Response of the Fusion Technology Institute to the Paper 'High-Temperature Carbon-Irradiation Issues for the SOMBRERO ICF Reactor' by Tobin Munsat, Rion Causey, Mike Ulrickson, and Ken Wilson

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UNIVERSITY OF WISCONSIN

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Introduction

The paper (referred to hereafter as MCUW, 1999) has addressed issues that relate to the SOMBRERO laser fusion reactor design conducted in the 1990-1 period and published in early 1992 (referred to hereafter as SOMBRERO, 1992). As background, it should be recognized that the original analysis was done on the basis of what was known in the 1990-91 time frame. That study was terminated before the SOMBRERO team had a chance for a "post-mortem" analysis of the preliminary design. As is often the case, such follow-on studies identify areas where improvement can be made with only minor modifications.

The issues raised by MCUW fall into 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) CFC first wall lifetime resulting from high temperature neutron irradiation.

- We disagree with the MCUW conclusions on the first three issues. On the other hand, we do agree that on the basis of new data (1994-96), there might be a higher T_2 inventory (≈1 kg) in the graphite structure. The issue of first wall lifetime remains just that, an issue. There is ample evidence for the 2-3 FPY life that we projected in 1991 although we would agree that further experimental data is needed before one would make this a firm design point.

- The potentially higher tritium inventory is not a "show-stopper" as there are engineering and/or materials solutions that would maintain the attractive features of the SOMBRERO design.

In the following analysis, it is assumed that the reader is familiar with the details of the SOMBRERO design and no attempt is made to duplicate the detailed information published in the report (SOMBRERO, 1992). However, a schematic of the SOMBRERO chamber, first wall, and blanket is repeated in Figure 1 for those not familiar with the previous work.

Summary of the Technical Issues in Question

Thermal Conductivity

The SOMBRERO first wall is composed of a 4D C-C composite cooled by flowing Li_2O on the backside (see 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 (Dinwiddie, 1991,

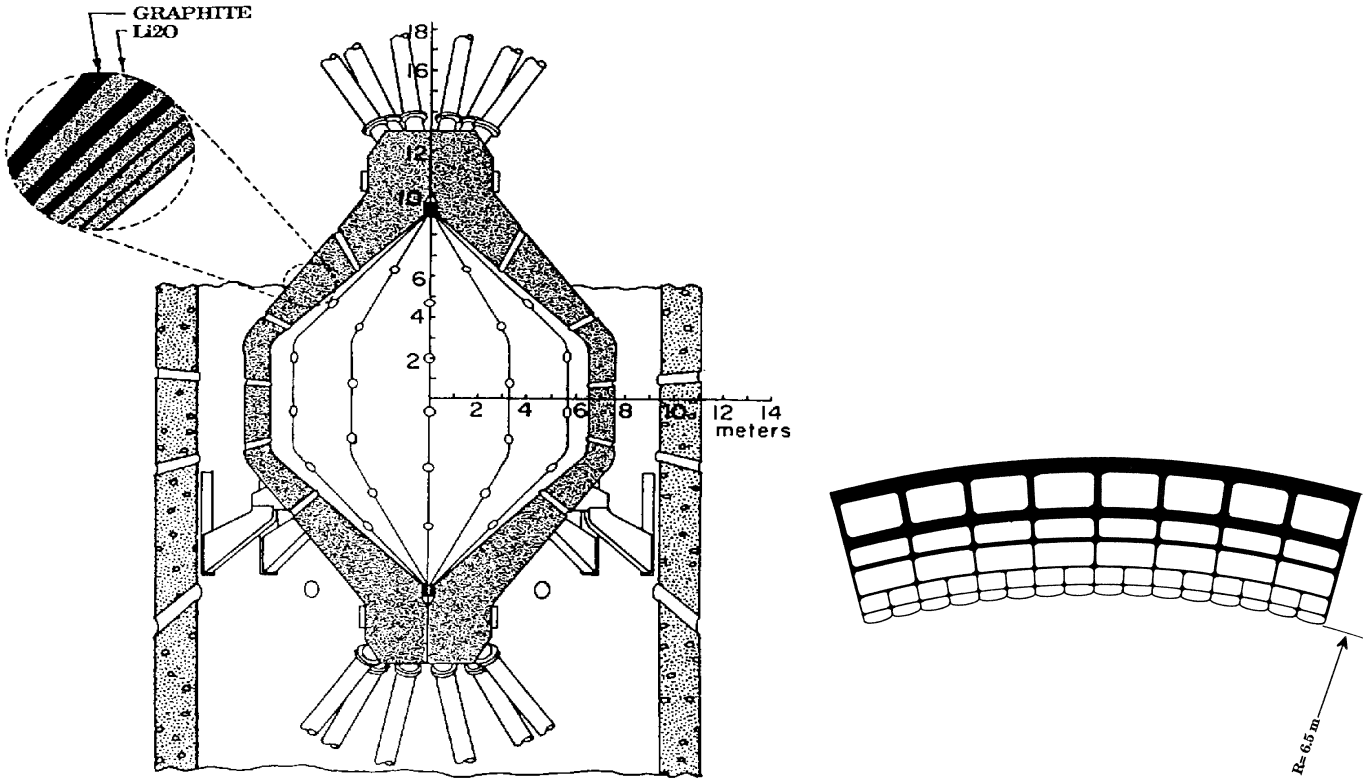

Figure 1. Schematic of the SOMBRERO chamber (left) and cross section of the blanket at the midplane (right).

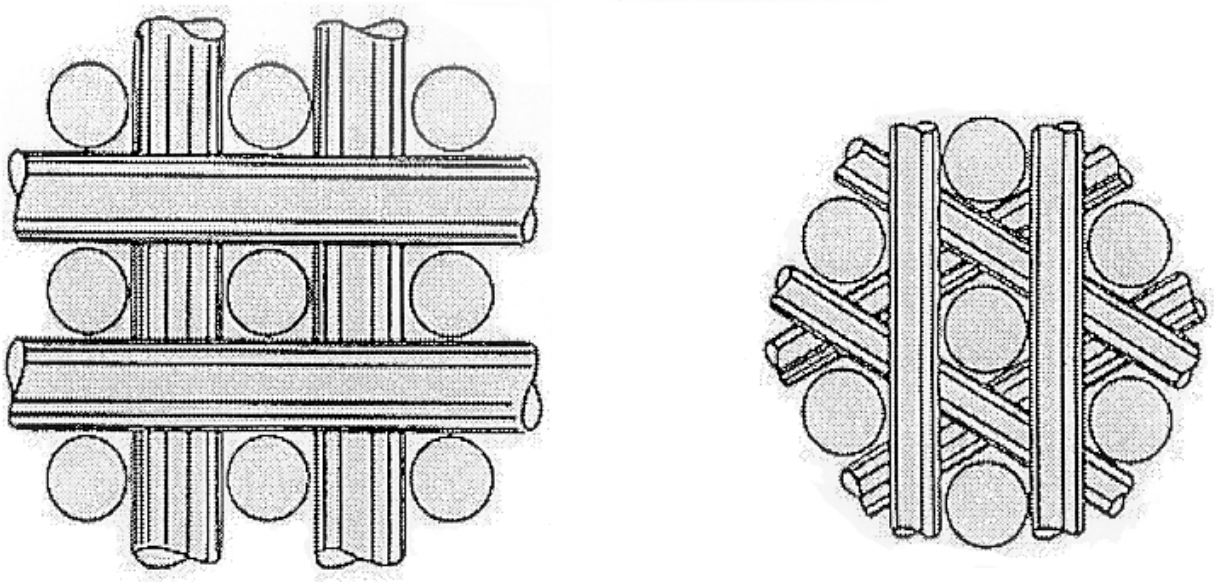

Figure 2. Example of woven graphite structures (courtesy of Mr. Leslie Cohen, Fiber Materials, Inc., Biddleford, Maine).

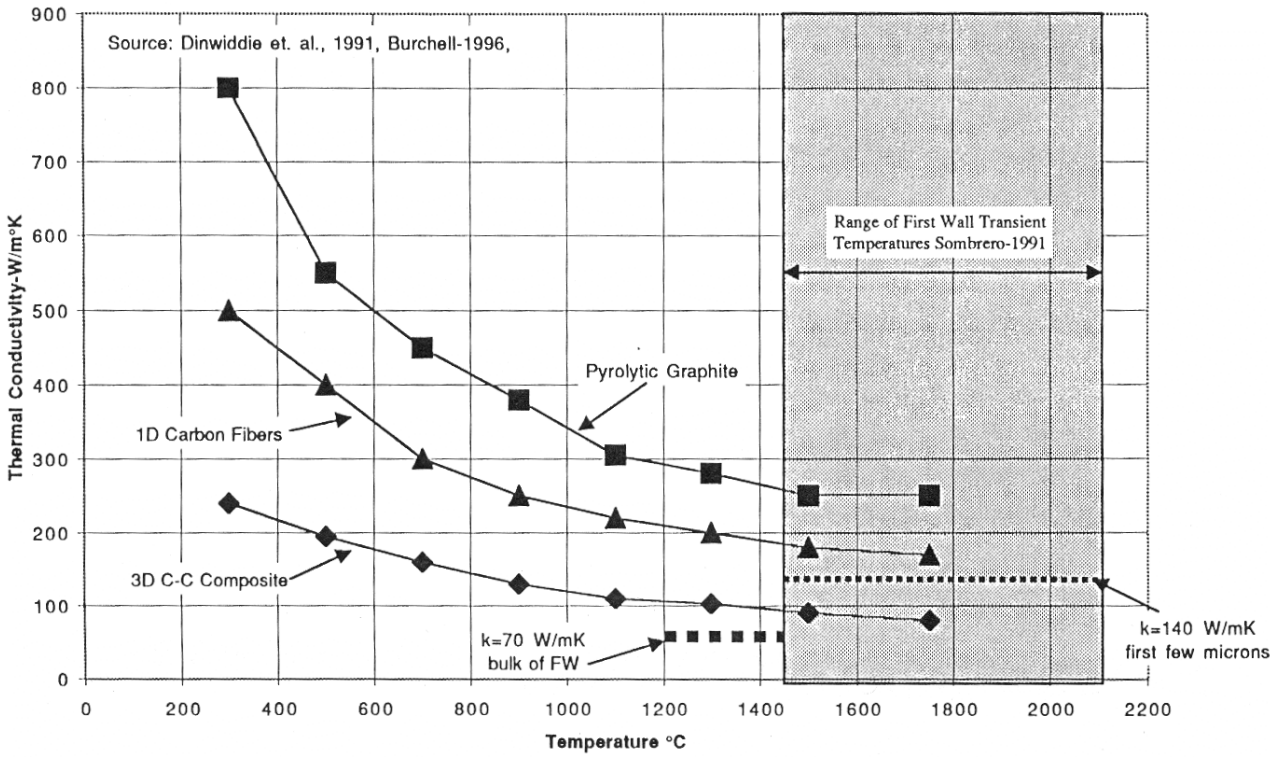

Figure 3. The thermal conductivity of pyrolytic graphite, carbon fibers, and C-C composites drops with increasing temperature.

and Burchell, 1996) shows how high temperatures and the type of graphite influence the thermal conductivity. The effect of irradiation will be treated separately.

The thermal conductivity is particularly important for the first few microns of the first wall facing the target. 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 evaporation. Beyond the first few microns, where the steady state temperature ranges between 1,250 and 1,450°C, the graphite structure must 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. Even though this may seem counterintuitive, there are good reasons for such a choice.

The value of 140 W/mK used for the first wall facing the target is slightly higher than the data 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 we had chosen 120 W/mK, the no evaporation criteria of SOMBRERO would not have been violated.

The question of neutron degradation of the thermal conductivity must also be addressed. It has been known for some time that neutron irradiation reduces the thermal conductivity of carbon. This effect is much more pronounced at low temperatures where the irradiation induced defects can accumulate in the crystal structure. In 1990-1 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 by Wu et al., 1994, and Bonal and Wu, 1996, 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 confirm our original assumption that the most appropriate value for k at this temperature would be the unirradiated value. At the lower temperature for the bulk of the first wall (≈ 1,200 to 1,500°C), the conservative value of 70 W/mK is used because the thermal conductivity would be expected to be significantly reduced from the unirradiated value.

The MCUW, 1999 analysis assumes that thermal conductivity in the first wall would be reduced to ≈ 1/3 of the unirradiated value (or 50 W/mK). This assumption was based on irradiation data from non-CFC's irradiated at temperatures of up to 1,000°C (although the data in Figure 4 is not consistent with this prediction). They admit that at 1,200 and 1,500°C, there is little or no effect on k (a conclusion consistent with Figure 4).

Using the thermal conductivities of 140 and 70 W/mK, we have calculated the peak and steady state temperatures in the SOMBRERO (1992) design. The computer code we used to calculate the temperature is BUCKY (Peterson, 1998). This code can include the time dependent energy flux to the first wall from the fireball (Figure 5) as well as temperature dependent thermal properties of graphite (including latent heat of vaporization). The peak first wall temperatures are given in Figure 6 as a function of thermal conductivity for two different design assumptions:

- The reference 1991 SOMBRERO heat flux of 15. 8 J/cm^2 for <0.1 ms
- The heat flux for the 1991 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 range from ≈2,150 °C for the 140 W/mK value to ≈ 2,500°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.

Wall Erosion

Our design philosophy in SOMBRERO was to avoid evaporation altogether by protecting the first wall through the use of a dilute Xe gas in the chamber and 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 a 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 (Peterson, 1996a, MacFarlane, et al., 1995). BUCKY 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

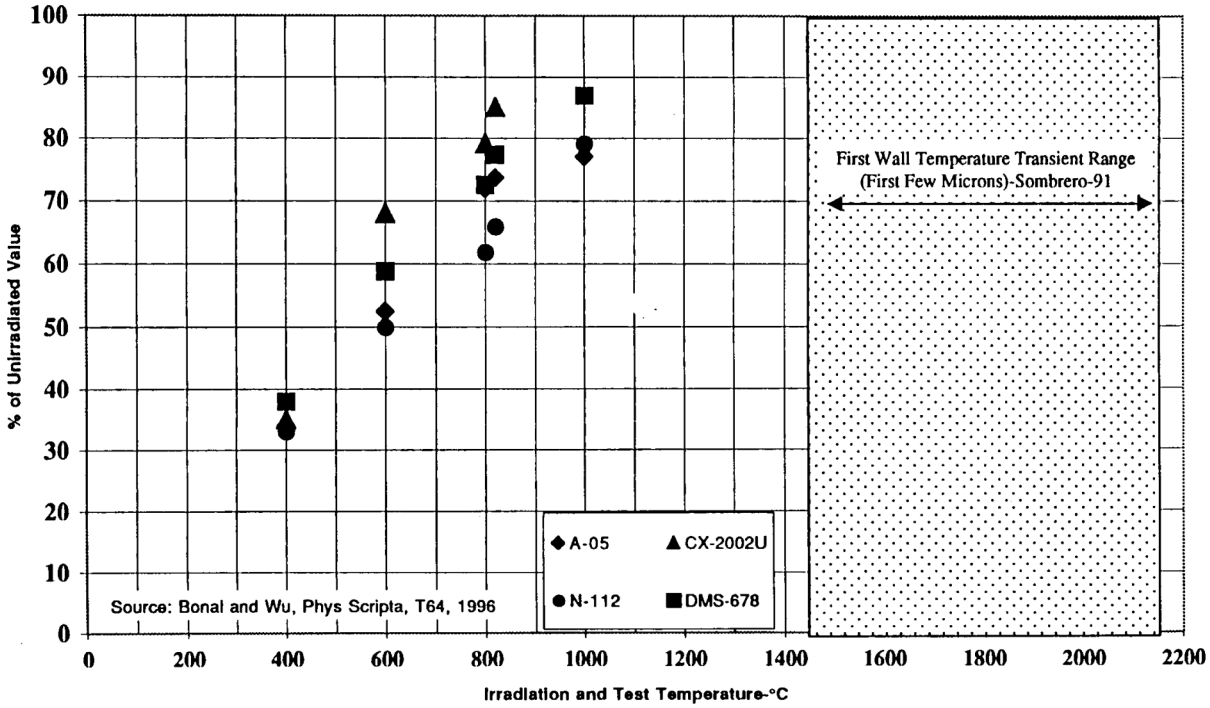

Figure 4. The neutron irradiated thermal conductivity of graphite at ≈1-2 dpa approaches the unirradiated value at high temperatures.

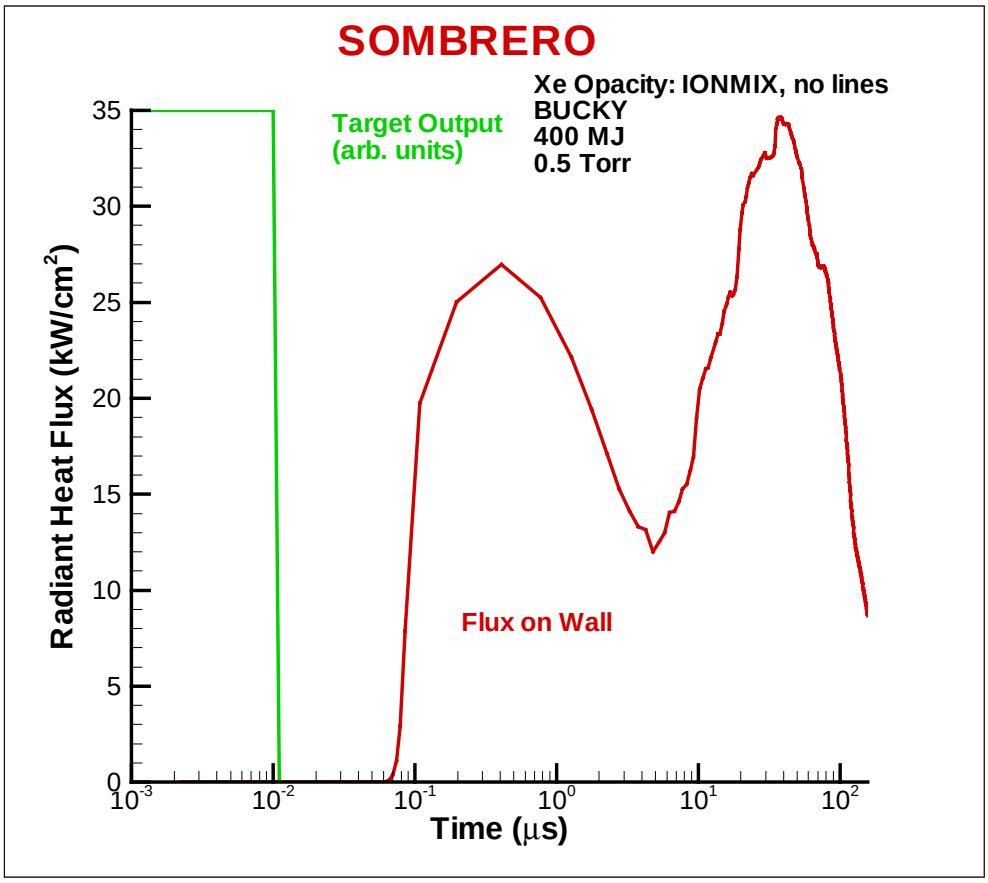

Figure 5. Radiant heat flux on the surface of the SOMBRERO target chamber wall. A 400 MJ yield, 0.5 torr xenon fill gas, and a 650 cm radius chamber has been assumed.

required for phase transitions. When there is not enough energy density to overcome the sensible heat and latent heat there is no phase transition, 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. Our approach has been to ignore any vaporization that is less than 1 Å thick. In BUCKY calculations for SOMBRERO, we calculated the amount theoretically evaporated in Å per shot and plotted that versus the thermal conductivity of 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 (Peterson, 1996b), pulsed vaporization experiments were performed on the Nova, Helen, and Phebus lasers. Pulsed x-rays of variable fluences vaporized measured amounts of various materials. The BUCKY code has been benchmarked to those experiments (Schirmann, 1996).

We have recently performed fully integrated fireball/wall response simulations with BUCKY with updated opacities (Ping, 1991). 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 calculations. The increased opacity 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 we will report the new, much lower power loads 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 the evaporation per shot drops below 1 Å per shot above 115 W/mK for the SOMBRERO, 1992 reference case and above 85 W/mK for the reference case if the first wall was moved back to 7 meter radius. Therefore our original choice of 140 W/mK could be relaxed either with the reference design or with a slightly modified design and still avoid first wall evaporation.

If in the worst case, all else fails, there are other methods of dealing with the erosion such as:

1) lowering the yield of the target and increasing the rep rate to > 6.7 Hz, or
1) 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.

For reference, the MCUW, 1999 analysis assumed that the peak reference heat flux in the SOMBRERO design existed for 0.5 ms. This heat flux was calculated to produce a peak temperature of 2,523°C (k=50 W/mK), which in turn gave an erosion rate of 8.8 mm/FPY using a vapor pressure related evaporation model.

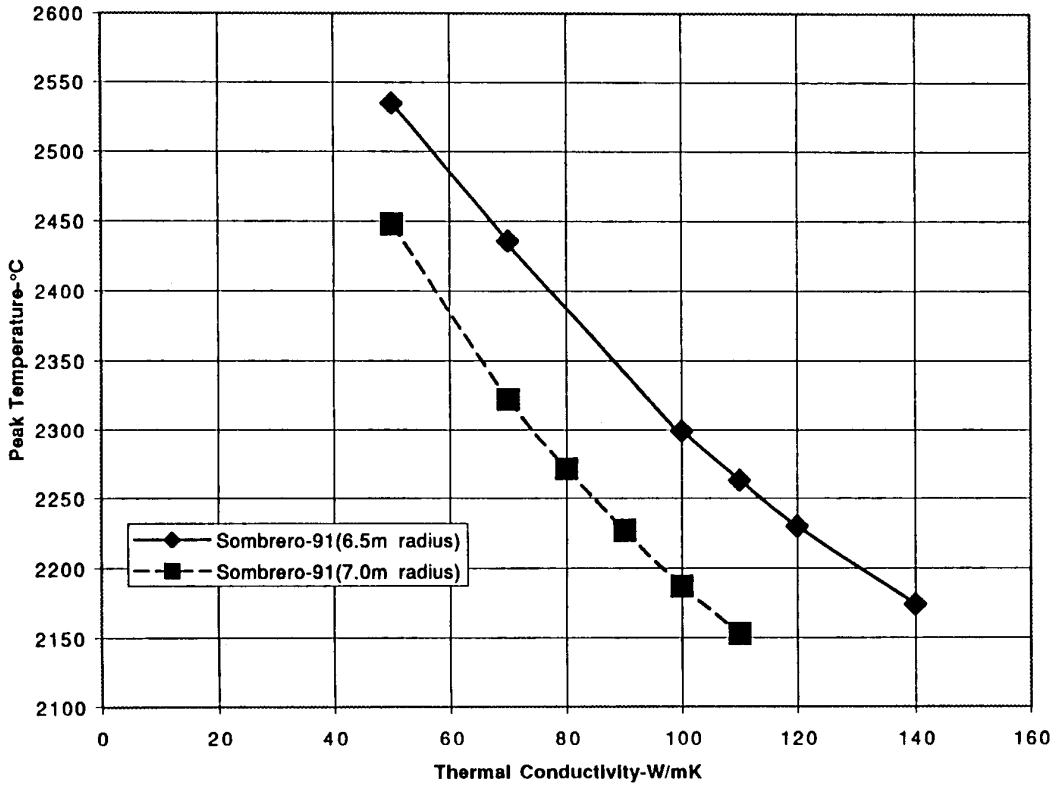

Figure 6. The peak first wall temperatures in SOMBRERO depend on the thermal conductivity of the first few microns.

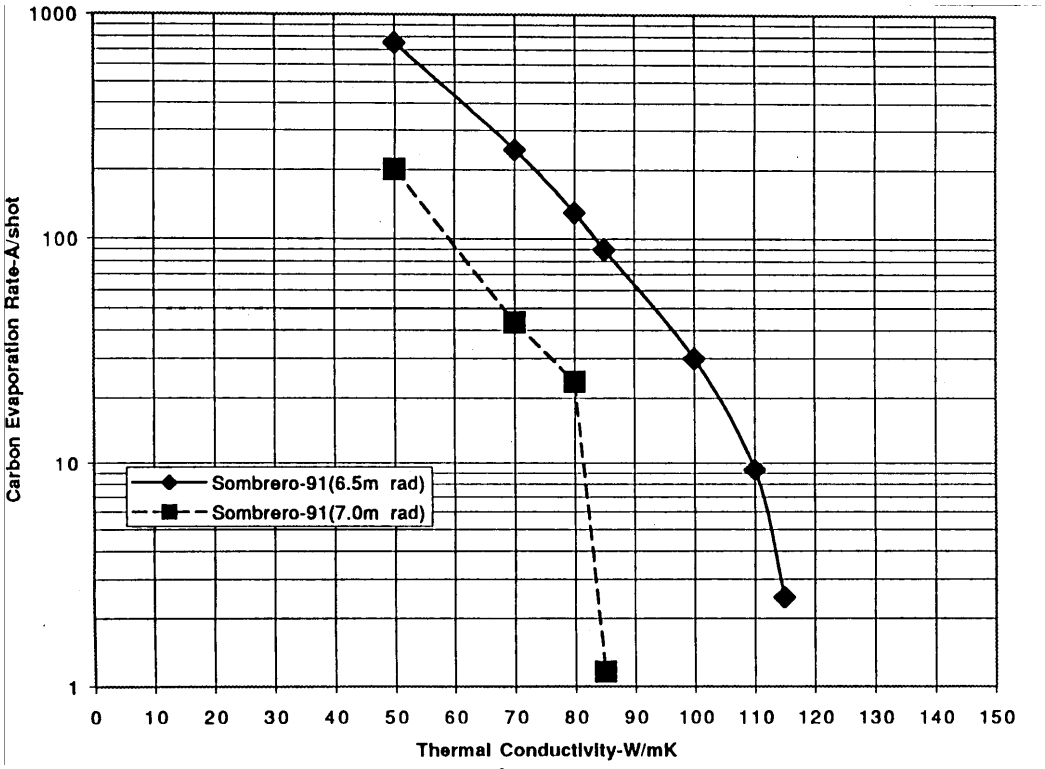

Figure 7. Once the evaporation is below a few Å per shot, there is essentially no erosion of the C-C first wall.

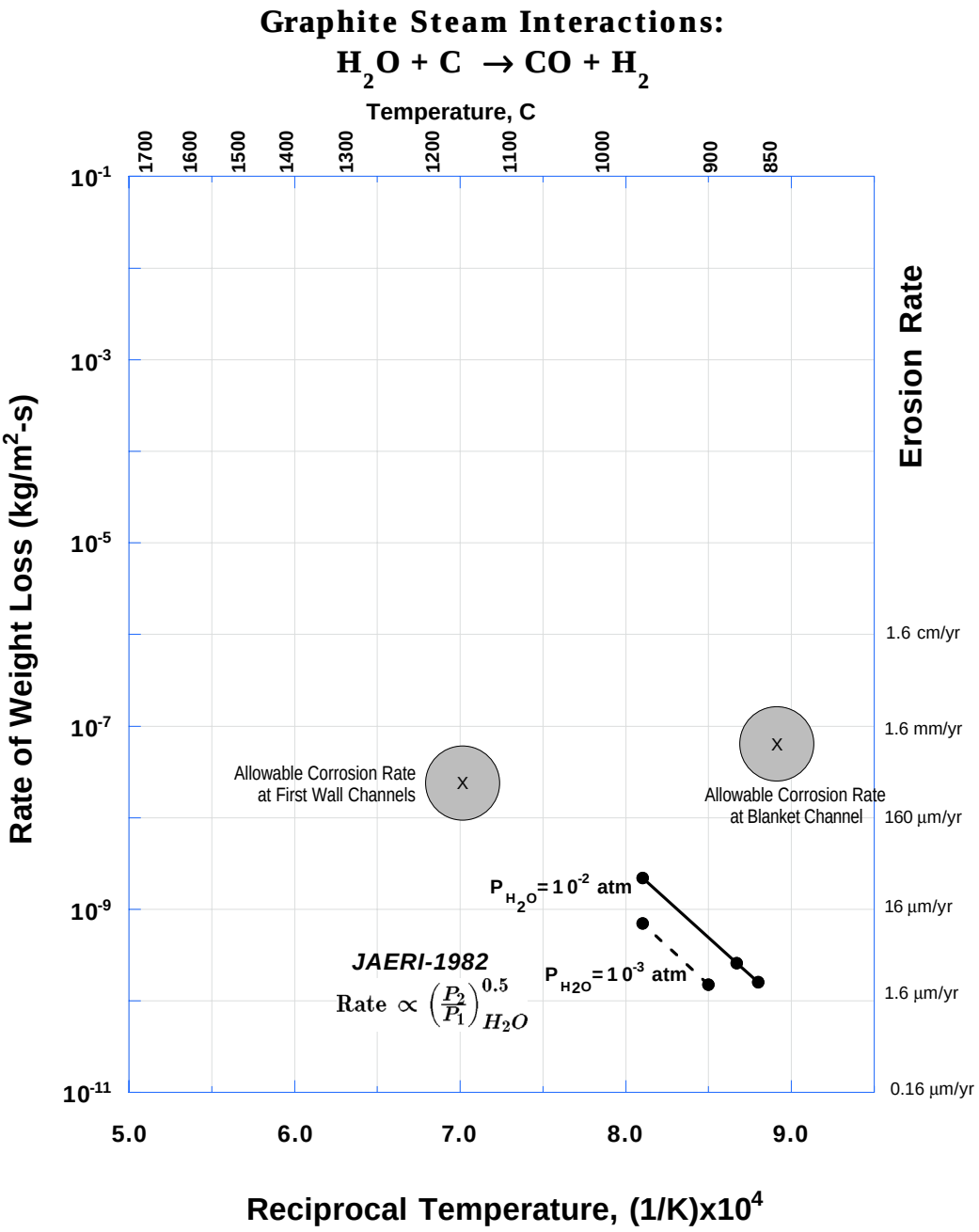

Figure 8. Basis for 1990 SOMBRERO analysis on carbon weight loss.

Our conclusion 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.

Tritium Transport

There was a concern raised in the MCUW, 1999 paper that "permeation through the last wall section is likely to be a safety issue." This observation may be the result of a misunderstanding of how the SOMBRERO blanket is designed. First of all, the unburned T and D atoms will not "strike the first wall with an energy of a few eV" as stated in the MCUW, 1999 report. The unburned D and T will be thermalized in the Xe chamber gas at ≈ 0.1 to 0.2 eV. Whatever D and T does get absorbed and eventually diffuses through the first wall will join the tritium released from the Li_2O and get oxidized to HTO (or T_2O) in the first

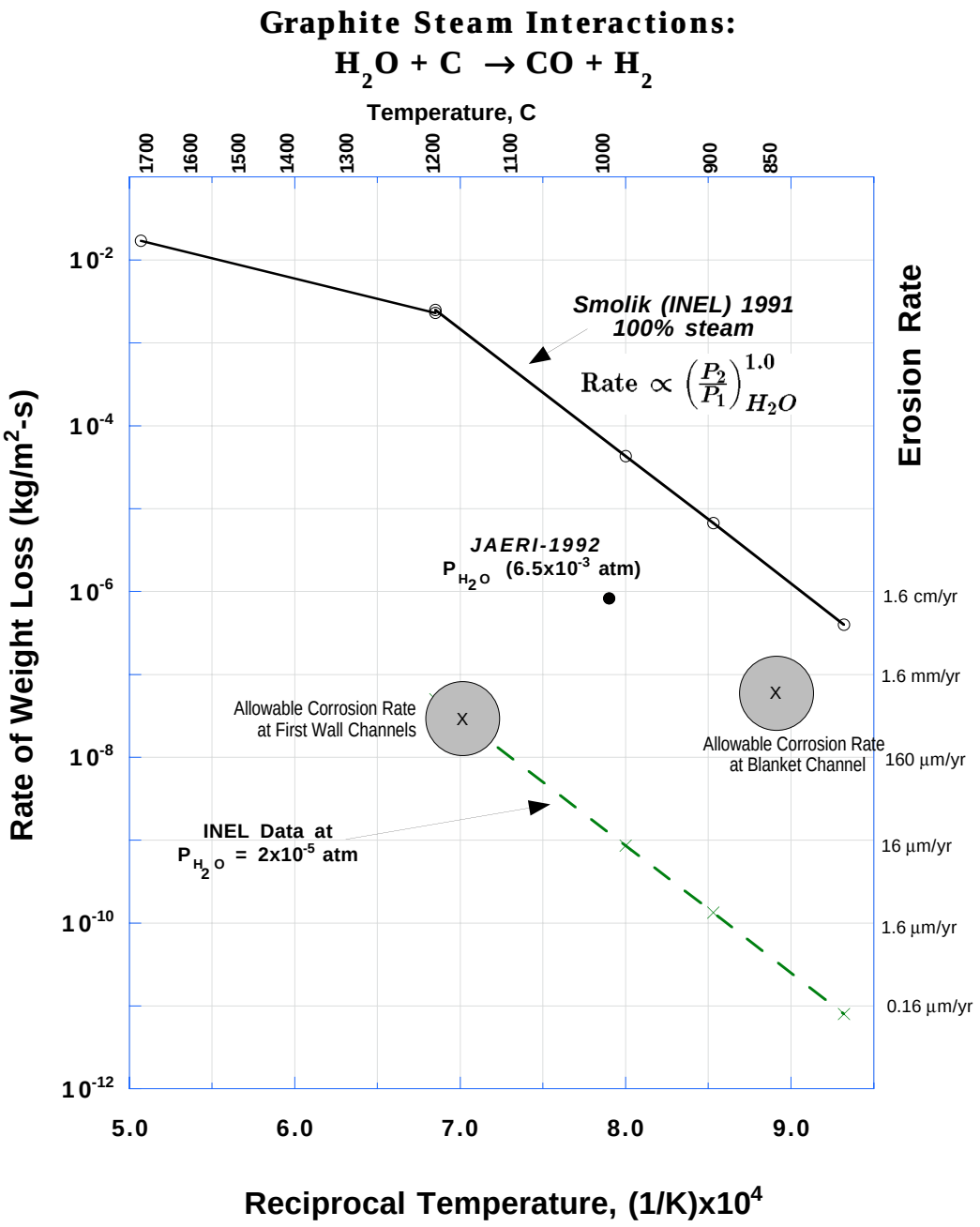

Figure 9. Effect of post-SOMBRERO information on carbon weight loss.

coolant channel. The diffusivity of HTO (or T_2O) is orders of magnitude lower than that of T_2 in materials.

The oxidation of T_2 to HTO (or T_2O) is accomplished by adding a small amount of steam in the He coolant gas (we used ≈ 64 Pa 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, …, coolant channel (see Figure 1). Therefore, the "leakage" between channels is related to the diffusivity of HTO, not T_2.

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. Our original analyses (in 1990-1) were based on experimental data from Hirooka and Imai, 1982, for the reaction rate of steam with neutron irradiated carbon. A summary of this data is given in Figure 8. We have placed the limits for erosion of the first wall and channel wall materials 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 data from Hirooka and Imai (1982) is scaled to 10^{-3} atm 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, we have found new data from Smolik et al., (1991) on carbon weight loss in steam (Figure 9) that confirms our original design concept but indicates that we should use an order of magnitude lower level of steam. Therefore, we have reduced the steam partial pressure to 2 Pa and that 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 the tritium to HTO at the rate that it is bred in SOMBRERO.

If we find 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, we do not anticipate any environmental problems due to tritium leakage.

Tritium Inventory

During the time that the SOMBRERO study was done (1990-1), the tritium inventory was assumed to be governed by the solubility relations in the literature at that time. There are four main locations for the tritium 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, we reasoned that there should have been little tritium absorbed and dissolved in the colder (≈ 800-900°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. Using the solubility expression of Causey et al., 1986, along with the steady state temperatures calculated for the first wall (1,200 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 the tritium retention has come to light. The main difference now is that the data of the mid-90's (Causey et al., 1996, and Kwast et al., 1996) 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 (100 to 1,000 appm) which strongly depend on the material and the number of surviving defects. Tritium concentrations of up to 2,000 appm (≈ 500 wppm) were measured (Causey et al., 1996) 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 we will also have hydrogen in the coolant (from the steam) which is roughly equal to the amount of tritium, this would leave the tritium to fill about 25 wppm of the lattice sites. This amounts to ≈ 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, we would estimate 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 we have converted the tritium in the blanket to HTO will make less tritium atoms available for diffusion into the graphite. However, it is not possible at this time to adequately assess this effect.

The amount of tritium retained in the graphite will vary between different materials and it is quite possible that we will find carbon with lower trap densities. 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 ≈ 75 g. This was calculated using the data of Strehlow, 1986.

If all else fails, boron carbide (Fujii et al., 1992) or SiC (Perez and Ghoniem, 1990) coatings could be applied to reduce the uptake of tritium.

In conclusion, we would agree that, on the basis of the recent irradiation data reported since the SOMBRERO design was completed, the tritium inventory in the blanket could approach 1 kg if coatings cannot be found to reduce the diffusion of tritium into the graphite. Experiments on the actual uptake of tritium in an environment where the tritium is contained as HTO need to be performed.

First Wall Lifetime

Graphite displays the 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 (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 to 1,300°C range (Mattas, 1985). At the time of the SOMBRERO study (1990-91), there was no high temperature (1,400 to 2,150°C), high fluence (50-75 dpa) neutron irradiation data on CFC's. Therefore, we used existing data on graphite irradiated at 1,100 to 1,300°C to 60 dpa to make our preliminary estimates of a first wall lifetime (Mattas, 1985). We also used the data generated by Birch and Brocklehurst (1987) which showed that in the 1,200 to 1,400°C range, the useful lifetime of some graphites could be in the 30-40 dpa (≈ 2-3 FPY) range (see Figure 11). On the basis of that information, we projected that the first wall life would be ≈ 30-45 dpa (≈ 2-3 FPY's in SOMBRERO). In addition, we stated that since the graphite that had been irradiated was not optimized for fusion applications, we would hope that optimized materials could be developed in the next several decades to double this lifetime to ≈ 75 dpa (5 FPY's). 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 graphite such as that expended on ferritic steel, vanadium, and SiC.

The MCUW, 1999 report states that "more realistic lifetime estimates are in the range of 15-30 dpa." This conclusion is only a factor of two below the data we had in 1990. Such a difference is not a cause for concern as long as the lifetime can approach 2 FPY's. Past system studies (Bünde, 1977) have shown that once the FW life exceeds 2 FPY's, the improvement of the capacity factor is relatively minor (see Figure 12).

On the issue of the first wall life, there is 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 1990, a hope consistent with all fusion power plant studies that in 10-20 years, new materials will be developed to improve the situation. In any case, even a 2 FPY life will make the SOMBRERO design attractive.

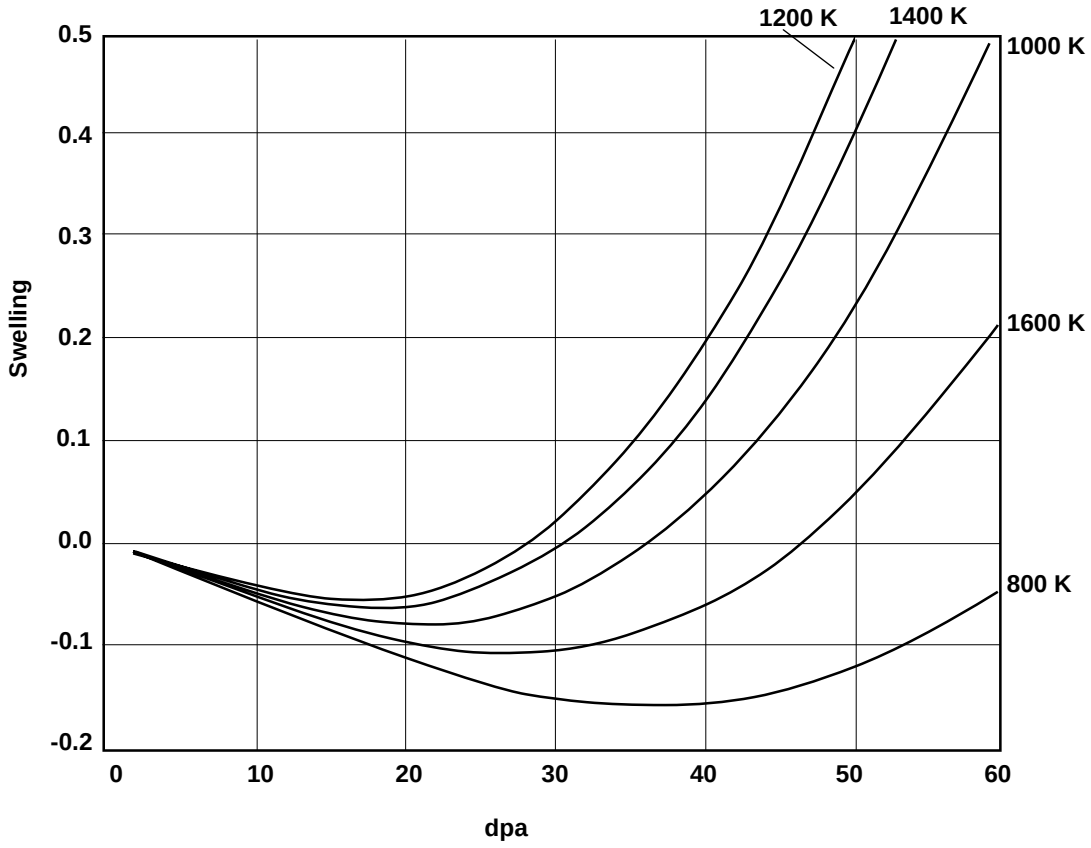

Figure 10. Swelling GraphNOL N3M (Mattas).

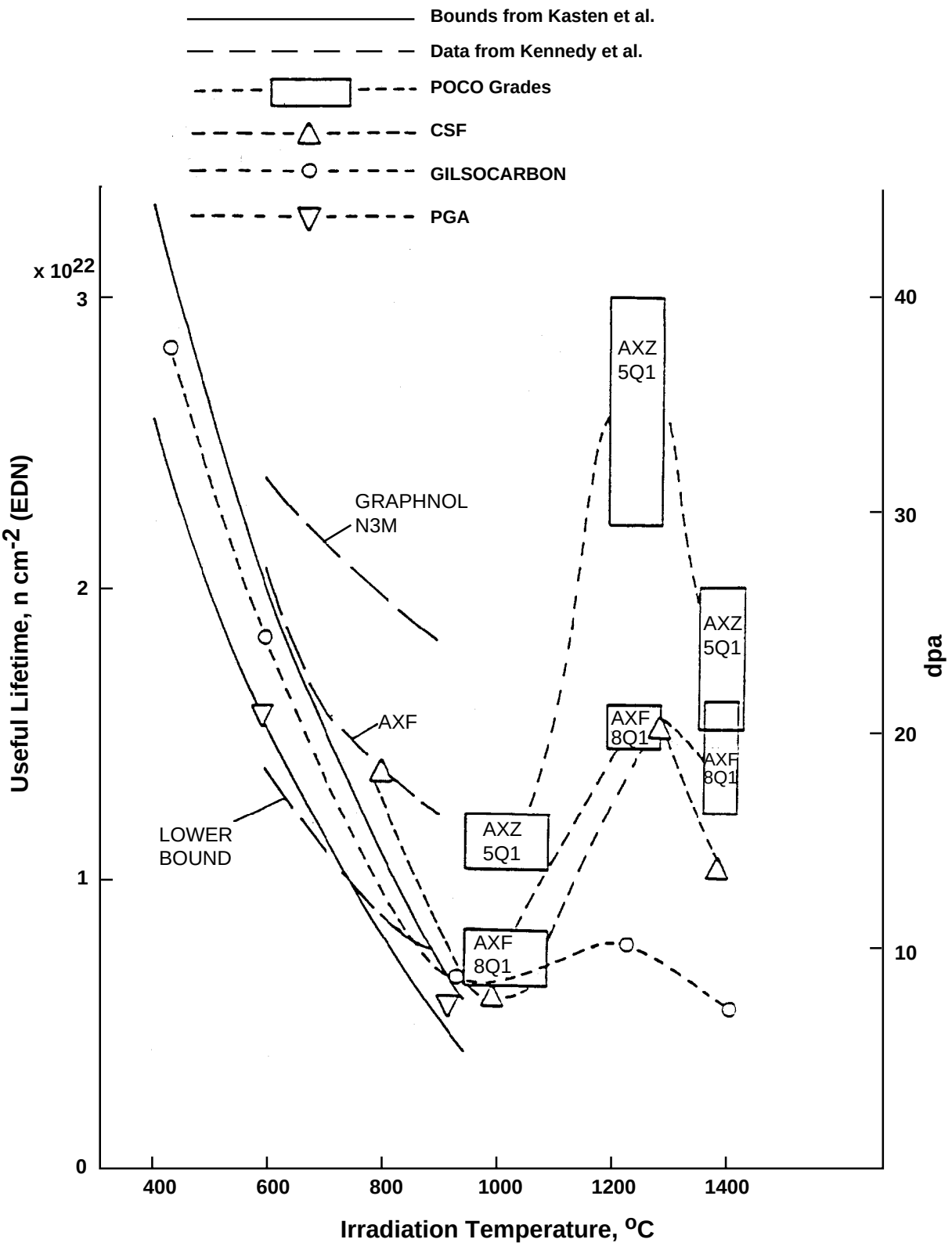

Figure 11. Useful lifetimes in neutron irradiated graphite (Birch and Brocklehurst).

Conclusions

The 5 main issues raised by the MCUW paper have been examined and we find that re-analysis of the SOMBRERO power plant study confirms the original design in 4 of the 5 cases. 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. A misunderstanding by MCUW about the form of the tritium in the Li_2O coolant zone was responsible for their concern over tritium leakage. 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 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. Design solutions to increase the first wall life also exist and should be re-examined with the SOMBRERO team.

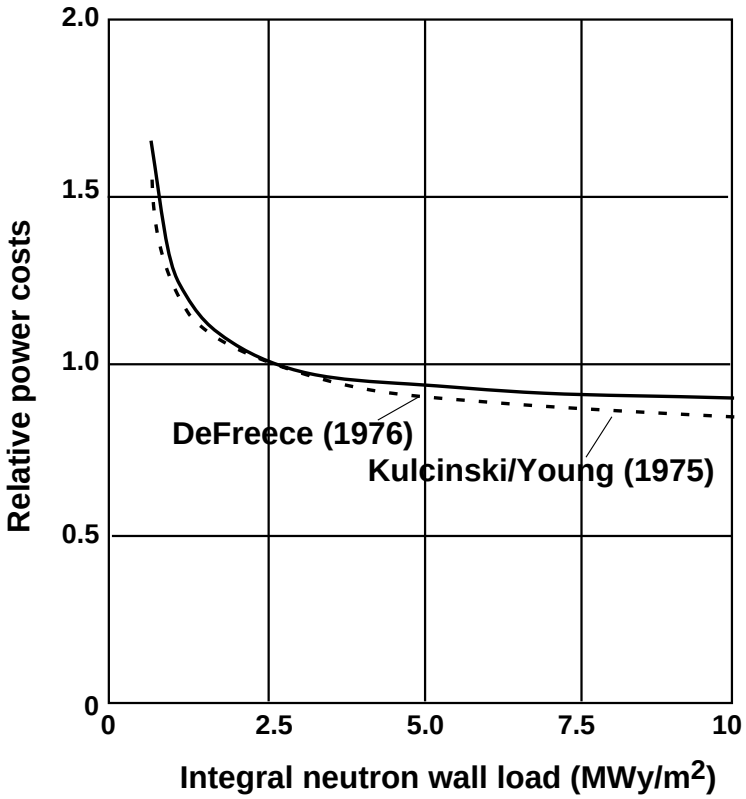

Figure 12. Relative power costs versus the integral wall load (Bünde,).

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