# Environmental and Energy Analysis of the Refeed Option of Depleted Uranium Hexafluoride

Scott W. White

February 1997

UWFDM-1044

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

# ENVIRONMENTAL AND ENERGY ANALYSIS OF THE REFEED OPTION OF DEPLETED URANIUM HEXAFLUORIDE


by

Scott W. White

Institute for Environmental Studies &
Fusion Technology Institute
University of Wisconsin-Madison
Madison, Wisconsin


February 1997


Work Sponsored by
Office of Facilities
Office of Nuclear Energy, Science and Technology
U.S. Department of Energy

## CONTENTS


ABSTRACT . . . . . 1

1 INTRODUCTION . . . . . 1

1.1 Description . . . . . 1
1.2 Scope of Analysis . . . . . 1

2 SPECIFICATION OF OPTIONS EVALUATED . . . . . 2

2.1 Overview . . . . . 2
2.2 Description of Options . . . . . 2

3 APPROACH AND METHODS . . . . . 3

4 RESULTS . . . . . 7

4.1 Energy . . . . . 7
4.2 Gaseous Emissions . . . . . 7
4.3 Products and Effect on Waste Facilities . . . . . 11

5 DISCUSSION . . . . . 14

6 SUMMARY AND CONCLUSIONS . . . . . 18

7 REFERENCES . . . . . 19

APPENDIX A: Data Using 100% Coal-Generated Electricity . . . . . A-1

APPENDIX B: Data Using 100% Nuclear-Generated Electricity . . . . . B-1

APPENDIX C: Centrifuge Enrichment Data . . . . . C-1


## FIGURES


1 Comparison of Input Energy Required to Produce Enriched Uranium from Natural Uranium and from Depleted Uranium . . . . . 9

2 Comparison of Total $CO_2$ Emitted for Gaseous Diffusion Enrichment when Electricity is 100% Nuclear Generated and 100% Fossil-Fuel Generated . . . . . 10

## FIGURES (Cont.)


C.1 Energy Requirements for the Fresh Feed and Refeed Options Using Gas Centrifuge Enrichment .......... C-6

C.2 $CO_2$ Emissions from Gas Centrifuge Enrichment for the Fresh Feed and Refeed Options .......... C-7


## TABLES


1 Energy Requirements for the Nuclear Fuel Cycle .......... 4

2 Fuel Emission Factors Used in this Study .......... 5

3 DOE Depleted Uranium Inventory .......... 6

4 Energy Requirements for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory - All Electricity from Coal .......... 8

5 $CO_2$ Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory .......... 8

6 $SO_x$ Emissions for Gaseous Enrichment Scenarios Involving the Depleted Uranium Inventory .......... 12

7 $NO_x$ Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory .......... 12

8 CO Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory .......... 13

9 Potential Amount of Enriched Uranium Produced from Tails at the Paducah and Portsmouth Facilities .......... 13

10 Effect of Using 100% Coal-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options .......... 16

11 Effect of Using 100% Nuclear-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options .......... 17

## TABLES (Cont.)


A.1 Environmental Impact of Producing 2% Enriched U for LWRs: Electricity Generated from 100% Coal .............................. A-3

A.2 Environmental Impact of Producing 3% Enriched U for LWRs: Electricity Generated from 100% Coal .............................. A-6

A.3 Environmental Impact of Producing 4% Enriched U for LWRs: Electricity Generated from 100% Coal .............................. A-9

B.1 Environmental Impact of Producing 2% Enriched U for LWRs: 100% Nuclear-Generated Electricity .................................. B-3

B.2 Environmental Impact of Producing 3% Enriched U for LWRs: 100% Nuclear-Generated Electricity .................................. B-6

B.3 Environmental Impact of Producing 4% Enriched U for LWRs: 100% Nuclear-Generated Electricity .................................. B-9

C.1 Energy Requirements for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory: All Electricity from Coal ...................... C-5

C.2 $CO_2$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory ............................................ C-5

C.3 $SO_x$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory ............................................ C-8

C.4 $NO_x$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory ............................................ C-8

C.5 CO Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory ............................................ C-9

C.6 Effect of Using 100% Coal-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options ......... C-10

C.7 Effect of Using 100% Nuclear-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options ......... C-11

# ENVIRONMENTAL AND ENERGY ANALYSIS OF THE REFEED OPTION OF DEPLETED URANIUM HEXAFLUORIDE

by

Scott W. White

# 1 INTRODUCTION

## 1.1 DESCRIPTION

The U.S. Department of Energy (DOE) is preparing a programmatic environmental impact statement (PEIS) that analyzes the alternative strategies for the long-term management and use of depleted uranium hexafluoride ($UF_6$). One alternative is long-term storage of the depleted $UF_6$ inventory for future enrichment. This study analyzes the energy requirements and environmental aspects of refeeding the depleted $UF_6$ inventory into a reactor-grade product.

## 1.2 SCOPE OF ANALYSIS

This report analyzes the energy requirements and air emissions of enriching the depleted $UF_6$ stockpiled at the Paducah, Ky., and Portsmouth, Ohio, facilities to different concentrations. These results are compared to those for the enrichment of fresh-feed natural uranium to similar concentrations. The mix of input electricity for enrichment is varied for each scenario to create sub-scenarios for air emissions. Finally, the quantity of enriched uranium product produced in each scenario and the subsequent reduction of cylinders required for storing depleted $UF_6$ are analyzed. Depleted $UF_6$ is also stored at the K-25 site near Oak Ridge, Tenn. However, the amount of uranium in the depleted $UF_6$ at this site is too low to warrant reenrichment (Hertzler and Nishimoto 1994).

# 2 SPECIFICATION OF OPTIONS EVALUATED

## 2.1 OVERVIEW

Three enrichment scenarios for refeeding the depleted uranium — enrichment to concentrations of 2%, 3% and 4% in $^{235}U$ — are analyzed on the basis that the depleted uranium at the Paducah and Portsmouth facilities range in concentration from 0.24% to 0.6% $^{235}U$. For each case, the total energy requirements have been calculated and compared to the requirements for the enrichment of natural uranium (0.711% $^{235}U$, fresh feed) to similar concentrations.

The air emissions associated with the energy requirement for each case were calculated by using the amount and type of input fuel for each process. Emissions of carbon dioxide ($CO_2$), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), and carbon monoxide (CO) were analyzed. Two subscenarios were used to analyze the gaseous emissions when using various sources of electrical input (100% coal and 100% nuclear). The results of the refeed scenarios were compared to results for enrichment of fresh feed to similar concentrations.

Finally, the quantity of enriched uranium product and reduction of storage cylinders at the Paducah and Portsmouth facilities were considered. Enriching the depleted uranium reduces the amount of depleted $UF_6$ and, thus, the number of cylinders that need to be stored in the future at DOE facilities.

## 2.2 DESCRIPTION OF OPTIONS

There are three base-case scenarios presented here, one for each of the three enrichment levels (2%, 3%, and 4%). For each case, the enrichment of the depleted $UF_6$ inventory at federal facilities with concentrations >0.24% $^{235}U$ is analyzed. One calculation for energy requirements and two calculations for air emissions, based on the input electrical mix (100% coal or 100% nuclear), are made for each of the three cases. The energy requirements and air emissions of refeed enrichment are compared to the natural uranium fuel cycle (mining, milling, conversion, and enrichment). The absolute amount of enriched uranium product is also calculated on the basis of the present distributions of depleted $UF_6$ at federal facilities in Paducah, Ky., and Portsmouth, Ohio.

# 3 APPROACH AND METHODS

A cradle-to-grave approach was used to analyze the energy requirements and air emissions associated with power production; the details of conducting this type of analysis are found elsewhere (White 1995). The energy associated with the capital investment is included in this approach, as is the direct energy requirement for operation of the process facilities. Air emissions are calculated from the energy data on the basis of fuel type and fuel emission factors. The cradle-to-grave approach is applied to analyze the capital and operating energy requirements associated with mining, milling, conversion, and enrichment processes for the uranium fuel cycle. Table 1 lists the energy requirements, by fuel type, to produce $UF_6$ ready to be enriched by the gaseous diffusion process. It was assumed that all fossil fuel (nonelectrical) energy used in mining, milling, and conversion was generated by fuel oil. The emission factors used in this study for both fossil-fuel and electricity-generating technologies are listed in Table 2.

The enrichment energy requirements were calculated by using the $^{235}U$ concentrations of the various feed and product concentrations and the assumption that the tails for all scenarios were 0.2% $^{235}U$. All calculations in the body of the report are based on the gaseous diffusion enrichment method, which requires 3.0 MWh/SWU (Cochran and Tsoulfanidis 1990). For comparison, calculations made by using gas centrifuge enrichment were included in Appendix C.

The energy requirements and emissions of pollutants were standardized per kilogram of uranium product; a summary of the details is given in the Appendices. These data were used to determine the total energy requirements and air emissions associated with enriching the entire usable depleted uranium at the two DOE facilities. (See Table 3 for the distribution of depleted uranium inventoried at each facility).

The storage cylinders were assumed to hold 12.2 metric tonnes of depleted uranium. Though the majority of cylinders used for storage of depleted uranium are 14-ton (12.7-tonne) vessels (Hertzler and Nishimoto 1994), it is assumed that the cylinders are not filled to the maximum. Approximately 42,000 cylinders are in place at Paducah and Portsmouth (Hertzler and Nishimoto 1994).

**TABLE 1 Energy Requirements for the Nuclear Fuel Cycle**

| Operation | Fossil Fuels (GJ(th)/kg Natural U) | Electricity (MWh(e)/kg Natural U) | Total GJ/kg Natural U |
|---|---|---|---|
| Mining[a] | 0.56 | 0.02 | 0.73 |
| Milling | 0.54 | 0.02 | 0.74 |
| Conversion | 1.43 | 0.02 | 1.61 |
| Total | 2.52 | 0.06 | 3.08 |

Note: 1 MWh(e) = 3.6 GJ/MWh(e)/ 0.4 electrical efficiency = 9 GJ(th)

[a] 59% surface and 41% underground mining was assumed.

Source: Rotty, Perry, and Reister (1976).

**TABLE 2 Fuel Emission Factors Used in this Study**

| Fuel | Emission Factor: kg $CO_2$/ GJ[a] | kg $SO_x$/GJ | kg $NO_x$/GJ | kg CO/GJ |
|---|---|---|---|---|
| Coal | 92.77 | 1.44[b] | 0.27[b] | 0.10[b] |
| Petroleum | 69.30 | 0.25[c] | 0.16[c] | NA[d] |
| Natural Gas | 50.53 | 0.0003[e] | 0.03[e] | 0.017[e] |
| Fuel Oil | 73.33 | 1.099[c] | 0.16[c] | 0.014[c] |

| Electricity Production Fuel | Emission Factor: kg $CO_2$/ MWh(e) | kg $SO_x$/MWh(e)[f] | kg $NO_x$/MWh(e)[f] | kg CO/MWh(e)[f] |
|---|---|---|---|---|
| Coal[b] | 964 | 7.5 | 2.7 | 0.25 |
| Nuclear | 7.8 | 0.0076 | 0.001 | 0 |

[a] Data from Mintzer (1988).

[b] Data from U.S. Environmental Protection Agency (EPA) (1988).

[c] Data from EPA (1985).

[d] Not available.

[e] Data from EPA (1992).

[f] Data from Yoshiki-Gravelsins et al. (1993).

Source: White (1995).

**TABLE 3 DOE Depleted Uranium Inventory (as of 6/30/92)**

| Actual Range of $^{235}U$ Assay (wt %) | Average $^{235}U$ Assay (wt %) | Paducah Weight (kg U) | Portsmouth Weight (kg U) | Total Weight (kg U) |
|---|---|---|---|---|
| < 0.21 | 0.2 | 73,573,520 | 20,628,143 | 94,201,663 |
| 0.21 to < 0.24 | 0.225 | 751,960 | 2,696,294 | 3,448,254 |
| 0.24 to < 0.26 | 0.25 | 51,882,729 | 39,634,865 | 91,517,594 |
| 0.26 to < 0.28 | 0.27 | 1,128,784 | 1,670,520 | 2,799,304 |
| 0.28 to < 0.31 | 0.295 | 28,269,806 | 4,584,079 | 32,853,885 |
| 0.31 to < 0.50 | 0.405 | 59,586,050 | 35,299,839 | 94,885,889 |
| 0.50 to < 0.60 | 0.55 | 506,479 | — | 506,479 |
| 0.60 to < 0.711 | 0.6555 | 2,930,985 | — | 2,930,985 |
| Total Weight | | 218,630,313 | 104,513,740 | 323,144,053 |

Source: Hertzler and Nishimoto (1994).

# 4 RESULTS

## 4.1 ENERGY

For all three main scenarios, the fresh-feed options required less input energy than was required to enrich the usable depleted uranium inventory to the desired enrichment level (see Table 4 and Figure 1). Obviously, the lower concentrations of $^{235}U$ in the refeed option require considerably more energy to enrich than the fresh feed. For this study, only the depleted $UF_6$ that has concentrations of >0.24% $^{235}U$ were considered. $UF_6$ with concentrations <0.24% $^{235}U$ was excluded because of the assumption that all enrichment processes would produce 0.2% $^{235}U$ tails and that it would not be profitable to work with such small differentials in the $^{235}U$ concentrations. Such an assumption reduces the usable depleted uranium by about 30%, but it should have an even smaller effect on the amount of enriched uranium produced.

## 4.2 GASEOUS EMISSIONS

The air pollutant emissions are greatly affected by the source mix for the electricity used to produce the enriched uranium. Since most of the energy required for uranium enrichment is in the form of electricity, whether the electricity is generated with coal or nuclear plants greatly influences the quantity of gaseous emissions.

The emissions associated with coal-generated electricity are much greater than those from nuclear-power-generated electricity, even when the amount of fossil fuel needed to mine, mill, and convert the uranium is considered (see Table 5). In comparing the fresh feed and refeed options, it is important to note that the fresh feed option includes mining, milling, and conversion processes in addition to enrichment, which is the only process included in the refeed option. However, the amount of pollutants associated with the increased energy required in the refeed option overwhelms any gaseous pollutants generated in the mining, milling, and conversion processes associated with fresh feed.

The air pollutants associated with mining, milling and conversion for fresh feed are not negligible in the nuclear subscenarios due to the direct use of fossil fuels in those processes (see Table 5). Note that the lower gaseous emissions associated with nuclear-generated electricity are sufficient to reverse the conclusions from the coal case (Figure 2).

**TABLE 4 Energy Requirements for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory - All Electricity from Coal**

| | | Energy Required [GJ(th)] | |
|---|---|---|---|
| Enrichment Scenario | Product Tonnes of Enriched Uranium | Fresh Feed (assuming 0.2% tails) | Depleted Uranium >0.24% (assuming 0.2% tails) |
| 2% | 16,032 | 1,161,673 | 1,930,917 |
| 3% | 10,306 | 1,372,902 | 2,189,458 |
| 4% | 7,594 | 1,499,589 | 2,338,557 |

**TABLE 5 $CO_2$ Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory**

| | $CO_2$ Emissions (tonnes) | |
|---|---|---|
| Enrichment Scenario | Fresh Feed | Refeed |
| *100 % Coal* | | |
| 2% | 114,472,876 | 201,046,344 |
| 3% | 137,237,990 | 227,965,541 |
| 4% | 150,794,327 | 243,489,602 |
| *100% Nuclear* | | |
| 2% | 12,617,381 | 3,787,469 |
| 3% | 9,310,230 | 4,294,594 |
| 4% | 7,795,922 | 4,587,049 |

Figure 1 Comparison of Input Energy Required to Produce Enriched Uranium from Natural Uranium and from Depleted Uranium (In all cases, the energy required to enrich the tails at Paducah and Portsmouth is higher than the enrichment process of natural U)

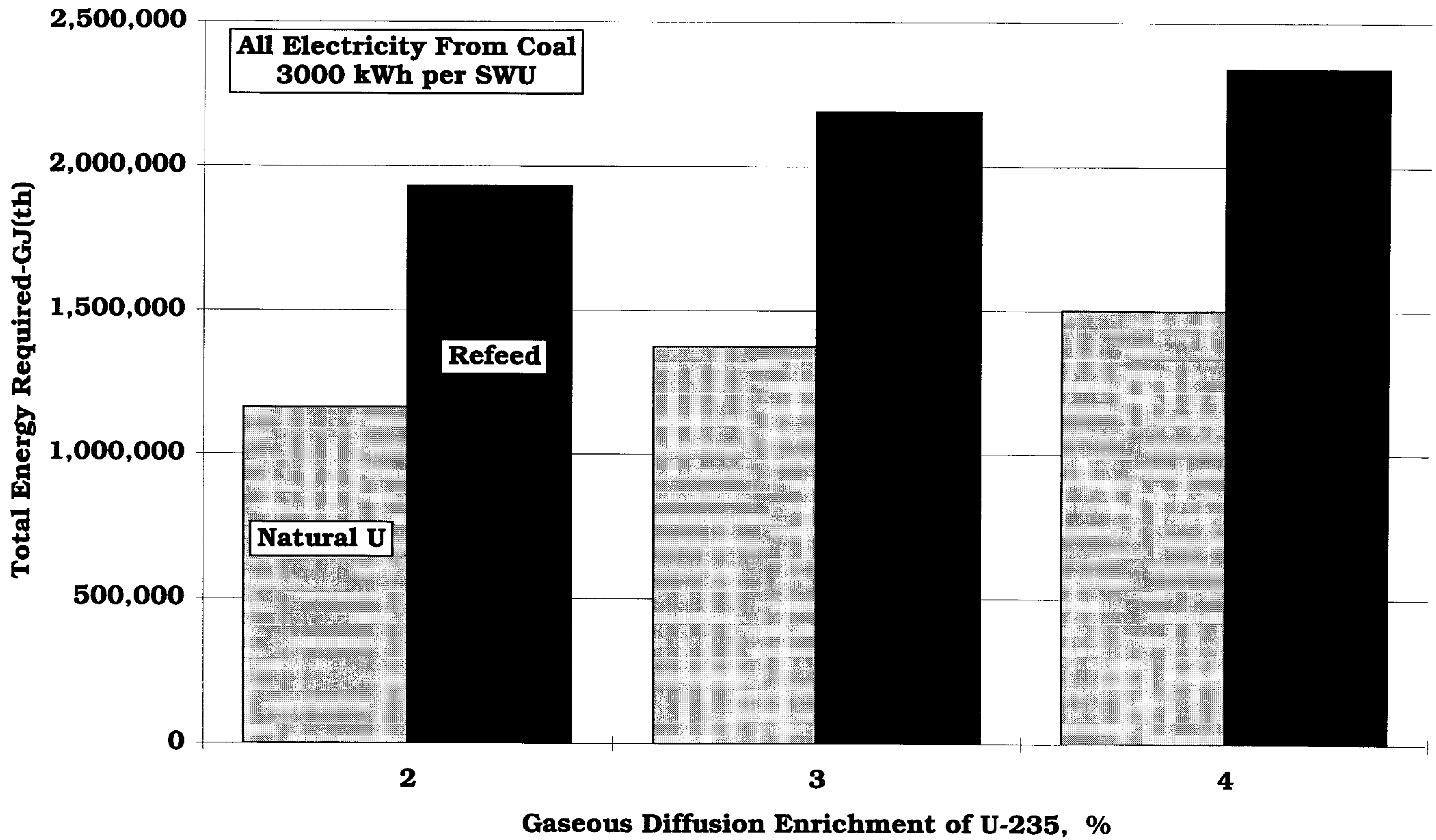
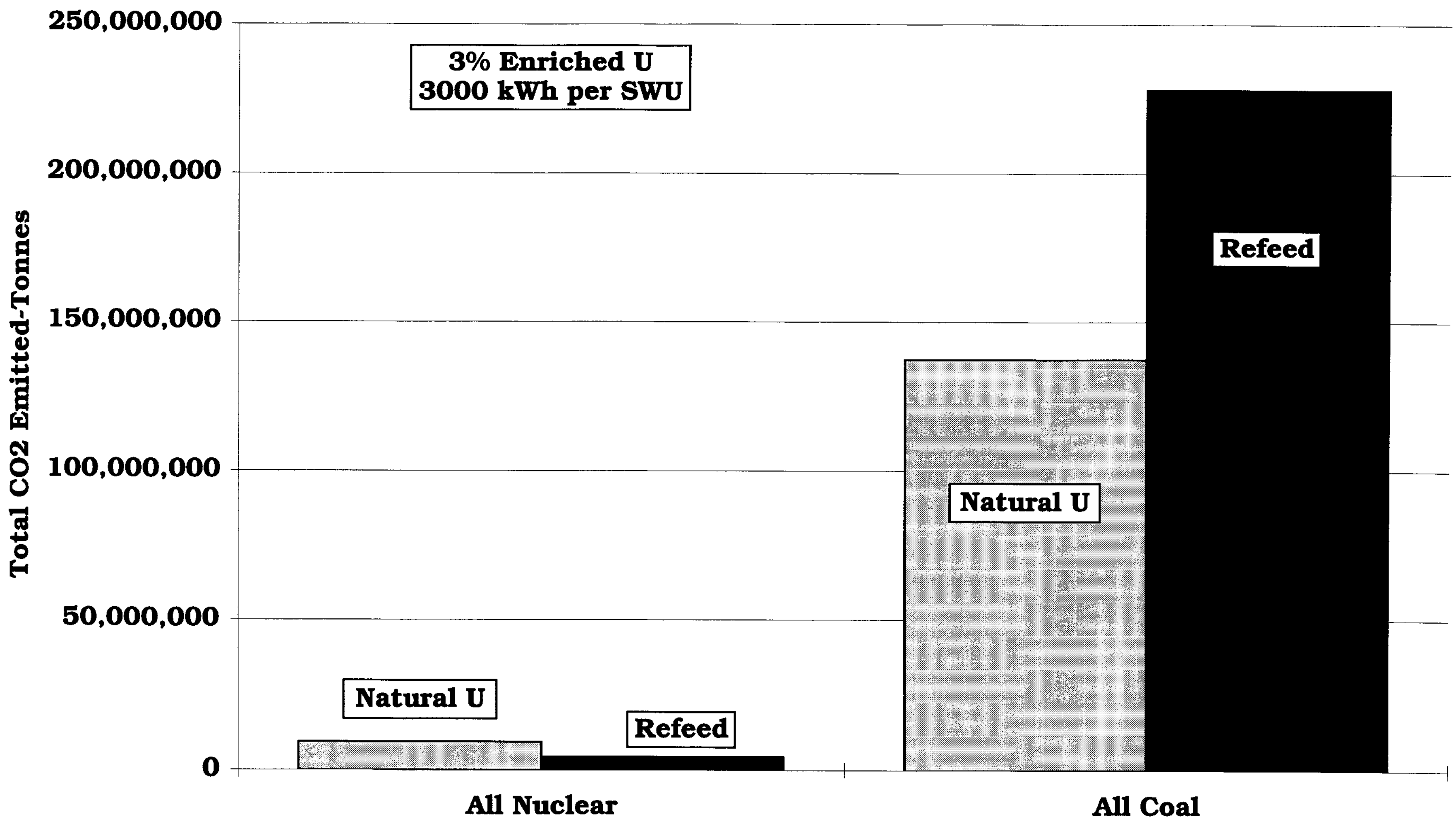


Figure 2 The Use of Nuclear Energy to Generate Electricity Can Greatly Reduce CO2 Emissions and Favors the Use of the Refeed Option over the Use of Natural U



The findings for each air pollutant ($CO_2$, $NO_x$, $SO_x$, and CO) follow a similar trend; they vary only in the magnitude of the pollutant emitted (see Tables 5-8). For the 100% coal-generated electricity case, the findings reflect those of the energy requirements, and the fresh feed option produces less air pollutants. In contrast, under the scenario where all the input electricity is generated by nuclear power, the refeed option produces less air pollutants.

### 4.3 PRODUCTS AND EFFECT ON WASTE FACILITIES

It can be seen from Table 9 that over 10,000 tonnes of 3% enriched uranium can be produced from the depleted uranium tails at just two U.S. facilities. This number increases to over 16,000 tonnes of 2% enriched product or drops to over 7,500 tonnes of 4% enriched product. In any case, there is a considerable energy resource available from uranium tails. For example, the 3% enriched uranium would produce 466 GW(e)-yr of electricity, which is more than six times the electric power generated from nuclear plants [77 GW(e)-yr] and 136% of the total electricity generated in the United States in 1995 (DOE 1996). Another way of looking at this amount is that this resource could provide the entire United States with electricity for 16 months. The energy potential from 2% uranium product is even greater.

An assumption was made that all storage cylinders hold 12.2 tonnes of depleted $UF_6$. A reduction of 921 to nearly 1,943 storage cylinders would occur if the refeed option were used.

**TABLE 6 $SO_x$ Emissions for Gaseous Enrichment Scenarios Involving the Depleted Uranium Inventory**

| Enrichment Scenario | $SO_x$ Emissions (tonnes) | |
|---|---|---|
| | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 975,553 | 1,579,857 |
| 3% | 1,127,301 | 1,791,392 |
| 4% | 1,220,971 | 1,913,383 |
| *100% Nuclear* | | |
| 2% | 177,455 | 34,215 |
| 3% | 124,910 | 38,796 |
| 4% | 100,492 | 41,438 |

**TABLE 7 $NO_x$ Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory**

| Enrichment Scenario | $NO_x$ Emissions (tonnes) | |
|---|---|---|
| | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 313,324 | 561,748 |
| 3% | 379,264 | 636,964 |
| 4% | 418,246 | 680,340 |
| *100% Nuclear* | | |
| 2% | 25,824 | 4,959 |
| 3% | 18,171 | 5,623 |
| 4% | 14,614 | 6,006 |

**TABLE 8 CO Emissions for Gaseous Diffusion Enrichment Scenarios Involving the Depleted Uranium Inventory**

| Enrichment Scenario | CO Emissions (tonnes) Fresh Feed | Refeed |
|---|---|---|
| *100% Coal* | | |
| 2% | 28,881 | 51,990 |
| 3% | 35,025 | 58,951 |
| 4% | 38,653 | 62,965 |
| *100% Nuclear* | | |
| 2% | 2,250 | 416 |
| 3% | 1,578 | 472 |
| 4% | 1,266 | 504 |

**TABLE 9 Potential Amount of Enriched Uranium Produced from Tails at the Paducah and Portsmouth Facilities**

| | | Enrichment | | |
|---|---|---|---|---|
| Parameter | Unit | 2% $^{235}U$ | 3% $^{235}U$ | 4% $^{235}U$ |
| Quantity of Enriched Uranium Product | tonnes | 16,032 | 10,306 | 7,594 |
| Total Electrical Energy | GW(e)-yr | 580[a] | 466[b] | 412[c] |
| Reduction in Cylinders[d] | Number | 888 | 571 | 421 |

[a] Assuming 40 $GWd_{th}$/MTU, 33% efficiency. Based on projections from the Energy Information Administration, Spent Nuclear Fuel Discharges from U.S. Reactors," 1994, and EIA, Form RW-859, "Nuclear Fuel Data," 1991.

[b] Assuming 50 $GWd_{th}$/MTU, 33% efficiency. Based on projections from the Energy Information Administration, Spent Nuclear Fuel Discharges from U.S. Reactors," 1994, and EIA, Form RW-859, "Nuclear Fuel Data," 1991.

[c] Assuming 60 $GWd_{th}$/MTU, 33% efficiency.

[d] Each cylinder contains 12.2 tonnes of depleted $UF_6$ per cylinder.

# 5 DISCUSSION

Tables 10 and 11 list the impacts of the three enrichment scenarios when using all-coal-generated and all-nuclear-generated electricity, respectively. A more detailed listing of the energy requirements, air emissions, and effects of the depleted uranium inventory can be seen in Appendices A and B.

From the perspective of energy conservation, the refeed option is not advantageous over the use of natural uranium in the uranium fuel cycle. The concentrations of $^{235}U$ in the depleted uranium are too low and the energy requirements are too high to justify an overall strategy of recycling the depleted uranium inventory on the basis of energy (and probably economic) arguments alone. Certain concentrations of depleted uranium, however, may warrant recycling. Appendices B and C show that the refeed of concentrations around 0.66% requires less overall energy to produce enriched uranium than the fresh feed scenario. The limiting factor is that the total mass of depleted uranium with these concentrations makes up just 1% of the total inventory (2,931 of 225,494 tonnes) or 4.6% of the enriched uranium product.

The energy advantage of the fresh feed option would be lessened by using a different enrichment method, such as the gas centrifuge, which requires approximately one-fifth the energy of gaseous diffusion. Because there are significant energy requirements associated with mining, milling, and concentrating natural uranium, the reduction of energy for enrichment would have a greater effect on the more-energy-intensive refeed option. Appendix A compares the fresh feed and refeed options using centrifuge enrichment.

From the environmental perspective, how the electricity is generated affects whether the refeed or fresh feed option is advantageous. When all electricity is generated using coal, the fresh feed option is clearly better. Less electrical input also means less gaseous pollutants. But when the electricity is generated by nuclear power, and likely hydro-power as well, the advantage, from an environmental standpoint, goes to the refeed option. Since most of the energy requirements of gaseous diffusion enrichment are electrical, the electrical mix has a great effect on the air emissions. The levels of air emissions associated with the mining, milling, and conversion processes in the fresh feed option are dominant in the all-nuclear-electricity case.

The reduction in cylinders is insignificant in comparison to the total number of cylinders. Of the nearly 42,000 cylinders currently being used to store depleted uranium at Paducah and Portsmouth, the reductions accrued in the 2%, 3%, and 4% enrichment scenarios range from 4.6% to 2.2%. This would imply that waste reduction and management benefits *alone* are not strong arguments for refeeding depleted uranium.

The energy potential of the enriched tails provides perhaps the biggest argument for the refeed option. The electrical energy potential of refeeding depleted uranium is large in comparison to the current use of nuclear power by the United States. The potential electrical energy provided by the 2%, 3%, and 4% enrichment scenarios range from 7.5 to 5.4 times that of nuclear power's 1995 contribution to the U.S. electrical grid. The size of this energy resource is not trivial.

**TABLE 10 Effect of Using 100% Coal-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options (Gaseous Diffusion Enrichment)**

| | 2% enrichment | | 3% enrichment | | 4% enrichment | |
|---|---|---|---|---|---|---|
| Quantity per Total Product Output | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] |
| Total depleted uranium feed (tonnes) | — | 225,494 | — | 225,494 | — | 225,494 |
| Product output (tonnes) | 16,032 | 16,032 | 10,306 | 10,306 | 7,594 | 7,594 |
| Total energy required [GJ(th)] | 1,161,673 | 1,930,917 | 1,372,902 | 2,189,458 | 1,499,589 | 2,338,557 |
| Total $CO_2$ emitted (tonnes) | 114,472,876 | 201,046,344 | 137,237,990 | 227,965,541 | 150,794,327 | 243,489,602 |
| Total $SO_x$ emitted (tonnes) | 975,553 | 1,579,857 | 1,127,301 | 1,791,392 | 1,220,971 | 1,913,383 |
| Total $NO_x$ emitted (tonnes) | 313,324 | 561,748 | 379,264 | 636,964 | 418,246 | 680,340 |
| Total CO emitted (tonnes) | 28,881 | 51,990 | 35,025 | 58,951 | 38,653 | 62,965 |
| Mass of refeed waste (tonnes) | — | 209,463 | — | 215,188 | — | 217,900 |
| Depleted uranium mass reduction (tonnes) | — | 16,032 | — | 10,306 | — | 7,594 |
| Reduction in number of 14-ton cylinders | — | 1,943 | — | 1,249 | — | 921 |
| Electrical energy potential from product [GW(e)-yr] | — | 580 | — | 466 | — | 412 |

[a] Depleted uranium in inventory at Paducah, Ky., and Portsmouth, Ohio.

**TABLE 11 Effect of Using 100% Nuclear-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options (Gaseous Diffusion Enrichment)**

| | 2% enrichment | | 3% enrichment | | 4% enrichment | |
|---|---|---|---|---|---|---|
| Quantity per Total Product Output | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] |
| Total depleted uranium feed (tonnes) | — | 225,494 | — | 225,494 | — | 225,494 |
| Product output (tonnes) | 16,032 | 16,032 | 10,306 | 10,306 | 7,594 | 7,594 |
| Total Energy Required [GJ(th)] | 1,377,882 | 2,340,506 | 1,642,310 | 2,653,889 | 1,799,846 | 2,834,614 |
| Total $CO_2$ emitted (tonnes) | 12,617,381 | 3,787,469 | 9,310,230 | 4,294,594 | 7,795,922 | 4,587,049 |
| Total $SO_x$ emitted (tonnes) | 177,455 | 34,215 | 124,910 | 38,796 | 100,492 | 41,438 |
| Total $NO_x$ emitted (tonnes) | 25,824 | 4,959 | 18,171 | 5,623 | 14,614 | 6,006 |
| Total CO emitted (tonnes) | 2,250 | 416 | 1,578 | 472 | 1,266 | 504 |
| Mass of refeed waste (tonnes) | — | 209,463 | — | 215,188 | — | 217,900 |
| Depleted uranium mass reduction (tonnes) | — | 16,032 | — | 10,306 | — | 7,594 |
| Reduction in number of 14-ton cylinders | — | 1,943 | — | 1,249 | — | 921 |
| Electrical energy potential from product [GW(e)-yr] | — | 580 | — | 466 | — | 412 |

[a] Depleted uranium in inventory at Paducah, Ky., and Portsmouth, Ohio.

# 6 SUMMARY AND CONCLUSIONS

The way in which the electricity is generated can have a significant effect on the total energy input and amount of gaseous pollutants emitted in a refeed process for utilizing depleted uranium stored at the Paducah, Ky., and Portsmouth, Ohio, facilities. If all the electricity is generated from coal, it is more advantageous to use natural uranium feed than to use the stored depleted uranium. This conclusion is true both from an energy input (economic) and from the total level of pollutants released. On the other hand, from the environmental standpoint, the use of nuclear-generated electricity favors the use of the refeed depleted uranium. The energy input (cost) advantage still lies with the use of natural uranium feed in the case of nuclear-generated electricity.

These conclusions could be changed if centrifuge or AVLIS technologies were used instead of gaseous diffusion enrichment. In that case the energy used and pollutants created during the mining, milling, and conversion processes will play an important role.

## 7 REFERENCES

Cochran, R.G., and N. Tsoulfanidis, *The Nuclear Fuel Cycle: Analysis and Management*. La Grange Park, IL: American Nuclear Society (1990).

Hertzler, T.J., and D.D. Nishimoto, "Depleted Uranium Management Alternatives," Idaho National Engineering Laboratory, EGG-MS-11416 (August 1994).

Mintzer, I., "Weathering the Storms in a Warming World," *Public Power*, **46**(6):15-21 (1988).

Rotty, R.M., A.M. Perry, and D.B. Reister, "Net Energy from Nuclear Power," Federal Energy Administration, FEA/B-76/702 (May 1976).

U.S. Department of Energy, "Monthly Energy Review," Energy Information Administration, DOE/EIA- 0035(96/09) (Sept. 1996).

U.S. Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors, Volume I, Fourth Edition," (September 1985).

U.S. Environmental Protection Agency, "Supplement B to Compilation of Air Pollutant Emission Factors; Volume I: Stationary Point and Area Sources," AP-42, Volume I, Supplement B (September 1988).

U.S. Environmental Protection Agency, "Supplement E to Compilation of Air Pollutant Emission Factors; Volume I: Stationary Point and Area Sources," AP-42, Volume I, Supplement E (October 1992).

White, S.W., "Energy Balance and Lifetime Emissions from Fusion, Fission and Coal Generated Electricity," Masters Thesis, University of Wisconsin-Madison (1995).

Yoshiki-Gravelsins, K.S., J.M. Toguri, and R.T.C. Choo, "Metals Production, Energy, and the Environment, Part I: Energy Consumption," *Journal of Metals*, **45**:15-20 (May 1993).

# APPENDIX A: DATA USING 100% COAL-GENERATED ELECTRICITY

**TABLE A.1 Environmental Impact of Producing 2% Enriched U for LWRs (Gaseous Diffusion Enrichment): Electricity Generated from 100% Coal**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 | | | | | | | | |
| Enrichment | % U-235 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SWUs required | SWU | 2.19413 | 5.78300 | 5.46529 | 5.11058 | 3.93502 | 2.93521 | 2.41938 |
| Feed rate | kg U(nat)/U(enr) | 3.52250 | 36.00000 | 25.71429 | 18.94737 | 8.78049 | 5.14286 | 3.95170 |
| Electrical input | MW(e)-h/kg U (enriched) | 6.58238 | 17.34899 | 16.39588 | 15.33175 | 11.80506 | 8.80562 | 7.25813 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 2.59 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.60 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.66 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | GJ(th)/kg-U prod. | 62 | 162 | 153 | 144 | 110 | 82 | 68 |
| Subtotal | GJ(th)/kg-U prod. | 72 | 162 | 153 | 144 | 110 | 82 | 68 |

**TABLE A.1 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 166 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 163 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 396 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $CO_2$/kg-U prod. | 6,415 | 16,908 | 15,979 | 14,942 | 11,505 | 8,582 | 7,073 |
| Subtotal | kg $CO_2$/kg-U prod. | 7,140 | 16,908 | 15,979 | 14,942 | 11,505 | 8,582 | 7,073 |
| *Environmental Impact: $SO_x$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.36 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.29 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.79 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $SO_x$/kg-U prod. | 50.41 | 132.86 | 125.56 | 117.41 | 90.41 | 67.44 | 55.58 |
| Subtotal | kg $SO_x$/kg-U prod. | 60.85 | 132.86 | 125.56 | 117.41 | 90.41 | 67.44 | 55.58 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.88 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $NO_x$/kg-U prod. | 17.92 | 47.24 | 44.65 | 41.75 | 32.15 | 23.98 | 19.76 |
| Subtotal | kg $NO_x$/kg-U prod. | 19.54 | 47.24 | 44.65 | 41.75 | 32.15 | 23.98 | 19.76 |

**TABLE A.1 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.08 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg CO/kg-U prod. | 1.66 | 4.37 | 4.13 | 3.86 | 2.98 | 2.22 | 1.83 |
| Subtotal | kg CO/kg-U prod. | 1.80 | 4.37 | 4.13 | 3.86 | 2.98 | 2.22 | 1.83 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U | | | | | | | | |
| Product output (2% U) | tonnes | 16,032 | 2,542 | 109 | 1,734 | 10,806 | 98 | 742 |
| Total energy required | GJ(th)[a] | 1,161,673 | 412,812 | 16,707 | 248,831 | 1,194,062 | 8,117 | 50,388 |
| Total $CO_2$ emitted | tonnes [a] | 114,472,876 | 42,981,816 | 1,739,477 | 25,908,235 | 124,325,269 | 845,133 | 5,246,414 |
| Total $SO_x$ emitted | tonnes [a] | 975,553 | 337,758 | 13,669 | 203,591 | 976,969 | 6,641 | 41,227 |
| Total $NO_x$ emitted | tonnes [a] | 313,324 | 120,097 | 4,860 | 72,391 | 347,380 | 2,361 | 14,659 |
| Total CO emitted | tonnes [a] | 28,881 | 11,115 | 450 | 6,700 | 32,150 | 219 | 1,357 |
| Mass of refeed waste | tonnes [a] | | 88,975 | 2,690 | 31,120 | 84,079 | 408 | 2,189 |

[a] Quantity per total product output.

**TABLE A.2 Environmental Impact of Producing 3% Enriched U for LWRs (Gaseous Diffusion Enrichment): Electricity Generated from 100% Coal**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 Enrichment | % U-235 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| SWUs required | SWU | 4.30647 | 9.88916 | 9.39496 | 8.84318 | 7.01453 | 5.45927 | 4.65686 |
| Feed rate | kg U(nat)/U(enr) | 5.47945 | 56.00000 | 40.00000 | 29.47368 | 13.65854 | 8.00000 | 6.14709 |
| Electrical input | MW(e)-h/kg U (enriched) | 12.91942 | 29.66749 | 28.18488 | 26.52955 | 21.04359 | 16.37780 | 13.97059 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 4.02 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.60 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.66 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | GJ(th)/kg-U prod. | 121 | 278 | 264 | 248 | 197 | 153 | 131 |
| Subtotal | GJ(th)/kg-U prod. | 133 | 278 | 264 | 248 | 197 | 153 | 131 |

**TABLE A.2 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 166 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 163 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 396 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $CO_2$/kg-U prod. | 12,591 | 28,913 | 27,468 | 25,855 | 20,508 | 15,961 | 13,615 |
| Subtotal | kg $CO_2$/kg-U prod. | 13,316 | 28,913 | 27,468 | 25,855 | 20,508 | 15,961 | 13,615 |
| *Environmental Impact: $SO_x$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.36 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.29 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.79 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $SO_x$/kg-U prod. | 98.94 | 227.20 | 215.85 | 203.17 | 161.16 | 125.43 | 106.99 |
| Subtotal | kg $SO_x$/kg-U prod. | 109.38 | 227.20 | 215.85 | 203.17 | 161.16 | 125.43 | 106.99 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.88 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $NO_x$/kg-U prod. | 35.18 | 80.79 | 76.75 | 72.24 | 57.30 | 44.60 | 38.04 |
| Subtotal | kg $NO_x$/kg-U prod. | 36.80 | 80.79 | 76.75 | 72.24 | 57.30 | 44.60 | 38.04 |

**TABLE A.2 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.08 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg CO/kg-U prod. | 3.26 | 7.48 | 7.10 | 6.69 | 5.30 | 4.13 | 3.52 |
| Subtotal | kg CO/kg-U prod. | 3.40 | 7.48 | 7.10 | 6.69 | 5.30 | 4.13 | 3.52 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U | | | | | | | | |
| Product output (3% U) | tonnes | 10,306 | 1,634 | 70 | 1,115 | 6,947 | 63 | 477 |
| Total energy required | GJ(th)[a] | 1,372,902 | 453,809 | 18,462 | 276,795 | 1,368,337 | 9,705 | 62,350 |
| Total $CO_2$ emitted | tonnes[a] | 137,237,990 | 47,250,433 | 1,922,271 | 28,819,776 | 142,470,733 | 1,010,498 | 6,491,830 |
| Total $SO_x$ emitted | tonnes[a] | 1,127,301 | 371,302 | 15,106 | 226,471 | 1,119,559 | 7,941 | 51,014 |
| Total $NO_x$ emitted | tonnes[a] | 379,264 | 132,024 | 5,371 | 80,526 | 398,081 | 2,823 | 18,139 |
| Total CO emitted | tonnes[a] | 35,025 | 12,219 | 497 | 7,453 | 36,842 | 261 | 1,679 |
| Mass of refeed waste | tonnes[a] | | 89,883 | 2,729 | 31,739 | 87,939 | 443 | 2,454 |

[a] Quantity per total product output.

**TABLE A.3 Environmental Impact of Producing 4% Enriched U for LWRs (Gaseous Diffusion Enrichment): Electricity Generated from 100% Coal**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 | | | | | | | | |
| Enrichment | % U-235 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SWUs required | SWU | 6.54371 | 14.12022 | 13.44951 | 12.70068 | 10.21893 | 8.10822 | 7.01924 |
| Feed rate | kg U(nat)/U(enr) | 7.43640 | 76.00000 | 54.28571 | 40.00000 | 18.53659 | 10.85714 | 8.34248 |
| Electrical input | MW(e)-h/kg U (enriched) | 19.63114 | 42.36067 | 40.34854 | 38.10203 | 30.65680 | 24.32465 | 21.05773 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 5.46 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.60 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.66 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | GJ(th)/kg-U prod. | 184 | 396 | 378 | 357 | 287 | 228 | 197 |
| Subtotal | GJ(th)/kg-U prod. | 197 | 396 | 378 | 357 | 287 | 228 | 197 |

**TABLE A.3 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 166 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 163 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 396 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $CO_2$/kg-U prod. | 19,132 | 41,283 | 39,322 | 37,133 | 29,877 | 23,706 | 20,522 |
| Subtotal | kg $CO_2$/kg-U prod. | 19,857 | 41,283 | 39,322 | 37,133 | 29,877 | 23,706 | 20,522 |
| *Environmental Impact: $SO_x$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.36 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.29 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.79 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $SO_x$/kg-U prod. | 150.34 | 324.41 | 309.00 | 291.80 | 234.78 | 186.28 | 161.27 |
| Subtotal | kg $SO_x$/kg-U prod. | 160.78 | 324.41 | 309.00 | 291.80 | 234.78 | 186.28 | 161.27 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.88 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $NO_x$/kg-U prod. | 53.46 | 115.35 | 109.87 | 103.75 | 83.48 | 66.24 | 57.34 |
| Subtotal | kg $NO_x$/kg-U prod. | 55.08 | 115.35 | 109.87 | 103.75 | 83.48 | 66.24 | 57.34 |

**TABLE A.3 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.08 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg CO/kg-U prod. | 4.95 | 10.68 | 10.17 | 9.60 | 7.73 | 6.13 | 5.31 |
| Subtotal | kg CO/kg-U prod. | 5.09 | 10.68 | 10.17 | 9.60 | 7.73 | 6.13 | 5.31 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U | | | | | | | | |
| Product output (4% U) | tonnes | 7,594 | 1,204 | 52 | 821 | 5,119 | 47 | 351 |
| Total energy required | GJ(th)[a] | 1,499,589 | 477,452 | 19,475 | 292,921 | 1,468,840 | 10,621 | 69,248 |
| Total $CO_2$ emitted | tonnes[a] | 150,794,327 | 49,712,106 | 2,027,686 | 30,498,836 | 152,935,061 | 1,105,862 | 7,210,051 |
| Total $SO_x$ emitted | tonnes[a] | 1,220,971 | 390,646 | 15,934 | 239,665 | 1,201,790 | 8,690 | 56,658 |
| Total $NO_x$ emitted | tonnes[a] | 418,246 | 138,902 | 5,666 | 85,218 | 427,320 | 3,090 | 20,146 |
| Total CO emitted | tonnes[a] | 38,653 | 12,855 | 524 | 7,887 | 39,548 | 286 | 1,864 |
| Mass of refeed waste | tonnes[a] | | 90,313 | 2,748 | 32,033 | 89,767 | 460 | 2,580 |

[a] Quantity per total product output.

# APPENDIX B: DATA USING 100% NUCLEAR-GENERATED ELECTRICITY

**TABLE B.1 Environmental Impact of Producing 2% Enriched U for LWRs (Gaseous Diffusion Enrichment): 100% Nuclear-Generated Electricity**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 | | | | | | | | |
| Enrichment | % U-235 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SWUs required | SWU | 2.19413 | 5.78300 | 5.46529 | 5.11058 | 3.93502 | 2.93521 | 2.41938 |
| Feed rate | kg U(nat)/U(enr) | 3.52250 | 36.00000 | 25.71429 | 18.94737 | 8.78049 | 5.14286 | 3.95170 |
| Electrical input | MW(e)-h/kg U (enriched) | 6.58238 | 17.34899 | 16.39588 | 15.33175 | 11.80506 | 8.80562 | 7.25813 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 2.72 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.75 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.80 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | GJ(th)/kg-U prod. | 75 | 197 | 186 | 174 | 134 | 100 | 82 |
| Subtotal | GJ(th)/kg-U prod. | 86 | 197 | 186 | 174 | 134 | 100 | 82 |

**TABLE B.1 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 148 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 142 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 376 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $CO_2$/kg-U prod. | 121 | 319 | 301 | 281 | 217 | 162 | 133 |
| Subtotal | kg $CO_2$/kg-U prod. | 787 | 319 | 301 | 281 | 217 | 162 | 133 |
| *Environmental Impact: $SO_X$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.21 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.12 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.64 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $SO_x$/kg-U prod. | 1.09 | 2.88 | 2.72 | 2.54 | 1.96 | 1.46 | 1.20 |
| Subtotal | kg $SO_x$/kg-U prod. | 11.07 | 2.88 | 2.72 | 2.54 | 1.96 | 1.46 | 1.20 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.32 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.31 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.82 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg $NO_x$/kg-U prod. | 0.16 | 0.42 | 0.39 | 0.37 | 0.28 | 0.21 | 0.17 |
| Subtotal | kg $NO_x$/kg-U prod. | 1.61 | 0.42 | 0.39 | 0.37 | 0.28 | 0.21 | 0.17 |

**TABLE B.1 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.07 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 2% | kg CO/kg-U prod. | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.01 |
| Subtotal | kg CO/kg-U prod. | 0.14 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.01 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U Product Output (2% U) | tonnes | 16,032 | 2,542 | 109 | 1,734 | 10,806 | 98 | 742 |
| Total energy required | GJ(th)[a] | 1,377,882 | 500,378 | 20,250 | 301,614 | 1,447,348 | 9,839 | 61,077 |
| Total $CO_2$ emitted | tonnes[a] | 12,617,381 | 809,725 | 32,770 | 488,080 | 2,342,137 | 15,921 | 98,836 |
| Total $SO_x$ emitted | tonnes[a] | 177,455 | 7,315 | 296 | 4,409 | 21,158 | 144 | 893 |
| Total $NO_x$ emitted | tonnes[a] | 25,824 | 1,060 | 43 | 639 | 3,067 | 21 | 129 |
| Total CO emitted | tonnes[a] | 2,250 | 89 | 4 | 54 | 257 | 2 | 11 |
| Mass of refeed waste | tonnes[a] | | 88,975 | 2,690 | 31,120 | 84,079 | 408 | 2,189 |

[a] Quantity per total product output.

**TABLE B.2 Environmental Impact of Producing 3% Enriched U for LWRs (Gaseous Diffusion Enrichment): 100% Nuclear-Generated Electricity**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 | | | | | | | | |
| Enrichment | % U-235 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| SWUs required | SWU | 4.30647 | 9.88916 | 9.39496 | 8.84318 | 7.01453 | 5.45927 | 4.65686 |
| Feed rate | kg U(nat)/U(enr) | 5.47945 | 56.00000 | 40.00000 | 29.47368 | 13.65854 | 8.00000 | 6.14709 |
| Electrical input | MW(e)-h/kg U (enriched) | 12.91942 | 29.66749 | 28.18488 | 26.52955 | 21.04359 | 16.37780 | 13.97059 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 4.23 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.75 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.80 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | GJ(th)/kg-U prod. | 147 | 337 | 320 | 301 | 239 | 186 | 159 |
| Subtotal | GJ(th)/kg-U prod. | 159 | 337 | 320 | 301 | 239 | 186 | 159 |

**TABLE B.2 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 148 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 142 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 376 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $CO_2$/kg-U prod. | 237 | 545 | 517 | 487 | 386 | 301 | 256 |
| Subtotal | kg $CO_2$/kg-U prod. | 903 | 545 | 517 | 487 | 386 | 301 | 256 |
| *Environmental Impact: $SO_x$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.21 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.12 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.64 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $SO_x$/kg-U prod. | 2.14 | 4.92 | 4.67 | 4.40 | 3.49 | 2.72 | 2.32 |
| Subtotal | kg $SO_x$/kg-U prod. | 12.12 | 4.92 | 4.67 | 4.40 | 3.49 | 2.72 | 2.32 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.32 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.31 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.82 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg $NO_x$/kg-U prod. | 0.31 | 0.71 | 0.68 | 0.64 | 0.51 | 0.39 | 0.34 |
| Subtotal | kg $NO_x$/kg-U prod. | 1.76 | 0.71 | 0.68 | 0.64 | 0.51 | 0.39 | 0.34 |

**TABLE B.2 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.07 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 3% | kg CO/kg-U prod. | 0.03 | 0.06 | 0.06 | 0.05 | 0.04 | 0.03 | 0.03 |
| Subtotal | kg CO/kg-U prod. | 0.15 | 0.06 | 0.06 | 0.05 | 0.04 | 0.03 | 0.03 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U | | | | | | | | |
| Product Output (3% U) | tonnes | 10,306 | 1,634 | 70 | 1,115 | 6,947 | 63 | 477 |
| Total energy required | GJ(th)[a] | 1,642,310 | 550,072 | 22,378 | 335,509 | 1,658,591 | 11,764 | 75,575 |
| Total $CO_2$ emitted | tonnes[a] | 9,310,230 | 890,141 | 36,213 | 542,930 | 2,683,976 | 19,037 | 122,298 |
| Total $SO_x$ emitted | tonnes[a] | 124,910 | 8,041 | 327 | 4,905 | 24,246 | 172 | 1,105 |
| Total $NO_x$ emitted | tonnes[a] | 18,171 | 1,166 | 47 | 711 | 3,514 | 25 | 160 |
| Total CO emitted | tonnes[a] | 1,578 | 98 | 4 | 60 | 295 | 2 | 13 |
| Mass of refeed waste | tonnes[a] | | 89,883 | 2,729 | 31,739 | 87,939 | 443 | 2,454 |

[a] Quantity per total product output.

**TABLE B.3 Environmental Impact of Producing 4% Enriched U for LWRs (Gaseous Diffusion Enrichment): 100% Nuclear-Generated Electricity**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| Feed U-235 | % U-235 | 0.711 | 0.25 | 0.27 | 0.295 | 0.405 | 0.55 | 0.6555 |
| Final U-235 | | | | | | | | |
| Enrichment | % U-235 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Tails | % U-235 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Production rate | kg U | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SWUs required | SWU | 6.54371 | 14.12022 | 13.44951 | 12.70068 | 10.21893 | 8.10822 | 7.01924 |
| Feed rate | kg U(nat)/U(enr) | 7.43640 | 76.00000 | 54.28571 | 40.00000 | 18.53659 | 10.85714 | 8.34248 |
| Electrical input | MW(e)-h/kg U (enriched) | 19.63114 | 42.36067 | 40.34854 | 38.10203 | 30.65680 | 24.32465 | 21.05773 |
| *Energy Input* | | | | | | | | |
| Mining | GJ(th)/kg-U prod. | 5.74 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | GJ(th)/kg-U prod. | 2.75 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | GJ(th)/kg-U prod. | 5.80 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | GJ(th)/kg-U prod. | 223 | 481 | 458 | 432 | 348 | 276 | 239 |
| Subtotal | GJ(th)/kg-U prod. | 237 | 481 | 458 | 432 | 348 | 276 | 239 |

**TABLE B.3 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: $CO_2$* | | | | | | | | |
| Mining | kg $CO_2$/kg-U prod. | 148 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $CO_2$/kg-U prod. | 142 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $CO_2$/kg-U prod. | 376 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $CO_2$/kg-U prod. | 360 | 778 | 741 | 700 | 563 | 447 | 387 |
| Subtotal | kg $CO_2$/kg-U prod. | 1,027 | 778 | 741 | 700 | 563 | 447 | 387 |
| *Environmental Impact: $SO_x$* | | | | | | | | |
| Mining | kg $SO_x$/kg-U prod. | 2.21 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $SO_x$/kg-U prod. | 2.12 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $SO_x$/kg-U prod. | 5.64 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $SO_x$/kg-U prod. | 3.26 | 7.03 | 6.69 | 6.32 | 5.08 | 4.03 | 3.49 |
| Subtotal | kg $SO_x$/kg-U prod. | 13.23 | 7.03 | 6.69 | 6.32 | 5.08 | 4.03 | 3.49 |
| *Environmental Impact: $NO_x$* | | | | | | | | |
| Mining | kg $NO_x$/kg-U prod. | 0.32 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg $NO_x$/kg-U prod. | 0.31 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg $NO_x$/kg-U prod. | 0.82 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg $NO_x$/kg-U prod. | 0.47 | 1.02 | 0.97 | 0.92 | 0.74 | 0.58 | 0.51 |
| Subtotal | kg $NO_x$/kg-U prod. | 1.92 | 1.02 | 0.97 | 0.92 | 0.74 | 0.58 | 0.51 |

**TABLE B.3 (Cont.)**

| Parameter | Units | Fresh Feed (0.711% U-35) | Refeed 0.25% | Refeed 0.27% | Refeed 0.30% | Refeed 0.41% | Refeed 0.55% | Refeed 0.66% |
|---|---|---|---|---|---|---|---|---|
| *Environmental Impact: CO* | | | | | | | | |
| Mining | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling | kg CO/kg-U prod. | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conversion | kg CO/kg-U prod. | 0.07 | 0 | 0 | 0 | 0 | 0 | 0 |
| Enrichment to 4% | kg CO/kg-U prod. | 0.04 | 0.09 | 0.08 | 0.08 | 0.06 | 0.05 | 0.04 |
| Subtotal | kg CO/kg-U prod. | 0.17 | 0.09 | 0.08 | 0.08 | 0.06 | 0.05 | 0.04 |
| *Mass Impacts of U.S. Depleted Uranium Inventory* | | | | | | | | |
| Total tonnes refeed | tonnes | | 91,518 | 2,799 | 32,854 | 94,886 | 506 | 2,931 |
| Total tonnes U | | | | | | | | |
| Product Output (4% U) | tonnes | 7,594 | 1,204 | 52 | 821 | 5,119 | 47 | 351 |
| Total energy required | GJ(th)[a] | 1,799,846 | 578,730 | 23,606 | 355,056 | 1,780,412 | 12,874 | 83,937 |
| Total $CO_2$ emitted | tonnes[a] | 7,795,922 | 936,516 | 38,199 | 574,561 | 2,881,111 | 20,833 | 135,829 |
| Total $SO_x$ emitted | tonnes[a] | 100,492 | 8,460 | 345 | 5,190 | 26,027 | 188 | 1,227 |
| Total $NO_x$ emitted | tonnes[a] | 14,614 | 1,226 | 50 | 752 | 3,773 | 27 | 178 |
| Total CO emitted | tonnes[a] | 1,266 | 103 | 4 | 63 | 316 | 2 | 15 |
| Mass of refeed waste | tonnes[a] | | 90,313 | 2,748 | 32,033 | 89,767 | 460 | 2,580 |

[a] Quantity per total product output.

# APPENDIX C: CENTRIFUGE ENRICHMENT DATA

## APPENDIX C: CENTRIFUGE ENRICHMENT DATA

The method used to enrich uranium for both the fresh feed and refeed options will alter the conclusions that can be drawn. The next generation of gas centrifuge enrichment plants are expected to require nearly 60 times less energy per SWU to enrich uranium than the current gaseous diffusion plants. Gaseous diffusion enrichment currently requires 3,000 kWh/SWU (Hertzler and Nishimoto 1994), while gas centrifuges are expected to require 50 kWh/SWU (Miller 1996). A reduction in enrichment energy requirements of this magnitude greatly favors the refeed option.

The fresh feed option requires 5-6 times more energy to produce the same amount of uranium product as the refeed option. The energy requirements for the fresh feed and refeed options are decreased by 85% and 98% respectively by using gas centrifuge technology (see Table C.1 and Figure C.1 for the energy requirements of the gas centrifuge and Table 4 for the comparative data for gaseous diffusion).

If one uses the centrifuge enrichment process on the depleted $UF_6$ at Paducah and Portsmouth, the air emissions are considerably less than those produced from the fresh feed option. The air emissions associated with mining, milling, converting, and enriching natural U more than double those of the refeed option when the electricity is produced by coal. The difference is considerably greater when the electricity is produced by using nuclear power.

Although the source of fuel for the electricity supply, coal or nuclear fission, affects the quantity of pollutants, in either subscenario the refeed option produces considerably fewer emissions of $CO_2$, $SO_x$, $NO_x$, and CO than the fresh feed option. Tables C.2-C.5 compare the emissions of $CO_2$, $SO_x$, $NO_x$, and CO for the two options using centrifuge enrichment and correspond with Tables 5-8 for the gaseous diffusion process. Figure C.2 compares the $CO_2$ emissions of the fresh feed and refeed options using the gas centrifuge process. Tables C.6 and C.7 list the impacts of the three centrifuge enrichment scenarios using all-coal- and all-nuclear-generated electricity, respectively.

**REFERENCES**

Hertzler, T.J., and D.D. Nishimoto, "Depleted Uranium Management Alternatives," Idaho National Engineering Laboratory, EGG-MS-11416 (August 1994).

Miller, D., URENCO, private communication, November 15, 1996.

**TABLE C.1 Energy Requirements for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory: All Electricity from Coal**

| | | Energy Required [GJ(th)] | |
|---|---|---|---|
| Enrichment | Product (Tonnes - Enriched U) | Fresh Feed (assuming 0.2% tails) | Depleted Uranium >0.24% (assuming 0.2% tails) |
| 2% | 16,032 | 190,411 | 32,182 |
| 3% | 10,306 | 194,720 | 36,491 |
| 4% | 7,594 | 197,205 | 38,976 |

**TABLE C.2 $CO_2$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory**

| | $CO_2$ Emissions (tonnes) | |
|---|---|---|
| Enrichment | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 13,345,457 | 3,350,772 |
| 3% | 9,640,027 | 3,799,426 |
| 4% | 7,931,038 | 4,058,160 |
| *100% Nuclear* | | |
| 2% | 10,712,263 | 63,124 |
| 3% | 6,906,439 | 71,577 |
| 4% | 5,104,551 | 76,451 |

Figure C.1 Energy Requirements for the Fresh Feed and Refeed Options Using Gas Centrifuge Enrichment (In all cases, the energy required to enrich the tails at Paducah and Portsmouth is lower than mining, milling, converting, and enriching natural U)

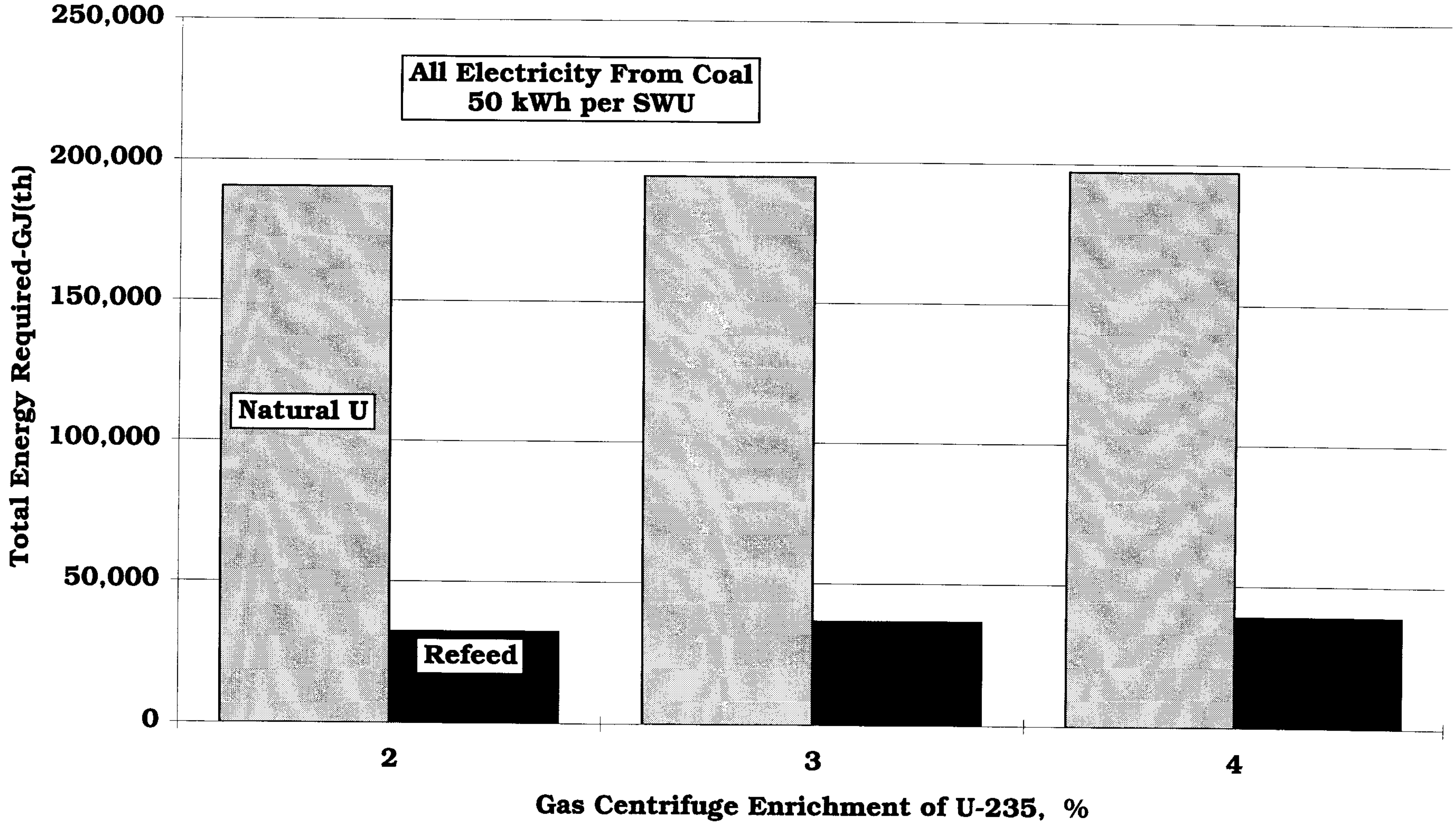


Figure C.2 The $CO_2$ Emissions Produced in Enriching the Tails at Paducah and Portsmouth are Considerably Less Than Those Produced from Mining, Milling, Converting, and Enriching Natural U by Gas Centrifuge Enrichment

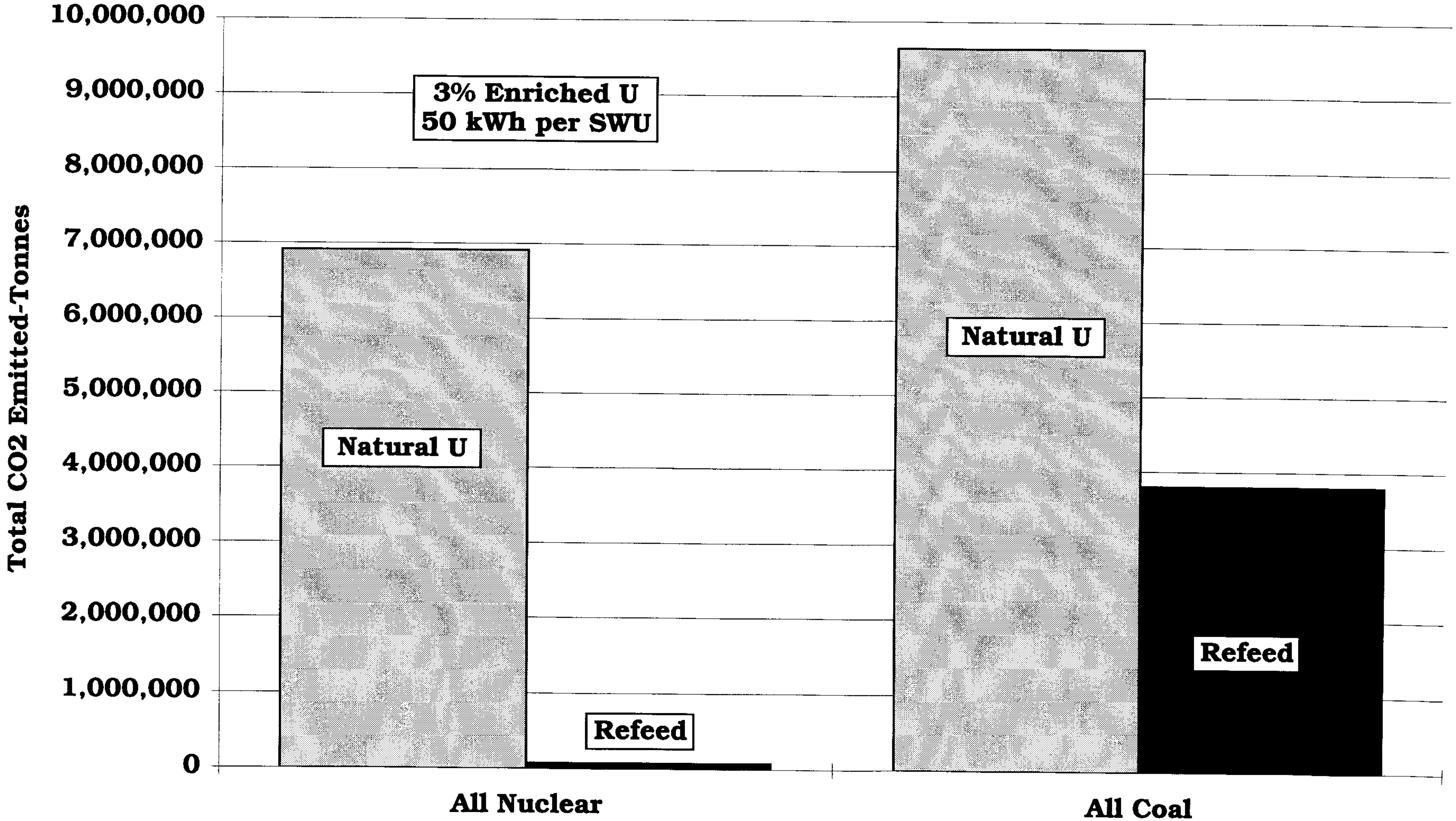


**TABLE C.3 $SO_x$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory**

| | $SO_x$ Emissions (tonnes) | |
|---|---|---|
| Enrichment | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 180,877 | 26,331 |
| 3% | 124,614 | 29,857 |
| 4% | 98,326 | 31,890 |
| *100% Nuclear* | | |
| 2% | 160,244 | 570 |
| 3% | 103,195 | 647 |
| 4% | 76,179 | 691 |

**TABLE C.4 $NO_x$ Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory**

| | $NO_x$ Emissions (tonnes) | |
|---|---|---|
| Enrichment | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 30,762 | 9,362 |
| 3% | 22,739 | 10,616 |
| 4% | 19,068 | 11,339 |
| *100% Nuclear* | | |
| 2% | 23,329 | 83 |
| 3% | 15,023 | 94 |
| 4% | 11,090 | 100 |

**TABLE C.5 CO Emissions for Centrifuge Enrichment Scenarios Involving the Depleted Uranium Inventory**

| | CO Emissions (tonnes) | |
|---|---|---|
| Enrichment | Fresh Feed | Refeed |
| *100% Coal* | | |
| 2% | 2,730 | 866 |
| 3% | 2,029 | 983 |
| 4% | 1,709 | 1,049 |
| *100% Nuclear* | | |
| 2% | 2,041 | 7 |
| 3% | 1,314 | 8 |
| 4% | 970 | 8 |

**TABLE C.6 Effect of Using 100% Coal-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options (Gas Centrifuge Enrichment)**

| | 2% enrichment | | 3% enrichment | | 4% enrichment | |
|---|---|---|---|---|---|---|
| Quantity per Total Product Output | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] |
| Total depleted uranium feed (tonnes) | — | 225,494 | — | 225,494 | — | 225,494 |
| Product output (tonnes) | 16,032 | 16,032 | 10,306 | 10,306 | 7,594 | 7,594 |
| Total energy required [GJ(th)] | 190,411 | 32,182 | 194,720 | 36,491 | 197,205 | 38,976 |
| Total $CO_2$ emitted (tonnes) | 13,345,457 | 3,350,772 | 9,640,027 | 3,799,426 | 7,931,038 | 4,058,160 |
| Total $SO_x$ emitted (tonnes) | 180,877 | 26,331 | 124,614 | 29,857 | 98,326 | 31,890 |
| Total $NO_x$ emitted (tonnes) | 30,762 | 9,362 | 22,739 | 10,616 | 19,068 | 11,339 |
| Total CO emitted (tonnes) | 2,730 | 866 | 2,029 | 983 | 1,709 | 1,049 |
| Mass of refeed waste (tonnes) | — | 209,463 | — | 215,188 | — | 217,900 |
| Depleted uranium mass reduction (tonnes) | — | 16,032 | — | 10,306 | — | 7,594 |
| Reduction in number of 14-ton cylinders | — | 1,943 | — | 1,249 | — | 921 |
| Electrical energy potential from product [GW(e)-yr] | — | 580 | — | 466 | — | 412 |

[a] Depleted uranium in inventory at Paducah, Ky., and Portsmouth, Ohio.

**TABLE C.7 Effect of Using 100% Nuclear-Generated Electricity on the Energy Requirements and the Environment for the Fresh Feed and Refeed Options (Gas Centrifuge Enrichment)**

| | 2% enrichment | | 3% enrichment | | 4% enrichment | |
|---|---|---|---|---|---|---|
| Quantity per Total Product Output | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] | Fresh Feed | Refeed[a] |
| Total depleted uranium feed (tonnes) | — | 225,494 | — | 225,494 | — | 225,494 |
| Product output (tonnes) | 16,032 | 16,032 | 10,306 | 10,306 | 7,594 | 7,594 |
| Total energy required [GJ(th)] | 200,595 | 39,008 | 205,818 | 44,231 | 208,830 | 47,244 |
| Total $CO_2$ emitted (tonnes) | 10,712,263 | 63,124 | 6,906,439 | 71,577 | 5,104,551 | 76,451 |
| Total $SO_x$ emitted (tonnes) | 160,244 | 570 | 103,195 | 647 | 76,179 | 691 |
| Total $NO_x$ emitted (tonnes) | 23,329 | 83 | 15,023 | 94 | 11,090 | 100 |
| Total CO emitted (tonnes) | 2,041 | 7 | 1,314 | 8 | 970 | 8 |
| Mass of refeed waste (tonnes) | — | 209,463 | — | 215,188 | — | 217,900 |
| Depleted uranium mass reduction (tonnes) | — | 16,032 | — | 10,306 | — | 7,594 |
| Reduction in number of 14-ton cylinders | — | 1,943 | — | 1,249 | — | 921 |
| Electrical energy potential from product [GW(e)-yr] | — | 580 | — | 466 | — | 412 |

[a] Depleted uranium in inventory at Paducah, Ky., and Portsmouth, Ohio.