

Westinghouse-Exelon EnCore[®] Fuel Lead Test Rod (LTR) Program including Coated cladding Development and Advanced Pellets

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Abstract

Westinghouse has developed **EnCore[®]** Fuel, an Advanced Technology Fuel that has the potential to significantly increase the tolerance for nuclear reactor severe accident scenarios. This technology could be “game changing” for the nuclear industry, with the capability of improving nuclear plant safety and reliability, and with the potential to provide financial savings to the utilities that operate the plants. Westinghouse and Exelon are jointly pursuing a Lead Test Rod (LTR) program to begin irradiation in Byron Unit 2 Cycle 22. The LTR program will include up to twenty (20) lead test rods (LTRs) of the 17x17 Optimized Fuel Assembly (OFA) design with coated **Optimized ZIRLO[™]** fuel rod cladding along with the fuel reload for Byron Unit 2 Region 24. Four (4) LTRs will contain uranium silicide pellets. Up to 16 rods will have coated cladding. Four (4) rods will contain **ADOPT[™]** pellets. Oxidation resistant chromium coatings have been applied to **ZIRLO[®]** and **Optimized ZIRLO[™]** cladding tubes using a cold spray process. Application parameters for cold spray have been optimized to achieve dense and adherent coatings, while polishing processes have been developed to achieve the thickness and surface finish required for in-reactor performance and seamless integration into current fuel designs, without a need for fuel assembly structure modifications. Optimized coatings have been subjected to extensive testing simulating normal operation and accident conditions, including corrosion in pressurized water, high temperature corrosion in steam, crud deposition, and mechanical testing. The effect of surface imperfections and scratches is being evaluated. Cold spray deposits particles and produces coatings in solid state, eliminating the need for controlled atmospheres, which has enabled the scalability of the process for full length tubes. The proposed Westinghouse accident-tolerant fuel pellet design is also expected to deliver improved fuel cycle economics as a result of the higher density and thermal conductivity of the uranium silicide (U_3Si_2) fuel pellets. Significantly more U^{235} can be packed into the same volume as uranium dioxide (UO_2), enabling longer fuel cycles while staying below the five percent enrichment limit that is the design basis for many operating plants. In addition, third feature of the LTR program, **ADOPT[™]** pellets are high density UO_2 pellets that enable higher U^{235} assembly loading, have lower fission gas release during transients and less washout from secondary failures. At high temperatures observed during ramp tests they are also softer than UO_2 which increases the PCI failure threshold [1]. Westinghouse-Exelon EnCore[®] LTR program will thus demonstrate integrated performance of three ATF features. The EnCore[®] LTR Accident Tolerant Fuel program, hence, paves the way to make safer fuel and with improved economics.

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Introduction and Westinghouse- Exelon EnCore Lead Test Rod Program

After the accident at Fukushima Daiichi, the U.S. Congress mandated the development of nuclear fuels with enhanced accident tolerance to improve performance under Beyond Design Basis Accident (BDBA) conditions. The major objectives for Accident Tolerant Fuel (ATF) designs included: 1) improved cladding reaction to high temperature steam; 2) reduced hydrogen generation; and 3) reduced BDBA source term. Exelon and Westinghouse Electric Co. have embarked on a joint initiative to gather fuel performance data on Westinghouse **EnCore®** accident tolerant fuel to advance the Congressional mandate. Figure 1 below shows depicts general layout of LTRs in two Fuel Assemblies. Exelon Byron Station unit 2 plans to load the two Lead Test Assemblies (LTAs) containing the Westinghouse **EnCore®** LTRs during the Spring 2019 refueling outage. The subject LTAs would remain in the Unit 2 core for three cycles; i.e., Cycle 22, 23 and 24; and will then be discharged during the Fall 2023 refueling outage.

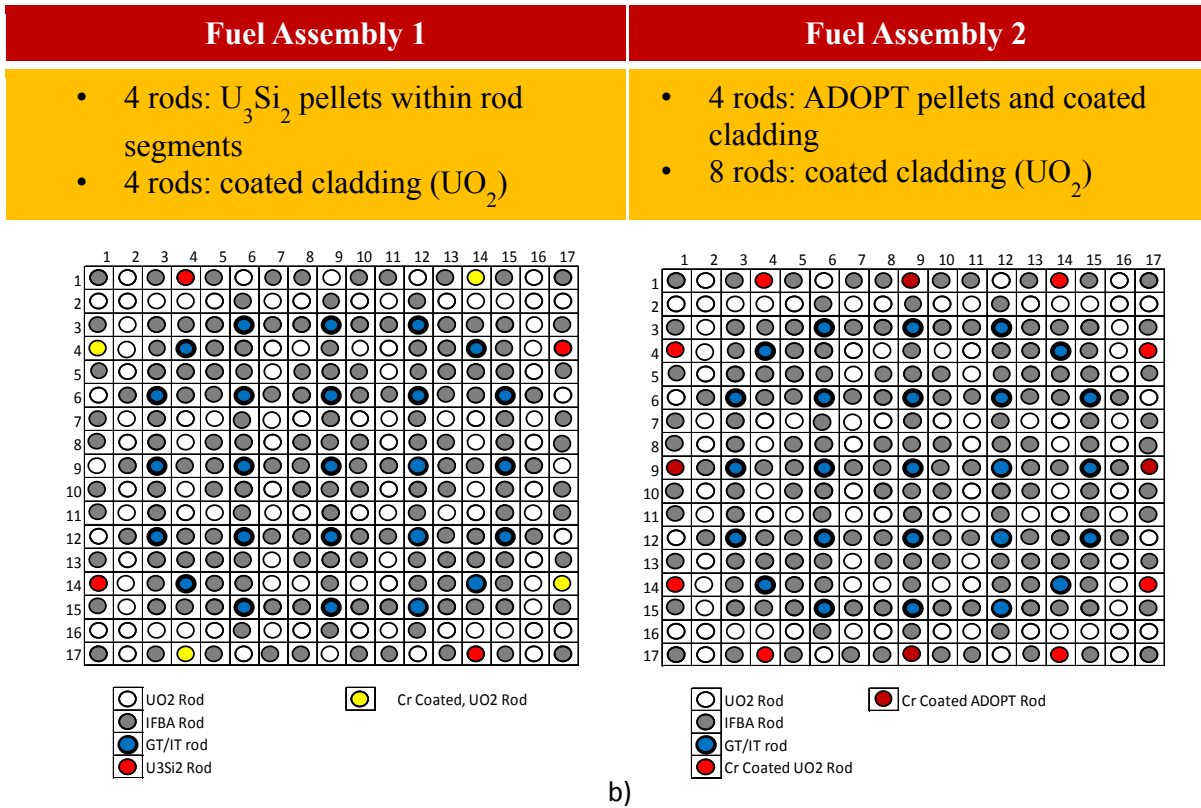


Figure 1 – Fuel Assemblies with LTRs

The objective of ATF is to increase the accident tolerance of the current fuel cladding designs to beyond design basis accidents, while maintaining or improving oxidation resistance under normal operating conditions. Modeling of accident scenarios in a pressurized water reactor (PWR) where cooling water is not re-introduced to the core after about 400 seconds shows that the zirconium-alloy cladding will exothermically burn in steam, particularly starting at about 1200°C, as shown in Figure 2 [2]. Once the steam/air exothermic oxidation initiates, destruction of the core is almost inevitable due to the large amount of exothermic chemical energy associated with zirconium-steam reaction. Additionally, hydrogen is produced as a by-product of this oxidation reaction and has the potential for igniting and causing further damage to containment. Oxidation resistance at normal operating temperatures (300°C to 320°C for PWRs and 250°C to 300°C for BWRs), was also deemed important as it improves cladding performance by way of reduced oxide layer thickness and hydriding of the cladding, thus increasing the

allowable fuel burn-up and improved economics [3]. However, in order to have a net benefit, the parasitic neutron absorption as a result of the coating must be kept to a minimum either by using coatings composed of low cross-section elements or by keeping the coating thicknesses at low values. Following a research program on different materials for coatings, chromium has been selected as the leading choice, as it meets the requirements of improved corrosion resistance in a wide range of temperatures without any significant neutron absorption penalty.

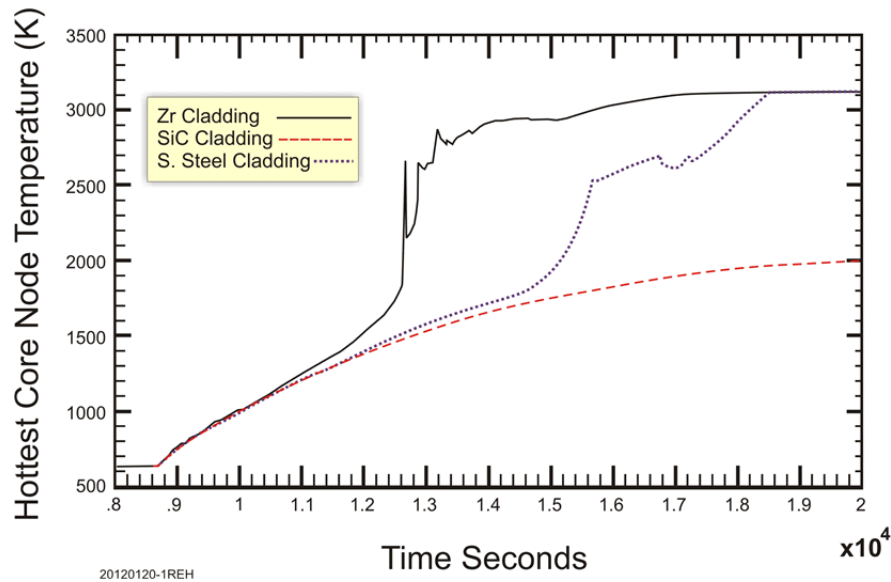


Figure 2. Modeling of beyond design basis accident core temperatures for long term loss of coolant

Applying an adherent coating to zirconium alloys is challenging since zirconium forms an adherent, dense native oxide layer on the surface. While this oxide layer provides zirconium with an effective corrosion resistant barrier in normal operation, it also makes it difficult to apply coatings that will remain adherent over a wide temperature range. Cold spray is a low temperature powder spray process which allows depositing metallic layers at room temperature and ambient conditions in a fast and economic way. Cold spray coating can be applied on variety of substrates including zirconium alloys and the deposition process disrupts the inherent oxide formed on the surface of the zirconium alloys, improving the adherence of the coating to the substrate. For these reasons, which considerably facilitate scalability, cold spray is the technology of choice for application of chromium coatings in Westinghouse ATF.

Coated Cladding Development

For the LTR program, oxidation resistant coatings are being applied on the outer surface of **Optimized ZIRLO** cladding tubes. The coating layer consists of a thin (20-30 microns) layer of chromium applied using cold spray. Cold spray is a solid-state coating method that deposits chromium particles onto the substrate by accelerating them to supersonic speeds using a carrier gas. The process facilitates scalability as it can be conducted in air, without melting the material to be applied. Parameters for cold spray such as powder type and size, carrier gas pressure and temperature, and application speed have been optimized to achieve dense and very adherent coatings. Details of the development have been reported in reference [4]. Uniform coating of full length tubes has been achieved by controlling rotational and axial translation of

the tubes relative to the cold spray nozzle. The process and condition of the tubes after coating are illustrated in 3.

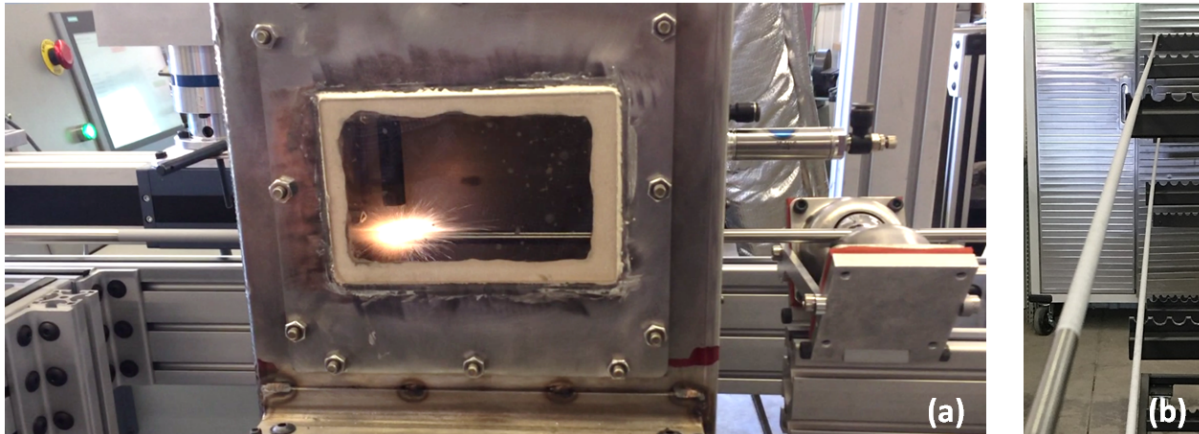


Figure 3 Cold spray coating of full length fuel cladding tubes. (a) Equipment for rotation and translation of tubes (axial translation occurs from right to left) and (b) condition of the tubes after coating

In order to achieve the final specified thickness and the same surface finish of current standard cladding, to enable seamless integration into the resident Westinghouse fuel without assembly design modifications, the coated tubes are polished. The coating process and the intermediate and final products are currently undergoing qualifications to meet the quality desired and required for the first insertion in a commercial reactor. Figure (a) shows the as-fabricated microstructure of the coating. The coating is completely dense without any observable porosity, while the interface between the chromium and the substrate illustrates the metallurgical bonding that produced a very strong adherence. This micrograph also illustrates the smooth outer surface of the coating after polishing.

Optimized coatings continue to be subjected to extensive testing simulating normal operation and accident conditions. Initial reports can be found in [4] and [5]. The test program includes corrosion in PWR conditions in static autoclaves and hydraulic loops, crud deposition, mechanical testing and high temperature corrosion in steam. Testing results have demonstrated that the coating does not affect the performance of the substrate mechanically and provides significant protection against corrosion in all conditions. The test program on coated cladding is being completed to satisfy the detailed Design Review process at Westinghouse.

Figure 4 (b) is an example of the results of high temperature steam oxidation testing of a tube, in this case on a coated tube before polishing (exposing more surface area of the coating), at 1200°C during 20 minutes, simulating a severe accident scenario. In this example both the inner and outer surface of the tube were exposed to oxidation, for comparison. The inner portion of the tube shows a thick zirconium oxide (over 100 microns thick) and the brittle oxygen-rich alpha layer stabilized at high temperature. Conversely, the coated outer surface of the tube shows only minimal oxidation, without any evidence of oxygen ingress into the substrate.

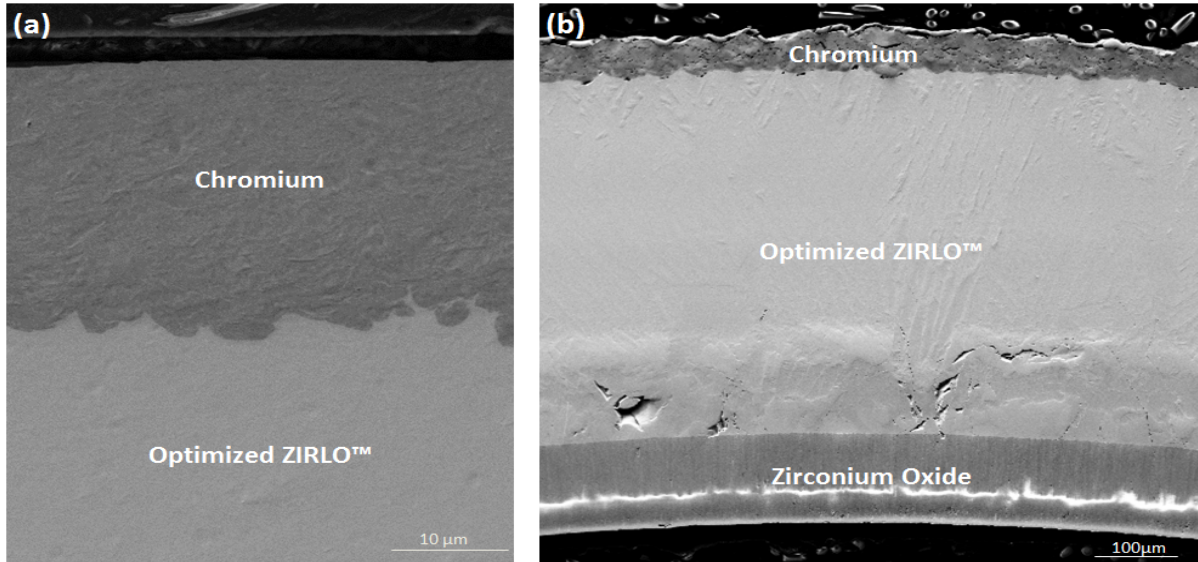


Figure 4 As-fabricated microstructure of cold spray chromium coating on Optimized ZIRLO cladding (a). Microstructure of cladding tube following oxidation in steam at 1200°C for 20 minutes

U₃Si₂ Pellet Development and Benefits as ATF

U₃Si₂ is an advanced high uranium density fuel form with improved thermophysical properties in comparison to the traditional UO₂ fuel form. The U₃Si₂ fuel provides a 17% increase in U²³⁵ density while remaining below the 5% U²³⁵ enrichment limit. In addition, it provides a 2 to 5 fold increase in thermal conductivity [6] which significantly increases the resistance of this fuel to centerline melt during power transient issues even though its melting point is 1665°C [7]. During accidents, it also significantly reduces the stored energy in the fuel and lowers the peak temperature during a loss of coolant accident (LOCA). The value of this fuel is about \$100/kgU. For a fuel plant producing 1500 metric tons U/year, this will result in added sales of ~\$150M/yr. The key properties of U₃Si₂ pellets are summarized below.

Key Properties of Westinghouse U₃Si₂ Fuel Pellet

Property	U ₃ Si ₂ Pellet
Melting Point (°C)	1665°C
Thermal Conductivity (W/m/K), at 600°C	15
Margin to Melt (°C) at 30 kW/ft.	885°C
Density (g/cm ³)	12.2
Water/Steam Reactivity	Low up to 300°C
Thermal neutron cross section in millibarns	Si 171 mb

Since 2017 Topfuel, Westinghouse and its partner Idaho National lab (INL) made good progress in optimizing the fabrication process of U₃Si₂ pellets, resulting in better yield and quality of the finished

pellets. To support the LTR, INL has commissioned a new production line with a new glovebox that is 3 times larger than previous one, and also installed a new tri-arc melter and new sintering furnace. The added capabilities significantly improved the production capability and quality control.

One of the weaknesses of U_3Si_2 fuel is water/steam corrosion resistance. When U_3Si_2 fuel is exposed to water and/or steam using the Thermogravimetric Analysis (TA) method and simulated autoclave tests at temperatures higher than 300 °C, it is oxidized faster than UO_2 and may result in higher fuel washout rate and/or larger pellet expansion as a result of oxidation [8,9]. To mitigate the fuel washout issue in unlikely events such as rod leaker, the U_3Si_2 fuel pellets will be placed in short segments so that the total amount of fuel subject to washout is significantly reduced. For the segmented rod design, the U_3Si_2 pellet OD is reduced to mitigate the pellet volumetric expansion due to oxidation in case of a leaker. In addition, the fuels stack length is also reduced to mitigate the amount of fuel washout. At the meantime, Westinghouse and its partners are actively conducting research and development to improve the corrosion resistance of U_3Si_2 fuel pellet and will employ the improved U_3Si_2 fuel form for future studies.

ADOPT Pellet

The Westinghouse **Advanced Doped Pellet Technology (ADOPT)** Development Program is based upon a standard UO_2 design containing additions of chromium and aluminium oxides and modified for high-density, reduced fission gas release in transient scenarios; better PCI performance; and improved secondary degradation behavior. The additives facilitate greater densification and diffusion during sintering, which result in a higher density and an enlarged grain size compared to undoped UO_2 . Whilst achieving the desired pellet properties, the amount of additives has been kept at a minimum in the **ADOPT** design. This has the benefit of reducing the amount of parasitic neutron absorption by the additives which especially chromium induces. The additives found to have the best overall effect were aluminum and chromium, alone or in different combinations [Figure 2, Ref 10]. These additives enable regulation of density and grain size in the pellets and provide enhanced resistance to degradation. See Figure 6 of reference 10 [10, 11,12]. It has also been shown through power ramp tests and bump tests that there is significantly less gas release from the **ADOPT** fuel during transients [13,14]. Demonstration fuel with **ADOPT** pellets have been irradiated in commercial LWR reactors in Europe to a rod average burnup of about 72 MWd/kgU.

High Density

A target density of 10.67 g/cm³ has been reached in full-scale reload fabrication.

PCI Performance

The additives and their effect on pellet microstructure make them considerably softer at high temperature, which is potentially beneficial for PCI performance [1]. Laboratory creep measurements have been performed to quantify the benefit. An increased density size is known to have a negative impact on PCI, but due to the higher creep, the overall effect is beneficial. This has been verified by power ramp testing of a segment with **ADOPT** pellets from the first lead fuel assembly rods that were discharged in 2002. The ramp test, performed in Studsvik, confirmed that **ADOPT** fuel pellets in combination with the Zr-Sn liner can sustain very high terminal powers without failure.

Fission Gas Release

Poolside gamma scanning of commercial rods has shown similar steady state gas release from both ADOPT and UO₂. A benefit of lower gas release from the larger grain ADOPT pellets has been observed during transients. [13,14]

Secondary Degradation

Tests on unirradiated pellets have shown that ADOPT pellets exhibit a smaller degradation in hot steam. The same effect may slow the onset of secondary degradation if a primary failure occurs. It is thought that the larger grain size and reduced porosity is beneficial in preventing fuel oxidation.

An in-reactor comparison has also been performed where short segments of both ADOPT and UO₂ fuel were irradiated in the Studsvik 2 reactor under conditions representative of those following a failure. The amount of fuel washout was measured and found to decrease with increased fuel density, and thus is more resistant to fuel washout relative to standard fuel.

Leading ADOPT Rods

The first ADOPT rods were inserted in 1999 followed by further test rods in 2000. As mentioned previously, some of the first rods have been discharged and segments have been successfully used in ramp and fission gas release (FGR) tests in the R2 reactor in Studsvik. The leading ADOPT rods have today reached a burnup of around 70 MWd/kgU. Thorough hot cell examinations performed at this burnup level have been used for updating the fuel performance code (STAV7) for modeling of ADOPT pellets at high burnup.

Over 2600 assemblies containing ADOPT fuel have been delivered. Detailed poolside measurements will carefully monitor their through-life performance as the irradiation proceeds. Currently ADOPT pelleting manufacturing capability is only in Vasteras, Sweden.

ADOPT High Burnup Verification Program

A program for high burnup data (> 70 MWd/kgU) is ongoing with a two-life program in a European BWR. The goal of the project is to verify the ADOPT pellets at very high burnup. Poolside FGR measurements have been performed at the start of the two-life program and additional measurements will be performed at end of life, including careful studies of the high burnup behavior of ADOPT pellets (hot cell examinations).

Summary

Chromium coating has been applied to Optimized ZIRLO™ tubes using optimized cold spray techniques. Chromium has been demonstrated to provide oxidation resistance in normal operation and LOCA conditions, and shows adequate mechanical performance under strain. Overall, tests results indicate that cold sprayed metallic coatings are a viable option for accident tolerant fuel towards insertion of lead test rods in the near future. Enriched U₃Si₂ pellets have significant benefits as ATF fuel. U₃Si₂ pellets are being fabricated at Idaho National Labs as part of the LTR program. ADOPT pellets have been

successfully irradiated in many reactors and with demonstrated benefits of higher density, PCI, Secondary degradation and lower fission gas release. Westinghouse-Exelon EnCore® LTR program will thus demonstrate integrated performance of three ATF features. The EnCore® LTR Accident Tolerant Fuel program, hence, paves the way to make safer nuclear fuel and with improved economics.

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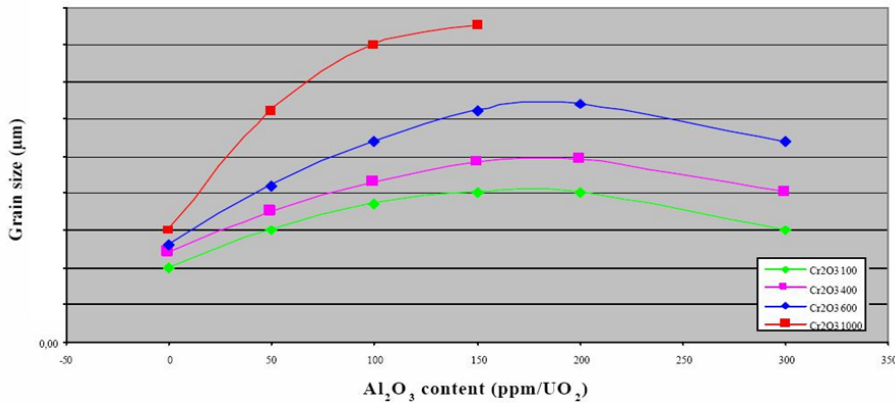


Figure 2. Grain size of ADOPT pellet as a function of alumina and chromia content.

From Ref 10

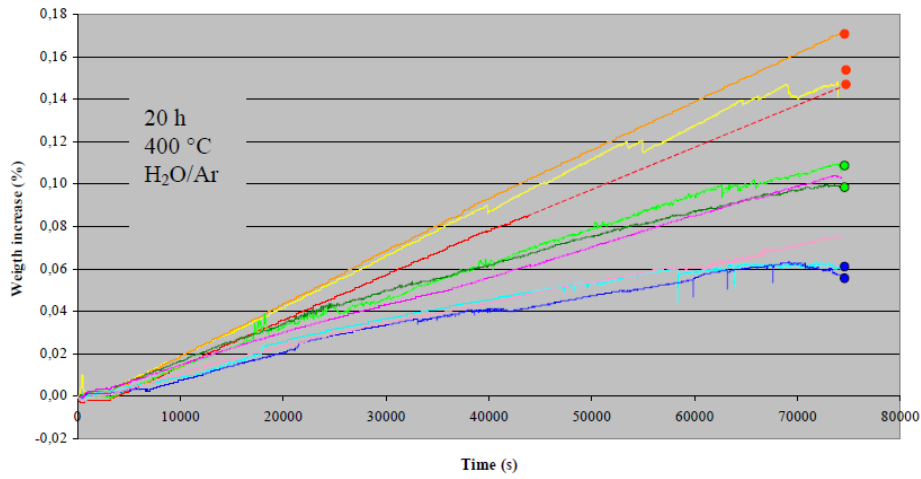


Figure 6. Weight gain in 400 °C steam, of doped and undoped pellets

From Ref 10