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NUCLEAR MICROREACTOR CONTAINMENT VESSEL CONCEPT USING COMPUTER-AIDED DESIGN FOR ADDITIVE MANUFACTURING

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Abstract: *The presented paper unveils an innovative approach for the construction of nuclear microreactor containment vessels through the integration of computer-aided design (CAD) and additive manufacturing technologies. By amalgamating these cutting-edge techniques, the research aims to develop a novel manufacturing process for nuclear microreactor containment vessels that not only enhances efficiency and precision but also offers valuable insights into lessons learned and future considerations.*
Additionally, the paper focuses on capturing the valuable lessons learned throughout the development process. By highlighting challenges encountered, solutions devised, and optimization strategies employed, the research aims to provide a comprehensive understanding of the intricacies involved in the design and manufacturing of nuclear microreactor containment vessels. Such insights can significantly contribute to the improvement of future designs and manufacturing processes, driving advancements in the field of nuclear energy.
Keywords: *nuclear microreactor, computer-aided design, additive manufacturing, containment vessel.*

1. INTRODUCTION

The nuclear industry relies significantly on technology that originated in the 1950s. However, with the continuous evolution of technology, there is now an evident opportunity to efficiently incorporate new technologies while utilizing existing proven principles and processes of nuclear reactors.

At present new technologies are reaching this domain with modular microreactors. As a compact and self-contained nuclear power system, a nuclear microreactor provides a reliable and sustainable energy source in small-scale settings [1]. These innovative devices, smaller than traditional reactors, incorporate advanced technologies and safety features to minimize risks and ensure efficient operation [2].

Utilizing nuclear fission, nuclear microreactors generate power by splitting heavy atomic nuclei, such as uranium or plutonium, into lighter fragments, releasing significant energy [30]. Fuelled by low-enriched uranium or advanced fuel materials, these reactors prioritize safety and extend their operational life.[2]

Nuclear microreactors offer versatility and portability, enabling deployment in remote areas or places with limited infrastructure [2]. They serve as reliable power sources for military bases, disaster-stricken regions, and isolated communities, contributing to sustainable energy solutions [2].

Throughout the design process, the objective is to develop a reactor vessel that meets specific criteria: a length of less than 1000 mm, a diameter of less than 300 mm, and a minimum thermal power output of 2 MW. This design aims to cater to the needs of small communities, hospitals, and power-consuming facilities.

1.1 Nuclear reactor vessel functions

Within the nuclear power plant, several functions and subfunctions are performed to ensure safe and efficient operation. Before identifying the functions, we first identified the high-level systems and/or equipment responsible for the processes Fig.1.

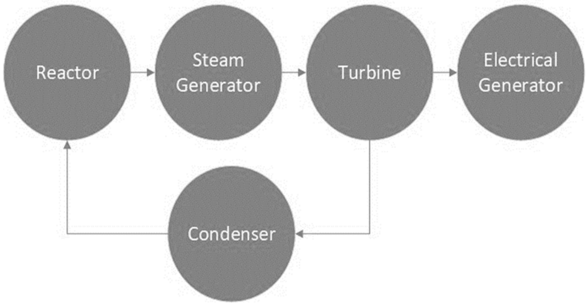

Fig.1 Identified systems/components of a nuclear power plant

The reactor vessel is a vital component of nuclear power plants, fulfilling essential functions to ensure nuclear reactors' safe and efficient operation. Its role in containment, pressure and temperature management, radiation shielding, structural support, and system integrity is crucial for maintaining the safety and reliability of nuclear power generation.

The primary function of a reactor vessel is to contain radioactive materials generated during the nuclear fission process. It acts as a barrier, preventing the release of radioactive substances into the environment and ensuring the safety of workers and the public. [3]

Reactor vessels are designed to withstand high pressures and temperatures, enabling efficient heat transfer and power generation. They maintain the coolant at optimal conditions, facilitating the controlled release of thermal energy [4].

The vessel serves as a shield, minimizing radiation exposure by attenuating and absorbing radiation emitted from the reactor core. This shielding protects both personnel working in the vicinity and the surrounding environment [5].

Reactor vessels provide structural support to core components, such as the reactor core, control rods, coolant channels, and internal systems. Their robust construction ensures the integrity and stability of the reactor system [6].

The vessel's design incorporates safety features to withstand extreme conditions, including potential accidents or malfunctions. It undergoes rigorous testing to ensure its ability to contain and control nuclear reactions, preventing the release of harmful materials [7].

1.2 Nuclear industry manufacturing technologies

The nuclear industry utilizes various manufacturing processes to fabricate components and systems for nuclear power plants. Some of the main manufacturing processes are:

- Forging involves shaping metal by applying a compressive force to it. It is commonly used to manufacture large, high-strength components such as reactor pressure vessels and steam generators [8].
- Casting involves pouring molten metal into a mould to obtain the desired shape. It is used to produce complex geometries and intricate components, including turbine blades, pump casings, and valve bodies [9].
- Machining processes such as milling, turning, and drilling are utilized to precisely shape and finish components. Machining is used to create tight tolerances and smooth surfaces for various nuclear components [10].
- Welding joins metal parts together by melting and fusing them. It is extensively used in the nuclear industry to fabricate piping systems, support structures, and containment vessels [11].
- Additive Manufacturing (AM), also known as 3D printing, builds components layer by layer using computer-controlled deposition of material. AM is increasingly being explored in the nuclear industry for producing complex geometries and prototypes [12].
- Extrusion involves forcing heated material through a shaped die to create a continuous profile. It is used for manufacturing fuel rods, cladding, and other nuclear fuel-related components [13].

Additive manufacturing emerges as a solution to alleviate the limitations imposed by conventional manufacturing methods. The design can be liberated from traditional constraints by employing additive manufacturing techniques, enabling greater flexibility and alignment with the intended design concept. Furthermore, since the new concept deals with single reactors for small communities, the production of just one vessel via additive manufacturing techniques will allow cost minimization, an important aspect of the manufacturing process.

The most suitable technique at this point in the research stage and the most likely to be selected to be used for the final model is Powder Bed Fusion (PBF) using Selective Laser Melting or Electron Beam Melting (EBM). [14]

The commercial or productive function of a nuclear reactor is to generate heat, this heat needs to be efficiently distributed to the working fluid, gas, water, or liquid metal. Having this in mind this paper focuses on the thermal design efficiency of the concept.

1.3 Advancements and Potential

The use of computer-aided design (CAD) for additive manufacturing in the design process of nuclear microreactors holds significant promise for the nuclear industry. This article explores the purpose and advantages of employing CAD for additive manufacturing techniques in the design of nuclear microreactors, highlighting enhanced design flexibility, customization, improved performance, rapid prototyping, material efficiency, and knowledge advancement. The discussion emphasizes the potential benefits and opportunities CAD-driven design optimization and additive manufacturing offer in developing efficient and compact nuclear power systems.

When referring to optimization, within this paper we address several aspects such as geometry design, thermohydraulic features and material selection and compatibility with the hypothetical environment.

CAD allows for intricate and complex designs that can be optimized for performance, safety, and manufacturability. This section highlights the advantages of utilizing CAD software in exploring innovative and optimized geometries for nuclear microreactors [15].

Additive manufacturing techniques enable the production of customized components, allowing for adaptable and scalable microreactor designs to suit specific power requirements and deployment scenarios [16].

CAD-driven design optimization can lead to improved performance, enhanced thermal management, and higher overall energy conversion efficiencies. AM techniques can further enable the production of intricate cooling channels and integrated structures, improving heat transfer capabilities [17].

Additive manufacturing sustains the production of customized components, allowing for adaptable and scalable microreactor designs tailored to specific power requirements and deployment scenarios. [18]

2. DESIGN CONCEPT

The design concept took three iterations (from Model 1 to Model 3) before reaching an agreed model for further development.

The model has an elongated spherical shape with pipes distributed along the inner surface of the vessel.

The pipes and the vessel must have an increased heat exchange surface, facilitating heat exchange with the environment and fluid within.

2.1 Conceptual Design Model 1

Conceptual Design Model 1, section view in **Fig. 2**, serves as a straightforward foundation incorporating a handful of fundamental ideas. It originated from the inspiration of the Calandria model [19], where the pipes traverse the containment vessel, but in this case, they have been repositioned and integrated alongside the vessel.

Fig. 2. Conceptual Design Model 1 - Section view

Estimations for the parameters were obtained using the available volume within the pipes and vessel for working fluid with material density considered at 25°C. These estimations were provided by the Ansys SpaceClaim material library [20]. This estimation was considered for all the conceptual design models presented in this paper.

2.2 Conceptual Design 2

Conceptual design model 2, presented in **Fig. 3,** aims to increase the pipe heat exchange surface and fluid flow within the vessel. The surface of the pipes covers almost all the surface of the middle component.

Fig. 3. Conceptual Design Model 2 - Section view

Based on the specifications mentioned above the model increased the surface area for the fluid by approximately 0.2 m^2 and it did not significantly alter the initial model. Therefore, another design iteration was needed.

2.3 Conceptual Design Model 3

The third concept presented in Fig. 4-6 is based on heat pipe working principles with two working fluids and cooling methods.
The first heat evacuation path with the environment surrounding the vessel and the second path is through the 16 pipes that pass through the vessel.
The idea is based on heat pipe working principles with two working fluids and cooling methods.

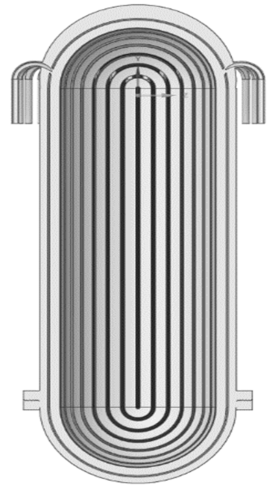

Fig. 4. Conceptual Design Model 3 – Side section view

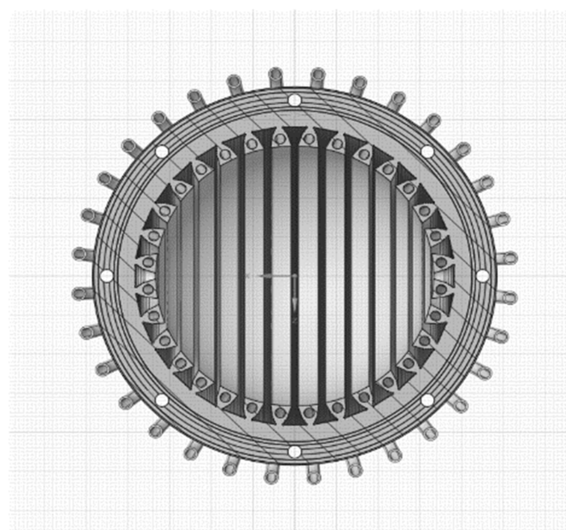

Fig. 5. Conceptual Design Model 3 – Top section view of the reactor vessel

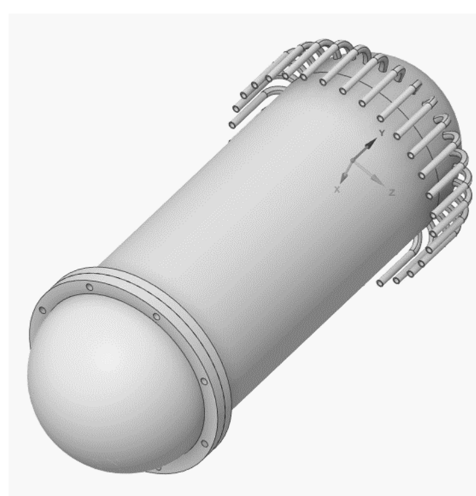

Fig. 6. Conceptual Design Model 3 – Side view

It can be noticed in Fig. 7 the increased difference in fluid surface area subject to heat exchange for each conceptual design.

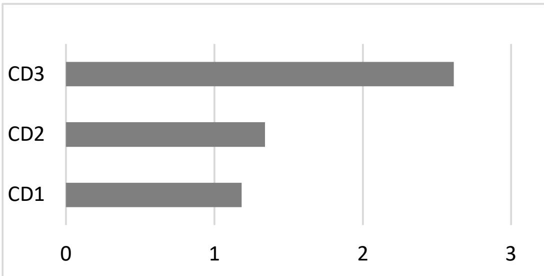

Fig. 7 Heat exchange surface area for each conceptual design

3. ADDITIVE MANUFACTURING CONSIDERATIONS

3.1 Identified research stages

Several stages were identified that were required through the process of designing and manufacturing a CAD model [21].

In the design and conceptualization stage, the design concept for the nuclear reactor containment vessel is developed, considering the specific requirements for nuclear containment, safety regulations, and the unique challenges associated with nuclear reactor systems. The design should consider factors such as structural integrity, radiation shielding, and access for maintenance and inspection.

For material selection and analysis: Stainless steel 316L is a commonly used material for nuclear reactor containment vessels due to its high corrosion resistance and mechanical strength. However, extensive research has been conducted to analyse the behaviour of stainless steel 316L under irradiation, high-temperature, and high-pressure conditions. This includes evaluating its resistance to stress corrosion cracking, radiation embrittlement, and creep deformation [22] [23].

The additive manufacturing process selected for manufacturing the nuclear reactor containment vessel should be capable of producing large-scale, high-integrity structures. Research is conducted to optimize the additive manufacturing parameters and process conditions to ensure the integrity and quality of the 3D-printed vessel. This includes layer adhesion, surface finish, and porosity control considerations.

Computer simulations and advanced modelling techniques are employed to optimize the design of the containment vessel. Finite element analysis (FEA) and thermal-hydraulic simulations are usually conducted to evaluate structural integrity, heat transfer characteristics, and coolant flow behaviour. These simulations help ensure the vessel's performance and safety under normal and accident conditions [24] [25].

Prototypes of the 3D CAD model will be additively manufactured using stainless steel 316L. These prototypes are subjected to rigorous testing and validation, including non-destructive testing (e.g., ultrasonic testing, radiographic testing) and mechanical testing (e.g., tensile, impact, and fracture toughness testing). Testing is conducted to verify the vessel's structural integrity, mechanical properties, and leak-tightness.

Robust quality control procedures are specific to the manufacturing process and materials are developed to ensure the production of high-quality containment vessels. Quality control includes monitoring the manufacturing process, inspecting the vessel for any defects or irregularities, and implementing stringent documentation and traceability measures. Adherence to nuclear industry standards and regulatory requirements is essential [26] [27].

3.2 Identified eligible material

During the design stage, several considerations were taken into account for subsequent production using additive manufacturing technologies with metals.

The first consideration is the material selection that is directly related to the two main types of additive manufacturing for metals, most suitable for this process - Direct Energy deposition (DED) and Powder Bed Fusion (PBF).

The mass of the model was designed using ANSYS SpaceClaim, considering Stainless Steel 316L alloy as a reference material.

This material was ultimately selected for the model as it is more commonly used and is resistant to high temperatures and difficult working environments such as ionizing radiation.

It is also a good choice for financial considerations as stainless steel is more economically feasible for production.

Several materials were identified in Table 1 and compared to available AM technologies, the comparison was made using information available in technical literature and publications [28-35].

Table 1

Eligible material [28-35]

Metal	DED Compatibility	PBF Compatibility
Titanium alloy (Ti-6Al-4V)	Yes	Yes
Zirconium Alloys (Zircaloy-4)	Limited	Limited
Stainless Steel (316L)	Yes	Yes
Inconel 718	Yes	Yes
Hastelloy	Yes	Yes
Cobalt-Chrome	Yes	Yes
Copper (Cu)	Yes	No

4. RESULTS

Considering identified literature [21] et. al. we adapted our own CAD models to additive manufacturing methodology.

Our methodology describes the iterative process of designing the intended model, identifying requirements, and refining them to industry practices and model capabilities.

The iterative process implies that the model, specifications, and requirements may change over time based on feedback from the analysis. The resulting methodology presented in Fig. 8 is based on the Pahl and Beitz process for conceptual design [21] and adapted to the various identified phases.

At its core, the Pahl and Beitz methodology [21] emphasizes a systematic and iterative design process, involving various stages such as problem identification, concept generation, evaluation, and embodiment design. The sixth stage within the methodology is the most laborious and intensive one as it includes the types of analysis suitable for a reactor vessel and comparison with acceptance criteria identified in technical literature such as ASME Boiler & Pressure Vessel Code et al. [27].

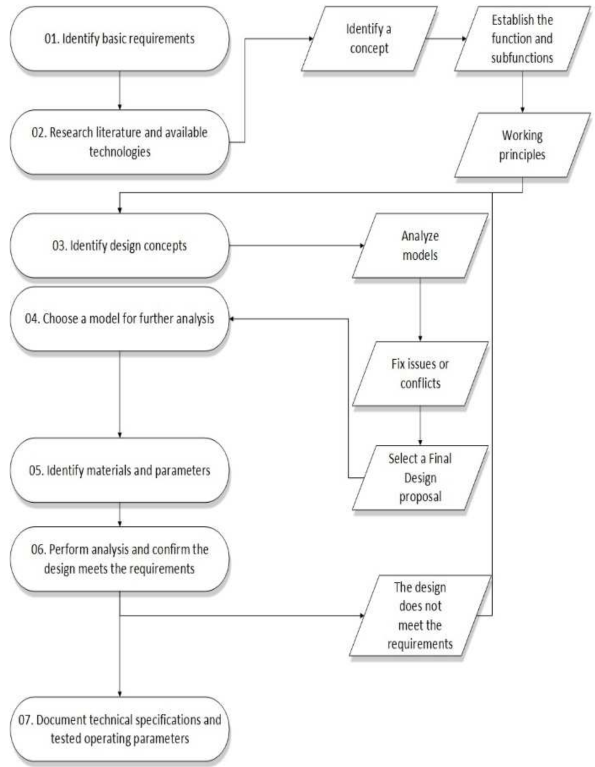

Fig. 8. Methodology – CAD to AM

Table 2

Conceptual Design - Requirements

Requirements	Acceptable parameters
Size	<1000mmx300mm
Material	Stainless Steel 316L
Heat exchange surface	> 2m2
Stress analysis	Up to 125 MPa
Thermo-hydraulic analysis for water	Temperature: Up to 315 degrees Celsius (600 degrees Fahrenheit)
	Pressure: Up to 100 bar (1,450 psi)
	Corrosion: Stainless steel 316L is resistant to corrosion in water, but it can be susceptible to stress corrosion cracking in certain environments.
Thermo-hydraulic analysis for helium	Temperature: Up to 500 degrees Celsius (932 degrees Fahrenheit)
	Pressure: Up to 150 bar (2,175 psi)
	Corrosion: Stainless steel 316L is not susceptible to corrosion in helium.
Leak-tightness	Leak rate = < 1.0 × 10-12 mbar·l/s

The design process is iterative and continuous improvement of the model should be possible.

Based on the methodology presented in Fig. 8 and the literature review [21] et al., we established a table with basic requirements to be used as acceptance criteria Table 2.

The information presented in Table 2 is chosen empirically and is subject to change based on the evolution of the design and feedback from analysis results.

The design should take into account different aspects required by AM processes – minimization and ease of removal of support structures, proper access to various parts of the vessel for final post-processing surfaces (e.g., milling and drilling), etc. Considering the information presented in Table 2, further work is required to improve the models.

To achieve successful additive manufacturing (AM) of the model, it is necessary to divide the model into two or more parts. This division facilitates better printing outcomes by reducing print failures, minimizing support material requirements, and ensuring the overall manufacturability of complex geometries.

In their comprehensive study on Design for Additive Manufacturing (DFAM),[37] Zeng et al. emphasize the importance of partitioning complex geometries into multiple parts for AM. They discuss how dividing models into smaller components allows for more efficient and reliable printing, as it reduces the risk of warping, distortion, and print failures. Moreover, the authors highlight the advantage of dividing the model into functional or assembly-oriented parts, enabling easier post-processing and assembly steps.

Table 3 presents a side-by-side comparison of the specifications of the three models that were developed in the design stage.

These specifications help with identifying the most suitable candidate for further analysis.

As the types of analysis to be performed are diverse and time-consuming, we will focus on a single chosen design to perform them.

They provide valuable data for optimizing reactor performance, understanding radiation effects on materials, and ensuring compliance with regulatory requirements.

Table 3

Conceptual Design Models – specification comparison

Parameter	CD 1	CD 2	CD 3
Vessel Mass	48,2219 kg	45,3332 kg	76,9689 kg
Height	0,25m	0,25mm	0,25mm
Width	0,25m	0,25m	0,25m (0,29 m – including pipes)
Length	0,67m	0,67m	0,7839m
Vessel Interior Volume	0,0241m³	0,0231m³	0,0241m³
Piping total volume	0,0011m³	0,003m³	0,0011m³
Vessel Material	Stainless Steel 316L	Stainless Steel 316L	Stainless Steel 316L
Vessel Material Density	8000 kg/m³	8000 kg/m³	8000 kg/m³
Working fluid	Water or Helium (Not defined yet)	Water or Helium (Not defined yet)	Water or Helium (Not defined yet)
Estimated water mass within the volume	22,92 Kg	23,1342Kg	25,2203Kg
Estimated volume of fluid	0,0229 m^2	0,0231 m^2	0,0251 m^2
Total fluid surface area	1,1833m^2	1,3411m^2	2,613 m^2
Estimated gas(helium) mass within the volume	0,0041 Kg	0,0041 Kg	0,0041 Kg
Piping information	10 pipes with 10 inlets and 10 outlets arranged in a circular pattern.	5 pipes with 5 inlets and 5 outlets arranged in a circular pattern.	16 pipes with 16 inlets and 16 outlets arranged in a circular pattern.
Pipe interior diameter	15mm	15mm	7,5mm
Vessel maximum thickness	12,5 mm	12,5 mm	13,2856 mm
Vessel minimum thickness	5 mm	2.5 mm	2.17 mm

The increase in mass presented in Table 3 for CD-3 is justified by the increase in heat exchange surface, these aspects are directly correlated. The number of pipes varies due to pipe diameter size, geometry constraints as well as fluid flow considerations. For example, in CD-3 due to the small pipe diameter we considered the maximum number of pipes that would be geometrically possible for the model.

5. CONCLUSION

The conceptual models are designed for additive manufacturing and are in the project stage. When all the analysis will confirm the feasibility of the project a scaled model will pe fabricated to validate the analysis results. The process of conceptualizing and developing a CAD model for additive manufacturing by itself must account for several factors without considering a difficult working environment such as one in a nuclear reactor.

Several analyses must confirm that the model can withstand such an environment.

The continuity of the pipes with the rest of the system was not considered to focus on the vessel design as the number of pipes, the pipe design and distribution within the vessel may change after analysis results.

The model was divided into two parts for additive manufacturing considerations to facilitate available printing options. The assembly between those two parts is also considered problematic and further research is needed to optimise this process from the tightness point of view.

By creating a lid, we divided the design into two parts. The lid can be observed in Fig. 7. The assembly process shall consider an intermediate sealant material between the lid and the vessel body.

The next step after the design stage is to theoretically verify its viability from the efficacy of heat transfer point of view through stress and thermohydraulic analysis, followed by experimental verification.

For the model to be economically feasible in implementation we need to further reduce the weight either by reducing the wall thickness of the vessel or by changing the internal structure further and this is another aspect that is currently under investigation.

A consideration for the future is that the model may be modified further to include other nuclear systems and components such as steam generators and steam turbines, but this modification with make the model more complex and more difficult to model in CAD analysis software.

For future work, the types of analysis to be performed include and may not be limited to:

- Stress analysis for the vessel to establish an acceptable, operational stress level.
- Thermo-hydraulic analysis involving water and/or helium at various temperatures and pressures to confirm efficient cooling and safe operation of the reactor vessel.
- Structural analysis to verify integrity under different loads.
- Dosimetry analysis to measure the radiation dose received by reactor components, including the vessel's structural materials and nearby instrumentation.
- Shielding Analysis to evaluate the effectiveness of the reactor's radiation shielding and determine the estimated radiation exposure of personnel and environment.

6. ACKNOWLEDGEMENTS

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CONCEPTUL VASULUI UNUI MICRO REACTOR NUCLEAR FOLOSIND PROIECTARE ASISTATĂ DE CALCULATOR PENTRU FABRICARE ADITIVĂ

Rezumat: Acest articol prezintă o abordare pentru construirea vasului unui micro reactor nuclear utilizând tehnologia de proiectare asistată de calculator (CAD) și tehnologii de fabricație aditivă. Obiectivul principal constă în valorificarea acestor tehnici avansate pentru fabricarea eficientă și precisă, oferind în același timp lecții învățate și aspecte de luat în considerare pentru viitor.

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