Geometrical, Spectral and Temporal Differences Between ICF and MCF Reactors and Their Impact on Blanket Nuclear Parameters

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ABSTRACT

Geometrical and spectral differences between inertial confinement fusion (ICF) and magnetic confinement fusion (MCF) facilities lead to significant variation of up to ~ 60% in peak values and profiles of the time averaged blanket nuclear parameters for the same first wall exposure. Simple scaling of radiation effects with neutron wall loading is inappropriate. These effects together with the temporal effects, that result in ~ 5 to 8 orders of magnitude higher instantaneous reaction rates in the pulsed ICF reactors, lead to significantly different blanket performances in the ICF and MCF reactor environments.

I. INTRODUCTION

The need for blanket and material testing 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. It is important to emphasize the need for integrated testing in the complex nuclear fusion environment. The MCF program has taken the lead in attempting to solve this problem by designing several test facilities.[1-3] On the other hand, it is commonly assumed by the ICF community that the MCF test program will provide data needed for designing the ICF reactors by simply scaling the nuclear parameters with the neutron wall loading.

Due to the geometrical, spectral and temporal differences between the ICF and MCF reactors, the nuclear parameters can be significantly different even when the first wall is exposed to the same neutron wall loading. In this paper, the impact of the geometrical and spectral differences on the time averaged blanket nuclear parameters will be investigated. The effect of the ICF pulsed nature on the time structure of the blanket nuclear parameters will be assessed.

II. DIFFERENCES BETWEEN ICF AND MCF REACTORS

While a cylindrical (or toroidal) chamber surrounds a volumetric distributed source in a MCF reactor, a point neutron source is usually surrounded by a spherical chamber in ICF reactors. Close examination of the problem reveals that due to the formal definition of the neutron wall loading, there can be substantial differences in the values and profiles of the different nuclear parameters per unit wall loading. The neutron wall loading is defined as the energy carried by uncollided source neutrons incident on a unit area of the first wall per unit time regardless of the direction of incidence. While the same neutron wall loading implies the same number of source neutrons incident on unit area of the first wall, the angles of incidence are quite different. In the ICF geometry all neutrons from the point source are incident perpendicular to the spherical wall resulting in less radiation effects in the first wall and more in the back of the blanket as compared to the MCF geometry where neutrons are incident on the cylindrical wall at different glancing angles.

Another important geometrical effect relates to the chamber radius. For various reasons, relating to plasma physics and the ability of first walls to stand high heat fluxes without melting, the radii of ICF and MCF facilities might be quite different. The minimum radius of an ICF chamber is likely to be at least 2 m to avoid melting of the first wall during the target explosion.[4] On the other hand, the MCF facilities of the tandem mirror type have wall radii in the range 0.2 - 0.4 m while the tokamak test facilities have radii in the range 0.7 - 1.5 m. These differences can impact the radiation effects in ICF and MCF facilities. In addition, the toroidal geometry of the toroidal test facilities leads to significant poloidal variation of wall loading and nuclear parameters.

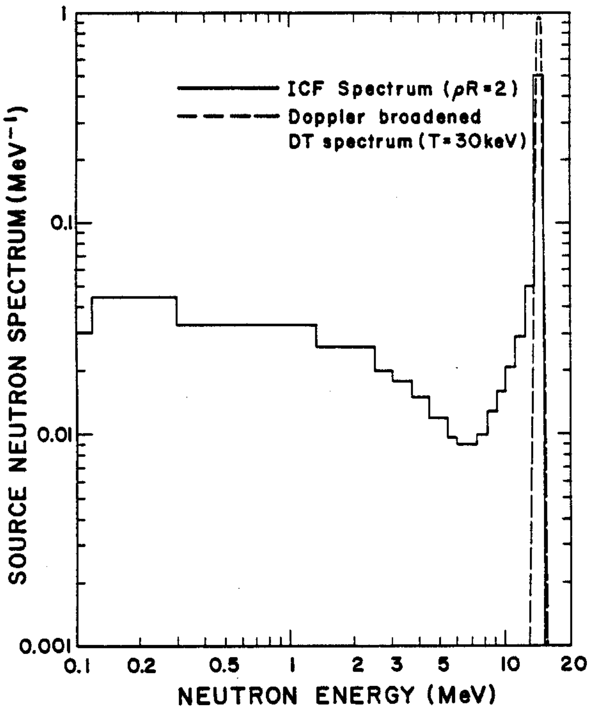

Fig. 1. Comparison of neutron source spectra in ICF and MCF reactors.

The main difference between ICF and MCF neutron source spectra is due to 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 from an ICF target can have average energies as low as 10 MeV depending on the target fuel compression (ρR). Figure 1 compares the MCF spectrum and a typical ICF target neutron spectrum.[5]

While current MCF reactor designs envision steady state operation for weeks or months before being interrupted, the situation for the ICF facilities is drastically different. The neutrons are born over a 10-100 ps time scale with a pulse repetition rate in the range 1-10 Hz. This leads to significant time structure for the damage and other nuclear parameters in the ICF blanket.

III. IMPACT OF GEOMETRICAL AND SPECTRAL DIFFERENCES

A. Calculational Models

To investigate the impact of geometrical and spectral differences between ICF and MCF reactors on blanket nuclear parameters we performed neutronics calculations for 4 cases. The geometrical and spectral parameters used are given in Table 1. In cases 1 and 4 a point neutron source is surrounded by a 2 m radius spherical first wall which is representative of the ICF reactor geometry. In cases 2 and 3 a cylindrical chamber surrounds a volumetric distributed neutron source. First wall radii of 2 m and 0.5 m are used in cases 2 and 3, respectively, representing large radius MCF (e.g. tokamak) and small radius MCF (e.g. tandem mirror) reactors. The ratio of the plasma radius to the wall radius was kept constant at 0.75. While monoenergetic 14.1 MeV neutron sources are used in cases 1, 2 and 3, a softened ICF target neutron spectrum is used in case 4. This spectrum shown in Fig. 1 was obtained by performing neutronics calculations for the HIBALL[5] target with ρR = 2 g/cm^2. These calculations indicated that for each DT fusion 1.05 neutrons leak from the target with an average energy of 12 MeV.

In order to concentrate on the analysis of the geometrical and spectral effects, the same blanket design was used in all four cases. A 0.4 m thick self-cooled $Li_{17}Pb_{83}$ blanket, consisting of 73 vol% $Li_{17}Pb_{83}$ (90% ^{6}Li), 7 vol% HT-9 and 20 vol% void, was used. The blanket is followed by a 0.6 m thick reflector made of 90 vol% HT-9 and 10 vol% $Li_{17}Pb_{83}$. The one-dimensional discrete ordinates code ONEDANT was used with cross section data based on the ENDF/B-V evaluation. The time-averaged nuclear parameters calculated included the atomic displacement (dpa) rate in HT-9, the helium production rate in HT-9, the tritium production rate and the power density resulting from nuclear heating. The spatial variation of these parameters was determined for the four cases. In addition, the overall integral parameters such as the tritium breeding ratio (TBR) and energy multiplication (M) were calculated and compared.

B. Geometrical Effects

Figure 2 shows the peak nuclear parameters in the blanket normalized to the same neutron wall loading of 1 MW/m^2. The spatial variation of these nuclear parameters in the blanket is given in Figs. 3, 4, 5, and 6. The cylindrical geometry of MCF reactors (case 2) results in higher peak nuclear parameters compared to the ICF spherical geometry (case 1). This is attributed to the fact that all source neutrons are incident perpendicular to the wall in the ICF geometry while the source neutrons are incident at different glancing angles on the cylindrical MCF wall resulting in more neutron interactions in the front zone of the blanket. Since this effect is related primarily to the angular distribution of the uncollided source neutrons, the effect is more pronounced for radiation effects produced by high energy neutrons. Our results show that the largest effect is on helium production (67%) and the smallest effect is on tritium production (20%). The peak values of power density and dpa rate in case 2 are higher than those in case 1 by ~ 40%.

Table 1. Geometrical and Spectral Parameters for the Cases Analyzed

	Case 1	Case 2	Case 3	Case 4
Chamber Geometry	Spherical	Cylindrical	Cylindrical	Spherical
First Wall Radius (m)	2	2	0.5	2
Neutron Source Distribution	Point	Uniform Cylindrical	Uniform Cylindrical	Point
Average Energy of Source Neutrons (MeV)	14.1	14.1	14.1	12

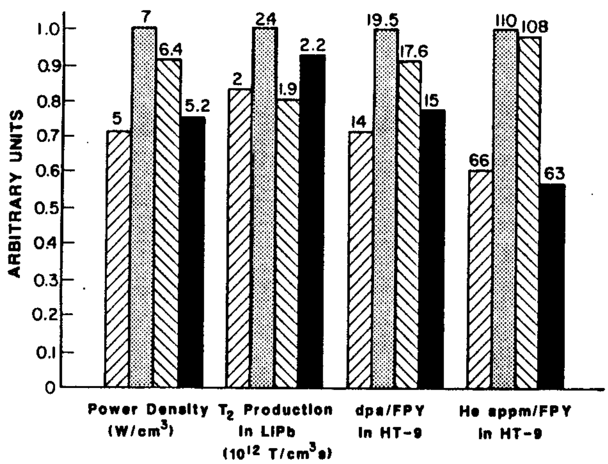

Fig. 2. Peak blanket nuclear parameters for 1 MW/m^2 wall loading.

The difference in geometry results also in different profiles for nuclear parameters in the blanket with larger gradients in the MCF cylindrical geometry as indicated in Figs. 3-6. This faster dropoff in cylindrical geometry, despite the smaller geometrical dropoff (1/R vs. 1/R^2 in spherical geometry), is due to the different angular distribution of incident neutrons as discussed above. Again the effect is more pronounced for nuclear parameters produced by high energy neutrons. The blanket peak to average ratio for helium production in case 2 is 48% higher than in case 1. The corresponding difference for tritium production is only 3%.

The effect of first wall radius can be assessed by comparing the results for cases 2 and 3. The peak values for the nuclear parameters are larger in the larger radius chamber for the same neutron wall loading. The reason is that the first wall has a larger view factor for secondary backscattered neutrons, eventually approaching 2π sr as the chamber radius goes to infinity. The largest effect occurs for tritium production that has a large contribution from the low energy reflected neutrons. The peak values for tritium production, power density, dpa rate and helium production in the smaller radius chamber are lower by 21%, 9%, 10% and 2%, respectively. The radial gradient in both the blanket and reflector is larger for the smaller wall radius due to the increased influence of geometrical attenuation as shown in Figs. 3-6. Since this is related to the geometrical attenuation of source neutrons, the largest increase in blanket peak to average ratio occurs for helium production where an increase of 25% was observed.

The combined geometrical effects for an ICF reactor versus a MCF test reactor of the tandem mirror type can be investigated by comparing cases 1 and 3. It is clear from Fig. 2 that the peak tritium production rate in the MCF geometry becomes slightly lower than that in the ICF geometry due to the larger radius effect. On the other hand, all other nuclear parameter have larger peak values in the MCF geometry. Larger gradients are obtained for all nuclear parameters as indicated in Figs. 3-6.

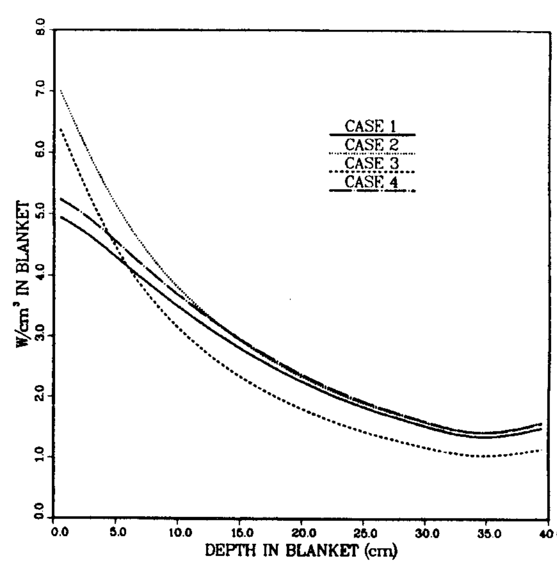

Fig. 3. Geometrical and spectral effects on power density.

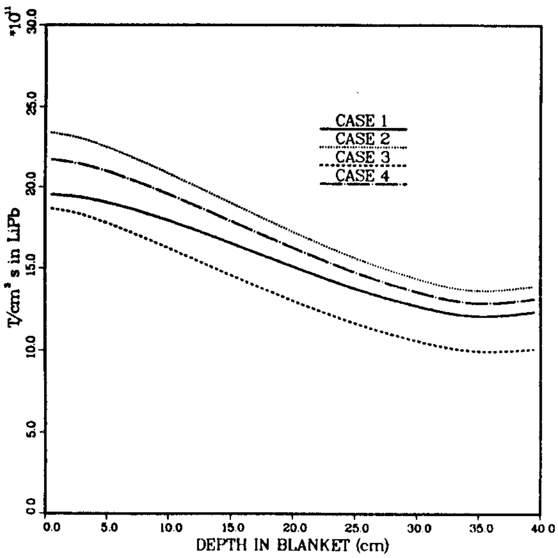

Fig. 4. Geometrical and spectral effects on tritium production rate.

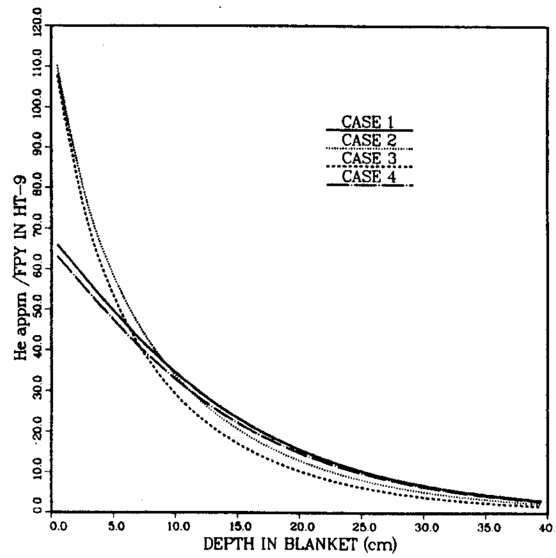

Fig. 6. Geometrical and spectral effects on helium production rate.

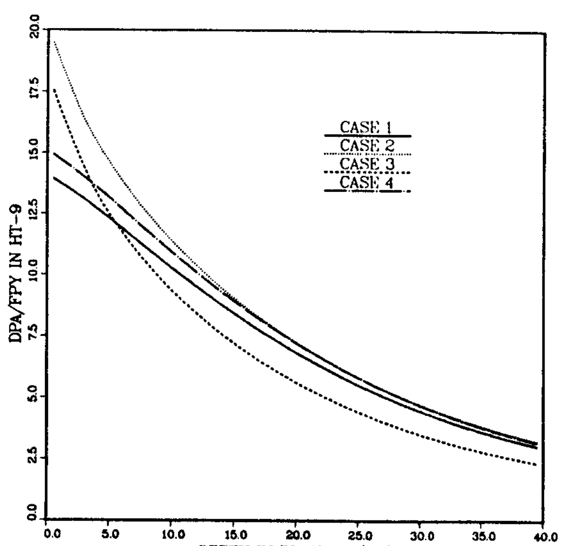

Fig. 5. Geometrical and spectral effects on dpa rate.

Although case 2 was used to represent a large radius MCF facility such as a tokamak, the toroidal geometry will introduce additional effects. We analyzed the effect of toroidal geometry on the poloidal variation of the neutron wall loading and the different nuclear parameters for a toroidal chamber with an aspect ratio of four.[6] Significant variation of wall loading was observed with a peak outboard wall loading of 11.6 MW/m^2, a minimum wall loading of 3.2 MW/m^2 and a peak inboard wall loading of 9.3 MW/m^2. The poloidal variation of the nuclear parameters has the same general shape as the neutron wall loading. However, the nuclear parameters per unit wall loading vary poloidally due to the different angular distribution of source neutrons incident on the wall. The peak dpa rate per unit wall loading on the inboard side is 18% higher than that on the outboard side. A factor of two higher dpa per wall loading occurs at the minimum wall loading location. These poloidal variations decrease as the aspect ratio increases. These toroidal effects should be taken into account when comparing nuclear parameters in ICF and toroidal MCF facilities.

C. Spectral Effects

The effect of neutron target interactions on the nuclear parameters of ICF reactors was previously analyzed.[5] For the same fusion power, neutron slowing down in the target results in lower radiation effects in the blanket even though a neutron multiplication of ~ 1.05 occurs in the target. Since our aim here is to compare the nuclear parameters in ICF and MCF blankets for the same first wall exposure, the results for the four cases were normalized to unit wall loading. Consequently, a 17.5% larger neutron source strength is required to achieve the same wall loading in case 4. The impact of the softer ICF neutron source spectrum on the nuclear parameters per unit wall loading can be assessed by comparing the results for cases 1 and 4.

The reduced reaction cross section for helium production more than counterbalances the

Table 2. Tritium Breeding Ratio and Energy Multiplication for the Four Cases Considered

	TBR			Energy Multiplication		
	Blanket	Reflector	Total	Blanket	Reflector	Total
Case 1	1.2070	0.1742	1.3812	0.9560	0.2715	1.2275
Case 2	1.2715	0.1550	1.4265	0.9943	0.2312	1.2255
Case 3	1.2032	0.1796	1.3828	0.9635	0.2672	1.2307
Case 4	1.1620	0.1643	1.3263	1.0080	0.2852	1.2932

17.5% higher required neutron flux resulting in ~ 4.5% less peak helium production. For the other nuclear parameters produced by reactions with less steep drop in cross section, the effect of neutron spectrum softening is not as pronounced. This leads to higher peak values per unit wall loading. The values for tritium production, dpa rate and power density are higher by 10%, 7%, and 4%, respectively. The results indicate also that a slightly larger gradient is obtained with the softer ICF spectrum ($\lesssim$ 2% increase) due to the smaller mean free path of lower energy neutrons.

D. Combined Geometrical and Spectral Effects

Comparing the results for cases 3 and 4 indicates that for the same first wall exposure, the peak values for helium production, dpa, and power density in ICF reactors are lower than those in MCF reactors of the tandem mirror type by ~ 42%, 15%, and 19%, respectively. On the other hand, the peak tritium production in ICF is ~ 16% larger. An even larger discrepancy exists between an ICF reactor and a large radius MCF facility as shown by comparing cases 2 and 4 in Fig. 2.

The integral nuclear parameters of interest such as tritium breeding ratio (TBR) and blanket energy multiplication (M) calculated for the four cases are given in Table 2. It is clear that the geometrical and spectral differences have less impact on the integral parameters. Even though calculations for case 4 take into account the 1.05 neutron multiplication in the target, the results show that the TBR in an ICF reactor is lower than that in a MCF reactor with the same blanket by ~ 4-7% depending on the wall radius. The energy multiplication defined as the total nuclear heating in the blanket and reflector divided by the neutron energy incident on the blanket, is higher in ICF than that in MCF reactors by ~ 6% with the fraction of nuclear heating in the reflector increasing from ~ 19 to 22%.

IV. IMPACT OF PULSED NATURE OF ICF REACTORS

A major difference between the ICF and MCF systems is the time over which the radiation effects are produced in the blanket. While time averaged nuclear parameters were compared in the previous section, adding the time structure of these nuclear parameters results in even larger differences. While steady state operation is envisioned for MCF reactors, neutrons are born over 10-100 ps time scales in ICF facilities. The uncollided neutrons travel towards the first wall at a velocity of roughly 50,000 km/s traversing a 2 m radius chamber in about 35 ns. The neutrons slowed down in the target take a longer time to reach the first wall. This time of flight spread results in most of the neutrons from the target arriving at the first wall over a time period of 5-10 ns. However, backscattered neutrons from the blanket extend the time period over which a particular radiation effect occurs. This period is larger for radiation effects produced by lower energy neutrons and at locations deeper in the blanket. Time-dependent calculations were performed for the HIBALL reactor[7] where the 7 m radius first metallic wall is protected by a 2 m thick blanket made of an array of SiC tubes filled with $Li_{17}Pb_{83}$. While most of the atomic displacement damage occurs over ~ 1 μs, the helium production occurs over only 26 ns.

Figure 7 gives a comparison between steady state damage rates in a typical MCF test facility (TASKA)[2] and pulsed damage in the SIRIUS-M[4] ICF test facility with the same wall loading and a 1 Hz repetition rate. The more than 8 orders of magnitude difference in displacement rates is accentuated by the time between shots where annealing can occur. It is therefore clear that the damage produced by 1 MW-yr/m^2 exposure under steady state conditions might bear no resemblance to 1 MW-yr/m^2 applied in a pulsed mode. The energy deposition rate in the blanket and first wall of HIBALL was also calculated as shown in Fig. 8. The time spread increases as one moves deeper in the blanket towards the first metallic wall. The peak to temporal average power density ratios in the front and back of the blanket are 8 x 10^6 and 2 x 10^5, respectively. This time dependence of energy deposition can lead to isochoric heating problems with significant coolant pressure waves.[8] Similar time structure was observed for the tritium production with longer time duration and

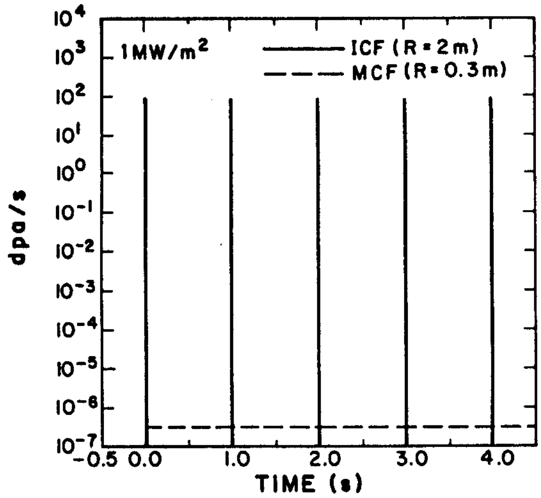

Fig. 7. Comparison between steady damage rate in MCF test facility and pulsed damage in ICF test facility.

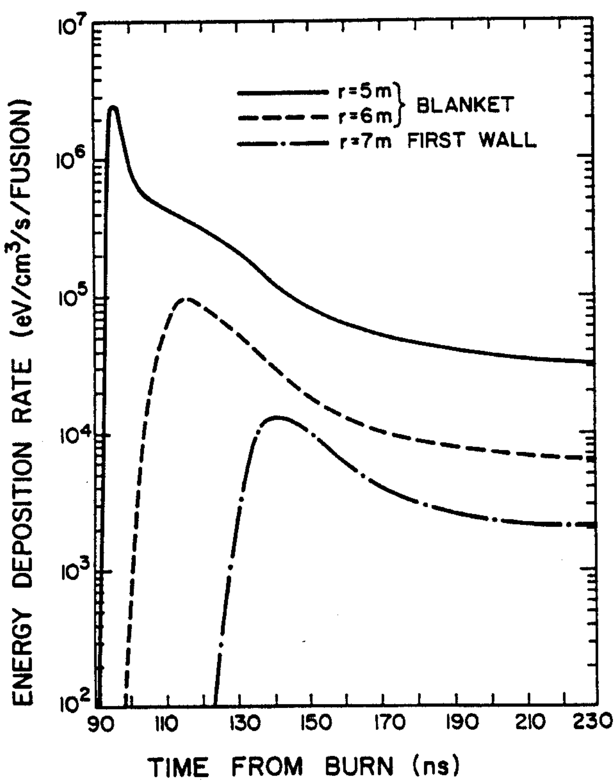

Fig. 8. Energy deposition rate in the HIBALL blanket and first metallic wall.

smaller peak to average values. This can have an impact on tritium diffusion and extraction.

V. CONCLUSIONS

Geometrical and spectral differences between ICF and MCF reactors can lead to significant variation of up to ~ 60% in the peak values and profiles of the time averaged nuclear parameters for the same first wall exposure. Such discrepancies can exist even for MCF reactors when different wall radii are used. Simple scaling of nuclear parameters with neutron wall loading is, therefore, inappropriate. These effects together with the temporal effects, that result in ~ 5-8 orders of magnitude higher instantaneous reaction rates in the pulsed ICF reactors, can lead to significantly different blanket performances in the ICF and MCF reactor environments. Hence, using data from MCF test facilities to predict blanket performance in the ICF reactors is inadequate and there is a need for a dedicated ICF test facility that properly simulates the geometrical, spectral and temporal conditions of the ICF reactors.

ACKNOWLEDGMENT

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