Sizewell C – Spent Fuel, safety, storage, environmental health and funding – a 2021 perspective. 03 June 2021

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Note: The paper's worthiness must be established by expert bodies notwithstanding the considerable effort expended to substantiate all relevant parts of the case made. It must be noted, however, that this exercise is made difficult by the complex area of the narrative and the lack of public domain information. Statements made in this document are my opinions, there is a basis to those statements and are therefore statements that any honest person could make.

1 – Safety: The handling of Spent Fuel.

This paper is a response to Electricité de France SA's (EDF)'s proposed Sizewell C and the nature, inventory and handling of its Spent Fuel.

1.1 Background

New fuel rods are relatively safe and easy to handle. The main components are Uranium-238 and Uranium-235 that have very long half-lives and do not require complex, shielded containment. Once in the reactor, a neutron-induced, chain reaction fission is established to produce heat. After 1-3 years the fuel rods become 'Spent' in that they lose their efficiency and are removed from the reactor core. The Spent Fuel now contains fission products, some with short half-lives that are intensely radioactive and transuranic elements including plutonium that have much longer half-lives. It takes several hundred thousand years for the ingestion radiotoxicity of Spent Fuel to become that of the uranium ore (including its decay products) from which it was derived. It also generates high levels of heat. Although heat falls rapidly in the Spent Fuel after reactor removal, it requires cooling for up to 140 years before reaching sufficiently low enough bentonite boundary temperatures for geological storage requirements. It also requires effectively shielding indefinitely.

Technical note 1: For Spent Fuel heat information see Hinkley C documents (the Pre-Construction Safety Reports, PCSR). The reactor thermal power will be 4500MW of which 97.4% is developed in the fuel and the full weight of the reactor core is 127 tonnes of uranium giving a heat loading of 34.5 MW per tonne uranium. For the cooling period of 140 years, see: 'NDA Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR' Jan 2014 section 6, page 6.

Technical note 2: The toxicity of a radionuclide is dependent on its activity, and on what type of radiation its radioactive disintegration (decay) gives rise to. A distinction is made between two types of radiation: external and internal. External radiation is emitted by an external radiation source and penetrates the body from the outside, internal radiation comes from radioactive substances that enter the body, via ingestion or inhalation. Most radionuclides are more toxic if they are inhaled than if they are ingested. Ingestion radiotoxicity is a tangible, quantifiable measure of the environmental and health risk associated with Spent Fuel. See, 'Spent nuclear fuel - how dangerous is it? A report from the project "Description of risk." Allan Hedin, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden March 1997 and IPFM, 'Spent Fuel from Nuclear Power Reactors, 2011', p.4. See Appendix 1 for a graph of ingestion radiotoxicity.

1.2 Proposed treatment of Spent Fuel at Sizewell C—the reclassification of waste.

It is proposed that the Spent Fuel produced over the full lifetime of operation of Sizewell C is to be stored onsite. This is despite clause 112 in the *Generic design Assessment UK EPR (Spent Fuel)*, which says: 'The ONR [Office Nuclear Regulation] have an assessment finding …to reduce the onsite storage period for the spent fuel produced by the reactor so that the fuel can be transported as soon as reasonably practical.' EDF has expressed no interest in reprocessing the Spent Fuel and we have no independent policy to do so. The construction of a new Geological Disposal Facility (GDF) was defined as a 'Base Case' requirement for new reactor build and ultimate disposal of Spent Fuel produced by new-build reactors: "We [The Environment Agency] note that the Government base case for new build is that a facility for long term storage of high-level waste and spent fuel will be available in time to receive the wastes from new reactor build." *'Generic design assessment UK EPR nuclear power plant design by AREVA NP SAS and Electricité de France SA, Final Assessment Report Spent Fuel,' clause 118.*

The paper continues: "EDF and AREVA take account of Government policy in their IWS [Integrated Waste Strategy], noting that spent fuel will be declared as waste and…then disposed of to the geological disposal facility" *op.cit., Clause 52.*

Also, according to the Government White Paper on Energy, *MAY 2007, MEETING THE ENERGY CHALLENGE, Clause 29 and Clause 99*: "Private sector developers would meet the full decommissioning costs and full share of waste management costs… [If they are to be] allowed to invest in new nuclear power stations…Government believes that new waste could technically be disposed of in a geological repository and that this would be the best solution for managing waste from any new nuclear power stations."

At present, however, Government, does '*not currently classify Spent Fuel as waste*', which is not consistent with the Generic Design Assessment (GDA). Spent Fuel is not included in these waste commitments and will only be stored in a GDF 'at some future time if it becomes re-classified as waste'. See Government White Paper *'Implementing Geological Disposal, Dept Energy Climate Change' July 2014, clause 2.11,2.17.*

In summary, Spent Fuel may be classified as waste when at some unspecified future date. However, Spent Fuel is highly radioactive, especially in the first 300 years, and although it serves no further purpose in power generation on the basis of current plans, it is not considered to be waste, thus is presumably separated from a major range of safety, risk and environmental recommendations.

1.3 Expert opinion on safety and technical issues of Spent Fuel for Sizewell C

In its *Initial Proposals and Options Consultation Stage1, para 2.2.16,* EDF declares that their new EPRs (The abbreviation generally expands to 'European Pressurised Reactor' and occasionally 'Evolutionary Power Reactor' and is the reactor type for Hinkley C and Sizewell C) will generate less spent fuel than existing reactors in the UK. This statement is incomplete. Less Spent Fuel means 'High Burn-up' - the uranium fuel rods (with higher enrichment than legacy to 4.9% U-235) stay in the reactor longer than in earlier conventional reactors and can run up to 65,000 MWd/tU (Megawatt days per tonne of Uranium). Advance Gas Cooled Reactors (AGRs) are 5000-30,000 MWd/tU for comparison.

While reactor coolant temperatures still have a maximum of 310 degrees C, the high power of the EPR is coming from a larger core and more fuel rather than burning at higher temperatures (hence the increased requirements of vast quantities of cooling water as the majority of heat generated by the reactor is waste). However, the High Burn-up Spent Fuel, when removed from the reactor is more delicate, more radioactive and has significantly higher decay heat than 'conventional' spent fuel. EDF has ONR (The Office for Nuclear Regulation) approval for high burn-up suggesting that safety systems are regarded as acceptable however, it is not clear that the implications have been fully considered. (see appendix 2 for examples of the extent of the higher radioactivity of High Burn-up spent fuel). Also, *NDA Geological Disposal Report, March 2010 no. NDA/RWMD/013, page 11*; *See Generic Design assessment, op.cit., p.9 for water requirements.*

Incorporated into the EDF design are containment and core-catcher structures to ensure that there is no large-scale release of radioactivity to the environment in the event of a core meltdown. However, outside the reactor containment zone with no 'core catcher' facility, are the Spent Fuel ponds that will contain approximately a full reactor core's worth of 'spent' fuel rods every 3-4 years (there are 241 fuel assemblies per core). Because of the higher heat and radioactivity of the high burnup Spent Fuel, it is recognised that safety margins need to be more rigorous and will depend on the effective and continuous removal of significant thermal power. Failsafe technologies will need to be incorporated at every stage of this process to mitigate risk as all these systems are vulnerable to mechanical failure, deliberate disruption or flood yet must operate flawlessly for 'an extended cooling period' (the NDA states 90-140 years) until the spent fuel has cooled sufficiently to be moved (assuming there is somewhere to move it to).

High Burnup is an exercise in reducing fuel cycle costs for the operator, however, High Burnup Spent Fuel is subject to a range of failures predominantly associated with increased cladding degradation: corrosion, hydrogen pickup and associated stresses, cladding and pellet interactions, internal fuel rod pressures, hoop stresses and, perhaps most importantly, failure tendency of High Burnup Spent Fuel may increase in a LOCA (Loss of Cooling accident). It seems clear that a full risk analysis on all aspects of High Burnup fuel use is not yet fully established.
IAEA - International Atomic Energy Agency: 'High Burnup Fuel: Implications and Operational Experience. Proceedings of a technical Conference Buenos Aires' Nov 2013. IAEA-Techdoc -CD-1798, Page 119.

This uncertainty of cladding integrity is raised in clauses 109 and 110 of the *Generic design Assessment UK EPR (Spent Fuel): "*The ONR commissioned the National Nuclear Laboratory (NNL) to carry out work to identify mechanisms that could lead to early failure of the fuel cladding or the fuel assembly during storage… There will be requirements for regular maintenance inspections on the fuel condition over the storage period, to maintain confidence that the fuel remains in a suitable condition". *'Generic design assessment UK EPR nuclear power plant design by AREVA NP SAS and Electricité de France SA, Final Assessment Report Spent Fuel'.*

1.4 The Cooling period, interim and long-term storage for Spent Fuel

According to the Environment Agency document, '*Generic design assessment UK EPR nuclear power plant design by AREVA NP SAS and Electricité de France SA. Final Assessment Report Spent Fuel, Clause 129:'* "NDA has published a generic Disposal Systems Safety Case (gDSSC) for a future Geological Disposal Facility (GDF), based on its understanding of the scientific and engineering principles supporting geological disposal (RWMD, 2010)…The review therefore confirms that there are no new issues arising from the generic DSSC that would challenge the fundamental disposability of the wastes and spent fuel expected to arise from operation of the AP1000 and EPR."

The expertise of the NDA's *Radioactive Waste Management Directorate (RWMD)* is acknowledged; however, it is essential to recognise that in the proposal for Sizewell C, there is no Geological Disposal Facility (GDF), no site for a GDF, and no design for a GDF.

There is also no consensus as to what the Cooling Period should be. Initial cooling must take place in in the Spent Fuel ponds for 'some years' followed by an 'extended period' of dry surface storage. The 'Generic Design Assessment' (ibid. clause 113) suggests an 'assumed period of 10 years… or up to 15 years in the Spent Fuel Pool' but that there is 'sufficient flexibility in the Spent Fuel Pool design to allow the Licensee (EDF) to meet any cooling constraints'. According to the Nuclear Decommissioning Authority (NDA): "In order to ensure the performance of the bentonite buffer [the clay encasement in a GDF], a temperature limit [is required.] Based on a canister containing four EPR fuel assemblies, each with the maximum burn-up of 65 GWd/tU and adopting the canister spacing used in existing concept designs, it would require of order of **140** years for the activity, and hence [decay] heat output, of the EPR fuel to decay sufficiently to meet this temperature criterion." *NDA 'Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR' Jan 2014 section 6, page 6.*

High Burn-up fuel, as explained in the appendices, will contain a significantly higher proportion of Plutonium 238 (for a burn of 65 GWd/tU this would be 4.3 times greater than in the spent fuel of Sizewell B) which has extremely high decay heat. The spent fuel will also have significantly higher percentage of Pu 240 which exhibits spontaneous fission. These are not ideal properties for deep geological disposal. See table in Appendix 2.

> *"It is acknowledged that the cooling period specified above is greater than would be required for existing PWR fuel to meet the same criterion* [due to its higher levels of radioactivity and high decay heat radioisotopes] *and RWMD proposes to explore how this period can be reduced. This may be achieved for instance through refinement of the assessment inventory (for example by considering a more realistic distribution of burn-up), by reducing the fuel loading in a canister* [which will increase the geological disposal footprint] *or by consideration of alternative disposal concepts. The sensitivity of the cooling period to fuel burn-up has been investigated by consideration of an alternative fuel inventory based on an assembly irradiation of 50 GWd/tU. For this alternative scenario it is estimated that the cooling time required will reduce to the order of* ***90 years*** *to meet the same temperature criterion."*
>
> NDA 'Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR' Jan 2014 section 6, page 6.

If fuel canister loading is reduced, the storage footprint will be increased which essentially removes the claimed benefit to high-burnup fuel.

Directly relevant to this debate are some of the findings from Fukushima: "When the earthquake and tsunami knocked out the cooling systems …several spent-fuel-rod pools also lost power, shutting down pumps (This is known as a LOCA – loss of coolant accident). Water in the cooling pools stopped circulating and began to boil off or leak out. As the water level fell, the spent fuel rods were exposed, and their temperatures soared. Several began to melt down, releasing extremely high levels of radiation into the air". *(The Week, 'Radioactive fuel rods – the silent threat. April 8th, 2011).*

Technical Note 3: *In view of the Fukushima accident, it is therefore a concern that EDF and AREVA can consider "long term wet storage of fuel as a solution that can be shown to be ALARP" - (risk as low as is reasonably practical). Their viewpoint, reported in the 'ONR Generic Design Assessment' continues: "…spent fuel can be stored safely in a long-term storage pool for the following reasons: Due to low storage temperatures and satisfactory water chemistry, the preservation of cladding integrity is ensured which in turn guarantees the retrievability of stored assemblies at any time during storage. Monitoring of the assemblies is simple and inspection is performed regularly. Other systems such as ventilation, filters or make-up water add to the safety of the facility. The pool water inertia gives the operator a grace period sufficient to deal with incidents before the fuel integrity is compromised. The option also offers flexibility in the long-term management of spent fuel and in the retrieval of assemblies." ONR - Generic Design Assessment – New Civil Reactor Build, Step 4 Radioactive Waste and Decommissioning Assessment of the EDF and AREVA UK EPR™ Reactor Assessment Report: ONR-GDA-AR-11-030 Revision 0 11 November 2011. Clause 192.*

Technical note 4: *Article published by Mari Yamaguchi, Associated Press, Dec 1, 2019, 8:50pm. 'Fukushima melted fuel removal begins 2021, end state unknown', FUEL RODS:*

"Together, the three melted reactors have more than 1,500 units of mostly used nuclear fuel rods still inside that must be kept cool in pools of water. They're among the highest risks at the plant because the pools are uncovered, and loss of water from structural damage or sloshing in the event of another major earthquake could cause fuel rods inside to melt and release massive radiation."

"TEPCO started removing the fuel rods from the Unit 3 pool in April 2019 and aims to get all 566 removed by March 2021. Removal of the rods from Units 1 and 2 is to begin in 2023. By 2031, TEPCO also plans to remove thousands at two other units that survived the tsunami to be stored in dry casks on the compound. More than

6,300 fuel rods were in six reactor cooling pools at the time of the accident, and only the Unit 4 pool has been emptied."

Clearly, fuel pond storage makes inspection of Spent Fuel much simpler, but it appears to be at the cost of overall plant security in event of a LOCA affecting the Spent fuel ponds.

The full analysis of the contribution of Spent Fuel in ponds to the radioactive debris and fallout from Fukushima will take time because of the ensuing chaos, however, Spent Fuel storage ponds will suffer water evaporation in a LOCA (loss of cooling accident) followed by possible explosion caused by the Spent Fuel zirconium cladding and a release of volatile radioactive fission products. As stated earlier *(1.3)* there may be an increased failure tendency in High Burnup Spent Fuel over legacy Spent Fuel in this situation. This could prove to be a greater source of a radiation leak than from the reactor itself. If the reactor has a cooling problem, it is within a strong internal containment vessel surrounded by an external containment vessel and has the benefit of a core-catcher. The Spent Fuel ponds, which, every 10 years reactor operation will contain the Spent Fuel of approximately three complete reactor cores.

In Summary, Spent Fuel is a high risk to the environment in event of a LOCA when in onsite cooling ponds. High burnup Spent fuel being hotter and more radioactive than legacy will increase the hazard. The Generic Design Assessment's position that there will be an 'assumed period of 10 years… or up to 15 years in the Spent Fuel Pool... but there is sufficient flexibility in the design to meet any cooling constraints', appears to show relative degrees of concern. Post-Fukushima it seems reasonable to suggest that Spent Fuel must be transferred from ponds into the more secure containment of dry cask surface storage immediately thermal constraints permit.

1.5 Cost of disposal for the Spent Fuel

The following statements show that there is no understanding or shared view about the cost of disposal of Spent Fuel, the most problematic and expensive item to deal with. This is not included in the 'share of waste management costs' (arising from confusion caused by Spent Fuel not being classified as waste, see 1.2)

"Government [we are told], is developing specific proposals to protect the taxpayer. Under these proposals, private sector developers would meet the full decommissioning costs and full share of waste management costs… [If they are to be] allowed to invest in new nuclear power stations. They would need to be in place before proposals for new power stations could go ahead." It continues: "The Government believes that new waste could technically be disposed of in a geological repository and that this would be the best solution for managing waste from any new nuclear power stations." *White Paper on Energy MAY 2007, MEETING THE ENERGY CHALLENGE*, clause 29 and 99.

However, Government continues: "In addition to existing wastes, there are some radioactive materials that are not currently classified as waste, but would, if it were decided at some point that they had no further use, need to be managed as wastes through geological disposal. These include Spent Fuel (including Spent Fuel from new nuclear power stations), plutonium and uranium." *BEIS National Policy Statement for Geological Disposal Infrastructure. A framework document for planning decisions on nationally significant infrastructure, 2008. Para.2.3.4*

This position is in direct contradiction with the Environment Agency Document, "*Generic design assessment for the UK EPR*", which clearly expresses: Clause 52: "…*spent fuel will be declared as waste*…"

Despite the Environment Agency's statement, Spent Fuel, the most problematic and expensive of all industrial waste to deal with, is not included in the 'share of waste management costs': it is 'not waste' and can be left onsite. Private Sector Developers who were to be held so manfully to financial account for the benefit of taxpayers appear to be freed from the full responsibility of dealing with Spent Fuel.

What are the projected costs of handling UK's nuclear waste? According to the *World Nuclear Waste Report 2019*, quoting *NDA 2018, Annual Report and Accounts 2017*: "The total costs of managing all of the UK's nuclear waste is very high…As of 2006, the NDA estimated the undiscounted future costs of its task to amount to £53 billion… By 2018 this had escalated to an estimate of £121 billion... The NDA now puts an uncertainty range on its central estimate of £99–£225 billion". *The World Nuclear Waste Report. Focus Europe. 2019. Berlin & Brussels. Page 134.* [*www.worldnuclearwastereport.org*](www.worldnuclearwastereport.org)

It is worth noting the clean-up cost of the LOCA at Fukushima - the Japan Centre for Economic Research, a private think tank, said the clean-up costs could mount to some $470 billion to $660 billion and take 30 to 40 years. Scientific American, '*Clearing the Radioactive Rubble Heap That Was Fukushima Daiichi, 7 Years On. The water is tainted, the wreckage is dangerous, and disposing of it will be a prolonged, complex and costly process.*' Tim Hornyak on March 9, 2018.

1.6 Geological storage of Spent Fuel – can fission products and actinides enter the water tables?

Geological storage is being considered by governments worldwide as a 'solution' to spent fuel storage. Unfortunately, the area is highly complex, socially and scientifically:

1.6.1 Hosting of the site

For geological disposal Government has been clear that communities hosting nuclear waste and Spent Fuel should be 'fully informed' and provided with a 'detailed and complete picture of the possible inventory'. Communities should also be able to enter into 'formal discussions with, and have access to information from', the developer.

Considering that East Suffolk is obliged to host all EDF's Spent Fuel produced over the 60-year lifetime of the plant plus 140 years beyond, it is essential that the local communities should be afforded the same guidelines offered to those hosting geological disposal. Communities can reasonably ask to be satisfied that high burn-up procedure (which provides fuel-cycle cost benefits for EDF but seems to lack full empirical data on the implications for the Spent Fuel in medium- and long-term storage) is sufficiently explained and qualified by EDF. A further full and open public consultation on Spent Fuel is owed to local communities whether they are a 140-year 'temporary' nuclear waste storage facility or a Geological Disposal Facility.

For information on involvement of Communities see: 'Dept Energy Climate Change Implementing Geological Disposal, A Framework for the long-term management of higher activity radioactive waste', July 2014, section 2,3,7.

1.6.2 The Spent Fuel itself – the water table transport mechanism

The containment devices used - whether concrete blocks, glassified rods, stainless steel canisters etc are subject to corrosion and degradation. We do not have empirical data for canister design longevity containing nuclear waste and without these data we must accept the consequences and likelihood of corrosion and some degree of nuclear waste exposure.

On the basis that canister corrosion must be assumed, the answer as to 'water solubility' and hence a 'transport mechanism' is still far from simple because it is not sufficient to consider the isotope of the element in isolation. There is a need to consider the precise chemical species and that depends on the oxidation state of the metal, the local pH, and on top of that the availability of other groups or ions that can bind to the metal. There is the problem of ionization in the surrounding region which can cause oxidation/reduction reactions which will raise a whole series of parallel questions about the chemistry and the mobility of the metal ions. All these factors contribute to the question of the solubility and the near impenetrable complexity of chemical changes associated with radioactivity.

The above words are taken from one of the most highly regarded chemists in the UK – as he says, the area is a '**brutally complex'**, and there is a large research effort at the University of Manchester (to mention just the UK's main centre, but of course there are huge efforts in any country that owns and operates nuclear power stations) working on many of these questions.

We should also consider the thorny question of 'belligerents': what would occur if belligerents any time in the next 100 thousand years dropped explosives into the Geological Disposal Facility—exactly what safeguarding is in place for such a consideration?

Would it not be wise to see if some of these problems could be understood, if not resolved, before new nuclear build takes place?

2 - Summary and recommendations

2.1 New nuclear fission power generation should be delayed until there is clear and consistent policy (and investment) regarding nuclear waste disposal. Currently, Government nuclear agencies are in a state of acute contradiction over Spent Fuel:

- Spent Fuel, according to the Office for Nuclear Regulation, must be removed from site 'as soon as reasonably practical', yet will remain onsite indefinitely.
- The Environment Agency has declared that 'Spent Fuel is waste', meanwhile, Government has declared Spent Fuel is 'not waste', thus separating Spent Fuel, the most problematic of all industrial material, from a major range of safety, risk and environmental recommendations.
- The GDA states that it is a 'base case condition' that a deep repository (GDF) would be constructed in time for new build EPR waste including Spent Fuel, however, we

do not have a geological disposal facility (GDF) nor even serious consideration for a GDF.
We also do not know if a GDF would represent suitable containment for Spent Fuel. (Spent Fuel that is deep and irretrievable in leaking canisters is more problematic than surface storage. GDF is not a straightforward consideration.)

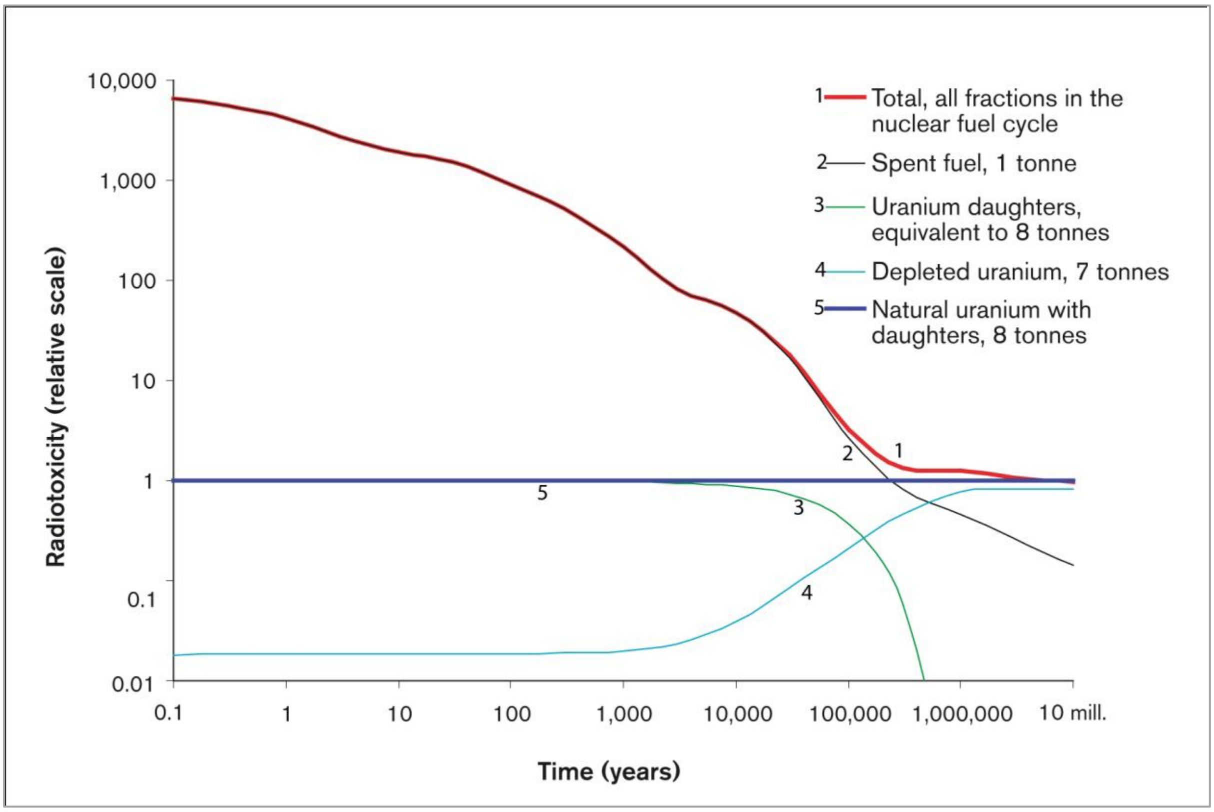
- For geological disposal, Government has been clear that communities hosting nuclear waste and Spent Fuel must be 'fully informed' and provided with a 'detailed and complete picture of the possible inventory' and 'have access to information from the developer'. East Suffolk, however, the host for all the Spent Fuel Sizewell C will produce, has not been afforded the same guidelines or respect. The copious documentation published by EDF on Sizewell C omits much information on the nature of the Spent Fuel or how it is to be cooled, packaged, and stored. *For information on involvement of Communities see: Dept Energy Climate Change Implementing Geological Disposal, A Framework for the long-term management of higher activity radioactive waste, July 2014, section 2,3,7.*

2.2 Government must consider the interim period before geological disposal is possible and impose the safest form of dry cask, surface storage as another base-case condition to deal with most of the critical 140 year highly radioactive period when the fuel is cooling. Spent fuel should be moved to dry storage as soon as thermal constraint allows and Spent Fuel ponds must only be used for cooling and not as a storage facility. The Fukushima Spent Fuel Ponds were, and remain, an extreme liability. EDF must satisfy local communities of the design, safety and intended use of the Spent Fuel ponds.

2.3 Much of the Sizewell C Spent Fuel will be notably hotter (from the generation of high decay heat isotopes) and more radioactive than its legacy counterpart and will contain high activity fission products as well as in the region of 27 tonnes of plutonium (per reactor) by the end of life for each of the two reactors. It will take several hundred thousand years for the ingestion radiotoxicity of this Spent Fuel to become that of the uranium ore (including its decay products) from which it was derived. It needs safeguarding and removal from coastal vulnerability. (ref: *Disposal System Safety Case document NDA Report DSSC/422/0.. See:* NDA *Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR Jan 2014* page 30/32, pdf pages 38-40.

2.4 East Suffolk is obliged to be a de facto nuclear waste storage facility during the period when the Spent Fuel is its most potent. It must be afforded a further public consultation to fully understand the nature, management and implications of the Spent Fuel. This consultation must inform on EDF's high burn-up procedure which provides fuel-cycle cost benefits for EDF but lacks full empirical data on the implications for the Spent Fuel in medium- and long-term storage (due to the greater heat, radioactivity and fragility).

Appendix 1- Graph of Ingestion Radiotoxicity comparing the ingestion radiotoxicity of Spent Fuel with that of the uranium ore (including its decay products) from which it was derived.



Note logarithmic scale of Time axis.

Graph of Ingestion Radiotoxicity comparing the ingestion radiotoxicity of Spent Fuel with that of the uranium ore (including its decay products) from which it was derived.

Relative ingestion radiotoxicity of uranium ore (line 5) and of the spent LWR fuel that could be

derived from it (line 2). Line 3 describes the toxicity of the uranium decay products that are separated in the uranium mill and line 4 that of the depleted uranium that is stored at the enrichment plant. Approximately eight tons of natural uranium are used to produce one ton of enriched uranium fuel (and seven tons of depleted uranium). Source: *A. Hedin, "Spent Nuclear Fuel - How Dangerous Is It?" SKB Technical Report 97-13, Swedish Nuclear Fuel and Waste Management Co., 1997*.

Appendix 2 - Information regarding nuclear fission and EPR (Hinkley C, Sizewell C) High burnup spent fuel.

A2.1 – Reactor core details

Sizewell C will be 2 x 1.6GW reactors.

Each Reactor core has 241 fuel assemblies (each 779Kg overall, 527Kg Uranium, 5m long and .9m diameter), an overall core Uranium mass of 127 tonnes.

Spent Fuel will be 90 fuel assemblies every 18 months which for 60 years results in approximately 3600 fuel assemblies (2,800 tonnes) of Spent Fuel per reactor at end of life.

Efficiency (approximate and using U235 for simplicity):

1) In a fission reaction 1 atom of U235 produces about 210 MeV = 32E-12 J
2) Power station output = 1.6 GW = 1.6E9 J/s
3) In 1 year output is 1.6E9 x 3600 x 24 x 365 = 5E16 J
4) This requires the fission of 5E16 / 32E-12 atoms of U235 = 1.56E27 atoms
5) Avogadro's number = 6E26 atoms per kilo-molecule
   (ie 235 kg of U235 contain 6E26 molecules, or atoms in the case of uranium)
6) So mass of U235 needed to generate 1.6 GW for a year = 1.56E27x235 / 6E26 = 611 kg

Of this, the mass conversion to energy using E=mc(2), {Joules = kg* m/sec(2) } appears to show that the mass change (binding energy change) for a 1.6GW reactor for one year is 0.56Kg.

A2.2 Background – how fission works

A nuclear reactor's purpose is to create heat. This is to produce steam that will then drive a turbine and produce electricity.

To do this the reactor establishes nuclear fission chain reactions. Radiation is a by-product of fission and a property of the elements created by the fission process. The energy comes from 'missing mass' (a variance in the mass of nucleons depending on their existence in an independent state or the binding energy of the nucleus they are contained within).

A2.2.1 The nature of Uranium fuel and its properties.

Natural Uranium is U-238 containing a very small percentage of U-235 (0.7%) and U-234 (0.005%). The Uranium 238 must be enriched up to around 5% U-235 for EPRs, higher than PWRs and BWRs, however Magnox and CANDU reactors use natural uranium.

The new fuel rods are relatively safe and easy to handle, U-238 and U-235 having very long half-lives so not very radioactive, and do not require complex, shielded containers.

U-235 is fissile and a naturally occurring isotope.

U-238 is not fissile, but fissionable and fertile in that it can *make* a fissile element.

These unusual characteristics are the key to heat generation.

A2.2.2 Fission, the Chain Reaction and its regulation.

U-235 nuclei will respond to thermal neutrons (slow, low energy neutrons) and explode into fission products (for example Xenon-140 and Strontium-93 plus 3 neutrons). The bulk of the released energy is in the kinetic energy of the fission products which changes to heat.

This is the start of the self-sustaining chain reaction. U-235 will fission in different ways producing a range of products, the relative amounts being known from measurement. The resulting fission products are always highly radioactive.

The energy release in this fission is some 50 million times more than an equivalent burning of hydrocarbon molecules. The energy release is so large because the nucleons in the fission products are more tightly bound than the parent nucleus, this is an 'effective weight loss' and energy conversion relates to $E = mc^2$

The neutrons emitted are high velocity and need to be slowed to be effective in fissioning (exploding) more U-235. This is done by a moderator. Magnox and AGR reactors use graphite; EPRs, PWRs, BWRs use light water. (Light water is H_2O, heavy water is D_2O which is used in the CANDU reactor). The moderator affects the required enrichment of the fuel (light water absorbs some neutrons).

So, the chain reaction in U-235 is established, heat builds, and radioactive fission products develop.

However, this is not the complete cycle. The Uranium 238 will also absorb some neutrons. Plutonium 239 (24,000 years half-life) is the effective result and is fissile in the same way as U-235 (which is why U-238 is regarded as fertile).

The plutonium Pu-239 created by the U-238 can now act as fission fuel and produce chain reactions in the same way as the U-235. Pu-239 fission produces approximately the same energy per fission as U-235 fission and leaves around 1- 1.3% isotopes in the Spent Fuel.

These critical chains of fissile U-235 and Pu-239 are the heat engine of the reactor; the radioactive fission products and actinides including plutonium forming the Spent Fuel.

A2.3 Efficiency of fission in nuclear reactors

It can be argued that for a given thermal energy produced in a reactor you need a fixed number of fissions of uranium or plutonium, (with an energy of 200-210MeV per fission), and hence produce a fixed amount of fission products and actinides. In theory, then we only depend upon the thermal efficiency of the reactor, rather than the burnup of the fuel, as regards the amount of fission products and long-life actinides produced per GWyear. In this respect the EPR appears to be marginally better than Sizewell B and most other PWRs around the world, marginally worse than the AGRs, and considerably better than the old Magnox reactors.

A2.4 High Burn-up fuel

High Burnup Spent Fuel from the new EPR reactors has been quantified for radioactivity by *Radioactive Waste Management Ltd* and the *Nuclear Decommissioning Authority*. Their datasets for high burn up Spent Fuel activity appear to show some marked nuances and particularities in the development of fission products and actinides by comparison with legacy Spent Fuel, something that EDF appears to describe as a benefit:

In clause 70 of the 'Generic design Assessment': "*EDF and AREVA claim the improvements in environmental performance of the UK EPR project with regard to waste and fuel include:*
a) a more efficient use of natural uranium resources;

b) a significant reduction in the quantity (volume, mass) of long-lived radioactive waste resulting from the fuel and its cladding owing to its: neutronic design (large core, neutron reflector) and the fuel management performance (high burn up)."

A2.5 High Burn-up Spent Fuel analysis using RWM (Radioactive Waste Management) data:

Data supplied by RWM (*Radioactive Waste Management Limited (RWM) is a wholly owned subsidiary of the NDA and is responsible for implementing Government policy on geological disposal)* suggest that by the year 2200 Sizewell C's Spent fuel will be generating 2,056,908 Tbq (Terrabecquerels) of radiation (20% of 10,284,544). By comparison, our Legacy Spent Fuel combined will be generating less radiation of 1,702,423 Tbq. This dataset is supplied by RWM is for communities to make a 'fully informed decision' about Spent Fuel. *Radioactive Waste Management Ltd, Geological Disposal, Disposal System Safety Case: Data Report December 2016,* see pages 32-34. Also, Government White paper on implementing Geological disposal, Dept Energy Climate Change, July 2014, clause 7.41.

RWM offers below a comparison of quantified descriptions of inventory extrapolated to 2200 for the radioactivity of two waste groups: legacy spent fuel waste to be managed and High Burn-up spent fuel (such as Hinkley C and Sizewell C) to be managed.

Nuclide Half Life (years)	All Legacy Spent Fuel TBq	High Burn-up Spent Fuel TBq (New Build Spent Fuel NB-SF)
I- 129 5730	6.64	31.3
Cl-36 300,000	3.09	71.7
Cs-135 2,400,000	130	515
Tc-99 2.1 x 10(5)	1780	12900
Pd-107 6.5 x 10(6)	22	135
U-234 2.4 x 10(5)	393	1730
U-235 7.0 x 10(8)	3.25	6.24
Pu-239 2.4 x 10(4)	4.81 x 10(4)	2.08 x 10(5)
Am-243 7.4 x 10(3)	3660	45100
Totals for 49 Nuclides	*1,702,423*	*10,284,544*
		(2,056,908 for Sizewell C)

Columns 2 and 3 are in TBq (Terabecquerels).

This table is a small sample of 49 nuclides listed. For the full list refer to: *Radioactive Waste Management Ltd, Geological Disposal, Disposal System Safety Case: Data Report December 2016,* see pages 32-34 (16-18).

The quantified radioactivities in columns 2 and 3 are calculated for the year 2200 when it is assumed that the (not yet designed or commissioned) geological repository (GDF) will be closed. Calculation is based on half-life of the elements quoted.
The 'Waste Group' for High Burn-up is drawn from the assumption of a 16GW new build and on that basis Hinkley C and Sizewell C would represent 40% of the total new build nuclear at 6.4 GW. (clause 3.4.3 and White Paper '*Implementing Geological Disposal, Dept Energy Climate Change July 2014* where it confirms: '*The current stated industry ambition for new nuclear development is 16 gigawatt electrical',* (clause 7.41))

It could be claimed, however, in refutation of this position, that legacy Spent Fuel might only represent approximately 8GW for 20 years as much legacy spent fuel has been reprocessed and is no longer classified as Spent fuel.
It is therefore interesting to take a different approach and look at a direct comparison of Spent fuel from Sizewell B and what will be produced by Sizewell C or Hinkley C:

A2.6 High Burn-up Spent Fuel analysis using NDA (Nuclear Decommissioning Authority) data.

Below is a direct comparison of a canister of Spent Fuel from Sizewell B and what would be expected from Sizewell C:

Radionuclide	Sizewell B Spent Fuel	EPR (Sizewell C) Spent Fuel	Ratio of EPR/SZB	Half life
	TBq per canister	TBq per canister		Years
C-14	0.0645	0.311	4.8	5700 years
C-36	0.000831	0.0157	19	300,000 years
Ni59	0.000908	0.0363	40	76,000 years
Se79	0.0318	0.0101	0.32	650,000 years
Sr-90	675	1270	1.9	28.0
Tc-99	1.03	1.89	1.8	211,000 years
Sn-126	0.0567	0.0859	1.5	230,000 years
I-129	0.00239	0.00481	2	1.5million
Cs-135	0.0302	0.0722	2.4	2.3 million
Cs-137	1020	2060	2	30.0
U-233	0.0000123	0.0000291	2.4	160,000 years
U-234	0.133	0.231	1.7	245,000 years
U-235	0.00153	0.00105	0.69	700 million years
U-236	0.0215	0.0367	1.7	23 million years
U-238	0.0246	0.0236	1	4.4 billion years
Np-237	0.0328	0.0694	2.1	2.14M
Pu-238	90.9	391	4.3	87 years. From U-235, High decay heat
Pu-239	25	31	1.2	24,000 years
Pu240	36.1	60.3	1.7	6500 years. Spontaneous fission, high decay heat
Pu-241	123	215	1.7	14 years
Pu-242	0.124	0.39	3.2	373,000 years

Am-241	283	497	1.8	432 years. Gamma radiation and builds over time from Pu 241
Am-242	0.732	0.821	1.1	432 years
Am243	1.14	6.26	5.5	7300 years

Table: Comparison of Radionuclide activities for one spent fuel canister from Sizewell B and one spent fuel canister from an EPR such as Sizewell C at 90 years cooling. *NDA, Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR. Jan 2014*. Pages 30-32 (pdf pages 38-40).

Notes from the above chart of Sizewell B and Sizewell C data:

1) Actinides are the elements between Uranium and Americium.

2) The comparison assumes an average fuel burn rate for Sizewell B and a maximum rate of 65GWd/Ut for Sizewell C.

3) For much of the first 100 years, the radioactivity is dominated by the fission products: mainly Strontium 90 and Caesium 137 (Sr-90, Cs-137). After a few hundred years radioactivity is dominated by the transuranics: Plutonium, Americium and Neptunium (Pu,Am,Np).

4) It takes several hundred thousand years for the ingestion radiotoxicity of Spent Fuel to become that of the uranium ore (including its decay products) from which it was derived.

5) An EPR such as Sizewell C operating for 60 years at 1.6 GW(e) would produce 3,600 spent fuel assemblies which is equivalent to 37.5 spent fuel assemblies for every GW(e) year (ref, NDA, ibid.p.29). This compares with Sizewell B which would produce 46.9 spent fuel assemblies for every GW(e) year. This is clearly a volume efficiency. (ref, NDA, ibid.) The volume efficiency, however, is now questionable as greater spacing will be required around EPR (Sizewell C) Spent Fuel canisters in a GDF due to greater heat and radiation and is also proposed that fuel loading per canister will be reduced for EPR fuel.

6) The Plutonium builds up from zero in new fuel to reach a concentration of about 1%, with a rough equilibrium being achieved between Pu being produced from neutron absorption by U238, and Pu239 being fissioned (Pu-239 becomes fuel along with the U-235). However, because the EPR is high burn-up, the Pu will have a higher percentage of Pu240/241/238 so the Pu present in the spent fuel is considered to be non “weapons-grade”.
This is an important point sometimes used to justify high burn up being a safeguard against proliferation and is an unsupportable argument. It is more inconvenient to build weapons out of reactor-grade material – reactor grade material produces heat to deal with (Pu 238 and Pu 240), and more gamma radiation so weapons handling is more difficult, the critical mass is higher and Pu 240’s spontaneous fission properties cause difficulties. All can be overcome by a high-tech capable entities and lower tech entities will just produce a bomb of a few kilotons less.
Note also that international rules require equal levels of safeguarding for all levels of plutonium with the sole exception of a Pu238 concentration greater than 80%.

7) The bare critical mass of weapons grade U235 is approximately 50kg and Plutonium less than 10kg.

8) This dataset appears to compare canisters at the same half-life age of 90 years.

9) The interdependency and daughter products of actinides are convoluted by creating 'build-up chains', for example: Pu-239 will decay to U-235; U-236 and U238 produce NP-237 which in turn produces Pu-238.

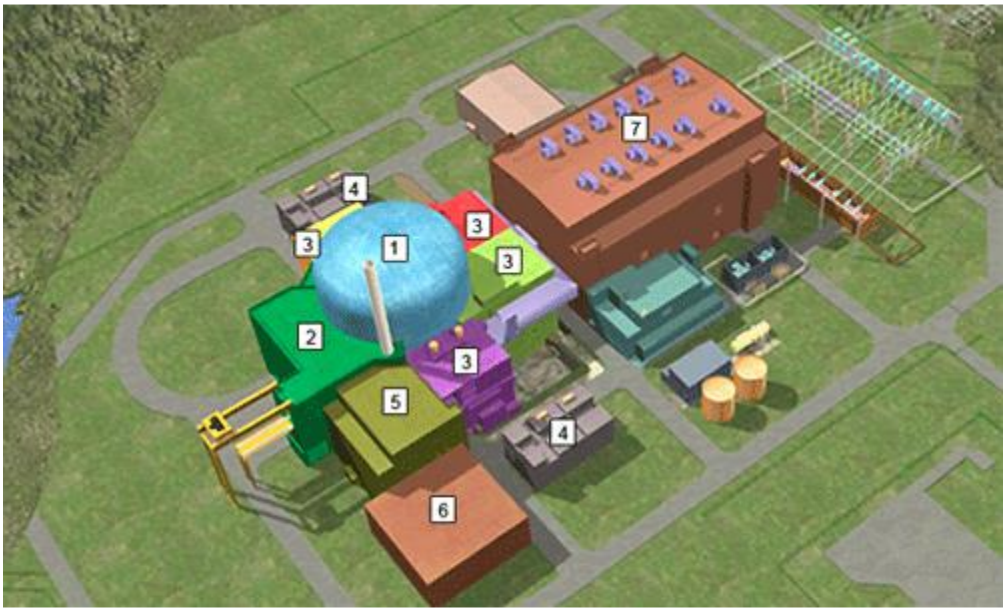
10) Secondary neutron activation through absorption (not fission) is a main reason for burn-up disparity. As regards PU-238 a 2-fold increase in burn-up results in a 4-fold increase (Pu-238 is produced from U-235) and PU 238 produces high decay heat. As the nuclear Decommissioning Authority dryly notes, "given the pessimisms associated with per-canister inventories, it can be seen that the radionuclide characteristics of spent fuel from an EPR are consistent with those from the Sizewell B PWR." *NDA, Geological Disposal Generic Design Assessment, ibid., p 33.*

Non-sequiturs notwithstanding, the long-term radioactivity and hence radiotoxicity of the spent fuel, which emanates from the actinides, will be notably increased by high burn up and hence could reasonably give rise to 'pessimisms'.

A2.7 – Brief note on Spent Fuel storage

The GDA (see section 1.3) makes clear that fuel rod cladding degradation and stress requires that High Burnup Spent Fuel is inspected 'to maintain confidence that the fuel remains in a in a suitable condition'. It is difficult to see how this assists earlier dry surface storage or potential geological storage. We do not have a plan, design or location for a GDF (Geological storage) however, non-retrievability of the stored waste is assumed. We therefore urgently need to establish whether a GDF that meets the standards required for our High burnup new reactor Spent Fuel and our legacy material is feasible. (Legacy waste in temporary store in Sellafield comprises 65 years' worth of High-Level Waste, including spent fuel from the AGRs, Sizewell B and including 146 tonnes of separated plutonium).

Reactor layout:



EPR™ reactor layout

The EPR™ reactor layout offers resistance to external hazards, especially earthquakes and aircraft crashes.
The outer shell protects the Reactor Building, the Spent Fuel Building and two of the four Safeguard Buildings including the control room

The spent fuel store is in building 2. Four others contain the emergency cooling equipment for the reactor. All these five building are protected against external hazards (flood, wind, cold etc) and external attack – using thick reinforced concrete walls. All this physical protection is one of the reasons why the EPR is so costly.

2 - Fuel Building

The Fuel Building, located on the same common basemat as the Reactor Building and the Safeguard Buildings, houses the fresh fuel, the spent fuel in an interim fuel storage pool and associated handling equipment. Operating compartments and passageways, equipment compartments, valve compartments and the connecting pipe ducts are separated within the building. Areas of high activity are separated from areas of low activity by means of shielding facilities.
The mechanical floor houses the fuel pool cooling system, the emergency boration system, and the chemical and volume control system. The redundant trains of these systems are physically separated by a wall into two building parts.