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K/ETO-112

Enrichment Technical Operations

LONG-RANGE GLOBAL WARMING IMPACT
OF GASEOUS DIFFUSION PLANT OPERATION

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TABLE OF CONTENTS

TABLE OF CONTENTS	iii
ABSTRACT	v
INTRODUCTION	1
MODEL DESCRIPTION	3
RESULTS AND DISCUSSION	11
CONCLUSIONS	37
ACKNOWLEDGEMENTS	39
BIBLIOGRAPHY	40

ABSTRACT

The DOE gaseous diffusion plant complex makes extensive use of CFC-114 as a primary coolant. As this material is on the Montreal Protocol list of materials scheduled for production curtailment, a substitute must be found. In addition to physical cooling properties, the gaseous diffusion application imposes the unique requirement of chemical inertness to fluorinating agents. This has narrowed the selection of a near-term substitute to two fully fluorinated material, FC-318 and FC-3110, which are likely to be strong, long-lived greenhouse gases. In this document, calculations are presented showing, for a number of plausible scenarios of diffusion plant operation and coolant replacement strategy, the future course of coolant use, greenhouse gas emissions (including coolant and power-related indirect CO₂ emissions), and the consequent global temperature impacts of these scenarios.

INTRODUCTION

Evidence supporting the theory that chlorofluorocarbons (CFCs) contribute to reduction of ozone in the stratosphere has prompted a significant national and international response over the last several years, most notably the September 1987 signing of the Montreal Protocol¹ and its adoption the following year by the major CFC producing and consuming nations of the world. More recently, this phase-out schedule has been accelerated. The planned reduction in production of CFCs in turn has significant implications for the operation of the Department of Energy's gaseous diffusion plant (GDP) uranium enrichment complex in the United States, since one of the regulated materials, CFC-114, is the primary coolant for the gaseous diffusion plants.

The CFC manufacturers were, even prior to the regulation of these substances, developing substitutes for the restricted materials in widest use. Most such potential substitutes are compounds termed HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons). These compound classes are chemically similar to CFCs or PFCs (perfluorocarbons, i.e. fully fluorinated hydrocarbons), but differ in that they contain one or more hydrogen atoms in place of halogens. The addition of hydrogen makes these compounds susceptible to reaction with hydroxyl radicals in the lower atmosphere, thus leading to their earlier removal, shorter atmospheric lifetime, and diminished ozone depletion and global warming potential relative to CFCs.

Unfortunately, the gaseous diffusion complex imposes requirements on its coolant that are not generally found in commercial cooling applications. Most notable is that the coolant must possess a reasonable degree of chemical compatibility with UF_6 . One of the compatibility issues that must be addressed in choosing a replacement coolant is the effect of coolant inleakage into the UF_6 stream in the cascade. UF_6 is a fairly potent fluorinating agent, so the possibility of rapid, exothermic, gas-phase or gas-surface reactions of UF_6 and a substitute coolant must be considered. In addition, gaseous diffusion equipment is routinely subject to off-line chemical cleanup treatments with other fluorinating agents, such as F_2 and ClF_3 , so the reactivity of residual coolant with these materials must also be minimal.

Because of this unique reactivity requirement, Martin Marietta Energy Systems, which operates the two US DOE diffusion plants, has initiated contacts with potential producers of substitute coolants. Candidate materials which could be produced in the quantities needed have been proposed, and have

undergone evaluation for chemical compatibility and cooling ability. The candidates that are considered to be plausibly commercially available in the medium term are $c\text{-C}_4\text{F}_8$ (also known as FC-318 or FC-c318), $n\text{-C}_4\text{F}_{10}$ (also known as FC-3110 or FC-31-10), and $\text{C}_2\text{F}_4\text{HCl}$ (also known as HCFC-124). Reactivity testing on HCFC-124 demonstrated that at simulated cascade inleakage conditions, it was 100 to 1000 times more reactive with F_2 and UF_6 than is the presently-used CFC-114². An absolute criterion on the tolerable coolant- UF_6 reaction rate has not been established, but this result, combined with the temporary status of HCFCs as environmentally acceptable substitutes, resulted in this substance being essentially dropped from consideration as a GDP coolant substitute.

The remaining two candidates are both perfluorocarbons. They are good infrared absorbers and are expected to be long-lived in the atmosphere. As such, they will be strong greenhouse gases. The long-term global warming potential for these two gases is not known, but has been estimated³ at 13 for FC-318 and 18 for FC-3110, which should be compared to a value of 4 for CFC-114; these values are relative to the global warming potential of CFC-11, which, by definition, is given a value of 1. The estimates made in Reference 3 are in principle rather uncertain due to the uncertainty in the atmospheric lifetime of the species, when taken over an infinite time horizon. Since the estimates used atmospheric lifetime estimates of 500 years for the two perfluorocarbons, the GWP computed over a time interval of 500 years should be approximately correct, and over a shorter horizon will overestimate their GWP.

In that earlier document³, the relative ozone depletion impact and global warming impact of the candidate coolants were estimated for the magnitude of the fugitive emissions prevalent in the GDPs. In the case of global warming, this impact was compared to the impact of indirect CO_2 emissions (due to electric power consumption by the GDPs) and the avoided CO_2 emissions (due to use of enriched uranium rather than coal in electricity production). In general, it was found that, on a per delivered kilowatt-hour basis, the global warming contribution of nuclear power was 4% that of coal-generated power. The global warming due to nuclear power is primarily due to CO_2 generated during (fossil-generated) production of power for the enrichment plants. Global warming due to coolant emissions was found to be small relative to that of these indirect CO_2 emissions, varying with coolant choice, but on the order of 1% to 16%.

Other sources have reached similar conclusions with regard to nuclear vs. coal CO₂ emissions. A study sponsored by the Friends of the Earth organization also listed the nuclear-related global warming impact as being approximately 4% that of coal-related power production.⁴

This report extends the work of K/ETO-50 to examine in more detail the future pattern of impacts under various coolant replacement scenarios, and makes a quantitative estimate of the influence on average global atmospheric temperatures of GDP operation. The work reported here is based on a "quick and dirty" model demonstrated for several oral presentations⁵ given locally at the DOE gaseous diffusion plants in late 1991 and early 1992. Both the previous work and this work require knowledge of many operational and phenomenological parameters, some of which are not well known. Many approximations and estimates have been made in order to allow *some* prediction to be made, however imprecise it may be. This work was begun primarily to develop a quantitative estimate of the magnitude of the contribution to global warming impact of GDP operation. In many ways, however, the interrelationship of the model's *inputs* proved to be more interesting and enlightening than its *outputs*. A major motivation for more formally documenting this work is to demonstrate to the reader the interrelationships among various controllable and partially controllable parameters, and their influence on the strategy of coolant replacement at the GDPs. The results presented here should not be regarded as quantitatively accurate predictions, but should demonstrate that a more refined treatment, using improved input parameters, could provide a valuable informational and strategic planning tool for the Uranium Enrichment Enterprise.

MODEL DESCRIPTION

The question addressed in this report was approached by creation of a computer model which was developed in the form of a spreadsheet operating under the software package Quattro Pro (a trademark of Borland Int'l). The specific spreadsheet file is named WARM_Sn.WQ! (where n may be 0, 1, 2, 3... representing several different scenarios). The model is generally based on the approximations and reasoning to be found in K/ETO-50, with a few additional assumptions and correlations. As the model stands as of this writing, numerous order-of-magnitude estimates and simplifying approximations are used which relate plant power, coolant load, coolant leakage, and similar parameters. These approximations should be refined if it were intended to

use the model output for other than general illustrative purposes. For now, this should be considered a "zeroth order model".

The general approach taken by the model is to define a series of globally "controllable parameters" (such as plant power level, coolant purchases, choice of alternate coolant), define the interrelationships of these parameters to other parameters of interest, then calculate a time series projection of the values of these parameters for the future of the gaseous diffusion complex. Parameters considered in the model are:

- 2-plant power level over time
- Coolant inventory (both CFC-114 and an alternate)
- Coolant additions
- Coolant leakage rate (i.e. emissions to atmosphere)
- Effect of improved conservation efforts
- Indirect CO₂ emission (due to GDP power use)
- Avoided CO₂ emissions (due to use of enriched U, in lieu of coal, for electric power generation)
- Atmospheric loading of GDP-related greenhouse gases
- Atmospheric destruction of GDP-related greenhouse gases
- Contribution of these emissions to global warming

Many of these parameters are constrained, sometimes externally and sometimes by the values of other parameters, as will be discussed in more detail below. For example, if the coolant inventory is too low, only a fraction of the GDPs will be able to operate (i.e. by consolidating the available coolant in some of the cells, and operating only those cells). Similarly, it is reasonably well established that idle GDP equipment will lose coolant at a significantly lower rate than when it is at full power, due to the lower vapor pressure of the coolant at lower temperature. Specific parameter relationships are as follows:

GDP Power Use over Time: Power level targets are an externally controlled parameter. In the results presented here, I have devised three scenarios for future power use, very loosely based on a near-term demand projection covering the period 1990-2005⁶. In general, it is assumed that demand will exist for GDP or other DOE enrichment services equivalent to about 3000 MW over the next several decades, with demand eventually declining (as GDPs are displaced by other enrichment capacity or nuclear energy by other energy sources). The three scenarios differ in the year in which initial significant AVLIS (Atomic vapor laser

isotope separation) production begins. Within a few years of this event, it is assumed that one of the GDPs is closed down, and that within the next decade or so the remaining GDP is also closed down. The dates for AVLIS introduction are taken as 2001, 2010 and "never". The three power demand projections are displayed in various scenario plots below, and the corresponding dates of significant events (AVLIS startup, GDP shutdowns) are listed in Table 1.

It should be noted that these scenarios are designed to illustrate a plausible range of future events; they carry no official weight or sanction. The author has no knowledge of the long-range strategic intentions of the UE enterprise.

Coolant Inventory vs. Plant Power: For normal operation (up to 3500 MW), the two GDPs need collectively 5440 metric tons (12,000,000 lbs) of coolant. If the on-site coolant supply is lower, the capacity of the plant is assumed to be reduced proportionately (i.e. plant power use capacity is 3500MW/12M# of coolant up to 12M#; above 12M#, it is assumed to be fully operational to its nominal capacity). The GDP complex CFC-114 inventory starts at 1000 MT above the "full" level, due to the residual Oak Ridge Gaseous Diffusion Plant Site coolant inventory. Quantitative aspects of this assumption are based mainly on intuition. This is one of the elements that would need refinement in a more thorough treatment. None of the scenarios presented in this report invoked situations in which coolant shortage reduced power use (and by implication SWU production) below the target, though that is a possible outcome of the model.

CFC-114 Additions: It is assumed that 300 MT of CFC-114 were purchased in the 1990-1991 period (roughly historical values), and that, in general, additional CFC-114 may be purchased in quantities up to 400 MT/yr (as needed) up to 1996, when production of CFC-114 ceases.

Alternate Coolant Additions: Alternate coolant purchases are scenario dependent and, in the model, user-controlled. The primary strategy used in the scenarios developed below is that which has been used in the past, namely additional coolant is purchased in quantities sufficient to keep the cooling systems full. Once a GDP closes, "full" is defined as one half the nominal two-plant capacity. An alternate strategy is also explored, namely that coolant purchases will be made sufficient to keep

adequate GDP capacity operating to meet power demand. In this strategy, for example, if one knew that the full capacity would not be needed in the near future, coolant from idle cells could be transferred into operational cells in lieu of making additional purchases.

The model allows alternate coolant purchases to be made at any quantity between a minimum and a maximum per year. This is somewhat arbitrary, but is intended to reflect economic production limits of the manufacturers of the alternate coolant at the upper end, and to reflect that if no purchases are made for years on end, the alternate might not be available later when needed. The precise values of these limits are a model input, but typical values might be 150 MT/yr and 50 MT/yr for the upper and lower limit respectively. In the scenarios presented in this report, however, this option was not exercised (i.e. no constraints on purchases were made).

Leakage vs. Plant Power: Leaks from the cascade are assumed to occur at 1% of coolant inventory per year from idle equipment, and 5% per year from equipment in use. The fraction in use is taken as the ratio of the power level to 2500 MW (this can go over 100% -- it's really a ratio of GDP power in a future year to the typical GDP level recently). This is a great oversimplification of a complex subject, but approximately duplicates recent experience at current power levels, and at zero power.

The different vapor pressures and molecular weights of alternate coolants will change the rate of leakage relative to CFC-114, other things being equal (i.e. at equivalent power level leak size). This has been handled by multiplying the leak rate calculated above by the vapor pressure ratio of the substitute coolant to that of CFC-114 at 180 °F times the molecular weight ratio of the two compounds. These values for FC-318, FC-3110, and HCFC-124 are 170%, 174%, and 140%, respectively.

Leak Reduction: A provision has been included for a leakage factor which is a multiplier for the leak rate. For a leakage factor of 100%, the leak rate is that described above; a leakage factor of 50% would result in 50% of the leakage computed above. This factor is computed by imposing a leakage improvement factor, a percentage which compounds each year. The base scenario uses an improvement factor 2%/year. In this case, after 5 years the leakage factor would be $(98\%)^5$ or 90.3%. Compound-

ing eventually results in large reductions in leak rates. After 30 years, 2% improvement per year results in a reduction in the basic leakage factor to 55% of the original rate; similarly, 4% improvement results in a rate 29% of the original. These are dramatic improvements, and may or may not be achievable, but are smaller than several arbitrary GDP coolant conservation targets set in recent years for a much nearer time frame.

Atmospheric Loading: Atmospheric loading is the cumulative surviving quantity of gases directly or indirectly emitted due to GDP use in or after 1990. Pre-existing atmospheric loading is not considered, nor are sources unattributable to GDP complex operation. Atmospheric loading of coolants is increased each period by the leakage from the GDPs, then decreased each period by destruction in the atmosphere per an exponential decay:

$$Q_f = Q_i e^{-dt/\text{lifetime}}$$

Q_i and Q_f are the time increment's initial and final values and "dt" is the length of the time increment.

Lifetimes: The "lifetime" values are taken, from Reference 3, to be 200 years for CFC-114, 6.6 years for HCFC-124, 400 years for CFC-115 (a reaction product of HCFC-124). Atmospheric lifetimes for FC-318 and FC-3110 have not been reported in the literature. Following reference 3, these are taken to be 500 years. Since the model will examine a much shorter time frame than that, there will be no substantial difference in the results were we to choose a much longer lifetime. It is recognized that CO_2 atmospheric retention is more complex than this simple exponential equation would indicate, but a median approximate lifetime of 230 years will be used as an approximation⁷.

Reactive Coolants: A provision is made for reactive coolants, such as HCFC-124, which may be partially converted to other species upon inleakage into the cascade. For HCFC-124, 95% of emission is taken as going to the atmosphere, and 5% into the cascade. Loss into the cascade converts to CFC-115 before escaping to the atmosphere.

Indirect CO_2 Emissions: Indirect CO_2 emissions are taken to be 0.99 kg of CO_2 (emitted at a coal-fired power plant) per kwh delivered to an end

user (such as a GDP or any other customer of electricity). Thus, enrichment of U at GDPs indirectly emits 0.99 kg of CO₂ per kwh used. This figure comes fairly directly from information in the Energy Information Agency's 1990 Annual Energy Review⁸. An earlier 1985 version of this document provided less direct information from which was calculated the slightly higher figure used in Reference 3, namely 1.25 kg CO₂/kwh. The recent value much more explicitly lists CO₂ emissions from electrical power generation due to coal, oil, and gas. For coal-fired electricity, the figure is between 0.96 and 0.99 kg/kwh for the years 1985 to 1989; for the national average electrical power (including coal, gas, oil, nuclear, hydro), the figure averages 0.66 kg/kwh. I use the figure of 0.99 kg/kwh as the appropriate figure for GDP power use's indirect emission of CO₂, since it is the author's understanding that GDP power comes essentially exclusively from coal-fired steam plants.

Avoided CO₂ Emissions: Enriched uranium is intended for use in nuclear power plants, which generate electricity that otherwise would most likely be generated by fossil fuel burning, primarily coal. By avoiding use of coal-fired power plants, uranium enrichment and subsequent nuclear power electrical generation in effect has a global cooling effect, relative to use of coal generated electricity. In other words, the "avoided CO₂ emission" and related global warming impact represents that due to nuclear energy's main competitive electrical energy generation process, coal-fired power.

It is assumed that the current power production of 2500 MW generates enough enriched uranium to fuel the U.S. nuclear industry, which delivers 577×10^9 kwh to the end user⁸. Enrichment of uranium therefore enables the avoidance of a great deal of CO₂ emission from coal-fired power. This assumptions are rather uncertain, and should be reexamined in a better treatment of this problem. It should, however, be of the correct order of magnitude, and agrees with results of similar analyses⁴. I have not attempted to determine the actual SWU production, nor the typical number of SWUs going into nuclear power from US fuel sources, nor accounted for the difference between enriched U imports and exports; a better treatment of this problem should account for this more accurately. Further, if there were no U.S. uranium enrichment industry, foreign sources would be available, in the short run at least, to satisfy US demand (there is a significant world-wide capacity surplus). I do not know the energy intensity of foreign sources. Almost certainly, centri-

fuge-based enrichment (Urenco; Russia) are less energy intensive than GDPs; Eurodif probably is more energy intensive than US GDPs. Any enrichment plant based in or near France (such as Eurodif) will get its electricity largely from nuclear sources, and thus not contribute significant CO₂ emissions.

Global Warming vs. Atmospheric Loading of Gases: Global warming per unit mass of a greenhouse gas emitted is deduced from a paper by Fisher et al.⁹ In that paper, model results are plotted showing the earth's average surface temperature increase over time for a sudden injection of 5x10⁹ kg of each of three coolants (CFC-11, -22, and -123). Upon injection, the temperature increases suddenly (time constant of less than 3 years) to a peak, then exponentially decays per the compound's atmospheric lifetime. It is assumed here that the instantaneous response goes according the equation:

$$C = \frac{dT}{\text{Mass}} \times \frac{(\text{Mol. Wt.})_{\text{CFC-11}}}{(\text{IR Strength})_{\text{CFC-11}}} \times \frac{(\text{IR Strength})_x}{(\text{Mol. Wt.})_x}$$

For each of the three coolants in Fisher's article, the value "C" was computed. The average value computed was

$$C_{\text{average}} = \frac{1.29 \times 10^{-13} \times (\text{Mol Wt.})}{(\text{IR Strength})} \text{ } ^\circ\text{C/kg}$$

where *IR Strength* is the integrated (base-e) absorbance in units of atm⁻¹ cm⁻², and molecular weight is in units of grams/mole. The reference CFC-11 values are already incorporated into this constant. The internal error on this for the three data points available was about 0.2 (base-10) log units, which is to say about 40%. In this report's model, temperature changes are calculated individually from each gas's atmospheric loading, multiplied by its individual warming factor "C".

Infrared Strengths: IR Strengths for coolants are computed from local experimental spectral data as an integrated natural log absorbance from 400 to 1500 cm⁻¹ per atm partial pressure per 1 cm pathlength, and compare well with literature data where it is available³. For CO₂, an effective IR strength is calculated from the estimated lifetime, GWP and molecular

weight by inverting the formula used in Reference 3 for estimating GWP. It will not be related to the real IR absorption cross-section due to the optical saturation of the atmosphere's infrared wavelengths throughout most of the CO₂ spectrum.

Specific values of material parameters are summarized in Table 2.

Table 2: Material Characteristics

Material	Units	CO ₂	CFC-114	FC-3110	FC-318	HCFC-124	CFC-115
Mol. Wt.	gm/mole	44	171	238	200	136.5	154.5
Lifetime	yrs	230	200	500	500	6.6	400
IR Str	atm ⁻¹ cm ⁻²	0.156	3988	9037	5530	4119	4922
"C"	°C/kg	4.54x10 ⁻¹⁶	3.00x10 ⁻¹²	4.88x10 ⁻¹²	3.55x10 ⁻¹²	3.88x10 ⁻¹²	4.09x10 ⁻¹²
Leak Ratio			1.00	1.74	1.70	1.40	

RESULTS AND DISCUSSION

We will now examine a number of scenarios involving different future GDP production and coolant substitute strategies. Scenario input parameters and results are presented in three different ways. First, the pertinent input parameters defining the scenarios are listed in Table 1. Second, selected 50-year time series for input and output values are plotted in Figures 1 through 10. Finally, global warming and cooling contributions for selected scenarios are plotted over a 200 year horizon in Figures 11 through 15.

Table 1 contains many entries summarizing the assumptions, intermediate results, and outputs of the various scenarios. The entries listed deserve some explanation:

Coolant "Buy Criterion" - The standard criterion is indicated by the entry "Fill" in this row of the table. Under this strategy, coolant purchases are made sufficient to keep the operating plant(s) cooling systems full. A second strategy, illustrated in scenario 8, is designated "minimum". Under this strategy, only enough coolant is purchased to fill that fraction of the plant equipment needed for current SWU production. The third

strategy, designated "Max 114", purchases relatively large quantities of CFC-114 (comparable to historical purchase rates) through 1996, then buys no further coolant of any kind.

Leak Improvement - This entry indicates the percent per year reduction in leakage.

Substitute coolant - designates the substitute coolant used in the scenario.

AVLIS Date - this is the date at which significant production of enrichment by the AVLIS process begins to displace the presumably less-economic GDP enrichment. Three basic AVLIS scenarios are used, with start dates of 2001, 2010, and no AVLIS (i.e. beyond 2040, if ever).

GDP 1 (and 2) Closed - these are the dates of last production of the first and second GDP. If AVLIS enters the picture, it is assumed that one GDP closes a few years later. Eventually, AVLIS or not, both GDPs are assumed to cease operation. Like the AVLIS dates, these dates are completely conjectural.

In addition to the above parameters, which are essentially inputs to the model, Table 1 lists some pertinent summary intermediate and output values. These are:

Coolant Disposal Date - This is the year in which it is assumed that the remaining coolant in the closed GDPs is disposed of (without venting to the atmosphere).

Coolant Disposal Quantity - These entries are the numbers of metric tons of CFC-114 and substitute coolant remaining in the GDPs at the disposal date.

Total Purchase - These entries are the total metric tons of coolants that were purchased (from 1990 onward) of CFC-114 and the substitute coolant. Note that this doesn't include the existing operating CFC-114 inventory in the plants as of 1990.

Total Emissions - These entries are the total metric tons of CFC-114, substitute coolant, indirect CO₂, and avoided CO₂ emitted during the course of the scenario.

Warming (Averaged over 200 years) - Entries here are the 200 year (1990 to 2190) average global warming, calculated as described in the previous section, due to the specific components listed (i.e. coolants, CO₂, or various subtotals). "Gross Warming" is the sum of all coolant and indirect CO₂ induced warming.

Cooling (Averaged over 200 years) - Effective average cooling due to avoided CO₂ emissions.

Net Cooling (Averaged over 200 years) - These entries are the cumulative total of warming and cooling contributions.

Relative Warming and Cooling - For easier comparison of scenarios, the average temperature changes are also presented as a ratio to a baseline scenario, namely scenario number 1. To illustrate, consider scenario 4 (which differs from scenario 1 only in using FC-3110 rather than FC-318 as the substitute coolant). From the table, it can be seen that the average warming due to the substitute coolant alone will be 41% larger in scenario 4. When total coolant emissions are considered (substitute *and* CFC-114) the average warming is only 15% higher in scenario 4. When indirect CO₂ emissions are considered, the difference in gross warming is less than 1%.

The scenarios presented here have been chosen to illustrate some of the (perhaps unexpected) interactions between various strategic choices and operational parameters, to illustrate some effects that may have a dramatic effect on the course of coolant replacement, and to show the magnitude of the differences (large or small) between various scenarios.

A Baseline Scenario

For purposes of discussion and comparison, scenario 1 (Figures 1 and 11) will be taken as the baseline. Like most of the scenarios, it uses a "fill to coolant capacity" criterion for determining new purchases. This criterion might also be termed a "replace all losses" tactic. AVLIS is assumed to appear in 2010, with one GDP closing in 2013, and the other in 2020. 2% improvement in leakage is assumed each year. The substitute coolant used is FC-318. The substitute coolant is purchased at a rate of about 300 MT per year from 1996 through 2010, after which no further purchases are needed, due to closing of one of the GDPs. Since only losses are replaced, CFC-114 continues to be used in the complex, though in an ever-diminishing proportion. Still, the time horizon of GDP operation and the leakage rates are such that at final shut-down, over half the coolant is still CFC-114. Approximately 3900 MT of coolant will have to be disposed of at the end of GDP operation.

The global warming contribution of the substitute coolant average 6.6×10^{-6} °C, whereas the contribution of CFC-114 emitted after 1990 averages 1.1×10^{-5} °C. Warming due to indirect CO₂ emission averages 2.2×10^{-4} °C. The total of all warming contributions averages 2.4×10^{-4} °C. Thus, in this scenario, coolant emissions contribute 7% of the total global warming impact due to GDP complex operation. Avoided CO₂ emissions contribute a much larger effective cooling averaging 5.8×10^{-3} °C. To put it another way, the average global warming impact of the nuclear energy generated under this scenario is 4% of that of the equivalent energy generated from fossil fuel power plants. Peak global warming (and cooling) values are not listed, but can be seen from Figure 11 to occur around the year 2025. For scenario 1, the maximum values are about 30% higher for the FC-318-induced warming and 45% higher for all other warming or cooling entries than the 200-year averages quoted above.

This scenario has been discussed in somewhat greater detail than those below, because it illustrates the main features of all the scenarios run. Significant points are:

- * Significant CFC-114 will remain throughout the life of the plants, unless it is deliberately removed in excess of leakage.
- * Total need for a substitute coolant may not be as large as the recent need for CFC-114, if even modest conservation gains can be

made.

- * Substitute coolant purchases may be needed for only a relatively short period of time, namely until the closing of one GDP.
- * Much of the coolant-related global warming impact will be due to CFC-114, due to the large quantity in the plants at the present time.
- * Coolant-related global warming (from both CFC-114 and a substitute) will be of the order of 10^{-5} °C. Warming due to indirect CO₂ emissions is an order of magnitude or more higher. Still, this must be compared to the avoided CO₂ emissions and warming more than an additional order of magnitude higher.

These conclusions qualitatively apply to all scenarios' results. The remainder of this report will examine the specific effects upon this baseline scenario's results of changes in particular parameter values.

AVLIS Scenarios

Scenarios 1, 2 and 3 differ only in the date of AVLIS introduction, the date for scenario 2 being earlier (2001), and for 1 being later (2010), while for 3 no AVLIS introduction occurs at all. The detailed power projections for the 2-GDP-plant complex for the three scenarios are plotted in Figures 1, 2, and 3. All scenarios use a "fill to coolant capacity" purchase strategy, use FC-318 as the substitute coolant, and assume a 2%/year improvement in leak rate. Since they differ primarily in how long the GDPs run, the most dramatic difference is in the total quantity of substitute coolant that must be purchased over the course of the operation. This ranges from a low (in scenario 2) of 1700 MT to a high (in scenario 3) of 6200 MT. In Figure 2 it can be seen that total purchase is made at approximately 250 MT per year for 7 years. Such a relatively short-term need for a substitute coolant could have significant cost implications if a dedicated production plant had to be amortized over such a short period of time.

It should be noted that the indirect CO₂ and avoided CO₂ emissions vary by scenario in a manner that is dependent only on the lifetime of the GDP

Figure 1: Scenario 1 Coolant and Power Time Series "Baseline Case"

Figure 2: Scenario 2 Coolant and Power Time Series "Early AVLIS Case"

Figure 3: Scenario 3 Coolant and Power Time Series "No AVLIS Case"

Figure 4: Scenario 4 Coolant and Power Time Series "FC-3110 Case"

Figure 5: Scenario 5 Coolant and Power Time Series "HCFC-124 Case"

Figure 6: Scenario 6 Coolant and Power Time Series "No Leak Reduction"

Figure 7: Scenario 7 Coolant and Power Time Series "Good Leak Reduction"

GDP Global Warming Scenario Parameters
 Alternate Coolant: C4F8 - AVLIS 2010 - 2%/yr Leak Improvement

Figure 8: Scenario 8 Coolant and Power Time Series "Minimum Purchase Case"

Figure 9: Scenario 9 Coolant and Power Time Series "No Substitute"

GDP Global Warming Scenario Parameters
 Alternate Coolant: C4F8 - No AVLIS - 0%/yr Leak Improvement

Figure 10: Scenario 10 Coolant and Power Time Series "High Leak; No AVLIS; No 114"

process, and not due to any choices of coolant substitute strategy or coolant conservation measures. Not included in those figures are the corresponding indirect or avoided emissions due to whatever energy or electricity-producing process has *displaced* the GDP production or nuclear power.

Coolant Choice

Scenarios 1, 4, and 5 differ only in the choice of the substitute coolant. These scenarios use, respectively, FC-318, FC-3110, and HCFC-124 as the substitute. FC-318 and FC-3110 are the current leading candidates to replace CFC-114, at least in the immediate future. A longer range search for an "advanced coolant" (i.e. alternate with reduced global warming impact) is underway, but is not in the mainstream of the CFC replacement program at present. HCFC-124 is very unlikely to be used as a substitute, its vapor pressure is a bit too high, and as it proved to be fairly reactive with UF_6 , which raises operational safety issues that are not at present resolved.² An advanced coolant, if found, will likely be a hydrofluorocarbon (HFC) or hydrofluoroether (HFE). HCFC-124 is used here in scenario 5, however, for two reasons. First, from a practical standpoint, the requisite data (IR strengths, atmospheric lifetime, vapor pressure, etc.) are available for HCFC-124, whereas they are not for conjectural HFCs and HFEs. Second, for purposes of this model, HCFC-124 is likely to behave similarly to an HFC or HFE coolant. One exception to this statement is that the vapor pressure of an advanced coolant of choice will (one hopes) be fairly close to that of CFC-114, whereas that of HCFC-124 is somewhat higher. The actual vapor pressure of HCFC-124 was, however, used in this scenario, leading to higher leakage than might be the case for an advanced coolant.

One factor that must be considered if a slightly reactive coolant is used is the fate of coolant leaking into the UF_6 stream. In the case of HCFC-124, reaction rates and coolant residence times in the UF_6 are such that the molecule will be fluorinated before eventually being purged from the system. The main reaction product of UF_6 and HCFC-124 is CFC-115. Therefore, in scenario 5, it is assumed that the fraction (taken as 5%) of coolant leakage that occurs via the UF_6 stream (rather than directly to cooling water or to the atmosphere) will be emitted as CFC-115 rather than as HCFC-124.

Results are listed in Table 1; parameters and results are displayed in Figures 1, 4, and 5; the contributions to global warming impact are displayed in Fig-

ures 11, 12, and 13. Substitute coolant emissions among these three scenarios vary slightly due to the different inherent leakage rates, FC-3110 being the highest and HCFC-124 being the lowest. As one might expect, it is the global warming contribution due to substitute coolant emission that is most dramatically different. The HCFC warming contribution is only 9% that of FC-318, due primarily to its shorter atmospheric lifetime. About half of its long-term warming contribution is due to the 5% converted to CFC-115. The FC-3110 warming contribution, on the other hand, is 141% that of FC-318, primarily due to its higher IR absorption strength. These differences are for the substitute coolant only. When contributions of CFC-114 emissions are added, the overall coolant emissions' warming impact ranges from 66% for HCFC-124 to 115% for FC-3110. When the coolant contribution is further aggregated with the indirect CO₂ emission's contribution, the effect of coolant choice all but disappears, ranging from a 3% improvement for the HCFC to a 1% degradation for FC-3110, compared to the reference FC-318.

Conservation Effects:

The baseline scenario includes a very moderate improvement in coolant leak rate of 2% reduction per year, compounded. This results in a basic leak rate of about 55% of the 1990 value (other factors being equal) by the year 2020. Much more optimistic leak reduction goals have been discussed on numerous occasions, ranging from loss rates from 50% to 10% of the 1990 values within a few (i.e. perhaps 5 to 10) years. Absent a comprehensive quantification of and tabulation of all leak sources, it is difficult to estimate realistic achievable leak reduction goals. To explore the implications of leak reduction, however, two further scenarios were run. These are designated scenario 6 and 7 in Table 1. The time series coolant use and inventory figures are plotted in Figures 6 and 7. These scenarios should be compared to scenario 1; the three scenarios differ only in their leak reduction factor, which ranges from 0% to 2% to 4% per year in scenarios 6, 1, and 7, respectively. The 4% per year reduction in Scenario 7 by 2020 yields a basic leak rate that is 29% of that prevailing in 1990; scenario 6, of course, results in no change in the basic leak rate. During 2-plant operation, actual losses of coolant are larger due to the inherently higher leak rate of the FC-318 (a consequence of vapor pressure and molecular weight).

The high leak rate scenario requires purchase of about twice the quantity of substitute coolant as does the low leak rate scenario. Due to higher leakage,

the global warming impact of the substitute coolant averages 72% higher in scenario 6 than in the reference scenario 1, while in scenario 7 it averages 44% lower. Global warming due to the all coolant leakage in scenario 6 is 36% higher than scenario 1, while that of scenario 7 is 25% lower. When aggregated with the larger impact of indirect CO₂ emissions, the overall warming in these two scenarios ranges from a 3% increase to a 2% decrease, relative to the reference scenario.

Even the moderate improvement in leak rate between scenario 6 and 7 results in a significant reduction in the quantity of substitute coolant needed (and ultimately emitted). Scenarios consistent with conservation targets mentioned earlier would result in much more dramatic decreases in the need for a substitute coolant. These targets may or may not be realistic, but an accurate estimate of future leak rate should be considered when estimating the magnitude of the annual purchase for a substitute coolant so as not to indirectly pay for the capital investment in an excessively large coolant production facility.

Alternate Buying Criterion

Most of the scenarios shown in this report use a buying strategy equivalent to that which has been pursued in the past, namely that sufficient coolant is purchased to replace losses and keep all the cooling systems essentially full. For the past many years, and for the foreseeable future, demand for enriching services from the GDPs does not require full plant capacity. Reduced production can be achieved by running a large number of cells at lower power per cell, or a smaller number of cells at higher power. There are, of course, economic and operational tradeoffs and limits to this, and any significant decrease in energy efficiency would manifest itself in increased indirect CO₂ emissions.

Nevertheless, an alternate coolant buying criterion is used in scenario 8 under which it is assumed that the plants are run in the "fewer cells at higher power" mode. Specifically, it is assumed that the number of cells on-line is proportional to the power demanded by the needs of SWU production. Only that fraction of the plant actually operating is kept full, and additional coolant is purchased only if needed to keep the operating fraction of the cells full. Other than the different coolant purchase criterion, scenario 8 is identical to scenario 1.

The result of this change in purchase criterion is that less substitute coolant is purchased (2500 vs 4200 MT), emitted (1600 vs 2400 MT) and disposed of (800 vs 1600 MT). The substitute coolant global warming contribution under this scenario is 33% lower, and the total coolant contribution 13% lower than those of the reference scenario.

The concept of purchasing coolant only for operational needs has been treated in a very simplistic manner, but a (carefully considered) variation of this could conceivably save a good deal of money and reduce emissions.

Two Extreme Cases

The scenarios presented so far have all varied only one choice or input parameter. Scenarios 9 and 10 present two more extreme cases, each devised by varying several parameters in the baseline scenario in the direction of maximizing or minimizing purchases and emissions.

Scenario 9 contemplates a strategy by which CFC-114 is purchased to replace GDP losses, but the K25 inventory is not used until after 1996, CFC-114 is no longer available for purchase. Thereafter, *no* alternate coolant is purchased. Leakage is assumed to improve at 2% per year (as in the base case). AVLIS is assumed to come on line in 2001 per the "early" scenario, and the GDPs cease operation in 2005 and 2020.

In this scenario, there is sufficient coolant (assuming the coolant consolidation discussed in scenario 8 is viable) to operate the plants throughout the scenario with no production curtailment. Since shutdown occurs earlier and since no substitute coolant was purchased, the global warming contribution under this scenario for coolants is 60% that of scenario 1.

Scenario 10 postulates a set of parameters that maximize emissions. No improvement in leak rate is assumed, AVLIS is assumed not to come into production, the GDPs run until 2020 and 2035. Total purchases of substitute coolant amount to 11,500 MT. Most of these purchases occur at a rate of about 460 MT/yr through 2020, but a small quantity is needed in the 2030-2033 timeframe, once the inventory of the first shutdown GDP is consumed.

The global warming impact of the substitute coolant in this scenario is four times that of the reference scenario; the combined warming due to both

coolants is about twice that of scenario 1. Including indirect CO₂ emissions, the overall warming is 41% larger, but most of this is due simply to the GDPs running longer; only 6% is due to increased coolant emissions.

The total substitute coolant emissions in these two scenarios run from zero to 11500 MT, and it is difficult at this time to say whether either is particularly improbable.

Global Temperature Impact

The original purpose in formulating the model described here was to provide a ready means of making order-of-magnitude estimates of the global warming impact over time of GDP coolant substitute choices, and to put it in perspective with other contributors to global warming. This goal may seem to have been lost in the examination of interrelationships among inputs and intermediate results. Figures 11 through 15, however, display the predicted 200-year course of global temperature impacts for 5 of the scenarios discussed above.

Many features of the plots are similar. For a given total GDP power projection, the warming effect of indirect CO₂ emission and cooling effect of avoided CO₂ emissions are identical. Only in Figure 15, deriving from a scenario in which the GDPs run for a longer period of time, do these values increase. In no case does the effect of coolant emissions add more than modestly to the indirect CO₂ impact.

Considering coolant effects separately, CFC-114 emissions are essentially identical in these five scenarios, producing a warming of about 10^{-5} °C. Where the scenarios differ significantly is in the contribution to warming of the substitute. In Figure 11, derived from scenario 1, warming due to FC-318 is moderately lower than the contribution of CFC-114. Figure 13, derived from scenario 4, illustrates that the contribution of FC-3110 is higher, being approximately equivalent to the contribution of CFC-114. Figure 12 derives from scenario 5. It illustrates that the impact of an HCFC would be much lower than that of a fully fluorinated species. The direct effect of the HCFC dwindles rapidly, as dictated by its short atmospheric lifetime. Its long-term effect will be due to derivatives that have been fluorinated by UF₆ (CFC-115 in the case of HCFC-124).

Cumulative GDP Global Warming Impact
 Alternate Coolant: C4F8 - AVLIS 2010 - 2%/yr Leak Improvement

Figure 11: Scenario 1 Global Warming Impacts "Baseline Case"

Cumulative GDP Global Warming Impact
 Alternate Coolant: C4F10 - AVLIS 2010 - 2%/yr Leak Improvement

Figure 12: Scenario 4 Global Warming Impacts "FC-3110 Case"

Cumulative GDP Global Warming Impact
 Alternate Coolant: HCFC124 - AVLIS 2010 - 2%/yr Leak Improvement

Figure 13: Scenario 5 Global Warming Impacts "HCFC-124 Case"

Cumulative GDP Global Warming Impact
 Alternate Coolant: None - AVLIS 2001 - 2%/yr Leak Improvement

Figure 14: Scenario 9 Global Warming Impacts "No Substitute"

Cumulative GDP Global Warming Impact
 Alternate Coolant: C4F8 - No AVLIS - 0%/yr Leak Improvement

Figure 15: Scenario 10 Global Warming Impacts "High Leak; No AVLIS; No 114"

Figure 14 illustrates the impact of scenario 9. In that scenario, no substitute coolant was used, so the only contributions to global temperature are those common to all the scenarios.

Figure 15 illustrates scenario 10. This was the highest emission case run. In this scenario, the effect of the substitute coolant is significantly larger than that of CFC-114, reaching and remaining at about 4×10^{-5} °C.

CONCLUSIONS

This report has described a rudimentary model which examines interrelationships among physical, strategic, and operational parameters influencing GDP-related global warming impact. Many of the relationships and data used here are considerable simplification of reality, but the results of the model are likely to be, in general, better than order-of-magnitude accurate. Several significant observations can be drawn from the scenarios presented.

First, the global temperature change due to GDP coolants is small in absolute magnitude, and a small component of the overall impact of GDP operation, which is dominated by indirect CO₂ emissions from power use.

Second, strategic choices, outside events, and (perhaps unexpected) interrelationships among operational parameters may have unrecognized consequences. For example, the effect of improved leak rates lead to striking reductions in the need for substitute coolants, as would an early closing of one of the GDPs. Plausible scenarios can be derived in which little or no substitute coolant is needed. That is not to say that it would be prudent to gamble on such events transpiring. It would, however, be wise to continually reexamine the course the enterprise is on so as to be aware of indirect implications of events, policies, and choices.

One means of possible reduction in cost and emissions would be to purchase coolant only for that fraction of the plant that is needed to provide near-term SWU production, rather than always keeping all cooling systems full. This would have to be fully evaluated for economic and operational practicality, and for energy efficiency, but if viable, could considerably reduce emissions and coolant cost.

Another conclusion that is evident from the scenarios is that unless it is deliberately removed from the plants, significant CFC-114 will remain for the life of the GDPs, and will need to be disposed of (along with whatever substitute might be used) at the end of that life.

Clearly, HCFC-124 (and by implication an HFC or HFE) has a much lower global warming impact than do the fully fluorinated coolants or, for that matter CFC-114. The higher atmospheric reactivity that leads to this also results in higher reactivity upon inleakage into the UF_6 stream. This raises safety and operational concerns (fouling of barrier by reduction deposits, exothermic reactions, and even the possibility of explosive reaction in the event of massive inleakage into the UF_6 stream). These potential increased hazards have not been quantitatively evaluated, nor is there an obvious mechanism for evaluating tradeoffs between environmental and safety issues.

It is recommended that a model similar to this one, but using more accurate and validated inputs be considered. Such a model would prove useful for informational and strategic guidance. In particular the implications of various policies or official plans could be evaluated (e.g. the recent coolant replacement strategies and conservation targets could have been better related to future coolant purchase needs, and the effect of possible AVLIS introduction or GDP closing could be more explicitly considered). Realistic coolant demand projections could be of benefit to prospective coolant vendors as well as the uranium enrichment enterprise. The relative environmental merits of various alternate coolants could be evaluated. This may well eventually be necessary in various regulatory venues, such as in internal environmental assessments or in EPA submissions.

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