IRREVERSIBLE NUCLEAR DISARMAMENT

Irreversibility Considerations in the Decommissioning of Fissile Material Production Facilities for Nuclear Weapons: Marcoule and Pierrelatte

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Cover photo: Pierrelatte site

Abstract

The arms reduction climate prevailing after the ending of the Cold War led to a general realisation in nuclear weapons states (particularly in the United States, France and the United Kingdom) that stocks of weapon-grade highly enriched uranium and plutonium would not require to be replenished for a considerable period of time. In light of this, much of the industrial infrastructure that had been developed for the production of these materials was considered redundant and many such facilities were permanently shut down for decommissioning.

This paper is concerned with the decommissioning of facilities such as plutonium production reactors and uranium enrichment facilities and, in particular, the point at which the dismantling process can be considered practically and definitively irreversible. This is taken here to mean that essential structures and equipment have been sufficiently removed or rendered inoperable so that the facility can no longer be used to fulfil the purpose for which it was established. Considered in these terms, practical irreversibility is analogous to the stage achieved in the decommissioning of civilian nuclear facilities when safeguards requirements — i.e., international oversight arrangements to prevent illicit use of fissile materials and associated facilities — no longer apply.

The experience of France is illustrative of national approaches to the dismantling of nuclear weapons complexes undertaken after the ending of the Cold War and is presented here as a case study. France decided at that time on the permanent closure and dismantling of all its facilities dedicated to the production of fissile material for nuclear weapons, ceasing production of weapon-grade plutonium in 1992 and of highly enriched uranium in 1996. In 1996, the French government announced a moratorium on the production of these materials and began the dismantling of the corresponding facilities immediately following the ending of production. It further announced that the planned dismantling programme was irreversible.

Keywords: Decommissioning, fissile material, nuclear reactor, plutonium, uranium enrichment, irreversibility, safeguards

Background

The ending of the Cold War in the late 1980s was followed by significant reductions in nuclear arsenals in the United States and the Russian Federation, which together hold the great majority of nuclear weapons currently stockpiled around the world. The global stockpile was estimated to be about 13 080 weapons at the beginning of 2021, representing a two-thirds reduction over the previous 50 years.[1] The 1990s also largely marked the end of nuclear weapons testing, with the Comprehensive Test-Ban Treaty being opened for signature in 1996. Although this treaty has not yet entered into force[2], no country, with the sole exception of North Korea, has undertaken nuclear tests since the turn of the century.[3]

The main materials required to produce thermonuclear weapons (fusion or hydrogen bombs) are highly enriched uranium (HEU), plutonium and tritium, an isotope of hydrogen that significantly increases the impact (`yield`) of the weapon. In modern weapons lithium-6 deuteride, which produces tritium when activated (bombarded by neutrons), is used as the fusion fuel. Production of these materials requires industrial facilities of very significant size, technical complexity and expense and, after the Second World War, only a few countries — primarily (though not solely) the nuclear weapon states (United States, Soviet Union, China, France and United Kingdom) — had the capability to develop such infrastructure in its entirety:

- Specialised enrichment facilities for production of weapon-grade HEU, typically enriched such that it contains more than 85% of the U-235 radioisotope.
- Facilities for conversion of uranium oxide (yellowcake – uranium in powdered form) to uranium hexafluoride, being the source material for the uranium enrichment process.
- Nuclear reactors designed for plutonium production (`production reactors'), which use natural or very lowly enriched uranium as fuel (plutonium is produced from U-238), e.g. the first generation of gas cooled, graphite moderated, reactors operated by the United Kingdom[4] and France.
- Reprocessing facilities used to separate uranium and plutonium from spent reactor fuel.

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[1] International Panel on Fissile Materials, Global Fissile Material Report 2022: Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy, July 2022.

[2] Although ratified by 177 countries (as of February 2024), these generally do not include those with nuclear weapon arsenals apart from France and the United Kingdom. The US and China signed the treaty but have not ratified it. The Russian Federation signed and ratified but withdrew its ratification in 2023, though it remains a signatory. Israel, North Korea, India and Pakistan have not signed the treaty.

[3] Comprehensive Test Ban Treaty Organization - https://www.ctbto.org (Accessed 20 January 2024).

[4] The UK's first Magnox reactors — Calder Hall (operated from 1956) and Chapel Cross (operated from 1958) —were designed for dual use, i.e. generation of commercial electricity and plutonium production for the country`s defence programme. From the mid-1960s these were used only for electricity production.

- Facilities for production of tritium in significant quantities, which is typically produced in military production reactors.
- Weapons production facilities, including facilities for production of components such as plutonium pits (the core of an implosion nuclear weapon).

The global stockpile of HEU peaked in the 1980s. After the end of the Cold War, as nuclear weapon arsenals declined, the United States and the Russian Federation declared large amounts of HEU as being excess to requirements and began downblending them to produce low-enriched uranium fuel for nuclear power reactors.5 No significant reductions in stockpiles of plutonium for weapons production have taken place over the past 50 years, though it should be noted that there also exists a larger civilian plutonium stockpile, comprising material recovered from reprocessing of spent nuclear fuel from nuclear power plants used for electricity production. This stockpile is gradually being reduced by blending with natural uranium in the production of MOX (mixed oxide) fuel for nuclear reactors.6 Whereas plutonium and HEU have half-lives of thousands of years, the half-life of tritium is 12.32 years, i.e., about 5% of the tritium inventory disappears naturally each year, unless replenished, and therefore stockpile reduction occurs naturally.

A range of approaches was adopted by the nuclear weapons states in the period post the Second World War. Light water moderated reactors — the dominant reactor type used globally for commercial electricity production — are generally considered unsuitable for production of weapons-grade plutonium due to the level of Pu-240 isotopes in the spent fuel.[7] By way of illustration, during the Cold War period France developed a fleet of reactors and a fuel reprocessing plant at Marcoule (Gard Department) to support the French nuclear weapons programme, together with a centre for uranium enrichment at Pierrelatte (Drôme Department). France ceased production of fissile material for nuclear weapons in 1992 (plutonium) and 1996 (highly enriched uranium). In 1996, it announced a moratorium on the production of these materials. Simultaneously, France decided to dismantle the corresponding facilities following an irreversible approach.[8] The experience of France in decommissioning its

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[5] International Panel on Fissile Materials, Global Fissile Material Report 2022: Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy, July 2022.

[6] Ibid.

[7] Weapon-grade plutonium is typically defined as having an isotopic ratio of Pu-240 to Pu-239 of no more than 10 percent. Pu-240 is considered problematic for weapons use due to its high rate of spontaneous fission with consequent higher neutron emission and higher heat production than Pu-239. See United States Department of Energy, Report of the Expert of Energy Plutonium Disposition Work Group: Analysis of Surplus Weapon-Grade Plutonium Disposition Options, April 2014 https://fissilematerials.org/library/doe14a.pdf and World Nuclear Association - https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx (Accessed 20 January 2024).

[8] Government of France, Le démantèlement des usines de production de matières fissiles pour les armes nucléaires (Dismantling the fissile material production facilities for nuclear weapons), 2010,

infrastructure to produce fissile material to support its nuclear weapons programme is considered in more detail later in this paper.

Decommissioning of Fissile Material Production Facilities for Nuclear Weapons

Nuclear Reactors

The process of decommissioning nuclear facilities in the military and civilian sectors, and the associated regulatory norms, are essentially the same, i.e., the main activities involved in decommissioning a plutonium production reactor are the same as those applicable to an electrical power reactor. Furthermore, the decommissioning of an enrichment plant or a reprocessing facility for spent nuclear fuel is essentially the same whether used in the military or civilian sectors. As well as decontamination and dismantling of the systems, structures and components which form part of the facility, decommissioning also involves the decontamination and/or removal of any soil or groundwater contamination which may have occurred during the lifetime of the facility.[9]

Decommissioning encompasses all activities leading to the release of the facility from regulatory control, including decontamination, dismantling and treatment of the resulting materials such that they can either be cleared from regulatory control or placed in storage or disposal facilities.[10] Following the permanent shutdown of a nuclear reactor, whether military or civilian, the next stage of activity is generally the removal of spent fuel from the reactor core and its placement in a storage pool to allow it to cool, before being transferred to a longer-term storage facility away from the reactor building. Early activities also typically include the removal and management of radioactive waste and residues from the operational period, establishment of facilities for management of materials from dismantling of the facility and modification of safety systems in preparation for the dismantling phase. The removal of spent fuel from a reactor results in a very significant reduction in the radiological hazard presented by the facility.

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https://onu.delegfrance.org/IMG/pdf_100329PM_BD.pdf; French National Assembly, Rapport d'Information sur la fin de vie des équipements militaires (Information Report on the end of life of military equipment), M. Grall (Member of the Assembly), March 2011, https://www.assemblee-nationale.fr/13/rap-info/i3251.asp.

[9] International Atomic Energy Agency, IAEA Bulletin Vol. 64-1, Nuclear Decommissioning, IAEA, April 2023 - https://www.iaea.org/bulletin/64-1; International Atomic Energy Agency, General Safety Requirements Part 6, Decommissioning of Facilities, IAEA, Vienna (2014).

[10] International Atomic Energy Agency, General Safety Requirements Part 6, Decommissioning of Facilities, IAEA, Vienna (2014).

Once the post-shutdown activities have been completed, the main dismantling activities may either be undertaken immediately (subject to regulatory authorisation), or they may be deferred. In the latter case part of the plant (typically the reactor building and its main components) may be placed in a state of 'safe enclosure', i.e., sealed up for an extensive period pending final dismantling – see Figure 1.

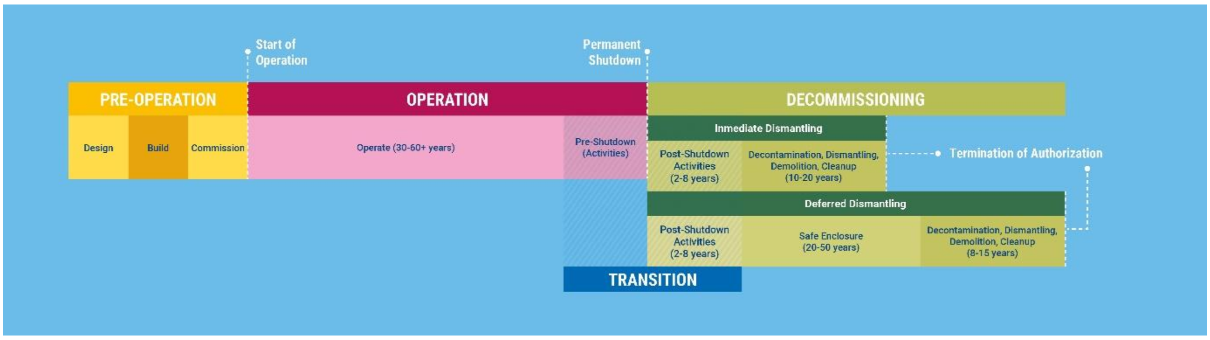

Figure 1:Typical Lifecycle of a Nuclear Power Plant[11]

There is currently little experience internationally of dismantling gas-cooled, graphite moderated, reactors (typical of the type used for plutonium production). These are expected to take significantly longer to decommission, and at significantly greater cost, than pressurised or boiling water reactors, owing to their much greater size and complexity.12 The absence of long-term management strategies and associated facilities for irradiated graphite represents an important current constraint on decommissioning these reactors.13 In general, regardless of the type of reactor, peripheral plant and structures, such as the turbines used for conversion of steam to electricity, are dismantled at an early stage in the process, and the reactor and associated core components are dismantled at a later stage.

Activities still ongoing after the removal of nuclear material and essential structures and equipment typically involve cleanup activities necessary to demonstrate compliance with site release criteria agreed with relevant regulatory authorities. This may include the decontamination or removal of any soil or groundwater in the vicinity of the nuclear facility that had become contaminated during the operational phase to levels deemed to be of safety significance. It may also concern building foundations and other facility material requiring removal due to levels of contamination which exceed criteria established by relevant national regulatory authorities.

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[11] International Atomic Energy Agency, IAEA Bulletin Vol. 64-1, Nuclear Decommissioning, IAEA, April 2023 - https://www.iaea.org/bulletin/64-1.

[12] Ibid.

[13] International Atomic Energy Agency, Report NW-T-2.16, Global Status of Decommissioning of Nuclear Facilities, March 2023.

Fuel Cycle Facilities

Fuel cycle facilities comprise those facilities associated with the early and late stages of the nuclear fuel cycle. They include facilities used for the production of nuclear fuel (prior to its use in a nuclear reactor), facilities involved in the mining and milling of uranium, together with facilities associated with the management of spent nuclear fuel after its removal from the reactor.[14] For the purposes of this paper, they are assumed to include those facilities associated with:

- Uranium conversion (to uranium hexafluoride).
- Uranium enrichment.
- Uranium fuel fabrication.
- Spent fuel storage.
- Spent fuel reprocessing and recycling.

The approach generally adopted to decommissioning fuel cycle facilities is first to reduce or remove materials with high levels of radioactivity which might be spread to other parts of the plant (i.e., are considered 'mobile'), and thereby enabling subsequent activities to be implemented with reduced risk. An important prerequisite to dismantling a fuel cycle facility is the retrieval and conditioning of large amounts of operational or legacy waste, including sludges, which may still be present inside the facility. These preliminary activities may take a considerable time, often in the order of 1-2 decades, which may mean that the time taken to complete decommissioning may be several decades overall.

Material and waste management activities play an important role throughout the decommissioning of a fuel cycle facility due to the large quantities of materials involved. These range from radioactive waste with significant amounts of long-lived radionuclides, requiring geological disposal or long-term interim storage, to large quantities of lightly contaminated steel, suitable for decontamination and clearance or recycling through dedicated processes.

The decommissioning of spent fuel reprocessing facilities is significantly more challenging than other types of fuel cycle facilities, e.g., due to high dose environments, criticality risks and the diverse nature of facilities used to manage the different radioisotopes that are separated and often concentrated during reprocessing. The presence of radioactive deposits and contamination with actinides throughout the facility — the removal of which takes considerable time and requires that the plant's safety functions are preserved through most of the decommissioning project — is also an important factor.

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[14] Ibid.

From a decommissioning perspective, large reprocessing facilities may be regarded as a collection of connected process facilities, including those concerned with mechanical disassembly of spent fuel, acid dissolution of the fuel fragments, solvent extraction and partitioning (to separate plutonium and uranium oxides), plutonium oxide conversion, uranium oxide conversion, and associated process liquor storage facilities. A typical decommissioning strategy may involve decommissioning activities proceeding at a different pace in different facilities, such that one facility may already being dismantled while another is still at the stage of post-operational cleanout. Such a sequencing approach adds additional challenges for the overall decommissioning project.

Achieving Irreversibility in the Decommissioning Process

Impacting Factors

A state of irreversibility is achieved progressively during the decommissioning of any nuclear facility, i.e., the effort needed to reverse the process such that the facility could be reused becomes progressively greater as the project proceeds. The reasons for this include technical factors — ageing and associated degradation of equipment — and factors related to knowledge of the facility and the competence needed to replace dismantled plant systems, structures and components. Eventually, a stage is reached when the facility may be considered definitively inoperable, meaning that the systems and equipment essential for its operation have been removed or otherwise destroyed and the facility would need to be entirely reconstructed if further use were considered. Factors impacting the degree of irreversibility achieved at a particular stage of the decommissioning process include:

Degree of uniqueness of the facility

Facilities operated for military purposes are generally prototypes or `first-of-a-kind` facilities, i.e., each is unique, and this in itself presents a challenge for reversibility. Unlike commercial facilities, military facilities often involve the design and construction of unique items of equipment, provided by specialist suppliers. Since such facilities have often operated for many decades, suppliers with relevant expertise may no longer exist or may have lost the competence necessary to fabricate the specific equipment required. Accordingly, 'retrofitting' a facility to operate it again after a long period of closure may prove impossible due to the absence of qualified equipment suppliers.

Extent of compliance with present day safety standards

Nuclear regulation generally evolves during the lifetime of any nuclear facility, with the result that facilities licensed for operation under earlier regulatory standards could not be licensed today without significant design changes. Regular safety reviews of nuclear facilities are undertaken, typically on a 10-year frequency, to ensure such facilities remain safe for continued operation. The outcome of such reviews often results in significant modifications to plant safety systems for compliance with then-current safety standards. In the case of a facility already undergoing decommissioning, the changes needed to achieve such compliance are likely to be very extensive, such that the effort needed to relicense the facility for renewed operation may be prohibitive.

Time elapsed since permanent shutdown of the facility

Current trends suggest that the preferred approach following permanent shutdown of a nuclear facility is to proceed immediately with its decommissioning, rather than to follow a deferred decommissioning strategy. This represents a significant change from the approach often followed in the past, particularly in the case of military facilities. An important consideration, in the case of the latter, is the extent of the cleanout activities already undertaken prior to designating the facility as being in safe enclosure, during which time only inspection and minimal maintenance activity tends to occur.

In cases where no extensive cleanout activities (e.g., removal of legacy material, flushing/rinsing of systems) were undertaken, and with limited ongoing heating and ventilation of the facility, extensive degradation of equipment such as pumps, valves and filters, may have occurred. It is probable that such equipment would need to be replaced if the facility were to be refurbished for future operation. The associated likelihood of there being incomplete knowledge of the condition of equipment and of the properties of legacy material still present in the facility exacerbates this challenge.

Other difficulties arise even when extensive cleanout of systems has been undertaken following permanent shutdown of a nuclear facility. The reagents and processes used, e.g., for a full decontamination of the primary circuit of a nuclear reactor, result in the removal of base metal from plant components and pipework systems (as well as the contamination layers), generally making the circuit components unusable for their original purpose.

Achieving Practical Irreversibility

The concept of practical (i.e., definitive) irreversibility during decommissioning of facilities used for fissile material production has a strong parallel in the approach being used to determine the application of international safeguards[15] obligations during the

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[15] Safeguards are a set of technical measures that are applied by the International Atomic Energy Agency (IAEA) on nuclear facilities and material. Through these technical measures, the IAEA seeks to independently verify that that nuclear facilities are not misused, and nuclear material is not diverted from

decommissioning of civilian nuclear facilities.[16] Here, implementation of safeguards obligations is focussed on removal/recovery of nuclear material, and the removal/rendering inoperable of residual structures and equipment essential for facility operation.[17] A corollary of this is that safeguards obligations may be terminated prior to the release of the facility from control by the relevant national regulatory authorities for nuclear and radiation safety, i.e., the formal termination of decommissioning.

Nuclear Reactors

A nuclear reactor may be considered inoperable in a practically irreversible sense once the reactor and its control systems and other components of the primary coolant loop (e.g., steam generators or heat exchangers, reactor coolant pumps and pressurisers) have been removed or otherwise rendered inoperable. This is typically achieved by the use of techniques such as cutting, crushing, melting, filling with concrete or drilling the plant components, such that the facility could no longer be used to handle, process, or utilise nuclear material. It corresponds to the point reached during dismantling when international safeguards obligations are no longer applied to civilian nuclear facilities. Given that the reactor core is not generally dismantled until a late stage of a decommissioning project, this means that — unless the core is already in a significantly degraded or damaged state — the facility may not be considered as inoperable in a definitive sense until decommissioning activities have reached an advanced stage.

Although practical irreversibility is not achieved until the reactor vessel and the items within or directly attached to it have been dismantled or removed, the progressive removal of the fuel charging machines and of the equipment which controls the level of power in the core (including the reactor control rod drives) and associated instrumentation and control systems make it increasingly difficult to reverse the dismantling process. In practice, therefore, there exists a spectrum of reversibility, i.e., the effort needed to return the facility to an operational state becomes progressively more onerous, until a state is reached where a new facility would need to be constructed.

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peaceful uses. Nuclear material in the context of safeguards means `special fissionable material (i.e. plutonium-239; uranium-233; uranium enriched in the isotopes 235 or 233) and `source material` (e.g., natural or depleted uranium, thorium).

[16] International Atomic Energy Agency, IAEA Safeguards Glossary 2022 Edition - https://www-pub.iaea.org/MTCD/Publications/PDF/PUB2003_web.pdf.

[17] Swan, K., Whitlock, J., Doo, J., and Tsutsui, K., *Safeguards Considerations for Post-Operational Facilities*, International Atomic Energy Agency Symposium on International Safeguards: Reflecting on the Past and Anticipating the Future, 2022.

Fuel Cycle Facilities

Fuel cycle facilities may be considered inoperable in a practically irreversible sense once the components essential to the process being undertaken have been removed or otherwise destroyed (e.g., through cutting, crushing, melting, filling with concrete, drilling), such that the facility could no longer be used to handle, process, or utilise nuclear material. For example:

- for a uranium enrichment facility using gas centrifuge technology, this would imply that the uranium hexafluoride feed systems and gas centrifuges, together with equipment essential for their operation, had been fully dismantled. The centrifuges comprise thin-walled cylinders spun at high speed in a vacuum environment by a rotor assembly and a system for feeding and extracting uranium hexafluoride in gaseous form. The centrifuges are arranged in a cascade system to achieve progressively higher levels of enrichment.
- for an enrichment facility using gas diffusion technology, it would imply that the feed systems and diffusion barriers, and equipment essential for their operation, had been fully dismantled. Other equipment essential for the operation of the diffusion assemblies include compressors, heat exchangers (to cool the hydrogen hexafluoride gas) and associated piping and valve systems. The assemblies are arranged in a cascade system to achieve progressively higher levels of enrichment.
- for a reprocessing plant, it would imply that the plant used for mechanical disassembly of spent fuel, acid dissolution of the fuel fragments, solvent extraction and partitioning (to separate plutonium and uranium oxides), plutonium oxide conversion, uranium oxide conversion, and associated process liquor storage facilities, together with equipment essential for their operation, had been fully dismantled.

Decommissioning fuel cycle facilities generally involves the early removal of highly radioactive components and materials, with the aim of reducing mobile sources of radioactivity as soon as possible in order to decrease the risk of spreading contamination to non-contaminated or lightly contaminated areas of the facility, or indeed the risk of radionuclide release to the environment in case of unexpected events (fire, flooding, etc.).

As with nuclear reactors, although practical irreversibility is not achieved until the essential components of a fuel cycle facility have been dismantled or removed (or are already in a significantly degraded or damaged state), the progressive removal of the feed systems and of the equipment which ensure the safety of the facility make it increasingly difficult to reverse the dismantling process. Again, therefore, there exists a spectrum of reversibility, and the effort needed to return the facility to an operational state becomes progressively more onerous and is likely to quickly become prohibitive in a practical sense.

Case Study - Decommissioning of Fissile Material Production Facilities for Nuclear Weapons in France

Introduction

France has been involved in the development of nuclear weapons since the Second World War, having established an Atomic Energy Commission (*Commissariat à l'Energie Atomique, CEA*) in 1945. It detonated its first nuclear weapon in February 1960 in the Algerian Sahara Desert (then part of France). CEA was also responsible for the early development of civil nuclear fuel cycles in France, under a separate organisational and management structure and subject to separate regulatory regimes. Nonetheless, each programme (civilian and military) was able to benefit from significant developments occurring in the other.

The French government ceased production of fissile material for its nuclear weapons in 1992 (plutonium) and 1996 (highly enriched uranium). In 1996, it announced a moratorium on the production of these materials. Simultaneously, France decided to dismantle the corresponding facilities:

- G1 (1956-1968), G2 (1958-1980), and G3 (1959-1984) were gas cooled and graphite moderated and were designed for dual use, i.e., plutonium production for the country`s defence programme and generation of commercial electricity.
- UP1 fuel reprocessing facility (1958-1997) reprocessed spent fuel from the G1, G2 and G3 reactors using the PUREX[18] solvent extraction process.
- Celestin 1 (1967-2009) and 2 (1968-2009) reactors, used for tritium and plutonium production (until 1992).
- Pierrelatte uranium enrichment centre (1964-1996) using gaseous diffusion technology.

The dismantling programme was launched immediately after the ending of production and the government announced that the dismantling of the facilities was irreversible. It further stated that this represented a considerable effort in terms of financial undertaking, as well as a challenge in terms of implementation and know-how.[19]

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[18] PUREX (plutonium uranium reduction extraction) is a chemical process involving dissolution of fuel in a solvent and separation of uranium and plutonium from other fission products.

[19] Government of France, Le démantèlement des usines de production de matières fissiles pour les armes nucléaires (Dismantling the fissile material production facilities for nuclear weapons), 2010, https://onu.delegfrance.org/IMG/pdf_100329PM_BD.pdf].

Pierrelatte

France began a gaseous diffusion programme in 1953 and, following the successful demonstration of a pilot plant at Saclay in 1958, a diffusion barrier plant was built in 1960 near the village of Pierrelatte (Drôme). The plant was comprised separate units designed to achieve a progressively higher level of enrichment. The first enrichment unit came into service in 1964, and the entire plant was operational by the beginning of 1967. Operations continued until 1996. The gaseous diffusion plant comprised four units of decreasing size, which corresponded to four levels of uranium enrichment:

- the low plant, the first to come into service and the largest, received a flow of natural uranium and delivered material enriched to 2% to the middle plant.
- the middle plant, commissioned in 1965, enriched the incoming flow to 6% and transferred it to the high plant.
- starting in 1966, the high and very high units increased enrichment to the level required for military applications.

The gaseous diffusion enrichment process involved concentrating uranium-235 by diffusing uranium hexafluoride (in gaseous form) through porous barriers. Because the difference in diffusion rate between the gas molecules containing the two isotopes is small, a very large number of diffusion stages had to be arranged in series. Each stage included a compressor to circulate the gas and two diffusers, containers in which the porous barriers were placed.

The plant stopped producing highly enriched uranium in 1996.[20] The last two sections were shut down in 1998, when the plant began to be dismantled. Following six years of preparatory activity, significant dismantling activities began in 2002 and lasted approximately one decade. Dismantling work was completed in 2010, by which time approximately 4 000 diffusers had been dismantled and packaged as waste for disposal, together with 1 330 tonnes of diffusion barriers, 1 200 km of pipework and 20 000 tonnes of very low level radioactive waste.[21] Completion of the dismantling of the diffusers and associated essential equipment (compressors, heat exchangers, etc.) meant that the plant was in a practically inoperable state and the decommissioning could not be reversed.

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[20] Government of France, Fact Sheet, Pierrelatte: uranium enrichment plant, 2009 - https://www.francetnp.gouv.fr/IMG/pdf/A_-_Pierrelatte.pdf.

[21] Government of France, Le démantèlement des usines de production de matières fissiles pour les armes nucléaires (Dismantling the fissile material production facilities for nuclear weapons), 2010, https://onu.delegfrance.org/IMG/pdf_100329PM_BD.pdf.

Marcoule

The CEA complex at Marcoule was established in 1952 as the main French facility for the production of plutonium for military purposes. In terms of this mission the complex is host to the following facilities:

- G1 gas-cooled reactor (40 MW thermal power, natural uranium fuelled, graphite moderated) – dual purpose, producing both plutonium and electrical power. The reactor was fully operational from September 1956 and was permanently shut down in October 1968. Following removal of the spent fuel, most of the facility has long been dismantled, apart from the reactor, which is currently in a state of safe enclosure awaiting final dismantling in due course. Completion of the decommissioning programme is dependent on the availability of a disposal route for irradiated graphite in France, which is expected to take several years.[22]
- G2 and G3 gas-cooled reactors (each 250 MW thermal power, natural uranium fuelled, graphite moderated) – dual purpose, producing both plutonium and electrical power. G2 reactor operated from 1958 to 1980 and G3 reactor from 1959-1984. Both reactors are currently in a state of safe enclosure, awaiting final dismantling in due course. Spent fuel and plant peripheral to the reactor have long been removed. Completion of the decommissioning programme is dependent on the availability of a disposal route for irradiated graphite in France, which is expected to take several years. The associated decommissioning programmes are expected to continue until 2050 [23]
- Celestin 1 and 2 heavy water cooled and moderated reactors (each 190 MW thermal power, fuelled with plutonium (originally) and later with enriched uranium). These reactors have been used for civilian isotope, tritium, and military plutonium production. Celestin 1 reactor operated from 1967 to 2009 and Celestin 2 reactor from 1968-2009. Both reactors are currently in a state of safe enclosure, awaiting final dismantling in due course. Spent fuel and plant peripheral to the reactor have long been removed. The associated decommissioning programmes are expected to continue until about 2050.[24]
- UP1 fuel reprocessing facility was operated from 1958 to 1997, employing the PUREX solvent extraction process. It was dedicated to reprocessing irradiated fuel from the G1, G2 and G3 reactors, extracting plutonium and recovered unburnt uranium. Production of plutonium halted in 1992[25] and dismantling

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[22] French National Assembly, Rapport d'Information sur la fin de vie des équipements militaires (Information Report on the end of life of military equipment), M. Grall (Member of the Assembly), March 2011, https://www.assemblee-nationale.fr/13/rap-info/i3251.asp

[23] Ibid.

[24] Ibid.

[25] Although production of weapon-grade plutonium ended in 1992, the facility was subsequently used to produce plutonium dioxide (PuO_2) for production of mixed oxide fuel (MOX) for commercial reactors,

activities at the facility have been ongoing since 1998 and are expected to continue to 2035-2040.[26] Essential components (including gloveboxes for transformation of plutonium dioxide to plutonium metal, spent fuel dissolvers and solvent extractors) have already largely been removed, such that a *de facto* state of irreversibility has already been achieved.

As regards the reactor facilities, significant progress has been achieved with the dismantling work, including with the removal of essential components. Also considering the significant period of time since the facilities were permanently shut down, the effort involved in restoring the facilities is such that this is now a very remote possibility:

- Removal of spent fuel and highly radioactive liquors from the reactors has made redundant much of the instrumentation and control systems required to ensure nuclear safety.
- Although the reactors remain in place, re-establishing the coolant circuits and the reactor instrumentation and control systems, in line with current safety standards, would be technically extremely challenging.

As regards the possibility of re-establishing the UP1 reprocessing facility, similar considerations apply as in the case of the reactors. In such a scenario the plant would need fully to meet the requirements of modern safety standards, again requiring that the instrumentation and control systems be largely redesigned and rebuilt. Given that spent fuel reprocessing comprises several constituent processes and associated facilities (mechanical disassembly of spent fuel, acid dissolution of the fuel fragments, solvent extraction and partitioning, plutonium oxide conversion, uranium oxide conversion, and high activity liquid waste evaporators[27]) the extent to which facilities could be reused differs for the individual processes. Nonetheless, in practical terms, the effort needed to re-establish the UP1 facility is again such that this eventuality is highly improbable.

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reprocessing spent fuel from other sources than G1, G2 and G3. For this purpose, it was connected to the APM reprocessing plant (‘*Atelier Pilote de Marcoule*’ (Marcoule Pilot Plant)).

[26] Government of France, Fact Sheet, Marcoule: UP1 spent fuel reprocessing plant, 2009 - https://www.francetnp.gouv.fr/IMG/pdf/E-MAR_UP1.pdf

[27] High activity liquid waste evaporators are used to concentrate aqueous waste raffinates from reprocessing, which contain the vast majority of the fission products from the spent fuel.

Conclusions

The possibility of restarting a shutdown facility has a number of dimensions, including:

- the continued existence and condition of essential systems, structures and components.
- the availability of knowledge and expertise to redesign, relicense and reoperate the facility in line with current safety standards.
- the ability of the supply chain to fabricate and install systems, structures and components that need to be replaced.

Decommissioning directly impacts the first of these dimensions and, furthermore, systems, structures and components may have been degraded by natural processes to such an extent that they have become obsolete and their replacement is no longer feasible. Such situations may arise:

- when the period of operation of the facility prior to shutdown was extensive, resulting in significant wear and tear of systems, structures and components, e.g., corrosion of pipes and vessels, high levels of activation and contamination.
- after a long period of inactivity following shutdown during which the environmental conditions in the plant have not been controlled.
- in situations where post operational cleanout activities have caused significant damage to key essential components, e.g., the reactor pressure vessel in the case of nuclear power plants and dissolvers and high-activity evaporators in the case of fuel cycle facilities.

A facility may therefore be in a state such that it would be highly impractical for it be relicensed and made to function again, even where only limited dismantling work has taken place, i.e., its shutdown status is already irreversible. It should be noted that key essential components typically cannot be repaired, once damaged, due to the extremely challenging quality requirements which apply to them, such that new components would need to be manufactured and installed in the plant.

The concept of irreversibility is considered here only in physical terms. In this context, there exists a spectrum of reversibility, i.e., the effort needed to return the facility to operation becomes progressively more onerous until a state is reached where a new facility would need to be constructed. In terms of defining when practical (i.e., definitive) irreversibility has been achieved, a parallel is drawn with the approach adopted for the termination of international safeguards during the decommissioning of civil nuclear facilities, i.e., the point at which all nuclear material has been removed from the facility and all essential equipment has been removed or destroyed. The facility may then be considered as no longer being capable of fulfilling the purpose for which it was established.

Depending on the time elapsed since permanent shutdown of a nuclear facility, the effort needed to reestablish partially dismantled systems, structures and components is likely to become prohibitive at a much earlier stage, e.g. due to general degradation and the need to achieve compliance with the safety standards then applicable. Indeed, no experience currently exists globally of such facilities being returned to operation.

It is recognised that irreversibility of a process does have other dimensions beyond the physical one, e.g., relating to the knowledge and expertise that would be needed to recreate dismantled facilities at some point in the future. Both knowledge and expertise diminish over time, particularly as personnel with appropriate competence disappear from the workforce. In addition to personnel involved in the development and operation of fissile material production facilities, the level of expertise available in the supply chain needed to support the construction, operation and decommissioning of such facilities is also a crucial consideration, as indeed is the knowledge and expertise of the relevant regulatory authorities.

Hazards arising from the presence of high levels of radioactivity, in combination with chemical and physical hazards typical of a major industrial facility, require the application of extremely rigorous levels of quality, safety and environmental management. Maintaining regulatory and supply chain competence to deal with such high levels of complexity is extremely challenging, particularly in situations where the workforce is not continuously engaged in projects in the nuclear sector. The redevelopment of the organisational and individual competencies needed for undertaking such activities in the nuclear domain is likely to be extremely time consuming and expensive, involving a combination of education and training in a range of highly technical fields. This may take many years or even decades, such that this aspect will itself have a major impact on reversibility of the dismantling of the industrial infrastructure necessary for the production of fissile materials for use in nuclear weapons systems.

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Working papers

Joelien Pretorius. **Staying the course: Lessons from South Africa for irreversibility of nuclear disarmament**. March 2023. York IND Working Paper#1.

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Research Reports

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