RECENT TRENDS IN ADVANCED TECHNOLOGY FUEL (ATF) IN EUROPE AND USA

LUSTOLDE MARTÍNEZ
Product Engineer
ENUSA INDUSTRIAS AVANZADAS S.A. S.M.E.

LUCILE FALLOT
Product Engineer
ENUSA INDUSTRIAS AVANZADAS S.A. S.M.E.

NURIA DONCEL
Responsible for Fuel in Operation
ENUSA INDUSTRIAS AVANZADAS S.A. S.M.E.

JORIE WALTERS
Principal Engineer
Accident Tolerant Fuel Technology
WESTINGHOUSE ELECTRIC COMPANY

KATHRYN METZGER
Director
eVinci Fuel
WESTINGHOUSE ELECTRIC COMPANY

BACKGROUND

Since the Fukushima accident in 2011, nuclear fuel vendors have been developing Accident Tolerant Fuels also referred to as Advanced Technology Fuels (ATF). These new technologies have the potential to enhance safety and economics by offering better performance during normal operation, transient conditions, and accident scenarios.

Westinghouse Electric Company (Westinghouse) is collaborating with the U.S. Department Of Energy (DOE) and utilities to deliver new accident tolerant fuel design, **EnCore**[1] Fuel, to the market through two phases. Near term **EnCore** Fuel consists of features like chromium-coated zirconium alloy cladding and **ADOPT™**[1] fuel (doped uranium dioxide) pellets, which could be incorporated within the RFA-2 fuel design. Longer-term Westinghouse **EnCore** fuel products involve cladding made of SiC composites and advanced fuel such as $U^{15}N$ pellets.

Thanks to a Framework Cooperation Agreement (FCA) signed in 2018 by ENUSA Industrias Avanzadas S.A., S.M.E. (ENUSA) and Westinghouse, Spain has been engaged in the ATF fuel development effort. Up to seven Joint Development Projects (JDPs) were launched and executed framed in the FCA, and the main goals achieved were the following: the contribution of ENUSA experience to the segmented rod concept in the ATF/**EnCore** Fuel, the assessment and quantification of the impact on the fuel rod thermomechanical behavior of Cr-coated and SiC concepts, and the analysis of the possible impact of the Cr-coated cladding in the water chemistry, among others [1][2][3].

In the most ambitious large-scale of these JDPs, initiated during the FCA and still on-going, ENUSA and Westinghouse developed a Lead Test Rod (LTR) program for Europe. This demonstration program for Doel-4 consists of introducing Cr-coated **Optimized ZIRLO™**[1] cladding rods in 4 Lead

[1]EnCore, ADOPT, Optimized ZIRLO, AXIOM, Low Tin ZIRLO and PRIME are trademarks or registered trademarks of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.

Test Assemblies (LTA) (standard RFA-2 OPT XLR fuel design). The LTRs were in non-limiting core positions and have undergone two consecutive 18-month cycles of irradiation to date with a third planned to initiate in 2023.

Cr-coated rods with standard UO_2 pellets are expected to provide some benefits with respect to safety due to the increased corrosion resistance, stability to neutron irradiation and resistance to high temperature steam oxidation of the ATF cladding technology [4][5].

Moreover, Small Modular Reactor (SMR) concept, which will use some features typical of commercial PWR design, could take advantage of the ATF cladding and fuel pellet developments. To meet the high uranium loading requirements as well as the needed high melting point, some of the revolutionary products such as uranium nitride and SiC-SiC cladding may be suitable for SMR applications [6].

ENUSA-WESTINGHOUSE COLLABORATION FOR INTRODUCING ATF IN EUROPE

This LTA program for Doel-4 has been composed of several steps such as design, manufacturing, pre-characterization, product delivery and monitoring of behavior of the LTAs during and after the irradiation.

Eight Cr-coated rods of 14 ft length were located at peripheral positions of each assembly to ease the inspection work before and after each cycle (Figure 1). In addition, eight reference **Optimized ZIRLO** rods were included next to LTRs to establish a direct comparison with them. Both Cr-coated and reference rods were pre-characterized to obtain a baseline to compare with the post-irradiation inspections results. All rods were loaded with UO_2 pellets. Slightly higher UO_2 pellet densities, along with higher initial backfill pressures than standard values, were implemented in some LTRs. The first feature is useful to compensate the neutron penalty of Cr coatings, whereas the second one allows mechanical studies of the irradiated fuel as helps to keep the gap open during irradiation [4].

According to the licensing requirements established by the Belgian regulatory authority (Bel-V) [7], the impact of Cr-coated LTRs on fuel design and safety evaluation was assessed by ENUSA and Westinghouse:

- The compilation of the most recent studies carried out on cold spray Cr-coated claddings, the impact of the Cr-coating on the applicability of design limits, codes and methods, as well as the accumulated experience through the irradiation programs developed so far,
- The assessment of fuel compatibility and safety for Doel-4,
- Review of the thermo-mechanical fuel rod design for Doel-4,
- The fuel safety assessment in the event of a loss of coolant accident for Doel-4 based on the current available information,
- These fuel design and safety evaluation studies were complemented with the Core Design and Safety Assessment for Doel-4, performed by Tractebel [5].

Westinghouse **Optimized ZIRLO** claddings coated with Cr were manufactured employing the cold spray deposition method. Cold spray deposition is a low temperature powder spray process, which allows depositing metallic layers at room temperature and ambient conditions. For that, Cr powder particles are propelled at supersonic velocities onto a substrate, which upon impact, plastically deform and accumulate to create a uniform coating across the substrate surface. This way, Cr-coatings are applied to finished zirconium-alloy tubes with uncoated ends to perform standard barcoding and end plug welding processes. After the Cr deposition, the coated tubes were polished to the desired nominal thickness to obtain a surface finish as similar as possible to current zirconium alloy cladding. The as-fabricated microstructure of the coating is shown in Figure 2, where no porosity is observed and a continuous interface between coating and substrate suggest a strong adherence [4].

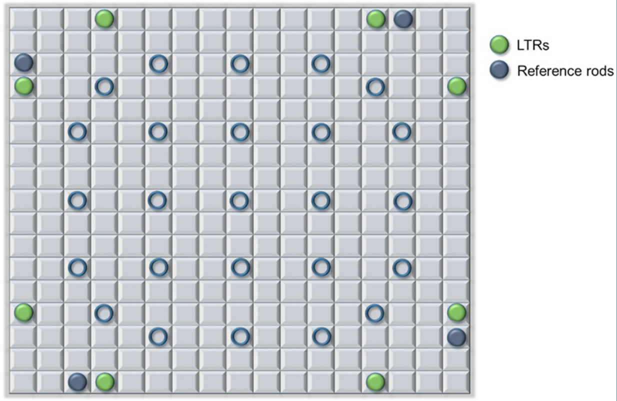

Figure 1. Location of LTRs and reference rods in fuel assemblies.

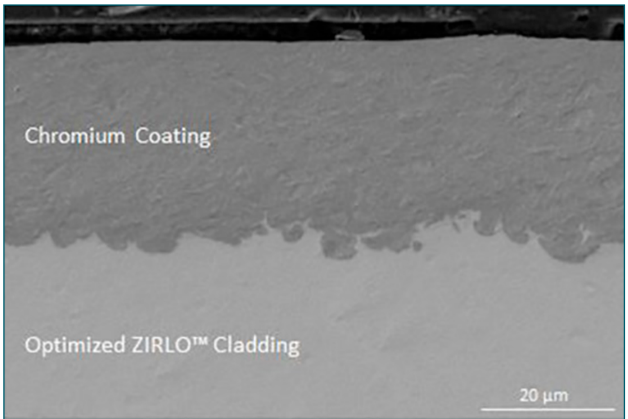

Figure 2. As-fabricated microstructure of the Cr-coated cladding.

ENUSA was responsible for manufacturing the LTAs. New handling requirements were implemented, as well as those related to the safety of the workers involved. Extensive design paperwork was completed before manufacturing including new drawings and specifications, reviewing the manufacturing documentation, defining the applicable qualifications, as well as establishing the characterization requirements applicable to the manufactured product. Apart from that, a standard manufacturing and quality process was followed. Visual images of the LTAs (Figure 3) were used to elaborate a reception guide for the nuclear plant, in which Cr-coated rods are easily distinguishable due to the absence of the standard debris-resistant oxide coating at the bottom of the fuel rods.

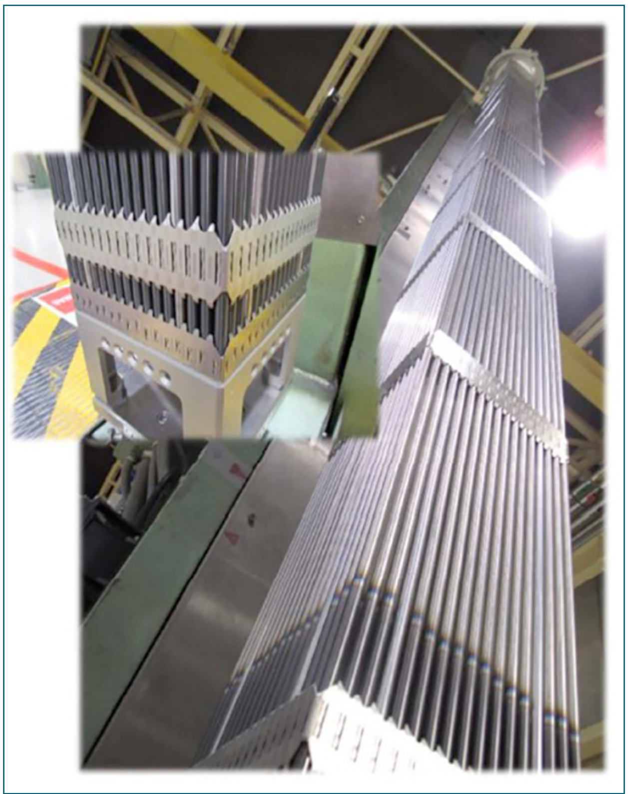

Figure 3. General view of a fuel assembly with Cr-coated rods and detail of the lower part of the LTAs fuel assemblies (Cr-coated rods without pre-oxidation at the bottom).

Demonstration LTAs were loaded in outage 31 of unit 4 of the Doel power plant where they would be irradiated during cycles 31, 32 and 33. Doel-4 nuclear power plant, located in north-eastern Belgium, is a Westinghouse design plant with three loops, 157 assemblies and a maximum power output of 3000 MWt.

Once irradiation started, typical monitorization activities were performed. Primary coolant activity was analyzed during the irradiation along with several inspection campaigns performed after each irradiation cycle, to assess the integrity of the Cr-coated rods.

The inspection scope after the first irradiation cycle in the core periphery of Doel 4 included the detailed visual inspection of the LTAs. Cr-coated rods appeared bright, clean and uniform, without coating delamination nor cracks, both in lower (Figure 4) and upper (Figure 5) areas of the LTRs. **Optimized ZIRLO** rods are oxidized as it is shown in Figure 4 due to its patchy appearance compared to the coated LTRs. Slightly lower crud deposition was observed in Cr-coated rods compared to standard **Optimized ZIRLO** rods (Figure 5). Inspection results of Doel-4 inspection campaign were in good agreement with the statements made on the Cr-coated rods irradiated in Byron unit 2 in the U.S. [8][9]. Based on all these observations, LTAs were approved to be reloaded for a second irradiation cycle in Doel-4 nuclear plant [10].

Next inspection campaign is planned for spring 2023, during the refueling outage after cycle 32, to check if the integrity of the Cr-coated LTRs is maintained after two irradiation cycles, before reloading them for a third irradiation cycle.

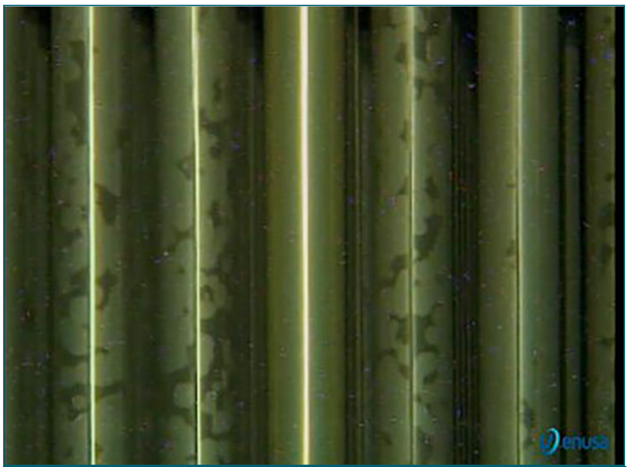

Figure 4. Comparison between different oxidation aspect for Cr-coated rod (center) and Optimized ZIRLO rods (Lower part of the fuel assembly)

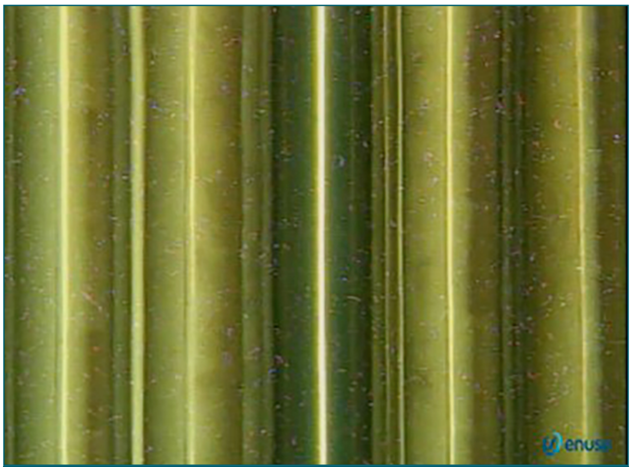

Figure 5. Different crud affinity between Cr-coated rod (center) and Optimized ZIRLO rods (Upper part of the fuel assembly).

ENCORE® FUEL CURRENT STATE OF THE ART AND LICENSING PLANS IN THE USA

Westinghouse is commercializing two high energy, high burnup (HEHB) **EnCore** accident tolerant fuel designs; Cr-coated zirconium alloy cladding with doped UO_2 **ADOPT** fuel pellets with greater than 5% ^{235}U enrichment recently licensed in the USA by the Nuclear Regulatory Commission (NRC) and SiC SiGA®[2] cladding with uranium nitride ($U^{15}N$) fuel planned to be licensed in the early 2030's. Additional LTRs and LTAs of the **EnCore** fuel are planned using Cr coated cladding and **ADOPT** fuel pellets to demonstrate HEHB performance up to 75 MWd/kgU.

Topical reports for **ADOPT** pellets and fuel burnup up to 68 MWd/kgU have been approved and Safety Evaluation Reports were issued by the NRC. Topical reports for coated cladding and high burnup fuel are in process of submission.

[2]SiGA is a trademark of General Atomics, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. Other names may be trademarks of their respective owners.

Regarding Cr-coated claddings, the Byron LTR program completed its second cycle last May 2022. A program is underway to reinsert several Cr-coated rods for a third cycle to achieve high burnups in 2023.. Results from pool-side and non-destructive irradiation examination of LTRs inserted into the Byron Unit 2 commercial reactor in Spring 2019 along with poolside results from the Doel Unit 4 inspection campaign performed in Autumn 2021 showed no-issues. Potential benefits for coated cladding in addition to those provided by corrosion resistance, based on the observations of little or no crud build-up, have been identified. In addition to hot cell inspections underway at Oak Ridge National Laboratory (ORNL), portions of LTRs irradiated in Byron 2 will ultimately be shipped to Idaho National Laboratory for fabrication of rodlets for loss of coolant accident (LOCA) and Reactivity-initiated Accident (RIA) testing in the Transient Reactor Test Facility (TREAT), along with power ramp testing in the Advanced Test Reactor (ATR). So far, previous poolside non-destructive examinations and preliminary destructive hot cell inspections [9] revealed no unusual occurrences.

The accident tolerance and performance benefits of **ADOPT** fuel pellets combined with Cr coated cladding are shown in Figure 6 [11]. **ADOPT** pellet contribution comes from its increased thermal stability and reduced in-pile densification, enhanced corrosion resistance during a leaking rod event, increased fuel creep at high temperatures reducing the degree of pellet-cladding mechanical interaction, and reduced fission gas release (FGR) under short-term transient conditions decreasing the potential for rod bursting. Furthermore, the increased uranium density of **ADOPT** fuel pellets offers improved fuel cycle economics by enabling a reduction in feed assemblies by allowing longer operating cycles [12].

Additional LTA programs within the U.S. will be devoted to licensing HEHB ATF fuels. Programs including high enriched pellets up to 6% ^{235}U and Cr coated cladding will provide validation of the HEHB and Cr-coated cladding topical reports in support of regions to be introduced in the late 2020s [11].

Additional LTR programs are also being explored in Europe to support use of Westinghouse ATF products.

In parallel, another important work line of the fuel development in the USA comes from the High Energy Fuel (HEF) Program promoted by Westinghouse to meet the challenging demands of the energy industry. Advanced fuel management strategies have been developed for both 18-month and 24-month cycles to economically optimize levelized cost of nuclear electricity generation, and these strategies require the use of advanced fuel technologies such as **ADOPT** pellets, **PRIME™** fuel advanced features and **AXIOM®**[(1)] Claddings. For one side, **PRIME** fuel features include **Low Tin ZIRLO™** grid strap material for improved corrosion resistance, lower growth and improved grid-to-rod fretting margin at higher burnups, tube-in-tube dashpot in guide thimble tubes for improved dimensional stability and a lower pressure drop advanced debris filter bottom nozzle to prevent inter-fuel assembly debris migration that further reduces the probability of debris-related leakers. On the other side, **AXIOM** cladding provides improved corrosion resistance, lower hydrogen pick-up, and lower creep and growth compared to current Westinghouse uncoated zirconium-alloy products in high burnup application [13].

OTHER COLLABORATIONS

Westinghouse continues to be actively involved on the Electric Power Research Institute (EPRI) Collaborative Research on Advanced Fuel Technologies (CRAFT) program on Alternate Licensing Methods and consequences of fuel fragmentation, relocation, and dispersal (FFRD).

Additionally, Westinghouse regularly exchanges information with the National Nuclear Laboratory (NNL) of the United Kingdom (UK) in a variety of **EnCore** fuel areas.

Finally, along with Pacific Northwest National Laboratory, Westinghouse and GA-EMS have partnered with the European Union sponsored IL TROVATORE project to establish the PERSEUS program to look at the effects of radiation on corrosion of SiC and Cr coated cladding [11].

The CEIDEN Technology Platform is a national network to promote research and development activities related to nucle-

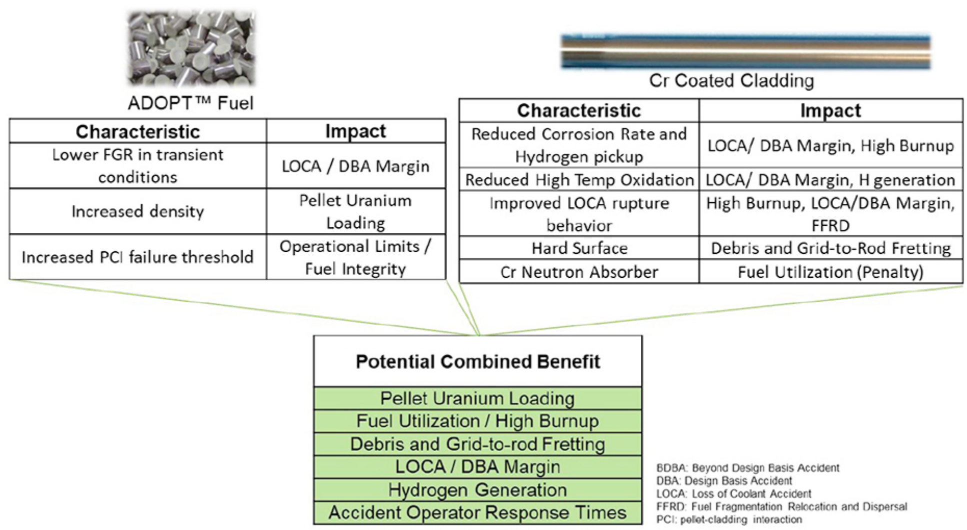

Figure 6. Benefits of using Cr coated cladding and ADOPT pellets.

ar fission energy with national and international organizations. Its members come from R&D departments from all entities involved in the nuclear energy cycle in Spain (Regulatory Body, Utilities, Fuel Cycle companies, R&D Research Centers, Universities, Fuel Vendors, etc.). Among the main strategies of CEIDEN are: (a) ensuring Spanish NPP life extension beyond 40 years, and (b) promoting national capabilities to ensure implementation and technical support of ATFs.

A specific CEIDEN ATF Program has been established in 2022 in which ENUSA was appointed as Technical Coordinator of the efforts and initiatives within this framework. This ATF program will provide support to all involved organizations to obtain public fundings where also EU taxonomy may help. Some of the ideas and proposals received from the participants are linked with the current knowledge gaps on near-term ATF technologies such as (1) on-site inspection techniques for coated rods, (2) Cr-coated cladding behavior in operation and (3) Cr-coating manufacturing techniques.

SUMMARY AND CONCLUSIONS

The introduction of enhanced ATF features requires a coordinated effort between scientific researchers, fuel manufacturers, inspection and testing developers, advanced capabilities laboratories and hot cells, experimental reactors, commercial nuclear plants, and regulators.

ENUSA in conjunction with the experience in collaboration projects with Westinghouse have made possible the introduction of Westinghouse's **EnCore** accident tolerant fuel in Europe throughout the irradiation of LTRs in Doel-4.

Westinghouse is leading several ATF projects in the USA through its HEHB and HEF designs as essential elements to assure the continuity of the energy generation by nuclear power plants worldwide.

Future projects related to the knowledge of the performance and improvements of the ATF products will be very valuable in the frame of the reinforcement of the ENUSA and Westinghouse collaboration.

Additionally, this advanced fuel development that includes all the knowledge on standard fuel design and operation for more than 50 years means an investment for the future design and manufacturing of Small Modular Reactors fuels.

Small Modular Reactors operated with advanced fuels, in which ENUSA and Westinghouse experience in ATF will be essential, will provide flexibility and power capacity as well as future possibilities for nuclear energy.

REFERENCES

[1]. M. Conner, Z. Karoutas, E. Lahoda, C. Muñoz-Reja, M. Quecedo, J. Romero, "Incorporating ATF and Advanced Features in the Robust Fuel Assembly (RFA) Design", Revista SNE, n 411, 2019.

[2]. C. Muñoz-Reja, J. Romero, M. Quecedo and R. Oelrich, "Fuel Engineering Innovation. "The Development of the Enhanced Accident Tolerant Fuels (ATF)", Revista SNE, n 403, 2019.

[3]. J. Vidal, I. Del Rio, J.L. Walters, Y. Long, O. Lissuain, "Out-Of-Reactor Creep Analysis Of Chromium Surface-Coated Optimized ZIRLO™ Cladding", Top Fuel, 2022.

[4]. L. Martinez, N. Doncel, I. Pastor, J.L. Walters, J. Zhang, A. Meert , "Cr-Coated Cladding Demonstration Program for Doel-4" SNE Annual Meeting, 2021.

[5]. J. Zhang, B. Vermeeren, C. Schinazi, C. Scheneidesch, A. Meert, N. Doncel, L. Martínez, J.L. Walters, "Design and Safety Evaluation of Cr-coated Lead Test Rods for Doel 4 nuclear power plant", Top Fuel, 2021.

[6]. Advances in Small Modular Reactor Technology Developments, IAEA, 2016.

[7]. N. Hollasky, G. Roussel, "Belgian licensing of Cr-coated lead test rods for Doel nuclear power plant unit 4", Top Fuel, 2021.

[8]. J.L. Walters, J.A. Nilsson, C.P. Haselden, J.H. Smith, S.D. Lazeski, W. Gassmann, I. Nanovsky, "Poolside Inspection of EnCore® Fuel Lead Test Rods at Exelon Byron Unit 2", Top Fuel, 2021.

[9]. L. Olson, E. Pitruzzella, J.L. Walters, E. Roberts, D. Mitchell, A. Mueller, L. Hallman, G. Pan, K. Metzger, B. Maier, J. Lyons, A. Jaworski, E. Lahoda, J. Kobelak, M. Shockling, N. Capps, J. Harp, "Accident Tolerant and High Burnup Hotcell PIE at ORNL", Top Fuel, 2022.

[10]. L. Fallot, L. Martinez, N. Doncel, J.L. Walters, J. Zhang, A. Meert, "Poolside Visual Inspection of Cr-Coated Lead Test Rods at Doel 4 after One Irradiation Cycle", Top Fuel, 2022.

[11]. Z. Karoutas, K. Metzger, E. Pitruzzella, C.Vallencour, E. Lahoda, A. Jaworski, A. Parsi, M. Anness, C. Hass, M. Limbäck, J. Wright, "Westinghouse EnCore® Accident Tolerant Fuel And High Energy Program", Top Fuel, 2022.

[12]. L. Hallman, D. Mitchell, Y. Long, L. Olson, A. Claisse, Z. Karoutas, E. Lahoda, J. Wright, "Westinghouse Advanced Doped Pellet Technology (ADOPT™) Fuel for PWR Applications", Top Fuel, 2022.

[13]. M. Boone, D.S. Wenzel, C. Guler, "Westinghouse High Energy Fuel for The Future", Top Fuel, 2022.■