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Economic Impact of Closing the Nuclear Fuel Cycle

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Changing the World's Energy Future

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Idaho National Laboratory

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Economic Impact of Closing the Nuclear Fuel Cycle

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis and Integration

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SUMMARY

This report assesses the economic impact in the United States of closing the nuclear fuel cycle, including the types and numbers of jobs that would be added by recycling facilities and subtracted due to reduced front-end activities. The analysis involved establishing the amount of materials or services needed at each stage in the fuel cycle, identifying the cost of those materials/services, determining the associated employment requirements, and finally identifying the ripple effects of the direct activities on indirect and induced economic and employment levels.

For comparison purposes, all fuel material flows are based on calculations to support a nuclear energy system generating 100 GWe-yr of electricity per year. All measures of fuel cycle activity were developed using parameters identified by the *2014 Nuclear Fuel Cycle Evaluation and Screening – Final Report* (E&S). The U.S. baseline directly compares to the once-through fuel cycle (OTC) using enriched uranium fuel in thermal reactors option defined by the E&S as "EG01." The E&S report also outlines multiple options for a closed fuel cycle with continuously recycled nuclear fuel, and two of those options are used here for evaluation. One option, "EG23," utilizes continuously recycled uranium and plutonium in fast reactors to provide the same 100 GWe-yr parameters used for the OTC example. The second closed cycle option, "EG29," also recycles uranium and plutonium but in a combination of fast and thermal reactors. In both continuous recycling scenarios, it was assumed that existing depleted uranium would be used for makeup material rather than mining natural uranium.

To complete this effort, it was necessary to establish a baseline comparison of domestic economic and employment impacts between the current once-through fuel cycle and the potential closed fuel cycles. In practice, the existing U.S. nuclear fuel cycle relies heavily on various imported products, so two cases of the baseline systems were developed based on (a) the domestic portion of the current fuel cycle (designated EG01a) and (b) if all non-domestic activities were instead performed domestically (designated EG01b).

The analysis was conducted in a steady-state system, so impacts of constructing new facilities were not considered. This includes any differences in the cost of thermal and fast reactors. The analysis also did not factor in the employment impacts associated with transportation or long-term storage and eventual disposal of spent nuclear fuel or high-level waste.

Results of the economic impact model are summarized in Table S1 and show the U.S. fuel cycle employment would increase considerably if U.S.-based suppliers were used for all fuel needs under a OTC scenario. Economic impacts would also increase under the analyzed closed fuel cycle scenarios.

The research results show fuel costs for OTC would increase substantially if all steps were completed by U.S. suppliers. However, the total cost of fuel would not increase over current expenditures if a fast-reactor-based closed fuel cycle was implemented. Fuel costs are only a small portion of total cost of nuclear-generated electricity.

Table S1. Summary of fuel cycle total economic impacts.

Total Impact Category	Once Through Cycles		Closed Fuel Cycles			
	*EG01a Today (Excluding Imports)	EG01b All Domestic Production	EG23 Base Employment	EG23 Minimum Employment	EG29 Base Employment	EG29 Minimum Employment
Employment	8,566	55,926	36,865	32,024	58,196	50,169
Total Output	$3,435	$20,704	$11,096	$10,680	$16,849	$16,161

Total Impact Category	Once Through Cycles		Closed Fuel Cycles			
	*EG01a Today (Excluding Imports)	EG01b All Domestic Production	EG23 Base Employment	EG23 Minimum Employment	EG29 Base Employment	EG29 Minimum Employment
Value Added	$1,529	$9,899	$5,775	$5,244	$8,970	$8,091
Labor Income	$756	$4,700	$3,258	$2,829	$5,143	$4,433

*Current EG01 fuel cycle steps from mining through enrichment are supported by imported products. Values associated with these imported steps are not included in these figures.

NOTE: US$ values in millions.

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ACRONYMS

BE	Base employment
BLS	Bureau of Labor Statistics
CBR	Cost Basis Report
E&S	Evaluation and Screening
FP	Fission products
LLW	Low-level waste
LWR	Light-water reactor
MA	Minor actinides
ME	Minimum employment
OTC	Once-through fuel cycle
PWR	Pressurized-water reactors
RU	Recovered uranium
TRISO	Tristructural isotropic
UNF	Used nuclear fuel
UOX	Uranium oxide

ECONOMIC IMPACT OF CLOSING THE NUCLEAR FUEL CYCLE

1. INTRODUCTION

The following report explores the workforce implications and economic impacts associated with existing and closed nuclear fuel cycle options for the United States. To quantify these impacts, it was necessary to estimate production costs, the number of jobs associated with each fuel cycle step, and the total labor costs. This report utilizes fuel quantities established for once-through and closed nuclear fuel cycle examples established by the *Nuclear Fuel Cycle Evaluation and Screening Report* (E&S) (Wigeland 2014) for 100 GWe-yr of electricity per year. This electricity production benchmark was applied to once-through fuel cycle (OTC) and closed cycle scenarios. Economic impacts for U.S.-based OTC nuclear fuel cycle production were estimated (EG01a). This EG01a OTC case specifically excludes any foreign production. An additional scenario was modeled to reflect the potential economic impact of sourcing all fuel cycle needs using U.S. producers (EG01b). The cost of producing these fuel quantities was calculated using data from the 2017 *Advanced Fuel Cycle Cost Basis Report* (CBR) (Dixon, et al. 2017). Industry reports were used to estimate the domestic cost of production in cases where foreign suppliers are currently being used. Employment estimates were created using information from industry reports and later combined with labor costs from the Bureau of Labor Statistics (BLS). Besides the end result of showing the economic impact of closing the nuclear fuel cycle, the findings associated with this report provide cost comparisons of closed and OTC fuel cycles. The report also identifies the potential cost of nuclear reactor fuel if produced exclusively by U.S. suppliers.

2. METHODOLOGY

The existing fleet of U.S. nuclear power reactors consists of 93 light-water reactors (LWRs), including 62 pressurized-water reactors (PWRs) and 31 boiling-water reactors (BWRs) (NRC 2023a). The economic impact model represents a slightly larger amount of electricity production than what the current U.S. nuclear reactor fleet produces in a 1-year period. The fuel cycle scenarios in the economic impact model were standardized to show fuel needs for 100 GWe-yr to facilitate comparison between models. Two cases were prepared to examine the life-cycle cost effects of front-end cost pricing on the fuel cycle component of electricity and the total annual cost for front-end materials and services. The effects of domestic versus foreign supply on domestic operations employment are also examined. To accomplish this, it was necessary to obtain employment and annual production information on existing U.S. fuel cycle facilities from publicly available sources.

For each step of the front-end fuel cycle, it was necessary to examine unit pricing and operational cost information from the CBR (Dixon, et al. 2017) and more recent trade press and online postings concerning actual U.S. facilities. No proprietary information was requested or used from any suppliers. It was possible to find recent (2021) and projected future employment levels for some facilities. The costs of employee benefits and payroll taxes were added to wages and salaries to create a forecasted total, or fully loaded, cost of employment for each step.

All cases were modeled based on equilibrium operation. The actual cost of transitioning to all-domestic fuel cycle production was not a part of this report's research scope but could be addressed in future work. Increasing fuel production enough to meet a 100 GWe-yr standard would require a significant investment, but it was not modeled in this report. The transition to a closed fuel cycle as described in EG23 and EG29 would also require investing in infrastructure, equipment, and workforce. Understanding the economic impact of that transition process could be included in future work. That future work may include estimating the number of facilities necessary to meet the fuel demand for the reactors identified in EG01, EG23, and EG29. The capital cost of equipment and facilities could provide additional insight regarding the greater economic impact of transitioning to a closed fuel cycle.

Table 1 shows a comparison of fuel cycle options and their associated steps that were included in the economic model. Detailed descriptions of the fuel cycle cases are in Section 5 of this report. Values associated with each fuel cycle step are located in Appendix B.

Table 1. Fuel cycle options—step comparison.

Fuel Cycle Steps	Once Through Cycles		Closed Cycles	
	EG01a Imports Excluded	EG01b All-Domestic Sourcing	EG23	EG29
Mining and Milling				
U3O8 to UF_6 Conversion				
Uranium Enrichment				
Enrichment Plant "Tails" DUF6 To DUOX Deconversion and Pkg.				
DUOX Shallow Geologic Disposal				
Fuel Fabrication				
Fuel Reprocessing				
Note: The lighter shading for "Mining and Milling" under EG01a reflects very low levels of activity. Disposal of OTC spent fuel and other high-level waste was not included.				

3. DATA DESCRIPTION

For this assessment task, generic fuel cycle material balance and life cycle cost models were gathered (Shropshire, et al. 2009). Costs were somewhat modified to approximate the present LWR OTC case with the EG01 100 GWe-yr equilibrium flowsheet as presented in the previously published E&S report. Models were also constructed for future fuel cycles, both once-through and recycling, involving high-assay, low-enriched uranium fuels for advanced reactors such as high-temperature reactors using tristructural isotropic (TRISO) fuel and sodium-fast reactors (SFRs) using metal-alloy fuel. The figures of interest for conducting this analysis are the total annual cost of the front-end fuel cycle, the fuel-cycle-related unit cost component of the unit cost of electricity, and the employment levels for the long-term annual operation of the front-end fuel cycle facilities (not including the reactors themselves). This report addresses the present once-through U.S. LWR fuel cycle identified in the E&S report as EG01, using conventional pelletized zirconium-clad UO_2 fuel enriched to 4%–5% U-235.

Flow diagrams are available in each fuel cycle section of this report to illustrate schematics supporting a fleet of LWRs generating electricity at a 100 GWe-yr capacity. This does closely approximate the electricity production from the existing U.S. fleet of over 90 LWRs. The quantity of front-end services required is basically driven by the fleet annual average demand of 2,192 MT of enriched U (as UO_2) at an enrichment level of ~4.3% U-235.

It was necessary to develop workforce forecasts for a closed fuel cycle. These forecasts are based on annual production and employment for Orano's recycling and mixed oxide (MOX) fuel fabrication facilities in France. Recycling efforts in France proved to be the best source of data.

Annual reports from Orano (2019) provided key employment and production figures that were scaled to match closed fuel cycle fuel production needs. A recycling facility in Rokkasho, Japan is under construction, but no public records could be found to provide accurate employment forecasts. In the United States, a MOX fuel fabrication facility was under construction at Savannah River but was ultimately terminated in 2019 (NRC 2019).

4. ONCE-THROUGH FUEL CYCLE CASES

The E&S report identified the evaluation group EG01 as "once-through using enriched-U fuel in thermal critical reactors (Wigeland 2014)." This group includes the current U.S. fuel cycle using UOX fuel in PWRs and BWRs. The analysis example for EG01 in the E&S report uses PWRs with an average fuel discharge burnup of 50 GWd and enrichment of 4.21%.

Currently, there is minimal uranium mining in the United States and no conversion, while 35% of conversion and all fuel fabrication is performed domestically. Case EG01a considers only the domestic portion of EG01 based on current practices. Case EG01b assumes a future case where all front-end material and services are sourced domestically.

The resulting mass flows for a fleet producing 100 GWe-yr of electricity are shown in Table 2.

Table 2. Mass flows for EG01 cases.

Front-end Fuel Cycle Step	Type of U and Product Chemical Form	EG01 Annual MTU or KgSWU for 100 GWe-yr	EG01a Domestic Quantity	EG01b Domestic Quantity
Mining and Milling	Natural U308	18,863	21	18,863
U308 to Uf6 Conversion	Natural UF6	18,863	0	18,863
Uranium Enrichment	SWUs	1.40E+07	4.95E+06	1.40E+07
Enrichment Product		2,192	775	2,192
Enrichment Plant "Tails" DUF6 to DUOX Deconversion and Pkg.	DUF6	16,671	5,894	16,671
DUOX Shallow Geologic Disposal	DUOX	16,671	5,894	16,671
Fuel Fabrication	LUO2	2,192	2,192	2,192

4.1 EG01a—Imports Excluded

EG01a is reflective of the current U.S. fuel cycle. Only some of the fuel cycle needs are satisfied by domestic U.S. suppliers. As used in the economic impact model, the 100 GWe-yr EG01a case is expected to use 2,192 MT of fuel annually. The production quantities used in the economic model are based on U.S.-procured front-end fuel cycle materials and services. Currently, those materials and services are limited to enrichment and fuel fabrication, with very limited mining activity. Only 0.11% of U.S. ore requirements were supplied domestically in 2021 (Energy Information Administration 2023). One-third of U.S. enrichment needs were supplied domestically by Urenco-USA (2023), and nearly all fuel fabrication was supplied by U.S. fabrication plants in South Carolina (Westinghouse), Washington (Framatome), and North Carolina (Global Nuclear Fuels/GE). The Honeywell Metropolis Works U_3O_8 to UF_6 conversion plant is currently off-line in the United States, so all uranium is imported as previously converted UF_6 from a foreign conversion plants such as ones in Russia (TENEX), Canada (Cameco), and France

(COMURHEX). Commercial DUF_6 deconversion and DUOX disposal facilities are not yet available in the United States. Those that do exist are for the Department of Energy-owned legacy enrichment plant tails only. See Appendix B for more detailed production quantities.

The sum of U.S.-sourced front-end steps comes out to an annual average of $1.37 billion in 2021 compared to over $4 billion for domestic- and foreign-sourced fuel. This means that over $2.6 billion dollars in front-end fuel cycle services were spent outside the United States.

It was also necessary to estimate employment effects for this case for the limited front-end materials and services that are U.S. sourced. The only data on individual facilities that was publicly available was the total employment level, which is often included on company websites (Urenco 2023). Detailed breakdowns of wage rates and staff counts by occupational category represent proprietary or human-relations-sensitive information. Basic knowledge of nuclear fuel cycle unit operations was used to assign rolled-up employment categories and wage rates for each front-end step. Once the quantity of workers was estimated, a “loaded” annual wage was estimated from basic hourly wage information found for workers (BLS 2022a). Based on the BLS Employment Cost Index (BLS 2023), each basic wage was increased by just over 30% to account for Federal Insurance Contributions Act taxes, unemployment insurance premiums, benefits, such as medical insurance, and paid leave, such as sick and vacation days. Note that only recurring annual operations costs are included. No data on the workforce levels to construct new facilities were available. For all front-end fuel cycle steps, most of the annual staffing is in both high skill categories, such as electricians, pipefitters, and welders, and lesser-skilled occupations, such as chemical operators, laborers, and truck drivers.

Evaluation Group EG01

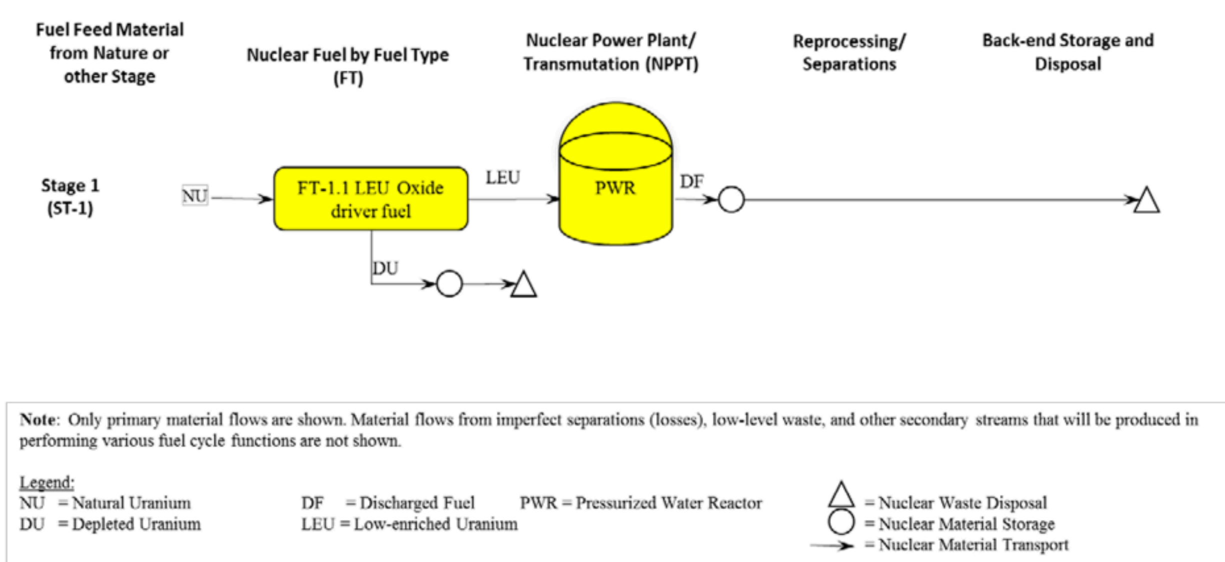

Figure B12. Material Flow Data of Analysis Example for EG01.

Figure 1. EG01 fuel cycle diagram from the E&S to illustrate fuel cycle characteristics.

4.2 EG01b—All-Domestic Production

The EG01b case is a hypothetical example of front-end fuel cycle costs based on fulfilling all fuel step needs using only domestic-procured fuel materials and services. Unit prices will be higher, and based on the trade press information (Els 2023), prices were assigned to each step based on domestic production cost estimates. For steps where the domestic capacity is insufficient, it was necessary to add new capacity based on data for existing "reference" facilities. It was assumed that new facility duplicates could be constructed, or new lines or mines could be added to these existing reference facilities at the same unit cost. The number of employees per MTU (or SWU processed) could also be a basis for estimating the total workforce needed for an expanded fuel cycle enterprise with many more workers. In this manner, the total anticipated employment for front-end activities supporting the entire LWR fleet could be calculated.

The following assumptions are made for each fuel cycle step. All ore and milling will be purchased from U.S. mines and yellowcake suppliers. The reference case for mining is a typical 700 MTU/yr in situ leaching mine. Pricing reflects the removal of the Russian-enriched UF6 (EUF_6) and low-cost Canadian, Kazakh, and Australian ores. The new enrichment capacity will be produced using Urenco-type centrifuge cascades. Urenco is undertaking a phased expansion of their New Mexico facility (World Nuclear News 2023). The higher prices used in this model reflect the removal of legacy Russian Cold War centrifuge capacity SWUs from the pricing determination. U.S. regulators will require eventual deconversion and geologic disposal of enrichment plant tails. Urenco is already working on the Nuclear Regulatory Commission's required licensing documents to process existing commercial tails at their New Mexico site (NRC 2023c). Deconversion cost data are based on actual Department of Energy facilities at two former gaseous diffusion enrichment plant sites, Paducah, KY and Portsmouth, OH, processing legacy Cold War enrichment plant tails, which amount to 800,000 MTU over several decades (U.S. Department of Energy 2022). Deconverted UOX-containing waste packages (steel cylinders) are assumed to be disposed as low-level waste (LLW) at existing U.S. LLW disposal facilities. Expansion and duplication of existing LLW disposal capacity may be needed to accommodate commercial LWR front-end fuel cycle "tails" waste.

The total annual and per unit fuel costs for this all-domestic front-end fleet would cost over $8.4 billion annually in 2022 U.S. dollars. Finished fuel would cost ~$3,850 per kgU, and a single 460 kgU PWR fuel assembly would cost just over $1.8 million. If domestic production was used, the fuel cycle component of the electricity generation cost would be $9.62 per megawatt-hour, compared to the current cost of $5.55 using imports (NEI 2022). Addressing potentially higher electricity prices due to higher nuclear fuel costs are outside the scope of this analysis. The 20% higher personnel costs are due to the inclusion of DUF_6 deconversion and disposal workers. EG01b forecasts an increase of domestic jobs by over seven times from the 2021 total of 1,471. The new employment estimate for EG01b is nearly 11,400 jobs, most of which will be in the mining and milling sector. Although front-end fuel costs under EG01b may be higher than under EG01, fuel costs are a relatively small component of the overall cost of electricity for nuclear power generation.

5. CLOSED FUEL CYCLE CASES

The definition of a front-end fuel cycle is straightforward. It includes fuel fabrication, while separations and reprocessing, USF storage, transport, and waste disposal are all back-end. Orano describes the first stage of recycling used fuel using the following four steps (Orano 2023):

1. Safe receipt and storage of fuel prior to reprocessing, including transporting used fuel and allowing it to cool in storage pools for 5–7 years.
2. Component separation and recovery of recyclable materials. In this step, used fuel rods are sheered into smaller pieces to allow nuclear materials to be dissolved using a nitric acid solution. Uranium and plutonium are then separated and purified.
3. Final waste conditioned. Roughly 4% of nuclear material cannot be reprocessed and is considered waste. In addition, the process results in leftover shells and ends of fuel rods. Remaining fission

products are mixed with molten glass in a vitrification process and cast into containers for long-term storage.

4. Temporary waste storage pending final disposal. Until permanent geologic disposal is available, leftover materials that cannot be recycled are stored on-site.

Orano's second stage involves manufacturing MOX fuel. At this point, the fuel manufacturing process is what is normally considered the front-end in a typical fuel cycle. This involves creating a powder mixture of plutonium and depleted uranium. The powder is compacted into pellets and baked at high temperatures to form a ceramic material. These pellets are ground to form cylinders using a high-precision process. Once inspected for imperfections, the pellets are inserted into metal sheaths to form a fuel rod. Rods are then grouped into fuel assemblies.

Fuel fabrication is usually considered a front-end step and would likely continue to be considered that way if it was done using reprocessed uranium. The actual step of reprocessing uranium would be considered a back-end fuel cycle step.

The U.S. Nuclear Regulatory Commission offers the diagram in Figure 2 to illustrate the whole fuel cycle, including options for steps in the used fuel recycling process.

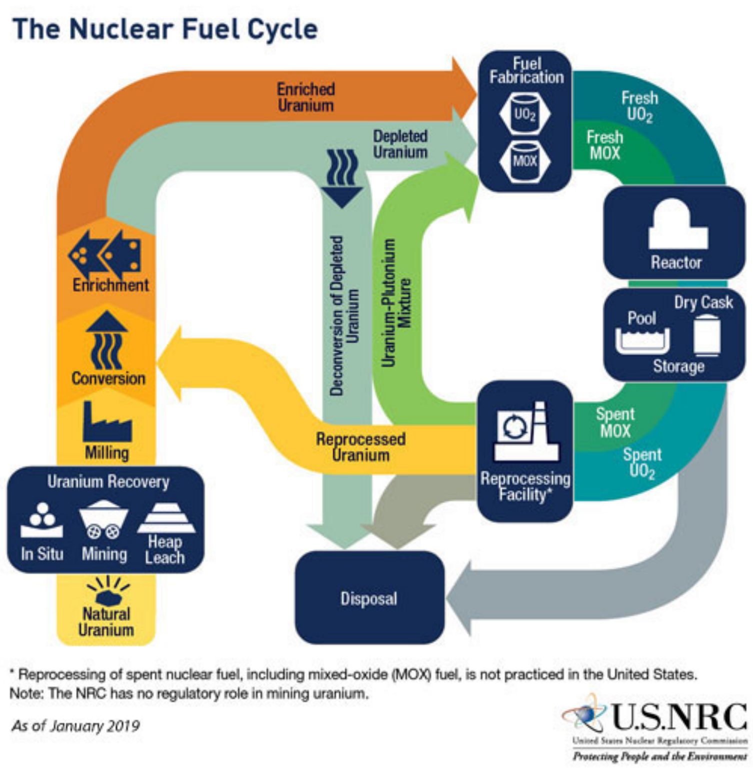

Figure 2. Diagram of the nuclear fuel cycle (NRC 2023b).

There are many variations of cases using recycled nuclear fuel. The following two cases were selected to demonstrate closed fuel cycle examples that utilize continuously recycled fuel sources and show the potential impacts of recycling fuel back into the same reactor type or entirely different reactors. Both cases were evaluated through the E&S. The selected closed fuel cycle cases are referred to as EG23 and EG29 from the E&S and will be described in detail in Sections 5.1 and 5.2. Similar to the EG01 examples, both closed cycle examples project the fuel needs under a 100 GWe-yr use case. In both closed fuel cycle cases, any natural uranium needs would be fulfilled by depleted uranium rather than mining. This analysis does not attempt to model the startup phase of reactors used in these cases; only equilibrium scenarios were modeled.

The La Hague facility in France, operated by Orano, was used to benchmark production statistics for used nuclear fuel recycling facilities. The La Hague facility has an annual plant capacity of 1,700 MT. This facility typically operates below capacity. No records were found indicating production had ever reached the plant's capacity. The facility reprocessed 1,213 MT of fuel in 2019 using 4,800 workers (Orano 2019). This results in a ratio of 3.96 workers per ton of fuel. Both closed fuel cycle scenarios reference this production ratio as the base employment (BE) production level. If the same number of workers could operate the recycling plant at its capacity, they would recycle fuel at a ratio of 2.82 workers per ton. This is referred to as the minimum employment (ME) production level. By using these two ratios, it allows for sensitivity in estimating U.S. fuel-recycling-related employment.

The Melox facility, also in France and operated by Orano, was used to benchmark production characteristics for MOX fuel fabrication. The Melox facility has a 195 MT fuel fabrication plant capacity. Similar to the La Hague facility, reported production levels reached 150 MT in 2019 (Orano 2019). Production level details for more recent years were not publicly available. The company's 2019 *Annual Activity Report* did indicate the facility employed 725 workers. Given the production and employment levels, they required 4.83 workers per ton of MOX fuel fabricated. This ratio is referred to in this analysis as a BE scenario. If the same number of workers was able to increase production up to plant capacity levels, they would only require 3.72 workers per ton of fuel fabricated. This is also referred to as a ME scenario. As discussed previously, by using these two ratios, it allows for sensitivity in estimating U.S. fuel-fabrication-related employment.

The U.S. Census Bureau (2023) shows nuclear fuel recycling and manufacturing industries share the same industry classification, NAICS Code 325180 for Other Basic Inorganic Chemical Manufacturing. By sharing the same NAICS code, the fuel recycling and fabrication industries would also share a similar staffing pattern. There is no public information regarding actual staffing patterns for fuel fabrication, and no recycling centers operate in the United States. Further discussions with industry experts familiar with the fuel recycling and fabrication process suggest the workforce would be very similar between the two types of facilities. For this purpose, staffing and wages for the U.S. fuel fabrication industry were used to forecast labor costs for both industries.

The fuel cost estimates are based on steady-state mass flows and unit costs for fuel cycle steps. The units required (e.g., kg of NU) are multiplied by the unit cost (e.g., $/kg of NU) to estimate the levelized cost based on the spending profile and an assumed uniform energy generation. For a commercial-scale system, this is a good approximation of the system costs.

The mass flows are taken from the analysis examples for EG01, EG23, and EG29 in the E&S (Wigeland 2014). The EG23 analysis example is for an SFR with continuously recycled U/Pu designed to break even in a closed fuel cycle. All used fuel is recycled, and all U/Pu utilized with no external fissile source required and no excess fissile material is produced. The EG29 analysis example is a symbiotic fuel cycle where excess fissile material bred in the SFR is consumed in the PWR. This is a closed fuel cycle where the relative size of the SFR and PWR fleets are such that all used fuel is recycled, and all U/Pu is utilized.

The unit costs were taken from the *Advanced Fuel Cycle Cost Basis Report* (Dixon, et al. 2017). The levelized costs include the capital operating, and maintenance costs, so they are not the sole indicators of the operational contributions but instead identify which components will provide the largest life cycle economic impacts and which components are only minor contributors. The CBR does estimate costs with the assumption that plants would operate at capacity.

5.1 EG23—Higher Burnup SFRs Only

The E&S (Wigeland 2014) provides the following technical description of the EG23 case:

> Continuous recycle of Pu/U in a sodium fast reactor (SFR): In this Analysis Example, an SFR core consists of driver and radial blanket fuels to achieve a breakeven conversion ratio (i.e., slightly higher than 1.0 to account for losses in the fuel separation and fabrication) in the equilibrium state. The U-Pu-Zr ternary metallic fuel is irradiated to burnup of 81.5 GWd/t in the driver fuel zone, while the U-Zr binary metallic fuel is irradiated to burnup of 23.5 GWd/t in the radial blanket zone. The average fuel burnup is 72.6 GWd/t. The discharged used nuclear fuel (UNF) is reprocessed to recover both plutonium (Pu) and recovered uranium (RU) that are recycled back into the SFR. The minor actinides (MA), fission products (FP), and material losses from fuel reprocessing are waste that is sent to disposal. Any low-level waste is also sent to disposal. Natural uranium is the only external makeup feed during fuel production, used for replacing the heavy metal destroyed by fission. Note that this is the traditional SFR breeder. In a growth scenario, the SFR would be configured to breed excess fissile material at a level commensurate with the demand for startup of new reactors.

The EG23 scenario is expected to use 1,247 MT of fuel to support 100 GWe-yr in operation, which is lower than the other cases presented in this report and is the result of higher fuel burnup. Under these conditions, the total expected fuel cost will reach $4 billion. This case would also require slightly more than 6,000 employees to support fuel fabrication efforts and an additional 5,000 employees for reprocessing used nuclear fuel, for a combined total of 11,000, assuming reprocessing and fabrication efforts utilize employees the same way Orano currently does. Under an ME labor scenario, the employment numbers decrease to 4,600 fabrication jobs and 3,500 reprocessing jobs. Total employment for the EG23 ME model is estimated to require more than 8,150 jobs. These EG23 employment estimates become important inputs used later in the economic impact modeling process.

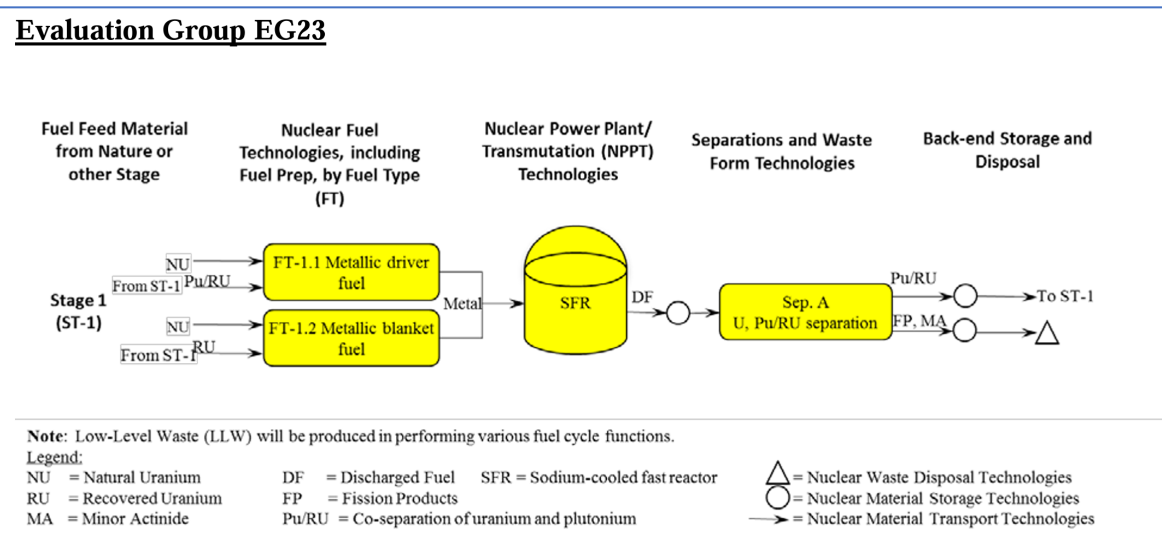

Figure B34. Material Flow Data of Analysis Example for EG23.

Figure 3. EG23 diagram to illustrate fuel cycle characteristics.

5.2 EG29—SFR Continuous Recycle, PWR Using MOX Fuel

The E&S (Wigeland 2014) provides the following technical description of the EG29 case:

> Pu/U produced in SFR used to operate PWR in a continuous recycle strategy: This is a two-stage Analysis Example involving SFRs and PWRs in which Pu is produced in the Stage 1 SFR breeder for use in running the Stage 2 PWR. The SFR in Stage 1 uses driver and blanket fuels. In the equilibrium state, Pu/U recovered from the reprocessing of the discharged driver fuels from the Stage 1 SFRs are mixed with NU (used as external feed) to make new Pu/U metallic driver fuel for Stage 1. The blanket is made from natural uranium and recovered uranium from the reprocessing of the Stage 1 blanket fuel. These driver and blanket fuels are irradiated to discharged burnups of 97 and 21 GWd/t, respectively. The excess Pu/U from the reprocessing of the discharged blanket fuel is recycled to Stage 2. The FP, MA and material losses during fuel reprocessing of the Stage 1 fuels are waste that is sent to disposal. Recovered Pu/U from Stage 2 PWR and excess recovered Pu /U from the blanket fuels of Stage 1 SFR are used to make Pu/U MOX fuel for the Stage 2 PWR. No NU is necessary since the Pu/U from Stage 1 brings enough RU. The Pu/U MOX fuel is irradiated to a burnup of 50 GWd/t in the Stage 2 PWR and the discharged UNF is reprocessed. The recovered Pu /U is recycled back to Stage 2. The MA, FP and material losses during fuel reprocessing are waste that is sent to disposal. Any low-level waste is also sent to disposal. Note that for this analysis example to be viable, it is necessary to feed the PWR (MOX) with the high fissile content Pu from the SFR blanket of Stage 1. If a less fissile Pu mixture is used (e.g., a blend of Pu coming from the SFR driver fuel and blanket) the necessary Pu content in the PWR (MOX) becomes higher than the upper limit required by the reactor safety (i.e., ~12% Pu) after a few recycles.

SFR to PWR electricity generation ratios in this case are described as 61.1% SFR breeder and 38.9% PWR. The combined total consumption is expected to require 2,068 MT of fuel. The fuel cost is expected to be just over $6 billion. Producing this larger quantity of fuel is expected to require nearly 10,000 employees for fuel fabrication and almost 8,200 employees for reprocessing, assuming labor productivity is similar to Orano operations in France. Under an ME labor utilization scenario, the EG29 case will require 7,700 employees for fuel fabrication and 5,800 employees for reprocessing efforts, for a combined total of 13,500 employees. These EG29 employment estimates become important inputs used later in the economic impact modeling process.

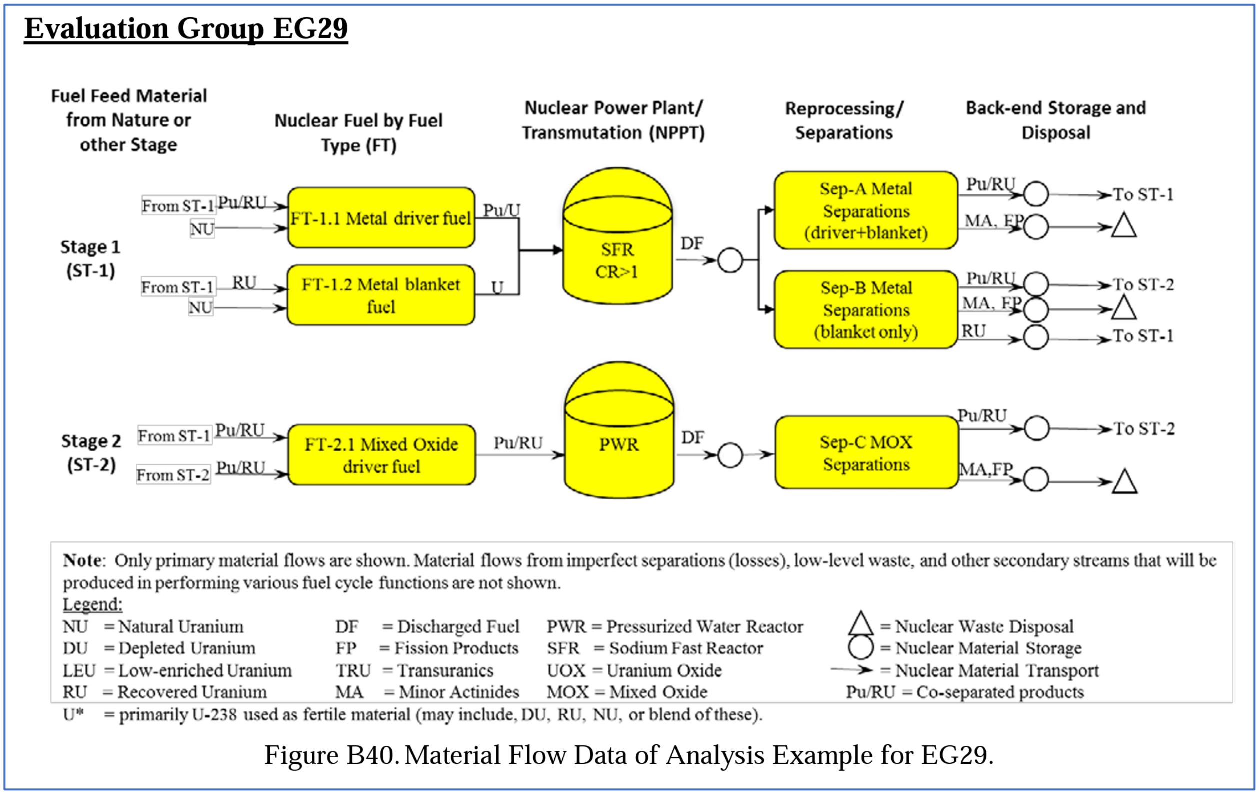

Figure 4. EG29 diagram to illustrate fuel cycle characteristics.

6. INPUT-OUTPUT MODEL OVERVIEW

Input-output modeling is an analytical framework used to study the interdependencies and interactions within an economy. It provides a way to analyze the flow of goods, services, and resources between different sectors of an economy and how changes in one sector can impact others. This modeling technique was first developed by Nobel Prize laureate Wassily Leontief in the 1930s and has since become an essential tool in economics, regional planning, and policy analysis.

The underlaying data behind input-output modeling represents the economy as a matrix of input-output coefficients. Each cell in the matrix represents the quantity of inputs required by each sector to produce a unit of output. By analyzing these coefficients, researchers can examine the linkages between sectors and predict the effects of external shocks. The input-output model can be used to estimate the plant-level, supply chain, and employee community spending effects of changes in final demand or production on the overall economy. By introducing a change in the final demand for a particular sector, such as an increase in industry spending, researchers can assess how this change ripples through the economy, affecting the dollar value of industry output, employment, and labor income. These changes in final demand are the pebble in the pond that send ripples throughout the rest of the economy.

Results of input-output modeling are specific to a defined region, based on economic data for that region. If new economic activity is introduced in the model for a specific industry, and an adequate local supply chain is not available, the model will automatically allow industry spending amounts to “leak.” For example, if a metal supplier is not available within the region, any spending for metal would not be included in the overall economic impact. This economic leakage reduces the multiplying effects of new economic activity and would result in lower job creation and less industry production. As a result, more developed economies with greater industry diversity tend to have higher economic impacts. Thus, input-output modeling is a powerful framework for understanding the structure and dynamics of an economy.

As mentioned previously, economic impact models are usually based on defined geographic areas. The model used in this report was applied to the entire United States rather than smaller regions. By selecting the entire United States, the model will automatically leverage industries across the nation as potential suppliers for recycling and fuel fabrication efforts. If future locations were established for closed fuel cycle steps, a smaller region could be defined. Selecting a smaller region would result in decreased economic impacts compared to a model using the entire United States.

Multiple software and web application developers have created commercially available economic impact models. This study uses the IMPLAN economic impact modeling application. IMPLAN utilizes data from government sources like the Bureau of Economic Analysis, BLS, and U.S. Department of Agriculture combined with their own proprietary models to create industry spending patterns for over 500 industries.

6.1 Model Result Definitions

The definitions in Sections 6.1.1 and 6.1.2 are used when discussing the results of input-out models as they relate to fuel cycle steps.

6.1.1 Impact Types

DIRECT: Companies specifically involved in fuel cycle steps

INDIRECT: Supply chain activity that supports fuel cycle step companies

INDUCED: Derived from household spending as workers receive paychecks

TOTAL: Combined total of direct, indirect, and induced impacts

6.1.2 Impact Categories

EMPLOYMENT: The number of jobs created or sustained

LABOR INCOME: The amount of income including employee compensation (wages, benefits, and payroll taxes)

VALUE ADDED: The value of combination of innovation and improvement made as basic resources and intermediate goods are processed into final goods or contributions to gross domestic product

OUTPUT: The dollar value of industry production

7. DIRECT IMPACTS OF FUEL CYCLE CASES

Direct impacts are the main driver behind the economic impact model. These direct impacts represent the changes in the final demand that are the pebble in the pond that send ripples throughout the rest of the economy. Direct impacts in this model are the result of company operations that are directly involved in producing key fuel cycle steps. For the existing EG01a and EG01b fuel cycle, direct impact industries include:

- Uranium mining and milling
- U3O8 to UF6 conversion

- Uranium enrichment
- Enrichment plant “tails” DUF6 to DUOX deconversion and packaging
- DUOX shallow geologic disposal
- Fuel fabrication.

The number of industries involved in the fuel cycle are consolidated under a closed fuel cycle scenario. In the EG23 and EG29 scenarios, previously considered front-end steps are consolidated into new processes for reprocessing and fuel fabrication. As mentioned previously, no additional mining would be required for the closed cycle due to existing DU that could be utilized.

Table 3 provides a comparison of direct impact values for each case. The employment row shows the estimated number of jobs at facilities directly involved in the fuel cycle steps. The output or revenue row shows the dollar value of industry production. This equates to revenue received by fuel cycle companies. From the perspective of the fuel buyer, this is the cost associated with purchasing fuel for operating a fleet of reactors at the 100 GWe-yr production level. Any additional reactor costs beyond fuel purchases are not included in this value. The value-added row of the table indicates the dollar value contribution to the gross domestic product. These values are typically the result of labor expenses plus the difference between the final price of fuel minus any intermediate goods required during the production process. The labor income row of the table is often referred to as a loaded cost of labor. It includes wages, salaries, benefits, and payroll taxes.

Comparing EG01a to EG01b shows the number of jobs that could be brought back to U.S. fuel cycle industries if all steps were completed domestically. Under the EG01b case, more than 7,500 jobs would be associated with domestic uranium mining activities alone. Domestic spending on existing fleet fuel supplies would increase from nearly $1.4 billion to $8.4 billion. The current estimated spending for the fuel supply under EG01a is slightly more than $4 billion, which suggests $2.6 billion is being spent on fuel supply needs being fulfilled by foreign producers. Higher fuel costs from domestic producers are a result of higher uranium mining costs. A mining organization report indicated most U_3O_8 can be economically mined at no less than $80 per pound (Uranium Prodcuers of America 2015) in 2022 dollars. The May 31, 2023 spot price for uranium was $54.55 per pound according to Cameco (2023).

Costs associated with the fuel supply for EG23 and EG29 differ due to the quantity of fuel needed. The higher burnup reactors in EG23 only require 1,247 MT of fuel while EG29 needs 2,068 MT. The other direct impact value differences all correlate with the quantity of fuel being produced. The BE and ME direct estimates differ based on the assumed labor productivity.

Table 3. Direct impacts by fuel cycle case.

Direct Impact Category	*EG01a Today (Excluding Imports)	EG01b All Domestic Production	EG23 Base Employment	EG23 Minimum Employment	EG29 Base Employment	EG29 Minimum Employment
Employment	1,425	11,366	10,962	8,157	18,178	13,528
Output or Revenue	$1,375	$8,435	$4,038	$4,038	$6,036	$6,036
Value Added	$478	$3,606	$2,115	$1,821	$3,350	$2,861
Labor Income	$186	$1,274	$1,257	$963	$2,068	$1,579

*Current EG01 fuel cycle steps from mining through enrichment are supported by imported products. Values associated with these imported steps are not included in these figures.

NOTE: US$ values in millions.

8. TOTAL ECONOMIC IMPACT RESULTS

Total economic impact results are available after running the direct impact figures through the input-output model. The results in Table 4 include the figures from Table 3 with additional values from indirect and induced impacts. Indirect impacts are a result of supply chain activity stimulated by companies involved in the fuel supply steps. Induced impacts are the result of employees spending paychecks at local businesses.

Detailed results of all four impact categories will be presented in Sections 8.1–8.4. Table 4 provides an overview of the total economic impact associated with each fuel cycle case.

Table 4. Total economic impact results.

Total Impact Category	*EG01a Today (Excluding Imports)	EG01b All Domestic Production	EG23 Base Employment	EG23 Minimum Employment	EG29 Base Employment	EG29 Minimum Employment
Employment	8,566	55,926	36,865	32,024	58,196	50,169
Total Output	$3,435	$20,704	$11,096	$10,680	$16,849	$16,161
Value Added	$1,529	$9,899	$5,775	$5,244	$8,970	$8,091
Labor Income	$756	$4,700	$3,258	$2,829	$5,143	$4,433

*Current EG01 fuel cycle steps from mining through enrichment are supported by imported products. Values associated with these imported steps are not included in these figures.

NOTE: US$ values in millions.

8.1 Detailed Employment Impacts

There is a significant difference in the employment impact associated with shifting fuel cycle production to domestic sources. The total domestic employment impact of EG01a grows from nearly 8,600 jobs to almost 56,000 in EG01b. Under EG01b, the indirect and induced employment accounts for 44,560 jobs split almost evenly between jobs created among supply chain companies and jobs created by employee spending.

The employment impact associated with a closed fuel cycle is driven by fuel quantities required for each scenario. EG23 required less fuel, only 1,247 MT compared to 2,068 MT for EG29. Employment impacts for the closed fuel cycle are more evenly distributed across the three impact types, but jobs from employee spending ended up creating the most employment impact. The largest employment impact from the closed cycle scenarios was from the EG29 BE case, which is estimated to create or sustain 58,200 jobs. The EG23 cases are expected to have total employment impacts ranging from 32,000 to 37,000 jobs.

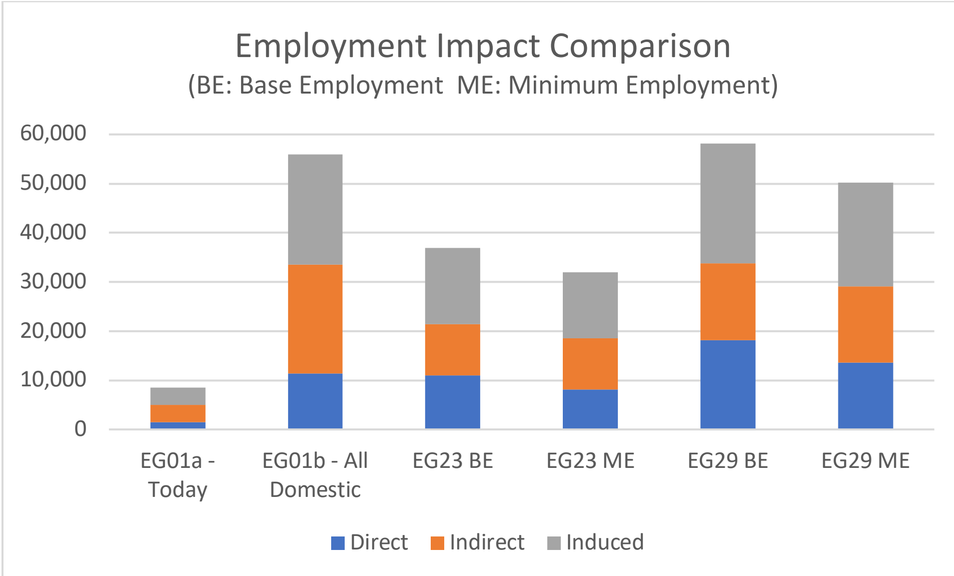

Figure 5. Comparison of employment impacts.

8.2 Detailed Total Output Impacts

Total output impacts for the once-through fuel cycle would increase from $3.4 for the EG01a case to $20.7 billion for EG01b. This would be a significant input into the economy. For comparison, Netflix earned $31.6 billion in revenue during 2022 (SEC 2023). Labor efficiency did not impact total output impacts for closed fuel cycle scenarios in a significant way. For EG23, total output impacts ranged from $10.7 billion (ME) to $11.1 billion (BE). Under EG29, the impacts increase to between $16.2 billion (ME) and $16.8 billion (BE). Total employment impacts were shared evenly across the direct, indirect, and induced categories.

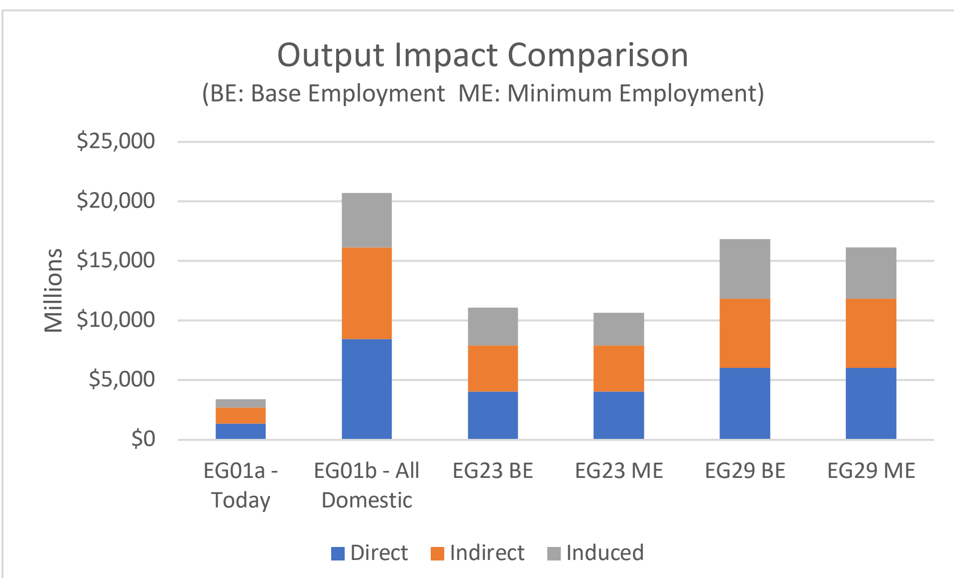

Figure 6. Comparison of output impacts.

8.3 Detailed Value-Added Impacts

Value-added impacts for each fuel case followed trends similar to total output impacts. The EG01b case increased value-added impacts from $1.5 to nearly $10 billion. The closed fuel cycle results ranged between $5.2 and $5.7 billion for the EG23 case. The need for greater fuel quantities under the EG29 case pushed value-added impacts to between $8.1 and $8.9 billion.

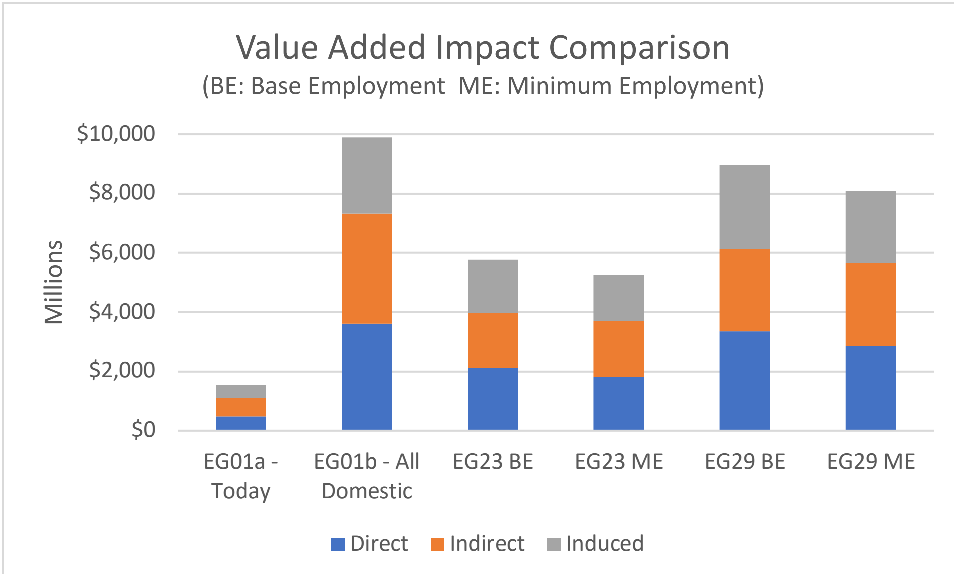

Figure 7. Comparison of value-added impacts.

8.4 Detailed Labor Income Impacts

Labor income impacts, which include all types of benefits, wages, and payroll taxes, increased from $756 million to $4.7 billion under the EG01a case. The EG23 and EG29 cases also made significant contributions to labor income. The EG23 cases showed labor income payments between $2.8 and $3.3 billion. The distribution of labor income was split almost evenly between the direct, indirect, and induced impact categories. The EG29 case had a larger labor income impact, again due to the increased employment associated with producing larger quantities of fuel. Labor income from the EG29 cases range between $4.4 and $5.1 billion.

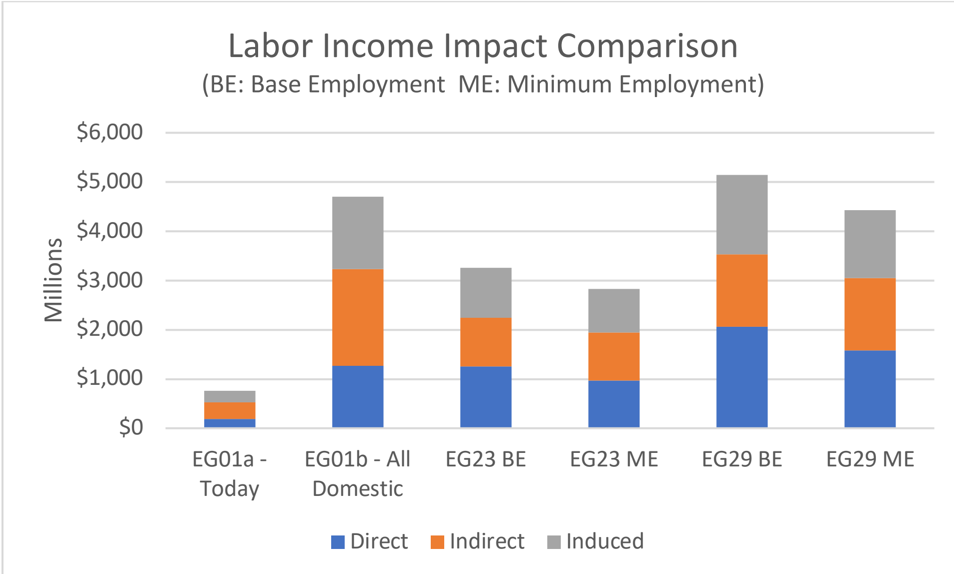

Figure 8. Comparison of labor income impacts.

9. OCCUPATION SHIFT FROM CLOSED FUEL CYCLE

Low unemployment rates and workforce shortages have cast more attention on staffing analysis in the nuclear industry. The nuclear reactor fuel production activities currently being conducted under the EG01a scenario are limited to enrichment and fuel fabrication. The skillsets necessary for these activities are well suited for the recycling and fuel fabrication work that will be undertaken under an EG23 or EG29 fuel cycle scenario. There is a possibility that some mining-related employment could be lost if a full transition to a closed fuel cycle is accomplished. These losses would equate to roughly 300 jobs. The EG01b case has a considerably different staffing pattern due to significant mining activity being included.

The occupational shift analysis results are based on BLS Industry-Occupation Matrix data (BLS 2021). These data come from industry surveys with responses from employers to capture staffing patterns that are common among industry types, including nuclear power generation. Employers complete surveys by indicating the number of workers on staff by occupation title. These occupation titles are based on standardized descriptions from the Occupation Employment and Wage Statistics program (BLS 2022a). Actual job titles used by the nuclear fuel industry may differ. As a result, employers would likely choose to allocate job counts to BLS occupation titles that are the best fit. For example, an in situ uranium mining operation may indicate they employ a certain number of underground mining machine operators even though the miners themselves are not working underground.

9.1 Fuel Cycle Top Jobs

Table 5 shows a ranking of expected job titles for the selected fuel cycle options ranked by the number of positions held. In this case, only jobs from the direct impact category are being analyzed. Future work could include an analysis of employment impacts on the indirect category to gain an understanding of how supply-chain-related employment is impacted. A table showing the actual count of occupations is available in Appendix A.

The mix of employment for the EG01b case highlights adding mining activity in the U.S. fuel cycle. This mix of employment suggests mining machine operators, truck drivers, extraction workers, and heavy equipment mechanics would be highly utilized. The EG23 and EG29 job mix transitions into production jobs, including a large number of machinery operators, engineers, and chemists.

Table 5. Top jobs by fuel cycle option.

Ranking	EG01b (all domestic)	EG23–EG29
1	Underground mining machine operators	Chemical processing machine setters, operators, and tenders
2	Driver/sales workers and truck drivers	Miscellaneous plant and system operators
3	Miscellaneous extraction workers	First-line supervisors of production and operating workers
4	Chemical processing machine setters, operators, and tenders	Industrial machinery installation, repair, and maintenance workers
5	Industrial machinery installation, repair, and maintenance workers	Crushing, grinding, polishing, mixing, and blending workers
6	Heavy vehicle and mobile equipment service technicians and mechanics	Chemical technicians
7	Maintenance and repair workers, general	Laborers and material movers
8	Laborers and material movers	Chemical engineers
9	First-line supervisors of production and operating workers	Packaging and filling machine operators and tenders
10	Crushing, grinding, polishing, mixing, and blending workers	Chemists and materials scientists

10. CONCLUSIONS

In conclusion, the economic impact of closing the fuel cycle would create or sustain a significant number of jobs and add to the U.S. gross domestic product. The total employment impact of an EG23 and EG29 closed fuel cycle would create or sustain between 37,000 and 58,000 domestic jobs. Direct employment impacts from the current fuel supply production in the United States are minimal compared to the potential impact if foreign fuel production was replaced with domestic sources. If fuel needs were supplied by U.S. companies, the direct employment impact would increase job counts from 1,400 to over 11,000. The EG01 total employment impact would grow from 8,600 to 56,000 jobs by sourcing fuel from U.S. producers.

The shifts in employment for a closed fuel cycle would require growing the current U.S. nuclear fuel workforce that currently exists among fuel fabricators and enrichment suppliers. The employment growth for these types of activities would be significant.

Besides the employment-related impacts, the transition to a closed fuel cycle would generate between \$2.8 and \$5.1 billion in labor income under the EG23 and EG29 scenarios. Under the EG01 scenario, labor income would increase from \$756 million to \$4.7 billion if fuel supply production was sourced domestically.

Estimated spending on foreign and domestically produced fuel under EG01 is just over $4 billion. Spending would increase to more than $8.4 billion if all aspects of fuel production were sourced in the United States. The total fuel cost for the EG23 case would be nearly the same ($4.04 billion) as EG01 under current importing conditions although the quantity of fuel needed would decrease from 2,192 MT to only 1,247 MT. The cost of fuel for EG29 is estimated at $6.04 billion. If domestic production was used, the fuel cycle component of the electricity generation cost would be $9.62 per megawatt-hour, compared to $5.55 if imports were used. All fuel material flows presented in this report are based on calculations to support a nuclear energy system generating 100 GWe-yr of electricity per year

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Appendix A

Occupation Shift Details

A-1. Top 25 Occupations with Count of Employees

Table A1. Top 25 occupations with counts of employees (ranked from greatest to least for EG01b).

Row Labels	EG01a	EG01b	EG23 ME	EG23 BE	EG29 ME	EG29 BE
Extraction Workers	3	1,559	10	14	17	23
Other Production Occupations	368	1,051	2,114	2,840	3,505	4,710
Other Installation, Maintenance, and Repair Occupations	96	821	551	740	913	1,227
Motor Vehicle Operators	25	722	142	191	236	317
Material Moving Workers	59	544	342	459	566	761
Engineers	93	475	535	719	888	1,193
Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	2	463	11	15	18	24
Construction Trades Workers	9	440	50	67	83	112
Business Operations Specialists	49	270	282	379	468	629
Life, Physical, and Social Science Technicians	51	242	295	397	490	658
Supervisors of Production Workers	66	239	382	513	633	850
Plant and System Operators	83	235	477	641	791	1,063
Metal Workers and Plastic Workers	28	220	162	218	269	361
Supervisors of Construction and Extraction Workers	1	192	2	3	4	5
Operations Specialties Managers	47	164	268	360	444	597
Supervisors of Installation, Maintenance, and Repair Workers	12	161	71	95	118	158
Physical Scientists	36	160	204	274	338	454
Top Executives	29	158	166	223	275	369
Other Construction and Related Workers	0	142	1	1	1	2
Material Recording, Scheduling, Dispatching, and Distributing Workers	37	141	212	285	351	472
Drafters, Engineering Technicians, and Mapping Technicians	22	138	129	173	213	287
Other Office and Administrative Support Workers	15	103	87	117	145	195
Secretaries and Administrative Assistants	16	92	94	126	155	208
Other Management Occupations	19	83	107	144	177	238
Supervisors of Transportation and Material Moving Workers	4	73	23	31	38	51

Appendix B

Material Flows and Costs for EG01 Cases

B-1. Unit Costs of Materials and Services for EG01 Cases

To determine economic activity, mass flows of each material and amounts of each service are multiplied by unit costs for those materials or services. The unit costs were taken from the CBR (Dixon, et al. 2017) for EG01a, as these unit costs reflect long-term average costs in global markets.

The escalated unit costs or prices from the most recent CBR are used. "What-it-takes" long-term average front-end fuel cycle prices in the CBR are based on profitable enterprises in a stable global market. Case EG01b, however, represents a constrained market where use of domestic-only resources removes some lower cost foreign materials and services from the CBR base cost/price data. Table B1 below shows the unit costs for both 100 GWe-yr LWR cases EG01a and EG01b, with the latter showing higher costs.

Table B1. Assumed unit costs or prices for two cases EG01a and EG01b

Fuel cycle step	EG01a: Recent situation with some materials and services from foreign providers	EG01b: All-front-end fuel cycle steps procured in U.S.-located facilities
Mining and milling (yellowcake U3O8) in $/lb U3O8	50	80
Mining and milling (yellowcake U3O8 price) in $/kgU	130	208
U3O8 to UF6 conversion price in $/kgU	15	30
Uranium enrichment price in $/SWU	100	160
DUF6 to DUOX deconversion cost in $/kgDU	22*	22
Shallow geologic disposal cost of deconverted DUOX	15.5*	15.5
Fuel fabrication in $/kgU	400	470

*Amount of material processed is zero for this case since commercial facilities do not exist.

The following considers each front-end fuel cycle step for the two cases:

- **Mine and Mill (Yellowcake U3O8)**

  EG01a: Assumed low spot market price for small amount of domestic uranium purchased in 2020–2021 timeframe. $130/kgU or $50/lb U3O8
  EG01b: Composite higher price based on sources below.
  Market clearing model for low-grade ores (Auzans, et al. 2014) $234/kgU or $90/lb U3O8
  Uranium Producers of America (2015) Letter $216/kgU or $83/lb U3O8
  Recent sales to DOE for fuel bank (S&P Global 2023) $183/kgU or $70/lb U3O8
  Upper range of S&P Global analysis (S&P Global 2022) $195/kgU or $75/lb U3O8
  Composite rounded value selected by author $208/kgU or $80/lb U3O8

- **U3O8 to UF6 Conversion**

  EG01a: Assumed low end of UxC spot price range (UxC 2023). $15/kgU
  EG01b: Calculated recent price from Honeywell/Metropolis Plant for DOE Fuel Bank purchase (S&P Global 2023). $36/kgU

- **Uranium Enrichment**

  EG01a: The average price paid in 2021 by reactor operators for 14 million SWU was $99.54 per SWU in 2021, with both quantity and price virtually identical to 2020. Selected value for analysis was rounded to $100/SWU.
  EG01b: The most likely (mode) long-term SWU price from Module C1 of the CBR was chosen. Escalated to 2022$, this price is $159.50 $/SWU. For this analysis, it is rounded to $160/SWU

- **DUF6 to DUOX Conversion**

  EG01a and EG01b: This step is U.S.-based but is not yet being implemented for DUF6 from Urenco, the only U.S. enricher, so zero material is assumed processed in EG01a. In scenario EG01b, it is assumed to be implemented, and pricing is based on the government's cost to deconvert legacy E-plant tails from the three now-decommissioned gaseous diffusion plants based on analysis of a recent audit (U.S. Department of Energy 2022) of this Midwest Conversion Service's operation of DOE-owned facilities at Portsmouth, OH and Paducah, KY. An average price of $22/kgDU is used.

- **Geologic Disposal of DUOX from DUF6 Deconversion**

  EG01a and EG01b: This step is U.S.-based but is not yet being implemented for deconverted DUF6 from Urenco, the only U.S. enricher, so zero material is assumed processed. In the EG01b scenario, it is assumed to be fully implemented, and pricing is based on the government's cost to deconvert legacy enrichment plant tails from the three now-decommissioned gaseous diffusion plants. The value of $15.5/kgDU is based on the mean value from the "what-it-takes" unit cost range in Module K2 of the CBR escalated to 2022 US$.

- **Fuel Fabrication**

  EG01a: A somewhat depressed market for fuel fabrication services in recent years has kept pricing most likely in the $400/kgU range.
  EG01b: The mean value of $470/kgU is the mean value from Module D1-1 ("LWR Fuel Fabrication") of the 2020 CBR which is nearing release. It reflects higher pricing due to a better market and actual production cost increases due to implementation of some new safety enhancement features which increase the accident tolerance of newer fuel designs.