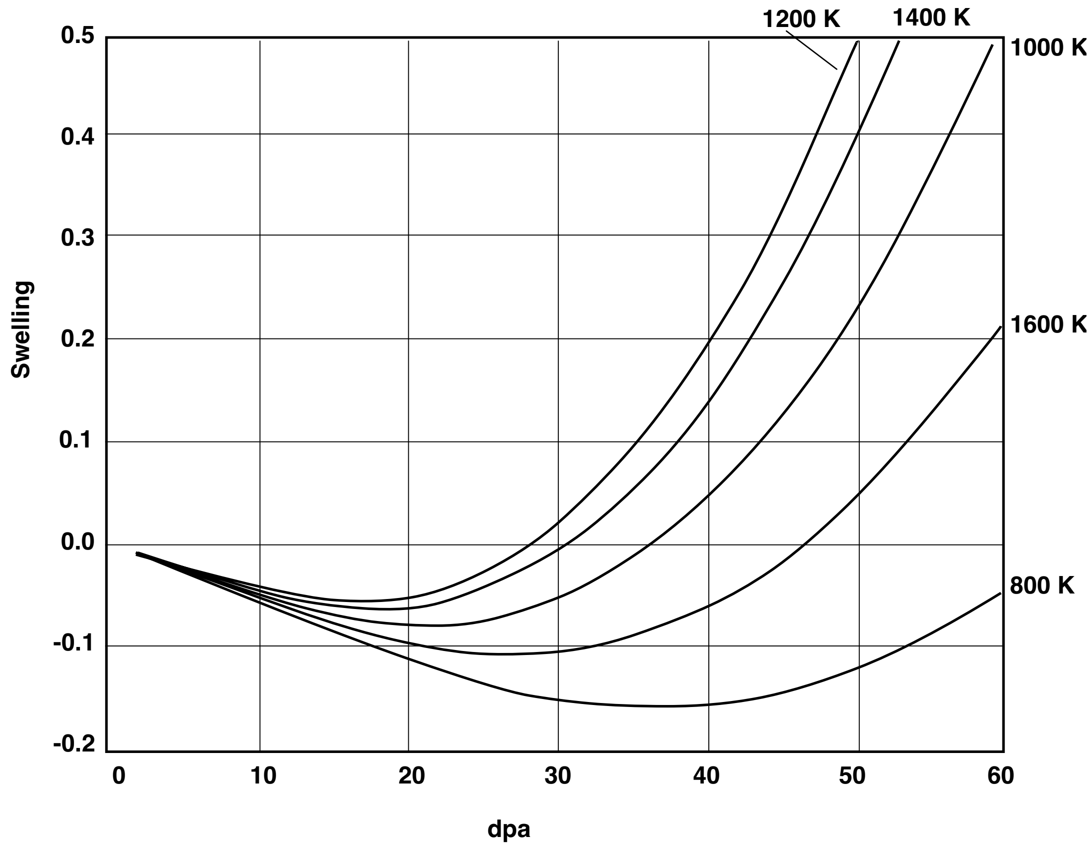

Figure 10. Swelling GraphNOL N3M (Mattas [21]).

actual uptake of tritium in an environment where the tritium is contained as HTO need to be performed.

6. First Wall Lifetime

Graphite displays a distinctive behavior under neutron irradiation in that it first contracts with increasing damage followed by a turnaround into a rapid expansion mode. The point at which the swelling reaches the unirradiated condition (net swelling equal to zero) is normally taken to be the useful life. An example of this behavior is illustrated in Figure 10 for neutron-irradiated N3M graphite in the 500°C to 1,300°C range [21]. At the time of the SOMBRERO study, there was no high temperature (1,400°C to 2,150°C), high fluence (50-75 dpa) neutron irradiation data on CFC's. Therefore, existing data on graphite irradiated at 1,100 to 1,300°C to 60 dpa was used to make preliminary estimates of a first wall lifetime [21]. The data generated by Birch and Brocklehurst [22] showed that in the 1,200 to 1,400°C range, the useful lifetime of some graphites could be in the 20-40 dpa range (see Figure 11). Based on that information, it was projected that, with some improvements, the first wall life could be ≈ 30-45 dpa (≈ 2-3 FPY in SOMBRERO). In addition, it was stated that since the irradiated graphite was not optimized for fusion applications, it was hoped that optimized materials could be developed in the next several decades to double this lifetime to ≈ 75 dpa (5 FPY). This was clearly a hope that has, up to now, not been realized. However, no real effort has been made to extend the useful life of

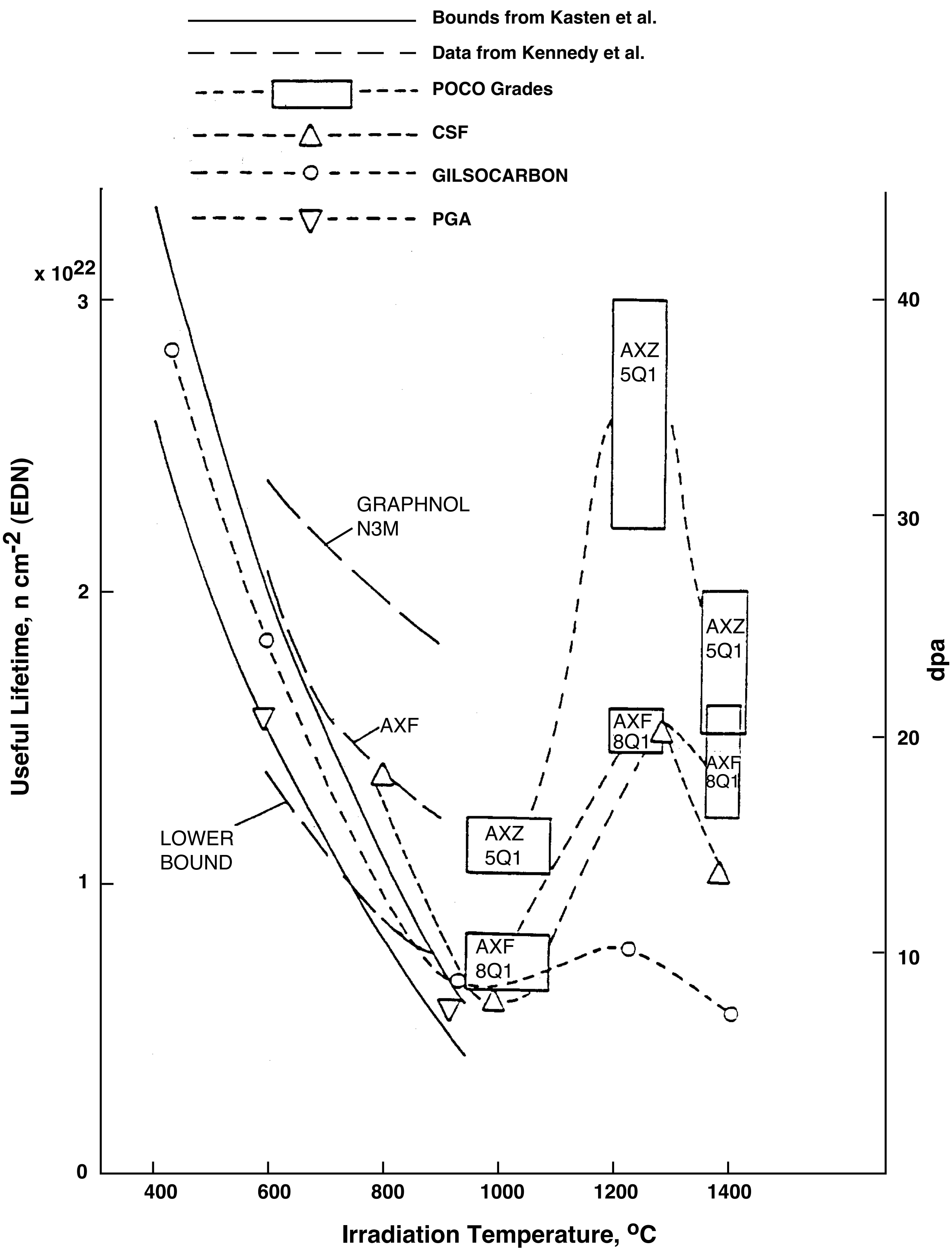

Figure 11. Useful lifetimes in neutron irradiated graphite (Birch and Brocklehurst, [22]).

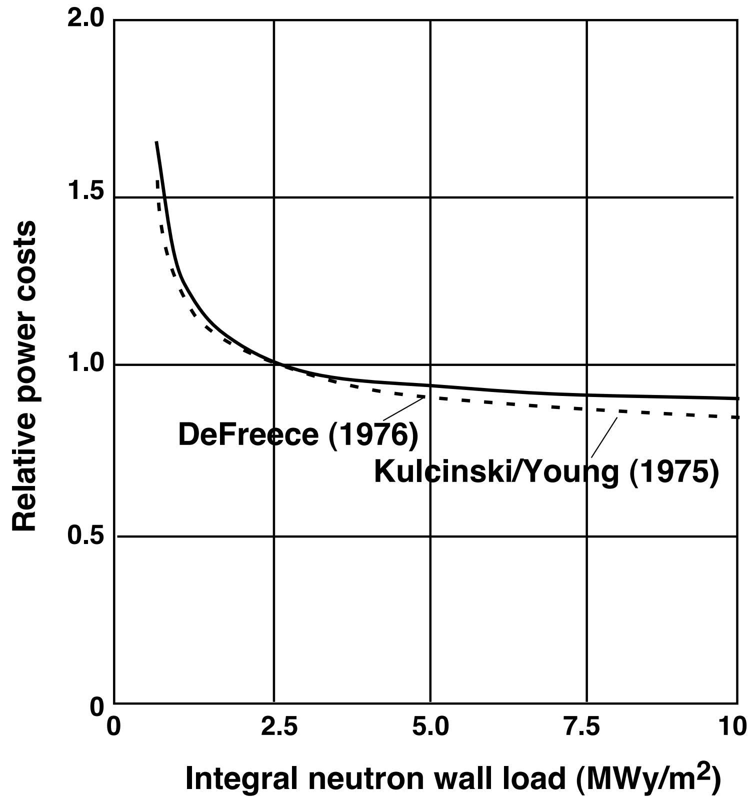

Figure 12. Relative power costs versus the integral wall load (Bünde, [23]).

graphite such as that expended on ferritic steel, vanadium, and SiC. On the other hand, past system studies [23] have shown that once the FW life exceeds 2 FPY, the improvement of the capacity factor is relatively minor (see Figure 12).

Summarizing the issue of first wall life, there appears no reason to modify the original conclusion that a 2-3 FPY life is achievable. Extrapolation to a 5 FPY life is just what it was in 1991, a hope consistently made in all fusion power plant studies, i.e., that in 10-20 years, new materials would be developed to improve the situation. In any case, even a 2 FPY life will make the SOMBRERO design attractive.

7. Conclusions

Of the five main issues raised by the reassessment of the SOMBRERO design, it is found that the original design is viable in four of the five areas. The high temperature of the first few microns of the first wall will remove most of the irradiation-induced defects so that the unirradiated value of thermal conductivity in the carbon fibers can be used. This will suppress significant erosion due to the interaction of the first wall with the radiation from the fireball. The conversion of T_2 to HTO reduces the tritium leakage through the graphite structure. Recent data (that became available after the SOMBRERO report was issued) on the increased trapping of tritium in neutron irradiated graphite does raise the potential level of T_2 inventory in the blanket region to ≈ 1-2 kg. Methods for reducing this level are proposed. Finally, the projected first wall life of 2-3 FPY appears to still be possible and experimental data on 4D weaves irradiated at high temperatures is critically needed.

Acknowledgements

The authors wish to acknowledge the financial support for this work from the Naval Research Laboratory and the technical support and advice from Dr. S. Bodner and Dr. J. Sethian. Our thanks also are extended to Dr. M. E. Sawan for unpublished results of neutronic calculations.

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