FUEL ENGINEERING INNOVATION. THE DEVELOPMENT OF THE ENHANCED ACCIDENT TOLERANT FUELS (ATF)

Nuclear fuel is a highly complex product that has been subject to continuous evolutions over the past 40 years and has reached a stage where it can be safely and reliably irradiated in commercial nuclear reactors. However, the basic design of uranium oxide fuel pellets clad with zirconium alloy tubing has remained as the standard for the vast majority of commercial nuclear power plants.
The Three Mile Island and Fukushima Daiichi accidents have shown that the current fuel designs are vulnerable under extreme conditions so there is a renewed interest in alternative fuel designs that increase the safety of today's light-water reactors. Accident-tolerant fuel (ATF) is the term used to describe new technologies that enhance the safety and performance of nuclear fuel under such conditions.
ATF must be available within a practical time frame for utilities to take advantage of its benefits, especially for second license renewals. A transformational shift in the way the fuel is designed and licensing is needed as the current processes for qualification and deployment of nuclear fuel technology are outdated, exceedingly complex and time consuming.

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INNOVACIÓN EN LA INGENIERÍA DEL COMBUSTIBLE. DESARROLLO DEL COMBUSTIBLE ATF

El combustible nuclear es un producto complejo que ha sufrido evoluciones continuas a lo largo de los últimos 40 años y que ha alcanzado un estado que le permite ser irradiado de una forma segura y fiable en los reactores comerciales. Sin embargo, el concepto básico de pastilla de óxido de uranio/vaina de aleaciones de circonio ha permanecido constante.
Los accidentes de Three Mile Island y Fukushima Daiichi mostraron que los diseños actuales de combustible son mejorables bajo condiciones tan extremas, lo que ha suscitado desarrollos tecnológicos que incrementen la seguridad de los reactores actuales de agua ligera. Accident-tolerant Fuel (ATF) es el término usado para describir nuevas tecnologías que aumenten la seguridad y mejoren el comportamiento del combustible nuclear en esas condiciones.
El combustible ATF debe estar disponible en un plazo de tiempo tal que permita a las plantas nucleares incorporar sus beneficios lo antes posible, especialmente de cara a la renovación de licencias. Es necesario un cambio radical en la forma en la que el combustible es diseñado y licenciado ya que los procesos actuales son excesivamente complejos y prolongados.

INTRODUCTION

Nuclear fuel is a highly complex product that has been subject to continuous evolutions over the past 40 years and has reached a stage where it can be safely and reliably irradiated in commercial nuclear reactors. During this time, there have been many improvements to the original designs and materials used. However, the basic concept of uranium oxide fuel pellets clad with zirconium alloy tubing has remained as the standard technology of choice for the vast majority of commercial nuclear power plants.

The Three Mile Island and Fukushima Daiichi accidents have shown that the current fuel designs are vulnerable under such extreme conditions so there is a renewed interest in alternative fuel designs that not only increase the safety of today's light-water reactors but also improve plant performance at a crucial time for the nuclear industry. This alternative fuel is called Accident-tolerant fuel (ATF) and the benefits that these fuels bring to the table could make the case for utilities to extend plant operations in these times, where a number of reactors are currently under economic stress and facing their second license renewal.

ATF must be available within a practical time frame for utilities to take advantage of its benefits. A transformational shift in the design and licensing approach is needed as the current processes are exceedingly complex. The current design and licensing processes in the nuclear field were developed decades ago when computers were limited in their capabilities. Today, computing power is much more advanced. The role of modelling and simulation is key to expedite the path from design and testing to commercial deployment. These new capabilities allow fuel licensing to move in a more efficient process.

ATF may incorporate the use of new materials and designs for cladding and fuel pellets. There are extensive programs all over the world supporting and promoting the development of ATF. For example, in the United States, the Department Of Energy (DOE) has since 2012 supported the development of ATF concepts through its Enhanced Accident Tolerant Fuel programme, which aims to develop new cladding and fuel materials that can better tolerate the loss of active cooling in the reactor core, while maintaining or improving fuel performance and economics during normal operations.

As the largest supplier of nuclear fuel and fuel components globally, Westinghouse has developed a world-class network of research, design and manufacturing partners. Leveraging the breadth and depth of its resources, combined with U.S. DOE awards, as well as utility funding, Westinghouse is collaborating with respected industry partners to deliver its revolutionary new accident tolerant fuel design, EnCore®[1] Fuel to the market on an aggressive, accelerated schedule, with lead test rods featuring corrosion-resistant coated claddings anticipated for delivery this year.

Spain found the opportunity to be engaged in the development of ATF fuel by means of a Framework Cooperation Agreement (FCA) signed in 2018 by Enusa Industrias Avanzadas (Enusa) and Westinghouse Electric Company to collaborate in the development of Westinghouse's EnCore® Accident Tolerant Fuel (ATF). The FCA establishes the framework that will regulate joint development projects (JDPs) launched by the companies in the area of codes and methods, licensing, used fuel and fuel fabrication and inspection technology.

WESTINGHOUSE'S EnCore® FUEL PROGRAM

EnCore® Fuel will offer design-basis-altering safety, greater uranium efficiency and estimated economic benefits up to hundreds of millions of dollars.

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Figura 1. Fuel concepts considered in the Westinghouse EnCore® Fuel.

Delivered in two phases, near term EnCore® Fuel features chromium-coated zirconium cladding and ADOPT™ fuel (doped uranium dioxide) pellets, offering benefits in safety and fuel economics. By making only incremental changes to the current Westinghouse cladding material (ZIRLO® or Optimized ZIRLOTM), and using ADOPT pellets, this near term solution offers better fuel performance with faster availability to the industry. Lead test rods will be inserted in a commercial reactor in spring 2019, with region quantities scheduled for 2023.

Longer term EnCore® Fuel technologies comprise cladding made of a silicon carbide ceramic matrix composite, with high- density uranium silicide fuel pellets. Westinghouse believes that the economic benefits of this combination distinguish EnCore® Fuel products from other ATF products in the industry. Figure 1 shows the fuel concepts considered in the EnCore® Fuel program.

The overall Westinghouse EnCore® Fuel product implementation timeline, including supporting activities such as irradiation tests, licensing and manufacturing is shown in the Figure 2. Many Westinghouse ATF activities are currently focused on preparations to insert the lead test rods (LTR) of the near term chromium-coated cladding and ADOPT pellets in Byron Unit 2 in the U.S. in spring 2019 [1], with a goal of region reloads by 2023. Westinghouse is also moving forward to irradiate uranium silicide pellets in lead test rods destined for the Byron reactor, to gain valuable operation experience.

SiGA cladding, the ceramic concept for the fuel cladding, filled with high-density uranium silicide fuel pellets will be irradiated in a commercial reactor in 2022.

A summary of the physical benefits of the EnCore® Fuel product is discussed in reference [2] and summarized here qualitatively:

U_3Si_2 Pellets

- Higher density improves fuel cycle economics for 18 and 24 month cycles.
- Increased thermal conductivity improves fuel thermal performance during normal operation and transients.
- Good irradiation behaviour (reduced swelling and fission gas release) improves stability during operation.

ADOPT Pellets

- Higher density and better thermal stability.
- Lower transient fission gas release at high burnups.
- Better oxidation resistance (in presence of air and water).
- Increased Pellet Cladding Interaction (PCI) margins at high temperatures.
- Ability of dopants to trap corrosive fission products.
- Potential for higher fuel creep rate to mitigate Pellet Cladding Me-

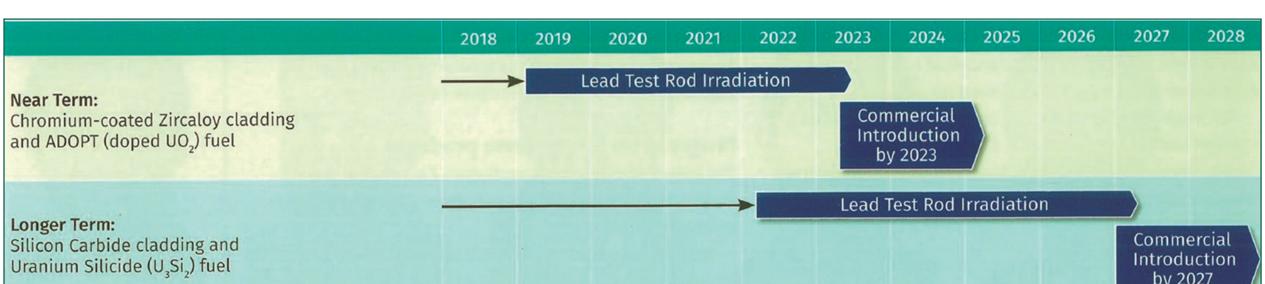

Figura 2. Implementation timeline for Westinghouse EnCore® Fuel products with supporting activities.

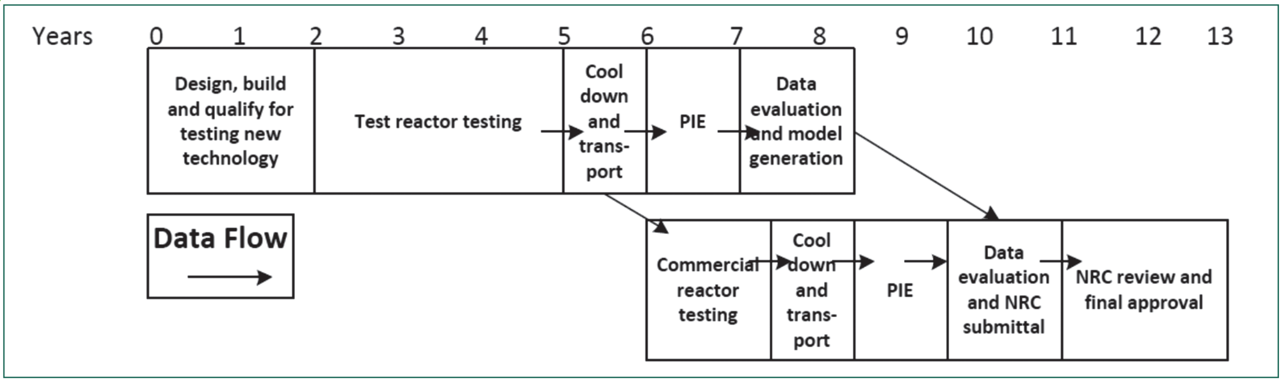

Figura 3. Timeline for Current Approach to Development and Licensing of New Nuclear Technology (NRC refers to the Nuclear Regulatory Commission in the U.S., as an example).

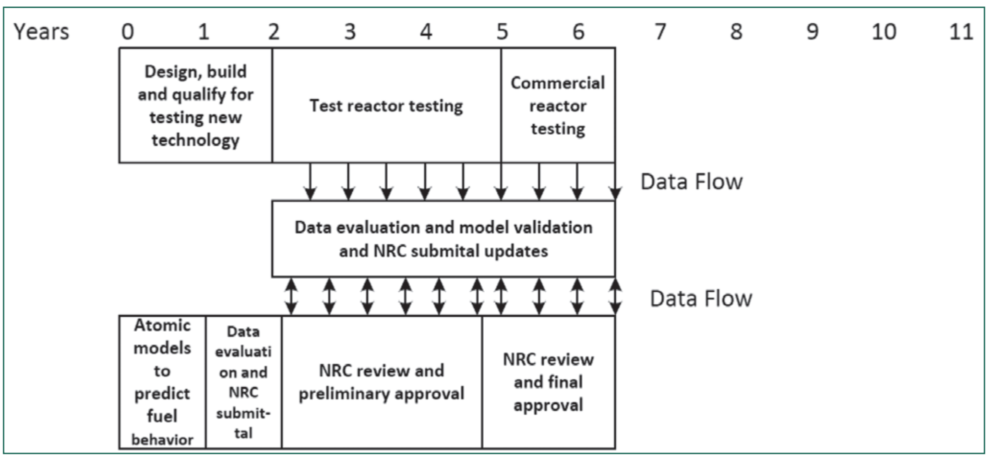

Figure 4. Ideal Timeline for Improved Approach to Development and Licensing of New Nuclear Technology (NRC refers to the Nuclear Regulatory Commission in the U.S., as an example).

chanical Interaction, PCMI (softer pellet).

Coated Claddings

- Higher temperature capability for accident conditions (1300 to 1400°C).
- Reduced corrosion and hydrogen pickup, and resistance to rod wear
- Reduced exothermic reaction energy during high temperature transients.
- Improved LOCA (loss of coolant) PCT (peak clad temperature) and RIA (reactivity initiated accident) depositions limits for DBAs (design basis accidents).

Details of the latest advances on the Westinghouse EnCore® Fuel program can be found in reference [2].

THE CHALLENGE OF EXPEDITING THE OPERATION OF ATF IN COMMERCIAL NUCLEAR POWER PLANTS

As it was introduced before, ATF must be available within a practical time frame for utilities to take advantage of its benefits, which is a real challenge considering the outdated and cumbersome current licensing models.

The "traditional" way to allow the implementation of a new nuclear technology has been driven by data collected after irradiation and post-irradiation examination (PIE). Figure 3 shows a schematic of what the timeline looks like for a new fuel to be operated in a commercial reactor if this approach is followed. As it can be seen, operation of ATF in reloads could take more than one decade.

The current licensing processes in the nuclear industry were developed decades ago when computers were limited in their capabilities. Today, computing power is much more advanced. The role of modelling and simulation is key to expedite the path from design and testing to commercial deployment. These new capabilities may allow fuel licensing to move in a more efficient process, removing barriers to innovation and implementing newer, even safer nuclear technology that will benefit the public and future generations.

Westinghouse is implementing this new view, to expedite the introduction of its EnCore® Fuel product by significantly reducing time for licensing, increasing reliability of models and therefore licensing decisions. Timeline of this approach is represented in Figure 4, showing that all process can be shortened by about 7 years with reference to the "traditional" approach.

To get EnCore® Fuel licensed and loaded in region quantities by 2027, Westinghouse has initiated a program that looks to apply advanced modelling and testing technology to fully leverage the value of existing and available test data. It is believed that this approach could help to compress the time from initial testing to commercial delivery, while improving the quality of the data and resulting design models used to analyse the fuel.

The following sections describe the different areas of work established to meet this goal.

Atomic Scale Modelling

The final objective of this area of work is advanced modelling to determine physical properties of irradiated materials.

New technologies have the potential to supply virtual data before testing. For fuel materials such as the ATF U_3Si_2, when data is limited, multiscale modelling is being conducted to define basic material behaviours on an atomistic scale. Using intermediate scale modelling, these fundamental atomistic scale models are translated into engineering scale models

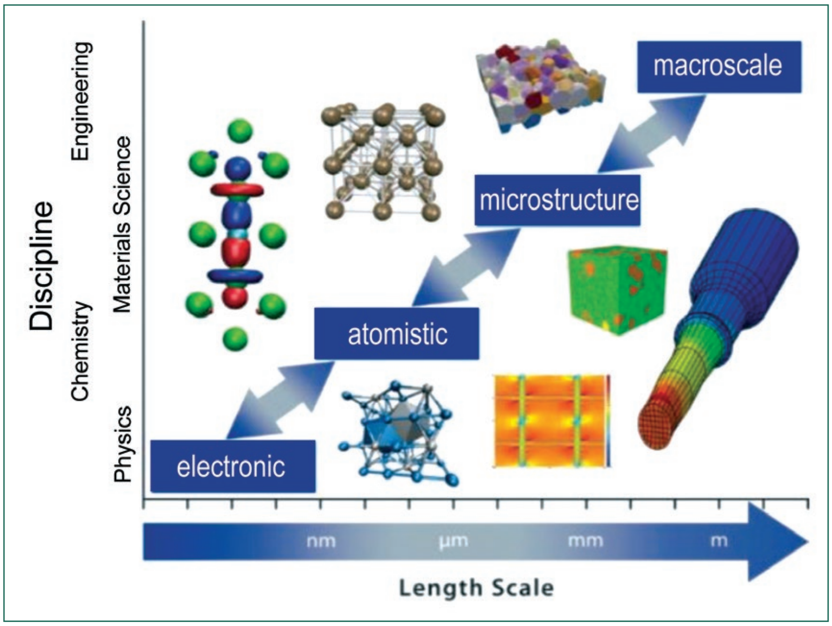

Figura 5. Multiscale mechanistic modelling process [4].

(Figure 5) for incorporation into fuel performance tools like BISON, a high fidelity finite element based fuel performance code developed by the Idaho National Laboratory (INL)[3]. Complex models such as fission gas transport and release, gas bubble formation and gas bubble swelling can be derived on this basis and then extended to incorporate the effects of time and burnup. With the completion of these models, advanced fuel performance codes will be capable of predicting ATF performance over the full range of planned operation, extending the understanding of expected behaviours beyond the range of available measured data. This can significantly reduce the time frame and cost for licensing by reducing the number of irradiation tests and the associated PIE cost and time.

The application of BISON to ATF design is part of the Westinghouse BISON ATF Test Stand effort performed in conjunction with the US DOE Consortium for Advanced Simulation of LWRs (CASL) and the Nuclear Energy Advanced Modelling and Simulation (NEAMS) Programs.

More details about these modelling efforts can be found in reference [4].

Collaborative efforts: CARAT network

Starting in 2012, Westinghouse has instituted and driven the formation of the "Collaboration for Advanced Research on Accident Tolerant Fuel" (CARAT) network which is complementary to the Westinghouse-led ATF program. This collaboration is aimed at obtaining world-wide technical support for the Westinghouse EnCore® Fuel program.

Focused on fundamental research this program provides a framework for performing research oriented work in support of the industrially oriented ATF program. The Westinghouse role in CARAT is to coordinate research topics, provide samples and materials, and provide a venue for the presentation of results, both in CARAT meetings and as an organizer of sections in journals.

CARAT consists of more than 50 research organizations, more than 200 scientists, engineers, and researchers who work together to advance the ATF technologies by developing fundamental understanding and generating important technical data that is needed for subsequent engineering work.

Real-Time and pool-side data generation

Capabilities to gather real-time in-reactor test data to verify the performance of the multi-scale models are being developed. This includes:

- Pool-side data generation that includes gamma emission tomography based on gamma-ray spectroscopy and tomographic reconstruction that can be used for rod-wise characterization of nuclear fuel assemblies without dismantling the fuel (pellet swelling, pellet-cladding interaction, pellet cracking). Moreover, if a spectroscopic detection system is added, different gamma-ray emitting isotopes can be selected for analysis, enabling non-destructive fuel characterization with respect to a variety of fuel parameters (e.g., fission gas release).
- Wired or wireless transmission technology for measurements of centerline temperature, fuel rod gas pressure and swelling of fuel.

In addition to the time and cost benefits that can be achieved with this approach, real-time and pool-side data generation provide increased confidence in predictability of performance, because the performance models will exploit a theoretical rather than just an empirical basis. The on-line supply of data to regulators should reduce time and effort required due to the reduction in the number of submission and review iterations that currently affect the critical path for commercialization.

ATF IMPLEMENTATION TIMELINE

The above described initiatives are only some examples of the most innovative ones that are being applied for the development and implantation of the ATF. Nevertheless, there are much more open lines, including supporting activities such as irradiation tests, licensing and manufacturing to achieve the overall Westinghouse EnCore® Fuel product implementation timeline tha is currently focused on the insertion of lead test rods (LTR) of the near term chromium-coated cladding and ADOPT pellets in Byron Unit 2 this year, with a goal of region reloads by 2023.

Westinghouse is also moving forward to irradiate uranium silicide pellets in lead test rods destined for the Byron reactor, to gain valuable operation experience. SiGA cladding filled with high-density uranium silicide fuel pellets will be irradiated in a commercial reactor in 2022.

Longer term EnCore® Fuel products are targeted for region implementation by 2027.

With reference to the European market, implementation of lead fuel rods is under discussion with a number of European countries. Different utilities have already expressed their interest on moving with LTRs as early as 2020.

CONTRIBUTION OF ENUSA TO THE ATF DEVELOPMENT

Spain's Enusa Industrias Avanzadas (Enusa) and Westinghouse Electric Company signed a Framework Cooperation Agreement (FCA) to collaborate in the development of Westinghouse's EnCore® Accident Tolerant Fuel (ATF)[5]

The FCA establishes the framework that will regulate joint development projects (JDP) launched by the companies.

Two projects were launched and executed during last year. The first JDP had the objective of evaluating the application of a segmented rod concept in the ATF/EnCore® Fuel rods for Byron, leveraging the experience of ENUSA as designer of two worldwide recognized segmented rod programs, the SRP (Segmented Rod Program) in Vandellos 2 and the LAX program (Lead Test Assemblies for the Liner, ADOPT and AXIOM Program) in EDF plants.

The second JDP was devoted to the assessment and quantification of the impact on the fuel rod thermomechanical behaviour of uncertainties in models, properties and manufacturing tolerances, existing today for uranium silicide fuel pellets, in comparison with ADOPT fuel.

Two more projects are already defined for 2019, involving the behaviour of the cladding made of silicon carbide ceramic matrix composite, followed by other projects in the areas of codes and methods, used fuel, fuel fabrication and inspection technology.

The signature of the FCA as well as the execution of the JDPs in a close collaboration between Westinghouse and ENUSA specialists is strengthening the technical and commercial relationship between Enusa and Westinghouse.

SUMMARY AND CONCLUSIONS

An objective as challenging as a radical change of concept for nuclear fuel requires a huge effort that, following a traditional approach, would take decades to achieve. This would not be affordable by a nuclear industry that needs the deployment of ATF to fulfil its commitment with society in terms of safety and economy.

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

Moreover, all new available technical computing and modelling capabilities, even those not explicitly developed inside the nuclear world, must be explored and exploited in this effort.

Following these bases, to meet the aggressive schedule for region implementation of all the ATF products, Westinghouse is applying a concurrent engineering approach to combine data gathered from the irradiation of instrumented lead test rods with advanced modelling to expedite ATF licensing and to shorten the commercial implementation schedule.

Proven engineering capabilities in the whole fuel cycle, developed by Enusa since its first foundation and its knowledge of the European market through the Westinghouse-ENUSA consortium, EFG (European Fuel Group), in conjunction with the experience in collaboration projects with Westinghouse; have made possible the incorporation of the Spanish nuclear industry in the development of ATF fuel by means of a FCA (Frame Cooperation Agreement) signed in 2018 by Enusa and Westinghouse to collaborate in the development of Westinghouse's EnCore® Accident Tolerant Fuel (ATF).

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