Decommissioning and dismantling

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Note
In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

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1 Concepts and facts

Decommissioning of nuclear power plants: three approaches

After final shutdown nuclear power plants, reprocessing plants and other facilities of the nuclear process chain have to be decommissioned and dismantled, in the first place to minimize health hazards posed by the radioactive materials in the facility. The UK Nuclear Decommissioning Authority [NDA 2015] Q646 states:

> "Like all other industrial plants, nuclear facilities have a lifespan after which they become less efficient and need to be closed down. After they cease operating, nuclear facilities must have their radioactive material removed before they are taken apart and the land they occupy is cleared and returned for future use."

Within the nuclear industry there are three generally accepted approaches to decommissioning of nuclear facilities [UNEP 2012] Q621, [IAEA-*wmbd-st-2* 2002] Q657:

- Immediate dismantling, known as 'DECON' in the USA
  All equipment, structures and other parts of a facility containing radioactive materials are removed so that the site can be treated as uncontaminated for either unrestricted use (usually referred to as a 'greenfield' site), or more restricted use ('brown field' site).
- Deferrred dismantling, known as 'SAFSTOR' in the USA
  After all the spent fuel is removed, the plumbing is drained, and the facility is made safe, dismantling is postponed to later ('safe enclosure'). The deferral periods considered range from 10-100 years.
- Entombment, or *in situ* disposal, known as 'ENTOMB' in the USA
  Once spent fuel has been removed, reactors can be entombed. This involves encasing the structures in a durable material such as concrete while its radioactivity decays. Entombment is a relatively new approach that is mainly considered in special cases such as small research reactors or reactors in remote locations.

Immediate dismantling
Advantages: Experienced operational staff from the facility are still available who know the history of the site, including any incident in the past that could complicate the decommissioning process.
Avoids the unpredictable effects of corrosion or other degradation of the reactor parts over an extended period, as a result of ageing, and eliminates the risk of future exposure to radiation.
Disadvantages: Levels of radioactivity in the reactor and other parts are higher than in case of deferred dismantling. This means that greater precautions must be taken during dismantling, and that larger volumes of decommissioning waste may be classified as radioactive. Higher costs?
According to [IAEA-*wmbd-st-2* 2002]:

> "An advantage of immediate dismantling is the retention and utilization of plant expertise on the site during the actual dismantling. This expertise could lessen the potential for accidents and would avoid radiation doses associated with retraining of personnel. This may be needed particularly in cases where there is a lack of records, where undocumented changes were made during construction or backfitting, and where experimental facilities are to be decommissioned."

Deferred dismantling
Advantages: Allows radioactive materials to decay to lower levels of radioactivity than in the case of immediate dismantling. This reduces both disposal problems and risks of harm to workers. In the meantime, robotic and other types of techniques that make dismantling safer and cheaper may undergo further development. Lower costs?
Disadvantages: Construction materials, including concrete and steel, deteriorate with time (ageing), making the eventual decommissioning more difficult. Personal knowledge of a site's history will be lost as time passes.

The US Nuclear Regulatory Commission (NRC) limits the surveillance period to up to 60 years. Technical studies showed that for US power reactors there is little benefit in delaying dismantling for longer periods. [IAEA-*wmbd-st-2* 2002] states:

> "As the storage period continues, expertise in the layout, maintenance and operation of the reactor lessens as personnel leaves the facility, so that at the time of dismantling there may be no one with personal experience of the facility. This expertise will have to be reacquired at the time of dismantling, with a corresponding penalty in costs, occupational exposure and other factors."

Entombment

This approach can reduce worker exposure to radioactivity since there is less handling of contaminated materials. However, long-term maintenance and monitoring are required.

It is not clear which advantages entombment would have compared to immediate or deferred dismantling. Dismantling has to occur anyway, and dismantling of an entombed reactor involves vastly more materials to be removed. Sometimes even permanent entombment seems to be proposed by covering the nuclear sarcophage with a man-made hill. Such an approach might be prompted by mere financial arguments, for this is the cheapest 'solution' at the moment of closedown.

Complete sequence of decommissioning and dismantling

The thermodynamic analysis of this study is based on complete dismantling of each nuclear power plant. The site is to be restored to conditions needed for unrestricted reuse. The UK Nuclear Decommissioning Authority has published detailed plans for the decommissioning and dismantling of closed-down nuclear power plants and other nuclear facilities [NDA 2006] Q365, [NDA 2009] Q501, [NDA 2015] Q646. The outline of the NDA plans correspond with the general outline from earlier publications. Starting from these publications this study assumes that the full sequence of decommissioning and dismantling of a nuclear power plant would comprise the following phases:

Phase 1. Clean-out

After final shutdown, the spent fuel is removed from the reactor and transferred to an interim storage facility. The reactor and associated systems are prepared for the next stage, e.g. draining the liquid systems, disconnecting most operating systems and controlling the atmosphere within the containment building. This phase may take 2-5 years to complete.

Phase 2. Decontamination, or decommissioning

After removal of fuel elements and other removable components, the reactor vessel and the connected cooling system are to be chemically and mechanically cleansed, to remove as much radioactive contamination as possible. The contaminating material is sometimes called CRUD, Corrosion Residuals & Unidentified Deposits, it contains activated corrosion products from the reactor and cooling system, fission products and actinides from leaking fuel pins and from uranium oxide contamination on the outside of the fuel pins.

After decontamination, which may take 5-20 years to complete, the reactor, the biological shield and other radioactive equipment within the containment is sealed for a cooling period.

Non-radioactive ancillary buildings of the plant, e.g. offices and buildings not needed for the safe store period, are demolished and removed from the site during this phase.

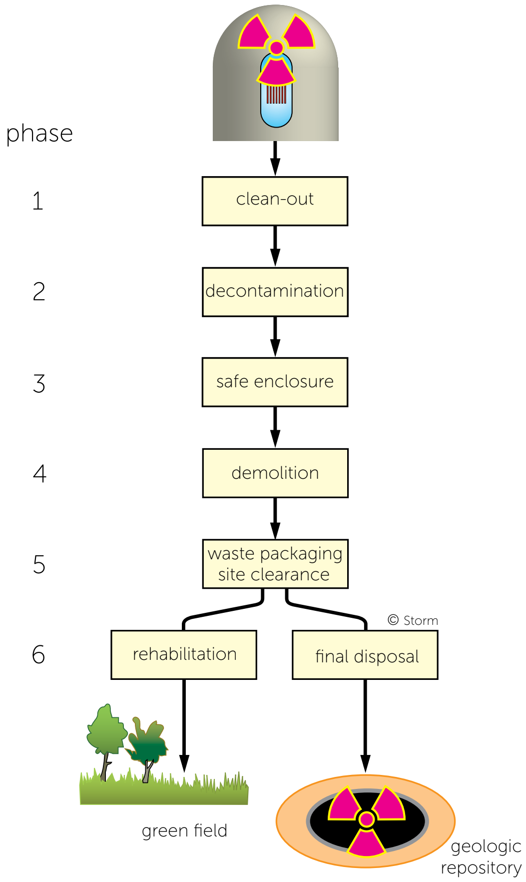

Figure 1
Sequence of activities of the decommissioning and dismantling of a nuclear power plant; the timescale may be as long as one century according to [NDA 2015] Q646. The last three processes, waste packaging, final disposal of the dismantling wastes and site rehabilitation, are not included in the NDA scenarios.

Phase 3. Safe-guarded cooling period, or safe enclosure, or safestor
During the cooling period following the decontamination, the nuclear island of the power plant is put into care and maintenance and has to be kept under surveillance. Operations and maintenance ensure that the plant remains in a safe condition. This cooling period may range from several years to more than a century. In many studies a minimum cooling period of 30 years or longer is considered, in which most of the short-lived activation products decay. After this period, the radioactive inventory is dominated by long-lived nuclides. It should be noted that little is known on the radionuclide composition and radioactivity of the parts to be demolished, for no commercial nuclear power plant has ever been dismantled after an average operating lifetime, e.g. 23 full-power years.

Phase 4. Dismantling, or demolition
The radioactive parts of the power plant are to be dismantled, cut into pieces and packed in containers for final disposal. Many of these activities have to be carried out with remotely controlled equipment, due to high radiation levels and the presence of radioactive dust.
Phase 4 may take 5-10 years. NDA suggests that this phase may start some 80-100 years after final shutdown.

Phase 5. Waste packaging and site clearance
In the current decommissioning & dismantling projects the wastes are usually stored in temporary facilities at the site of the NPP. Actually phase 5 should coincide with phase 4: immediately after release the radioactive rubble and scrap should be packaged in suitable containers, removed from the site and transported to a

geologic repository and sealed off from the biosphere definitively. Temporary storage should be avoided as much as possible to prevent illicit trafficking and other unwanted happenings.
All contaminated materials are to be removed from the site, including foundations and underground structures. In a unknown number of cases also large volumes of contaminated soil have to be removed and disposed of in a geologic repository.

Phase 6. Final disposal of wastes and rehabilitation of the site
The packaged wastes, spent fuel and decommissioning wastes, are transported to a geological repository and sealed off from the biosphere definitively.
Few if any of the known studies include the packaging and final disposal of the dismantlings waste. The analysis of this study includes the activities needed to isolate all radioactive waste from the biosphere indefinitely in a geological repository.
Rehabilitation, restoring the site to greenfield condition after removal of all radioactive materials, comprises returning fresh top soil to the site and replanting the site with indigenous vegetation.
In many cases the groundwater may turn out to be contaminated by artificial radionuclides. It is not clear what could be done to remediate this kind of contamination. It may be possible that the site cannot be released for unrestricted reuse.

Legacy to be decommissioned and dismantled

More than 95% of the current global inventory of human-made radioactivity is present in nuclear power plants, reprocessing plants and interim storage facilities of spent fuel (cooling pools, dry casks). The remainder of the human-made radioactivity is distributed over very large volumes of structures and waste present in other nuclear installations (e.g. fuel fabrication plants, enrichment plants, research reactors, experimental facilities), and stored in temporary or semi-permanent waste storage sites, such as shallow burial sites. Apart from the controlled sites containing radioactive materials there are numerous sites with contaminated soil and groundwater as a result of uncontrolled radioactive discharges.
In addition massive amounts of radioactivity is present in ship reactors and thousands of military installations left over from the Cold War, such as reprocessing plants. Although military applications of nuclear technology are not addressed in this study, the discussion of decommissioning and dismantling in this chapter broadly applies also to military nuclear installations. Health hazards are the same, wether caused by radioactivity from civil or from military nuclear installations.

In 2015 the global number of civil nuclear power plants was according to [IAEA-*rds2* 2018] Q652:

- 150 permanently shutdown,
- 438 in operation or operable,
- 70 under construction.

All these 658 NPPs are to be decommissioned and dismantled someday. 93 commercial NPPs in 16 countries are in some phase of decommissioning [IAEA-*wmdb-st-1* 2001] Q656. According to the IAEA research database: 650 research reactors, 292 are operational in 58 countries, 358 are shut down, of these 109 are decommissioned. In addition around 400 submarine reactors are to be decommissioned, producing about 800 Mg radioactive waste each. It is not clear what will happen with the discarded military reactors; the former Soviet Union has dumped 16 ship reactors at sea [UNEP 2012] Q621.

All those installations and sites must be decommissioned and cleaned up and all radioactive materials must be isolated from the biosphere in such a way that they cannot reenter the human environment, in order to minimize the nuclear health hazards for our childern, grandchildern and the generations to come. This task will be a formidable challenge in economic and societal sense, and not so much in technical sense.
This chapter discusses in more detail various aspects of the decommissioning and dismantling of civil

nuclear power plants; most of these aspects apply also to other nuclear installations.

The world has nearly 30 plants for spent fuel reprocessing, according to [ENS 2016] Q667 and [nucl-reproc-wiki 2016], with nominal processing capacities vaying from 1 Mg used uranium per year to about 3000 Mg U/a. Many of these plants, military installations from the Cold War or experimental plants from the 1960s, are shut down, but none is decommissioned yet. Some 12 reprocessing plants are still operating. All these plants and sites are to be decommissioned and dismantled someday.

Country	Location	Capacity tU/a	Commissioning or operating period
B	Mol	60	1966-1974
D	Karlsruhe	35	1971-1990
F	Marcoule, UP 1	600	1958-1997
F	La Hague, UP 2	800	1966-1974
F	La Hague, UP 2-400	400	1976-2003
F	La Hague, UP 2-800	1,000	1996
F	La Hague, UP 3	1,000	1990
GB	Windscale	300/750	1951-1964
GB	Sellafield, Magnox	1,500	1964
GB	Dounreay	8	1980-1998
GB	Sellafield, THORP	900	1994
IND	Trombay	60	1965
IND	Tarapur	100	1982
IND	Kalpakkam	100	1998
J	Tokai Mura	90	1977-2006
J	Rokkashomura	800	2006/2007
RUS	Mayak B*	400	1948-196?
RUS	Tscheljabinsk	400	1971
RUS	Krasnojark	800	
USA	Hanford, T-Plant *		1945-1956
USA	Hanford, B-Plant *	1 t/d	1945-1957
USA	Hanford, REDOX *	15 t/d	1952-1967
USA	Hanford, PUREX *	2,400	1956-1972/1983-1988
USA	Savannah, River Site *	~ 3,000	1952-2002
USA	West Valley	300	1966-1972

Table 1

Reprocessing plants, world-wide, * only military use. Source: [ENS 2016] Q667. Not listed here are reprocessing plants in China and Pakistan, see [nucl-reproc-wiki 2016] Q668.

Radioactivity of reactors and other structures

A large waste stream looming in the future will be formed by the decontamination waste, rubble, debris and scrap released during decontamination and dismantling of nuclear facilities, the reactor in the first place. The reactor vessel, internal and external structures of the reactor and the biological shield (concrete part of the building nearest to the reactor) will become radioactive by activation (neutron capture) of nonradioactive construction materials and by contamination with radioactive materials.

Activation

The radioactive inventory of the nuclear island increases with operational lifetime of the reactor, and is related to the total neutron flux (by activation) and contamination of the system. Typically, the inventory of a large PWR or BWR after about 20 full-power years, are estimated to be in the order of 100-600 PBq (petabecquerel: 1 PBq = $1*10^{15}$ Bq), one year after final shutdown and excluding spent fuel elements and control rods.

For short-living nuclides, an equilibrium between activation and decay will be reached after 10-20 full power years. According to a German study [Watzel et al. 1978] Q108, equilibrium will be reached in about 20 years. In their study only ^{55}Fe and ^{60}Co are taken into account, as in most other studies. For long-lived radionuclides, no equilibrium will be reached and the radioactive inventory of the reactor will grow with the operating life of the reactor. The inventory of activation products increases with the neutron flux [IAEA-389 1998] Q81.

Contamination

The radioactive inventory also rises during the operational years by progressive contamination of the system, despite of chemical and mechanical decontaminating activities during operation of the reactor.
The radioactive inventory caused by fission products from leaking and contaminated fuel pins and by activated corrosion products, CRUD (Corrosion Residuals & Unidentified Deposits), will be a function of the full power operating time. According to [Watzel et al. 1978] Q108 the contamination of the cooling system reaches saturation after about 5-6 years operation of the reactor. This supposition has still to be empirically confirmed. The inventory of contamination products a large PWR or BWR at equilibrium may be in the order of 1-5 PBq.

Not just the amount of radioactivity, but also the kind of the radionuclides contaminating the system has consequences for the way of demolition and handling the wastes. With longer operating times, the amounts of long-lived radionuclides by activation increase, and the chances of contamination with fission products and actinides increase, and consequently the health hazards.
In many cases large volumes of soil under and around a nuclear power plant or other installation will be contaminated by leaks and small accidents. The chances of contamination and the extent of it will grow with time due to unavoidable ageing processes.

The radioactive inventory of a nuclear power plant, after removal of the spent fuel elements and control rods, is an important parameter for the efforts needed to decommission and dismantle the plant. Dismantling will be increasingly difficult and energy-intensive as the radioactive inventory rises, due to several factors, e.g.:

- larger amounts of radioactive waste materials
- the fraction of long-lived radionuclides
- increasing fraction of troublesome nuclides (e.g. alpha emitters)
- decontamination of the reactor vessel and associated installations will become increasingly difficult and will require more energy, materials and equipment
- the (cumulative) radiation doses will be higher, so more material has to be removed by remotely controlled equipment and robots
- more auxiliary equipment and packaging materials will be needed
- more man-years are required
- more health and safety measures are demanded.

Typically, the inventories of large PWRs or BWRs after about 20 full-power years, are estimated to be in the order of 100-600 PBq (1 PBq = $1 \cdot 10^{15}$ Bq), one year after final shutdown and excluding spent fuel elements and control rods. The wide spread in the estimates is not explained and points to large uncertainties in the models used for the calculation of the inventories. Little or no empirical data based on actual measurements are available.
According to a US study [DOE 1978] Q278, quoted in [Lipschutz 1980] Q54, the inventory of a 1200 MW LWR after about 40 years operation typically will be about 15 MCi (555 PBq). This figure must be the result of a model calculation, as no nuclear power plant of that power existed in 1978, and no nuclear power plant reached a lifetime of 40 years in 1978.
Activation products present in the structures to be dismantled are, among others:
in steels and equipment parts, acording to [NCRP-*141* 2002] Q272, [NCRP-*81* 1993] Q256, [Woollam 1984] Q192:
H-3, C-14, Mn-54, Fe-55, Co-57, Ni-59, Ni-63, Zn-65, Nb-94, Ag-108m
and in concrete, according to [IAEA-*293* 1988] Q36:
H-3, C-14, Cl-36, Ca-41, Eu-152, Eu-154.

Contamination

The radioactive inventory of a nuclear power plant also rises during the operational years by progressive contamination of the system, despite of chemical and mechanical decontaminating activities during operation of the reactor. The activity caused by fission products from leaking and contaminated fuel pins and by activated corrosion products will be a function of the full power operating time. Little empirical data are known in the open literature.

Some fission products to be expected in the scrap metal and dismantling debris are, according to [NCRP-*141* 2002] Q272: Sr-90, Tc-99, Ag-110m, I-129, Cs-134, Cs-137, Ce-144.

Small amounts (less than 1% of total activity) of transuranic nuclides are expected to be present, e.g: Pu-238, Pu-239, Pu-240, Am-241, Am-243, and Cm-244.

These transuranics may dominate the hazard if an inhalation or ingestion pathway is significant.

Dismantling of reprocessing plants

Dismantling of a reprocessing plant will be an exceedingly hazardous and demanding task. Reprocessing plants are among the largest industrial complexes in the world. The hot cells, storage bunkers for solid wastes and storage tanks for liquid wastes are extensively contaminated by fission products, activation products, uranium, plutonium and other actinides. When a hot cell at a reprocessing plant becomes too radioactive as a result of prolonged use or of some technical failure, the cell will be closed and the reprocessing activities will be continued in a newly built cell; the same holds true when a storage facility gets filled. As a result of this practice at reprocessing plants volume and mass of the radioactive contaminated construction materials grows with time.

During the first phase after shutdown a reprocessing plant has to be decommissioned and cleaned up. This implies that all radioactive wastes resulting from the reprocessing of spent fuel have to be removed from their storage bunkers and tanks, packed into safe and durable containers and transported to a geologic repository.

This phase will be a daunting task, for reason of the degraded materials of the storage facilities and the massive amounts of wastes to be packed and safely removed: many thousands of cubic meters of liquid waste, many thousands of tonnes of solid waste. Special new plants have to be built for processing and packing the wastes. The chances of spills, unnoticed leaks and accidents are large, because this job might take decades.

After the cleanup phase has been finished, the buildings and associated equipment have to be demolished. The debris and scrap, most of it heavily contaminated by radionuclides have to be packed in safe and durable containers and transported to a geologic repository. Dismantling of the huge buildings will generate massive amounts of debris an scrap, to be counted in hundreds of thousands or even millions of tons. It may be inescapable that radioactive dust, aerosols and gases escape during the dismantling phase.

Costs of decommissioning and dismantling will be exceedingly high, due to the heavy contamination, the large volumes of wastes to be removed, often with robotic equipment, the massive amounts of radioactive dismantling waste and the long timeframe: from start to greenfield condition may take 100 years. Experiences with dismantling the West Valley reprocessing plant in the USA and some minor DOE plants for processing nuclear materials, are far from encouraging.

Unavoidably substantial amounts of radionuclides wil be released into the environment during cleanup and demolition of the buildings. What will happen with the immense amounts of radioactive debris and scrap? Serious risks are posed by the poor controllability of the handling of the debris and scrap, by illegal trade and criminality and by the trend to relax the exposure standards and allowed discharge limits when costs are mounting.

During the initial years of nuclear technology and reprocessing, during the 1940s, 1950s, 1960s and Cold War, little care has been paid to protection of the health and safety of the workers and the general public and protection of the environment.

Uncertain radioisotopic composition

Decommissioning and dismantling of an nuclear power plant or other nuclear facilities release large amounts of activated and contaminated scrap metals (thousands of tonnes from each nuclear power plant) and concrete rubble (tens of thousands of tonnes). From reprocessing plants these figures are at least a factor of ten higher. How controllable are that radioactive wastes?
Detection of many nuclides in scrap metal or concrete rubble is difficult if alpha emitters (U, transuranics) or low-energy beta emitters are involved; low-energy gamma emitters may escape detection as well [NCRP-141 2002] Q272. Absence of an easily detectable nuclide (e.g. Co-60, Cs-237) in no way warrants the absence of other radionuclides.

So, when scrap metal or rubble is cleared for unrestricted use after superficial screening with a radiation detector, how sure we are wether all nuclides present in the materials have been measured and accounted for? Or, are the clearance standards based on just a few easily detectable nuclides?
The biological properties of tritium and carbon-14, are poorly known. How about the knowledge on the biological behaviour of other radionuclides potentially present in the dismantling wastes?

2 Physical assessment

A detailed physical/thermodynamical assessment of decommissioning and dismantling of nuclear power plants, including waste packaging and final disposal in a geologic repositiry is addressed in report m40 *Radioactive waste management*.

Energy investment of decommissioning and dismantling

As far as known not one decommissioning + dismantling sequence of a nuclear power station, as represented by Figure 1, has ever been completed. Reported cost figures are often unclear with regard to the phases of the sequence that were included and which were not. In most cases the sequence was performed no further than phase 3: safe enclosure. In some cases the reactor vessels of small and experimental NPPs were transported to temporary storage sites. Also it remains unclear wether the total cost are mentioned or only the part that one of the stakeholders had to pay.
Few studies mentioned the (expected) energy investment, for example: [Ecoinvent 2003] Q333 estimated it at 0.2 PJ, [WNA-*eroi* 2017] Q155 at 0.9 PJ, [Vattenfall 2005] Q152 at 4.4 PJ. In view of the long timescale of the full decommissioning + dismantling sequence, possibly about a century, and the unexplained wide range of reported estimates, this study concludes that the reported figures are underestimates of the actual energy investment.
For those reasons this study bases its estimate of the energy consumption of decommissioning + dismantling on the estimated cost,according to the same method as the construction cost.

Cost figures reported in the open literature vary widely: from a fraction of the construction cost to more than the construction cost, see for instance [NDA 2006] Q365, [NDA 2015] Q646, [SWI 2011c] Q649, [IPOL 2013] Q842. Even after a few full-power days, a nuclear reactor becomes so radioactive, that dismantling costs may rise to as much as about 60% of the construction costs, e.g. Niederaichbach [Schwald et al. 1995] Q25, [Liebholz 1995] Q32, [Komorowski & Meuresch 1995] Q33, [NEA 1996] Q61.

First-of-a-kind projects often enjoy subsidies by governments (sometimes hidden), certainly when strategic important technologies are involved.
For instance, the radioactive components of Elk River, Shippingport and Maine Yankee have been transported intact by barge to state-owned disposal facilities. The cost of packaging and final disposal of that dangerous material obviously is not included in the published dismantling costs.

A bookkeeping method may trouble the discussion about the real energy requirements of decommissioning and dismantling. If in 2019 an amount of $100 million is invested at an average 4% interest, for decommissioning after 100 years, one may argue: after 100 years the capital will be 100M$ • 1.04^{100} = 5.05 G$, in the year 2119. Apart from the unusual long term and the large uncertaintities regarding the value of a fund 100 years from now (who cares today about shares from 1919?), an amount of 5.05 billion in dollars of 2119, if available, surely will not have the same 'work potential' as 5.05 G$ in 2019. The financial reserves mentioned in [IPOL 2013] Q842 may have less significance than suggested.

Using energy units the method would not work. An activity requiring 80 PJ in 2019 will need atleast the same in 2119. Requirements of energy, materials and manpower do not inflate. These quantities will not change by bookkeeping concepts, subsidies or by deferring the moment of dismantling beyond a certain cooling period.
After a cooling period of a several decades the activity of the short-lived nuclides Fe-55, Co-60 has decayed to a low level, but what is 'low'? What level is 'negligible? After the first decades the radioactivity of the

construction will decrease very slowly. Unknown is the activity of the radionuclides that are not measured. The risks of dispersion of radioactive materials into the biosphere, by inevitable physical/chemical deterioration processes and by human behaviour, increase with time. The entropy of the radioactive waste irrevocably will increase over time by spontaneous processes, according to the Second Law. Consequently the energy requirements of the safe isolation of the waste from the biosphere will increase over time.

The cost of decommissioning and dismantling the US West Valley reprocessing plant - that operated between 1966 and 1972 and reprocessed 640 Mg of spent fuel - is estimated at about $16bn [UCS 2007] Q421, 100 times the construction cost, excluding final disposal of the radioactive waste and contaminated soil. If all goes well the sequence may be finished by about 2050. These figures are not reassuring when decommissioning and dismantling of other, larger reprocessing plants, e.g. Sellafield (UK) and The Hague (France), come into the picture. [NDA 2015] Q646 estimated the cost of decommissioning Sellafield in 2014 at £ 80bn, and the estimates are still rising.

Advanced reference reactor

Based on the available evidence this study assumes a cost of decommissioning + dismantling of the advanced reference reactor (see also report m19 *Reference reactor and EPR*) equal to the average construction cost:

c = 6.5 G$(2000)/GWe

From the cost figure the specific energy investment and CO_2 emission can be estimated using the energy/cost ratio of construction, e = 12.34 MJ/$(2000):

$E_{decom+dism} = c*e = 6.5*10^9*12.34 = E_{th} + E_e = 80$ PJ $\qquad J_{th}/J_e = 4.8$

The thermal component of the energy consumption is:

$E_{th} = (4.8/5.8)*80 = 66.2$ PJ

CO_2 emission:

$m = 66.2*10^9*75 = 4966$ Gg CO_2

specific CO_2 emission:

$\gamma = 4966*10^9/219*10^9 = 22.7$ gCO_2/kWh

These figures include:

- clean up
- decontamination of the nuclear components
- operation and maintenance during safeguarded period after final shutdown
- actual demolition of the radioactive components
- site clearance,

but excludes waste packaging and final disposal of the dismantling waste.

Evidently this is a rough estimate of the energy investment of decommissioning + dismantling. In view of the long history of sizeable cost escalations within the nuclear industry and especially with regard to new technologies, the above figure might be not overestimated. At the time of writing (2019) few, if any, decommissioning + dismantling sequences in the world have been completed, and vrtually no empirical data are pubished. Large cost escalations are intrinsic to new technology projects according to [RAND 1981] Q126:

"Severe underestimation of capital costs is the norm for *all* advanced technologies."

According to [RAND 1979] Q127 escalations in cost estimates of energy process plants with factors 2-5 are not uncommon.

Radioactive waste from decommissioning and dismantling

The part of the construction materials of a nuclear power plant that become radioactive waste, depends partly on the cumulative neutron flux during the operational life and therefore on the thermal power and the full-power time of the reactor. Higher power and longer operational lifetime will result in larger volumes of radioactive materials materials, which will be more heavily activated and contaminated.
According to [IAEA-293 1988] Q36 10.7% of the construction steel mass (including reinforcing steel) will become radioactive waste and 8.0% of the concrete, by activation reactions and contamination. If the total fraction of radioactive material would remain constant at 8.8%, independent of higher construction masses, the amount of radioactive waste released from a reactor with a construction mass of 1000 Gg would be about 88 Gg.
Thierfeldt 1995 [Q41] cites percentages of 2-3% of the mass becoming radwaste and 6% of the construction mass becoming materials for restricted reuse after decontamination. The last phrasing is an euphemism for low-radioactive materials of unknown radioisotopic composition, which may be reused in other nuclear facilities. The figures of Thierfeldt are based on the dismantling of Niederaichbach, a 100 MWe plant with a full-power time of only a few weeks.

Reuse of contaminated and/or activated concrete and steel, by mixing it with fresh steel or concrete, seems incompatible with any sustainability principle. The potentially hazardous isotopic composition and specific activity of the dismantling debris will largely remain unknown. Moreover, such a policy would introduce a very high risk of uncontrolled trade in radioactive materials, already an underrated problem today. This assessment assumes that all radioactive dismantling waste is packed in containers that are permanently stored in a geologic repository.

No large commercial nuclear power station has ever been completely dismantled, including packaging the waste for final disposal, and it is still unclear how the nuclear industry will manage the dismantling waste. Data are exceedingly scarce in the open literature. The concept used in this study is based on [IAEA 293 1988] Q36 and [Berg & Görtz 1995] Q46. The publication years of these studies show how old these concepts are and also that during the past three decades virtually no progress has been made with this aspect of the nuclear legacy.
An unanswered question is what to do with the radioactive coolant and off-gas. By way of approximation, this study assumes that only the coolant present in the reactor system at final shutdown, will be immobilized and packed for final disposal. The tritiated cooling water (HTO or T_2O) will be fixed in cement and packed in appropriate containers. A problem may become the pressure build-up of the helium-3 decay product in the tritiated concrete.

In this study the coolant, water containing tritium, other radionuclides and added chemicals, is immobilized in cement, with about 25 mass-% water [IAEA-203 1981] Q74. With a density of the resulting hardened cement of d = 2.7 Mg/m^3, 1 m^3 water can be fixed in 1.5 m^3 cement.
In this study no cooling water will be immobilized during operation. This assumption means that virtually all of the tritium and carbon-14 generated in the coolant of the reactor during its operational lifetime, together with low quantities of other radionuclides (see e.g. [IAEA-377 1985] Q44 and [NRC 1996] Q16) will be discharged into the environment, as is the present practice. This means a non-sustainable situation in the sense that an unknown but irreversible harm is being inflicted on the environment.
Other unknowns exist about the amounts of contaminated soil and the extent of contamination of the foundations of the nuclear power plant. Experience from the past learns that always leaks occur in the technical system of a nuclear power plant during its operation, often unnoticed. A complete dismantling process must include removal of the foundations of the nuclear power plant in order to achieve adequate site clearance. Based on the scarce information available only rough estimates are possible with regards to the amounts of dismantling waste. This study assumes that 10% of the concrete of an average nuclear

power plant, or 85 Gg, becomes radioactive by contamination and that 10 000 m³ of contaminated soil has to be removed from the site.

The waste containers for decommissioning waste in the [Ecoinvent 2003] Q333 study are large concrete boxes (wall thickness 10 cm) with a steel liner: height 2.4 m, width 2.5 m and length 4.5 m. The displaced volume is 27 m^3 and the internal volume (waste capacity) is 21.6 m^3. The loaded mass of this type of container would be some 70 Mg. This type of container might be difficult to handle, it would require specialized heavy transporters, vulnerable to mishaps and not very appropiate to be transported into a deep geologic repository. For that reason this study assumed that the dismantling waste would be packed in containers of type V3 and V4 (see report m40 *Radioactive waste management*). The way of packaging and the number of resulting waste containers are summarized in Table 2 for the advanced reference reactor.

Table 2

Categories of dismantling waste from the advanced reference reactor and needed containers

material	mass waste Mg	volume waste m^3	assumed waste class	type container	number of containers	displaced volume m^3
decontamination	7500	5000	HLW	V3	17241	20345
steel/ stainless steel	3000	380	HLW	V3	1309	1545
steel	10000	1266	LLW	V4	732	3000
other materials	1000	500	LLW	V4	289	1185
coolant	1000	1500	LLW	V4	867	3555
concrete	85000	35417	LLW	V4	20472	83935
contaminated soil	20000	10000	LLW	V4	5780	23699
sum	127 500	54 063			46691	137265

Table 3

Energy investments and CO_2 emission of the complete sequence of decommissioning + dismantling the advanced reference nuclear power plant, including packaging the waste in appopriate containers and final disposal in a geologic repository

process advanced reference nuclear power plant	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	CO2 g/kWh
decommisioning + dismantling	80 000	66 000	4965	22.67
waste packaging in V3 and V4 containers	26 641	22 048	1654	7.55
final disposal in repository	33 374	31 030	2327	10.63
sum	139 974	119 783	8946	40.85

3 Practice and experiences

Ambiguous definitions of decommissioning and dismantling

Decommissioning is a general term for a formal process to remove something from an active status. In the publications of the nuclear industry the term 'decommissioning' may have different connotations. The designation 'decommissioned' may refer to a status of a nuclear power plant that has reached Phase 3 of the sequence as discussed in Chapter 1, see also Figure 1: safe-guarded cooling period (safe enclosure, safestor). In the reports the term may also refer to another status,for example Phase 2 or Phase 1.
Dismantling is understood to include demolishing all radioactive structures of a nuclear power plant, or other nuclear installation, and removing the debris from the site. Also the term 'dismantled' is ambiguously used and may refer to different statuses of nuclear installations. In many cases the foundations, radioactive or not, are left in place and in most cases the debris are stored on the site, sometimes including the spent fuel elements.

Dismantled nuclear reactors

Table 4
Examples of actually dismantled nuclear power plants.

reactor	power MW	T_{100} FPY	radioactive inventory PBq	radioactive waste	reported cost (10^6)	year	cost $(2016) ($10^6$)	refs
Elk River	58 (th)	2.50	0.35	2450 m^3	6.15 $	1974	30	1
Shippingport	72 (e)	6.16	0.45-1.11	6200 m^3	91.3 $	1990	167	2
Niederaichbach	321 (th)	0.050	0.56	3418 Mg	270 DM	1998	198	3
HDR	100 (th)	0.05-0.2	0.0004-0.37	325-840 Mg	100 DM	1995	78	4
MZFR	200 (th)	12.5	80.8	n.a.	440 DM	1995	344	5
Karlsruhe FR-2	44 (th)	n.a.	n.a.	n.a.	245 DM	1995	194	6
Kahl VAK	15 (e)	16.0	n.a.	n.a.	300 DM	1998	219	7
Maine Yankee	790 (e)	15.6	n.a.	59000 Mg	635 $	2002	859	8

n.a. not available
(1) BWR. [Harman *et al.* 1976] Q166, [IAEA-*179* 1975] Q178.
(2) Prototype PWR. [NEA 1996] Q61, [IAEA-*377* 1995] Q44, [*atw*-5 2003] Q57, [Wood 1991] Q181, [Crimi 1984] Q193.
(3) Experimental GCHWR. [NEA 1991] Q188, [Schwald *et al.* 1995] Q25, [Gallenberger *et al.* 1981] Q173, [Komorowski *et al.* 1998] Q191-2, [NEA 1996] Q61, [Komorowski & Meuresch 1995] Q33, [Liebholz 1995] Q32, [*Nuclear Endineering International*, May 1981 pp 36-40]
(4) Experimental reactor, now nuclear test facility. [Komorowski & Meuresch 1995] Q33, [Kuczera 1997] Q35, [Valencia 1998] Q!61, [Watzel *et al.* 1979] Q171.
(5) Experimental PHWR. [Komorowski & Meuresch 1995] Q33, [Kuczera 1997] Q35, [NEA 1996] Q61, [NEA 1991] Q188, [Komorowski *et al.* 1998] Q191-2, [Roser 1991] Q190.
(6) Research reactor. [Komorowski & Meuresch 1995] Q33, [Kuczera 1997]Q35, [Komorowski *et al.* 1998] Q191-2.
(7) Experimetal BWR. [Bergelson *et al.* 2002] Q50, [Eickelpasch 1998] Q51, [IMechE 1998] Q191.
(8) PWR. [Wald 2003] Q220, [Maine Yankee 2003] Q221, [WNA-*decom* 2019] Q157.

According to [WNA-*decom* 2019] Q157 about 17 nuclear reactors had completed the full decommissioning sequence by the end of 2016, but WNA made not clear which ones. The WNA statement would mean that these 17 reactors are dismantled, but the actual status remains unclear. In none of the cases were the radioactive wastes disposed of in a geologic repository, as far as known. Table 4 summarises data of a number of actually dismantled reactors as found in the open literature; the table does not list all 17 reactors mentoned by WNA, due to lack of reported data.

Comments to Table 4

The decommissioning and dismantling of Elk River, Shippingport and Maine Yankee are not representative of future projects. The reactor vessel and other radioactive equipment have been removed intact and transported by ocean barge to state-owned storage facilities in Hanford and Barnwell. The radioactive concrete parts (e.g. biological shield) have been blasted by explosives. It is not clear what happened with the radioactive dust and debris.

The foundations of the three plants are still in place. Not known is why the foundations have not been removed. The materials may be (partially) radioactive by activation reactions, contamination and leakages during the operational life of the reactor. In neither case the processing of the radioactive wastes for final disposal and the final disposal itself are included in the reported costs.

Table 4 leaves many questions open. For example, the wide spread and low values of the radioactive inventory of Shippingport, compared to the values of Niederaichbach and MFZR, are unexplained. Also the the wide spread (with a factor 100) of the reported value of the radioactive inventory of the HDR is unexplained. To facilitate comparison, the cost figures in Table 4 are corrected for inflation and converted to dollars of the year 2016. The conversion is based on the US Consumer Price Index. The same is done in following tables. For the conversion of valuta, the ratio's 2.00 DM/$ and 1.60 $/£ are used.

Table 5

Some decommissioning and dismantling projects in progress.

reactor	type	power MW(e)	T_{100} FPY	radioact. inventory PBq	radioact. waste Mg	report cost	year	cost $(2016)	refs
Greifswald 1	VVER	440	10.72						
Greifswald 2	VVER	440	10.39						
Greifswald 3	VVER	440	9.35						
Greifswald 4	VVER	440	8.32						
Greifswald 5	VVER	440	0.062						
sum 1-5 KGR				350	95228				
Rheinsberg (KKR)	VVER	62	16.6	100	13302				
sum 5 KGR + KKR						DM 13G	1990	12G	1
Gundremmingen A	BWR	250	n.a.	20	2680	n.a.		-	2
JPDR	prot.BWR	12	n.a.	n.a.	n.a.	$ 130M	1987	273M	3
Humboldt Bay	BWR	63	n.a.	n.a.	n.a.	$ 500M	1985	1.1G	4

n.a. not available

(1) [Sterner *et al.* 1995] Q150, [*Nuclear Engineering International*, April 1991 p7], [Roser 1991] Q190.

(2) [CND-KRB-A 2007] Q297.

(3) [NEI-10 1987] Q179, [Yokota & Ishikawa 1990] Q186, [NEA 1991] Q188.

(4) [*Nuclear News*, September 1985 p.34], [WNA-*decom* 2019] Q157

Decommissioning of the West Valley reprocessing plant

The decommissioning and dismantling of the US West Valley reprocessing plant, which operated from 1966-1972 and reprocessed 640 tonnes of spent fuel, will cost from 2007 on at least $5.2bn and will take another 40 years to complete. Very likely the final cost will be considerably higher. The construction cost of the reprocessing plant was estimated at $28M in 1963 ($150M-180M in 2006 dollars). Cleanup of the whole site (1335 ha) is estimated at $8.3bn. Up until 2007 several billions of dollars already have been spent on West Valley [UCS 2007] Q421. The activities do not include removal of the radioactive waste from the site. The HLW is stored in casks for about 50 years, the contaminated soil and dismantling debris are disposed of in landfills onsite.

The total costs of decommissioning + dismantling + site clean-up may amount to some $16bn, about 100 times the construction cost, and are expected to rise further during the coming decades. These figures point to a specific post-operational cost of about $25000 per kilogram reprocessed heavy metal (HM). Assumed the plutonium content of the reprocessed spent fuel was 0.9%, the specific post-operational cost would become about $2.8M per kilogram plutonium.

The extremely long timeline, 45 years from 1972 until 2017 and another 40 years expected, shows how demanding the decommissioning of even a relatively small reprocessing plant is. This conclusion is affirmed by the exceedingly high costs.

Cleanup of the Hanford Site

Although military applications of nuclear technology are not discussed in this study, the decommissioning and dismantling of a military complex and the hazards evoked by the radioactive wastes are not different from civil installations. Empirical figures with regard to decommissioning and dismantling of nuclear installations are very scarce, the more so regarding reprocessing plants. An indication of the size and timescale of this kind of activities may be given by the figures of the cleanup of the Hanford Site in the State of Washington in the USA.

The US Department of Energy (DOE) is responsible for one of the largest nuclear cleanup efforts in the world, managing the legacy of five decades of nuclear weapons production. At its peak, this national weapons complex consisted of 16 major facilities, including vast reservations of land in the States of Idaho, Nevada, South Carolina, Tennessee and Washington. DOE [DOERL 2015] Q653 provided some figures on the cleanup of the Hanford Site, but many questions remain unanswered.
Hanford made more than 20 million pieces of uranium metal fuel for nine nuclear reactors along the Columbia River. Five huge plants in the center of the Hanford Site processed 110 000 tons of fuel from the reactors, discharging an estimated 450 billion gallons (1.7bn m^3 = 1.7 km^3) of liquids to soil disposal sites, 56 million gallons (212 000 m^3) of radioactive waste are stored in 177 large underground tanks, 67 tanks presumed to have leaked. The plutonium production ended in the late 1980s, Hanford produced 2/3 of nation's plutonium.
The site measures 586 sq mi (1518 km^2) with 1012 waste sites, 522 facilities and 9 plutonium production reactors near the Columbia River.

The cleanup started in 1989, after an agreement was reached between DOE, US Environmental Protection Agency (EPA), and Washington State, known as Tri-Party Agreement, for bringing the Hanford site into compliance with federal and state environmental regulations; the annual budget is $2bn, and the workforce comprises 9288 employees.

Some figures:
- 6 reactors were cocooned
- spent fuel was transported to dry storage
- 939 waste sites were remediated
- 428 facilities were demolished, and 17 million tons (15.4 million metric tons) of soil and debris removed
- Pu-contaminated waste was retrieved and shipped off site
- 12.5 bn gallons (47,3 million m^3) groundwater was treated, and 157 tons of contamination removed.

From the statements follows that the nuclear reactors at the site are not dismantled, and that the spent fuel is still in temporary storage. DOE made not clear to which storage facilities the wastes are transported. From one temporary storage facility to another? What exactly does mean the term 'remediated'? What happened with the plutonium-contaminated waste? To which standards are the radioactive wastes treated?

DOE spent more than $164bn during the period 1989-2015 for cleaning up its nuclear-waste sites, about $50bn for the Hanford site. [DOERL 2015] Q653 gives no information on the total expected costs, nor on the expected timescale of the cleanup activities. It is not clear what activities are funded and what activities remain to be done.
Little information is given on radioactive waste quantities (volumes, masses), and no info on radioactivity of the materials, nor on their isotopic composition. No information is given about deactivated, and discarded reactors that are stored at Hanford, such as ship reactors and the Shippingport reactor, nor on other radioactive nuclear installations transported to Hanford for storage.

Notable is the quote from *Nature* of 18 May 2017:

> The United States is still fighting the cold war. But the opponent is no longer the Soviet Union. The enemy is now the legacy of an arms race and decades of government indifference to the mess that has been left behind.

Decommissioning in the UK

In its publication *Nuclear Provision* [NDA 2015] Q646 the UK Nuclear Decommissioning Authority explains 'the cost of cleaning up Britain's nuclear legacy' covering the costs of decommissioning 17 nuclear sites across the UK, some dating back to the 1940s. Current estimate of clean-up costs in excess of £115bn, spread over the next 120 years or so. Taking account of numerous uncertainties, the range is likely to be £90-220bn (€117-286bn). Two quotes from [NDA 2015]:

> Learning from the past
> The costs of decommissioning the 17 sites covered by the Nuclear Provision are all publicly funded.However, the second generation of nuclear power stations, the Advanced Gas-Cooled Reactor (AGR) fleet, are operated by EDF Energy and funds are set aside towards their future decommissioning programme via the Nuclear Liabilities Fund.
> The next generation of nuclear power stations will be built by the private sector, with decommissioning plans and cost forecast in place at the outset. The latest generation of reactors are vastly more efficient than the early designs and are expected to be cheaper to dismantle.
>
> Responsibility
> The Nuclear Decommissioning Authority (NDA) owns 17 historic sites on the Government's behalf and is responsible for deciding how they should be decommissioned.

The: cost estimates of Sellafield doubled from £40bn - £80bn during years 2009-2014, and are still rising; the cost estimates other facilities decreased from about £35bn to £30bn.
Sellafield is a densily packed site - just 6 sq km - housing thousands of buildings, many storing highly hazardous waste.

The oldest facilities were built in great haste during the early years of the Cold War with no plans for how they would be decommissioned.
Record-keeping in the early days was poor by modern standards meaning much work has to be carried out to confirm the nature and state of the material held in these facilities.
The NDA estimates that at least one third of today's costs for the environmental restoration of Sellafield could be attributed to the site's military abjectives, with the remaining proportion associated with the civil energy programme.

A timeline of 120 years is envisioned for the decommissioning activities. One may compare the period 1895-2015 and 2015-2135.

> Calculating the total costs of decommissioning is extremely difficult.
>
> ...
>
> As the timeline shows technological advances during the 120 years from 1896-2015 were huge and profound. The next century will also bring significant advances and while today's estimates are based on the best information available now, forecasts for many years into the future must inevitably be very uncertain.

This legacy comprises of 10 commercial nuclear power stations (22 Magnox reactors, joint power of 4.2 GWe), a number of other nuclear installations, waste storage facilities and a part of the reprocessing site at Sellafield. The planned activities include the construction of a geological disposal facility. Decommissioning of Sellafield alone is estimated at £67bn-163bn (€87bn-212bn).
Likely in practice these cost will rise significantly; the steep rise of the estimates during the past few years (doubling of the cost of Sellafield decommissioning from 2009-2014) most likely will continue in the future. cost overruns are the rule in the nuclear industry, the more so in view of the first-of-a-kind character and immense complexity of the decommissioning operations.

Gas-cooled and experimental reactors

Concerning graphite-moderated reactors [WNA-*decom* 2019] Q157 remarks:

> A 2006 report commissioned by EPRI states: "The graphite moderators of retired gas-cooled nuclear reactors present a difficult challenge during demolition activities. As a result, utilities have not dismantled any moderators of CO_2 cooled power reactors to date." However, it concludes that adequate information exists to enable the safe dismantling and processing of graphite moderators, and that the three main options for disposal of this graphite are oxidation to the gas phase and release as carbon dioxide (difficult), direct burial, or recycling into new products for the nuclear industry. In each case, opportunities exist for pre-processing to concentrate or remove radionuclides to enhance the safety of the chosen option. The radionuclide inventory of irradiated graphite is unusual in comparison with other nuclear wastes. Cobalt-60 and tritium are the principal isotopes of short-term importance, carbon-14 and chlorine-36 are dominant in the longer term.

Still another issue is deserving attention. The end-point of the clean-up and decommissioning activities of which NDA estimated the costs are not well defined. One may wonder how far stretches the horizon of NDA? The [NDA 2006] Q365 uses the terms 'clean-up and decommssioning' in relation with the cost figures. This might imply that later stages of the sequence (see Figure 1) are not included in the cost figures. Packaging and sequestration of the dismantling waste is not mentioned at all in the NDA *Strategy*. The limited horizon of the NDA (see also Figure 2) seems to be confirmed by the following quote from the BNFL *Annual Report and Accounts 2004* [BNFL 2004] Q366 (this report is removed from the site on 1 Feb 2008):

> The board of BNFL has long estimated its provisions for decommissioning and waste management on the assumption that the existing plants and buildings are demolished and sites are cleared, but not to the extent that the sites would be returnd to farmland. This reflects the approach which industry typically follows where there is is no requirement in law or otherwise to do more than ensure that the industrial site is made safe.

This statement also seems to exclude the last stages from the sequence: site clearance, waste packaging and waste sequestration (final disposal).

The ultimate cost of the decommissioning and dismantling of the UK nuclear facilities might turn out far higher than even the most pessimistic reported estimates.

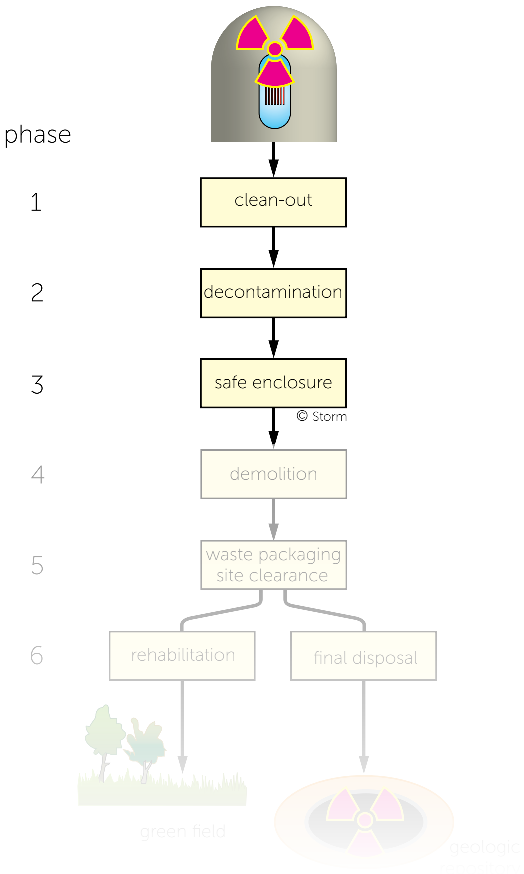

Figure 2

A timeline of 120 years for the clean-up and decommissioning of British shut-down nuclear facilities is envisioned by the UK NDA. The end-point of the NDA planning remains hidden in a hazy description. This figure is based on [NDA 2006] Q365.

Canadian NPD Closure Project

The Nuclear Power Demonstration (NPD) reactor in Rolphton, Ontario (Canada) was a CANDU: heavy water moderated, cooled by pressurized heavy water and fuelled with natural uranium.

In 1988, after the facility was shut down, total residual radioactivity in the NPD reactor system was estimated to be 2×10^{15} Bq. Since shut down, 29 years of radioactive decay have reduced radioactivity considerably. The total radiological inventory in 2012 was calculated to be 7.5×10^{13} Bq and by 2017 the total radiological inventory will have declined to 4.1×10^{13} Bq. The dominant radionuclides are Fe-55, Co-60, Zn-65, C-14, Mn-54, Ni-63, and H-3 [CNL-*decom* 2016] Q749. Based on data from the report the productive lifetime is calculated at 17.1 FPY. The report did not mention a cost estimate of the decommissioning project.

Some quotes from [CNL-*decom* 2016]:

> The 20 MW Nuclear Power Demonstration (NPD) reactor was Canada's first nuclear power reactor to supply electricity to Ontario Hydro's electrical distribution grid. NPD began operations in 1962 and for 25 years served as an important training facility for future reactor engineers and operators. In 1988, following permanent shutdown

of the reactor, removal of the fuel and power generating equipment from the site, Ontario Hydro transferred the responsibility of monitoring and licencing of NPD to Atomic Energy of Canada Limited (AECL).
While AECL still owns the NPD site, Canadian Nuclear Laboratories is responsible for the facility, which is presently in the Storage with Surveillance phase of decommissioning under a Decommissioning Waste Facility License issued by the Canadian Nuclear Safety Commission (CNSC).
The NPD site currently consists of a limited number of structures, including the main reactor building, a diesel generator, a guardhouse and a ventilation stack. Several temporary structures are being added to support the decommissioning project.

Proposed decommissioning technique - The proposed in-situ decommissioning activities include removing the above ground structure and placing contaminated materials into the below grade structure. The below grade structure, reactor vessel and systems and components will be sealed by grouting. The structure will then be capped with concrete and covered with an engineered barrier. In-situ decommissioning will isolate the contaminated systems and components inside the below grade structure.

As disposal options for nuclear waste within Canada are currently not available, in-situ decommissioning can safely reduce Canada's nuclear legacy liabilities at this property. In-situ decommissioning results in a concrete monolith which provides a robust and durable containment to allow for continued radioactive decay. This approach is consistent with the International Atomic Energy Agency (IAEA) 'Decommissioning Strategies for Facilities Using Radioactive Material' [3]. The IAEA considers the entombment strategy an acceptable approach for member states that do not waste disposal options such as Canada. Also the NPD proposed approach is consistent with the IAEA strategy as the dominate contribution to the source term involves short lived radioactive isotopes and the longer lived isotopes are principally activation products.

Obviously the 'Ontario procedure' is not a dismantling as represented in Figure 1. The radioactive materials are out of sight, but far from isolated from the biosphere. The site needs permanent surveillance. The fact that this concept and other, similar concepts have been published in several countries and that a variant of the Ontario concept has been used in the LCA (life cycle assessment) by WNA may indicate that in the view of the nuclear industry this method of decommissioning a nuclear power plant is an adequate option. This thought is affirmed by the above quote and the statement of BNFL, as quoted in the previous section, regarding the NDA activities in the UK.

4 Costs and liabilities

Decommissioning in the USA

West Valley reprocessing plant
The decommissioning and dismantling of the US West Valley reprocessing plant may cost about $16bn - that would be 100 times the construction cost - and will take another 40 years to complete [UCS 2007] Q421. The activities do not include removal of the radioactive waste from the site. The HLW is stored in casks for about 50 years, the contaminated soil and dismantling debris are disposed of in landfills onsite.

Cleanup of the Hanford Site
DOE spent more than $164bn during the period 1989-2015 for cleaning up its nuclear-waste sites, about $50bn for the Hanford site. [DOERL 2015] Q653 gives no information on the total expected costs, nor on the expected timescale of the cleanup activities. It is not clear what activities are funded and what activities remain to be done.

Three nuclear power plants
In the report [EPRI 2008] Q645 three decommissioning projects in the USA are discussed, that may be seen as examples of cost estimates in the USA. The reported costs do not include de cost of long-term on-site storage of spent fuel. It is not clear what status of decommissioning and dismantling the three projects achieved. The EPRI report does not explain what caused the differences in the cost estimates. These figures may suggest that decommissioning costs do not depend on the power rating of the nuclear power plant.

Table 6
Three decommissioning projects in the USA, Source: [EPRI 2008] Q645.

power plant	type	power MW	total decommissioning cost $(2008)	decommissioning cost $(2008)/ GWe
Connecticut Yankee	PWR	560	850 M	1.52 bn
Maine Yankee	PWR	860	500 M	0.581 bn
Yankee Rowe	BWR	185	750 M	4.05 bn

Decommissioning in the UK

In its publication *Nuclear Provision* [NDA 2015] Q646 the UK Nuclear Decommissioning Authority explains 'the cost of cleaning up Britain's nuclear legacy' covering the costs of decommissioning 17 nuclear sites across the UK, some dating back to the 1940s. Current estimate of clean-up costs in excess of £115bn, spread over the next 120 years or so. Taking account of numerous uncertainties, the range is likely to be £90-220bn (€117-286bn).
The total cost of operations, decommissioning and clean-up of the nuclear installations listed by the NDA in its [NDA 2006] Q365 have been estimated at £62.7bn, of which £12.3bn for the decommissioning of the reactors in Table 7. NDA emphasizes:

> The total cost of operations, decommissioning and clean-up could increase significantly.

Table 7

Estimates of the decommissioning cost of 27 gas-cooled graphite-moderated reactors at 12 sites in the UK, permanently shut down per 31 December 2006. Sources: [NDA 2006] Q365 and PRIS Database Q751.

power plant	net power MW (1)	T_{100} FPY (2)	decom cost 10^9 £ 2006	decom cost £/kWh 2006	decom cost 10^6 $/MW 2016 (3)
Berkeley 1+2 (4)	276	17.98	0.7737	0.018	5.34
Bradwell 1+2 (5)	246	25.22	1.0866	0.020	8.41
Calder Hall 1 - 4	200	32.05	1.0739	0.019	10.23
Chapelcross 1 - 4	200	32.42	1.3321	0.023	12.69
Dungeness A1+A2	450	15.39	1.0014	0.017	4.24
Hinkley Point A1+A2	470	22.57	1.2137	0.013	4.92
Hunterston A1+A2	300	21.82	1.0717	0.019	6.80
Oldbury A1+A2 (6)	423	29.31	1,0766	0.018	8.76
Sizewell A1+A2	490	15.43	0.8706	0.015	3.95
Trawsfynydd 1+2	390	13.81	1.1160	0.024	5.45
Windscale AGR (7)	32	11.62	0.6939	0.213	41.30
Wylfa 1+2 (6)	980	11.85	1.0065	0.010	1.96
sums	4198		12.3167		
averages		18.78		0.018	5.59

Notes

(1) The nominal net power of most reactors have been down-rated during the first years of operation [PRIS Database].

(2) Based on PRIS Database.

(3) Assumed 1 £(2006) = 1.60 $(2006), and 1 $(2006) = 1.19 $(2016) according to US Consumer Price Index.

(4) The construction cost of Berkeley 1+2 has been estimated in 1963 at 495 million US$ [McLain 1964] Q203, or about 2752 $(2000)/kW.

(5) The construction cost of Bradwell 1+2 has been estimated in 1963 at 480 million US$ [McLain 1964] Q203, or about 2669 $(2000)/kW.

(6) Still in operation per 31-12-2007

(7) The Windscale complex houses the Windscale Pile, which was the scene of Britain's worst nuclear accident in 1957 when the Pile caught fire.

Table 8

Estimates of the decommissioning cost of three experimental reactors in the UK, permanently shut down per 31 December 2006. Sources: [NDA 2006] Q365 and PRIS Database Q751

power plant	net power MW (1)	T_{100} FPY (2)	decom cost 10^9 £ 2006	decom cost £/kWh 2006	decom cost 10^6 $/MW 2016 (3)
Dounray DFR	14	4.37			
Dounray PFR	234	3.48			
sum Dounray	248		2.9495	0.384	22.65
Winfrith SGHWR	92	13.60	0.4775	0.044	9.89

(1) The nominal net power of most reactors have been down-rated during the first years of operation [PRIS Database].

(2) Based on PRIS Database.

(3) Assumed 1 £(2006) = 1.60 $(2006), and 1 $(2006) = 1.19 $(2016) according to US Consumer Price Index.

The statement of the NDA is confirmed by *Nature*: newer cost estimates of clean-up of closed-down Magnox reactors and othe nuclear facilities in the UK amount to £85-170bn, 60% of which are expected to be used up at Sellafield [*Nature*, 23 November 2006, p.415].
This increase would mean that the decommissioning cost of the reactors from Table 7 would cost some £17-34bn, corresponding with a mean of 4050-8100 £/kW, or some 5500-11000 $(2000)/kW. For the Berkely and Bradwell nuclear power plants a decommissioning cost of 11000 $(2000)/kW equals 400% of the construction costs (see also notes 4 and 5 of Table 7).
Large cost escalations in such massive effort might be expected anyway, as the topical RAND studies have shown [RAND 1979] Q127, [RAND 1981] Q126. There are no reasons to expect that no further cost escalations would occur.

French estimate

The widely different cost estimates of ongoing or future decommissioning projects that have been published raise some questions, see for example [Dorfman 2017] Q750:

> How much has France, Germany and UK set aside for decommissioning ?
> Whereas Germany has set aside €38 billion to decommission 17 nuclear reactors, and the UK Nuclear Decommissioning Authority (NDA) estimates that clean-up of UK's 17 nuclear sites will cost between €109 – €250 billion over the next 120 years – France has set aside only €23 billion for the decommissioning of its 58 reactors. To put this in context, according to the European Commission, France estimates it will cost €300 million per gigawatt (GW) of generating capacity to decommission a nuclear reactor – far below Germany's assumption at €1.4 billion per GW and the UK of €2.7 billion per GW.
>
> How can EDF decommission at such low cost?
> EDF maintain that because of standardisation of some of the reactors and because there are multiple reactors located on single sites, they can decommissioning at a low cost. Does this claim stack up ? Well, probably not. Reactors are complex pieces of kit, and each has a differing operational and safety history. In other words, nuclear reactor decommissioning is essentially a 'bespoke' process.
>
> Why has EDF underestimated the costs of decommissioning and waste storage ?
> Even EDFs €23 billion limited provision for decommissioning and waste storage is a large sum of money for a company that has huge borrowings and enormous debt, which is currently running at €37 billion, Standard and Poor and Moodys (the two biggest international credit rating agencies) have already downgraded EDFs credit-worthiness over the corporations potentially ill-advised decision to go ahead with attempting to construct two more of the failing Areva reactor design (the EPR) at Hinkley Point, UK. And any significant change in the cost of decommissioning would have an immediate and disastrous impact on EDFs credit rating – something that the debt-ridden corporation can simply not afford.

Extrapolation of Greifswald figures

Extrapolating the estimated dismantling costs of the Greifswald and Rheinsberg power stations to a large reference PWR power station is difficult. This because of the low power rating of Rheinsberg and the specific construction features of Greifswald, with two reactors in one containment with common equipment. If the six plants together are considered to be equivalent with three large PWR's with T_{100} = 20 full-power years, one can speculate a cost figure of about 3970 M$(2016) per reference PWR of 1 GWe. Taking into account the almost certain cost escalation, possibly with a factor 2-5 [RAND 1979] Q127 and [RAND 1981] Q126, the final cost might come 8-20 G$(2016) per GWe. The assumed average construction cost of a 1 GWe PWR is 9 G$(2016). Based on these figures, dismantling cost may rise to 88-133% of the construction costs, or more.

The figures of the NDA (see Table 7) suggest decommissioning costs of 200-400% of the construction cost for Magnox reactors. as is explained above. These estimates likely do not include the last stages of the sequence, site clearance, waste packaging and sequestration.

Even after a few full-power days, a nuclear reactor becomes so radioactive, that dismantling costs may rise to as much as about 60% of the construction costs, e.g. Niederaichbach [Schwald *et al.* 1995] Q25, [Liebholz 1995] Q32, [Komorowski & Meuresch 1995] Q33, [NEA 1996] Q61.

Swiss estimate

The cost of decommissioning Switzerland's five nuclear power plants, total net electrical capacity 3333 MWe, is estminated at more than SFr 20bn (= € 18.0bn, assumed 1€ = 1.11 SFr) - ten per cent more than five years ago [SWI 2011c] Q649. Decommissioning becomes 17% more expensive, and disposal costs 10% more, as modernised geological repository for the waste are expected to be more expensive.
The figures from SWI point to a specific cost of 18.0 bn€/3.333 = 5.41bn €/GWe, or € 3.6bn per reactor.

View of the WNA

In its publication [WNA-*decomcosts* 2015] Q654 World Nuclear Assocation states:

> The Financial Times has focussed on the IEA World Energy Outlook comment on nuclear decommissioning costs, with a headline reading "Bill for shutting nuclear plants will reach $100bn". To be clear the $100bn figure is for decommissioning of almost 200 reactors, nearly half of the reactors currently operating, between now and 2040. This might seem to be a significant sum, but it needs to be put context. The table below lists other costs listed in the IEA World Energy Outlook.

	annual costs
global nuclear decommissioning, average per year	$4bn
upstream oil and gas development costs by 2030	$900bn
fossil fuel subsidies 2013	$550 bn
renewables subsidies 2013	$120bn

> Nuclear decommissioning costs are a tiny fraction of the investment needed in upstream oil and gas development or fossil fuel or renewables subsidies. They are also a small fraction of overall generation costs, only a few tenths of a cent per kWh.
> The IEA World Energy Outlook states: "Decommissioning costs account for less than 1.5% of generation costs in all regions, on the assumption that they are accrued over the entire economic lifetime of plant operation." (IEA WEO p396).
> The IEA figures are consistent with other estimates of decommissioning costs, including a much longer report produced by the OECD in 2003 (The IEA was established in the OECD framework). These costs are recognised by industry and nuclear regulators and funds are already being set aside to carry out decommissioning in the future.
> The commitment of the nuclear industry to properly funding decommissioning costs compares well to preparations made elsewhere in the energy sector.

The WNA figures point to decommissioning cost of $100bn/200 = $0.5bn per reactor, ten times lower than the Swiss estimate.
WNA assumes that future decommissioning costs will be paid by nuclear power plant owners, but this construction has yet to be proved. Up until now only 'legacy' installations are being dismantled, under the responsibility of governments, and not one decommissioning of a modern NPP has been paid by 'funds set aside' by the nuclear industry.

Another publication [WNA-*decom* 2019] Q157 states:

> An OECD Nuclear Energy Agency survey published in 2016 reported US dollar (2013) costs in response to a wide survey. For US reactors the expected total decommissioning costs range from $544 to $821 million; for units over 1100 MWe the costs ranged from $0.46 to $0.73 million per MWe, for units half that size, costs ranged from $1.07 to $1.22 million per MWe. For Finland's Loviisa (2 x 502 MWe) the estimate was €326 million. For a Swiss 1000 MWe PWR the detailed estimate amounts to CHF 663 million (€617 million). In Slovakia, a detailed case study showed a total cost of €1.14 billion to decommission Bohunice V1 (2 x 440 MWe) and dismantle it by 2025.

In its publication WNA does not comment on the wide differences between the cost figures. The UK decommissioning & dismantling cost estimates, Table 7 and Table 8, are not mentioned. The quoted figure of a Swiss PWR does not accord with the figure mentioned by [SWI 2011c] Q649: 5.41bn €/GWe, or € 3.6bn per reactor.

Comments by Reuters

In *Business & Financial News* of Jan 19 2015 [Chestney & De Clercq 2015] Q754 report:

- Decommissioning cost estimates range widely
- Experts see IEA's $100 billion estimate as too low
- Waste disposal and long-term storage not included
- Adequate provisioning more important than cost estimate

The International Energy Agency (IEA) said late last year that almost 200 of the 434 reactors in operation around the globe would be retired by 2040, and estimated the cost of decommissioning them at more than $100 billion.
But many experts view this figure as way too low, because it does not include the cost of nuclear waste disposal and long-term storage and because decommissioning costs - often a decade or more away - vary hugely per reactor and by country.

Although technology used for decommissioning might gradually become cheaper, the cost of final waste depositories is largely unknown and costs might spiral over time. Reactor lifespans are measured in decades, which means financing costs and provisions depend strongly on unpredictable interest rate levels.
"The IEA estimate is, without question, just a figure drawn out of the air. The reality is, the costs are quite phenomenal," said Paul Dorfman, honorary senior research associate at the Energy Institute, University College London.
The U.S. Nuclear Regulatory Commission estimates that the cost of decommissioning in the United States - which has some 100 reactors - ranges from $300 million to $400 million per reactor, but some reactors might cost much more.
France's top public auditor and the nuclear safety authority estimate the country's decommissioning costs at between 28 billion and 32 billion euros ($32-37 billion).
German utilities - such as E.ON, which last month said it would split in two, spinning off power plants to focus on renewable energy and power grids - have put aside 36 billion euros. .
Britain's bill for decommissioning and waste disposal is now estimated at 110 billion pounds ($167 billion) over the next 100 years, double the 50 billion pound estimate made 10 years ago.
Japanese government estimates put the decommissioning cost of the country's 48 reactors at around $30 billion, but this is seen as conservative.
Russia has 33 reactors and costs are seen ranging from $500 million to $1 billion per reactor.

Remarks

In this chapter widely different cost estimates of the decommissioning and dismantling of nuclear power plants and other nuclear facilities are quoted. The differences may have various causes, such as:

- The presented costs may refer to different statuses of decommissioning.
- A number of reactors were dismantled in experimental projects. It is not clear which part of the presented costs are specificly related to a given reactor. First-of-a-kind projects often enjoy subsidies by governments (sometimes hidden), certainly when strategic important technologies are involved.
  For instance, the radioactive components of Elk River, Shippingport and Maine Yankee have been transported intact by barge to state-owned disposal facilities. The costs of packaging and final disposal of that dangerous materials obviously are not included in the published dismantling costs.
- In several cases the radioactive materials are stored at the site. It remains unclear if all radioactive materials will be removed from the site, and if so how the materials will be disposed of.
- Political and other non-technical arguments may play a role, for example in case of the French estimates by the EDF.
- It is not clear wether the reported costs refer to the costs to be paid by the owner/operator of the nuclear power plant, or to the total costs, including the costs to be paid by the government/taxpayer after the liability of the owner/operator ends.

5 Responsibilities and liabilities: view of the nuclear industry

View of the IAEA

A nuclear facility is defined by the International Atomic Energy Agency [IAEA-*wmbd-st-2* 2002] Q656 as:

> A facility and its associated land, buildings and equipment in which radioactive materials are produced, processed, used, handled, stored or disposed of on such a scale that consideration of safety is required.

Decommissioning is defined as:

> Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository which is closed and not decommissioned). The use of the term decommissioning implies that no further use of the facility (or part thereof) for its existing purpose is foreseen…
>
> …For a repository, the corresponding term is closure.

The IAEA has formulated radioactive waste management principles relevant to selecting a decommissioning strategy, but they are not prescriptive in nature. Principle 4 reads:

> *Protection of future generations*
>
> Radioactive waste shall be managed in a way that the predicted impacts on the health of future generations do not exceed relevant levels that are acceptable today.

Principle 5 reads:

> *Burden of future generations*
>
> Radioactive waste shall be managed in a way that will not impose undue burden on future generations.

The IAEA Member States are given the flexibility of evaluating how to implement these principles. It can be generally assumed that 'undue' delays in decommissioning of nuclear facilities should be prevented, but the interpretation of 'undue' is left to national authorities.

The decision on how to proceed with the decommissioning of a nuclear facility depends on a number of factors, namely:

- legislative and regulatory requirements
- waste arisings and national waste management strategy
- spent fuel management strategies
- physical conditions of the plant
- owner's interest, including planned use of the site
- availability of technology and other resources
- social considerations
- decommissioning cost and funding
- radiological exposures.

Clearance criteria are probably the most important regulatory requirements essential to safe and cost-effective planning and implementation of decommissioning, according to [IAEA-*wmbd-st-2* 2002] Q656. Large amounts of materials resulting from decommissioning contain very low levels of radfioactivity or could be readily decontaminated to achieve such levels. Assuming that these materials should be all managed and disposed of as radioactive wastes would result in unnecessary penalties in terms of operational difficulties and significant extra costs. It is generally possible to establish radiological criteria and associated activity levels according to which materials can be released from regulatory control.

The above cited statements of the IAEA illustrate the flexibility of the the regulations and criteria.

Three general methods for removing solid materials/wastes from the facility can be identified als follows:

- Clearance for unrestricted reuse or disposal

- Authorized release/reuse within the nuclear industry or in the public domain
- Storage/disposal under radiologically controlled and monitored conditions.

Criteria to be met for these methods vary between countries. Sometimes the criteria are based on nationally applicable regulations, while in other situations they are based on a case-by-case evaluation.
With regard to ecommissioning cost and funding [IAEA-*wmbd-st-2* 2002] states:

> Whatever choices and decisions are made, it is the responsibility of the owner of a nuclear power plant to make a financial provision sufficient to cover the costs of all stages of decommissioning up to final dismantling, in accordance with pertinent national legislation and funding requirements.
>
> Deferment of dismantling may improve the funding of the task by allowing time to accrue additional funds where these may not previously have existed or by discounted cash flow considerations over a reasonable period of time. This, together with radiological aspects, appear to be a major factor for the UK's Magnox operator to delay dismantling up to about 100 years.

The IAEA report mentions principal decision criteria for deferred dismantling and principal decision criteria for direct dismantling.
According to the IAEA the US Nuclear Regulatory Commisssion (NRC) provided in 2001 a simple algorithm to calculate decommissioning costs that would ensure that pertinent financial requirements are being met. The IAEA does not exemplify this striking statement: it suggests that it would be possible to reliably calculate the costs of a very complex sequence of activities, costing billions of euros and taking decades to complete. No such sequence has ever been completed at time of writing of this study (2019).

The report [IAEA-*wmbd-st-4* 2005] Q659 discusses reuse of decommissioning sites, it mentions 11 aspects of the differences in approach between demolition and redevelopment. New nuclear build is proposed on old nuclear sites, apparently to avoid requirement of complete dismantling and its related costs.

Decision criteria for deferred dismantling:

- Lack of availability of a repository
- Lack of funds for direct dismantling
- Radioactive decay of some radionuclides, and consequently:
  - Reduction of local dose rates
  - Reclassification of some radioactive wastes

Decision criteria for direct dismantling:

- Availability of facility staff
- Allows re-employment of staff
- Use of specific expertise
- Use of existing infrastructure, including an available repository
- Experience with licensing procedures
- No long-term site commitment
- Unrestricted use of the grounds for other purposes
- Public and political acceptance

The IAEA reports do not mention absolute criteria, based on scientifically controllable evidence, and do not discuss indepedent inspections. The IAEA reports emphasise compliance with internationally agreed regulations, which turn out to be adaptable to local conditions and financial considerarions.

View of the WNA

The World Nuclear Association *Position Statement* [WNA-*decom* 2006] Q655 - not updated at time of writing in 2019 - presents the nuclear industry's perspective and policy on the important subject of decommissioning of civil nuclear industry sites. Some quotes:

> Inevitably, each country and each company employs a decommissioning strategy appropriate both to the type of site to be decommissioned and also to a specific national, local and technical context. Despite such diversity, this Statement reflects a confident industry consensus that a common dedication to sound practices throughout the global nuclear industry is well established and continues to enhance an already robust record of safe and affordable decommissioning of all types of civil nuclear industry sites, from uranium mines to nuclear power reactors.
>
> This text focuses solely on modern civil programmes that contribute to nuclear electricity generation. It does not deal with the sites from military or early civil nuclear programmes. These sites fall into the category of "legacy activities", which are generally accepted as the responsibility of national governments. It bears emphasis, however, that the decommissioning of legacy activities has also been conducted safely, and the experience gained has enhanced the process of successful decommissioning of modern civil nuclear industry sites.
>
> ...
>
> Decommissioning is defined as all steps leading to the release of a nuclear site – including facilities, land, buildings and equipment – from regulatory control. These steps include the processes of decontamination and dismantling. The nuclear owner/operator is the entity responsible for all aspects of a site's decommissioning.
>
> Two main objectives: render the site permanently safe and to restore it, as far as practicable, for reuse; no significant health risk may be borne by people nor may any danger be posed to the environment.

Regulatory criteria and internationally agreed rules are indispensable according to WNA. As pointed out in the previous section the notion 'regulatory control' turns out to have little practical meaning. Standards and internationally agreed rules are easily adaptable to the needs at a given moment at a given location.
A statement from [WNA-*decom* 2006] reads:

> There is now a wealth of industry experience in decommissioning. Worldwide, over 100 mines, 90 power reactors, 250 research facilities and many other fuel cycle facilities have been, or are being, successfully decommissioned.

This statement seems questionable in view of the facts discussed in the previous chapter. Which situation does WNA designate 'successfully decommissioned'? Does this term mean nothing more than 'removed from an active status'? As far as known few depleted uranium mines, if any, are adequately rehabilitated; usually depleted uranium mines are abandoned after the last container of yellow cake leaved the site.
According to [WNA-*decom* 2019] Q157 about 17 nuclear reactors had the full decommissioning process completed by the end of 2016, chiefly small and experimental reactors. Only a small number of these 17 are actually demolished and in several cases the reactor was transported to a storage site, and often the foundations are left in place. Radioactive wastes are stored at the site or at governmental storage sites and not isolated from the biosphere in a geologic repository. In none of the cases, as far as known, the complete procedure as presented in Figure 1 has been completed. The present experience in decommissioning is not representative for the hundreds of nuclear power plants yet to be decommissioned.

WNA discusses the aim to minimize contamination, maximize recovering, recycling and reuse (four R's). Disposal is used only as a last resort. Typically, over 90% of the volume of waste generated during decommissioning of a nuclear facility has little or no radioactive contamination, and most of the remainder has only a very low level of radioactivity. Thus only a small percentage of waste material must be dealt with as low- or intermediate-level radioactive waste. WNA does not make clear what is called a 'safe' decom site nor what provisions are made to dispose of the removed radioactive materials.
WNA does not mention the approach planned in Finland and Sweden to dispose of dismantling waste in a separate geologic repository, see for example [IAEA-349 1993] Q43, [Vattenfall 2005] Q152, [Sjöland 2014] Q704, [SKB 2018] Q839.

[WNA-*decom* 2006] Q655 states:

> Equally as important as the re-use of materials and waste is the re-use of land, water bodies and buildings after site decommissioning. In commercial terms, the optimal re-use of a successfully decommissioned nuclear site may well be to build a new nuclear facility there.

Would this mean that in case of reusing a decom site for a new nuclear facility the decommissioning activities need to comply with less stringent standards for cleanup, and that more radioactive materials at the site are tolerated?
What if not a new nuclear facilitiy would be built at a decom site intended for reuse?

Other quotes from [WNA-*decom* 2006] read:

> Regulations apply throughout decommissioning and thereafter, and the owner/operator maintains control after decommissioning until all regulatory requirements are satisfied. At this final stage, authorities can decide to partially or fully discharge the owner/operator's responsibilities and liabilities for the decommissioned site."
>
> "While the overall cost for decommissioning is significant, it is not prohibitive or even dominant. This cost is normally planned for at an early stage and is recognized as a basic responsibility of the owner/operator. Normal industry practice is to build a decommissioning fund during the lifetime of a facility. Because decommissioning costs are relatively small compared to the lifetime value of a nuclear facility's output, the financial resources necessary for decommissioning can be accumulated through a very modest incremental addition to the price of electricity from nuclear power plants or nuclear fuel-cycle services. Accruing the resources sufficient to achieve sound decommissioning is a recognized responsibility of the site owner/operator. The systematic nature and affordability of financing for decommissioning modern civil nuclear facilities should not be confused with the entirely different situation of managing legacy activities. These involve sites from military or early civil nuclear facilities and tend to be expensive and complicated.
>
> ...
>
> *Summary*
>
> The safe decommissioning of civil nuclear sites is a widespread, well-demonstrated reality. The nuclear industry's strong record reflects a high degree of expertise and responsibility toward the well being of current and future generations. Accumulating experience and knowledge will serve to reinforce this already robust record of safety and achievement.
>
> The nuclear industry has in recent decades successfully fulfilled its responsibilities for decommissioning its facilities and continues to meet these obligations with professional dedication and technological skill.

WNA discusses in its publication responsibilities of the nuclear industry but does not mention the notion 'liability'. In this context the above quoted statements raise some questions:
Who is the owner/operator many decades after final shutdown of a nuclear facility? Who is liable for the costs of a safe decommissioning of a nuclear power plant or other nuclear facility, many decades after its final shutdown?
Looking at the declining nuclear capacity worldwide, how sure society can be that in the future, for example in the years 2050 - 2150, sufficient nuclear expertise and human skills are available to accomplish the task our generation postponed to the future?

Uranium mines

About decommissioning of uranium mines [WNA-*decom* 2006] reads:

> At uranium mines, the decommissioning of mills poses challenges similar to those at other front-end facilities. Due to their large volumes and low radioactive levels, uranium tailings that result from conventional (mechanical) mining usually remain on site. Decommissioning work includes improving the long-term containment of tailings basins; placing a cover on top of tailings to reduce both water infiltration and the emission of radon gas; and collecting, treating and monitoring water discharges from tailings basins and mines (Tailings themselves are not a decommissioning waste as they result from mining operations.). For mining operations using in-situ leaching (ISL), the decommissioning process centres on the recovery of injection well pipes and process wastes, and on the restoration of underground water quality through treatment and monitoring.
>
> For both NPPs and nuclear fuel cycle facilities, the final decommissioning steps are the restoration of the site's landscape and long-term monitoring and institutional control. Restoration work for an NPP involves a relatively small area as compared to a uranium mine, where a much wider swath of terrain has been disturbed.

IAEA standards

Regarding regulations and standards [WNA-*decom* 2006] reads:

> Uniformity in regulatory standards facilitates predictability, planning, and efficiency in all areas of nuclear industry practice, including the decommissioning process. There is thus an increasing effort internationally to develop agreed universal standards that will lend consistency and coherence to national regulatory regimes. Recently the IAEA adopted international standards on the removal from regulatory control of materials containing trace levels of radioactivity; these standards were particularly designed to govern the use or disposal of bulk quantities of such materials as may occur during decommissioning. These standards - and similar IAEA standards for land and water bodies at decommissioned sites - are milestones in regularizing the process of achieving safe and efficient re-use of decommissioned nuclear facilities.
>
> For the lower volumes of intermediate level wastes, the common practice is disposal or storage as an interim measure. For very low-level radioactive material and wastes, countries currently vary in their practices for exemption and clearance, with some countries permitting unrestricted recycling and re-use.

Cost and finance of decommissioning

With respect to costs and funding [WNA-*decom* 2019] Q157 reads:

> Decommissioning costs for nuclear power plants, including disposal of associated wastes, are high relative to other industrial plants but are reducing, and contribute only a small fraction of the total cost of electricity generation.
>
> ...
>
> In most countries the operator or owner is responsible for the decommissioning costs.The total cost of decommissioning is dependent on the sequence and timing of the various stages of the program. Deferment of a stage tends to reduce its cost, due to decreasing radioactivity, but this may be offset by increased storage and surveillance costs. Even allowing for uncertainties in cost estimates and applicable discount rates, decommissioning contributes a small fraction of total electricity generation costs. In USA many utilities have revised their cost projections downwards in the light of experience.Financing methods vary from country to country. Among the most common are:
>
> *Prepayment*, where money is deposited in a separate account to cover decommissioning costs even before the plant begins operation. This may be done in a number of ways but the funds cannot be withdrawn other than for decommissioning purposes.
>
> *External sinking fund* (Nuclear Power Levy): This is built up over the years from a percentage of the electricity rates charged to consumers. Proceeds are placed in a trust fund outside the utility's control. This is the main US system, where sufficient funds are set aside during the reactor's operatinig lifetime to cover the cost of decommissioning.
>
> *Surety fund, letter of credit, or insurance* purchased by the utility to guarantee that decommissioning costs will be covered even if the utility defaults.In the USA, utilities are collecting 0.1 to 0.2 cents/kWh to fund decommissioning. They must then report regularly to the NRC on the status of their decommissioning funds. About two-thirds of the total estimated cost of decommissioning all US nuclear power reactors has already been collected, leaving a liability of about $9 billion to be covered over the remaining operating lives of about 100 reactors (on the basis of an average of $320 million per unit).An OECD Nuclear Energy Agency survey published in 2016 reported US dollar (2013) costs in response to a wide survey. For US reactors the expected total decommissioning costs range from $544 to $821 million; for units over 1100 MWe the costs ranged from $0.46 to $0.73 million per MWe, for units half that size, costs ranged from $1.07 to $1.22 million per MWe. For Finland's Loviisa (2 x 502 MWe) the estimate was €326 million. For a Swiss 1000 MWe PWR the detailed estimate amounts to CHF 663 million (€617 million). In Slovakia, a detailed case study showed a total cost of €1.14 billion to decommission Bohunice V1 (2 x 440 MWe) and dismantle it by 2025.

How secure are such fundings many decades after final shutdown of a nuclear power plant?

6 Predictable problems for the future

Even if alle nuclear power plants would be closed down, the nuclear legacy will predictably pose serious problems for the near and far future. These problems are related with aspects such as:

- escalating costs, rthe relationship with the energy debt and dthe latent CO_2 emission
- availability of skilled personnel, knowledge plant history, expertise
- increasing releases of radioactive materials into the human environment
- ageing of materials and structures
- relaxation of exposure and release standards; currently there are large differences between countries and agencies
- uncertainties regarding the economic capacity in future
- orphan sources
- illicit trafficking
- nuclear terrorism

The high and continually escalating costs of waste management and disposal may provoke undesirable developments and hazardous situations. Some conceivable scenarios are:

- Standards in regulations may be relaxed to admit higher concentrations of radionuclides in materials for clearance, because of economic reasons. Clearance is the controlled release of materials into the public domain. Once released the materials are no longer subject to regulation.
- Diluting radioactive materials with nonradioactive or using concrete rubble as landfill or road paving. Reuse of contaminated and/or activated steel and concrete by 'diluting' it with fresh steel or concrete, as proposed in [IAEA-293 1988] Q36, might be very risky, in the first place because of the potentially hazardous and unknown isotopic composition of the scrap and rubble and unknown biological behaviour of a number of nuclides, and in the second place because of the high risk of uncontrolled trade in radioactive materials.
- Increase in uncontrolled shipments of radioactive materials. High commercial value of the high-grade metals used in construction of nuclear power plants, may stimulate illegal trade in radioactive scrap metals, released at the demolition of the plants. Illegal trade in radioactive materials already is becoming an uncontrollable problem.

In Europe, with its many different countries, the situation is far more complex and probably more problematic, leaving aside the management and disposition of radioactive concrete and other construction materials.
In case of waste released by dismantling nuclear power plants and other nuclear facilities, it would be wise to avoid shipments and trade of radioactive debris as much as possible and packing the materials at the source: the reactor.

Not just the amount of radioactivity, measured in Bq, but also the kind of the radionuclides contaminating the system has consequences for the way of demolition and handling the wastes. With longer operating times, the chances of contamination with fission products and actinides increase, and consequently the health hazrds.

The radioactive inventory of a nuclear power plant, after removal of the spent fuel elements and control rods, is an important parameter for the efforts needed to decommission and dismantle the plant. Dismantling will be increasingly difficult and energy-intensive as the radioactive inventory rises, due to several factors, e.g.:

- larger amounts of material are to be classified as radioactive wastes
- the fraction of long-lived radionuclides increases
- the fraction of troublesome nuclides (e.g. alpha emitters) increases

- decontamination will become increasingly difficult
- the (cumulative) radiation doses will be higher, so more material has to be removed by remotely controlled equipment (robots)
- more auxiliary equipment and packaging materials will be needed
- more man-years are required
- more health and safety measures are demanded.

Typically, the inventory of a large PWR or BWR after about 20 full-power years, are estimated to be in the order of 100-600 PBq (1 PBq = $1*10^{15}$ Bq), one year after final shutdown and excluding spent fuel elements and control rods. The wide spread in the estimates is not explained and points to large uncertainties in the models used for the calculation of the inventories. Little or no empirical data based on actul measurements are available.
According to a US study [DOE 1978] Q278, quoted in [Lipschutz 1980] Q54, the inventory of a 1200 MW LWR after about 40 years operation typically will be about 15 MCi (555 PBq). This figure must be the result of a model calculation, as no nuclear power plant of that power ever reached a lifetime of 40 years in 1978, if such a large plant existed at all.

How long would an entombed reactor remain safe?
Factors to be taken into account are, among other:
- ageing of materials and structures, accelerated by radiation,
- human intrusion, knowledge?
- how well is the covering structure constructed? leaks and natural disasters may occur, the tomb has to last many decades,
- if knowledge get lost, would future generations know why and how to dismantle the tomb?

Orphan sources

Lost or uncontrolled radiation sources ('orphan sources') are a major subject of concern to the metal recycling industry and also to the general public in terms of potential economic loss or public health impact.
Inadvertently melting radioactive scrap metal or devices containing sealed radioactive sources are frequently found in construction and demolition debris, especially from industrial facilities; the frequency increases each year [NCRP-141 2002] Q272. Gamma-emitting nuclides, such as ^{137}Cs, ^{60}Co and ^{241}Am are those most commonly detected. The nuclides are detected in the off-gas, slag and/or furnace dust of steel mills. Inadvertent meltings have also occurred at mills naking metal products from recycled aluminium, carbon, copper, nickel, lead, zinc and gold.
Sometimes sources containing nuclides such as ^{3}H, ^{90}Sr or ^{85}Kr are found by spotting warning labels or signs on scrapped equipment.
International trade in recycled metals and finished products made from recycled metals is complicating the controllability of radioactive scrap metals. Not all countries are equally meticulous in their regulations and control regarding nuclear materials.
Volatile beta-emiters, such as ^{3}H and ^{14}C (as CO_2), may escape detection at all and are likely discharged from the mills into the environment undetected. What is known about other hard-to-detect radionuclides?

Findings of the National Council of Radiation Protection and Measurements [NRCP-141 2002] Q272, concerning potentially radioactive scrap metals, are indicative of an urgent and problematic situation in the USA:

> 'There is an urgency to establish consistent national/international policies and standards.'

Unknowns

The reports of the IAEA and WNA on decommissioning and dismantling leave a number of questions to be unanswered, such as:

- the costs of the various steps of the dismantling process
- radioactive inventory of metal and concrete structures
- composition of the radionuclide inventory
- which radionuclides are measured and which are not
- what quantities of the various radionuclides are present in the debris and scrap
- volumes and masses of the radioactive wastes
- specific activity of the different wastes
- requirements of equipment, energy, materials and human skills
- ways of handling and packaging of the radioactive wastes from decommissioning
- unambiguous quantitative criteria
- safe isolation of the dismantling waste
- measures to counteract illegal trade of radioactive materials, in the knowledge that a number of dangerous and long-lived radionuclides are not or hardly detectable with common radiation detectors
- guarantees to society that the regulations and standards regarding the nuclear wastes will not be governed by short-term market-economic considerations, but will be based on solid physical, biochemical and medical evidence.

Future challenges

The unprecedentedly long time scale of decommissioning & dismantling, including isolation of the radioactive wastes, raises unprecedented challenges, due to a number of unsolved issues, such as:

- Rising energy requirements for the same task the longer the activities are postponed.
- Risks of evaporating expertise needed to fulfil the task.
- How to educate skilled personnel decades from now? It is conceivable that nuclear power is phased out during the coming decades or century.
- How to secure the required knowledge and documentation of the nuclear structures and of the history of nuclear power plants, reprocessing plants and other installations?
- The investments of materials, energy and human effort may be seen as economic losses.
- Questions may raise about liability: who is liable in the year 2117? The owner/operator from 2017, a century before?
- Questions may raise about the availability of decommissioning funds: would a fund set aside in 2019 still exist by 2119 to 2169? If so, would those funds be sufficient for the activities?
- Could the task be accomplished in a time of economic decline?
- Risks of loss of knowledge of locations, composition and hazards of radioactive wastes.
- Risings risks of terrorism, leaks, large and insidious accidents, natural disasters, military conflicts.

The high and continually escalating costs of waste management and disposal may provoke undesirable developments and hazardous situations. Some conceivable scenarios are:

- Criteria in regulations may be relaxed to admit higher concentrations of radionuclides in materials for clearance, because of economic reasons. Clearance is the controlled release of materials into the public domain. Once released the materials are no longer subject to regulation.
- Diluting radioactive materials with nonradioactive or using concrete rubble as landfill or road paving. Reuse of contaminated and/or activated steel and concrete by 'diluting' it with fresh steel or concrete, as proposed in [IAEA-293 1988] Q36, may be very risky, in the first place because of the potentially hazardous and unknown isotopic composition of the scrap and rubble and unknown biological

behaviour of a number of nuclides, and in the second place because of the high risk of uncontrolled trade in radioactive materials.

- Increase in uncontrolled shipments of radioactive materials. High commercial value of the high-grade metals used in construction of nuclear power plants, may stimulate illegal trade in radioactive scrap metals, released at the demolition of the plants. Illegal trade in radioactive materials already is becoming an uncontrollable problem.

In Europe, with its many different countries, the situation is far more complex and probably more problematic, leaving aside the management and disposition of radioactive concrete and other construction materials.
In case of waste released by dismantling nuclear power plants and other nuclear facilities, it might be wise to avoid shipments and trade of radioactive debris as much as possible and packing the materials at the source: the reactor dismantling site.

Après nous le déluge?

Reports of the IAEA and WNA on decommissioning and dismantling of nuclear power plants, reprocessing plants and other nuclear installations are dealing with regulations, paperwork, bookkeeping aspects and 'we-must-do' statements.
From the reports emerges a little conclusive picture of the way the nuclear industry intends cope with the challenges of the nuclear legacy. The reports express a liitle decisive policy to tackle the task of paying the entropy bill of the nuclear generated electricity consumed on credit during the past six decades. Statements on costs and liabilities are vague and ambiguous. Statements on health hazards, if mentioned, are characterised by downplaying and denying. Decommissioning of reprocessing plants is not discussed.

Reports on waste management, inextricably connected to decommissioning and dismantling, are dealing with complex formulations of regulations that leave ample room for adaption to local conditions and financial considerations. Scientifically quantified criteria are lacking. Recommendations for sound and independent inspection system to classify the radioactive wastes are lacking.
The IAEA and WNA reports do not contain estimates of the amounts of decommissioning & dismantling wastes to be expected, nor recommendations or regulations how to package and to dispose of the radioactive wastes.
The reports of the IAEA and WNA seem to suggest that exhaustive regulations are sufficient to cope adequately with the nuclear legacy, to guarantee a safe world for the future generations.
Fact is that all human made radioactive materials are still present in the human environment in mobile condition. Not one repository in the world for safe isolation from the biosphere is in operation.

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