EC6 Design Improvements and Confirmatory Testing

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Abstract

The EC6 confirmatory testing program is a fundamental component of the EC6 development project to confirm design enhancements from the CANDU 6 Reference Qinshan plant. The confirmatory testing and analysis activities planned focuses on the testing needed to support the application for a construction licence. The program comprises work planned and executed by Candu Energy Inc. and work that has been completed to ensure EC6 product readiness for new build or refurbishment project implementation.

The key objectives of the testing program are:

- Verification of design changes.
- Validation of computer codes, assumptions and models.
- Demonstration and performance testing of new control computers and control centre equipment.

This paper provides a description of the completed testing program for key EC6 design improved features or equipment particularly those for reactor core components:

- Pressure Tubes and rolled joints
- Calandria Tubes and rolled joints
- Fuel Channel Annulus Spacer
- Shutoff units in Shutdown Systems #1

1. INTRODUCTION

The Enhanced CANDU 6®[1] (EC6®) builds on the proven high performance design such as the Qinshan CANDU 6 reactor, and has made improvements to safety, operational performance, and has incorporated extensive operational feedback. The EC6 design is also based on the extensive knowledge base of CANDU® technology gained over many decades of operation and supporting Research and Development studies. Completion of all three phases of the pre-licensing design review by the Canadian Regulator – the Canadian Nuclear Safety Commission has provided a higher level of assurance that the EC6 reference design has taken modern regulatory requirements and expectations into account and further confirmed that there are no fundamental barriers to licensing the EC6 design in Canada. [1]

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The EC6 design is based on the defence-in-depth principles in INSAG-10 [2] and provides further safety features that address the lessons learned from Fukushima. [3] With these safety features, the EC6 design has strengthened accident prevention as the first priority in the defence-in-depth strategy, as outlined in INSAG-10. As well, the EC6 design has incorporated further mitigation measures to provide additional protection of the public and the environment if the preventive measures fail.

The EC6 Confirmatory Testing and Analysis Program is part of the EC6 Development Project to support changes to the design and safety analysis of EC6, CANDU Generic Action Items (GAIs) and CANDU Category 3 Safety Items (CSI). The confirmatory testing and is a fundamental component of the EC6 program to confirm design changes from the CANDU 6 Reference Qinshan plant. The confirmatory testing and analysis activities planned focuses on the first phase of testing needed to support the application for a construction licence. This paper provide a summary of the EC6 product enhancements, the driver for the design improvements and the confirmatory testing planned and completed for each technology areas. For the reactor components, a summary of the testing objectives and the test results and assessments are described.

2. EC6 PRODUCT ENHANCEMENTS

The EC6 design has an appropriate combination of inherent, passive safety characteristics, engineered features and administrative safety measures to effectively prevent and mitigate severe accident progressions.
For loss of coolant accident (LOCA) analyses, the safety margin metrics include peak transient system reactivity, energy deposition to fuel, peak fuel centreline temperature and peak sheath temperature. All of these goals have been met with the CANDU 6 reference design and supporting analysis. However, new features and improvements are required to further improve safety margins for new build design in addition to the safety system. The design changes are:

- Reducing void reactivity hold up by an increase of pressure tube thickness to reduce creep rate. Reducing coolant void effect by tightened limits on operating conditions: Tighten moderator and coolant purity limits, Tighten moderator poison limit, and Lower side to side flux tilt limit.
- Increasing safety margin by reducing maximum operating powers with a flatten core radial power distribution.
- Lower core average moderator temperature to provide more subcooling during a LOCA with loss of emergency core cooling by relocating the moderator nozzles to produce more uniform temperature distribution of the moderator inside the calandria and reduction of the hot temperature spots at the top of the core.

The EC6 specific reactor core equipment design changes, which are incremental improvements to the CANDU 6 Qinshan Reference Plant design, include the following:

- Fuel Channels: Pressure tube thickness has been increased slightly and manufacturing processes refined to minimize deformation. Calandria tube design was upgraded to seamless with slightly higher thickness, and calandria tube – end shield rolled joint has been improved to increase core protection for pressure tube failures.

- Reactivity Control Mechanisms: EC6 incorporates two design refinements for the reactivity control system. First, the number of adjuster rods has been reduced from 21 in the current CANDU 6 to 11 in the EC6. The neutronic and mechanical designs of these adjuster rods have also been significantly simplified, standardized and has been optimized to reduce the total reactivity load, while achieving a sufficiently flattened core flux and power distribution, with adequate load-cycling capability.
- The reduction in the number of adjuster rods enables the EC6 to install additional absorber rods. The expanded system of absorber rods has sufficient negative reactivity to maintain the core in a guaranteed shutdown state (GSS) without requiring the addition of neutron poison in the moderator. This Rod-based GSS capability greatly reduces the time to enter and exit from a major maintenance outage, and also reduces occupational dose and moderator cleanup burden.

3. EC6 DEVELOPMENT OR CONFIRMATORY TESTING PROGRAM

The objectives of the EC6 confirmatory test and Analysis activities carried out during the EC6 Development Project are to provide support to the EC6 engineering design process in the form of information that can be assessed and used to confirm designs and safety analyses, and also to provide the test data required for verification of the design. The Test Program interacts with and supports the engineering design process.

The summary of the testing results for the verification of the reactor core components design changes are in Section 4 of this paper, but EC6 has also completed testing programs for other CANDU product technology areas as follows:

A number of test programs have also been completed to cover EC6 design safety performance specifications for various accident conditions as well as postulated severe accidents conditions such as calandria tube contact boiling; reactor vault refractory material; aircraft crash impact and calandria tube survivability in a spontaneous pressure tube rupture event. The last item is addressed as part of the calandria tube integrity testing program in Section 4.

In support of validation or verification of computer codes, assumptions and models used in safety analysis and safety performance assessment, extensive code applicability assessment for fuel codes, physics codes and thermalhydraulic code have been performed including the integration of Reactor Physics Tool set. Additional RD-14M testing on emergency injection has been done for CATHENA code verification.

Demonstration and performance testing work has also been undertaken of new control computers and control centre equipment to support the design changes to the Instrumentation and Control systems/components to address equipment obsolescence, OPEX feedback, and modernization of the control and display system to current standards.

- Changes are being implemented to Shutdown System No. 1 to computerize neutronic trips for EC6 to improve Large LOCA safety margins and to address OPEX feedback for the

CANDU 6 reactors in operation. To further improve trip computer platform diversity between SDS1 and SDS2, an FPGA based digital platform is being evaluated for use as SDS1 trip computers.

- The DCC control computers in the reference design are being replaced with a modern Distributed Control System (DCS) for EC6. Part of the testing is to demonstrate the control software can be ported to function correctly on the new hardware.
- The EC6 version of the C6 Analytical Dynamic Simulator has been developed to confirm the dynamic behaviour of the core due to reactivity device changes, AOO assessment; DCS control functional specification validations, and other process system design assist functions.
- A modern control centre in the Main Control Room (MCR) has been provided for EC6 to address obsolescence of components, improved plant reliability, improvement of safety parameter display for post-accident monitoring and OPEX feedback and to meet modern control room standards. The Advanced Control Centre Information System (ACCIS) developed by Candu, has been qualified and configured for EC6 implementation.

4. REACTOR CORE COMPONENT ENHANCEMENT

The main drivers for the changes for reactor core components are to address the following:

- Reactor core physics design optimization.
- Safety-significant OPEX
- Full performance (no ROP degradation at end-of-life).
- Annulus spacer issues – material degradation.
- Improved spacer detectability throughout the life of the reactor
- Improved detection for leak-before-break.
- Generic Action Item GAI-95G02 - end fitting ejection.
- GAI-95G04 - positive void reactivity treatment in large loss of coolant accident (LLOCA) analysis.

To address the above, the reactor assembly is upgraded to increase pressure tube and calandria tube thickness, strengthen positioning assembly, improve spacer design, change calandria to symmetric support, reinforce step and increase end shield tube sheet thickness to ensure 60 year life and meet required seismic level. The calandria tube will also be seamless (instead of seam-welded) with thick ends.

The number of adjusters is reduced, moderator isotopic is increased, guide-tube tensioning springs are relocated to above the calandria shell and the reference power shape is revised to meet core performance characteristics at End of Life (EOL).

LOCA margin is improved by using heavier SOR accelerator springs, lighter SORs, increasing coolant isotopic, reducing the flux tilt limit, providing contour parking for the shutoff rods, limiting the moderator poison concentration, adding full-size SORs, replacing ion chambers with fission chambers and adding two new fast linear rate trips. [4]

The following sections will provide descriptions of specific reactor design features / enhancements to be demonstrated by the confirmatory test programs.

4.1 EC6 Shutoff Units

4.1.1 Change Description

The drivers for these design changes are to improve the safety margins for the Large LOCA design basis accident, change in seismic requirement, and replacement of some obsolete parts of the drive assembly. The changes comprise of:

- Adding four new shutoff unit locations (at corners of calandria assembly). One new shutoff unit configuration is required for those locations. The new configuration will have a new guide tube length. The reference C6 design has 28 shutoff rods. With the reduction of in-core adjusters from 21 to 11, ten more spaces vacated by the adjuster rods are available.
- Using contour parking for shutoff rods. The design change requires a new shutoff rod assembly configuration.

The key changes as compared to the existing CANDU 6 shutoff unit design affecting rod performance is that the shutoff rod was lightened and the rod accelerator spring was redesigned to give a higher preload force and longer compression/extension stroke. Lighter shutoff rods require thinner stainless steel cladding, thinner neutron absorbing cadmium material, and change in the push rod material from stainless steel to titanium. An evolutionary development of the existing drive mechanism design was used for these tests.

The change to the drive is required to address obsolescence issues with the traditional drive mechanism. The EC6 adopted the ACR drive assembly since the manufacturing of the ACR drive assembly was already completed. The new drive mechanism, while using key components proven designs, has a smaller footprint on the RM Deck, is simpler to maintain and is less expensive to produce. Objective of the testing is to confirm design changes for improvement of Shut-off rod insertion performance meet safety analysis goals and to confirm new drive mechanism assembly design, adapted from ACR, to replace obsolete CANDU 6 design.

Change to the shutoff rod accelerator spring design is required to improve SDS1 performance. The EC6 rod accelerator spring will be fabricated from Inconel X750 (the same as is used in other CANDU plants), but has a similar stroke and preload. The new design will be subject to tests to confirm that spring wear is not an issue for the high-force long-stroke spring if fabricated from Inconel X750.

4.1.2 Testing Summary

The SDS1 test program comprises:

a) Concept testing for selection of acceptable accelerator spring.
    - Investigative wear test to confirm the acceptability of the accelerator spring, spring seat and spring housing selected for EC6. Testing will identify any potential wear issues to finalize design and spring selection for qualification testing.

b) Seismic qualification testing of the drive assembly and basic seismic testing of the shutoff unit guide assembly to validate seismic analysis and models.

c) Testing to provide data for validation of engineering analysis in the following areas:
   - Functional capability following a design basis earthquake (DBE) event. Shutoff unit structures will survive without compromising the ability to effect a shutoff rod insertion,
   - Functional capability during a design basis earthquake (DBE) event. Shutoff unit can effect a shutoff rod insertion during a DBE.
   - Functionality testing to demonstrate that the drive assembly remains operable during a DBE event.

d) Qualification testing to demonstrate (1) the shutoff rod time-to-distance travel under expected nominal moderator conditions and (2) durability through endurance testing, and
   - Verification that the complete shutoff unit satisfies the insertion performance requirements to meet safety analysis goals. Testing comprises of basic performance testing to verify that time to distance performance requirements are met under normal operating conditions.

e) Environmental qualification testing to verify rod release function of shutoff unit drive mechanism during adverse environmental conditions.
   - Testing to prove that the shutoff unit drive mechanism satisfies requirements for external environmental conditions and expected peak internal pressures.

The new shutoff unit design used for the qualification testing consists of the following major components: a shutoff rod, a rod accelerator spring, a guide tube for the rod, a drive mechanism that effects a rapid release of the rod for insertion into the reactor and withdraws it when no longer needed, a thimble to provide an extension to the reactor's pressure boundary for parking the rod and radiation shielding. Each of the above components were manufactured to reactor-grade standards and assembled in a test tank for performance testing.

The tests run simulated nominal reactor conditions for moderator level and temperature and local flow conditions around the guide tube. In addition, a group of high moderator level tests were run to approximate the worst-case conditions for a shutoff unit outside the expected damage zone during an in-core LOCA. Correction factors were applied to account for the use of light water instead of heavy water for the moderator in these tests.

Observed average performance results closely matched predicted values and provided a significant performance improvement, reducing the Gate 1 time by over 20 percent as compared to the existing CANDU 6 design. EC6 Safety performance objectives were met in all cases, even with the in-core LOCA simulation.

In summary, qualification testing of the new shutoff unit design demonstrated its ability to meet its performance objectives and validated the analysis methodology used to generate pre-test predictions of rod insertion performance needed for Physics and Safety assessments.

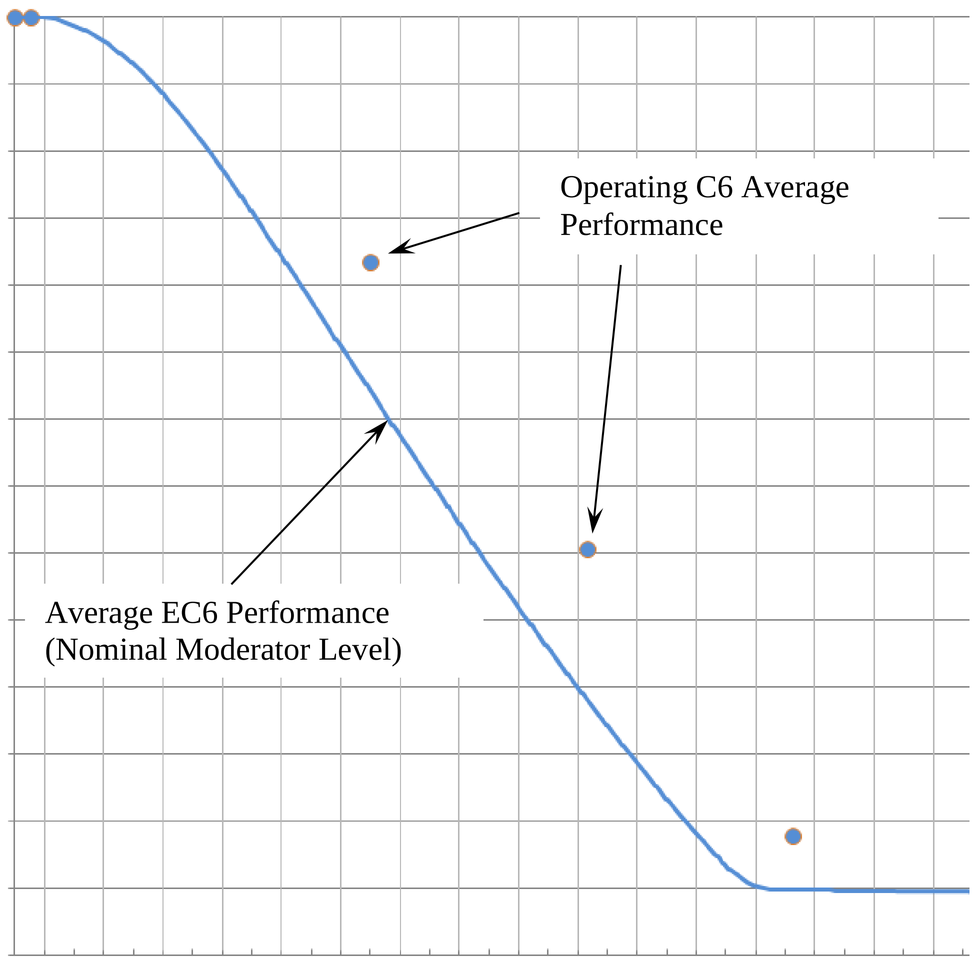

Figure 1: EC6 SOU Performance curve (Rod position vs time)

4.2 Pressure Tubes (PT) and PT Rolled Joint

4.2.1 Change Description

The pressure tubes used for the material qualification testing and rolled joint qualification testing were manufactured based on the EC6 technical specifications with increased wall thickness and solid billet quench to enhance grain size and reduce diametral strain. Moreover, the existing tight tolerance controls during the manufacturing process were utilized to add additional control to the average diameter of the pressure tube. The EC6 pressure tube design with these enhancements will result in a minimum of 245,000 EFPH of reactor operation without de-rating. The diameter of rolled joint region has been increased to accommodate thicker pressure tube. To streamline coolant flow during thermal-syphoning, particularly under accident condition with two phase flow, the design orientation of feeder connection for the twelve 12 end fittings on lower periphery have been rotated by to 15 degrees to prevent steam bubble collection in the feeders.

Feasibility of Dynaloy™ application to the end fitting in the rolled joint region to reduce hydrogen ingress was assessed through a series of development testing because lower hydrogen ingress will result in increased pressure tube lifetime. However, the results of the pressure tube rolled joint development testing with C6 zero clearance rolled joints using Dynaloy coated EF hubs show higher than acceptable helium leak rates were found for some joints. Hence, Candu decided not to use Dynaloy coating for EC6 pressure tube rolled joints.

4.2.2 Testing Summary

Pressure tube testing includes:

a) Qualification of pressure tube material by verifying material properties for code compliance for a thicker tube in EC6.
b) Pressure tube rolled joint qualification testing with representative thicker EC6 pressure tubes to demonstrate that the joints meet the requirements for helium leakage, pull out strength, and pressure tube residual stresses.

The examinations and test activities conducted by Canadian Nuclear Laboratories at Chalk River for EC6 pressure tube qualification include: Chemical analysis; Microstructure characterization and Mechanical property testing. The concentrations of niobium, hydrogen and nitrogen were within the specification. The α-grain thickness, texture and dislocation results were within the specification. The UTS and 0.2% yield strength for tensile testing satisfied the specified minimum standard values. Based on the above, the EC6 pressure tubes manufactured with an increase in thickness met the technical specifications.

The qualification testing of the EF-PT rolled joint using the EC6 pressure tube sections with increased thickness (same batch of pressure tube used in above material qualifications) was completed to demonstrate that the EC6 design meets the requirements as specified in CSA N285.2 for leak tightness, residual stresses and mechanical integrity. The testing was also used to show various joint characteristics after the rolling process and to further understand the end of life behaviour. During the testing, the wall reduction of the test joints and diametral fit between the EF hub ID and the PT OD were varied so that the effect of these variables on the performance of the joint could be reviewed.

All of the test joints had acceptable helium leak rates before and after thermal soak and cycle testing and also after the accelerated stress relation (EOL). As well all the test joints achieved pull out forces higher than the acceptance level. This was true even for the test joints that completed the end of life behaviour simulation. The residual stresses measured during this testing are similar to the results found in previous testing.

4.3 EC6 Seamless Calandria Tube

4.3.1 Change Description

The driver for the use of seamless calandria tubes (as opposed to the traditional seam-welded in CANDU6) with thickened ends and increased wall thickness is GAI – 95G02 and CSI –AA07 related to pressure tube failure with consequential loss of moderator followed by end fitting ejection.

The calandria tube is manufactured as seamless using a proprietary internal roll extrusion process and is slightly thicker when compared with operating CANDU 6 with thickened ends and improved rolled joints for safety margin enhancement:

- Seamless calandria tube (CT) with thickened ends and improved rolled joints (RJ) are expected to survive pressure tube rupture to help mitigate core damage.
- A seamless calandria tube prevents the impact of in-core LOCA and provides the operator with adequate time to cool down the reactor.
- Target for core damage frequency (CDF) less than 10-6 per reactor year.

4.3.2 CT and CT RJ Testing Summary

Calandria tube testing to confirm that the manufactured EC6 calandria tube and the new rolled joint design meet the design requirements will comprise the following tests:

a) Development of a manufacturing process.
c) Material characterization of calandria tubes to establish that the material meets the acceptance criteria of the appropriate standard and design requirements.
d) Hydrostatic test of short calandria tube spools to evaluate burst and creep behaviour independently from the rolled joint.
e) Leak tightness and pullout strength tests with rolled joints using EC6 seamless qualification tubes.

The manufacturing of the full length EC6 seamless calandria tubes for material qualification testing and the various calandria tube sections to be used for calandria tube integrity testing and for calandria tube rolled joint testing have been delivered based on the EC6 technical specification for seamless calandria tubes. Testing has started and we expect the test results will confirm that the EC6 calandria tubes and CT RJ meet the material qualification requirements and the CT RJ meet the specified performance requirements.

4.3.3 Calandria Tube Integrity Testing Summary

The calandria tube integrity tests are being performed to confirm that the calandria tube survives a spontaneous pressure tube rupture event thus preventing subsequent in core damage and potential ejection of the end-fitting. Testing will be conducted in the two stages. The staged approach is to obtain early confidence of the design change by performing integrity tests on EC6 seamless calandria tube sections and then on calandria tube sections with rolled joints. Tests will be done with flanges welded at the ends of the spools for the above. The integrity tests show that the EC6 seamless calandria tube with increase thickness shows no signs of CT pressure boundary leakage when subjected to internal pressures of up to 13 MPa (g). In addition, when subjected to constant internal pressure in range of 10 to 11 MPa(g) at high temperature, the creep rate of the EC6 calandria tube spools is much slower than that for current CANDU 6 CT; therefore , the expected time to rupture at these pressures surpassed the acceptance criteria with a significant margin. Further creep rupture confirmatory testing is being carried out using EC6 calandria tube sections with rolled joints.

4.4 Fuel Channel Annulus Spacer

4.4.1 Change Description

Change to stronger, tight fitting Zr 2.5Nb 0.5Cu with welded girdle wire (to address material degradation issues associated with nickel alloy Inconel X-750, reduce burnup penalty, achieve lifetime reliable detectability, and eliminate the potential for eutectic point between spacer and pressure tube).

The key drivers for the design change include the followings:

- Elimination of concerns with the ability of nickel alloy X-750 to be suitable for extended operation as a result of material degradation mechanisms such as embrittlement and void swelling (caused by irradiation induced transmutation chain of ^{58}Ni).
- Prevent in service mobility of the spacer by making it a tight-fitting design,
- Achieve detectability using Eddy Current to facilitate PIP & ISI and enhanced compliance with CSA N285.4, and
- GAI – 89G04 related to spacer location and repositioning.

4.4.2 Testing Summary

The annulus spacer test program is being performed in two stages. In the development stage, a set of non-reactor grade material (Zr-2.5Nb) spacer is fabricated to examine the manufacturability of the EC6 spacers design and to provide feedback to the final design. Several low tensioned springs are fabricated to simulate the in-reactor relaxation due to thermal and irradiation creep and to examine mobility of the spacers under these conditions. In addition, a series of testing were performed to assess resistance of the spacer to free rolling, simulating an end-of-life effect of increase in pressure tube diameter which causes the closed-loop welded girdle wire to become tight against the spacer coil.

In the qualification stage, a set of spacers were fabricated in accordance with the quality assurance requirements for qualification testing using the same material and standard as a reactor order. Several spacers were subjected to simulated in reactor loading conditions (with the exception of radiation) to evaluate spacer integrity under repeated (cyclic) loading; and to evaluate the corresponding pressure tube and calandria tubes wear. In addition, more spacers with very high values of relaxations (higher relaxation rate than what was already tested during the development process) were subjected to vibration and interaction with calandria tube to evaluate mobility under simulated vibration excitation. Test results demonstrated that the contact wear in the pressure tube, calandria tube and spacer are insignificant and the spacer meets the fatigue requirements. Vibration testing also confirmed that the fully relaxed spacers as long as they are not loose on the pressure tube they are installed to would not become mobile under acceptable excitation amplitudes.

4.5 Positioning Assembly (SI 31124)

The CANDU 6 positioning assembly stud is changed, such as when the stud is threaded to the fuelling tubesheet it will be locked with a proprietary two piece cam lock washer to prevent loosening from the tubesheet.

Replace C6 positioning assembly with a stronger design to address seismic loading and end fitting ejection at the locked end of the channel.

The result from the test program has confirmed that the design change will prevent the positioning assembly stud from loosening from the tubesheet.

5. SUMMARY

The EC6 design is also based on the extensive knowledge base of CANDU® technology gained over many decades of operation and supporting Research and Development studies. The confirmatory testing and analysis activities are near completion to ensure EC6 product readiness for new build or refurbishment project implementation.

Performance testing and material qualification testing of improved EC6 reactor components show improved robustness and performance of the shutoff units, the higher operating life margin for the pressure tubes, the improved safety margin for the seamless calandria tubes and successful verification of the enhanced EC6 spacer behaviour with new materials.

6. REFERENCES

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