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Measures of the environmental footprint of the front end of the nuclear fuel cycle

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ABSTRACT

Previous estimates of environmental impacts associated with the front end of the nuclear fuel cycle (FEFC) have focused primarily on energy consumption and CO_2 emissions. Results have varied widely. This work builds upon reports from operating facilities and other primary data sources to build a database of front end environmental impacts. This work also addresses land transformation and water withdrawals associated with the processes of the FEFC. These processes include uranium extraction, conversion, enrichment, fuel fabrication, depleted uranium disposition, and transportation.

To allow summing the impacts across processes, all impacts were normalized per tonne of natural uranium mined as well as per MWh(e) of electricity produced, a more conventional unit for measuring environmental impacts that facilitates comparison with other studies. This conversion was based on mass balances and process efficiencies associated with the current once-through LWR fuel cycle.

Total energy input is calculated at 8.7×10^{-3} GJ(e)/MWh(e) of electricity and 5.9×10^{-3} GJ(t)/MWh(e) of thermal energy. It is dominated by the energy required for uranium extraction, conversion to fluoride compound for subsequent enrichment, and enrichment. An estimate of the carbon footprint is made from the direct energy consumption at 1.7 kg CO_2/MWh(e). Water use is likewise dominated by requirements of uranium extraction, totaling 154 L/MWh(e). Land use is calculated at 8×10^{-3} m^2/MWh(e), over 90% of which is due to uranium extraction. Quantified impacts are limited to those resulting from activities performed within the FEFC process facilities (i.e. within the plant gates). Energy embodied in material inputs such as process chemicals and fuel cladding is identified but not explicitly quantified in this study. Inclusion of indirect energy associated with embodied energy as well as construction and decommissioning of facilities could increase the FEFC energy intensity estimate by a factor of up to 2.

1. Introduction

Electricity generation costs have traditionally provided the most important measure of comparison between generation technologies. Yet monetary cost alone does not thoroughly depict the full environmental and societal impact associated with electricity production. Some resources are utilized by energy producers and consumers at no direct cost, but society may ultimately pay a price for their non-sustainable use.

Governments, including that of the United States, have recognized the importance of quantifying these indirect and external impacts. When the environmental effects of a project are likely to be significant, the National Energy Policy Act (1970) requires an Environmental Impact Statement (EIS) to be prepared and submitted for public review. In addition to direct effects, the EIS must address "changes in the pattern of land use and… effects on air and water" as well as "effects on natural resources… or health." (NEPA, 1970) The NEPA guidelines therefore suggest that energy consumption, carbon footprint, water consumption, land use and public health impact together provide a reasonable measure of the environmental 'footprint' of a technology. This manuscript will address energy consumption, water consumption, and land use.

The objective of this study is to quantify this footprint for the front end processes of the nuclear fuel cycle. The front end processes considered here are conversion of yellowcake to uranium hexafluoride; enrichment; management and/or disposal of depleted uranium; fuel fabrication; and transportation associated with the flow of materials through the front end facilities. Uranium mining, milling, and refining are addressed in Schneider (2010).

While the processes comprising the front end of the fuel cycle are all built upon mature technologies that operate at industrial scales, the footprint of one or more processes is likely to evolve with time. For example, although centrifuge technology is not new, it has evolved through successive technology generations, each one offering better economic performance and, by some measures, a reduced environmental footprint. Entirely new technologies may also emerge for other front-end processes. Past examples include in-situ and heap leaching for uranium production, neither of which were in wide use as recently as the 1970s. A future example may be laser-based enrichment which,

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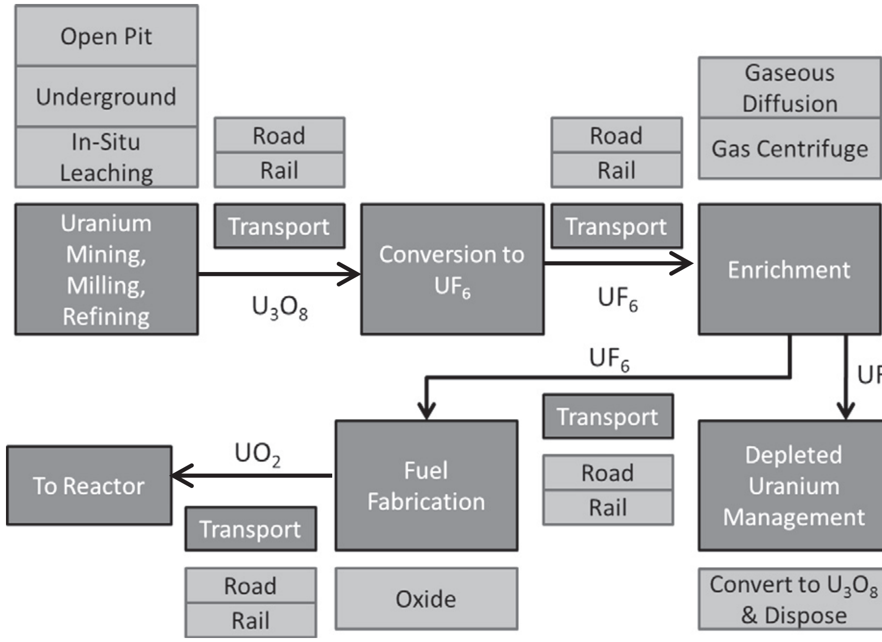

Fig. 1. Mass flows in the front end of the reference fuel cycle.

after being investigated at the laboratory scale for decades, is now moving toward commercial-scale operation.

Uranium production offers another example of the time evolution of the environmental footprint. As higher-grade and easier-to-mine uranium deposits are extracted, production will move to less economically attractive resources. Generally these deposits are associated with lower-grade or less accessible ore bodies — from which extraction and refinement of uranium is more energy-intensive. Providing bounding forecasts of this evolution is a focus of Schneider (2010).

The fuel cycle processes, along with the technology options considered for each and the flow of uranium between them, are shown in Fig. 1. The environmental impacts for each process will be identified and normalized to a unit of uranium throughput along with the impacts of transportation between each of the process steps.

This paper is structured as follows. Section 2 provides a brief survey of the study scope and methodologies. Sections 3.1 through 3.5 apply inventory analysis techniques to estimate the environmental footprint of the technology options considered for each of the processes during their operations. Section 3.6 assesses the impacts of the transportation between each process step. And Section 4 provides conclusions and recommendations for further study.

This paper is a distillation of a report (Schneider et al., 2010) that provides detailed documentation behind the results summarized here. Readers are referred to Schneider et al. (2010) when more information regarding the provenance of the data and analyses are desired.

2. Scope and methodology

This study begins the inventory analysis component of a life cycle assessment (LCA) of the environmental impacts of nuclear electricity production. Life cycle assessment refers to a cradle-to-grave approach to the accounting of impacts from the raw material extraction, through production, and disposal stages of the life cycle for any product. Standards for conducting an LCA are outlined by the International Standards Organization (ISO) (ISO, 1997); these are in turn based on approaches defined by the US Environmental Protection Agency (EPA, 1993).

A holistic life cycle assessment would also include the energy and other environmentally-related inputs to the industries supporting the production of the good. As examples, sulfuric acid and other chemicals consumed in uranium milling, cement utilized in plant construction, and distillate vehicle fuel employed to transport vehicles all contain embodied energy. Embodied energy is the energy utilized to manufacture the products and equipment that serve as an input to the production of another good. A full LCA would also consider impacts resulting from construction and decommissioning.

Energy consumption as reported here does not include the embodied energy of commodities such as the aforementioned process chemicals, cement, or fuel. It does include the thermal energy liberated when the fuel is combusted as well as the electrical energy transmitted into the site. Electrical transmission losses are not accounted for; these may vary from near zero (when electricity is generated on site or in immediately proximate facilities) to ten percent of generated electricity or more.

An estimate of the carbon footprint from direct energy consumption is made by applying emission factors taken from data published by the Energy Information Administration for the fossil fuels and domestic electricity generators (EIA, 2010b) and from CARMA (2010) for foreign and world-average electricity generation. All factors employed in this study are given in Table 1.

Land use is reported in units of square meters of land transformed per unit of throughput. Choice of this unit implies that land utilization is cumulative in the same sense as energy consumption. It would also be possible to report land use in different units such as square meters of land occupied per unit of annual throughput capacity. This subtle change would imply that land is a fully renewable resource returned to its undisturbed state at some time after the capacity is retired. This measure would be meaningful only if weighted with the duration that

Table 1
Emission factors.

Carrier	Factor	Unit
Gasoline	68	kg CO_2/GJ(t)
Distillate fuel[a]	79	kg CO_2/GJ(t)
Coal — industrial coking	89	kg CO_2/GJ(t)
Natural gas[a]	51	kg CO_2/GJ(t)
Coal — fired electricity (US average)	272	kg CO_2/GJ(e)
Natural gas fired elec. (US average)	114	kg CO_2/GJ(e)
Electricity — US Grid average	168	kg CO_2/GJ(e)
Electricity — Canada Grid average	59	kg CO_2/GJ(e)
Electricity — Australia Grid average	248	kg CO_2/GJ(e)
Electricity — World average[a]	153	kg CO_2/GJ(e)

[a] Used to compute process emissions for summary tables within this document.