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DESIGN CONSIDERATIONS FOR PIECE (PIE CELLS AT ESS)

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ABSTRACT

A feasibility study of equipping a PIE (Post Irradiation Examination) facility infrastructure at ESS in the post-construction phase of the project is under consideration. In this paper, the scope, the design requirements and the top-level system architecture of the PIECE (PIE Cells at ESS) facility are presented. The proposed PIECE facility aims at fulfilling the following three objectives: to measure the mechanical properties of irradiated target station structural components for the purpose of estimating component lifetimes, to study new candidate materials for the target station components applications for longer lifetime and higher reliability, and to perform fundamental researches on the irradiated materials in the framework of international collaboration. The presented study provides necessary inputs for currently on-going target station design activities such that the PIECE facility can be readily incorporated into the ESS infrastructure in the post-construction or in the operation phase of the project. Vice versa, the currently base-lined target station design provides the constraints on the scope of the PIECE facility. The roadmap for developing the PIECE plan from the current feasibility study towards the post-construction phase project with dedicated resources is presented.

1. Introduction

The European Spallation Source (ESS) will deliver the world's highest flux of slow neutron beams for the basic and applied researches investigating the molecular building blocks of matter. In normal operations, the spallation target will be receiving a high power (5 MW) proton beam to provide neutrons to scientific instruments.

The spallation target is surrounded by the moderators and reflectors as shown in Fig. 1. Before impinging on the target, the intense proton beam passes the proton beam window that separates the helium atmosphere surrounding the target zone from the high vacuum of the accelerator tunnel. The target and the proton beam window are subject to incident high intensity proton beam irradiation, where the target materials are subject to spallation neutron irradiation as well. The moderators and the reflectors are exposed to a large flux of spallation neutron shower from the target.

The lifetimes of the target, the proton beam window, the moderators and the reflectors are largely limited by the material degradation, which is caused by radiation damage. Unfortunately, there is a scarcity of engineering data for the properties of high-energy hadron irradiated materials. The uncertainty in the radiation damage effects on materials necessitates a high level of conservatism in the component design lifetimes and operation of the ESS target station, which will drive the operational costs upward. It is therefore reasonable to plan a R&D onsite infrastructure at ESS to understand the characteristics and behaviour of the engineering materials that are exposed to proton and neutron fluxes.

A feasibility study of equipping a PIE (Post Irradiation Examination) facility infrastructure at ESS in the post-construction phase of the project is under progress. The dedicated materials research R&D infrastructure is named to be PIECE (PIE Cells at ESS) in this paper. The proposed PIECE facility aims at investigating the properties of materials that are irradiated by high flux protons and neutrons at the ESS target station by fulfilling the following three objectives:

- Determine the lifetimes of the irradiated engineering materials and provide the operational information of the target station for the optimization of the operational cost,
- Study new candidate materials for the target station systems applications for longer lifetime and higher reliability,
- Perform fundamental researches on the irradiated materials in the framework of international collaboration.

In this paper, the scope, the design requirements and the top-level system architecture of the PIECE (PIE Cells at ESS) facility are presented. The presented study provides necessary inputs for currently on-going target station design activities such that the PIECE facility can be readily incorporated into the ESS infrastructure in the post-construction or in the operation phase of the project. Vice versa, the currently base-lined target station design provides the constraints on the scope of the PIECE facility. The roadmap for developing the PIECE plan from the current feasibility study towards the post-construction phase project with dedicated

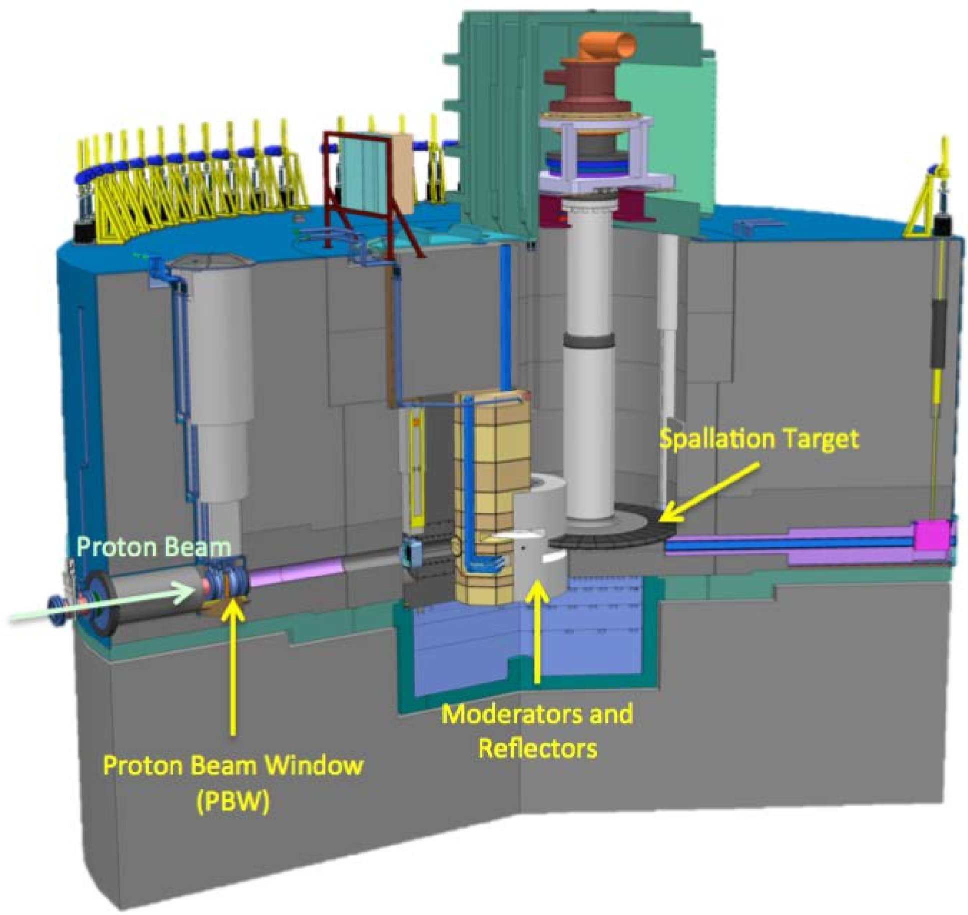


Figure 1: Layout of the ESS Target Monolith that houses the spallation target, moderators, reflectors and proton beam window (figure credit: N. de la Cour).

resources is presented.

2. System Requirements

The system requirements of the PIECE is linked to the top level ESS constraint requirement, “ESS shall limit operational cost” [1]. At the top level, the system requirements for the PIECE can be categorized into 4 sub-requirements, the functional requirements, the constraint requirements, the safety requirements and the interface requirements.

Functional Requirement: The PIECE shall deliver scientific knowledge about the engineering materials that are irradiated by high flux protons and neutrons at ESS.

- The materials shall be irradiated by protons and neutrons.
- The irradiated materials shall be prepared for PIE samples.
- The PIE samples shall be investigated scientifically.
- The PIECE shall process and handle radioactive materials.

Safety Requirement: The PIECE must obey the “General Safety Objectives” of ESS [2].

- The radiation exposure to the personnel shall be limited.
- The radioactive contamination level shall be limited.

Constraint Requirement: The scope of the PIECE shall be limited.

- The project cost shall be limited.
- The space shall be limited.

Interface Requirements: The PIECE has interfaces to the top-level systems of ESS as below.

- Target Station:
  - o The irradiation station and shielded cells shall be stationed at the target station.
  - o The target station shall provide handling and logistics support to the PIECE.
- Integrated Control System:
  - o Chosen PPS (Person Protection System) signals shall be monitored at PIECE.
- Site Infrastructure:
  - o Site infrastructure shall provide enabling utility systems to the PIECE.
- Radioactive Materials Handling Facility:
  - o The radioactive materials handling facility at ESS shall handle the disposal of radioactive wastes from the PIECE.
- Neutron Science Facility:
  - o The neutron science facility shall provide a research lab for the chemical and radiological analyses of irradiated specimens.

3. System Architecture

The PIECE system is broken down into the 6 subsystems according to allocated functionality. The top-level system architecture of the PIECE and the allocated specific functions are summarized in Table 1.

System	Allocated functions
Irradiation Station	Irradiate the materials at the ESS target station.
Process Cells	Take the parts from the irradiated materials for PIE.

Sample Preparation Cells	Prepare specimen for PIE.
Research Cells	Scientifically investigate the PIE specimen.
Handling & Logistic System	Handle, transport and dispose the radioactive materials.
Utility System	Enable the operation of PIECE.

Table 1: Top-level system architecture of the PIECE.

Each of the 6 sub-systems is described in the following sub-sections.

3.1 Irradiation station

At the ESS target station, the irradiated materials for the PIE can be obtained in two ways, from the irradiated system components and from the dedicated irradiation modules.

3.1.1 Operating system components

The material samples can be obtained from the used components after their lifetimes. These are the target wheel, the moderators, the reflectors and the proton beam window.

For reference, the spallation material tungsten in the target wheel will receive maximum 0.9 DPA (displacement per atom) per year at 5 MW beam power [3]. The beam upstream part of the tungsten is subject to proton radiation damage, whereas the beam downstream region will get damages from the mixture of protons and spallation neutrons. The target shell will be made of stainless steel (316 LN) and the window part of the target shell will receive maximum 1.2 DPA per year from the impinging high-energy (2 GeV) protons. The lifetime of the target wheel is designed to be 5 years.

The proton beam window separates the high vacuum region of the accelerator tunnel from the spallation region, which is surrounded by sub-atmospheric helium atmosphere. The window is made of aluminium alloy (6061-T6) and it is under direct proton beam irradiation. Following the experience at SNS [4], the lifetime of the aluminium alloy window is 6 months, which is limited by the helium production rate, calculated to be maximum 3900 He-appm/year.

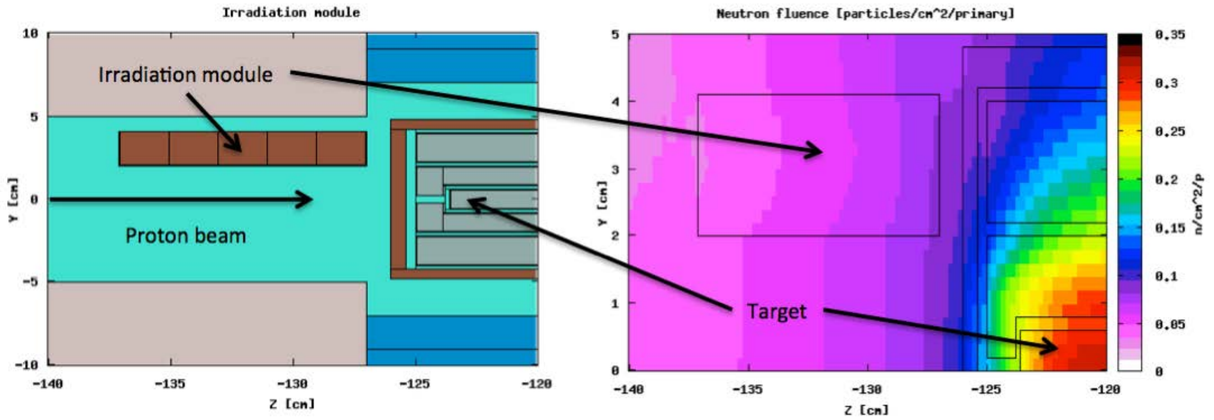
The moderator and the reflector canisters will be made of aluminium alloy (6061-T6). The aluminium alloy canisters will receive damages mainly from spallation neutrons. In the region subject to maximum neutron flux, the aluminium alloy will receive 19 DPA per year. Operational experiences from other spallation sources suggest the moderator canister lifetime of one year.

3.1.2 Irradiation module

The PIE of the materials from the irradiated components will provide the information about the radiation damage for the real operational conditions. But, it is difficult to investigate the material properties of future candidate materials under well-defined irradiation conditions. Furthermore, the post treatment of the already radioactive materials into the precision test specimen involves handling complications.

Irradiation module is a dedicated system in which materials of interest are irradiated in well-defined conditions. The control parameters for irradiation include the irradiation temperature, the neutron fluence and the proton fluence. The samples for the destructive PIE tests can be machined before irradiation and put into the module.

With the irradiation module, only the spallation neutrons can be used for material irradiations, with a fairly small fraction of scattered protons. The reason is that the presence of the module within the proton beam footprint might disturb the neutron fluence to the scientific



instruments.

Figure 2: FLUKA model for the irradiation module (left) and the neutron fluence map (right).

As the moderator and the reflector systems will occupy the top and the bottom region of the target, where the neutron flux is the highest, a potential location for the irradiation module is at the beam upstream region of the target. Figure 2 shows the geometry model of the irradiation zone, which is prepared for FLUKA simulations. Also shown in Fig. 2 is the neutron fluence map.

The DPA calculations show that approximately 10 dpa/year in iron samples will be obtained in approximately 0.1 litres of irradiation volume near to the target. The typical He-appm/dpa ratio is 13. The engineering for the irradiation module with the equipment for temperature control and the sample handling could follow the concept of Vladimirov and Möslang [5]. Considering the DPA per year and the He-appm/dpa ratio, the irradiation module also could be used for fusion materials irradiation.

3.2 Process cell

In the process cell of the target station, the test materials will be taken. This can be done by cutting irradiated components from the operated systems or by taking samples from the irradiation module. The acquired sample materials will be transported to the sample preparation cells.

The process cell is a level-IV sub-system in the ESS global system architecture, which is mainly dedicated to receive radioactive components from the target station, process the components for the intermediate storage, external shipment and for the refurbishments.

Figure 3 shows the schematic layout of the active cells of the ESS target station, which has the process cell as a sub-component.

3.3 Sample preparation cells

A range of specimen geometries will be machined into precision test samples as required for destructive and non-destructive PIE. As the radioactivity and the contamination level of the raw materials from the process cell will be high, the sample preparation cells must be shielded and equipped with the remote handling devices.

The sample preparation cell consists of shielded cells and a number of glove boxes. The shielded cell will be equipped with master-slave manipulators and handles high dose materials. The materials with lower dose will be handled in glove box. There are space allocations for two shielded cells for sample preparation in the active cell area of the target building, as shown in Fig. 3.

The sample preparation cells must fulfill the top-level functional requirements as listed below:

- The radioactive materials shall be machined to precision PIE specimen.
- The PIE specimen must be cleaned.
- The PIE specimen must be polished.
- The PIE specimen must be examined non-destructively.

To fulfill the requirements, the equipment listed below is foreseen.

- EDM (electrical discharge machining) machine.
- Ultrasonic cleaner
- Surface grinder/cleaner
- Sample activity measuring devices
- Sample dimension measuring devices
- Sample defects measuring devices

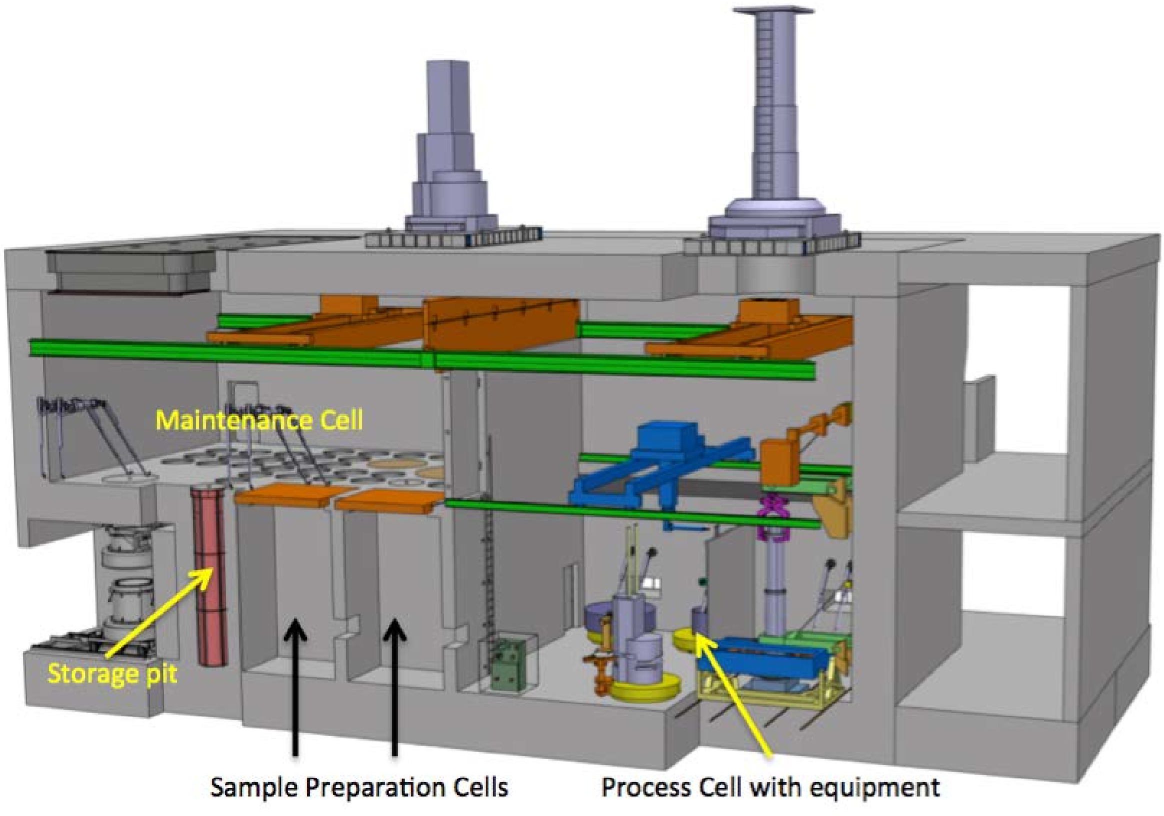


Figure 3: Layout of the active cells that include the process cell and the sample preparation cells (figure credit: P. Erterius).

3.4 Research cells

In the research cells, the mechanical properties, the thermal properties, the microstructures and the radiochemical properties of the irradiated materials will be investigated.

3.4.1 Mechanical test cells

The mechanical test specimens are classified in two categories, the specimen miniaturized for standard tests and the specimen for non-standard tests. The standard tests with miniaturized specimens include the tensile tests, the compression tests, the fracture toughness tests and the fatigue tests. The non-standard tests include the shear punch tests and the ball punch tests. These tests are to be performed at different temperatures, and all the test equipment shall be furnace compatible.

The mechanical tests will be performed in three dedicated shielded cells equipped with master-slave manipulators and a glass window with 18 inches in diagonal. The shielded cells typically have the inside dimension of 3 m [Width] x 2 m [Depth] x 2.5 m [Height] with 30 cm thick shielding walls made of steel. The cells will be placed on the ground floor of the technical gallery area at the ESS target station. Each cell will provide maximum 10 tons of loading to the building structure of the target station. The schematic layout of the shielded cells on the floor of the technical gallery is shown in Fig. 4.

3.4.2 Thermal test cells

The thermal test cell is a shielded cell equipped with thermal property measurement devices such as differential scanning calorimeter and laser flash apparatus. It is also equipped with manipulators and an 18-inch lead-glass window. In the thermal test cell, the electric conductivity will also be measured to investigate the Franz-Wiedemann law between the electric and thermal conductivity.

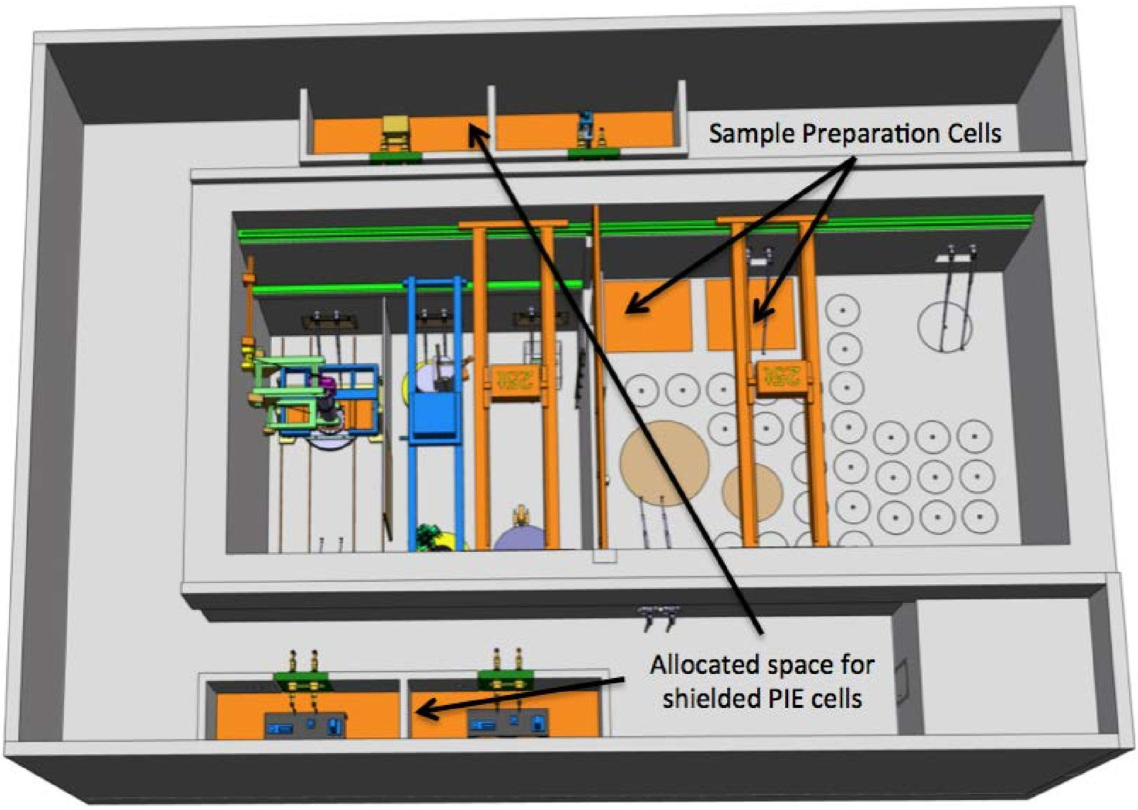


Figure 4: The space allocated for the shielded PIE Cells on the ground floor of the target building (figure credit: P. Erterius).

3.4.3 Microscopy lab

For the microscopic structure analysis of the irradiated materials, the microscopy cell will be equipped with the devices such as optical microscope, metallographic microscope, transmission electron microscope, and scanning electron microscope and X-ray diffractometer. The microscopy lab will be located in the research lab building of the "Neutron Science Facility" at ESS, which will be built attached to the experimental hall.

3.4.4 Radiochemistry lab

The radiochemistry lab is dedicated to the chemical mass concentration and isotopic analyses of irradiated materials. This will be located in the research lab building of the "Neutron Science Facility" at ESS, which will be built attached to the experimental hall.

3.4.5 Data analysis lab

The measurement data from the test equipment in the research cells will be processed and analyzed in the data analysis lab. This will be located in the neighborhood of the mechanical and thermal test cells.

3.5 Handling and logistic system

The handling and logistic system includes the transport casks, transport carts, manipulators and storage containers. The radioactive PIE materials must be transported inside and outside the target building, within the site boundary of the ESS. The intermediate storage and the final waste release will be provided by the existing active cells system of the target station.

3.6 Utility system

The enabling systems such as ventilation system, power supply, water supply and the monitoring systems belong to the utility system. It enables the operation of the PIECE.

4. Conclusions

In this paper, the top-level requirements and the system architecture of the PIE infrastructure of the ESS are presented. During the construction phase of the ESS project, a fractional scope of the PIECE (PIE Cells at ESS) is included in the plan with dedicated resources as briefly described in Table 2.

Subsystems Level 1	Subsystem Level 2	ESS project plan status
Irradiation Station	Operating Components	Resources allocated for complete engineering
	Irradiation Module	Resources allocated for conceptual design
Process Cell		Resources allocated for complete engineering
Sample Preparation Cells		Resources allocated for the shielding walls.
Research Cells	Mechanical Test Cells	Resources allocated for conceptual design
	Thermal Test Cells	Resources allocated for conceptual design
	Microscopy Lab	Resources allocated for lab spaces
	Radiochemistry Lab	Resources allocated for lab spaces
	Data Analysis Lab	Resources allocated for lab spaces
Handling and Logistic System		Resources allocated for conceptual design

Utility System		Resources allocated for conceptual design

Table 2: Project scope of PIECE during the construction phase of the ESS project.

During the project period, the conceptual design of the PIECE will be made together with cost and resources estimations. Based on these, a gate will be set up to assess the value of the facility to ESS and to science community. It will then be decided whether to elevate the status of the PIECE to a project proposal level together with tailored facility scope.

5. References

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