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Nuclear power plant lifetime extension: **A creeping catastrophe**

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The Bellona Foundation is an international environmental NGO based in Norway. Founded in 1986 as a direct action protest group, Bellona has become a recognized technology and solution-oriented organizations with offices in Oslo, Brussels, Kiev, St. Petersburg and Murmansk. Altogether, some 60 engineers, ecologists, nuclear physicists, economists, lawyers, political scientists and journalists work at Bellona.

Environmental change is an enormous challenge. It can only be solved if politicians and legislators develop clear policy frameworks and regulations for industry and consumers. Industry plays a role by developing and commercializing environmentally sound technology. Bellona strives to be a bridge builder between industry and policy makers, working closely with the former to help them respond to environmental challenges in their field, and proposing policy measures that promote new technologies with the least impact on the environment.

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LIST OF ABBREVIATIONS

AMP	Ageing management program
BWRs	Boiling water reactors
IAEA	International Atomic Energy Agency
LBP	Late blooming phases
LTO	Long-Term Operation
PLEX	Plant Lifetime Extension
PLIM	Plant Life Management
PTS	Pressurized thermal shock
PWRs	Pressurized water reactors
RPV	Reactor pressure vessel

NUCLEAR POWER PLANT LIFETIME EXTENSION: A CREEPING CATASTROPHE

Introduction

The global nuclear reactor fleet is ageing; the average age of the 442 operating commercial reactors is over 26 years[1]. Where the reactors are older, such as in the USA, Canada and the European Union, there are so few reactors under construction, that it would be impossible to replace the old units as they reach the end of their designed lifespans[2]. There are several reasons behind this phenomenon, but the most important factor is the price of building new units. The construction costs of those designs currently available on the market are enormous[3], and investments on liberalized markets are too risky in comparison with other energy production solutions, such as renewables. As a result, private investors tend to choose alternatives. The other option for maintaining nuclear energy production is to extend the operation of the ageing reactors. As the construction costs of these reactors have already been paid, lifespan extensions are viewed as highly profitable.

Plant Lifetime Extension (PLEX), Plant Life Management (PLIM) and Long-Term Operation (LTO) are three different names describing the same activity – extending the operation of old nuclear power plants beyond the lifespans they were designed for.

At present, more than 90 nuclear reactors within the United Nations Economic Commission for Europe are awaiting decisions on whether their lifespans will be prolonged. These decisions are due to come within the next eight years[4]. There are ongoing lifespan extension procedures underway in Armenia, Belgium, Bulgaria, the Czech Republic, Finland, France, Hungary, the Netherlands, Slovenia, Spain, Sweden, Ukraine and the UK. Other countries are expected to follow soon[5].

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1 https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx.

2 https://pris.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByRegion.aspx

3 https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

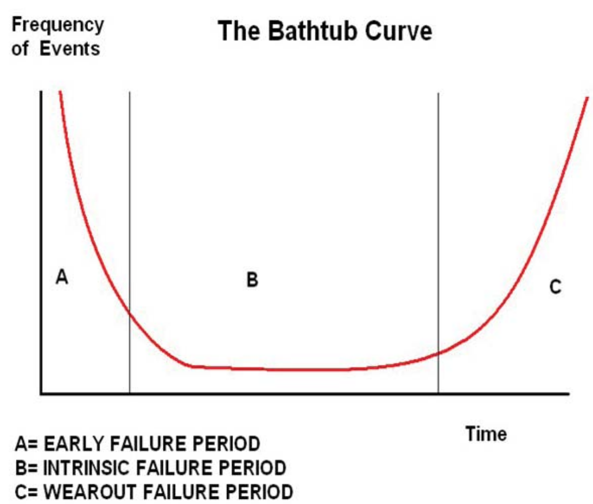
4 https://www.unece.org/fileadmin/DAM/env/eia/documents/WG2.7_May2018/2018_05_17_RS_Espoo_WG__Workshop_IC_Chair_final_clean_rev.pdf.

5 http://www.nuclear-transparency-watch.eu/wp-content/uploads/2017/06/presentation-JH-in-ENSREG-2017.pdf
See also:
https://www.unece.org/fileadmin/DAM/env/eia/documents/Workshop_on_env_and_health_impacts_Lisbon_2019/session1.1._UNECE_presentation_LTE_of_NPPs_05.06.2019_rev.pdf

Background

These ageing reactors pose a safety concern to the whole world. The UN's International Atomic Energy Agency (IAEA) defines reactor ageing as a process in which the characteristics of a structure, a system or components change with time or use[6].
No human-made structure can be made absolutely safe from failure at present. The risks for catastrophe change as nuclear reactors age, much like the risks of death by accident or illness change as people get older. For nuclear reactors, this means aggressively monitoring risk during the three stages of plant lifetime, from when it first goes into operation until it nears the end of its designed lifetime.

These stages are called the break-in phase, midlife phase, and the wear-out phase. These phases conform to a bathtub curve. During the break-in phase, we see a higher rate of incidents and accidents. For instance, the accidents at Chernobyl and Three Mile Island occurred relatively soon after these reactors started operation. During the midlife phase, the curve tends to plateau. Then it rises again as more accidents and incidents are observed during the wear-out phase (see graph below)[7].



The process of materials degradation within a nuclear reactor is very complex. There are many different types of materials within the reactor itself. These include more than 25 different metal alloys within the primary and secondary systems[8], to say nothing of the concrete containment vessel, the instrumentation and control systems, and other support facilities. When this diverse set of materials is placed in the complex and harsh environment coupled with load, degradation over an extended life is difficult to track and observe.

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6 https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1830_web.pdf.

7 http://www.beyondnuclear.org/safety/2014/10/30/beyond-nuclear-warns-nrc-against-weakening-rpv-embrittlement.html.

8 https://www.sciencedirect.com/science/article/pii/S1369702110702200. Materials challenges for nuclear systems.

But controlling and mitigating these degrading processes is essential during reactor operation, as well as during power uprate considerations[9], and, of course, when weighing whether or not to extend a reactor's runtime.

In general, the safety of the ageing nuclear power plant can be maintained with measures to monitor and control ageing processes known as an ageing management program (AMP). Key elements of the AMP are in-service inspections, monitoring of thermal and mechanical loads, optimizing operational procedures in order to reduce loads and, where needed, replacement of systems, structures and components[10]. In principle, all components crucial for safety in pressurized water reactors (PWRs) or boiling water reactors (BWRs) can be replaced except two: The reactor pressure vessel (RPV), and the containment structure[11]. PWRs are typical in most of the currently operating nuclear power plants. The RPV is the most important of these items from safety perspective, and its integrity thereby determines a reactor's lifetime. It is therefore essential to monitor the RPV and to accurately predict the changes that occur within it during operation.

The most important processes causing RPV ageing are neutron radiation, material fatigue, mechanical and thermal stresses from operation and different corrosion mechanisms[12]. The key sites for reactor degradation occur along the beltline weld region, the outlet/inlet nozzles, the instrumentation nozzles and flange closure studs, all of which are subjected to neutron irradiation and to mechanical and thermal loads[13]. The extent of neutron embrittlement or irradiation induced degradation is controlled by fabrication and operational variables, mainly the chemical composition of the RPV beltline material (particularly copper, phosphorus and nickel concentrations) and neutron fluence; other important variables include: irradiation temperature, neutron spectrum and flux, thermomechanical history, concentration of other impurities or minor alloying elements[14].

Neutron radiation embrittlement is considered the primary ageing degradation phenomenon occurring in materials making up RPVs. It starts at the nanometer level. As the RPV is exposed to neutron radiation, embrittlement occurs in areas adjacent to the core[15]. Should an embrittled RPV encounter a flaw, and if certain severe system transients[16] occur, the flaw could rapidly propagate through the vessel and challenge the integrity of the RPV. The severe transients of concern, known as pressurized thermal shock (PTS), are characterized by a rapid cooling of the internal RPV surface in combination with repressurization of the RPV[17]. Failure of the pressure vessel constitutes an accident beyond

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[9] https://www.nrc.gov/reactors/operating/licensing/power-uprates.html

[10] Plant Life Management Models for Long Term Operation of Nuclear Power Plants, IAEA Nuclear Energy Series, No. NP-T-3.18, VIENNA.

[11] INTEGRITY OF REACTOR PRESSURE VESSELS IN NUCLEAR POWER PLANTS: ASSESSMENT OF IRRADIATION EMBRITTLEMENT EFFECTS IN REACTOR PRESSURE VESSEL STEELS. IAEA NUCLEAR ENERGY SERIES No. NP-T-3.11, VIENNA.
See also:
HEAVY COMPONENT REPLACEMENT IN NUCLEAR POWER PLANTS: EXPERIENCE AND GUIDELINES. IAEA NUCLEAR ENERGY SERIES No. NP-T-3.2, VIENNA.

[12] HANDBOOK ON AGEING MANAGEMENT FOR NUCLEAR POWER PLANTS, IAEA Nuclear Energy Series, No. NP-T-3.24, VIENNA.

[13] REVIEW OF ASSESSMENT METHODS USED IN NUCLEAR PLANT LIFE MANAGEMENT based on contributions by members of NULIFE Expert Groups 2 and 3.

[14] https://www.tandfonline.com/doi/pdf/10.1080/00223131.2013.772448?needAccess=true

[15] INTEGRITY OF REACTOR PRESSURE VESSELS IN NUCLEAR POWER PLANTS: ASSESSMENT OF IRRADIATION EMBRITTLEMENT EFFECTS IN REACTOR PRESSURE VESSEL STEELS. IAEA NUCLEAR ENERGY SERIES No. NP-T-3.11, VIENNA.

[16] https://www.nrc.gov/reading-rm/basic-ref/glossary/transient.html.

[17] Pressurized thermal shock in nuclear power plants: good practices for assessment. Deterministic evaluation for the integrity of reactor pressure vessel. IAEA-TECDOC-1627, VIENNA.

the design basis[18]. Safety systems are not designed to cope with this emergency. Pressure vessel failure can lead to immediate containment failure. A core meltdown accident with high and early radioactive releases would be the consequence.

Main challenges

When considering lifespan extensions, it is critical to assess higher neutron irradiation embrittlement on the materials in light water reactor RPVs. This allows for a clear assessment of the RPVs structural integrity. To generate this data, tests are carried out on the key alloys of steel used within RPV. These include several steels irradiated in the test or research reactors[19]. The primary alternative to obtain the required higher fluence is irradiation of materials in test reactors at much higher rates than in power reactors. Such data are crucial in understanding the radiation embrittlement mechanisms, and how it affects mechanical properties over extended periods of time.

Currently, there is not enough data on embrittlement trends to assess with a high degree of accuracy how they would behave in reactors running on extended lifespans.

Some of main reasons for this are:

– Most of the data on RPVs embrittlement has been obtained from specimens irradiated in research reactors (high neutron fluxes to obtain high fluence in a relatively short time), as opposed to irradiations performed as part of power reactor surveillance programs. Many of the test reactor specimens have been exposed to fluences far higher than anticipated, even at or beyond design lifetime. However, because of the accelerated exposure achieved in test reactors versus in power reactors, concerns persist that different damage mechanisms may be active in these different reactor environments. If true, this would make test reactor data an unreliable predictor for the power reactor embrittlement[20].

– There are indications of late segregations of Ni, Mn and Si – the so-called late blooming phases (LBP) – near the end of design lifetime. The delayed embrittlement caused by this LBP could produce a great threat to the mechanical performance of RPV steels – such as hardening and embrittlement – and could have serious implications on RPV life extension[21].

In addition to the effect of neutron irradiation embrittlement, there is a need to understand long time thermal ageing effects i.e. those beyond design lifetime. Thermal ageing is degradation of a material over time, due to temperature[22]. The understanding of long time thermal ageing effects is not, at present, very pronounced so there is a need for assurance that it will not present itself as another embrittlement mechanism.

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[18] https://www.nrc.gov/reading-rm/basic-ref/glossary/beyond-design-basis-accidents.html

[19] https://www.world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/research-reactors.aspx

[20] https://cnic.jp/english/newsletter/pdffiles/nit83.pdf, Embrittlement Forecast of Light Water Reactors' Pressure Vessel Steels. Professor Hiromitsu Ino, Department of Mechanical Engineering, College of Engineering, Hosei University. Nuke Info Tokyo, Japan.

[21] https://www.tms.org/pubs/journals/jom/0107/odette-0107.html

[22] AGEING MANAGEMENT FOR NUCLEAR POWER PLANTS: INTERNATIONAL GENERIC AGEING LESSONS LEARNED (IGALL). IAEA SAFETY REPORTS SERIES No. 82, VIENNA.

It is true that extending reactor lifespans is more economical than building new units. But saving pennies today may cost us billions in the future. We cannot continue to put economic viability of the nuclear industry ahead of safety.

Bellona's position

For its part, Bellona believes it has a role in warning the public about the risks of ageing nuclear reactors and the problems associat-ed with their runtime extensions – which are often granted with lit-tle to or no real regulation.

We would therefore urge that a monitoring system be put in place to gather data specifically related to accidents and incidents taking place at reactors that have been granted runtime extensions. This would allow operators to better anticipate risks when considering extensions, as well as add to transparency about incidents at an in-ternational level.

We also recommend better and more uniform regulation when reac-tor runtime extensions are being considered. The Espoo Convention is the most convenient avenue to accomplishing this. Signatory na-tions should be required to conduct environmental impact studies on proposed extensions, which should include worst-case scenarios for accidents.

Other NGOs have a robust role to play as well. They can organize working groups and liaise with authorities to insure that the rele-vant regulators are licensing runtime extensions in a safe and trans-parent manner. Such networks would be especially important for countries housing risk-prone reactors, because it could help bring those countries into line with the transparency their neighbors should expect.

NGOs can also help create a comprehensible dialogue around reac-tor runtime extension issues. Often, the information on such projects released by authorities is arcane and overwhelming, leaving the general public baffled and disengaged. NGOs can also help prod more reticent national regulators to release the information that the public should know and understand.

NGOs can furthermore become valued independent experts on runtime extensions, and thereby help authorities establish uniform guidelines and standards to be used when runtime extensions are being considered. This would be of particular use to the European Union as a whole, where we believe uniform standards to limit the practice of reactor runtime extensions should long ago have been put in place.

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