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ARTICLE

Circular Economy through the Prism of Nuclear Material and Waste Management

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In a circular economy, resources are continually reused as possible, retrieving the maximum value from them while recovering and regenerating products and materials at the end of each lifecycle. This approach delivers societal benefits by limiting waste production and preserving natural resources. The decommissioning working group of World Nuclear Association is, among other tasks, working to shape industry positions related to radioactive waste management and decommissioning. The prevailing viewpoint asserts that circular economy principles should be applied within the nuclear industry, particularly in waste management and decommissioning activities.

KEYWORDS: circular economy, sustainability, recycling, reuse

I. Introduction

The World Nuclear Association is an international organization representing the global nuclear industry. With its extensive network of nuclear companies worldwide, it serves as a unified body encompassing all facets of the nuclear industry. Its membership includes entities involved in various segments of the nuclear sector.

The Decommissioning Working Group within World Nuclear Association actively monitors industry developments and plays a critical role in shaping industry positions. It advocates for sustainable strategies, representing the nuclear industry's interests in the international environment and regulatory landscapes. Recognizing the significance of optimizing resources and reducing waste for the benefit of society, the working group has focused on the circular economy. This initiative serves as an extension of the Methodology report developed a few years ago,[1)] acknowledging the pivotal importance of establishing a mindset geared towards maximizing resource utilization and waste reduction.

An approach that aims to maximize the use of resources and minimize waste to the extent reasonable should be established. All components and buildings have limited lifetimes, but these should be extended as much as practicable for society to derive maximum benefit from them. At the end of their operable lives, parts should be reused if still fit for purpose or, if applicable, recycled to minimize the amount of waste for disposal.

The cradle-to grave-approach should only be used as a last resort, where it is not possible to minimize negative impacts on the environment or consumption of resources in line with a circular economy.

The United Nations Economic Commission for Europe (UNECE) states: "The circular economy is a new and inclusive economic paradigm that aims to minimize pollution and waste, extend product lifecycles, and enable broad sharing of physical and natural assets. It strives for a competitive economy that creates green and decent jobs and keeps resource use within planetary boundaries."

In terms of the relevance of nuclear safety to a circular economy, the authors of this paper consider both short- and long-term safety perspectives to be integral aspects of a circular economy. Short-term specific routines are applied so that radiologically hazardous materials are not released to the environment. At the same time, the regulatory requirements should not result in unnecessary hurdles for the implementation of a circular approach. In the long term, the sustainability of society depends on the transition from a linear to a circular economy; this principle should become the main driver of an holistic safety approach, embedding not only radioprotection aspects but also environmental impacts mitigation considerations and, consequently, societal aspects (sustainability, public acceptance, employment securitization.

The following sections provide an overview of a circular economy followed by the application of circular economy principles to the nuclear industry, and in particular how low-level waste management is related to lifetime extension and decommissioning activities. In this regard, the necessary conditions (regulatory, social, industrial, economic and environmental) to deploy a circular economy will be addressed, including the expected assets as well as its benefits and outcomes. Even though reprocessing of spent fuel is an essential part of a circular economy in the nuclear sector, the focus of this paper is on the large volume of low-level contaminated materials. As a reminder, this category encompasses almost 90% of the generated materials and waste by nuclear operations, whatever they are.

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II. Circular Economy at a Glance

Most societies have over the past centuries, with a few exceptions, been built on a Linear Economy, i.e. take, make, use and dispose. Also, the nuclear industry has since the start many decades ago, very much been built on a linear economy way of thinking. This lifestyle and industrial approach is neither sustainable nor accepted onwards. To make the approach sustainable over time, it should be based on a strive towards a Circular Economy.

A Circular Economy is much more than purely a waste and materials management system as illustrated in **Fig. 1**. As previously mentioned, although this paper discusses the application of a Circular Economy to the nuclear industry in general, this paper focuses on low-level contaminated materials and waste perspectives.

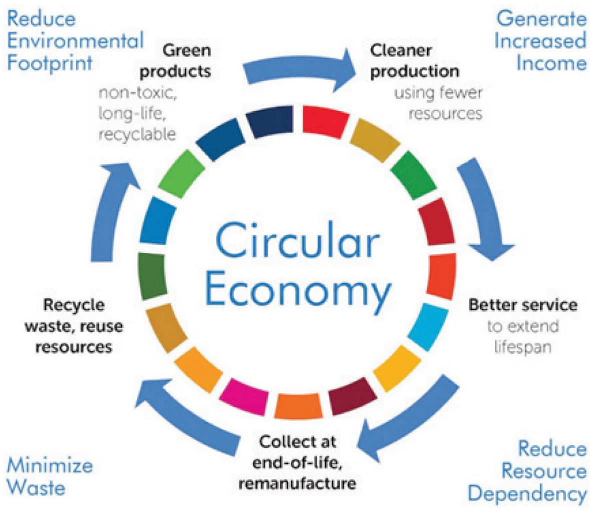

Fig. 1 Circular economy overview (Image courtesy: UNIDO)

According to the IAEA's definition, a Circular Economy is a policy in which resources are kept in reuse or recycling for as long as possible, retrieving the maximum value from them, then recovering and regenerating products and materials at the end of each lifecycle. It is an approach focused on delivering positive society-wide benefits by limiting waste production and preserving natural resources.

The objective of the paper is to illustrate how the required paradigm shift towards the Circular Economy principles within the nuclear industry and particularly in the waste management and decommissioning activities can be performed, and not at least what has been done to date. The paper will address identified necessary conditions (regulatory, social, industrial, economic and environmental) to deploy the Circular Economy principles.

The paper, provided by experts of the Decommissioning Working Group within the World Nuclear Association, will stress that it is essential to establish a mindset aiming at making most out of resources and minimizing waste, to the benefit of the society. Any component or building has a limited lifetime, some significantly longer than other. The facility lifetime can often be extended thanks to additional maintenance including replacement of specific components, instead of complete dismantling and demolition followed by new build. Such latter approach, experienced up to now, lasts several decades and cannot be considered anymore as a circular economy incentive.

At the end of life, parts should be reused if still fit for purpose or, if applicable, recycled, to minimize the amount of waste for disposal and to take benefit of the properties to get most value out of it in its following lives/uses. Indeed, the material should be recycled in a way preserving its properties and values or even improving them all along the further uses.

The Linear Economy approach, also called cradle to grave, must be the last option. Safety must always be secured but it must not be an excuse for not striving towards sustainability. Sustainability and safety can and should be part of the same discussion as they both relate to safety, but in different time perspectives. Short term specific routines are to be applied to secure that materials that can bring a radiological hazard are neither released nor remaining in a building for reuse. At the same time, the regulatory requirements must not cause unnecessary hurdles for the implementation of a circular approach. Long term, the survival of humanity depends on its environment preservation. Only the transfer from a Linear to a Circular Economy can foster and secure this essential objective for mankind. This consideration makes the transition from linear to Circular Economy the overall driver of safety approach.

Hence, any incentive, innovation, new regulations facilitating the safe extension of energy power supply means allowing low carbon production and optimization of already picked up raw resources, should be promoted and improved. The extension of NPPs lifetime up to reaching the end of life of concrete buildings, foreseen by the WG since 2019, is one of these potential promising stakes to be developed.

III. Sustainability Achievements to Date

Through the experience gained from decommissioning projects combined with a strive towards sustainability, the nuclear industry has in practice taken steps towards sustainability and a Circular Economy approach:

- Implementation of reuse and recycling principles, not at least characterisation of items and components for safe and efficient reuse and recycling.
- Identification of criteria for sustainable material and waste strategies, including technological feasibility, cost considerations, environmental impacts, and regulatory compliance.
- Reduction of waste volume, preserving repository space and minimizing resource needs.
- Innovations to reduce secondary waste from treatment operations.
- Recommendations for nuclear facility design to enhance the back-end conditions towards a circular material flow.

The most significant opportunities for reuse and recycling are found in three primary categories:

- Reuse of Buildings and Equipment

Offers substantial value whether items are repurposed within or outside the nuclear sector.

- Recycling of Metals
  The prime opportunity for recycling as they can be reused repeatedly without any loss in quality.
- Recycling of Concrete
  Need attention due sheer volumes involved and the environmental impact from production of new concrete, making it a critical area for focus.

In addition, lifetime extensions and turning nuclear facilities into a second life, fit very well into a document about sustainability and circular economy.

1. Reuse of Buildings and Equipment

Significant investments are made in the buildings, infrastructure, and equipment of nuclear plants throughout their operational lifetimes. In a circular economy framework, these assets should be repurposed wherever feasible to extract maximum value for new ventures.

One option, which has not been explored extensively thus far, involves transforming nuclear plant decommissioning projects into modernization endeavors where end-of-life equipment is replaced. Another possibility under consideration is converting decommissioned nuclear plants into Small Modular Reactor (SMR) facilities to leverage existing infrastructure and expertise. If these avenues are not viable or preferred, there are numerous alternative options for repurposing buildings, infrastructure, and equipment within the nuclear sector or in conventional applications. Following clearance, materials can be processed by conventional industries for use in new products.

2. Recycling of Metals

Metals from nuclear installations offer versatile recycling opportunities, both within and outside the nuclear sector, like:

- Recycling to the conventional metal industry after general or specific clearance.
- Recycling to the conventional metal industry after decontamination, melting, and clearance in a nuclear licensed treatment facility.
- Recycling for licensed practices, such as repurposing as shielding blocks, manufacturing of waste containers, etc.

3. Recycling of Concrete

The cement sector ranks as the third largest industrial energy consumer globally, accounting for 7% of industrial energy use and 27% of carbon dioxide emissions. Concrete rubble represents a valuable resource that can be recycled for various purposes, including use as aggregate for new concrete, backfilling in nuclear decommissioning projects, road construction, etc.

Studies and practical applications demonstrate that new concrete made using recycled high quality concrete rubble, can match the strength of concrete made from virgin materials.

Considerable efforts are underway in the conventional industry to further enhance and optimize the recycling of concrete, aiming to maximize resource efficiency and minimize environmental impact.

IV. Case Studies

1. Reuse of Buildings, Infrastructure, and Equipment

The development of processes to reuse buildings, infrastructure and equipment has accelerated when installations in older facilities has reached the end of life.

Two examples from the nuclear industry are presented below.

- Slovakia

As shown in **Fig. 2**, the turbine hall of the Bohunice A1 nuclear plant has been reused as a radioactive waste/metal treatment facility that includes facilities for the unrestricted release of metals.[2)]

Fig. 2 The Bohunice A1 turbine hall while in operation (Left). The turbine hall after the conversion to a radioactive waste treatment facility (Right). (Images courtesy IAEA.)

- Sweden

As shown in **Fig. 3**, a former research reactor hall at the Studsvik industrial site has been converted into a facility for the management of sealed sources from research, industry and hospitals owned and operated by Cyclife. The radioactive sources managed are either reused in new applications, recycled or conditioned for disposal. Redundant shields are reused or recycled back to conventional industry after clearance.

Fig. 3 Former research reactor hall converted into a facility for the management of sealed sources. (Image courtesy Cyclife)

2. Recycling of Metals

There are many examples of successful recycling of metals. Most of the metals at a nuclear installation can be qualified for clearance and recycling locally at the nuclear installation, while other material will require treatment in a dedicated treatment facility. The following is an example of the latter.

• France - PWR steam generators

In France, clearance of metals and other materials from nuclear installations for recycling into the public domain is in general prohibited. However, following a change in the regulatory framework by the French Government in 2022, some metals can be released without restrictions after melting.

A project applying the new conditions was carried out with the transport, treatment, and clearance of six PWR steam generator upper parts from the Fessenheim nuclear power plant.

The six low contaminated components, about 115 tonnes each, were transported on waterways to the Cyclife facility in Sweden. The unloading of one of the components at arrival to Sweden is shown in **Fig. 4.**

Fig. 4 Arrival of steam generator upper parts for treatment at the on-site harbour (Image courtesy Cyclife)

The components were treated by segmentation (see **Fig. 5**), decontamination and melting. The molten metal was sampled prior to casting to ensure high precision analysis of the radiological inventory in the metal.

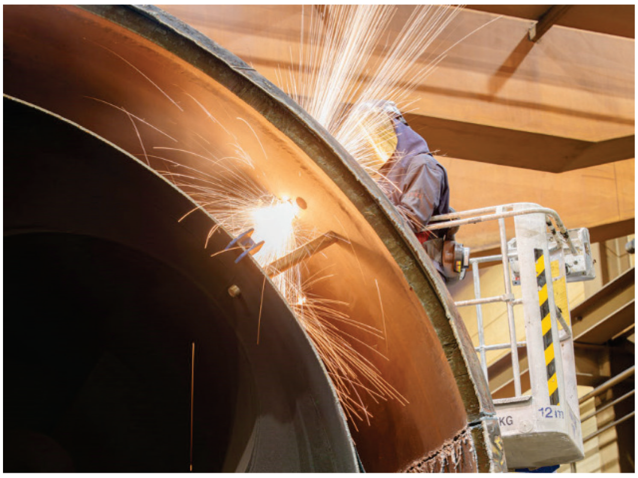

Fig. 5 Segmentation of steam generator upper part (Image courtesy Cyclife)

Following the complete clearance procedures, 100% of the metal was qualified for safe recycling to the conventional industry for the manufacturing of new products. The residues from the treatment (cutting and decontamination residues, melting slag and filter dust) were conditioned, packed, and assessed with regards to radioactivity content prior the return to France for disposal as radioactive waste. The lower parts of the steam generators will be shipped to Sweden for treatment in 2025.

3. Recycling of Concrete

There are many recycling examples for concrete. In most cases the concrete rubble is used in non-qualified ways and not to produce new concrete. This phenomenon is sometimes described as downcycling and should generally be avoided within a circular economy.

Two examples[3)]:

• Switzerland – conventional industry

The extensive experience gleaned from numerous building construction projects in Switzerland under-scores a promising trend: approximately 90% of the demand for concrete can be fulfilled through re-cycled sources. Although this statistic has not been systematically monitored, it reflects a substantial shift towards sustainable construction practices. Notably, data from 2016 reveals that over 1,730 buildings in Switzerland have been certified, mandating a minimum of 50% recycled concrete content. Moreover, the city of Zurich has enacted stringent regulations stipulating that public buildings must predominantly utilize recycled concrete in their construction. These initiatives showcase Switzerland's commitment to promoting environmental stewardship and resource efficiency within the construction industry, setting a commendable precedent for sustainable urban development worldwide.

• Germany – conventional industry

In 2016, Germany achieved recycling rates exceeding 90% for building rubble, road construction waste, and other construction debris. However, the utilization of this recycled material often fell into low-value recovery methods such as landfill construction or backfilling excavations. Only a small fraction of recycled aggregates found their way into concrete production for building construction, where their potential for high-quality applications could be fully realized.

Nuclear sector

The practice of taking benefit of concrete rubble for non-qualified purposes, such as filling cavities, is indeed widespread within the nuclear industry. However, the utilization of concrete from nuclear installations to produce new concrete remains rare, if existing at all.

This observation underscores that the current waste management practices within the nuclear sector are not circular in terms of concrete. While several concrete recycling methods for non-qualified purposes are well established, the history of circular economy applications for concrete within nuclear industry are rare. The low economic benefit of turning concrete rubble into new concrete might be a hurdle to overcome when aiming to make the nuclear backend circular.

V. Conclusions

A Circular Economy approach within the nuclear industry is needed to demonstrate sustainability and to attract the younger generation to the industry as well as increasing the confidence of the population.

A Circular Economy approach should apply to not only the nuclear fuel cycle, but also to the large volumes of slightly contaminated materials, which with proper management could be reused or recycled instead of being disposed of as radioactive waste.

The experiences gained and the studies performed worldwide clearly indicate that it is possible for the industry to adopt a circular economy. There has been a considerable amount of progress in this area, but much more is needed to be done.

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