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FUEL CYCLE

FIFTY YEARS OF NUCLEAR FUEL QUALIFICATION AT SCK•CEN

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ABSTRACT

Nuclear fuel qualification implies a wide range of experimental and theoretical studies throughout the different stages of the generic fuel development and qualification process.
Throughout its history, the Belgian Nuclear Research Centre SCK•CEN has been involved in the wide variety of research topics required by the different qualification stages of nuclear fuels. Both UO_2 and MOX light water reactor (LWR) fuels have been addressed right from the start of the research centre. In the last decade, more elaborated research on research reactor (RR) fuel is being implemented as well. The paper provides an overview of the various fuel research and development efforts undertaken and key fuel behaviour phenomena assessed by the SCK•CEN within its fifty years of existence.

1. Introduction

Nuclear fuel Qualification encompasses experimental and theoretical research to generate data and descriptive codes that allow one to prove that a nuclear fuel system will function in a predictable, appropriate and safe manner in all anticipated service-life conditions. In the course of the half century lifetime of nuclear fuel, the nuclear fuel development and qualification has evolved into a four stage process [1]: a first exploratory phase that, starting from the envisaged fuel duties, narrows down the material and design choices towards the selection of a reference fuel concept; a second phase evaluates and improves the fuel concept to develop a fuel specification for a reference design; within a third phase data are generated on the reference design that support the licensing safety case for the reference design; the fourth and final phase generates the appropriate data that feed and validate the descriptive code such as to allow final qualification of the fuel for a specific application.
The comprehensive set of experimental test facilities present at the nuclear research centre of Belgium, SCK•CEN, was intensively used over the last 5 decades within all four phases of fuel development and qualification. For the irradiation tests, both the BR2 and BR3 reactors at the SCK•CEN site played a key role. BR3 was the first PWR in Western Europe and as such was a demonstration unit of an industrial power station. It served as a test reactor for prototype nuclear fuels and was an education centre for the operating staff of the nuclear power plants. BR3 achieved its first criticality on August 19, 1962. On October 25 of the same year, BR3 was connected to the electricity grid. On June 30, 1987, the BR3 reactor was the first PWR in Europe to be permanently shut down, and since 1989 its decommissioning serves as a dismantling pilot project within Europe. The BR2 reactor is designed in 1956-1957, constructed in 1957-1960, commissioned in 1961-1962 and has been operational as a multi-purpose material test reactor since 1963. Its core comprises ~ 80 channels that can be loaded in a flexible manner with the basic driver fuel or control rods, experiments or production facilities – fig 1. Base irradiations as well as transient condition testing of nuclear fuels were and are still performed in dedicated loops of the BR2.
The second essential asset with regard to nuclear fuel qualification is the hot laboratory infrastructure LHMA allowing post-irradiation examinations – fig 2. The infrastructure can accommodate all current fuel designs, from full-size industrial rods of nuclear power plants to experimental rodlets, as well as research reactor fuel plates. Moreover full-size rods can be refabricated into smaller rodlets to be submitted to dedicated irradiation tests into the BR2 core, e.g. to perform transient tests. The non-destructive analysis tools allow monitoring of

the general fuel behaviour indicators, i.e. the overall visual aspect, the dimensional stability, the clad integrity and corrosion resistance, the inner components condition, the power and rating and the fission gas release into the rod plenum. Detailed destructive and radiochemical analyses allow a more in-depth evaluation of the fuel behaviour indicators and an in-depth assessment of the fuel burnup, power and composition, as well as the various thermo-mechanical phenomena at play in order to feed and validate fuel performance codes.

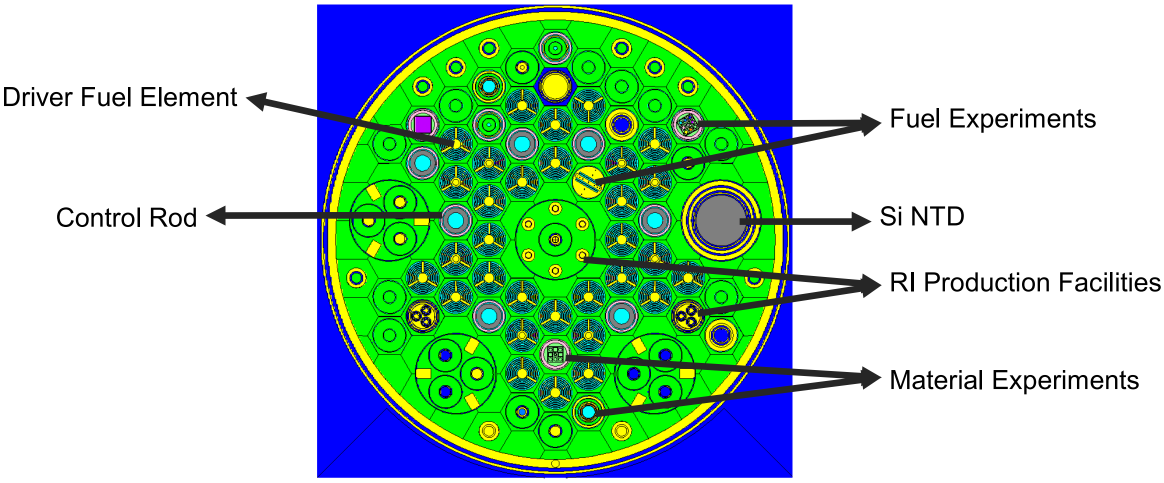

Fig 1. Mid-plane cross section of a typical BR2 core.

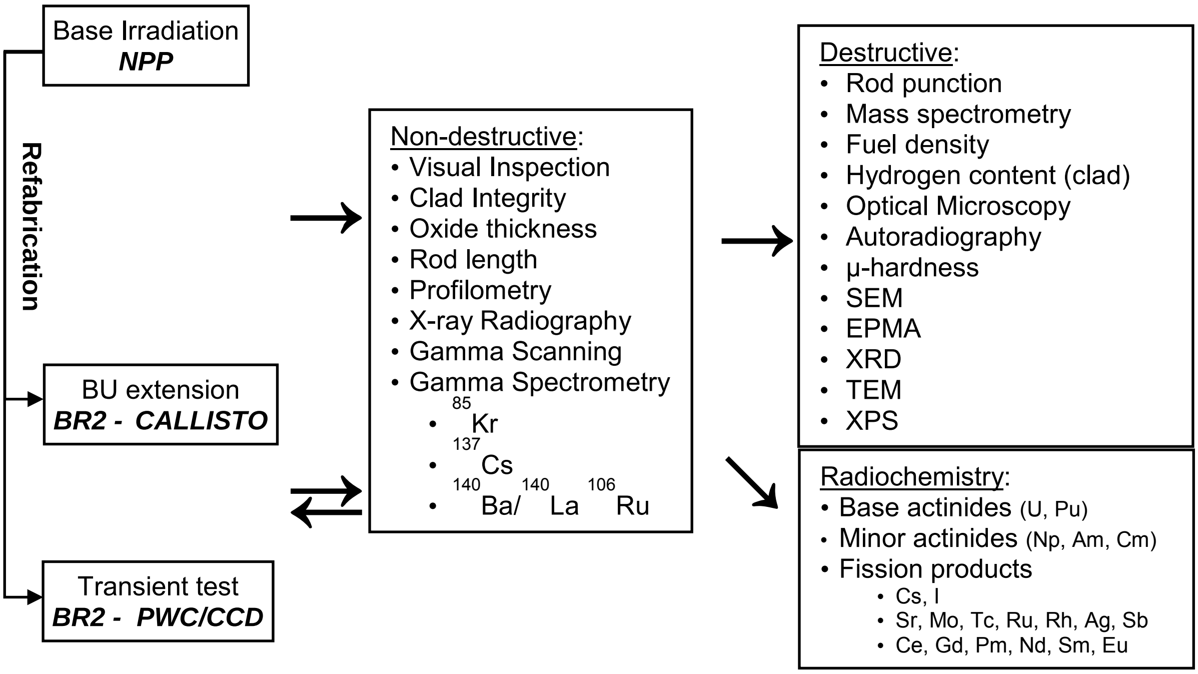

Fig 2. Fuel research infrastructure at SCK•CEN's hot laboratories.

2. Fuel qualification at SCK•CEN

Both LWR (light water reactor) and LMR (liquid metal reactor) reactor fuel qualification have been addressed right from the start of SCK•CEN. The qualification of common UO$_2$ fuel, the development and qualification of MOX fuel ((U,Pu)O$_2$ – Mixed Oxide Fuel) and the qualification of advanced zirconium based claddings are three main realizations in the LWR fuel area. In the last decades, SCK•CEN is engaged in more elaborate research reactor (RR) fuel qualification as well. Here the qualification of high density LEU fuel (Low Enriched Uranium, i.e. $^{235}U < 20\%$) for high performance research reactors worldwide, like BR2, is under realization.

2.1. LWR fuel development and qualification

LWR fuels perform in a high-temperature, high-pressure, high-irradiation environment for three to five years. The never ending motive for enhanced economy, operational flexibility, and excellent reliability places great demands on nuclear fuel and fuel assemblies.
SCK•CEN's LWR fuel research was initiated in the BR3 reactor of SCK•CEN where the fuels were irradiated under nominal PWR conditions. It included the study of generic fuel degradation mechanisms such as pellet clad mechanical interaction, clad creep, chemical evolution of the fuel with burnup, fission gas release etc. Also material-specific research such as clad optimization for utilization at elevated burnup, the study of gadolinia-doped fuel, studies on the effect of different UO_2 feed powders with respect to in-pile densification and swelling, were often for the first time studied in the BR3.
SCK•CEN's LWR fuel research was also oriented to the deployment of mixed $(U,Pu)O_2$ or MOX fuel in light water reactors. Although MOX fuel was initially intended to be exclusively used in Fast Breeder Reactors, some limited activities on its use in Light Water Reactors were conducted already as early as 1963. Until the mid-1980's the LWR MOX research remained limited, but with the decrease of R&D activities on Fast Breeder Reactor developments in the mid-1980's followed by a complete stop in 1991 of this research in Belgium, the research on MOX use in LWR's rapidly gained interest. SCK•CEN and BELGONUCLEAIRE conducted this research for both PWR's and BWR's. For PWR MOX, the own BR3 reactor served as main reactor until its closure in 1987 and for BWR's, the Dutch Dodewaard prototype reactor was mainly used.
Since the 1990's, fuel research uses fuel rods issued from industrial PWR and BWR reactors for base irradiation and Material Test reactors (BR2, HFR, OSIRIS or R2) for transient tests. Until today, the hot laboratories of SCK•CEN continue to contribute to the study of LWR fuel, not only for the study of experimental or prototype fuels, but also in the context of return-of-experience and failure analysis.
LWR fuel operating conditions continue to become more demanding with

- core operating cycle lengths in the 18-to-24-month range;
- discharge burnup levels in excess of 50 GWd/tHM;
- reactor upratings leading to higher core temperatures;
- modified reactor coolant chemistry such as elevated lithium levels within PWR's which can decrease margin to fuel corrosion limits.

A few of the key experimental programs that contributed to the evolution of LWR fuel as we know it today will be highlighted.

2.1.1. UO2 fuel programs

2.1.1.1. HBEP (1978-1990)

The principal purpose of the HBEP program was the study of fission gas release at elevated burnup, anticipating that the fission gas release could be enhanced by effects solely due to burnup-related fuel changes. While the influence of burnup on fission gas release thresholds is well-established today, this knowledge was not available at the time this program was initiated. The program contained two main experimental sections: a first objective was to provide fission gas release data on standard PWR and BWR fuel rods and a second objective was to study the impact of several variables (fill gas pressure, annular versus solid pellets, grain size) on the fission gas release.
For the first objective to be reached, a total of 45 standard fuel rods from three different fuel vendors were irradiated in four different reactors: two PWR's (BR3: 12 rods and Obrigheim:

21 short segments) and two BWR's (Würgassen: four short segments and Monticello: eight short segments). The burnup ranged between 30 GWd/tHM (typical EOL burnup for the considered period) and 55 GWd/tHM ("high burnup"). Of these 45 fuel rods, sixteen were selected for a so-called "power-bump", defined as a mild transient with the aim to enhance fission gas release. Twelve of the power transients were performed in the HFR (Petten, the Netherlands) and four in the R2 (Studsvik, Sweden). All fuel rods did undergo detailed post-irradiation investigations in various laboratories throughout Europe.

For the second objective, a total of 37 fuel rods, from six different fuel vendors were irradiated in two different reactors: one PWR (BR3: 28 rods) and one BWR (TVO: 9 rods). For each of the fabrication variables (such as grain size, fill gas pressure, annular pellet type), several fuel rods were manufactured and irradiated under slightly varying conditions. The burnup ranged typically between 50 and 70 GWd/tHM, with two rods containing annular pellets who were irradiated to "ultra-high" burnup of 80 GWd/tHM.

Although the HBEP program was not the only program that studied the possibility to extend the burnup from the range originally considered for light-water reactors (25-30 GWd/tHM) to burnup-levels well in excess of that range, it was the first attempt to create a broad data base comprising 82 fuel rods coming from seven different fuel manufacturers, base irradiated in four different power reactors, transient tested in two different test reactors and investigated in seven hot laboratories. In the period during which the HBEP program was running, the so-called "rim effect" was clearly established. The HBEP project does not claim to be the only program that identified this previously unknown irradiation induced effect which has its impact on fuel performance at elevated burnup, but the program made a major contribution to the role that the highly distorted peripheral zone of a fuel pellet has on non-thermal fission gas release.

2.1.1.2. TRIBULATION (1980-1990)

The TRIBULATION program was an international cooperation between fourteen partners (utilities, fuel vendors and research institutes) and aimed to study the impact of power transients on the post-transient fuel rod performance. The major scope of the project was to demonstrate the suitability for further irradiation of fuel rods after a class II transient. The particularity of the program was that it aimed to demonstrate this up to burnups of 70 GWd/tHM, i.e. well beyond the burnup which was at that time applied in PWR's (~35 GWd/tHM). It consisted of the irradiation of 48 fuel rods of similar design (i.e. PWR 17x17) and overall material choice (UO_2 fuel, zircaloy-4 clad), with various modifications in terms of cladding production (degree of cold work), UO_2 feed material (feed powder issued from the AUC, ADU and IDR routes, fuel rod pressurization level), fuel pellet design (solid pellets, annular pellets, pellet height, dish and chamfer design). The program mainly consisted of a burnup accumulation in the BR3 up to 40 GWd/tHM, transient testing in BR2 and further irradiation in the BR3 up to 70 GWd/tHM. After the base irradiation, after transient testing and at end-of-life, the fuel rods were extensively examined.

The program evidenced and quantified the impact of different options for the UO_2 pellet manufacturing, clad manufacturing and fuel rod design options on the susceptibility for Pellet-Clad Mechanical Interaction (PCMI) during class II transients. The success of the TRIBULATION test program is related to the fact that it complemented separate-effect tests for various design options in an integral test. The influence of the metallurgical state (degree of cold work) on irradiation assisted clad creep rate and rod growth was evidenced. Also the impact of fuel production parameters (feed material, additives and sintering characteristics) on the pellet densification and swelling rates was elucidated. Together with the geometrical design choices (gap size) and rod characteristics (initial fill gas pressure), they define the moment at which the fuel and cladding are in firm contact (from which moment on the fuel is "PCMI constrained").

2.1.1.3. GAP & GAIN (1983-1991)

Both programs GAP and GAIN were conducted to study Gd_2O_3-doped UO_2. At the moment of initiation of these programs, Gd_2O_3 doped fuel was already used in BWR reactors, and it was anticipated that for future implementation of increased cycle lengths (18 months) for PWR's or increased burnup limits, their use would be extended to the latter type of reactors as well to reduce power peaking and to limit the critical boron content at beginning of cycle. In Belgium, the transition to longer cycle lengths was indeed introduced from the mid 1990's. The GAP program studied the consumption of the ^{155}Gd and ^{157}Gd isotopes for different Gd concentrations. To this end, five Gd_2O_3 doped fuel rods with Gd content varying between 3% and 10% were irradiated in well-characterized fuel assemblies for one cycle in the BR3 reactor. In the post-irradiation program, the five Gd_2O_3 doped fuel rods and eighteen UO_2 rods were studied by non-destructive means and a selection of seven rods (the five doped fuel rods and two UO_2 rods) were destructively analysed. The main focus was the detailed radiochemical analysis and radial depletion profile of the absorbing isotopes of Gd. The results were used to reduce uncertainties in the burnup calculations and to benchmark neutronic codes with the aim to later exploit the use of burnable poisons in PWR's.

The GAIN program studied the effect of doping the UO_2 matrix with Gd_2O_3 on the thermal and mechanical properties of the fuel and to understand the behaviour of Gd_2O_3 doped fuel up to high burnup. Although Gd_2O_3 is physically compatible with UO_2 and forms a solid solution with the same fluoride structure at least in the range of concentrations relevant for its use in PWR reactors, it was known that upon doping, the thermal conductivity is reduced and the melting temperature is lowered. To maintain similar margins as for UO_2, some restrictions in the use of Gd_2O_3 doped fuel were anticipated at the moment of introduction of this project. Also densification and swelling behaviour is different for the doped fuel as compared to standard UO_2, and this has its impact on the timing of PCMI occurrence. To establish a broad data base that includes various fabrication process variants that might impact the fuel behaviour, a total of 26 Gd_2O_3 doped fuel rods, provided by five different fuel vendors, who each used its specific fuel manufacturing process were irradiated in the BR3 reactor. The burnup varied between 10 GWd/tHM up to 72 GWd/tHM. A selection of six fuel rods was transient tested in two different MTR's (BR2 and OSIRIS) to test the PCMI resistance under transient conditions (non-failure/failure threshold determination).

2.1.2. Dedicated MOX fuel programs

2.1.2.1. PRIMO (1986-2001) and DOMO (1987-1997)

Both programs studied the mechanical, thermal and neutronic properties of mixed uranium-plutonium dioxide (MOX) fuel under representative PWR (PRIMO) and BWR (DOMO) irradiation conditions. The main purpose of both projects was to gather the necessary information to permit licensing of MOX fuels in PWR/BWR reactors by demonstrating the ability of MOX fuel to sustain irradiation conditions comparable to uranium dioxide fuel. As secondary objective, fabrication variables in the MOX production route were tested to understand the influence of the fabrication process on the MOX fuel behaviour. In the PRIMO program, both direct blending of PuO_2 and UO_2 (also called "reference MOX" in the jargon used at that time) and the two-step process (MIcronized MASter blend or MIMAS process) were compared. In the DOMO program, the MIMAS process and a process based on intensive co-milling of a co-precipitated $(U,Pu)O_x$ with UO_2 powder were compared. A third objective common to both projects was to obtain data packages that allow to benchmark neutronic codes for MOX assemblies.

In the PRIMO program, 16 MOX fuel rods were investigated. The fuel was provided by three fuel developers with two major variants (MIMAS and direct blending) and for the MIMAS variant, three different designs were compared. The fuel rods were base irradiated in the BR3 (15 rods) and Saint-Laurent (one rod) reactors up to a burnup between

20 and 60 GWd/tHM (BR3 irradiation) and up to 27 GWd/tHM (Saint-Laurent irradiation). The PRIMO program was an all-MOX program in the sense that it did not contain sibling UO_2 rods. A selection of these rods was transient tested in various test reactors: BR2 (1 rod), OSIRIS (5 rods) and R2 (2 rods). The transient tests were performed with different amplitudes and power excursion rates with the aim to test the resistance to PCMI of MOX fuel and to study the thermal behaviour in the context of fission gas release. The transient conditions were chosen in order to allow comparison of the results obtained on MOX with results obtained for UO_2 (from earlier programs). The post-irradiation examinations were performed in five laboratories.

In the DOMO program, 60 experimental fuel rod segments of reduced length and assembled into 15 fuel rods of standard length were irradiated in the Dodewaard BWR reactor (core height = 2m) to various burnup levels in three campaigns (nominal burnup values were 20, 40 and 60 GWd/tHM). After each campaign, a selected number of segments were unloaded and investigated in various hot laboratories throughout Europe. Each campaign also included step-wise transient tests in the BR2 material test reactor (9 tests in total) up to high linear rating (>600W/cm) to approach the non-failure/failure threshold. The post-irradiation program was conducted in two laboratories.

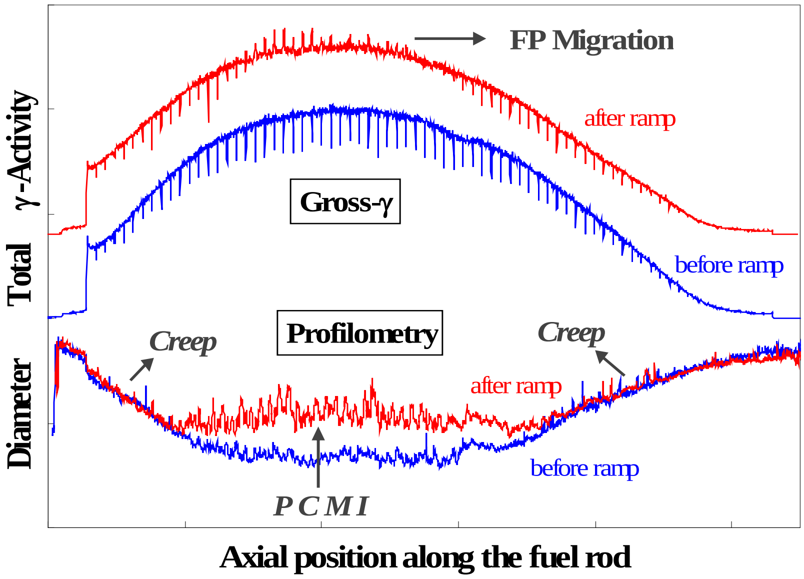

Fig 3. Non-destructive examination of nuclear fuel rod before and after transient test exhibiting two fuel performance key issues.

- Top curves: total gamma activity scan:
  - before the transient test, the fuel pellets can be individually counted as pellet-pellet interfaces have lower activity;
  - after the transient test, volatile fission products are released from the fuel matrix resulting in radio-active ^{137}Cs condensates in the colder pellet-pellet interfaces.
- Bottom curves: fuel rod diameter evolution.
  - before the transient test the cladding is fully collapsed onto the fuel in the central part of the fuel rod;
  - after transient test, the cladding is pushed outward due to the combined effect of thermal expansion of the fuel and gaseous swelling (bubble formation);
  - the Pellet-Cladding Mechanical Interaction PCMI can in some cases cause cladding failure.

Both PRIMO and DOMO programs were conducted for licensing purposes. The thermal and mechanical behaviour of MOX fuel is in general terms similar to the behaviour of UO_2 fuel:

almost identical densification & swelling behaviour, a higher centreline temperature in MOX fuel due to the combined effect of a flatter radial power profile and lower thermal conductivity. This leads to a slightly higher thermal fission gas release in MOX versus UO_2 at comparable linear ratings, but such effects were demonstrated to be well-predicted by the fuel performance codes and neutronic . A particular and unexpected finding was the excellent resistance of MOX fuel to PCMI

2.1.2.2. GERONIMO (1997-2005) and TOP-GUN (2000-2005)

The GERONIMO program was initiated in 1997 to study MOX fuel irradiated in commercial nuclear power plants. The purpose of the program was to investigate thermal and mechanical behaviour of MOX fuel at high and very high burnup (between 50 and 70 GWd/tHM) under steady state and fast transient conditions and to construct a neutronic dataset relevant for 9x9 BWR fuel bundles. To this end, twelve full length fuel rods and fourteen short segments were extracted from fuel assemblies irradiated in the German BWR plants GUN C and GUN B, transported to the SCK•CEN for post-irradiation examination and transient testing in the BR2 reactor (three transient tests). The transient tests were primarily oriented to investigate fission gas release and pellet swelling under fast transient conditions but remaining below the PCMI failure threshold. The neutronic data set consisted of radiochemical analysis of a number of samples covering different power ratings and burnups and a systematic gamma scanning of a large number of fuel rods from the assemblies from which the rods were extracted and from adjacent fuel assemblies. The latter examinations were performed by pool side inspections at the power plant. The MOX fuels were all of the same design (MIMAS type), and were of prototypical enrichment for the design of 9x9 BWR MOX fuel assemblies. The specific assembly design included six different Pu enrichments, varying between 1.15% and 5.52 % $Pu_{fissile}$ and for the program, one set of fuel rods with an enrichment of 2.6% $Pu_{fissile}$ and a set with an enrichment of 5.5% $Pu_{fissile}$ were selected.

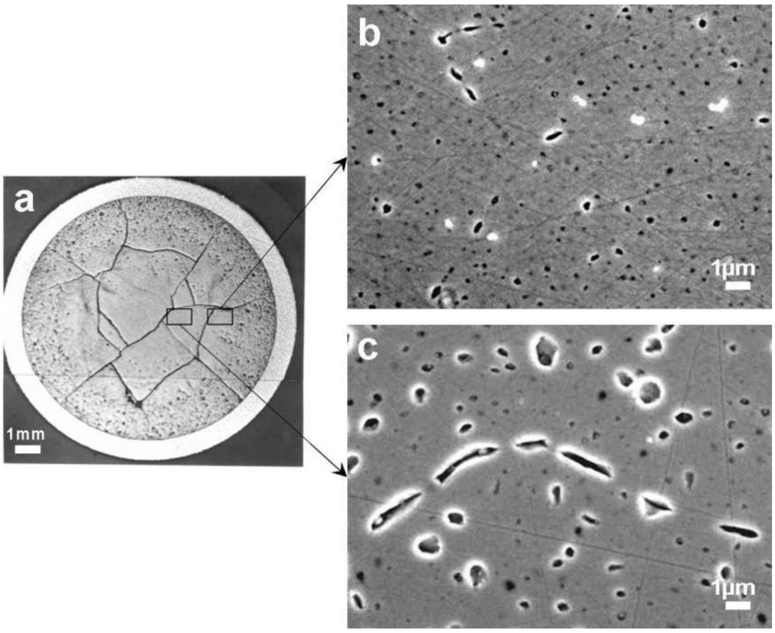

Fig 4. Fuel rod cross section after a mild transient: (a) macroscopic view showing the typical crack pattern of irradiated nuclear fuel with six radial cracks and one circumferential crack which is typical for fuel having sustained elevated linear rating; in the colder peripheral zones (b), small fission gas bubbles are observed; more towards the centre (c), the fission gas bubbles are larger.

The TOPGUN project aimed to study MOX at ultra-high burnup (up to 80 GWd/tHM), also using fuel rods irradiated in commercial nuclear power plants. The selected fuel rods were fabricated by the same manufacturer and the same process and the rods were extracted from fuel assemblies of the same BWR power plant as for the GERONIMO project. The TOPGUN project is considered as a complement to the GERONIMO program, with the exception that the focus of the TOPGUN program lies on the fuel rod thermal and mechanical behaviour under nominal operating conditions only and the neutronic dataset at ultra-high burnup.

The essential findings from the programs was that there are no specific phenomena appearing at these very high burnups, which are substantially above the range applied today or in the foreseeable future in Light Water Reactors. Within the expected behaviour, but for the first time also quantitatively assessed, was the fact that there is a substantially higher release fraction of He to the free volume as compared to the fission gases Xe and Kr. The GERONIMO and TOPGUN programs for the first time measured thermal conductivity of MOX fuels at ultra-high burnup and the findings seemed to indicate that the thermal conductivity degradation is less than what could be expected from extrapolation of values obtained at lower burnup. Given the experimental uncertainties, the latter measurements are to be confirmed

2.2. RR fuel development and qualification

Since the 1970's, proliferation concerns have led the global nuclear community to invest in the minimization of Highly Enriched Uranium (HEU) in the civil circuit. Historically, all uranium enriched above 20% ^{235}U is considered HEU, while below that threshold it is called Low Enriched Uranium (LEU). The main civil uses of HEU (enrichment >90% ^{235}U) are as fuel for many research reactors and as base material for irradiation targets in the production of radioisotopes for medical applications. In both fields therefore, alternative materials needed to be developed to permit HEU-LEU conversion of fuels and targets, while allowing users to continue their operations without severe losses in performance or increase in costs.

Research reactor fuels, certainly for the western high performance research reactors such as the Belgian BR2 reactor mentioned before in this paper, typically consist of plates of only <1.5 mm thick, containing a dispersion of grains of an HEU compound (typically UAl_x with $x \approx 3$) in a pure Al matrix. This 'meat' is sandwiched by hot rolling in between an Al alloy cladding (Fig. 5). Typical loadings used are ~1.3 g_U/cc. These plates are curved in many reactors and several are put together to form a fuel assembly. Power levels reached are typically 300-600 W/cm² and burnups go to 50% ^{235}U plate average, with peaks to 80% ^{235}U at the maximum flux plane.

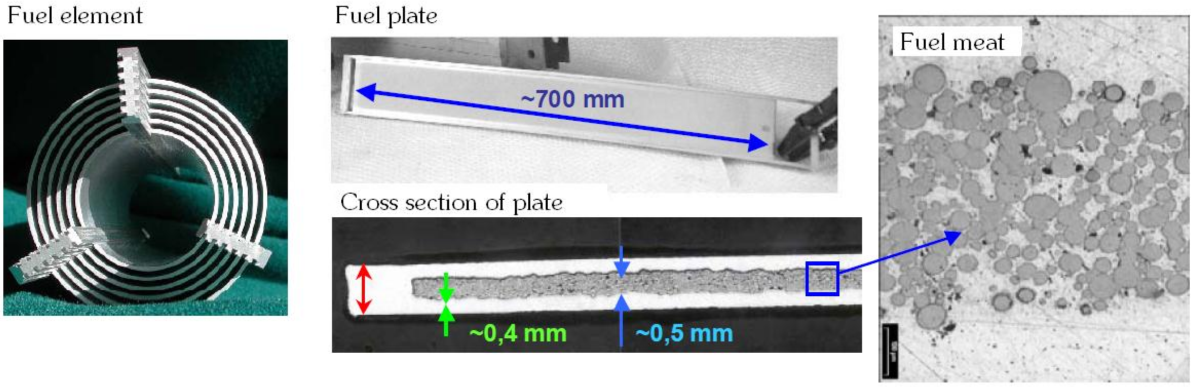

Fig 5. Dispersion fuel plates consist of a mixture of fuel grains in an Al based matrix (right image). This mixture is sandwiched between 2 Al alloy cladding plates, which creates a fuel plate (middle images). Several fuel plates, sometimes curved, are combined to form a fuel assembly (left image).

Research and development of a uranium compound to replace the high enriched UAl_x grains by a low enriched alternative have led to 2 main development paths: U_3Si_2 and U-7w%Mo alloy. Because the maximum loadings at which these compounds could be introduced in the Al matrix by existing fuel production technologies were $4.8g_U$/cc and $8g_U$/cc respectively, the former would not allow the increased uranium loading (×3.7) to compensate fully for the reduced enrichment (÷5). The latter fuel would be able to accomplish that, even though the Mo in the alloy is a neutron absorber and as such reduces the reactivity of this fuel a little.

It is clear that, as an operator of a powerful research reactor fuelled with HEU fuel and a supporter of non-proliferation, SCK•CEN is active in the development and qualification of LEU alternatives for its own reactor and others in the world. This activity has increased markedly in the last 10 years, mainly related to the development of U(Mo) as an LEU fuel for the high performance research reactors and to the need for fuel qualification for the Jules Horowitz Reactor project of CEA. A large number of irradiation experiments and post-irradiation examinations in different frameworks were performed at the BR2 reactor and the LHMA hotlab over the last 10 years.

These programs also provided a critical mass for the research reactor fuel R&D at the LHMA hotlab, allowing development of dedicated tools for the measurement of plate fuels where before adaptations of the existing tools, which are dedicated to fuel pins, were used. The Bench fOr Non-destructive Analyses of Plate- and Rod-Type fuel Elements (BONAPARTE) was developed and built at SCK•CEN, providing a specialized measurement bench to assess the plate thickness and oxide thickness variation across plate surfaces. The bench is capable of measuring both flat and curved fuel plates and allows unique datasets on the fuel behaviour to be generated. The coupling of all available data to accurate positioning on the plate provides for a wealth of data for fuel performance modelling.

2.2.1. Uranium silicide (U_3Si_2) dispersion fuel

Silicide fuels were qualified mainly with the intent to convert the low and medium power reactors, which strictly did not require the high density fuels to reach their performance with LEU fuel. The qualification of the silicide fuel, up to a loading of $4.8g_U$/cc, was accomplished with the NUREG-1313 document issued by US-NRC in 1988 [2]. From then on, a large number of research reactors were converted using that fuel type, leaving only the most powerful ones functioning with HEU because their performance parameters did not allow conversion to LEU with a fuel at $4.8g_U$/cc. Nevertheless, the silicide fuel was further developed, not in the least as a possible startup fuel for the Jules Horowitz Reactor (JHR) under construction in CEA Cadarache, France. In the frame of that requirement, several irradiation experiments were performed at SCK•CEN, using the mixed element approach and eventually even using a dedicated loop in the BR2 reactor. A standard BR2 element consists of 6 concentric tubes, each built up out of 3 curved plates swaged together in a stiffener frame. In a mixed element, the outer shell is replaced by 3 plates of the fuel that requires testing.

The mixed element silicide irradiations and their associated PIEs were published in open literature [3, 4]. In one experiment in 2002-2004 [3], the plates were insufficiently cooled to dissipate the high power, which led to general corrosion of the cladding and, even though the irradiation had to be stopped prematurely, to very interesting information on the off-normal behaviour of the silicide fuel. As it turns out, even in such conditions of steam ingress in the meat of the fuel, the U_3Si_2 fuel grains did not present any major problems. In the high power-high burnup conditions reached in the second irradiation campaign (2006-2008), the stable and predictable behaviour of the silicide fuel under these circumstances was demonstrated [4]. The fuel was irradiated at peak heat fluxes (beginning of life) of over 400 W/cm^2 up to a peak burnup of >80% ^{235}U (55% plate average). The post-irradiation examinations, including non-destructive measurements of the plate swelling, the oxide growth and the gamma spectrometry, as well as destructive microstructural work with optical and electron microscopy and spectroscopy are crucial for feeding the modelling of fuel behaviour in dedicated computer codes.

Eventually, this work evolved into a fuel assembly qualification program using a dedicated loop in the BR2 reactor, called the Enhanced Velocity Irradiation Test Apparatus (EVITA) loop. The loop can accurately replicate JHR operating conditions (specifically cooling water speed and element power) and accommodates JHR assemblies in true geometry. Several of these JHR assemblies were irradiated and examined over the last years and the PIE feedback has already led to improvements in the assembly design. The examinations include assessment of fuel assembly geometric evolution as well as the confirmation of the stable fuel plate behaviour. At the microscopic level, the destructive PIE demonstrates the operational margins of the silicide fuel under prototypic JHR irradiation conditions.

2.2.2. Uranium-molybdenum alloy (U-7w%Mo) dispersion fuel

The uranium-molybdenum alloy fuel was used in the past as a fast reactor fuel candidate [5] and, because of its stable irradiation behaviour at low temperatures, was demonstrated to be a good candidate for high density dispersion fuels [6]. After promising screening irradiation experiments in subsize plates [7, 8, 9, 10], full size dispersion fuel plates consisting of atomized U-7w%Mo fuel in a pure Al matrix were built and irradiated. A first relatively high power experiment, called the FUTURE test, was performed at the BR2 reactor and revealed pernicious swelling effects in the fuel plates [11, 12]. Simultaneously, other experiments confirmed the excessive plate swelling observed in that experiment [13, 14, 15, 16]. It was revealed through extensive PIE work at SCK•CEN that the main cause for the poor plate performance could be traced back to the interaction between the U(Mo) particles and their surrounding matrix. When these amorphous interaction layers (ILs) grew too thick and almost all Al matrix was consumed, large crescent shaped voids developed at the interface between the IL and the remaining matrix, which eventually led to the pillowing of the plate (development of blisters on both sides of the plate) as shown in Fig. 6.

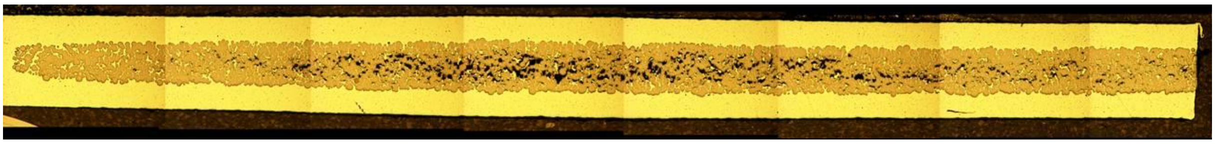

Fig 6. Optical micrographs showing the development of voids, leading to excessive swelling as observed in the FUTURE U(Mo)-Al dispersion fuel plates.

While the research reactor fuel community was investigating possible solutions to this phenomenon, SCK•CEN extended the PIE on the FUTURE fuel to transmission electron microscopy (TEM) work, demonstrating the amorphous nature of the IL and the unique behaviour of Xe fission gas in the U(Mo) kernels [17, 18]. Later on confirmed by others [19], the fission gas was shown to organize itself in a superlattice of nanometer sized bubbles, evenly spaced with a symmetry grafted on the U(Mo) crystal lattice. Technologically, this allows for storage of large amounts of gas in the U(Mo) in a very stable way and provides a mechanism by which the crescent voids may get filled with gas.

Based on historical data and more detailed observations of fuel behaviour in the screening experiments, a solution to the fuel-matrix interaction phenomenon was proposed by the international community: addition of Si to the Al matrix [20]. Some of the basis for that solution was also provided by SCK•CEN in examinations of old BR1 fuel [21], described in the next section. Microstructural PIE examinations at SCK•CEN on the French low power irradiation tests (IRIS-3 and IRIS-TUM) clearly demonstrated the beneficial effect of Si and showed that local higher concentrations of Si on the kernel-matrix interfaces sometimes suppressed the IL formation entirely or at least severely reduced it [22, 23, 24, 25, 26]. At other locations in the fuel, still relatively extensive IL formations were observed. Nevertheless, high power tests were needed to conclude on the success of the Si solution and a fuel qualification program was initiated in Europe (LEONIDAS initiative associating SCK•CEN, CEA, ILL and CERCA and supported by the US-DOE) [27, 28].

The first irradiation of LEONIDAS, called E-FUTURE, was a selection irradiation in which 4 different full size, flat U(Mo)-Al(Si) dispersion fuel plates were manufactured, irradiated and examined [29]. Different Si contents (4 and 6%) and heat treatments were tested simultaneously. Unfortunately, all fuel plates developed pillowing during the last of their 3 irradiation cycles, although clear indications for the beneficial effect of Si were once again observed, in the non-destructive analyses as well as in the microstructure analyses. The non-destructive results obtained on these plates with the BONAPARTE bench showed the superb capabilities of the correlated measurements, providing fuel and plate swelling data at an unprecedented level of detail (see Fig. 7) [30, 31].

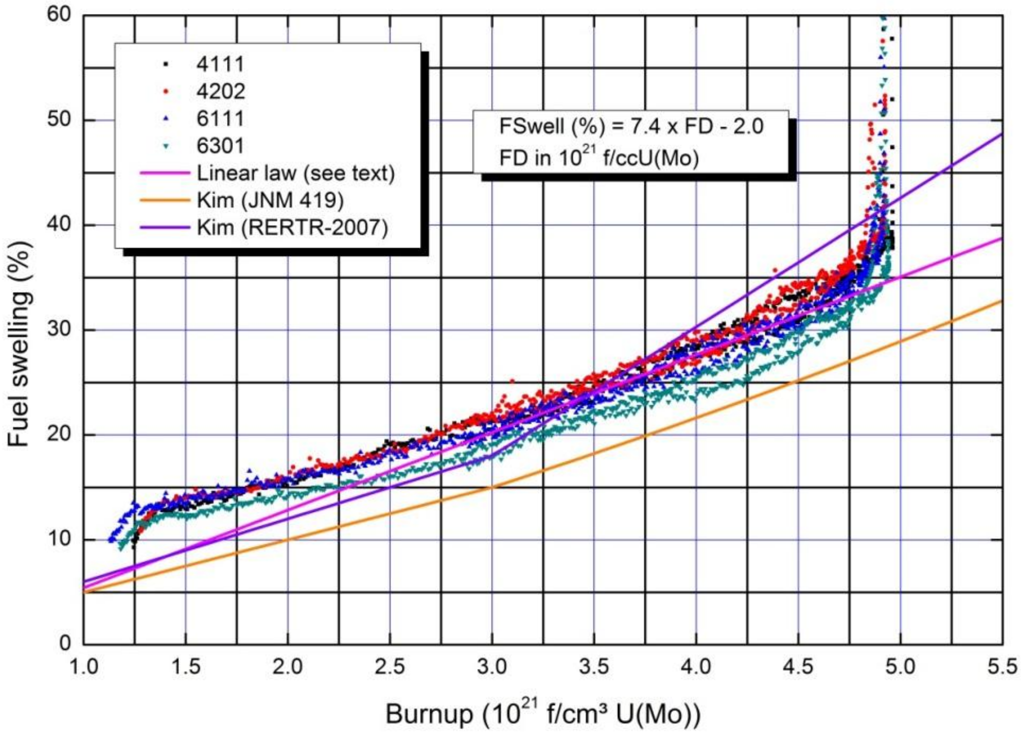

Fig 7. Comparison of the U(Mo) irradiation swelling measured in the E-FUTURE fuel plates and literature fuel swelling laws as given in [33] and [34]. Also shown is the linear relationship developed on basis of the data points between 2.5-4.5×10^{21} f/cm³ U(Mo) burnup generated in the studies of the E-FUTURE plates with the BONAPARTE bench.

The spectroscopic microanalyses [32] identified once more the excessive IL formation, by athermal mechanisms due to the low irradiation temperature of the fuel, as the culprit for the poor irradiation behaviour. The IL formation pushes out fission products ejected from the fuel kernel and sweeps them together, forming a weakened interface with the matrix, mechanically reducing the plate strength and eventually leading to pillowing. The results also clearly showed the association of local thin ILs on fuel kernels and local higher Si concentrations on those surfaces and vice versa of thick IL and low Si contents.

It were the latter observations that triggered SCK•CEN to invest in a more fundamental fuel development program. Keeping in mind that the athermal fission fragment recoil cascades and energy losses are responsible for the formation of the IL, rather than temperature driven diffusion, and that locally higher Si contents on the fuel kernel surfaces effectively suppressed IL formation, the concept of fuel kernel coating was developed as an alternative solution to the fuel-matrix interaction issues. Surrounding the fuel particles with a Si layer avoided the need for the Si to migrate (thermally during plate production or athermally in pile) to the kernel surface from the matrix and effectively concentrates the Si where it is required. Alternatively, coating the U(Mo) particles with an interdiffusion barrier (ZrN was chosen), would keep the recoiling U and Al atoms apart and therefore also inhibit IL formation by suppressing its athermal formation mechanism. In the framework of the Surface Engineering of Low ENrIched Uranium-Molybdenum (SELENIUM) fuel project [35, 36, 37], SCK•CEN, in association with the University of Ghent, developed a powder coater based on PVD magnetron sputtering setup to coat the particles and produced full size flat fuel plates for irradiation [38]. These fuel plates are currently undergoing irradiation in the BR2 reactor in conditions similar to the E-FUTURE experiment [39]. At the moment, the SELENIUM plates have at least behaved as good as the E-FUTURE plates and have completed their 3 irradiation cycles successfully without fission product release. Very recently, visual inspections under water have not shown any clearly present anomalies on the plates which could indicate pillowing has occurred. From March 2013, post-irradiation examinations on these plates will start in the hot cells of LHMA.

Based on the information on the positive effect of Si gathered in the E-FUTURE test, the LEONIDAS initiative and US-DOE decided to launch a second E-FUTURE type test based on the Al-Si matrix solution. The EFUTURE-II irradiation was aimed at testing higher Si contents (7-12%) and introducing the Si in the matrix in the form of an alloy, which created a finer dispersion of the Si particles [40]. Although E-FUTURE II was irradiated under very similar conditions to E-FUTURE and SELENIUM, it showed a markedly different behaviour, with 2 plates buckling after one cycle and 2 others after the second cycle. No such buckling was ever observed before and causes are under investigation. All the E-FUTURE II and the SELENIUM plates are scheduled to undergo non-destructive and destructive PIE in 2013.

2.2.3. Underlying research for the RR fuel community

Besides the irradiations and PIE campaigns in the frame of the fuel development, the availability of spent research reactor fuel at SCK•CEN has triggered several scientific and technological investigations that have supported and oriented the research reactor fuel community over the last 15 years. Particularly, the fuel of the BR1 reactor, even though it is very different in concept from the plate fuels of the BR2, has been instrumental in supporting the LEU dispersion fuel development. BR1 fuel consists of pure Al cans in which slugs of natural uranium metal were inserted. The metal slugs were bonded to the Al cladding by a molten Al-Si eutectic during fabrication. After 50 years in the BR1 reactor at low temperature and low fission rate, this is a very effective long term diffusion experiment demonstrating the effect of Si on the U-Al interdiffusion. Microstructural analyses of irradiated BR1 slugs [41, 21] have shown the effectiveness of Si in suppressing the U-Al interaction and the preference of U for Si rather than Al. This was backed up by measurements of the activation energies for reaction between U and Si, compared to reaction between U and Al [42].

On the other hand, an unfortunate incident in 1976 caused a flow channel blockage in a fuel element in the BR2 reactor, causing part of the element to melt. Such events are not entirely uncommon in the research reactor environment, but they are seldom investigated further because most research reactors do not have hot cells available for examinations. In this case, the partially molten fuel plate was brought into the hot cell and examined. A set of detailed microstructural analyses, investigating the propagation of the temperature regimes and deterioration mechanisms, was performed and reported in open literature [43]

3. Conclusion

The present review covers a few aspects of a three-decade timespan of LWR nuclear fuel research to which SCK•CEN contributed. The emphasis of this review lies on the research efforts conducted to improve the understanding of LWR fuel under standard operational conditions (i.e. normal operation and incidents of low and moderate frequency) and with the aim to use the results in a licensing context. The latter objective directly has the consequence that the results should be statistically relevant, which means that a relatively large number of fuel rods need to be studied. The experimental programs therefore are always conducted in a truly international context and for all programs, several reactors were used and many hot laboratories.

One notices that in the early days, fuel performance programs included huge design variables (annular pellet versus solid pellet), the effect of which was still to be understood. The later programs start from well-established designs for which the behaviour was rather to be confirmed than understood. The major issues, however, remained unchanged: the thermal behaviour of nuclear fuel remains a topic of research since it governs both the release of fission gas and the solid swelling of fuel and the resistance to failure due to pellet-clad mechanical interaction. Both aspects have their impact on the operational flexibility of the plant operator and thus have an obvious economic impact.

Contrary to LWR nuclear fuels, where the heat production is the prime functionality, research reactor fuels are meant to produce high neutron fluxes. The therefore required high fission densities give rise to fuel designs that focus on high fissile material densities that can accommodate the concurrent high heat fluxes and high fission products accumulations. Hence thin fuel plates composed of fissile material bearing compounds in intimate contact with high heat conducting materials that are assembled into elements optimized for coolability are being developed. The major issues in this fuel configuration are related to the interaction between these components, the phenomena associated with the accomodation of the large amounts of (gaseous) fission products being formed, and the efficient evacuation of the high heat fluxes, e.g. preventing elevated temperatures that induce fission product migration and high (corrosive) clad temperatures. The fine-tuning of the present high-density LEU RR fuel design focuses on fabrication measures that cope with these issues.

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PLENARY SESSION:

ISSUES & CHALLENGES FOR THE FUTURE OF NUCLEAR

THE SYSTEM COSTS OF DIFFERENT POWER GENERATION TECHNOLOGIES: A NEW LOOK AT THE COMPETITIVENESS OF NUCLEAR POWER

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Abstract

The advent of significant amounts of intermittent renewables such as wind and solar, highlight the fact that the often-quoted plant level costs are only a subset of the overall costs to the electricity system of a given technology. Costs at the system level include the costs for grid reinforcement, extension and connection, the costs for short-term balancing and long-term adequacy of capacity. This paper, which is based on a recent NEA report, provides clear conceptual definitions of system costs, a survey of the system effects of nuclear energy, an assessment of the ability of nuclear power to provide flexible back-up in the presence of intermittency, and, most importantly, the first systematic empirical assessment of the system costs of different technologies. It identifies and quantifies the very significant differences in system costs between nuclear and renewable technologies, which it advocates should be made more transparent to policy makers. The paper provides a new and comprehensive look at the role and competitiveness of nuclear power in the light of the new realities of power markets in OECD countries.

1. The Competitiveness of Nuclear Power

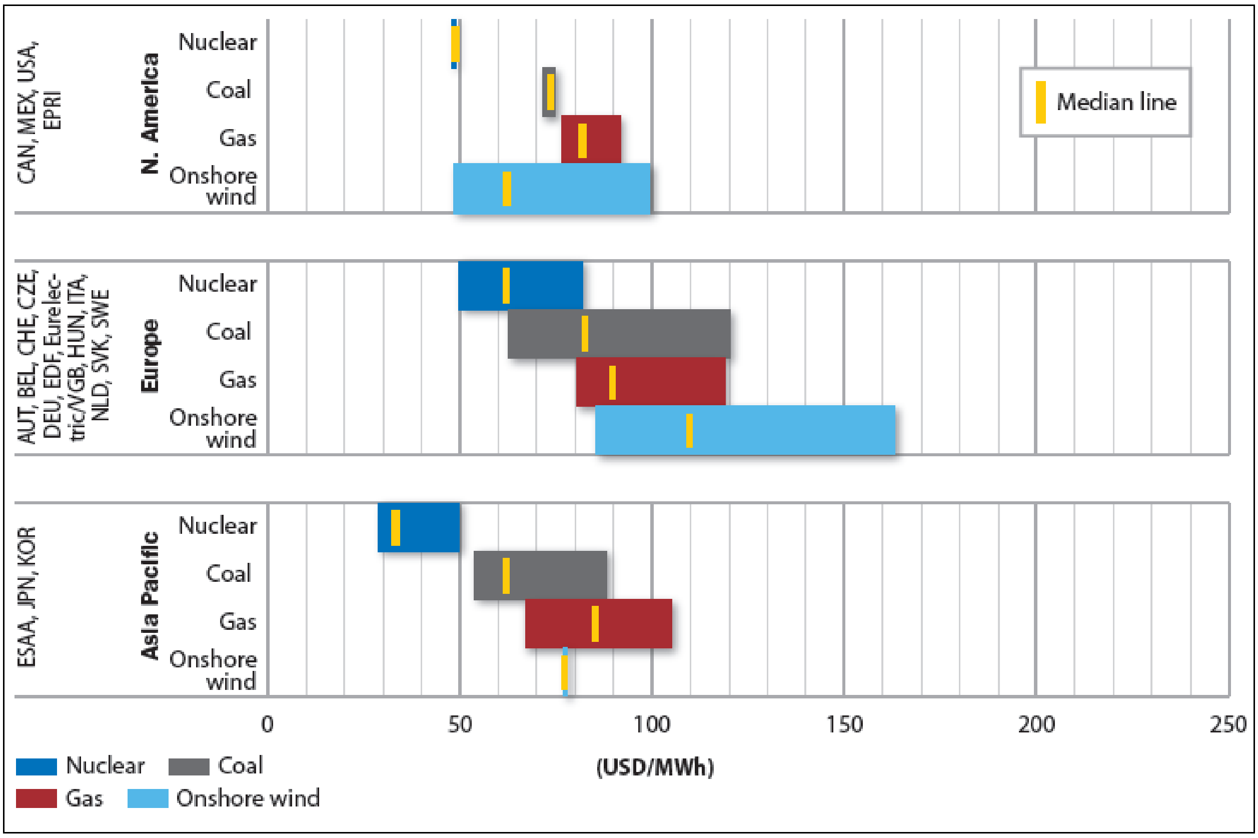
Nuclear power has advantages in an energy system because of its contributions to security of supply [1], to reduction of greenhouse gas emissions [2] and in providing stable electricity prices over the long period of operation. However, in liberalised markets, financing of nuclear is a challenge as investors lack the guarantees on long term returns, essential to the financial case for building new nuclear.

As a result, few nuclear power plants are being built in liberalised markets and those which are, or might be, have needed innovative financing schemes e.g. the cooperative model in Finland, the Build-Own-Operate model in Turkey and the concept of a ‘strike price’ with contracts for difference being proposed in the UK. Project financing from banks or the market seems unlikely, but there is some move to equity partnerships between utilities and vendors. Recent experiences in France and Finland with ‘first-of-a-kind’ reactors have increased the concern over financing and the risk exposures of investors.

However, despite these issues, the projected costs of nuclear over a 60 year lifetime indicate that it remains a sound financial proposition if a long term view is taken. For example, Figure 1, shows the Levelised Cost of Electricity for nuclear in comparison to coal, gas and renewable energies taken from the IEA/NEA study [3].

A further issue that complicates the situation for investors is the introduction of larger shares of intermittent renewable energies, using feed-in tariffs, with long periods of price guarantees.

Figure 1: Levelised Cost of Electricity for power plants to be constructed before 2015.



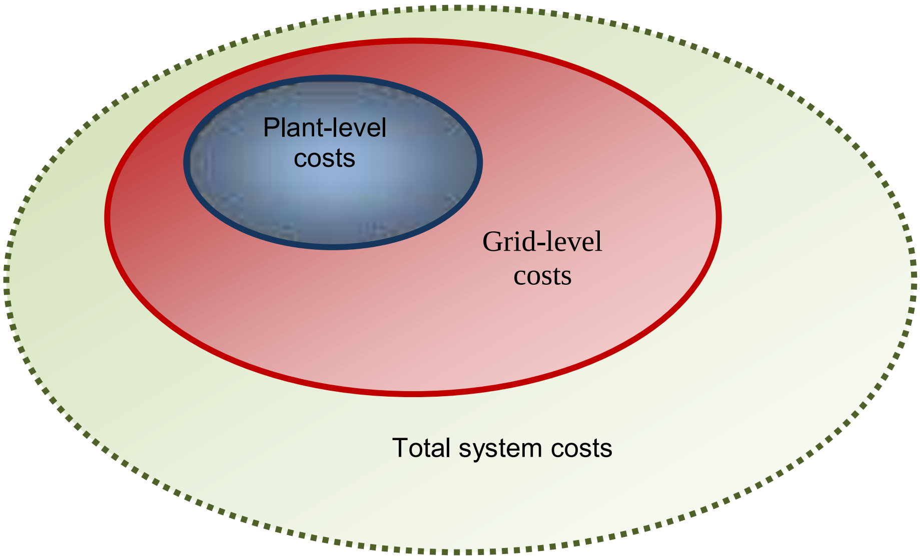
This has many distorting effects on the electricity system, as well as on the competitiveness of baseload technologies, such as nuclear. However, such strategies to increase renewables penetration often ignore the full cost to the electricity system of these sources of electricity production. Hence this report will seek to identify and quantify the system costs of electricity generation to give a truer picture of the total costs to the electricity system of each of these technologies. In this paper, we concentrate on grid costs, but in the recent NEA report [4], the total system costs are more fully discussed.

2. What are system costs

System costs in this paper are defined as the total costs above plant-level costs to supply electricity at a given load and given level of security of supply. In principle, this definition would include costs external to the electricity market such as environmental costs or impacts on the security of supply. This study however focuses primarily on the costs that accrue inside the electricity system to producers, consumers and transport system operators. This subset of system costs that are mediated by the electricity grid are referred to in the following as “grid-level system costs” or “grid costs” (see Figure 2).

Such grid-level system costs can be divided broadly into two categories: (1) the costs for additional investments to extend and reinforce transport and distribution grids as well as to connect new capacity to the grid; and (2) the costs for increased short-term balancing and for maintaining the long-term adequacy of electricity supply in the face of the intermittency of variable renewable energies.

Figure 2: Plant-level, grid-level and total system costs



This study also deals with the pecuniary and dynamic effects of variable renewables. The three principal effects falling into this category are:

a) Lower and more volatile electricity prices in wholesale markets due to the influx of variable renewables with low marginal costs.

b) The reduction of the load factors of dispatchable power generators (compression effect) as low-marginal cost renewables have priority over dispatchable supply.

c) The de-optimisation of the current production structure coupled with the influx of renewables implies an increasing wedge between the costs of producing electricity and prices on electricity wholesale markets.

The objective is to draw attention to the fact that system costs are an increasingly important portion of the total costs of electricity and must be recognised and internalised in order to avoid serious challenges to the security of electricity supply in the coming years.

3. Nuclear power and system effects

Nuclear power, of course, has its own system costs. The most important relate to its specific siting requirements, the conditions that it poses for the outlay and technical characteristics of the surrounding grid, as well as specific balancing requirements due to the size of nuclear plants. Siting constraints may also affect the overall economics of the nuclear power plant, via a longer time for site selection, additional investment costs for upgrades or reduced overall efficiency of the plant. However, those costs are mainly borne by the nuclear power plant developer and only impose limited additional costs on the electricity system as a whole. The specific arrangements in place in OECD countries may be different with regard to the special conditions that nuclear power plants impose on the electrical system in terms of higher requirements for grid stability and security, specific conditions for the grid lay-out, as well as the interaction between the overall generation system and nuclear plants due to the latter's operational characteristics.

All these system costs are real, but are overall in the range of USD 2-3 per MWh, slightly above those of other dispatchable technologies but well below those of variable renewables (see Table 1 below). At least as important as the system effects of nuclear plants themselves is their ability to deal with the system effects generated by other technologies, in particular variable renewables. The short-term intermittency of wind and solar plants puts great demands on the dispatchable providers of residual demand to vary substantial portions of their load in very short time frames. The ability to follow load will become an increasingly important criterion to choose between different back-up technologies.

Based on the French and the German experiences, nuclear power has the technical capabilities to engage in load-following in a manner similar but somewhat less dynamically than other dispatchable technologies. While new nuclear designs can operate at a power level as low as 25% of their rated capacity, most of the older designs cannot be operated for a prolonged period below 50% of their rated capacity.

Table 1: The load-following ability of dispatchable power plants in comparison

	Start-up Time	*Maximal change in 30 sec*	*Maximum ramp rate (%/min)*
Open cycle gas turbine (OCGT)	10-20 min	20-30 %	20 %/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20 %	5-10 %/min
Coal plant	1-10 hours	5-10 %	1-5 %/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5 %/min

4. Measuring system effects

The most innovative contribution of the NEA study [4], however, is certainly the systematic quantitative assessment of grid-level system costs in a number of selected OECD countries. On the basis of a common methodology and a large number of country specific studies for the underlying data, the costs for short-term balancing and long-term adequacy as well as the costs for grid connection, extension and reinforcement required for different technologies were calculated for Finland, France, Germany, the Republic of Korea, the United Kingdom and the United States. Technologies included were nuclear, coal, gas, onshore wind, offshore wind and solar PV. System costs were calculated at 10% and 30% penetration levels of the main generating sources.

The results show that system costs for the dispatchable technologies are relatively modest and usually below USD 3 per MWh. They are considerably higher for variable technologies and can reach up to USD 40 per MWh for onshore wind, up to USD 45 per MWh for offshore wind and up to USD 80 per MWh for solar, with the high costs for adequacy and grid connection weighing heaviest. The costs for variable renewables would be lower by roughly USD 10 to USD 20 (USD 26 in the case of UK solar) per MWh if the costs for back-up were not included, under the assumption that current electricity systems of OECD countries already have sufficient dispatchable capacity to cover demand at all times. While this may be an admissible assumption in the short run, it would not be a correct assumption for the long run when existing capacity needs to be replaced.[1]

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[1] The costs of dispatchable back-up for variable renewables are due only in the case that assumes that variable renewables are installed to cover genuinely new demand. In the case that the working assumption is that variable renewables are introduced into systems with dispatchable capacity that is already fully capable of satisfying demand at all times, the back-up costs can be dispensed with and thus the system costs will be lower. The study also presents an alternative methodology to calculate the costs of providing back-up capacity.

Table 2: Grid-level system costs in selected OECD countries

Finland

	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.06	0.06	0.00	0.00	8.05	9.70	9.68	10.67	21.40	22.04
Balancing Costs	0.47	0.30	0.00	0.00	0.00	0.00	2.70	5.30	2.70	5.30	2.70	5.30
Grid Connection	1.90	1.90	1.04	1.04	0.56	0.56	6.84	6.84	18.86	18.86	22.02	22.02
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	0.20	1.72	0.12	1.04	0.56	4.87
Total Grid-Level System Costs	***2.37***	***2.20***	***1.10***	***1.10***	***0.56***	***0.56***	***17.79***	***23.56***	***31.36***	***35.87***	***46.67***	***54.22***

France

	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.08	0.08	0.00	0.00	8.14	8.67	8.14	8.67	19.40	19.81
Balancing Costs	0.28	0.27	0.00	0.00	0.00	0.00	1.90	5.01	1.90	5.01	1.90	5.01
Grid Connection	1.78	1.78	0.93	0.93	0.54	0.54	6.93	6.93	18.64	18.64	15.97	15.97
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	3.50	3.50	2.15	2.15	5.77	5.77
Total Grid-Level System Costs	***2.07***	***2.05***	***1.01***	***1.01***	***0.54***	***0.54***	***20.47***	***24.10***	***30.83***	***34.47***	***43.03***	***46.55***

Germany

	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	7.96	8.84	7.96	8.84	19.22	19.71
Balancing Costs	0.52	0.35	0.00	0.00	0.00	0.00	3.30	6.41	3.30	6.41	3.30	6.41
Grid Connection	1.90	1.90	0.93	0.93	0.54	0.54	6.37	6.37	15.71	15.71	9.44	9.44
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	1.73	22.23	0.92	11.89	3.69	47.40
Total Grid-Level System Costs	***2.42***	***2.25***	***0.97***	***0.97***	***0.54***	***0.54***	***19.36***	***43.85***	***27.90***	***42.85***	***35.64***	***82.95***

Korea

	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.03	0.03	0.00	0.00	2.36	4.04	2.36	4.04	9.21	9.40
Balancing Costs	0.88	0.53	0.00	0.00	0.00	0.00	7.63	14.15	7.63	14.15	7.63	14.15
Grid Connection	0.87	0.87	0.44	0.44	0.34	0.34	6.84	6.84	23.85	23.85	9.24	9.24
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	2.81	2.81	2.15	2.15	5.33	5.33
Total Grid-Level System Costs	***1.74***	***1.40***	***0.46***	***0.46***	***0.34***	***0.34***	***19.64***	***27.84***	***35.99***	***44.19***	***31.42***	***38.12***

United Kingdom

	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.06	0.06	0.00	0.00	4.05	6.92	4.05	6.92	26.08	26.82
Balancing Costs	0.88	0.53	0.00	0.00	0.00	0.00	7.63	14.15	7.63	14.15	7.63	14.15
Grid Connection	2.23	2.23	1.27	1.27	0.56	0.56	3.96	3.96	19.81	19.81	15.55	15.55
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	2.95	5.20	2.57	4.52	8.62	15.18
Total Grid-Level System Costs	***3.10***	***2.76***	***1.34***	***1.34***	***0.56***	***0.56***	***18.60***	***30.23***	***34.05***	***45.39***	***57.89***	***71.71***

United States												
	System Costs at the Grid Level [USD/MWh]											
Technology	***Nuclear***		***Coal***		***Gas***		***On-shore wind***		***Off-shore wind***		***Solar***	
Penetration level	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*	*10%*	*30%*
Back-up Costs (Adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	5.61	6.14	2.10	6.85	0.00	10.45
Balancing Costs	0.16	0.10	0.00	0.00	0.00	0.00	2.00	5.00	2.00	5.00	2.00	5.00
Grid Connection	1.56	1.56	1.03	1.03	0.51	0.51	6.50	6.50	15.24	15.24	10.05	10.05
Grid Reinforcement and Extension	0.00	0.00	0.00	0.00	0.00	0.00	2.20	2.20	1.18	1.18	2.77	2.77
Total Grid-Level System Costs	***1.72***	***1.67***	***1.07***	***1.07***	***0.51***	***0.51***	***16.30***	***19.84***	***20.51***	***28.26***	***14.82***	***28.27***

Establishing estimates for grid-level system costs also allows calculation of the total costs of electricity supply with and without variable renewables. Introducing variable renewables up to 10% of the total electricity supply will increase per MWh cost, depending on the country, between 5% and 50%, whereas satisfying 30% of demand might increase per MWh costs by anything between 16% and 180% (the latter relating to solar in Finland).

While onshore wind is usually the variable technology with the lowest grid-level system costs and solar PV the one with the highest, country-by-country differences are more important than technology-by-technology differences. This means that natural endowments and circumstances matter enormously. It may also explain to some extent differing public and policy attitudes towards the large-scale deployment of variable renewables in different countries.

The NEA study attempts to analyse the impacts of the deployment of variable renewables on the load factors and profitability of dispatchable technologies in the short run and on their optimal capacities in the long run. Table 3 below provides a first indication of the losses in load factors. It shows that those most heavily affected in the short run are indeed the technologies with the highest variable costs, which are hit hard by the unavoidable decline in electricity prices due to the influx of 10% or 30% of electricity with zero marginal cost that will push the supply curve towards the right. So gas then coal suffer most but nuclear load factors are also reduced.

Table 3: Electrical load and profitability losses in the short term

		10% Penetration level		***30% Penetration level***	
		Wind	***Solar***	***Wind***	***Solar***
Load losses	***Gas Turbine (OCGT)***	-54%	-40%	-87%	-51%
	Gas Turbine (CCGT)	-34%	-26%	-71%	-43%
	Coal	-27%	-28%	-62%	-44%
	Nuclear	-4%	-5%	-20%	-23%
Profitability losses	***Gas Turbine (OCGT)***	-54%	-40%	-87%	-51%
	Gas Turbine (CCGT)	-42%	-31%	-79%	-46%
	Coal	-35%	-30%	-69%	-46%
	Nuclear	-24%	-23%	-55%	-39%
Electricity price variation		-14%	-13%	-33%	-23%

In the long run, the situation changes as high-fixed costs technologies will leave the market due to reduced numbers of full load hours. While average electricity prices will tend to remain stable as low-variable cost baseload providers will leave the market, their volatility will increase strongly.

The analysis in the study show that the large increases of electricity supply costs as the share of variable renewables rises result from a combination of higher investment costs, balancing and adequacy costs as well as additional expenses for transmission and distribution. Both calculations also show a rapid decline in wholesale electricity prices as a function of the increasing share of low marginal cost renewables. Electricity systems with very high renewable shares will have electricity prices equal to or below zero during a high number of hours of a year. This remains a major challenge for dispatchable technologies which, unlike renewables, do not receive any subsidies.

5. Internalising system effects through capacity mechanisms and technological change

The introduction of large amounts of variable renewables creates a radically new situation in electricity wholesale markets, which will require rapid adaptation from all actors. Currently, dispatchable producers ensuring the public good of security of electricity supply are exposed to increasing commercial pressures due to the lower wholesale electricity prices and reduced load factors resulting from the influx of large amounts of electricity from subsidised renewables. This requires the creation of new and innovative institutional, regulatory and financial frameworks that would allow the emergence of markets that remunerate so-called “flexibility services”, which includes the provision of short-term balancing services and, in particular, sufficient amounts of dispatchable long-term capacity.

It also requires rethinking the mechanisms through which subsidies are administered. While member countries are free to choose the energy mix they prefer, the combination of fixed feed-in tariffs (FITs) and grid priority for renewables, means that the latter have no incentive to adjust their load to overall market conditions. More efficient mechanisms would be feed-in premiums (FIPs) or an obligation for all providers, including producers based on variable renewables, to feed-in stable hourly bands into the system, even if this means subsequently remunerating the latter for the added costs.

A particular role in this context could be played by capacity mechanisms to remunerate dispatchable capacity purely for its availability in time of need. Already today, the technical and pecuniary system effects of variable renewables are putting considerable stress on the long-term adequacy of the electricity systems of OECD countries. The clear implication is that dispatchable technologies, including nuclear, will require that a portion of their revenues be derived from other sources if they are to stay in the market and provide the necessary back-up services.

6. Conclusions and Recommendations

System costs in electricity markets are a major issue. While all technologies have system costs, those generated by variable renewables are of at least an order of magnitude larger than those of dispatchable technologies. In addition, they are in the process of creating, and to some extent have already created, a market environment in which dispatchable technologies are no longer able to finance themselves through revenues in “energy only” electricity wholesale markets. In addition, system costs tend to increase over-proportionally with the amount of variable electricity injected into the system. This has serious implications for the security of electricity supplies. It is only due to the subdued demand for electricity in the current low-growth environment of OECD economies and the considerable excess capacity constructed during more favourable periods in the past that more serious stresses have so far been avoided.

The magnitude of both technical and pecuniary system costs implies that they can no longer be borne in a diffuse and unacknowledged manner by operators of dispatchable technologies as an unspecific system service. Economically speaking, dispatchable technologies are expected to provide the unremunerated positive externality of long-term flexible capacity for back-up.

System costs require (a) fair and transparent allocation mechanisms to maintain economically sustainable electricity markets and (b) new regulatory frameworks to ensure that balancing and long-term capacity provision provided by technologies, such as nuclear, can be adequately provided and appropriately remunerated; and (c) development of flexibility resources based on a systems approach where full costs and interdependencies are recognised. This will require increasing the load following abilities of dispatchable low-carbon back-up including nuclear, expanding storage, rendering demand more responsive and increasing international interconnections.

7. References

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