Abstract

Westinghouse successfully supplied VVER-440 fuel assemblies to Lovisa (Finland) from 2001 to 2007. After losing two bids in 2007, Westinghouse decided to close down the supply chain and design development for the VVER-440 design.

Since September of 2015, Westinghouse and eight European consortium partners are in a project; ESSANUF (European Supply of Safe Nuclear Fuel), with the objective to diversify the nuclear fuel supply to Russian designed VVER-440 reactors operating in Europe. The program is funded by the European Union’s (EU’s) Euratom Research and Training Programme under Horizon 2020.

Design upgrades of the Westinghouse VVER-440 designs have been evaluated with respect to their feasibility for future use. Material development, operational experience, customer feedback and competitor design modifications have been considered and a conceptual design has been developed which contains an upgraded spacer grid which benefits from design features from Westinghouse VVER-1000 fuel design. In addition materials are proposed to be upgraded using the latest experience from Westinghouse VVER, PWR and BWR programs.

Based on review feedback from a concepts and issues review of the proposed VVER-440 conceptual design Westinghouse recognizes the importance of a longer pellet stack and will continue to evaluate necessary top- and/or bottom nozzle modifications to enable a longer fuel rod.

A scope description and a high level milestone schedule for a development program with a goal to implement the proposed changes within two years have been outlined within the ESSANUF project.

To support the introduction of the upgraded VVER-440 fuel design methods and methodologies within the technology areas nuclear-, fuel rod- and thermal hydraulic design as well as criticality- and fault analyses have been evaluated. The approach used was to select and validate the most suited set of codes by inventing what codes are used in the different countries with VVER-440 reactors and thereafter define the methodologies to be applied. To enable effective analyses it is important to have well defined and preferably automated interfaces between the codes for the transfer of data and results. To achieve this different forms and code couplings have been developed.

An attempt to develop a generic fuel licensing approach for the countries that are using Russian design VVER-440 type reactors has been carried out in ESSANUF. The concept is to limit the number of events to be re-analyzed by considering them covered by more limiting events. Also a generic Interface Document for Fuel Licensing (IDFL) has been suggested.

Two project review meetings with independent experts empowered by the European Commission have been carried out to evaluate project progress and fulfillment of project commitments with satisfactory results.

The ESSANUF project ends in October 2017.

1. Introduction

Westinghouse successfully supplied VVER-440 fuel assemblies to Lovisa (Finland) from 2001 to 2007 in region quantities following a successful Fuel Design and Lead Test Assembly Program. The Lead Test Assemblies (LTAs) were manufactured at Springfields (UK) and the 7 reloads were assembled by ENUSA (Spain). After losing two bids in 2007, Westinghouse decided to close down the supply chain and design development for the VVER-440 design.

Since September of 2015, Westinghouse and eight European consortium partners are in a project; ESSANUF (European Supply of Safe Nuclear Fuel), with the objective to diversify the nuclear fuel supply to Russian designed VVER-440 reactors operating in Europe. The program is funded by the European Union’s (EU’s) Euratom Research and Training Programme under Horizon 2020. Westinghouse’s consortium partners include VUJE, ÚJV Řež, LUT, NNL, NucleoCon, NSC KIPT, JRC-ITU and ENUSA. With these partners the ESSANUF consortium is represented in all countries with VVER-440 reactors within the European Union and Ukraine, Figure 1-1.

The goal of ESSANUF is diversification of fuel suppliers by Westinghouse re-entering the supplier market with an upgraded VVER-440 fuel design.
specifically supported by methods and methodologies in full compliance with international nuclear safety standards.

Specific objectives of ESSANUF are:

- Define the necessary modifications to Westinghouse VVER-440 fuel assembly design to fulfil the customers’ needs and the regulatory requirements
- Establish a development program for this modified design, including required testing and verification
- Assess the manufacturability of this modified design and define any changes needed to the manufacturing processes and equipment
- Get a clear understanding of customer and regulatory requirements in each country in the EU with VVER reactors as well as in Ukraine, and determine which analyses are needed to be performed to fulfil these requirements
- Establish the design and licensing analyses capabilities, select and validate the most suited set of codes and define the methodology to be applied. Prepare data, and interfaces between the codes to enable effective analysis
- Establish an European VVER-440 community through the project partner organizations for development and licensing in the respective countries
- Carry out extensive communication activities for public awareness and dissemination of results

For general information about the ESSANUF project please visit the ESSANUF homepage: www.essanuf.eu.

2. Mechanical design

Westinghouse successfully supplied the NOVA E-3 (fixed) and NOVCA (follower) VVER-440 fuel designs to Loviisa (Finland) from 2001 to 2007. A high level overview of the NOVA E-3 is presented in Figure 2-1 below.

- Length: 3.2 m
- Total Weight: 220 kg
- Weight of U/UO2: 126/143 kg
- Weight of Components: 77 kg
- Clad/shroud/grid material: Zircaloy-4
- No of grids: 7
- No of fuel rods: 126
- Shrouds (Channels): Two types of assemblies; Fixed and follower
- Skeleton with one instrument tube same fabrication as PWR (bulging)
- 312 fuel assemblies in core
Within the ESSANUF project the NOVA E-3 and NOVCA designs were evaluated with respect to their feasibility for future use at VVER-440 NPPs. Material development, operational experience, customer feedback and competitor design modifications were considered and it was concluded that the Westinghouse designs need to be upgraded prior to reintroduction to the market.

Experience from Westinghouse VVER-1000 program was utilized to mitigate grid-to-rod fretting indications from Loviisa post irradiation inspection (PIE) programs. Grids are proposed to be modified with VVER-1000 grid springs/dimples, which have larger contact area. Also two more mid-grids are proposed to be added to reduce grid span which will further mitigate grid-to-rod fretting. To accommodate the associated increased pressure losses, the inner strap thickness will be reduced to that used in the VVER-1000 design. This reduces the pressure drop sufficiently to compensate for the increased pressure loss from two more grids in the assembly.

The materials in the fuel assemblies are proposed to be upgraded using the latest experience from Westinghouse VVER, PWR and BWR programs: Optimized ZIRLO™ for cladding tubes and ZIRLO® for the central tube. The options for grid material are Low Tin ZIRLO® or Zr1%Nb. Experience from the ongoing project to introduce Low Tin ZIRLO as standard material for BWR fuel channels will be used to choosing the channel material for the upgraded VVER-440 design.

Customer feedback and competitor design benchmarking were used to evaluate if additional design changes were necessary. An increased fuel rod pitch and a reduced shroud thickness were proposed. These changes would be in agreement with design changes made by the other VVER-440 fuel vendor. Based on the result of an equilibrium core design study of the impact on neutron physics it was concluded that the benefit from increased fuel rod pitch and a reduced shroud thickness would not compensate for the increased development cost from implementing these design changes to the fuel.

Solid pellets and a longer pellets stack were proposed. Solid pellets are already included in all Westinghouse fuel designs. However, the size of the plenum for the current NOVA E-3 is not sufficient for a longer pellet stack without a longer cladding tube and a longer fuel rod is not possible without top and/or bottom nozzle modifications. More room between nozzles will be needed to accommodate growth of a longer fuel rod. It shall be noted that from open source conference papers it is concluded that Westinghouse pellets have a higher uranium density than competitor pellets (for NOVA E-3, the UO₂ weight is 143 kg).

The outer rod diameter, cladding thickness and outer pellet diameter were proposed to be reduced. These changes were evaluated to have positive impact on the neutron economy and are beneficial from a fuel cycle cost perspective. However, the reduction of the pellet diameter and cladding thickness impose major challenges on the fuel performance and the manufacturing and an extensive development program would be required. Therefore it was decided not to pursue these design changes.

A development plan including scope description and a high level milestone schedule with the goal to implement design modifications within two years have been outlined within the ESSANUF project. The design modifications would initiate a development program which includes design analyses and testing.

3. Methods and methodologies

One main goal of ESSANUF is to establish the design and licensing analyses capabilities for an introduction of an upgraded Westinghouse VVER-440 fuel design. The approach used was to select and validate the most suited set of codes by inventing what codes are used in the different countries with VVER-440 reactors and thereafter define the methodologies to be applied. To enable effective analyses it is important to have well defined and preferably automated interfaces between the codes for the transfer of data and results. To achieve this different forms and code couplings have been evaluated and developed.

Methods and methodologies within the technology areas nuclear-, fuel rod- and thermal hydraulic design as well as criticality- and fault analyses have been evaluated. It was not possible to evaluate all of the large number of transients and accidents which are included in the fault analyses concept. Therefore it was decided to limit the evaluations within this technology area to LOCA and RIA analyses.

3.1. Nuclear design

One very important aspects of a nuclear fuel supply is the capability to accurately and reliably predict the nuclear reactor core behavior during its operation. Among many, the parameters that need to be accurately calculated are the detailed power assembly and fuel rod power distributions, power
peaking factors and the critical boron concentration. The accurate prediction of those and many other core parameters is necessary to ensure safe operation of the reactor core at any given point during the fuel cycle.

In ESSANUF the Westinghouse code package APA-H (ALPHA-H, PHOENIX-H and ANC-H) has been validated for the purpose of VVER-440 core design related work. Although the APA-H is successfully used for core design work for VVER-1000 type plants, it has to be separately tested for VVER-440 reactors as their design employs certain unique technical solutions (e.g. follower assemblies, which can be moved out and in into the core during operation), which pose a challenge from the point of view of the computer code.

The APA-H code package was used to model Loviisa Unit 1 reactor core operation during cycles 25-32 and a comparison was made between APA-H calculated parameters and data registered during the actual plant operation made available by the courtesy of the utility Fortum.

The conclusion from the APA-H validation is that even though the validation results in general are acceptable, it is recommended to perform further benchmark with measured power distributions in order to get a better understanding of the accuracy of the code package, and if needed improve the methodology and/or modelling.

3.2. Fuel rod design

The development and verification of computation tools and methodologies for new VVER-440 fuel rod design (FRD) analyses have been evaluated within ESSANUF.

One or more fuel performance computer codes to be used within the ESSANUF consortium to license the new fuel design in the target countries were selected. Potential codes identified are TRANSURANUS, STAV, PAD and ENIGMA. In order to allow selection from within these codes, information on the commercial and technical aspects of the codes was obtained from the ESSANUF consortium partners and the TRANSURANUS was selected as the recommended code based on this information. However, TRANSURANUS is used by several technical support organizations to Regulatory Bodies in the different countries with VVER-440 plants. Therefore an independent code might also be required. For this reason a limited scope for the ENIGMA code within ESSANUF was carried out, identifying deltas and the need for implementation of Westinghouse material models. ENIGMA was used for licensing the BNFL NOVA E-3 and NOVCA fuel but cannot be considered ready to use in its current version due to proposed new materials.

None of the proposed FRD codes have the capability to fully addressing cladding instantaneous collapse and creep collapse or clad stresses criteria. For this reason an auxiliary tool is needed. This will require an implementation of cladding creep models and ensuring that a coupling with the selected code could be done. Currently the only proposal is to couple TRANSURANUS with ABAQUS.

Validation and verification of the Westinghouse-specific version of the TRANSURANUS code was carried out within ESSANUF. The work covers the validation and verification of fission gas release, rod internal pressure, cladding corrosion, fuel temperature, cladding burst and steam oxidation computations with Westinghouse-specific best-estimate and conservative models. A statistical evaluation method was used to prove the correct simulation of the different physical phenomena in PWR fuel rods and the adequate bounding of the experimental data.

3.3. Thermal hydraulic design

Thermal hydraulic correlations, codes and methodologies have been evaluated.

Selection of one or more core thermal hydraulics codes to be used within the ESSANUF consortium to license the new fuel design in the target countries has been carried out. The scope is mainly for DNBR evaluation to be performed consistently with the licensed safety analysis method. Typically (but not necessarily) the evaluation is performed with a sub-channel analysis code which relies on clearly defined thermal-hydraulic models and geometrical discretization (to be defined along with the methodology). The boundary conditions for transient analysis are provided by a system code.

An inventory of core thermal hydraulic codes to be used to license a new fuel design in the target countries was made based on information from the ESSANUF consortium partners. The outcome was two recommended codes: the Westinghouse version of VIPRE, VIPRE-W, with the APROS code (which also has system thermal-hydraulics capability) remaining as an alternative option. VIPRE-W models of the old and new fixed assemblies and old and new 19-rod Critical Heat Flux (CHF) test bundles were set up.

Computational Fluid Dynamics (CFD) models of the upgraded VVER-440 fixed assembly design, and of the corresponding 19-rod CHF test bundle were developed to predict the assembly pressure
drop, CHF and thermal mixing behavior. A single-phase CFD model of the old (BNFL) fixed assembly design was constructed using the SolidWorks Flow software, and this model was in turn used to construct an equivalent model of the new fixed assembly design; the two models were then used to provide assembly pressure drop and thermal mixing predictions. Similarly, a two-phase CFD model of the old 19-rod CHF test bundle was constructed using the ANSYS FLUENT software, and this model was in turn used to construct an equivalent model of the new 19-rod CHF test bundle; the two models were then used to analyze the CHF behavior.

It was found that the thermal mixing for the new assembly is enhanced which is consistent with the smaller grid spacing. The predicted CHF is on average 8% higher for the new 19-rod bundle than for the old 19-rod bundle, again consistent with the smaller grid spacing.

Thereafter effort was put into defining appropriate Critical Heat Flux (CHF) and pressure drop loss coefficient correlations for the upgraded VVER-440 fuel assembly design. Four distinct CHF correlations were considered for use in predicting CHF for the new fuel assembly design: the optimized Bezrukov correlation; the Smolin correlation; the PG correlation; and the WVHI and WVLO correlations. Effort was focused on the optimized Bezrukov correlation since it is the reference CHF correlation for NOVA E-3 assemblies and since the correlation has a simple form.

The limited set of CFD predictions makes tuning the optimized Bezrukov correlation for application to the upgraded assembly of limited value. In addition, deficiencies in using CFD models to predict Departure from Nucleate Boiling (DNB) have been observed. Hence, tuning has been limited to determining a multiplication factor that allows the optimized Bezrukov correlation to, on average, produce predicted CHF values consistent with the new assembly CFD results. Finally, with respect to CHF correlations, all NOVA E-3 test data and CFD predictions were obtained for a uniform axial power distribution, and therefore it is not possible to determine an appropriate non-uniform shape factor.

Pressure drop loss coefficient correlations (loss coefficient as a function of Reynolds number) have been developed for each component of the new fixed assembly design, and for the new fixed assembly as a whole. At a Reynolds number consistent with typical normal operating conditions (215,100) the new fixed assembly overall loss coefficient is ~8% lower than that for the old fixed assembly.

It can be concluded that the requirements for hydraulic effects, DNB and coolant conditions in the upgraded VVER-440 assembly design are met. This include also hydraulic lift forces, core flow instability, effect of rod bow on DNB, core bypass flow and void fraction limit. Using CFD modeling the predicted CHF is on average 8% higher for the new assembly. However, to develop definitive CHF and loss coefficient correlations for the upgraded VVER-440 assembly design CHF testing and pressure drop testing would be required.

3.4. Nuclear criticality safety

An integrated nuclear criticality safety (NCS) methodology for the countries that are using Russian design VVER-440 type reactors has been defined. The integrated methodology uses IAEA guidelines as the basis, complemented by information of national specifics provided by ESSANUF project partners. Cases that need to be considered for various transport and storage scenarios in the different countries as well as accident scenarios are also identified.

The use of SCALE code system is given as a recommendation based on country specific information from the consortium partners. SCALE is the code licensed for NCS analyses in Ukraine and it is also used in most other countries. In countries that do not enforce the use of a specific code for licensing calculations, it might be possible to use e.g. Monte Carlo code Serpent A comparison between calculation results obtained with Serpent and SCALE has been carried out.

3.5. Fault analyses

The work on the “Fault Analysis” technology area within ESSANUF targets safety analysis codes, coupling of codes and safety analysis methodologies. It was not possible to evaluate all of the large number of transients and accidents which are included in the fault analyses concept. Therefore it was decided to limit the evaluations within this technology area to LOCA and RIA analyses. The same recommendation was given by the ESSANUF external reviewers during the review meeting in September 2016.

Methodologies for these selected scenarios, as well as coupling of the selected simulation tools for the corresponding licensing calculations have been developed and reviewed by the ESSANUF consortium partners.

The proposed general Design Basis Accident (DBA) methodology is to focus on thermo-mechan-
ical analysis because a valid conservative safety analysis exists. A set of key safety parameters for each accident is defined which conservatively bind the values in subsequent cycles. If a reload safety parameter is not bound specific analyses are required to ensure maintenance of safety criteria.

The ESSANUF consortium partners provided their input to Westinghouse about which code suites they use for various transient and accident analyses. Westinghouse has evaluated this input to make a recommendation of the code suite to be used for the fuel licensing.

The following code couplings were selected to be carried out within ESSANUF:
- TRANSURANUS-ATHLET
- TRANSURANUS-RELAP
- TRANSURANUS-SERPENT
- TRANSURANUS-DYN3D
- DYN3D-ATHLET
- DYN3D-VIPRE to be considered
- APROS to be considered for Finland

Work with these code couplings and their validation is still ongoing. The ESSANUF project will complete in October 2017.

4. Fuel licensing

An attempt to develop a generic fuel licensing approach for the countries that are using Russian design VVER-440 type reactors has been carried out in ESSANUF. The concept is to limit the number of events to be re-analyzed by considering them covered by more limiting events. Also a generic Interface Document for Fuel Licensing (IDFL) has been suggested.

When a new fuel design is introduced, a review of the plant analysis of record (AOR), usually FSAR and other relevant documents is performed to identify which analyses are fuel-dependent and need to be part of the licensing analyses. The main source of the reference safety analysis is the plant FSAR Chapter 4, 6 and 15. From the identified analyses it is also determined which are one-time analyses, and therefore only needed to be verified for the introduction of the fuel the first time, and which are cycle-dependent and need to be verified each subsequent reload.

As a result of the evaluation each analysis should fall into one of the following categories:
- Affected by the introduction of a new fuel design, and is potentially limiting requiring that the event is verified for each reload.
- Affected by the introduction of a new fuel design, but not by different reloads with that design requiring that the analysis is verified for the introduction of the new fuel design, but not for subsequent reloads.
- Potentially affected by a new fuel design, but is bound by a more limiting event of the same frequency category.
- Not affected by the introduction of a different fuel type
- A “Suggested Integrated VVER-440 Licensing Scope with IDFL template” has been developed which contains:
  - A suggested approach to licensing a new fuel design based on the information contained in reports mentioned above describing the conditions in the countries operating VVER-440 in the European Union and Ukraine and Westinghouse’s current methodology for the reload safety analysis.
  - An Interface Documents for Fuel Licensing template specifying the standard information required to licensing a new fuel design.
  - A general disposition of events to identify which type of analysis needs to be considered for introducing new fuel designs and which type of analysis can be considered covered by other more limiting events.

5. Workshops and review meetings

Two workshops and one concept and issues review meeting have been held within the ESSANUF project to fulfill the objectives of obtaining a clear understanding of the customer and regulatory requirements in each country in the EU as well as in Ukraine. In addition, two project review meetings with independent experts empowered by the European Commission have been carried out to evaluate project progress and fulfillment of project commitments. The results were satisfactory.

5.1. Fuel licensing workshop

A fuel licensing workshop was held in Prague at the ÚJV Rež offices on June 15-16, 2016. Members of the Regulatory Bodies and Utilities in countries that are using Russian design VVER-440 type reactors were invited to participate at the workshop and to provide input to the proposed licensing scope. All the regulatory bodies, with the exception of the Czech Republic, and all the Utilities, with the
exception of Energoatom, attended the workshop.

The workshop was aimed to get a clearer understanding of the regulatory requirements in the EU and Ukraine and determine which analyses are needed to fulfill these requirements. By Regulator and Utilities presentations a better knowledge of the fuel licensing process and requirements in the different countries was gained.

The workshop also included work in groups to receive feedback from Regulators and Utilities on the draft licensing concept in the ESSANUF deliverable “Suggested Integrated VVER-440 Licensing Scope with IDFL template”. In general the suggested approach to licensing and the analysis scope were considered acceptable in most countries but countries with no experience of changing fuel vendor were somewhat less willing to accept an approach where only a limited number of events are re-analyzed while the other are considered covered by more limiting events.

5.2. Concept and issues review meeting

The purpose of a Concepts and Issues (C&I) review is to provide an early opportunity for designers/reviewers/customers to review the design concept and to identify and discuss issues with the design concept. The focus of the C&I is on identifying risks and on any non-treated items associated with the design.

In February 2017, a review of the proposed modified VVER-440 conceptual design was performed. In addition to the subject matter experts of Westinghouse and the consortium members, representatives of four different utilities were present and actively engaged in the meeting. The objective of the meeting was to review whether the new fuel design meets design requirements and fulfills customer expectations. Related methods and methodologies, manufacturability, supply chain and transport were also within the review concept.

Important feedback from the utilities was that a longer pellet stack is important and Westinghouse will evaluate necessary top- and/or bottom nozzle modifications to enable a longer fuel rod. Some utilities also considered the modified pitch and thinner shroud as important design features. However, Westinghouse position remains that these changes would show little benefit at significantly increased development costs.

Otherwise the proposed design concept including the related methods and methodologies was accepted by the reviewers and the utilities.

5.3. Methods and methodologies workshop

The “Workshop methods and methodologies” was carried out June 13-14, 2017 in Finland at LUT with consortium members and the utilities Forsum, MVM Paks NPP, Slovenské Elektrárne, Energoatom and ČEZ as well regulatory bodies from Finland, Hungary, Czech Republic, and Armenia. In total 35 persons attended the workshop which focused on fuel rod design, thermal hydraulic design, nuclear criticality safety and fault analyses as described in Sections 3.2 – 3.5 above. The fault analyses focused on methods and methodologies for LOCA and RIA analyses.

The workshop was successfully accomplished with active participation from all participants providing very valuable input to the continuing work of methods and methodologies development.

6. Concluding remarks

Since September of 2015, Westinghouse and eight European consortium partners are in a project; ESSANUF (European Supply of Safe Nuclear Fuel), with the objective to diversify the nuclear fuel supply to Russian designed VVER-440 reactors operating in Europe. The ESSANUF consortium is represented in all countries with VVER-440 reactors within the European Union and Ukraine. The program is funded by the European Union’s (EU’s) Euratom Research and Training Programme under Horizon 2020.

Design upgrades of the Westinghouse NOVA E-3 and NOVCA designs have been evaluated with respect to their feasibility for future use at VVER-440 NPPs. Material development, operational experience, customer feedback and competitor design modifications have been considered. A conceptual design has been developed which contains an upgraded spacer grid which benefits from design features from Westinghouse VVER-1000 fuel design. In addition materials are proposed to be upgraded using the latest experience from Westinghouse VVER, PWR and BWR programs.

A concepts and issues review of the proposed VVER-440 conceptual design has been carried out. Based on review feedback Westinghouse recognizes the importance of a longer pellet stack and will continue to evaluate necessary top- and/or bottom nozzle modifications to enable a longer fuel rod. Westinghouse position remains that a modified pitch and thinner shroud would show little benefit at significantly increased development costs.
It can be concluded that the requirements for hydraulic effects, DNB and coolant conditions in the upgraded VVER-440 assembly design are met. Using CFD modeling the predicted CHF is on average 8% higher for the new assembly. However, to develop definitive CHF and loss coefficient correlations for the upgraded VVER-440 assembly design CHF testing and pressure drop testing would be required.

A scope description and a high level milestone schedule for a development program with a goal to implement the proposed changes within two years have been outlined within the ESSANUF project.

Methods and methodologies within the technology areas nuclear-, fuel rod- and thermal hydraulic design as well as criticality- and fault analyses have been evaluated. Due to the large number of transients and accidents which are included in the fault analyses concept it was decided to limit the evaluations within this technology area to LOCA and RIA analyses. The approach used is to select and validate the most suited set of codes by inventing what codes are used in the different countries with VVER-440 reactors and thereafter define the methodologies to be applied. To enable effective analyses it is important to have well defined and preferably automated interfaces between the codes for the transfer of data and results. To achieve this different forms and code couplings have been evaluated and developed.

The proposed methods and methodologies as well as proposed code couplings have been reviewed and discussed in a workshop in June 2017.

An attempt to develop a generic fuel licensing approach for the countries that are using Russian design VVER-440 type reactors has been carried out in ESSANUF. The concept is to limit the number of events to be re-analyzed by considering them covered by more limiting events. Also a generic Interface Document for Fuel Licensing (IDFL) has been suggested. In general the suggested approach to licensing and the analysis scope are considered acceptable in most countries but countries with no experience of changing fuel vendor were somewhat less willing to accept this approach.

The European Union (EU) has carried out two independent reviews of the ESSANUF project with satisfactory results. The ESSANUF project will complete in October 2017.

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