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UWFDM-894

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NEUTRONICS ANALYSIS FOR THE LIGHT ION BEAM REACTOR LIBRA-LiTE

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ABSTRACT

Neutronics analysis has been performed for LIBRA-LiTE. Using liquid lithium as a coolant and breeder results in more attractive neutronics performance features compared to $Li_{17}Pb_{83}$. The final focusing magnets and the front rows of the INPORT tubes have to be replaced every 1 and 3 years, respectively. The steel chamber wall, roof, and bottom plates are lifetime components. The overall reactor tritium breeding ratio and energy multiplication values are 1.405 and 1.123, respectively.

I. INTRODUCTION

LIBRA-LiTE is a 1000 MWe power plant conceptual design using light ion beam driven inertial fusion.[1] A schematic picture of the LIBRA-LiTE target chamber is shown in Fig. 1. The fusion targets are imploded by 6 MJ pulses of 30 MeV Li ions at a repetition rate of 3.9 Hz. The target gain is 100 leading to a yield of 600 MJ. LIBRA-LiTE uses ballistic ion propagation which has potential advantages over propagation using plasma channels. However, it requires that the final focusing magnets be placed close to the target. To maximize the lifetime of the focusing magnets, a liquid metal conductor in a metal case is used. The use of a liquid metal conductor avoids resistivity increases due to neutron damage that any solid conductor would experience. Liquid lithium is used as the conductor in the final focusing magnets. The lifetime of the magnets is determined by the radiation damage to the front metallic casing. Neutronics calculations have been performed to determine the lifetime and replacement frequency for the magnets.

The tritium breeding blanket uses liquid lithium, flowing in woven porous tubes (INPORT tubes)[2] as a breeding material and coolant. To protect solid surfaces from the target x-rays, the blanket tubes and the focusing magnets are continuously coated with liquid lithium which is partially vaporized during each shot. The low activation ferritic steel modified HT-9 alloy is used as structural material. Tritium breeding in the blanket is required to achieve tritium self-sufficiency. In addition, the INPORT tubes are required to protect the metallic chamber wall to allow it to be a lifetime component. The roof of the target chamber is a large dry dome that is far enough from the target such that it needs no liquid metal coating for protection from target x-rays. The location of the roof is determined such that neutron damage occurs slowly enough for the roof to be a lifetime component. The bottom liquid lithium pool is also required to be deep enough for the bottom steel plate to last for the whole reactor life.

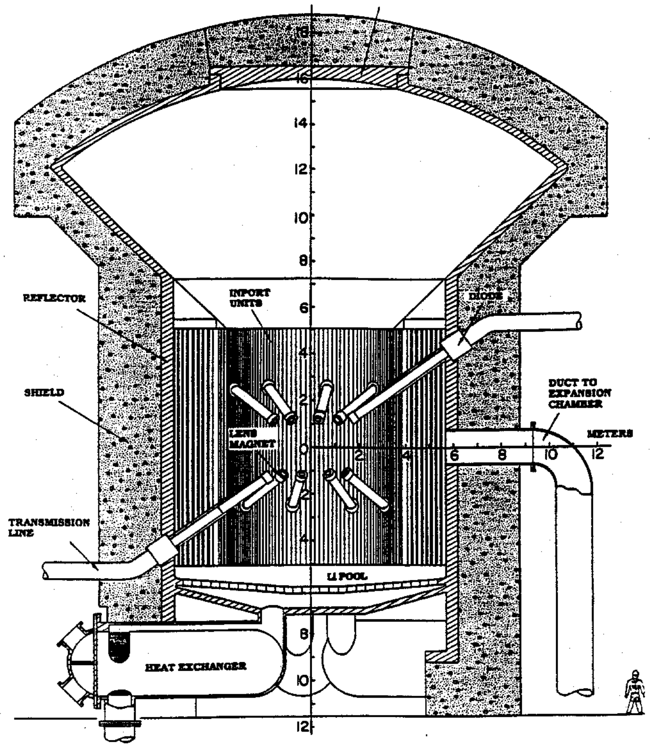

Fig. 1. Schematic picture of LIBRA-LiTE target chamber.

In this paper, the results of the neutronics analysis performed for LIBRA-LiTE are presented. The dimensions of the different reactor regions are determined for the design goals to be achieved. In addition, the lifetimes for the INPORT tubes and final focusing magnets are identified. The impact of replacing Li by the $Li_{17}Pb_{83}$ eutectic, as a coolant and breeder, on the reactor performance is also assessed.

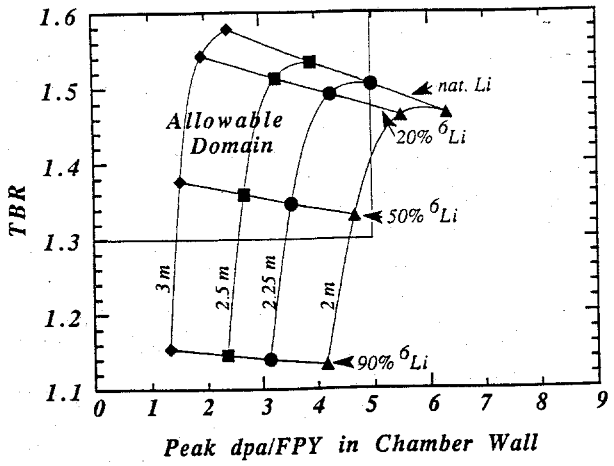

Fig. 2. TBR and chamber wall damage rate for different blanket design options.

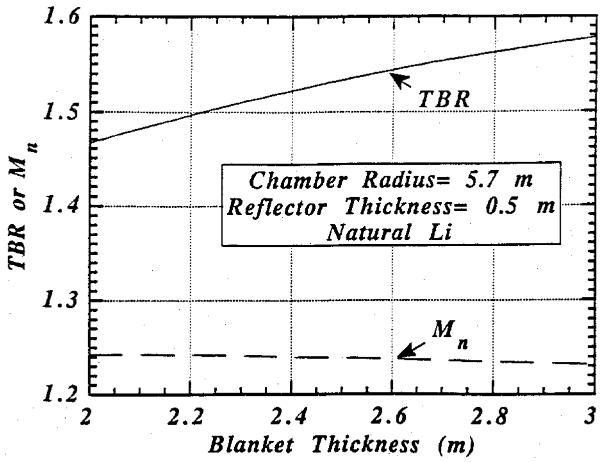

Fig. 3. TBR and nuclear energy multiplication as a function of blanket thickness.

II. CALCULATIONAL METHOD

Neutronics analysis has been performed for LIBRA-LiTE by performing several one-dimensional spherical geometry calculations for the different regions surrounding the target. The discrete ordinates code ONEDANT[3] was utilized along with 30 neutron - 12 gamma group cross section data based on the ENDF/B-V evaluation. A point isotropic source is used at the center of the chamber emitting neutrons and gamma photons. The target spectrum takes into account neutron multiplication, spectrum softening and gamma generation resulting from the interaction of the fusion neutrons with the dense target material. One-dimensional spherical geometry neutronics calculations have been performed for the target configuration at ignition.[4] The DT core is compressed to 485 times its solid density to a ρR-value of 2 g/cm^2 resulting in significant neutron target interactions. A uniform 14.1 MeV neutron source was used in the compressed DT fuel zone. For each DT fusion reaction, 1.025 neutrons are emitted from the target with an average energy of 11.64 MeV. In addition, 0.013 gamma photons are emitted with 3.85 MeV average energy. 2.1% of the fusion energy is lost in endoergic reactions in the target and 69.5% of the target yield is carried by neutrons and gamma photons. The rest of the target yield is carried by x-rays and debris which deposit their energy as surface heat. The results presented here are normalized to a 600 MJ DT fuel yield and a repetition rate of 3.9 Hz.

III. INPORT TUBE REGION

The primary goal of the neutronics analysis performed for LIBRA-LiTE is to determine the blanket design that satisfies tritium self-sufficiency, large energy multiplication (M), and wall protection requirements. The blanket is made of banks of INPORT tubes with 0.33 packing fraction. The liquid lithium breeder flows in tubes which are made of the ferritic steel alloy HT-9. The tubes consist of 2 vol.% HT-9 and 98 vol.% Li. A 0.5 m thick reflector consisting of 90 vol.% HT-9 and 10 vol.% Li is used behind the blanket. A minimum local (1-D) tritium breeding ratio (TBR) of 1.3 is required in the INPORT tubes and reflector. This relatively high TBR is required to achieve overall tritium self-sufficiency with a simple roof design that does not have a breeding blanket. In addition, the INPORT tubes are required to provide adequate protection for the front of the reflector (chamber wall) to make it last for the whole reactor life. In this study, we adopted a conservative end-of-life dpa limit of 150 dpa for HT-9. Hence, for 30 full power years (FPY) of operation, the peak dpa rate in the chamber wall should not exceed 5 dpa/FPY. The inner radius of the chamber wall is determined by the diode location to be 5.7 m.

Several calculations have been performed for different blanket thicknesses and lithium enrichments. The results are mapped in Fig. 2. In order to satisfy the tritium breeding and wall protection requirements, the design point should be in the box indicated in the upper left corner of the graph. For a fixed lithium enrichment, increasing the blanket thickness results in significant reduction in chamber wall damage, a small enhancement in the TBR, and slight reduction in energy multiplication as indicated in Fig. 3. Decreasing the lithium enrichment for a given blanket thickness results in a small increase in chamber wall damage and a significant increase in TBR. Lithium enrichment was found also to have a negligible effect on energy multiplication.

The peak damage rate in the INPORT units nearly doubles as the blanket thickness increases from 2 m to 3 m. Hence, there is a strong incentive for reducing the blanket thickness. Therefore, the blanket design point should be close to the right boundary of the allowable domain indicated in Fig. 2. Along this boundary different designs can be chosen ranging from 1.9 m thick blanket with 50% ^{6}Li enrichment to a 2.25 m thick blanket with natural lithium. Comparing the nuclear performance for these two design points reveals that they yield nearly the same M with the thicker blanket resulting in 15% higher TBR. On the other hand, the thinner blanket results in 20% longer life for the INPORT tubes while requiring about an order of magnitude more expensive lithium that is enriched to 50% ^{6}Li in order to

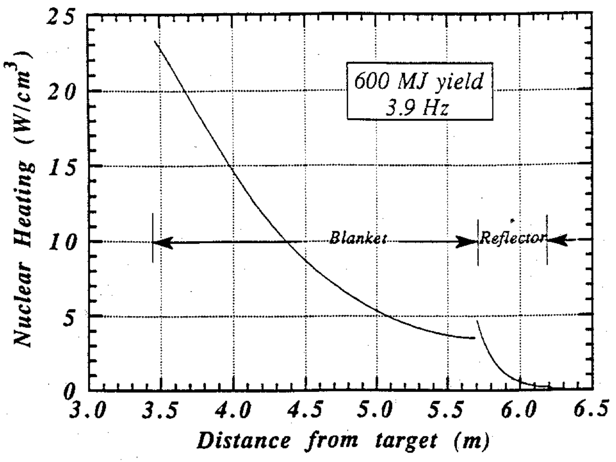

Fig. 4. Spatial variation of nuclear heating in the INPORT units and reflector.

provide adequate chamber wall protection. Based on these results, the reference design point was chosen to be a 2.25 m thick blanket with natural lithium.

The front surface of the INPORT tubes is at 3.45 m from the target and is exposed to a neutron wall loading of 10.6 MW/m^2. The peak dpa rate in the INPORT units is 68 dpa/FPY implying a lifetime of 2.2 FPY which corresponds to about 3 calendar years (CY) at 75% availability. Gradual reduction in the replacement frequency for the INPORT tubes can be achieved as one moves toward the back of the blanket with the back row of tubes being replaced only once during the reactor life. The peak dpa and helium production rates in the chamber wall are 5 dpa/FPY and 18.8 He appm/FPY, respectively. The chamber wall will last for the whole reactor life. Since spherical geometry has been used in the calculations, the damage rates given above represent the worst case conditions at the midplane of the cylindrical chamber. The local TBR is 1.504 and the local blanket nuclear energy multiplication M_n, defined as the ratio of nuclear heating to the energy of direct neutrons and gamma photons incident from the target onto the blanket, is 1.242. The spatial variation of nuclear heating has been calculated and is given in Fig. 4. The power density peaks at 23.3 W/cm^3 in the front INPORT tubes and drops to 3.5 W/cm^3 in the back tubes. The peak power density in the chamber wall is 4.8 W/cm^3.

IV. REACTOR ROOF

The roof of the chamber is a large dome that is required to be a lifetime component. The roof is 50 cm thick and consists of 80 vol.% HT-9 and 20 vol.% Li. Lithium drops dripping from the roof will not interfere with the beams as they will be vaporized by the blast wave before reaching the beam lines. The peak dpa rate in the roof has been calculated as a function of distance from the target. Based on these results, the roof of the LIBRA-LiTE chamber is located at 16 m from the target to ensure that it lasts for the whole reactor life. The roof is exposed to a neutron wall loading of 0.49 MW/m^2. The peak dpa and helium production rates in the HT-9 roof are 5 dpa/FPY and 28 He appm/FPY, respectively. The local TBR and M_n values are 0.558 and 1.299, respectively.

V. BOTTOM LITHIUM POOL

The bottom of the chamber consists of a lithium pool which is formed by the coolant flowing through the INPORT tubes. It drains through a 15 cm thick perforated plate made of HT-9, which acts as a reflector as well as a shock damper. This perforated plate consists of 80 vol.% HT-9 and 20 vol.% Li. The depth of the Li pool at the bottom of the reactor was determined to allow the bottom perforated plate to be a lifetime component. The upper surface of the pool is at 5 m from the target and is exposed to a neutron wall loading of 5 MW/m^2. The peak damage rate in the bottom plate was determined as a function of pool depth. The results indicate that the pool depth should be at least 0.75 m implying that the bottom plate should be located at 5.75 m from the target. The peak dpa and helium production rates in HT-9 are 5 dpa/FPY and 22 He appm/FPY, respectively. The local TBR and M_n values are 1.575 and 1.221, respectively.

VI. FINAL FOCUSING MAGNETS

The final focusing magnets utilize lithium as a conductor flowing in a metallic case. Each of the 30 magnets has a center bore radius of 9 cm, a 12.8 cm thickness and a length of 50 cm. Ballistic propagation of the light ions requires the magnets to be located as close as possible to the target. The lifetime of the magnets is determined by radiation damage to the front metallic casing. The peak damage rate in the front of the magnet was calculated as a function of distance from the target. The location of the magnet is determined to be 2.05 m from the target to achieve a peak dpa rate of 150 dpa/CY implying magnet replacement every one calendar year. The neutron wall loading at the front surface of the magnet is 29 MW/m^2. The peak helium production is 1700 He appm/FPY. The local TBR and M_n values for the magnets are 1.017 and 1.034 respectively. Nuclear heating profiles in the magnet have been determined for use in the thermal hydraulics analysis. The nuclear heating deposited in each magnet is 3.87 MW with the peak power density being 191 W/cm^3 in the front casing.

VII. BIOLOGICAL SHIELD DESIGN

The reactor shield is designed such that the occupational biological dose rate outside the shield does not exceed 2.5 mrem/hr during reactor operation. The biological shield consists of 70 vol.% concrete, 20 vol.% carbon steel C1020 and 10 vol.% He coolant. Figure 5 gives the dose rate at the back of the shield at the reactor midplane as a function of shield thickness. A 2.6 m thick shield is required for an acceptable dose rate of 2.5 mrem/hr. Similar calculations performed for the chamber roof indicate that the biological shield thickness above the roof should be 2.75 m thick.

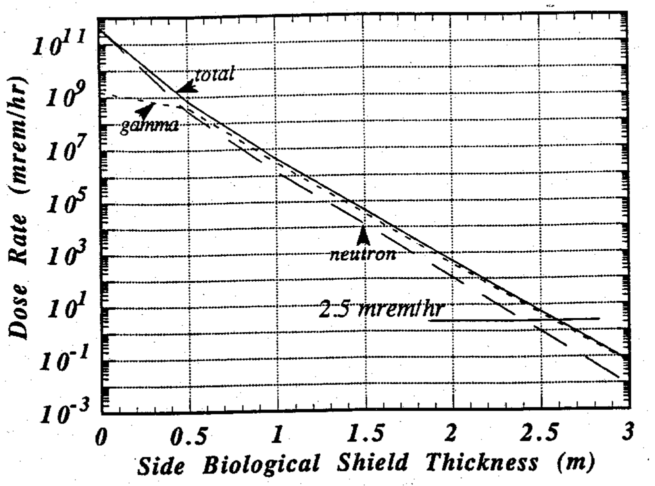

Fig. 5. Effect of side biological shield thickness on dose rate during reactor operation.

VIII. OVERALL REACTOR NEUTRONICS PARAMETERS

Table I lists the main neutronics parameters for the different regions of the reactor chamber. Using the coverage fractions and local nuclear parameters calculated for the different reactor regions surrounding the target, the overall reactor TBR and M_n can be determined. Table II indicates that the overall TBR and M_n values in LIBRA-LiTE are 1.405 and 1.211, respectively. Taking into account surface heating by the x-rays and debris, the overall reactor energy multiplication, defined as the ratio of the total power deposited by x-rays, debris, neutrons and gamma photons to the fusion power, is 1.123.

IX. NEUTRONICS PERFORMANCE WITH LITHIUM LEAD

The option of using the $Li_{17}Pb_{83}$ eutectic as a coolant and breeder instead of liquid lithium has been considered. Figure 6 shows the impact of blanket thickness and lithium enrichment on the local TBR in the INPORT units and the damage rate in the chamber wall for $Li_{17}Pb_{83}$ coolant and breeder. The results indicate that a 1.7 m thick blanket with a lithium enrichment of 90% ^{6}Li should be used. Even though the front surface of the INPORT units will be at 4 m from the target compared to 3.45 m in the lithium case, the lifetime of the INPORT units is reduced by 27% due to neutron multiplication in the lead. Neutronics calculations for the final focusing magnets indicate also that the magnet lifetime is reduced by 43% when $Li_{17}Pb_{83}$ is used. Table III gives a comparison between the neutronics related parameters obtained using Li or $Li_{17}Pb_{83}$ in LIBRA-LiTE. While using $Li_{17}Pb_{83}$ results in nearly the same overall TBR and M, the lifetimes of the INPORT units and final focusing magnets are reduced, a slightly bigger roof should be used, and highly enriched lithium must be used. A factor of five higher coolant/breeder cost results from using $Li_{17}Pb_{83}$.

TABLE I

Neutronics Parameters for the Different Regions of LIBRA-LiTE

Coolant/breeder	Liquid Li
Lithium enrichment	7.42% ^{6}Li
Blanket:	
Chamber wall radius	5.7 m
Inner radius of blanket	3.45 m
Neutron wall loading	10.6 MW/m^2
TBR	1.504
M_n	1.242
Peak INPORT dpa rate	68 dpa/FPY
Peak INPORT He production rate	602 He appm/FPY
Power density in the front INPORT tube	23.3 W/cm^3
Minimum INPORT lifetime	2.2 FPY
Peak chamber wall dpa rate	5 dpa/FPY
Peak chamber wall He production rate	18.8 He appm/FPY
Peak power density in chamber wall	4.8 W/cm^3
Chamber wall lifetime	30 FPY
Roof:	
Distance from target	16 m
Thickness	0.5 m
Neutron wall loading	0.49 MW/m^2
TBR	0.558
M_n	1.299
Peak dpa rate	5 dpa/FPY
Peak He production rate	28 He appm/FPY
Lifetime	30 FPY
Bottom:	
Distance of pool surface from target	5 m
Li pool depth	0.75 m
TBR	1.575
M_n	1.221
Peak dpa rate in steel plate	5 dpa/FPY
Peak He production rate in steel plate	22 He appm/FPY
Lifetime	30 FPY
Magnets:	
Distance of magnet front from target	2.05 m
Magnet length	0.5 m
Neutron wall loading	29 MW/m^2
TBR	1.017
M_n	1.034
Peak dpa rate	200 dpa/FPY
Peak He production rate	1700 He appm/FPY
Peak power density in front case	191 W/cm^3
Peak power density in Li	88 W/cm^3
Nuclear heating per magnet	3.87 MW
Lifetime	0.75 FPY
Biological Shield:	
Thickness at midplane	2.6 m
Thickness above roof	2.75 m
Operational dose rate at back of shield	2.5 mrem/hr

TABLE II

Overall Reactor Tritium Breeding Ratio and Energy Multiplication

Region	Coverage Fraction	TBR	M_n
INPORT	77.52%	1.504	1.242
Beam ports	1.45%	0	0
Magnets	7.03%	1.017	1.034
Roof	5.15%	0.558	1.299
Bottom	8.85%	1.575	1.221
Total reactor	100%	1.405	1.211

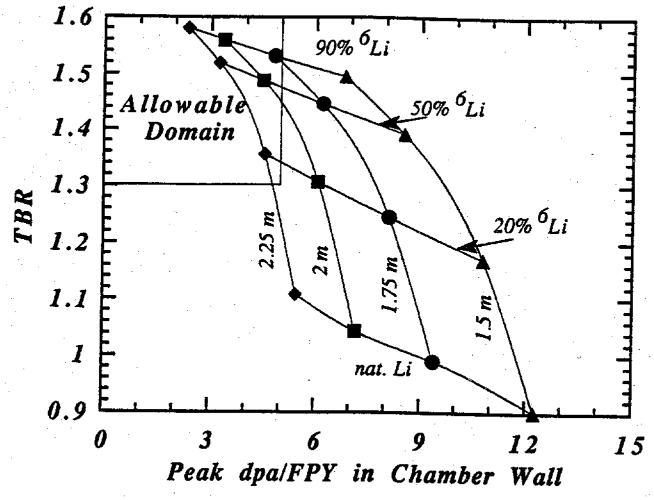

Fig. 6. TBR and chamber wall damage rate for different blanket designs utilizing $Li_{17}Pb_{83}$ as the coolant and breeder.

The factor of ∼17 higher density for $Li_{17}Pb_{83}$ will require more support structure for the piping and final focusing magnets and larger pumping power. The higher electrical resistivity of $Li_{17}Pb_{83}$ results in increasing the dissipated power in the final focusing magnets by a factor of ∼4 with a significant increase in the recirculating power. Furthermore, the $Li_{17}Pb_{83}$ vapor has a lower thermal conductivity and a higher atomic mass and, therefore, condenses more slowly than Li resulting in limiting the achievable repetition rate. In addition, the vapor in the chamber resulting from $Li_{17}Pb_{83}$ is expected to excessively scatter the ion beam. The safety concern related to using Li is the possibility of having a lithium fire. The use of an intermediate heat transfer circuit will prevent the accidental mixing of lithium with the steam cycle. On the other hand, the lead in $Li_{17}Pb_{83}$ produces polonium-210 which has a high radioactive hazard potential. The low tritium solubility in $Li_{17}Pb_{83}$ results in lower tritium inventory in the coolant but will increase the potential for tritium leakage from the primary coolant loop to the intermediate and secondary loops. Based on this comparison, liquid lithium is chosen as the reference breeder and coolant in LIBRA-LiTE.

TABLE III

Neutronics Parameters for LiPb vs. Li

	Li	LiPb
% ^{6}Li	7.42	90
Blanket thickness (m)	2.25	1.7
Inner radius of blanket (m)	3.45	4
INPORT lifetime (CY)	3	2.2
Magnet lifetime (CY)	1	0.57
Roof distance from target (m)	16	17
Pool depth (m)	0.75	0.55
Overall TBR	1.405	1.415
Overall energy multiplication	1.123	1.144

X. SUMMARY

Neutronics analysis has been performed for the LIBRA-LiTE light ion beam fusion reactor that utilizes ballistic ion propagation. The front metallic casing of the final focusing magnets placed at 2.05 m from the target is exposed to significant neutron flux resulting in one year magnet lifetime. The front few rows of the INPORT tubes should also be replaced every three years. A 2.25 m thick blanket utilizing natural liquid lithium will allow the chamber wall to last for the whole reactor life. The roof of the chamber is a large bare dome located at 16 m from the target to allow it to be a lifetime component. A concrete shield that is 2.6 m thick on the side and 2.75 m thick at the top of the chamber is required to yield acceptable operational dose rates. The overall reactor tritium breeding ratio and energy multiplication values are 1.405 and 1.123, respectively. Using liquid lithium results in more attractive neutronics performance features compared to $Li_{17}Pb_{83}$.

ACKNOWLEDGEMENTS

This work was supported by Kernforschungszentrum Karlsruhe and Sandia National Laboratories.

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