Differences Between Neutron Damage in Inertial and Magnetic Confinement Fusion Materials Test Facilities

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Fusion Technology Institute
Nuclear Engineering Department
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Fusion Technology Institute, 1500 Johnson Drive
University of Wisconsin-Madison, Madison, WI 53706

Abstract

It is a common misconception that the unit of neutron wall loading, the MW/m^2, can be applied equally to the calculation of damage in fusion reactor materials whether it is produced by neutrons from inertially confined fusion (ICF) plasmas or magnetically confined fusion (MCF) plasmas. It is shown that, depending on the geometry of the fusion device, the displacement and/or transmutation rates in any given material could vary by as much as 50-75%. In addition, it is shown that the neutron source spectra from a MCF plasma is considerably different than that from an ICF plasma and these differences can cause the damage parameters to be as much as 10-15% different for the same MW/m^2 neutron wall loading. The difference in the instantaneous damage rate between ICF and MCF can be as much as a factor of 10^8. With such large differences between ICF and MCF test facilities, it is concluded that great care must be exercised when comparing data between the two confinement approaches.

I. Introduction

The need to test structural materials under realistic fusion reactor conditions has been discussed in both the magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) communities for over a decade. The MCF program has taken the lead in attempting to solve this problem by sponsoring several test reactor studies such as FERF,[1] TETR,[2] INTOR,[3] TASKA,[4] TASKA-M,[5] TDF,[6] FEF,[7] etc. Most of these studies have concentrated on providing a neutron, thermal, and corrosive environment which would closely simulate that to be expected in the first demonstration reactor or the first commercial magnetic fusion reactor.

In contrast to the MCF technology program, the efforts of the ICF technology program have been on conceptual design of commercial power plants and there has been a curious lack of near term test facility designs. The singular exception is a brief scoping study of a device called LA FERF[8] in 1975 at LLNL.

Perhaps the difference in the current testing philosophy of the two programs can best be understood by the following general paraphrasing of the problem:

From the Magnetic Fusion Approach

"Given the intense radiation environment of a fusion reactor, how can we develop materials which will operate safely?"

From the Inertial Fusion Approach

"Given the materials we have, how can we modify the fusion environment to allow the materials to operate safely?"

Despite the fundamental difference in approach, it is commonly assumed by the ICF community that the MCF materials programs will provide the data needed for designing the inertial confinement reactors. Part of this paper will be devoted to showing why such an assumption may not be appropriate.

Another objective of this paper is to show why the damage conditions in an ICF environment are so different when compared to a MCF reactor and why a separate ICF materials test facility may be needed. As an example of such a facility, some preliminary data from a laser driven test facility, SIRIUS,(9) will be given.

II. Specific Differences in Neutron Damage Rates Between Inertial and Magnetic Confinement Test Facilities

There are at least three major reasons why the neutron damage in ICF and MCF materials test facilities can be significantly different even when the samples are exposed to the same level of radiation (quoted in $MW\text{-}y/m^2$ for this study). These discrepancies arise from:

A. Geometrical effects,

B. Spectral effects, and

C. Temporal effects.

Before considering the combined effects of these parameters, it is worthwhile to examine them individually.

III. Geometrical Differences

At first glance, one would not expect that the damage per $MW\text{-}y/m^2$ in the first wall of a sphere surrounding a point source of neutrons would be significantly different than that in a cylindrical (or toroidal) chamber surrounding a volumetric distributed neutron source. Closer examination of the problem reveals that due to the formal definition of the neutron wall loading, Γ (usually in MW/m^2), there can be substantial differences in damage rates depending on the geometry.

The formal definition of Γ is given below

$$\Gamma = \iint \bar{n} \cdot \bar{J}(\bar{\Omega}) S(E) E \, dE d\bar{\Omega} \tag{1}$$

where: $\bar{n}$ is the unit normal to the first wall

$\bar{J}$ is the neutron angular current

$S(E)$ is the neutron source energy spectrum

$d\bar{\Omega} = 2\pi d(\cos\theta)$

θ = angle between the incident neutron direction and $\bar{n}$

E = the neutron energy.

Since the neutron angular current is equal to $\bar{\Omega}\psi(\bar{\Omega})$, where $\psi(\bar{\Omega})$ is the neutron angular flux, we can rewrite Eq. (1) as follows,

$$\Gamma = \overline{\cos\theta} \, \bar{E} \int \psi(\bar{\Omega}) \, d\bar{\Omega} \; . \tag{2}$$

$\bar{E}$ is the average neutron source energy. The average cosine of the angle between the incident neutron direction and the normal to the wall, $\overline{\cos\theta}$, is given by

$$\overline{\cos\theta} = \frac{\int (\bar{n} \cdot \bar{\Omega}) \; \psi(\bar{\Omega}) \; d\bar{\Omega}}{\int \psi(\bar{\Omega}) \; d\bar{\Omega}} \; . \tag{3}$$

A better understanding of the impact that Eqs. (2) and (3) can have on the damage produced in the first wall is obtained from Fig. 1. Two extreme cases

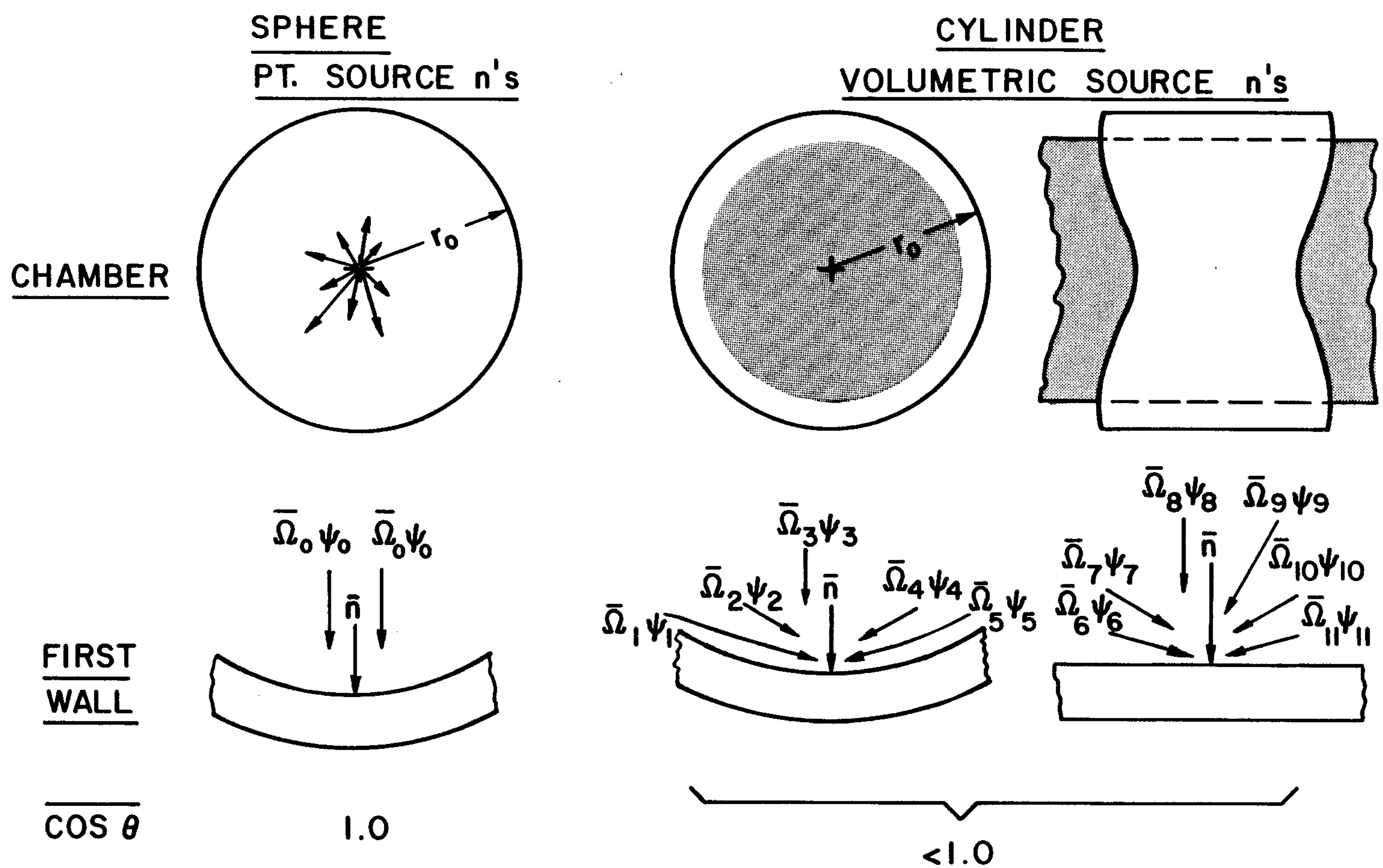

Fig. 1. Geometrical aspects of neutron interaction with ICF and MCF first walls.

are considered; the first is a spherical wall surrounding a point source of neutrons and the second is an infinite cylindrical wall (the same radius as the sphere) surrounding a uniformly distributed volumetric neutron source.

The units for Γ are normally expressed in MW of neutron energy (1 MW = 6.25×10^{18} MeV/s) passing from the plasma side of the first wall into the blanket per square meter of surface area. It is important to note that Γ does not include backscattered neutrons from the blanket and is not a flux but rather Γ is a current density of neutrons on their initial pass through the first wall. Neutron fluxes (from which we calculate dpa and transmutation rates) are related to the wall loading.

Turning back to Fig. 1 we find that all the neutrons emitted from an ICF target in the center of a spherical chamber enter the first wall parallel to the unit normal. This means that $\theta = 0$ and $\overline{\cos\theta} = 1$ so that the wall loading is simply expressed by:

$$\Gamma = \bar{E}\psi_0 \ . \qquad (4)$$

However, since the neutrons from a cylindrical distributed source can enter the first wall at various angles, $\overline{\cos\theta} < 1$. This means that in order to obtain the same MW/m^2 of wall loading in the first wall of a sphere and a cylinder, the uncollided neutron flux must be higher in the cylindrical case. The higher the uncollided flux, the higher the damage and transmutation rate in the first wall. To some degree this increased damage level in the first wall will be compensated by a faster dropoff in the damage rate as one proceeds from the first wall into the blanket of a cylindrical chamber.

However, since we are mainly concerned with the maximum damage, the first wall values will be used for the rest of this report.

A quantitative example will illustrate the above point quite nicely. The dpa and helium production rates were calculated for an Fe first wall for both geometries of Fig. 1 with r_0 = 2 meters. The first wall was surrounded by a 60 cm steel and water blanket and the results were normalized to 1 MW-y/m^2 of neutron exposure. A summary of the result is shown in Fig. 2 for a monoenergetic 14.1 MeV neutron source.

Based on 1 MW of neutron energy crossing a 1 m^2 area of first wall for 1 year, we see that there is a 50% increase in the damage rate of the cylindrical first wall compared to the spherical chamber. The situation is even more severe for helium production as 67% more helium is produced per MW-y/m^2 in the cylindrical wall compared to the spherical wall. Fortunately, the appm He/dpa ratios are only 11% different.

IV. Spectral Differences

The main difference between ICF and MCF neutron spectra is due to the slowing down of neutrons in the highly compressed target before they hit the first wall. Whereas the neutrons emanating from a MCF plasma have a rather well defined energy at 14.1 MeV, those escaping an ICF target can have average energies as low as 10 MeV at high ρR values (ρ is the compressed density of the fuel and R is the radius of the compressed zone). The relationship between the average neutron energy impinging on the first wall of an ICF reactor versus the ρR value of the fuel is shown in Fig. 3.[10] The lower the average energy of the impinging neutrons (see Equation 2), the higher the value of ψ that is required to achieve the same wall loading.

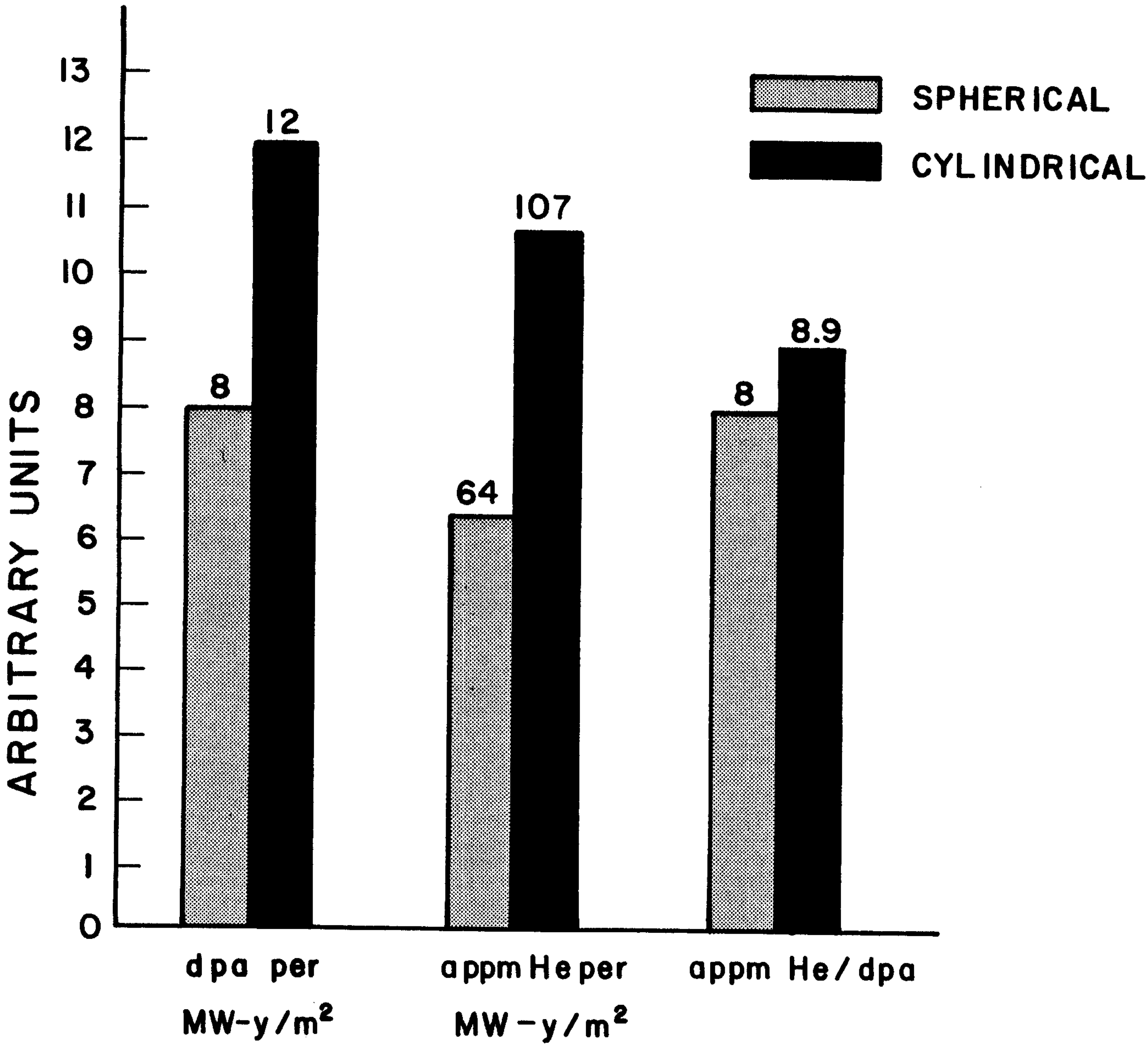

Fig. 2. Comparison of damage parameters in Fe first walls of equal radii (2 m) spherical and cylindrical chambers.

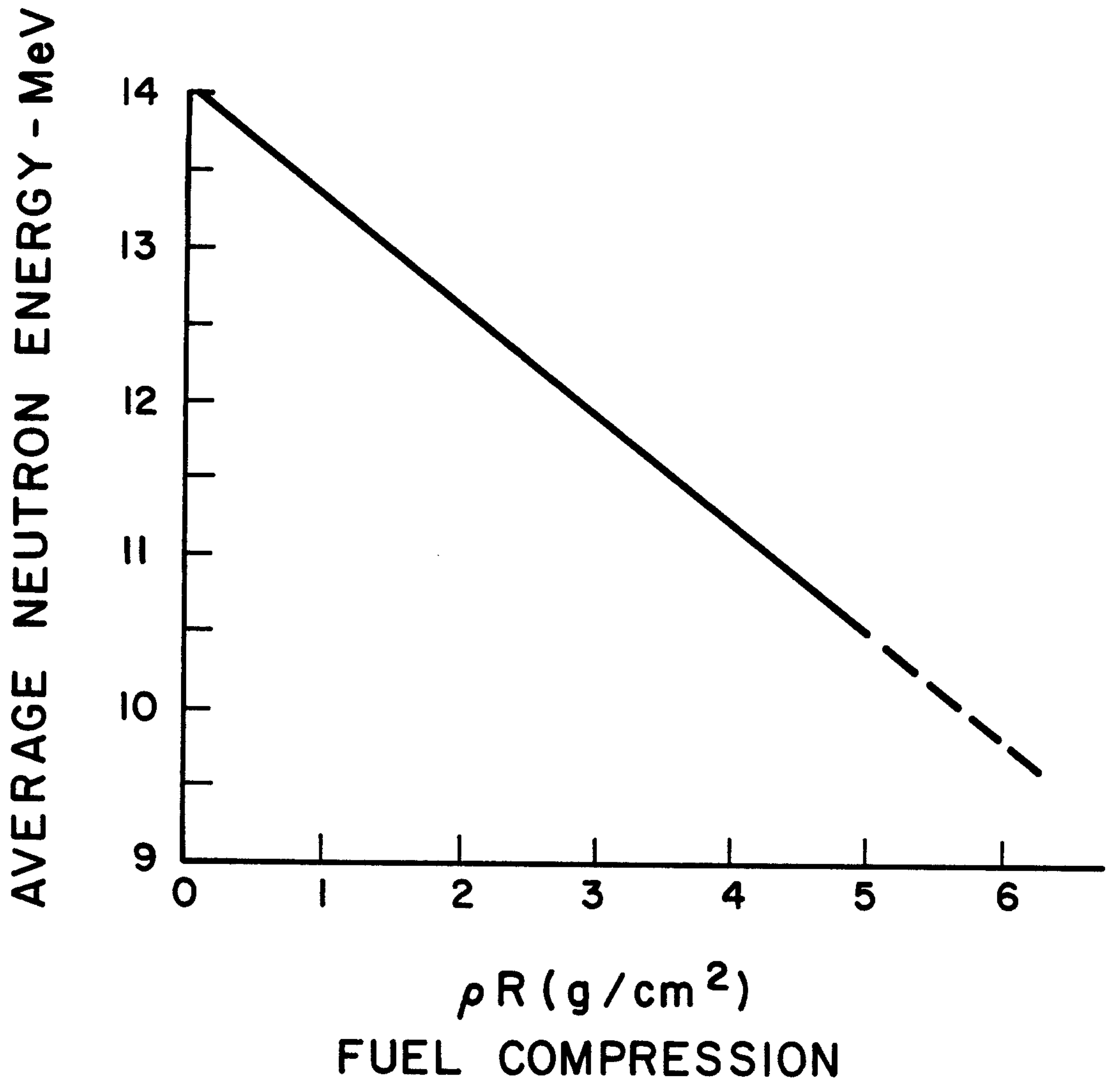

Fig. 3. Effect of fuel compression on average energy of neutrons emitted from the target.[10]

This can be illustrated by the following calculation. Let us assume the same spherical geometry, first wall configuration, and point neutron source as in III. The only parameter to be varied will be the energy distribution of the neutrons. Three cases were considered:

- uncollided, monoenergetic — $\bar{E}$ = 14.1 MeV
- uncollided, Doppler broadened with a 30 keV temperature — $\bar{E}$ = 14.1 MeV
- collided spectrum from a ρR = 2 target — $\bar{E}$ = 12.5 MeV

A comparison of the Doppler broadened and the target neutron spectra is shown in Fig. 4 and the results of the calculation are given in Fig. 5 where the dpa, He production and He/dpa ratios are compared. Because of the lower average neutron energy, a larger neutron source strength (approximately 13%) is required to achieve an exposure of 1 MW-y/m^2. However, the degraded neutrons cause somewhat less displacement damage than the 14.1 MeV neutrons and that is why the total dpa produced per MW-y/m^2 is only 9% higher. The Doppler broadening of the MCF source has a relatively small effect on the dpa values and aside from some reactions which have thresholds at 14 MeV and higher it is not as important as other effects considered here.

When the amount of He produced was calculated for the various spectra it was found to be essentially the same in spite of the 13% higher neutron flux required indicating a balancing of the lower He production cross section and the higher neutron flux. The He/dpa cross section was lower for the degraded neutron spectrum because the He production cross sections are more sensitive to energy than the displacement cross sections.

The blanket material choice also impacts the neutron flux and spectrum at the first wall. As shown in Fig. 5, there is a large effect on the first wall

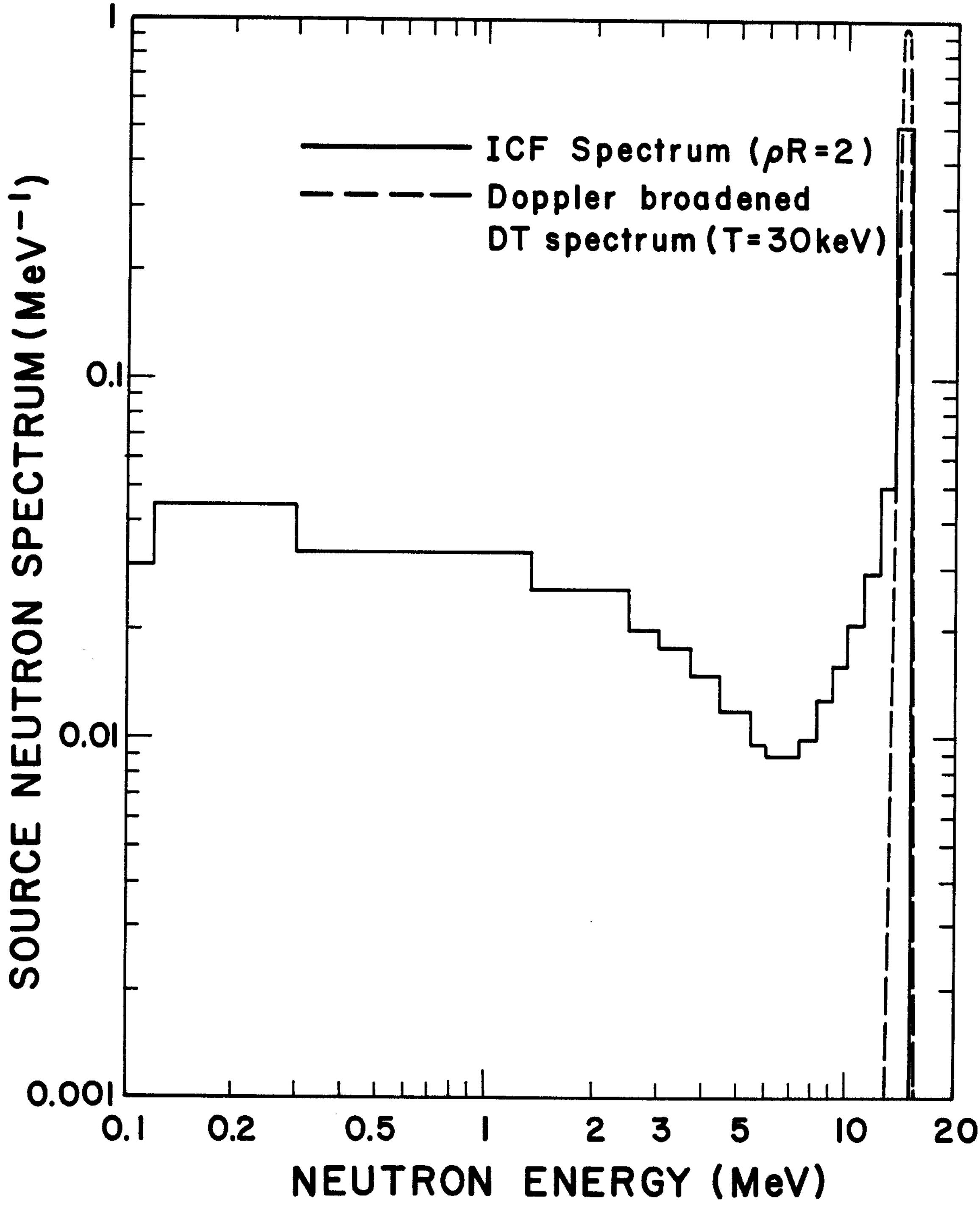

Fig. 4. Comparison of neutron spectrum for an ICF target with ρR = 2 g cm^{-2} vs. a 30 keV Doppler broadened MCF spectrum.

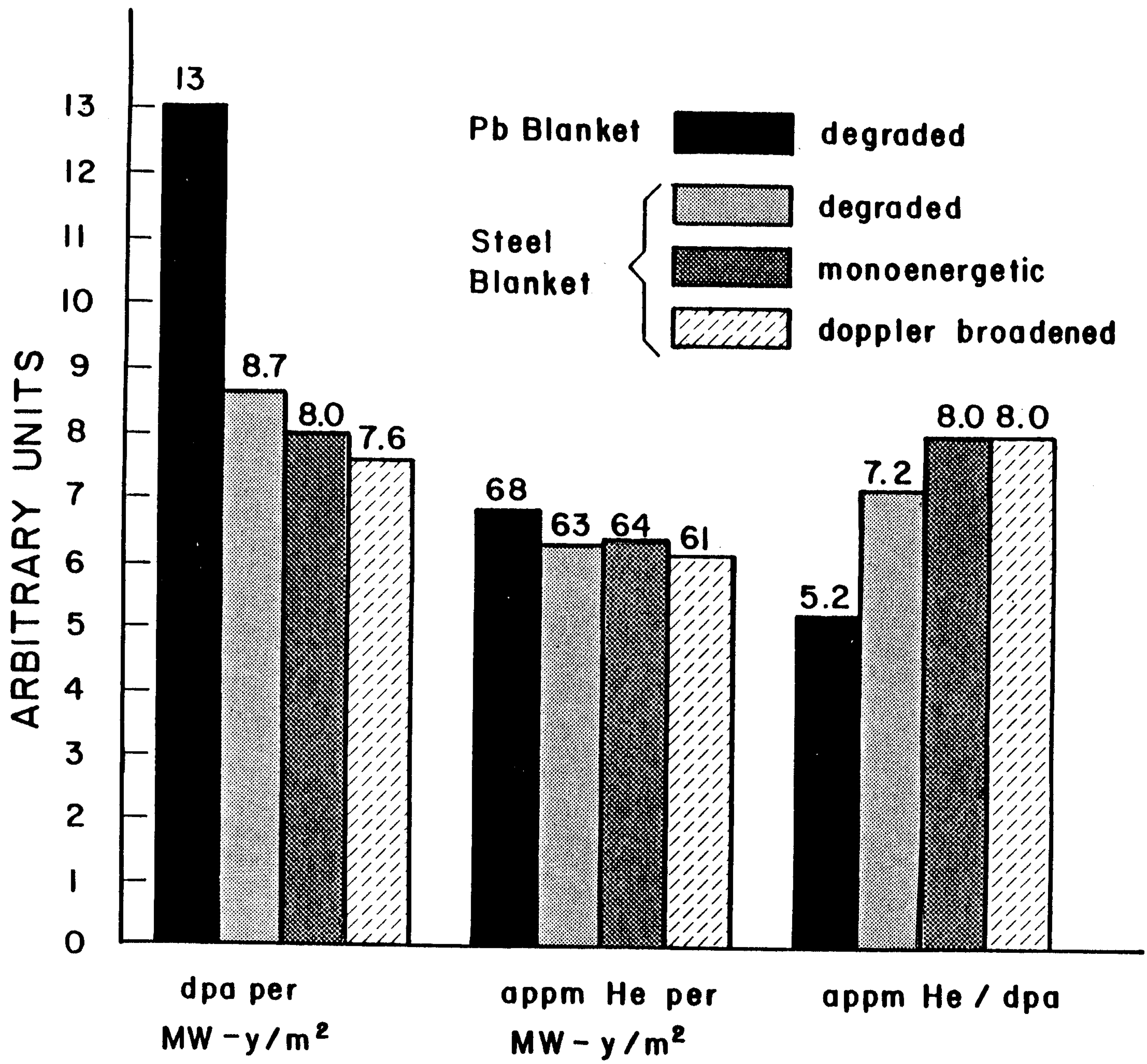

Fig. 5. Spectral effects on damage parameters in a spherical Fe first wall.

damage parameters resulting from replacing the steel blanket by a lead blanket (i.e., to represent a power blanket where neutron multiplication is maximized). Neutron multiplication in lead enhances the neutron flux at the first wall yielding ~ 50% higher dpa rate. On the other hand, the He production rate increases only slightly, as most of the secondary neutrons have energies below the (n,α) threshold energy. The He to dpa ratio decreases by ~ 30%. Such effects would occur in both ICF and MCF reactors.

V. Comparison of SIRIUS and TASKA Fusion Test Facilities

The geometrical and spectral effects previously illustrated can now be combined to demonstrate how dependent the damage conditions might be on the reactor confinement concept. The input to the calculation is summarized below:

	SIRIUS[9]	TASKA[4]
Type	Laser	Tandem mirror
Chamber geometry	Spherical	Cylindrical
Radius of chamber - m	2.0	0.3
n source distribution	Point	Volumetric
n energy distribution	$\rho R = 2$ g cm^{-2} $\bar{E} = 12.5$ MeV	14.1 MeV

The results of the damage produced in an identical Fe first wall with a 60 cm thick Fe/H_2O blanket are shown in Fig. 6.

The damage rate in the TASKA first wall is 21% higher than in the SIRIUS first wall for the same neutron wall loading. An even larger difference occurs for the helium production with the Fe producing 62% more helium in the

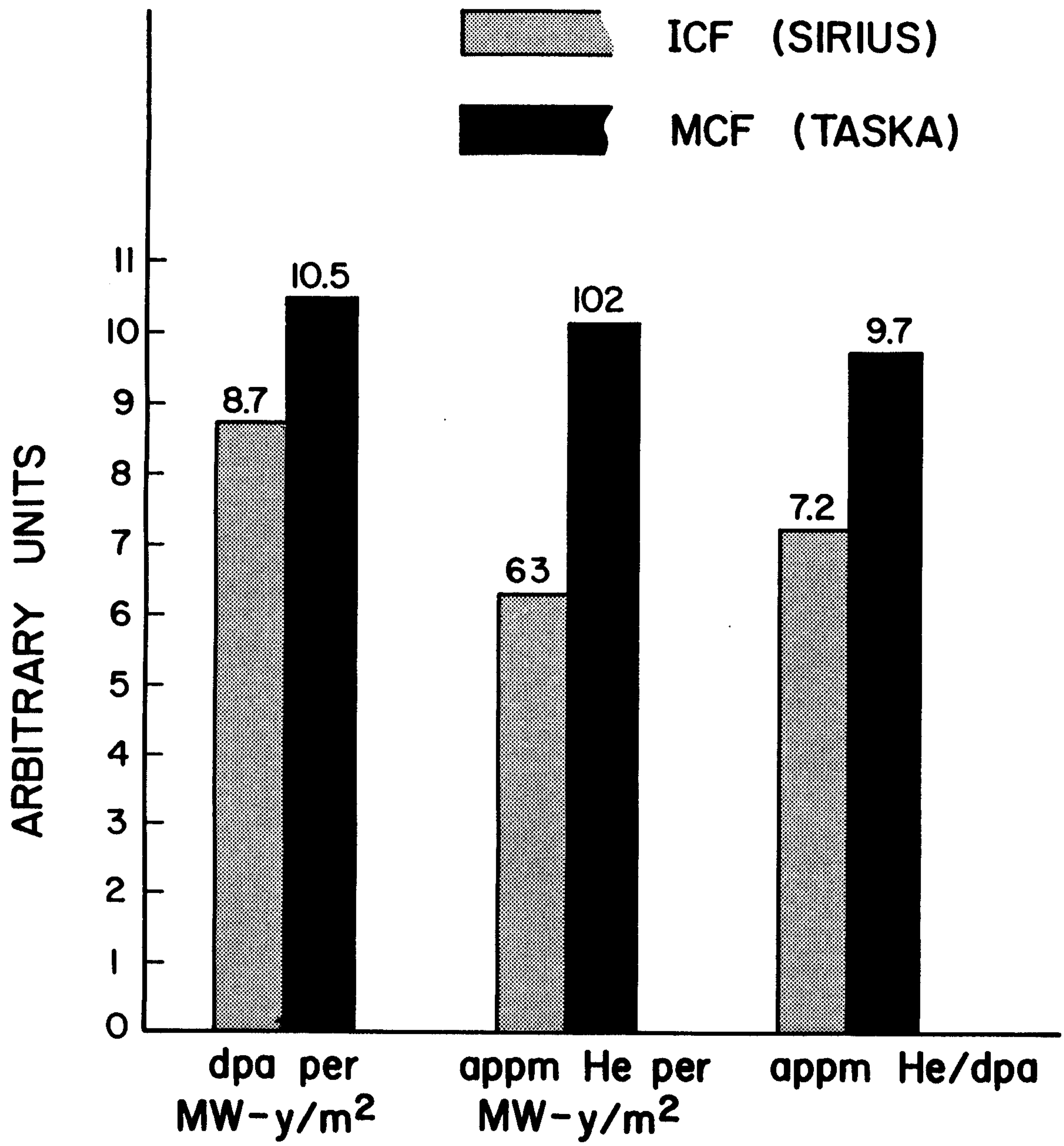

Fig. 6. Comparison between damage effects in typical ICF (SIRIUS)[9] and MCF (TASKA)[4] fusion test facilities.

magnetic fusion test facility versus the ICF reactor. The He/dpa ratio reflects both of these differences and is 35% higher in the MCF case.

While this simple calculation illustrates the fact that materials respond differently in the two environments, there are factors which could make the discrepancies even larger. For example, the larger the radius of the MCF system, the higher the dpa rate in the Fe first walls. The reason for this is that the first wall has a larger view factor for secondary backscattered neutrons, eventually approaching 2π steradians as the chamber radius goes to infinity. Since the secondary neutrons do not generally produce more He, the He/dpa ratio will decrease. Another effect that could widen the difference between ICF and MCF facilities is the use of higher ρR (i.e., more than 2 g cm^{-2}) targets. This would tend to reduce the He production rate while perhaps even increasing the dpa rate at the same $MW\text{-}y/m^2$, thus reducing the He/dpa ratio even more.

In summary, this brief exercise should illustrate why materials scientists must be aware that damage units per $MW\text{-}y/m^2$ are very design dependent. Simply, a $MW\text{-}y/m^2$ of damage produced in a MCF facility may be quite different than a $MW\text{-}y/m^2$ of damage produced in an ICF system. Normalization on other parameters such as thermonuclear power released in the plasma (or target) or even including the energy released in the blanket could give even different results.

VI. Time Related Effects

A major difference between the ICF and MCF systems is the time over which the displacement and transmutation damage is produced. The "traditional" MCF condition envisioned is a steady state damage rate of 10^{-7} to 10^{-6} dpa/s which may last for weeks or months before being interrupted.

The situation for the ICF test facilities is drastically different. The neutrons are "born" over a 10-100 picosecond time scale and the uncollided neutrons travel toward the first wall at a velocity of roughly 50,000 km/s. This means that the neutrons could traverse a 2 meter radius spherical chamber in roughly 35 ns. Of course, those that get downscattered in the target have slower velocities, but usually all of the neutrons from the target arrive at the first wall over a time period of 5-10 ns. For a 1 MW/m^2 wall loading at 1 Hz rep rate, this "first wave" of neutrons can produce damage rates on the order of 70 dpa/s (see Fig. 7). Backscattered neutrons from the blanket extend the damage time for another 50 ns or so but usually 99% of the displacement damage is produced in less than 10 ns. This leaves a relatively long time between shots where the damage can anneal out or agglomerate into different microdefects. Figure 8 illustrates the wide difference in instantaneous damage rates for a 2 m radius ICF materials test facility like SIRIUS[9] and for a MCF test facility like TASKA[4] (r = 0.3 m). The more than 8 orders of magnitude difference in displacement rates is accentuated by the time between shots where annealing can occur.

A recent review of pulsed damage effects by Simonen, Ghoniem and Packen,[11] concluded that there is sufficient experimental and theoretical evidence to be concerned about this phenomenon. Pulsing effects on precipitate phase stability and large changes in swelling and interstitial loops have been observed in stainless steel.[12] Large changes in the void microstructure in Ni irradiated under pulsed conditions have also been observed.[13] While there is no experimental evidence with a high neutron fluence at the

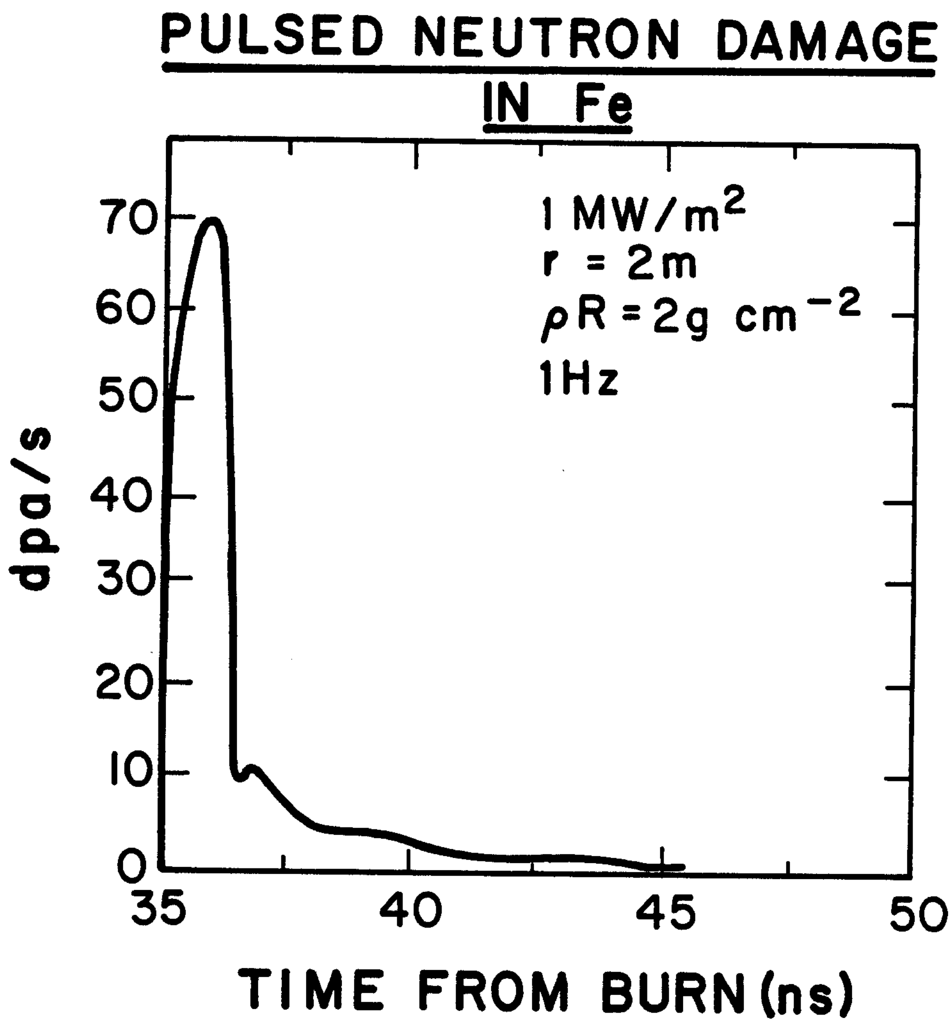

Fig. 7. Calculated pulsed damage rate in Fe first wall of an ICF test facility.

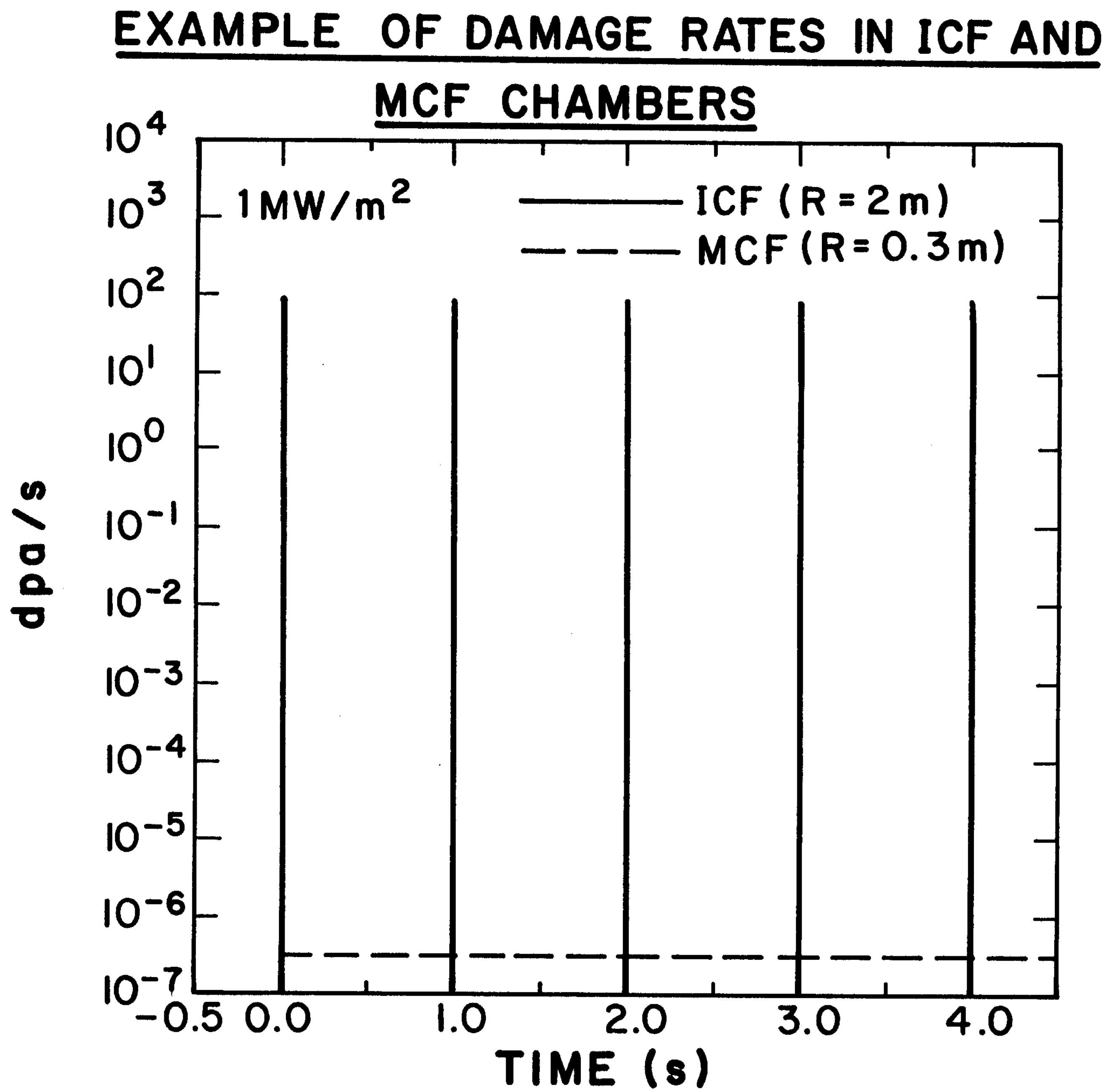

Fig. 8. Comparison between steady damage rate in a typical MCF test facility and pulsed damage in a typical ICF test facility.

damage rates shown in Figs. 7 and 8, it should be clear that in addition to the geometrical and spectral differences, the damage produced by 1 $MW\text{-}y/m^2$ exposure of metal under steady state conditions may bear no resemblance to 1 $MW\text{-}y/m^2$ applied in a pulsed mode.

VII. Conclusions

It has been shown that the neutron exposure unit of a $MW\text{-}y/m^2$ is not adequate to relate materials response in MCF and ICF environments. Geometrical differences between the characteristic spherical ICF chambers and cylindrical tandem mirror chambers can cause differences of 50% or more in the typical response functions like displacement damage and transmutations. Inclusion of spectral effects due to downscattering in the ICF targets can add even further uncertainty to the MCF/ICF materials comparisons. When the time structure of the damage produced is added to the other effects, it is clear that materials information generated to meet MCF applications may not be adequate to determine their behavior in ICF environments.

Finally, it is concluded that the ICF community needs to consider its own materials test facilities and that reliance on MCF facilities may not be in the best interest of the ICF program in the long run.

Acknowledgment

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