

Cradle to Cradle: Turning Nuclear “Waste” into Nuclear Fuel

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Abstract

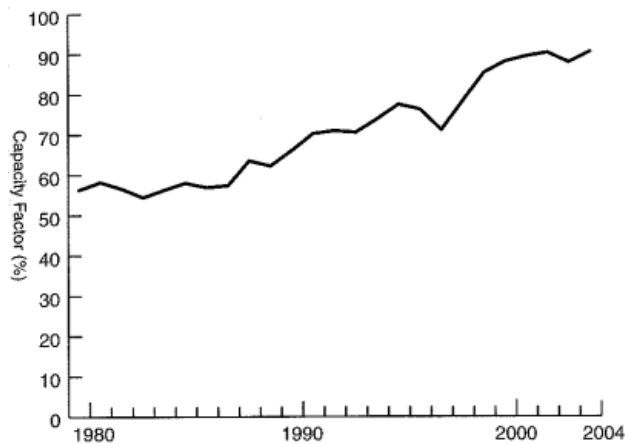
The global society is faced with a dilemma of increasing energy demand and the need to decrease harmful greenhouse gas emissions. Nuclear energy has been proposed as a part of an ‘energy mix’ necessary to address the climate-energy nexus. The following paper addresses waste by-products from the nuclear power industry. Using the cradle-to-cradle theory, in which “waste” equals “food,” the paper explains how a closed-loop nuclear industry should form part of the solution to our energy problem. The cradle-to-cradle concept, technical closed-loop options for used nuclear fuel, benefits and limitations to closed-loop processes, as well as key figures for a cradle-to-grave versus cradle-to-cradle nuclear industry are provided.

I. Introduction

In a greenhouse-constrained yet ever-growing world, there is an imminent need to provide reliable energy, free from climate change-contributing emissions and able to sustain the energy requirements of future generations. Yet short-sightedness has put us in a fragile situation. The necessary solutions and technologies have not been developed or have not been deployed sufficiently by the time we need them—now. The urgency of our present situation is best summed up in the work done by the Intergovernmental Panel on Climate Change (IPCC), which suggests that by 2050, global greenhouse gas (GHG) emissions must be cut by at least 50% globally in order to avert catastrophic changes in our planet’s climate system (IPCC, 2007). By 2050, global population is expected to rise to 9 billion, while global energy demand is expected to at least double (European Commission, 2006). One solution to this problem is nuclear energy. In this white paper, I will present information that addresses waste by-products from the nuclear power industry. I will use the cradle-to-cradle theory in which “waste” equals “food” in order to explain how a closed-loop industry should form part of the solution to the climate-energy nexus.

Some of the history of nuclear energy is far from noble. After various scientific advancements in atomic and fission theory, most of the early research focused on weapons development for use in World War II (DOE, 1994). However, nuclear technology’s potential to now help solve humanity’s dual constraint-and-need energy problem is both viable and remarkable. With only one uranium fuel pellet of seven grams, one can produce as much energy as one metric ton of coal. With only one gram of plutonium, an element produced in nuclear reactor chemical reactions, one can produce more energy than one metric ton of petrol. It is hard to deny the efficiency of nuclear technology in producing energy. Nuclear reactor engineering is a well-established and mature field, with different successful designs in operation. Plant performance has also sharply increased over the years (**Figure 1**). In addition, the most abundant uranium supplies can be found in stable countries, including Canada and Australia. As prominent environmentalist and creator of the Gaia theory, James Lovelock stated, “nuclear energy also happens to be the safest, the most economical and reliable of energy sources” (Lovelock, 2009).

Figure 1: Nuclear Power Plant Performance in the United States (Sweet, 2006)



Dramatically Improved U.S. Nuclear Power Plant Performance
Source: Nuclear Regulatory Commission

Many solutions to environmental problems create unwanted by-products and consequences. The use of food crops for biofuels is one example. Nuclear energy, as historically produced, is another. One such problem with nuclear energy is waste—the subject of this white paper. In addition to fusion—the idea of using sun-like temperatures to fuse together nuclei and generate energy with less long-lived radioactive products (long-term research phase)—and generation IV design reactors—those that can burn long-lived waste in the reactor (medium-term research phase)—there is another idea for treating nuclear waste that is already in practice in some parts of the world. It is an idea that we apply when we throw our glass bottles in a select colored bin, when we buy paper with a certain circular or triangular symbol, when we fertilize our garden with composted organic waste...it is recycling.

II. Solution

A. Cradle-to-Cradle – The Concept

Most of the spent fuel from nuclear reactors follows a typical one-way cradle-to-grave model as described in Braungart and McDonough’s book *Cradle to Cradle*. That is to say, “resources are extracted, shaped into products, sold, and eventually disposed of in a ‘grave’ of some kind” (McDonough & Braungart, 2002). However, we can move towards a more intelligent design by employing a cradle-to-cradle concept within the nuclear industry. Braungart and McDonough propose a philosophy based on the idea that products should be designed so that they can provide “food” or “fuel” for new products or natural cycles. Although the authors go on to advocate smaller utility units, unlike the current large-scale nuclear power plants, their model of eco-effectiveness provides an appropriate framework for taking a look at spent fuel recycling. (There are also a number of small-scale nuclear power reactors in a well-advanced developmental stage).

Braungart and McDonough describe two discrete metabolisms on the planet—biological metabolism, or the cycles of *nature*, and technical metabolism, or the cycles of *industry*. Spent fuel is a product of technical metabolism; the used fuel can stay in a closed-loop technical cycle and can continually circulate as valuable nutrients for industry. In some parts of the world, where spent fuel is presently recycled, the process entails much of what the authors advocate—the concept of a product of *service*. When finished with a product, “the

manufacturer replaces it, taking the old model back, breaking it down, and using its complex materials as food for new products” (McDonough & Braungart, 2002). When a nuclear utility is finished with a fuel element, this is exactly what can happen.

B. Cradle-to-Cradle – Technical Options for Used Nuclear Fuel

At the end of a fuel’s life in reactor and after a total cooling period of approximately four to eight years in water pools, it can undergo a recycling process. The procedure entails the partial or total separation of the products created during the nuclear reactions in reactor (isotopes of uranium and plutonium, minor actinides, and fission products). Spent fuel from a typical pressurized water reactor contains:

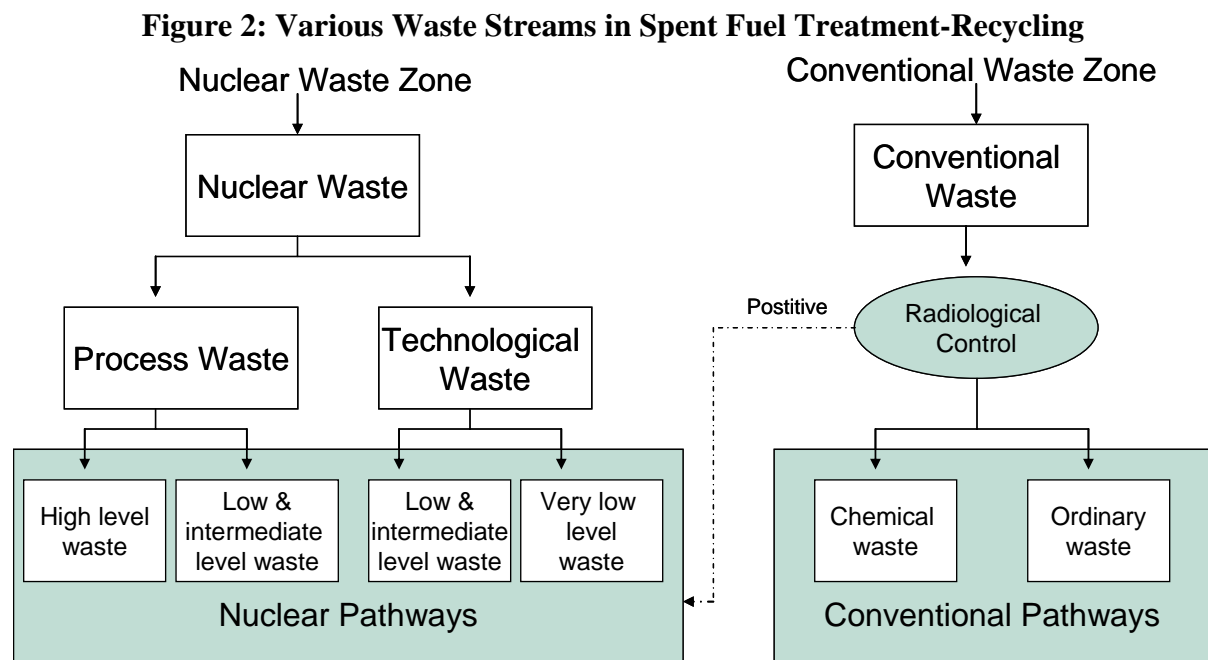
- 94.2% uranium (U-232: 0.1-0.3%; U-234: 0.1-0.3%; U-235: 0.5-1.0%; U-236: 4-0.7%; balance: U-238)
- 1.2% plutonium
- 4.5% fission products
- 0.11% minor actinides (americium, curium, neptunium)

There are various recycling technologies of varying maturity, including:

- Hydrometallurgical processes (well-proven technologies). These processes involve dissolving the fuel elements in concentrated nitric acid and separating products through solvent extraction steps (WNA, 2009).
 - Plutonium Uranium Extraction (PUREX, a hydrometallurgical process that produces reusable uranium following re-enrichment, plutonium, intermediate and high level wastes)
 - Uranium Reduction Extraction (UREX, a hydrometallurgical approach in which plutonium is not valued or reused and is not separated from the minor actinides)
 - UREX+ (UREX process where uranium is recovered initially for recycle and the residual is treated to recover plutonium with other transuranics—unstable chemical elements with atomic numbers greater than that of uranium)
 - Co-extraction (COEX™, a hydrometallurgical process that separates a combined uranium and plutonium from the other products)
- Electrometallurgical processes (a non-aqueous electrolytic processes, or pyroprocessing techniques). These techniques are in the early stages of development; the process involves volatilisation, liquid-liquid extraction using immiscible metal-metal phases or metal-salt phases, electrolytic separation in molten salt, and fractional crystallisation (WNA, 2009).
- Magnetic separation processes (early stages of development); physical separation using magnetic susceptibility of spent nuclear fuel related compounds (Nuttall, 2005)
- DUPIC (Direct use of used PWR (Pressurized Water Reactor) fuel in CANDU (Canada Deuterium Uranium) reactors). CANDU reactors use non-enriched natural uranium; early-stage research is taking place under a bilateral joint research programme (WNA, 2009).

PUREX is the most readily available and mature process (more than 60 years old); it is a solvent extraction process developed at Hanford in the northwestern United States in the early 1950s (Nuttall, 2005). This process can be used so that roughly 95% of the spent fuel material is recycled. There are two major waste streams that come about from a nuclear fuel treatment-recycling process: technological (equipment, metallic waste, etc.) and radioactive

waste from the PUREX process (see **Figure 2**). The various industrial chemicals used during the process are recycled to various degrees to optimize resources (again, cradle-to-cradle concepts); otherwise, chemicals are treated before being safely released in liquid or gas form. Some technological equipment is re-used in various nuclear applications while others are compacted by a 2500 ton press (reducing the volume by a factor of five) and placed into standard stainless steel containers and welded. The remaining 5% of the spent fuel material is high-level radioactive waste primarily made up of fission products; this ultimate waste is vitrified with boron, placed in standard stainless steel containers, and welded shut for cooled storage until geological disposal or other methods are developed (Nutall, 2005). Vitrification is a process used to solidify concentrated solutions of fission products and transuranic elements separated during spent fuel recycling by mixing them with a glass matrix at high temperature; this glass can safely store the radioactive products (thermal stability, lixiviation resistance, irradiation resistance, resistance to alternation with time, homogeneous). Accomplishing the goal of zero nuclear process waste in the nuclear industry will require recycling and destroying, in a new type of reactor, the separated waste products so they no longer require a repository. Five of the six Generation IV reactors being developed have closed fuel cycles which recycle all the actinides.



The uranium recovered through recycling can be re-enriched and used as new fuel in a reactor. The plutonium-uranium mixture recovered from used fuel can be used to make mixed oxide fuel (MOX), and used as new fuel in a nuclear power plant (NEI, 2006). MOX fuel, because of the plutonium component, is far more energy-giving than the enriched uranium fuel from which it came originally. MOX is used in 36 PWRs in Europe (Germany, Belgium, Switzerland, France). A reactor that uses 30% MOX will consume as much plutonium as it produces; MOX has also already been re-recycled. In this way, the spent fuel cycle moves away from what Braungart and McDonough call “downcycling,” in which the recycled material is made into something of a lesser quality. On the contrary, the used fuel is “upcycled”; the material is rematerialized instead of dematerialized.

C. Cradle-to-Cradle – Application for Used Nuclear Fuel

Various advocates of spent fuel recycling provide the following list of benefits:

- The radiotoxic trace in any repository/long term storage is significantly decreased.
- The average half-lives of wastes would be much shorter.
- The physical size of any waste repository would be greatly reduced (Nutall, 2005).
- When recycling is employed in the current nuclear energy cycle, the volume of final waste is reduced by a factor of 4-5 and the radiotoxicity of the waste is reduced by a factor of 10.
- Early reduction of used fuel inventories at reactor sites
- Reliance on existing technology
- An option for the nuclear power sector to protect itself against potential rises in uranium prices
- In the case of the United States, the cash flow requirements for recycling could fit until 2030 within the current financing resources available for a cradle-to-grave strategy (BCG, 2006).
- Vitrified high level waste is more stable in the long term when compared to untreated spent fuel.

Those that are not in favor of the cradle-to-cradle option primarily cite the following two reasons:

- A recycling nuclear fuel industry creates more opportunities for terrorist attacks (proliferation concerns) (Sweet, 2006).
- The option is too expensive.

Proliferation concerns are lessened by employing an array of safeguards, including a recycling process that does not separate plutonium at any point in the process, material containment and surveillance monitoring, environmental sampling, independent verification, and physical protection.

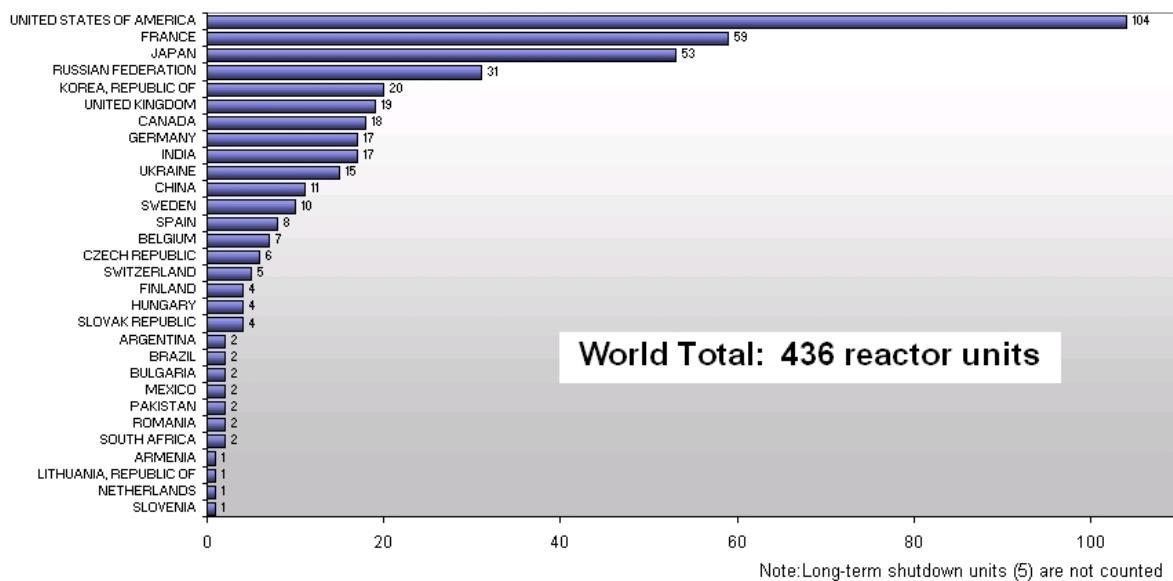
The net costs of recycling used fuel is a multifaceted issue; one must factor in the capital costs, the operational costs, the value of the recovered products, and the reduction in waste volumes (and thus the costs of disposal after recycling). The final disposal cost of a cradle-to-grave strategy is subject to a high level of uncertainty (and thus makes comparison difficult). Recycling used fuel undoubtedly reduces uncertainties in disposal costs and future fuel costs. For cradle-to-cradle cycles, recycling added 10% to the cost of nuclear fuel in 2000, but added a negative cost in 2006 (Barre & Bauquis, 2007). There are two major reports that address the economics of recycling in the United States that give very different cost figures. One report uses a recycling strategy cost of 1,000 USD per kg of heavy metal (Bunn, 2003). Another report uses a recycling strategy cost of 520 USD/kg (BCG, 2006). Both studies compare recycling to a complete “burial” of high level waste.

If we are to move in the direction of eco-intelligent design that employs cradle-to-cradle industrial concepts, the opposite of which brought us to our current vulnerable state with regard to energy and climate change, then environmental economics must be employed to show the value of closed loop systems. In addition, job creation and the honing of high and transferable skills involved in the nuclear industry should be a factor. An average nuclear power facility in the United States employs 800 workers and creates hundreds more for the

community (DOE, 2008). A nuclear fuel recycling facility employs thousands of workers and creates thousands more for the community. At the La Hague recycling plant in France, there are more than 5,000 direct jobs and more than 10,000 indirect and direct jobs in total.

It is useful to show a volumetric comparison of the status quo of the “no-recycling” option versus that of recycling. First, let’s take a look at the amount of civil nuclear waste today and in the future. The annual requirements for a 1000 MWe PWR include 21.5 metric tons of fuel (assuming a fuel burn up rate of 45000 MWdays/ton, a thermal efficiency of 34% and an average capacity factor of 90%). Assuming minimal changes in mass at the end of a fuel’s first usage (nuclear fuel rods are changed on average from twelve to eighteen months in reactor), one would expect to have roughly 21.5 t of fuel yearly, per 1,000 MWe PWR reactor. The chemical composition of this fuel will have changed, with various fission products and plutonium resulting; however, the changes in mass of the fuel elements will be small. As seen in **Figure 3**, there are more than 400 nuclear power plants in the world (IAEA, 2000). These reactors range in size, technology and capacity. There are over 8 thousand tons (8,020 t) of spent fuel produced yearly (using the estimate of 373 GWe of nuclear power currently and assuming on average a 1000 MWe reactor). With a once-through cycle, in which cradle-to-cradle concepts are *not* employed, this amount needs to go into a “grave.” If we employed the currently proven recycling technologies, we could save 95% of this from being buried and the associated environmental, health, safety and security risks. We could reduce 8 thousand tons of waste yearly to just over 400 tons. To provide an idea of space consumption, one ton of used fuel corresponds to approximately two cubic meters of space.

Figure 3: Number of Reactors in Operation Worldwide (IAEA, 2000)



What about future projections for nuclear reactors? A World Nuclear Association projection shows at least 1100 GWe of nuclear capacity by 2060, and possibly up to 3500 GWe, compared with 373 GWe today (WNA, 2007). Taking the lower bound of 1100 GWe, one could expect a total of 1100 reactors worldwide by 2060, assuming that they are 1000 MWe reactors. Using the same assumptions, this leads us to roughly 24,000 tons of nuclear waste yearly without a cradle-to-cradle approach. With recycling, this value could be around 1,000 tons of nuclear waste.

III. Conclusion

The sustainability management method of cradle-to-cradle also applies to our greenhouse-constrained energy system. We can help by reducing our energy demand (changing to efficient light bulbs, taking mass transportation, insulating homes, using daylight, turning off computers at night, etc.). We can help by reusing energy (using solar-powered calculators, panels, and cookers, capturing heat generated elsewhere to heat parts of buildings, etc.). We can also help by recycling the raw products used to create energy, by turning the waste from nuclear reactors into new fuel to be re-applied to create more energy in reactors. It's doable, it's being done, there are many approaches, and it can be used on nearly all the waste.

The nuclear fuel recycling solution presented is not new; however, with our new awakenings to what is required for sustainable development, it is a reborn option. The solution is also not by any means a panacea to the energy demand versus climate change dilemma. It is, as part of the solution to creating low carbon energy, a very useful way of using sustainability concepts to reduce unwanted by-products of a solution. So by creating a closed-cycle, recycling spent fuel, and applying cradle-to-cradle concepts to nuclear energy, we can form a part of the solution to the energy crisis. We can imitate nature's cradle-to-cradle system in which waste is eliminated, and at the same time upcycle industrial spent fuel into fuel that is of equal or higher quality.

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