PNNL-31722

Recommendations for an Applicant to Calculate Activity Data for Greenhouse Gases Estimates

September 2024

Saikat Ghosh

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Contract DE-AC05-76RL01830
Interagency Agreement: 31310019N0001
Task Order Number: 3131002F0009

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Pacific Northwest National Laboratory
Richland, Washington 99354

Acronyms and Abbreviations

CFR	*Code of Federal Regulations*
CO	carbon monoxide
CO_2	carbon dioxide
CO_2(e)	CO_2 equivalent
EF	emission factor
EPA	Environmental Protection Agency
g/hp-hr	gram(s) per horsepower-hour
GHG	greenhouse gas
g/T-mi	gram(s) of pollutant per ton-mile
hp	horsepower(s)
hp-hr	horsepower-hour(s), unit of energy
kW	kilowatt(s)
kWh	kilowatt-hour(s)
lb/MWh	pound(s) per megawatt-hour
LWR	light-water reactor
mi	miles
MT	metric ton(s)
MW	megawatt(s)
MWe	megawatt(s) electrical
MWh	megawatt-hour(s), unit of energy
N	number of engines
NRC	U.S. Nuclear Regulatory Commission
NR GEIS	Generic Environmental Impact Statement for Licensing of New Nuclear Reactors
PPE	plant parameter envelope
SAFSTOR	safe storage
scf	standard cubic foot/feet
SWU	separative work unit
UniStar	UniStar Nuclear Services, LLC
VMT	vehicle mile(s) traveled

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1.0 Introduction

In 2009, the U.S. Nuclear Regulatory Commission (NRC) directed the NRC staff to address climate change issues and consider the impacts of the emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in its environmental reviews for major licensing actions (NRC 2009b). To implement this direction from the Commission, the staff issued guidance in 2011 and updated guidance in 2014 in Attachment 1 to Interim Staff Guidance COL/ESP-ISG-026 (NRC 2011; NRC 2014). This guidance provides a simpler method than the method described in RG 4.2 Rev. 3, that an applicant can use to meet the plant parameter envelope (PPE) value from the Generic Environmental Impact Statement for Licensing of New Nuclear Reactors (NR GEIS). NRC staff estimated the 97-year lifecycle GHG emissions from a reference 1000 megawatt electrical (MWe) light-water reactor (LWR) for various activities associated with construction, operation (including uranium fuel cycle), and decommissioning of nuclear power plants and presented the results in Appendix H of the NR GEIS. Appendix H of the NR GEIS includes estimates of direct emissions from construction equipment and emergency diesel engines in a nuclear facility and indirect emissions from workforce vehicular traffic, fuel transportation and the uranium fuel cycle.

The NR GEIS Section 3.3 extended the estimates in Appendix H for the installation of two 1000 MWe nuclear reactors on the same site. Scaling factors were used to extrapolate the GHG emissions of a reference 1000 MWe reactor to a two-unit nuclear reactor plant (each reactor unit generating 1000 MWe). GHG emission estimates for building, operation, decommissioning and safe storage (SAFSTOR)[1] for a two-unit nuclear reactor plant would be based on the plant's physical size, and therefore estimates for these source categories were assumed to be twice the value of the reference 1000 MWe reactor. However, GHG emissions from the fuel cycle (including fuel transportation) were scaled upward by a factor of 3, based on plant efficiencies greater than the 80 percent assumption in Appendix H. Table 1 below shows the PPE emissions for two 1000 MWe nuclear reactors as provided in NR GEIS. The total GHG emissions for two 1000 MWe reactors were calculated as 2,534,000 metric tons (MT) of CO_2 equivalent (CO_2(e)) based on a 97 year GHG life cycle period. The GHG emissions lifetime of 97 years for a reference nuclear reactor includes a 7-year building phase, 40 years of operation, 10 years of active decommissioning, and 40 years of SAFSTOR operations (NRC 2024). Construction equipment and vehicular traffic from workers commute would contribute to the GHG emissions during a 7-year building phase. Uranium fuel cycle, vehicular traffic, fuel and waste transportation, and testing of standby diesel generators would contribute to GHG emissions during the 40-year operations phase. While NRC's regulations allow up to 60 years of reactor facility decommissioning, Appendix H estimated that most of the GHGs would occur over an estimated 10-year period during which to the licensee would engage in significant demolition and earth-moving activities, as discussed in Supplement 1 to NUREG-0586 (NRC 2002). Vehicular traffic by the workforce during a 40-year SAFSTOR period would additionally contribute GHG emissions. The carbon footprint for a 40-year SAFSTOR period was separately analyzed from the decommissioning activities as provided in Table YYYY-2 of the staff issued guidance in 2011 (NRC 2011).

[1] A type of decommissioning in which the facility is placed in a safe, stable condition and maintained in that state (safe storage) until it is subsequently decontaminated and dismantled to levels that permit license termination. Radioactive decay occurs during the SAFSTOR period, thus reducing the quantity of contaminated and radioactive material (NRC 2002).

Table 1. Plant Parameter Envelope Values for Green House Gas Emissions as Provided in Generic Environmental Impact Statement for Licensing of New Nuclear Reactors

Life Cycle Phase	Process categories	Activity Duration (years)	Based on 1000 MWe Reactor Emissions (MT CO_2(e))	Based on Two 1000 MWe nuclear reactors Scaling Factor	Based on Two 1000 MWe nuclear reactors Emissions (MT CO_2(e))
Construction	Equipment	7	39,000	2	78,000
	Workforce Traffic		43,000	2	86,000
Plant Operations	Diesel engines	40	181,000	2	362,000
	Workforce Traffic		136,000	2	272,000
Uranium Fuel Cycle	Fuel Enrichment	40	540,000	3	1,620,000
Fuel and Waste Transportation	Truck Traffic	40	14,000	3	42,000
Decommissioning	Equipment	10	19,000	2	38,000
	Workforce Traffic		8000	2	16,000
SAFSTOR	Workforce Traffic	40	10,000	2	20,000
Total	**-**	-	990,000	**-**	**2,534,000**

CO_2(e) = CO_2 equivalent; MT = metric ton(s); MWe = megawatt(s) electrical; SAFSTOR = safe storage.

Figure 1 provides a visualization of the GHG emissions breakdown by different categories for two 1000 MWe nuclear reactors. The bulk of the emissions are contributed by the uranium fuel cycle and plant operations. Therefore, it is recommended that an applicant provide the best available data for these two source categories to demonstrate the GHG emissions from the proposed site.

An applicant is required to demonstrate that the total 97-year GHG lifecycle emissions from the new reactor would be equal to or less than the PPE value from the NR GEIS for a 1,000 MWe LWR of 2,534,000 MT CO_2(e). Regulatory Guide 4.2, "Preparation of Environmental Reports for Nuclear Power Stations," Revision 3 (RG 4.2) provides the methods that an applicant can use to estimate its GHG emissions for various activities. The NR GEIS relied upon a method described in the RG 4.2 Revision 3 and in Interim Staff Guidance COL/ESP-ISG-026, "Environmental Issues Associated with New Reactors" (NRC 2018, NRC 2014). As an alternative to the method in RG 4.2 Revision 3, a simpler method is provided in this document that an applicant can use to meet the PPE value from the NR GEIS without the need for a detailed GHG emissions estimation.

This document provides an approximate account of the activity data that were used for the generation of the GHG estimates in Appendix H of the NR GEIS. The activity data were retrieved for a 1000 MWe reference reactor from data sources in Appendix H and then extrapolated for two 1000 MWe nuclear reactors using the same scaling factors for the relevant source categories. An applicant can determine if its proposed activity for relevant source categories in Table 1 is equal to or lower than the corresponding activity data for two 1000 MWe nuclear reactors as provided in Section 2.0 of this report.

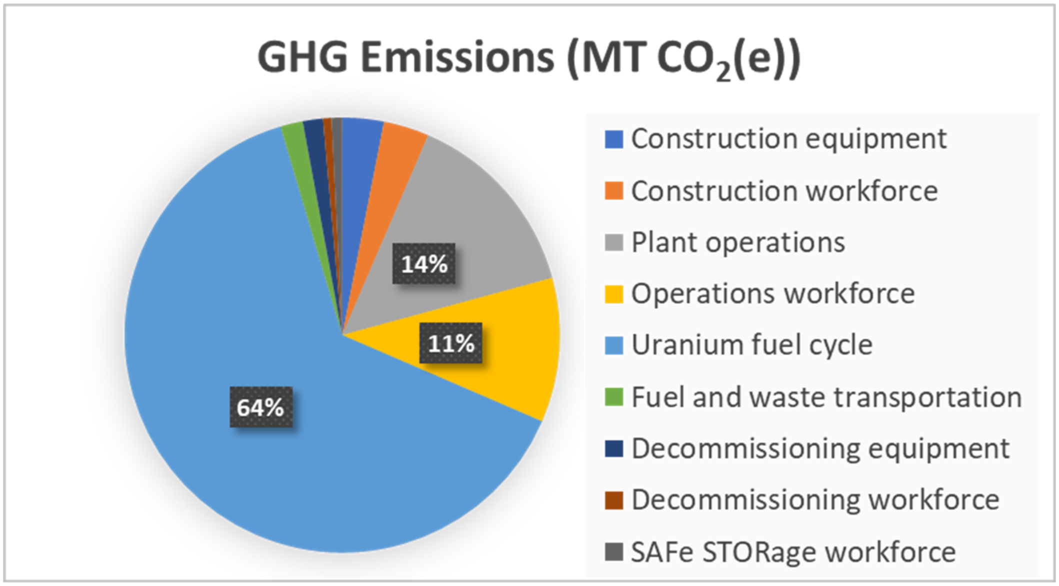

Figure 1. Percentage Distribution of Total Green House Gas Emissions for Two 1000 MWe Nuclear Reactors.

2.0 Activity Data Plant Parameter Envelope

Table 2 summarizes the activity data based on GHG emissions from construction, operation, and decommissioning two 1000 MWe reactors. An applicant can use these values as upper bounding PPE values to meet the PPE emissions target of 2,534,000 MT of CO_2(e) in Table 1.

Table 2. Upper Bounding Activity Data Based on Two 1000 MWe Nuclear Reactors for an Applicant to Demonstrate Its Total Lifecycle Green House Gas Emissions Equal to or Below 2534,000 MT CO_2(e)

Life cycle phase	Process categories	Activity PPE	Activity Unit Based on Two 1000 MWe Nuclear Reactors
Construction	Equipment	281,800	MWh total energy output
	Workforce Traffic	2,000	Onsite staff driving 40 mi per day
Plant Operations	Generators	560,000	MWh total energy output
	Workforce Traffic	1,100	Onsite staff driving 40 mi per day
Uranium Fuel Cycle	Ore milling and fuel enrichment	25	Million SWUs
Fuel and Waste Transportation	Truck Shipments	350	Truck shipments per year with one-way distance of 1000 mi
		700,000	VMT per year (round trip)
Decommissioning	Equipment	140,000	MWh total energy output
	Workforce Traffic	400	Onsite staff driving 40 mi per day
SAFSTOR	Workforce Traffic	80	Onsite staff driving 40 mi per day

MWe = megawatt(s) electrical; mi = mile(s); MWh = megawatt(s)-hour; PPE = plant parameter envelope; SAFSTOR = safe storage; SWU = separative work unit; VMT = vehicle mile(s) traveled.

3.0 Methodology

3.1 Uranium Fuel Cycle

The uranium fuel cycle starts with uranium ore mining and uranium milling. In the United States, most uranium is extracted through the in-situ recovery process, where uranium is removed from the underground deposits, brought to the surface, and then further processed. The uranium is eventually processed into yellowcake (U_3O_8) (NRC 2009a). Thereafter, the yellowcake is converted to UF_6 and enriched (e.g., increase the isotopic concentration of U-235 to 5 percent) in an enrichment plant using a gas centrifuge process. It is further converted into nuclear fuel in a fabrication facility by mechanically and chemically converting the UF_6 gas to UO_2 powder. The powder is further processed into fuel rods and transported to a reactor. After use in the nuclear reactor, the spent fuel is put into long-term storage, typically by first being placed into a spent fuel pool for several years until, after several years of cooling, the spent fuel can be loaded into passively cooled NRC-certified “dry” storage casks and appropriately placed within an independent spent fuel storage facility.

The NRC’s Table S-3, which is codified in Title 10 *Code of Federal Regulations* (CFR) Section 51.51(b) assumes that approximately 135,000,000 standard cubic feet (scf) of natural gas is required per year to generate process heat for certain portions of the uranium fuel cycle. Natural gas is burned to supply process and building heat during various stages of the uranium fuel cycle including milling, UF_6 conversion, and fuel fabrication facilities (AEC 1974, NRC 1976). Significant amounts of CO_2 can be emitted from such natural gas combustion in the uranium fuel cycle. Table S-3 assumptions are based on a 1000 MWe LWR nuclear power plant operating at 80 percent capacity. The reference 1000 MWe LWR would require about 5 million separative work units (SWUs)[2] to generate fresh fuel (3.2 percent U-235) from about 11,640 MT natural uranium over the lifetime of 40 years (AEC 1974). Appendix H calculated 7440 MT CO_2(e) emissions per year based on natural gas consumption data from Table S-3 and a conversion factor of 0.551 MT CO_2 per thousand scf of natural gas combustion. For a 40-year operational life of a 1000 MWe LWR, this is 298,000 MT of CO_2(e).

Additionally, a large amount of electrical energy is consumed by the centrifuge plants to enrich the raw uranium fuel. Appendix H calculated the amount of enriched fuel and SWUs needed to enrich the fuel in a centrifuge based on the fuel burnup in a 1000 MWe power plant with 95 percent capacity and 35 percent thermal efficiency. More details about these calculations and assumptions are provided in Napier (2020). Appendix H shows the total uranium fuel of 1043 MT of 5 percent U-235 required in a 1000 MWe nuclear reactor during the operational period of 40 years. To produce 1 ton of 5 percent enriched uranium with 0.25 percent U-235 in the depleted uranium stream requires extraction of 10.3 tons of natural uranium and 7,923 SWUs. Thus, 1043 MT of enriched uranium would require about 8.26 million SWUs and 10,743 MT of natural uranium. Because a centrifuge enrichment facility requires about 50 kilowatt hours (kWh) per SWU, a total of 413,200 megawatt-hour (MWh) is needed to produce 40 years’ worth of uranium enriched to 5 percent U-235 for fuel for the lifetime operation of the plant. For the existing centrifuge enrichment plant in the United States, the regional average CO_2 emission factor is 1,248 pound(s) per megawatt-hour (lb/MWh), and the total CO_2 emission is about 243,000 MT. The CO_2 emissions from the centrifuge facility may increase up to 824,000 MT for generating 20% enriched uranium for a 1000 MWe reactor.

[2] SWU is the amount of energy required in the enrichment process to separate the U-235 and U-238 in the feed assay.

Thus, Appendix H of the NR GEIS calculates the total GHG emissions as 540,000 MT CO_2(e) from electricity consumption by a gas centrifuge for fuel enrichment and natural gas combustion for generating process heat. These uranium fuel cycle GHG emissions from a reference 1000 MWe reactor can be extrapolated to 1,620,000 MT CO_2(e) for two 1000 MWe reactors using a scaling factor of 3. The scaling factor is based on plant efficiencies greater than the 80 percent assumption for the LWR in Appendix H of the NR GEIS. It is to be noted though that the enrichment process (indirect emissions from electricity consumption) already accounted for 95 percent efficiency. Nevertheless, a scaling factor of 3 would provide a conservative bounding value for GHG emissions from the uranium fuel cycle.

Based on the above assumptions, two 1000 MWe nuclear reactors would require 3129 MT of enriched uranium fuel over the lifetime of 40 years based on a scaling factor of 3. About 24.8 million SWUs would be required to generate 3129 MT of 5 percent enriched uranium. Thus, the expected SWUs for an applicant's project should be equal to or less than 24.8 million SWUs to meet the GHG target in the NR GEIS. This target quantity of SWUs is a conservative estimate for both indirect centrifuge plant emissions and natural gas combustion for process heat. The natural gas combustion-related CO_2 emissions are based on a 1000 MWe LWR in Table S-3 that had a lower number of SWUs.

An applicant can calculate the SWU requirements based on its proposed fuel burnup, capacity, and annual fuel requirement (amount of enriched uranium fuel) as shown above. An applicant can determine its SWUs and natural uranium requirements using an SWU calculator (e.g., https://www.uxc.com/p/tools/FuelCalculator.aspx).

3.2 Construction

GHGs (primarily CO_2) can be directly emitted from various diesel engines operated for construction activities such as dewatering and earthwork, batch plant, concrete, rigging, shop fabrication, warehouse, and equipment maintenance. Indirect GHG emissions can be attributed to vehicular traffic due to the onsite workforce. These two source categories have a different set of methods to calculate GHG emissions as outlined in Appendix H of the NR GEIS.

3.2.1 Equipment

Construction activities typically generate GHG emissions from the use of off-road vehicles that are fueled with diesel or gasoline. Appendix H of the NR GEIS calculated the GHG emissions from various construction activities based on carbon monoxide (CO) emissions provided by UniStar Nuclear Services, LLC (UniStar) in their application for a 1000 MWe power plant (UniStar 2007). The CO emissions from all these activities were converted to CO_2 emissions with a scaling factor of 172 tons of CO_2 per ton of CO. UniStar compiled emission factors from various data sources including the U.S. Environmental Protection Agency's (EPA's) NONROAD model. The emission factors for nonroad compression engines are generally based on the rated horsepower (hp) and the model year. Depending on the model year, EPA provides emission factors under five regulations that establish up to four tiers of federal nonroad emission standards[3] (EPA 2018). UniStar compiled a detailed level of activity data for various off-road diesel engines during the proposed 7 years of construction.

[3] 40 CFR Part 89 provides Tier 1, 2, and 3 exhaust emission standards and 40 CFR Part 1039 provides Tier 4 emission standards.

Appendix H calculated the total GHG emissions (primarily CO_2) as 39,000 MT of CO_2(e) during 7 years of construction of a 1000 MWe power plant. This was scaled to 78,000 MT CO_2(e) for the construction of two 1000 MWe reactors based on a scaling factor of 2.

A simplified activity data of 281,800 MWh was back-calculated using CO_2 emission factor (EF) (=172*1.2 gram per horsepower-hour [g/hp-hr]) for a 175-300 hp compression engine that would generate 78,000 MT CO_2(e) emissions. An applicant can compute the total energy output based on the number of engines (N) used in construction and combined yearly hours of use as shown below:

$$Total\ Energy\ (MWh) = \sum_{N} \frac{Horsepower\ (hp) \times Total\ No.of\ hours\ of\ operation\ (h)}{1341\ {}^{hp}/_{MW}} \quad (1)$$

The total number of operating hours is equal to the product of hours per year and duration of activity in years. The total energy consumption (MWh) is equivalent to the sum of energy consumption for all N engines at a site.

These calculations assume the EF for 150-300 hp diesel engines. If an applicant has gasoline engines, this value would be still conservative since EF for gasoline engines are much lower than those for diesel engines. Similarly, diesel engines with higher power capacity (>300 hp) would also have lower emissions. More activity of lower capacity engines (Tier 1) would have higher emissions. An applicant should describe assumptions used while demonstrating their activity data to meet the GHG PPE values in Table 2.

For example, the same amount of GHG emissions (78,000 MT) would be generated by using 200 diesel engines with 300 hp, each operating for 900 hours per year over the construction period of 7 years.

3.2.2 Vehicular Traffic from Workforce

Vehicular traffic emissions occur during the commute of the workforce to and from onsite construction sites. The total GHG emissions in Appendix H of the NR GEIS were computed as 43,000 MT of CO_2(e) by combining the number of round trips (=1000), average commute distance, days per year of commute, duration of construction, vehicle fuel efficiency, and CO_2 emissions (MT) per gallon. This method assumed 365 days per year of commuting, the fuel efficiency of 21.6 mpg, and the CO_2 EF of 0.0089 MT per gallon of fuel. More detailed calculations and assumptions are provided in Chapman et al. (2012).

Vehicle miles traveled (VMT) is a general traffic indicator that can also be used as a bounding value for such estimates. It can be calculated as follows:

$$VMT\ per\ day = \frac{Trips}{day} \times \frac{distance\ (miles)}{trip} \quad (2)$$

CO_2 emissions were then calculated from the VMT estimate:

$$CO_2\ Emissions = \frac{VMT}{day} \times \frac{commuting\ days}{year} \times duration(years) \times vehicle\ fuel\ efficiency\ \frac{miles}{gallon} \times \frac{CO2\ EF}{gallon} \quad (3)$$

The number of trips per day can be assumed to be equal to the number of onsite staff assuming that each workforce staff drives one car to work (no carpooling). Thus, 2000 onsite staff driving for 40 miles (mi) per day over 7 years would generate the same amount of GHG emissions for construction activity of two nuclear reactors, i.e., 86,000 MT of CO_2(e). Thus, a volume of 80,000 VMT per day over the period of 7 years would also generate the same GHG emissions.

3.3 Plant Operations

Similar to construction activities, CO_2 can be directly emitted from operations of standby and emergency diesel generators and indirectly emitted from vehicular traffic.

3.3.1 Diesel Fired Generators

Appendix H of the NR GEIS shows the CO_2 emission calculations based on CO emissions from four emergency generators (10130 kilowatts [kW]) operated for a total of 600 hours per year and two station blackout generators (5000 kW) operated for 200 hours per year as provided in the UniStar application (UniStar 2007). The total emissions were calculated as 181,000 MT of CO_2(e) for a 1000 MWe power plant using a conversion factor of 172 tons of CO_2 per ton of CO emissions. This value was scaled to 362,000 MT of CO_2(e) for two 1000 MWe nuclear reactors.

The combined activity was 280,000 MWh energy output during 40 years of operations of the emergency generators for a 1000 megawatts (MWs) reactor. This output can be scaled to 560,000 MWh energy output for two 1000 MW nuclear reactors. For example, five diesel generators with 10,000 kW heat input operating for 40 years with 280 hours per year would generate the same emissions of 362,000 MT of CO_2(e). An applicant may calculate the total activity of N diesel generators for operations using Equation 3 above.

3.3.2 Vehicular Traffic from Workforce

Vehicular traffic emissions for operations were computed in Appendix H of the NR GEIS in a manner similar to construction activities. A workforce of 550 onsite staff was used to compute the total emissions during 40 years of operations with the same fuel efficiency and CO_2 EF. Thus, this value can be scaled to 1100 onsite workforce staff driving 40 mi per day over 40 years for two 1000 MW nuclear reactors. A volume of 44,000 VMT per day over 40 years would also generate the same GHG emissions of 272,000 MT CO_2(e).

3.4 Fuel and Waste Transportation

Appendix H of the NR GEIS computed CO_2 emissions from fuel and waste transport by truck and rail shipments to and from a LWR using survey data in Table S-5 of Supplement 1 to WASH-1238 (AEC 1972). The CO_2 emissions were calculated using a CO_2 EF of 64.7 grams of pollutant per ton-mile (g/T-mi) for trucks and 32.2 g/T-mi for rail shipments. The transportation package's weight was assumed as 23 MT and 100 MT for truck and rail shipments respectively. These data were based on an 1100 MWe model LWR in WASH-1248. The total VMT per year equals 155,000 mi of rail shipments and 20,000 mi of rail shipments including the return of empty packages for fresh and spent fuel (two-way trips). The total emissions for a model 1100 MWe reactor in Appendix H of the NR GEIS was 14000 MT CO_2(e) from both truck and rail shipments using the CO_2 EF for trucks and rail. It is assumed that all the radioactive waste transport is by rail for CO_2 emission calculations.

These emissions can be extrapolated to 42,000 MT CO_2(e) for two 1000 MWe nuclear reactors based on the scaling factor of 3. The total VMT can be back-calculated to be 700,000 mi per year from these emissions for two 1000 MW reactors assuming all the shipments are transported by trucks. If rail transport is used for shipments, the total VMT should be significantly less than this target value since emissions are higher from rail shipments.

An applicant may calculate the total VMT for truck shipments for N fuel and waste shipments using the following equation:

$$Total\ Vehicle\ Miles\ Travelled\ (VMT) = \sum_{N} Number\ of\ Shipments\ per\ year\ (truck) \times Typical\ one-way\ distance\ (miles) \times 2 \times No.of\ operating\ years \quad (4)$$

Alternatively, 350 truck shipments per year with an average one-way distance of 1000 mi would result in the same emissions of 42,000 MT CO_2(e).

3.5 Decommissioning

3.5.1 Equipment

Appendix H of the NR GEIS assumes that the emissions and related activity for decommissioning would be one-half (a factor of 0.5) of those for construction activities. Thus, the total energy consumption (MWh) for the decommissioning equipment in Table 2 was calculated as one-half of that for construction, i.e., 140,000 MWh, resulting in 38,000 MT of CO_2(e) for two 1000 MWe nuclear reactors.

An applicant can make the same assumption that emissions would be one-half those of their construction activities. If the applicant has more detailed data, then they can use the above equation 3 to compute the total power consumption (MWh) for all equipment utilizing their horsepower output and number of operating hours.

3.5.2 Vehicular Traffic from Workforce

Appendix H of the NR GEIS computed CO_2 emissions for a 1000 MWe power plant based on 200 round trips per day, 40 mi per trip, 250 days of work in a year, and 10 years of decommissioning activities. The total VMT is equal to 8000 mi per day for 200 onsite staff. This could be extrapolated to 16000 mi per day contributed by 400 onsite staff to generate 16,000 MT of CO_2(e) for two 1000 MWe nuclear reactors.

3.6 SAFSTOR Workforce Vehicular Traffic

Appendix H of the NR GEIS computed the vehicular traffic emissions of 10,000 MT of CO_2(e) for a 1000 MWe reference reactor based on 40 onsite employees during 40 years of SAFSTOR activities. This can be extrapolated to 80 onsite staff driving 40 mi per day for 365 days per year over 40 years for two 1000 MWe nuclear reactors. The total VMT per day would be 3200 mi per day.

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