URANIUM OXIDE RECYCLING TO GIVE MORE USTAINABLE POWER GENERATION

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Abstract

In broad terms there are two routes for irradiated nuclear fuel, the closed cycle involving recycling and the open cycle culminating in direct disposal. The benefits of following the closed cycle are presented. The environmental burdens associated with open and closed cycles are compared using Life Cycle Assessment (LCA) for non-active burdens and human irradiation. Consideration is given to the extension of the nuclear fuel cycle to include a proportion of MOx fuel elements within a reactor core, and the impact in terms of total activity, waste volumes and Integrated Toxic Potential (ITP) discussed. The potential of moving to a fast reactor cycle is also raised in support of the recycling of spent nuclear fuel giving sustainable power generation.

1. INTRODUCTION

Nuclear power has been used to generate electricity in the UK since the 1950's and today represents some 18% of the installed capacity and supplies some 31% of the electricity produced. In terms of spent fuel management, UK Government policy is that it is for the owners of the spent fuel to decide on the appropriate spent fuel management option based on their own commercial judgement, subject to meeting regulatory requirements. In broad terms two options exist the open cycle culminating in direct disposal of the fuel or recycling to recover products which can be utilised in further energy production. This paper addresses some of the issues regarding the sustainability of recycling.

2. DESCRIPTION OF THE NUCLEAR FUEL CYCLE

An outline of the nuclear fuel cycle is given in Figure 1. The open cycle refers to the mining and milling of U_3O_8 , uranium enrichment, fuel manufacture, nuclear power generation, intermediate spent fuel storage, spent fuel conditioning and final disposal, whereas the closed cycle moves to recycling following intermediate spent fuel storage, leading to the refabrication and recycling of uranium, and the interim storage of waste prior to vitrification and final disposal.

This description of the closed fuel cycle could also be extended to include further steps in the fuel cycle, for example the use of both plutonium and uranium oxides in the manufacture of mixed oxide (MOx) fuel, which could be cycled through the system either once or twice; or extension of the cycle to include future fuel cycle technology, for example fast breeder reactors.

The benefits in moving to further steps in the fuel cycle can be viewed in terms of the energy potential of MOx and future fuel cycles per unit mass, compared to that of uranium oxide and other forms of energy production.

Comparisons can also be made as to the value of recycling spent fuel as the majority of the fuel is available for recycling into new fuel elements, for e.g. in the case of the LCA model [1] 94.25% of the uranium is available for recycle (based on a PWR reactor, burn-up 40MW d/kg HM). Direct disposal would result in the permanent loss of this energy resource, which would have to be substituted with further uranium mining and milling or by other forms of energy production. In the case of non renewable energy production this loss would constitute a gain in the production of greenhouse gases.

To produce 1Tjoule[1] of electricity from nuclear power requires 0.87 kgU in UO_2 fuel. After irradiation 0.82 kgU remains, therefore 94.25% of the uranium or potential energy value remains (energy potential is also available in the 0.0087 kgPu in PuO_2). Following recycling, further energy can be produced over a number of UO_2 cycles following enrichment. Taking one further cycle to produce 1TJ of electricity by nuclear generation results in an emission of 10.55Te of CO_2. However, had the irradiated fuel been directly disposed of and 1TJ of electricity been produced using non renewable energy production, the resulting CO_2 emission would be for Gas 119.4Te CO_2 or Coal 302.7Te CO_2 [2]. Further recycling could then recover the remaining energy resource from the second cycle.

Comparison of world resources (known and assured) demonstrates the energy value per tonne of resource and the benefits of moving from thermal fuel cycles to fast reactor cycles. If uranium reserves were utilised in an open cycle, then ^{238}U and fissile uranium and plutonium would be lost from the resource base, which could be utilised in both thermal MOx and fast reactors. This would represent a substantial loss in energy reserves, which could contribute to a reduction in greenhouse gases, the CO_2 output per TW(h) being 3.5% of that produced by coal as shown in Table 1.

In the interests of sustainability, the effects of global warming and agreements made in Kyoto to reduce emissions of greenhouse gases, following an open fuel cycle culminating in direct disposal does not constitute an effective use of valuable energy resources.

TABLE 1. COMPARISON OF ENERGY VALUES, RESOURCE AVAILABILITY AND CO_2 GENERATION

Energy production	Tonnes	CO_2/TW(h)[2]	World Reserves[3]
Uranium/ MOx TWh	7.65	38000	44 TW years
Uranium fast reactor TW(h)	0.084	38000	4000 TW years
Coal TWh	155128.6	1090000	842 TW years.

[1]Note: 1TWh equals 3600 TJ's.

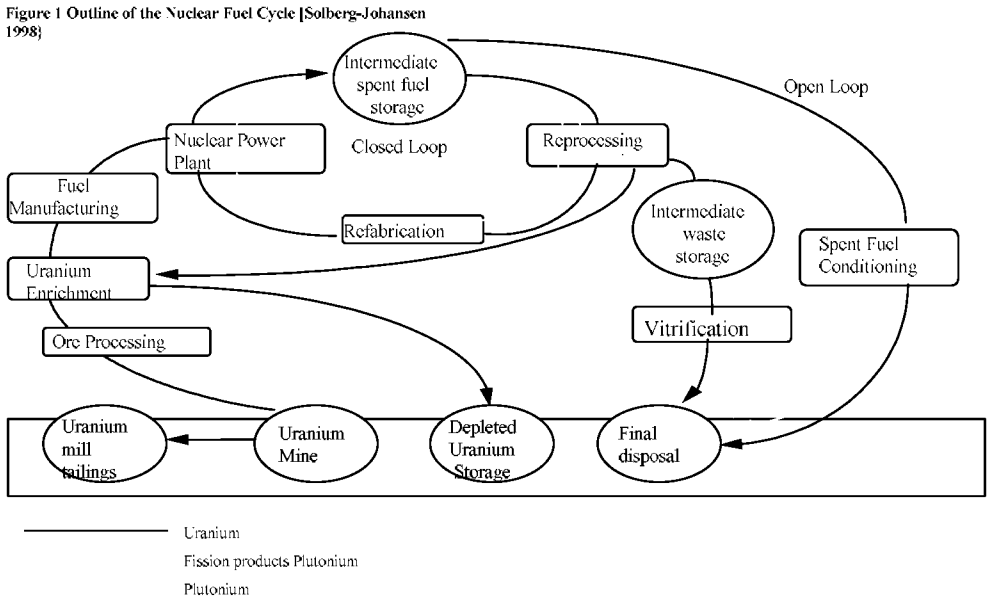

FIG.1. Outline of the nuclear fuel cycle [1].

3. LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is an approach which has been developed to assess the complete environmental impact of a product, process or service. The concept originated in the 1970's to determine the most environmentally efficient way of packaging beverages. Since then LCA has developed to become a tool that is widely used to support environmental management. Development of the LCA methodology has now progressed to the stage where associated international standards have been developed, the ISO14040-3 series [4], the Society of Environmental Toxicity and Chemistry, SETAC have also published a 'Code-of-Practice' [5].

BNFL sponsored an environmental LCA of the nuclear fuel cycle in 1995 at the Centre for Environmental Strategy, School of Chemical, Civil and Environmental Engineering, University of Surrey, UK. The study compares open and closed fuel cycles and assesses their impacts in terms of environmental burdens. An additional methodology was also developed to assess the impact of discharges and wastes, proposing a new LCA impact category "human irradiation" [1].

LCA models have been constructed for the open and closed fuel cycles based on the Thorp design flowsheet. The models consider specific facilities in the fuel cycle and allows site dependent issues, for example ore grade, to be made transparent. The models relate to the normal operation of the facilities concerned but do not include commissioning and decommissioning. The results from the model allow comparisons to be made between mining and milling, and reprocessing; and between open and closed fuel cycles overall. Models have been created using PEMS 3 LCA software developed by Pira International to assess the non-active burdens associated with the different fuel cycles. The Human Irradiation category was developed by Solberg-Johansen 1998 [1], as a separate model, as currently there are no impact categories within LCA methodologies to assess the impact in human terms of radiological discharges and wastes. Where impact is assessed it is in terms of the total number of Becquerels, which results in large numbers being produced but with no measure of their impact.

Within the LCA methodology, models are related to a functional unit, which denotes the amount of a product to which the mass balance over the model has been related, in this case the functional unit is the production of 1 TJ of electricity from a PWR reactor. Results from the impact assessments of these models are presented below supporting the use of the closed fuel cycle. Two mining and milling sites have been assessed Mine A, with an ore grade of 0.035% U_3O_8 and Mine B, with an ore grade of 0.3% U_3O_8 These mines have been used to represent the range of ore grades available on the market, they do not represent direct customers. Tables II and IV and Figure 2 show the comparisons between reprocessing only and mining and milling, (i.e. the source of Uranium) whereas Table III and VI compare the entire open and closed fuel cycle.

It is important to recognise at this stage that comparisons between impact categories cannot be made as they have different units of measure as shown in Table II. Percentages in the Table refer to the contribution to a category by one facility and dividing it with the sum of all the scores in that category.

It can be seen from this impact assessment that reprocessing has the lowest impact in all categories except for ozone depletion, where the impact is higher than Mine B (0.3%). This is due to the indirect influence of electricity consumption and the method of generation in the United Kingdom, which results in higher levels of Volatile Organic Compounds VOC's, in the UK mix of electricity compared to Mine B (0.3%) where electricity is generated using diesel.

TABLE II. ENVIRONMENTAL PROFILES - NON-ACTIVE BURDENS (1/TJ) [1]

Environmental profiles - non active burdens (1/TJ)							
Impact Categories		**Thorp reprocessing Plant**		**Mine A uranium Mine 0.035%**		**Mine B uranium Mine 0.3%**	
Fossil reserve depletion	kg Oil	9.04E+00	5%	9.30E+01	55%	6.80E+01	40%
Abiotic depletion (reserve base)	kg/kg	2.39E-14	0%	4.88-09	50%	4.88E-09	50%
Abiotic depletion (reserve-to-use)	year $^{-1}$	1.70E-01	5%	1.58E+00	49%	1.49E+00	46%
Human toxicity	kg body weight	8.38E-01	4%	2.07E+01	87%	2.28E+00	10%
Ecotoxicity (aquatic)	m^3	1.41E-05	6%	2.87E-05	12%	1.94E-04	82%
Acidification	Kg SO_2	7.03 E-01	4%	1.74E+01	87%	1.85E+00	9%
Nutrification	Kg Phosphate	2.56E-02	6%	3.04E-01	75%	7.53E-02	19%
Ozone depletion	kg CFC_{11}	5.97E-04	6%	9.81E-03	93%	1.75E-04	2%
Greenhouse effect	Kg CO_2	5.55E-01	6%	7.40E+02	75%	1.90E+02	19%
Photochemical Smog	kg Ethylene	3.29E-03	8%	1.59E-02	37%	2.38E-02	55%

Mine A (0.035%) is the highest contributor to almost all the categories, due to the low grade ore, resulting in the high usage of energy and materials in the milling step. Mine B (0.3%) generally has a lower impact due to the higher grade of ore, exceptions are the high contributions to ecotoxicity and photochemical smog categories. These differences are due to the fact that Mine A mine has a strict water management strategy, there being no recorded effluents from the site, and high contributions to photochemical smog reflecting the different forms of energy supply.

The case study indicates that reprocessing in the closed fuel cycle can contribute positively and avoid some burdens from uranium mining and milling at both sites. For Mine A avoided burdens are gained in the following categories, Abiotic depletion (reserved based), Human toxicity, Acidification, Nutrification, Ozone depletion and the Greenhouse effect. For Mine B improvements occur for abiotic depletion (reserve based) and ecotoxicity.

Comparisons made for the whole of the open and closed fuel cycles, indicate that in terms of non radioactive burdens the cycles are broadly equal. Although this is dependent on the ore grade, the comparison between the closed cycle (Mine A) and the open fuel cycle (Mine A) being the closest, due to the lower grade of ore. Comparisons are given in Table III again differences in ozone depletion are due to the method of electricity generation.

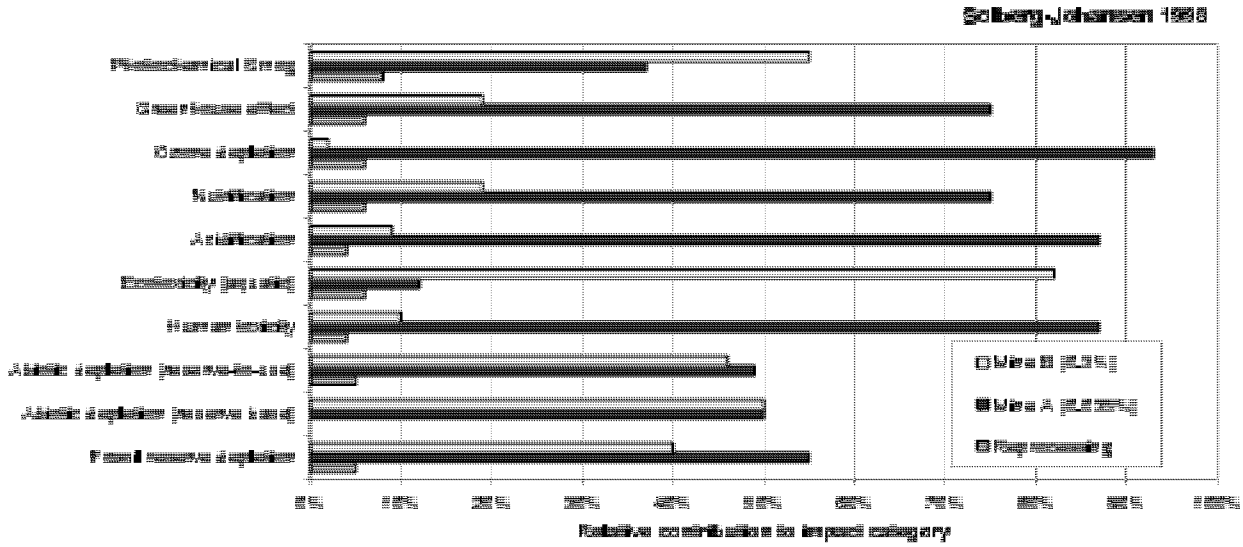

FIG.2. Comparison of reprocessing (only) with mining and milling at Mine A and Mine B.

TABLE III. COMPARING OPEN AND CLOSED CYCLES (1/TJ) [1]

Comparison of Open and Closed loop fuel cycles								
Impact Category	**Open Loop** (mining @ Mine A)		**Open Loop** (mining @ Mine B)		**Closed Loop** (mining @ Mine A)		**Closed Loop** (mining @ Mine B)	
Fossil reserve depletion	9.30E+01	50%	6.80E+01	49%	9.37E-01	50%	7.10E+01	51%
Abiotic depletion (reverse base)	4.88E-09	52%	4.88E-09	52%	4.44E-09	48%	4.44E-09	48%
Abiotic depletion (reverse-to-use)	1.58E+00	50%	1.49E+00	49%	1.61E+00	50%	1.52E+00	51%
Human toxicity	2.07E+01	51%	2.28E+00	44%	1.97E+01	49%	2.91E+00	56%
Ecotoxicity (aquatic)	2.87E-05	42%	1.94E-04	50%	4.03E-05	58%	1.91E-04	50%
Acidifiation	1.74E+01	51%	1.85E+00	44%	1.66E+01	49%	2.38E+00	56%
Nutrification	3.04E-01	50%	7.53E-02	44%	3.02E-01	50%	9.41E-02	56%
Ozone depletion	9.81E-03	51%	1.75E-04	19%	9.52E-03	49%	7.56E-04	81%
Greenhouse	7.40E+02	50%	1.90E+02	45%	7.29E+02	50%	2.29E+02	55%
Photochemical Smog	1.59E-02	47%	2.38E-02	49%	1.78E-02	53%	2.50E-02	51%

As part of the development of the LCA for the nuclear fuel cycle a new methodology was developed to assess the impact of processes in terms of Human Irradiation. This new environmental burden category includes sub categories for direct discharges for freshwater, marine water and air. The impacts are assessed as " the annual risk of a detrimental health effect for an individual in a critical group." The methodology is presented in Reference [1].

The availability of data to assess the various elements of the fuel cycle varies, for spent fuel recycling; radioactive emissions to air and water; and the categories of radioactive solid waste, are well documented and characterised. For mining and milling however, the data is less comprehensive,

the information on active discharges and the radiological impacts from mill tailings being more limited. Mine A has no reported effluents due to their strict water management strategies. Mine B reports some controlled releases of effluent from their ponds. Reported emissions to air in both cases are all non-active, except for Radon. Other radionuclides however, have not been included, the long life alpha emitters, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, and ^{210}Po. The wastes from the mines are also classified as LLW, but no information on the composition of these tailings was available.

To address the differences in the data sets for reprocessing compared to mining and milling, information from the ETH inventory [6] has been used to supplement the information. The ETH Uranium mine is a 'model' mine based on average values collected from literature, data originates from mines with comparable ore grade to Mine B (0.3%), being representative of open cast mining of medium to high grade deposits.

Mine A and Mine B have total risk (TJ^{-1}) scores lower than reprocessing, however, for the reasons stated this cannot be seen as an accurate assessment of the impacts associated with mining and milling. When data for the ETH mine is used to supplement the data set indications are that risks from the direct discharges are greater/ comparable to that of reprocessing (same order of magnitude). Table IV.

It is worth noting that if the assessment of impact had been carried out based on total activity rather than total risk the picture would have been different, which indicates the importance of applying screening factors Table V.

Extending the assessment to the whole of the open versus closed fuel cycle, reprocessing will reduce some of the burdens from mining and milling, however; overall the total burdens are similar. Table VI.

This LCA of the fuel cycle currently relates to uranium oxide recycling. The fuel cycle has been extended within the nuclear industry to include the production and use of Mixed Oxide Fuel (MOx). It is BNFL's intention to extend the model to include the production, use and recycling of MOx Fuel. In addition the model is based on the design flowsheet for Thorp, rather than operational data.

MOx fuel consists of a mixture of uranium and plutonium oxides, the plutonium substituting for fissile ^{235}U. The use of this fuel enables plutonium to be utilised as a energy resource rather than being stored or disposed of directly in spent fuel. The benefits of producing and recycling MOx fuel have been assessed and compared to that of direct disposal. The outcome is discussed below, in terms of the volume of waste, radioactivity and radiological toxic potential. The results are based on the recycling of valuable uranium and plutonium products of previous irradiations and covers several cycles of fuel irradiation, pond cooling, recycling and fuel fabrication. The scenario covers 60 years of PWR operation split into six tranches each lasting 10 years and generating 1 GW.y of electricity. The first tranche consists of uranium fuel exclusively, following which in the second tranche first generation Mox (a) assemblies are utilised, to displace some of the reactor core, and after 20 years second generation Mox (b) is available for use in the core. Both MOx (a) and (b) can be produced from recycled products. In the open cycle the reactor uses 160t of enriched uranium fuel over 60 years, whereas the closed cycle requires 140 t of uranium fuel, 11.6 t MOx (a) and 8.4 t MOx (b) [7].

4. VOLUME OF NUCLEAR WASTE FORMS.

Comparison can be made of the volumes of the waste streams for different fuel cycles, including mining and milling tailings, low level waste (LLW), intermediate level waste (ILW) and high level waste (HLW). Direct disposal (open cycle) is compared with MOx recycle in Table VII.

From Table VII it is clear that total waste arisings are lower for the closed cycle, the arisings of mine wastes which dominate the totals are 12.5% lower for the same energy output, reflecting the reduced uranium fuel requirement due to Pu recycling. . This benefit is extended to 25% by recycling uranium and plutonium, indicating the potential loss of energy resource had the irradiated fuel been directly disposed of, rather than recycled. Overall the total volumes are comparable for open and closed cycles for HLW and ILW. The benefit comes in the amount of heat generating, long lived waste, which requires the most careful handling and disposal, which is roughly a factor of ten lower for the closed cycle. Similar proportions of the various waste stream categories exist for Uranium Oxide recycling, demonstrating the benefit of recycling versus direct disposal.

The situation regarding the generation, storage, use or disposal of plutonium is also of interest. For the open cycle although no plutonium is separated for storage or reuse there is an accumulation of plutonium in the irradiated fuel, which will be directly disposed of in a repository. Over six tranches this represents a quantity of 1600 kg, when ready for disposal after 40 years, the ^{241}Pu has largely decayed to ^{241}Am, leaving 1500kg in total. (This is the quantity left at the time of disposal, not the greater quantity generated from neutron capture in the uranium, a major fraction of which was fissioned prior to discharge from the reactor. For the same energy output, the closed cycle leaves about 750 kg of plutonium in the MOx (b) assemblies, plus the uranium and MOx (a) assemblies left after the last generation once the ^{241}Pu has decayed. This reduction, compared to the open cycle, represents the quantity of recycled plutonium which is fissioned in MOx fuel. The use of

TABLE IV. AERIAL AND LIQUID DISCHARGES [1]

Human Irradiation: Direct discharges	Thorp Reprocessing	Mine A Uranium Mine	Mine B Uranium Mine	ETH Uranium Mine
Marine	1.20E-09	N/A	N/A	N/A
Freshwater	N/A	N/A	2.00E-13	6.90E-09
Air	3.0E-11	6.40E-11	3.60E-12	9.40E-11
Total risk (TJ^{-1})	1.20E-09	6.40E-11	3.80E-12	7.00E-09

TABLE V. AERIAL AND LIQUID DISCHARGES FROM THORP AND THE ETH MINE BASED ON TOTAL ACTIVITY [1]

Liquid discharges Thorp Bq/TJ	Liquid Discharges ETH mine Bq/TJ	Aerial Discharges Thorp Bq/TJ	Aerial Discharges ETH mine Bq/TJ
3.26E+07	1.60E+08	2.67E+11	2.00E+09

TABLE VI. HUMAN IRRADIATION IN THE OPEN AND CLOSED FUEL CYCLE (THORP AND ETH MINE) [1]

Human Irradiation (TJ^{-1})	Open Fuel Cycle	Closed Fuel Cycle
(direct discharges)	8.27E-09	8.78E-09

TABLE VII. WASTE VOLUME ARISINGS

Waste Arising	Waste Volume / GW(e)y Direct Disposal	Waste Volume / GW(e)y MOx Recycle*
Uranium Mining and Milling.	20,000 m^3	17,500m^3 recycling of Pu only 15,000m^3 recycling of both U and Pu
Reactor Operation	50m^3 ILW	50m^3 ILW
	200m^3 LLW	200m^3 LLW
Spent Fuel Management	40m^3 HLW	3.3 - 4.9m^3 HLW
	6m^3 ILW	23 - 31.4m^3 ILW
	? LLW (not available)	92.4 – 105m^3 LLW
Cycle total	20,296m^3	17,891m^3 - 15,391m^3.

*The figures quoted for the recycle case are based on the upper range of the values in the table.

the closed cycle strategy results in about a 50% reduction in total plutonium over that of the open cycle which would otherwise be accumulated by a direct disposal strategy [7].

The overall radioactive content of the final waste products is also important; recycling of spent fuel separates uranium and plutonium, from fission products and actinides. Besides making use of the plutonium as a valuable source of energy, recycling results in the conversion of plutonium atoms (other than ^{241}Pu) having relatively long half lives, into shorter lived fission products. Consequently there is an overall reduction in activity in the medium to long term for the full MOx recycling scenario when compared to the open cycle/ direct disposal route. The reduction in activity, varies from a few percent in the earlier years to over 30% in the medium and long term. This reduction is due to the fact that at longer cooling times plutonium and its daughter products, principally americium, are the dominant species. The significant reduction in activity in the medium and long term is entirely due to reduced plutonium levels, reflecting the lower residual plutonium content in the closed MOx cycle. (The activity of spent MOx fuel is dominated by short lived fission products in the early years, there being an enhanced quantity of ^{244}Cm. This has a relatively short half life (18 years) which after about 100 years reduces to a minimal contribution (2%)) [7].

5. COMPARISON OF OPEN/ CLOSED FUEL CYCLES IN TERMS OF TOXIC POTENTIAL.

As stated in the LCA section comparing radioactivity for open and closed cycles in terms of Becquerels provides a simplistic method for comparing fuel cycles. This however can be misleading, giving insufficient weight to the longer lived nuclides of relatively low specific activity, notably the actinides. In terms of waste forms from open and closed cycles for disposal in an underground repository adequate weighting can be given to important toxic radionuclides, by the use of a methodology, which calculates radiological toxic potential [8].

Toxic Potential (TP) has been developed as a methodology for assessing the impact of different waste forms. The Toxic Potential of a given quantity of any radionuclide is defined as the volume of water into which it would have to be completely dispersed so that the water is considered safe to drink. More specifically it is the volume of water into which it would have to be dispersed, such that an "average" man would not exceed his annual recommended dose limit of 1 mSv if all his drinking water came from a source contaminated with that radionuclide.

$$\text{Toxic Potential } (m^3 \text{ water}) = \frac{\textit{Radionuclide Activity (Bq)} \times 0.712 m^3 \textit{ water/year.}}{\text{Annual Limit of Intake (Bq/year)}}$$

The toxic potential of any waste or residue can be calculated by summing the toxicities of all the radionuclides present giving a comparison for a single point in time. To compare a span over time integrated toxic potential is used, obtained by summing the toxic potentials for each year over the time period under investigation.

For the first 100 years the total radioactivity of the closed cycle is higher than the direct disposal scenario, the isotopic composition also results in the integrated toxic potential being higher for the first 500 years. This is due to the enhanced ^{244}Cm activity in the irradiated MOx fuel. After 500 years, because of ^{244}Cm relatively short half life, the medium to long term toxicity is dominated by plutonium and differences become apparent between open and closed cycles. It is reasonable to argue that, it is the timescales of several hundred years and more that are important, because no waste repository would be expected to disperse radionuclides to the environment on shorter timescales. By 100, 000 years the integrated toxic potential for the closed cycle is around 35% lower than the open cycle. This reflects the consumption and use of recycled plutonium, and the consequent formation of fission products with short half lives. Reduced plutonium levels also result in lower quantities of daughter radionuclides, such as americium, produced by radioactive decay, which contributes to the overall reduction in toxicity over the medium and long term [7].

The above indicates the benefit of producing MOx fuel. LWR MOx recycle can be regarded as a interim step towards a truly sustainable fast reactor fuel cycle since the MOx cycle is fully compatible with fast reactor cycles. In that the plutonium remains useable in fast reactors, whilst utilising fissile plutonium instead of enriched uranium, helping retain fast reactor fuel cycle options open for whenever market conditions are right. In the absence of a fast breeder programme MOx does not represent a negative impact on the nuclear fuel cycle over that of direct disposal as benefits have been gained in the utilisation of reprocessed uranium and plutonium, the necessity for enrichment has been removed, waste volumes for both mining and milling and HLW have been reduced along with the ITP of the HLW.

Following the MOx cycle, eventually there is a build up of plutonium isotopes that are not fissile in a thermal neutron spectrum preventing further indefinite recycle of plutonium. Fast breeders are a much larger step towards sustainability, since all the plutonium isotopes are able to contribute to fission's in the fast spectrum. Combined with a breeding ratio of 1.0 or more, fast reactors allow the full energy potential of the ^{238}U to be realised (theoretically approaching 100 times that of thermal reactors, though realistically perhaps a little less).

The fast neutron spectrum also affects the equilibrium inventory of minor actinides (MA's) because most of these are also fissionable to a greater or lesser extent with fast neutrons. Rather than most of the MA's accumulating, as they do in a thermal reactor, they tend to equilibrate at lower levels, measured in activity or ITP per GW.y of electricity [9]. There are exceptions, notably ^{244}Cu, which tends to accumulate, but the overall result is a benefit compared to thermal reactors.

The higher number of neutrons per fission in fast reactors allows more flexibility in the fuel cycle. There are fast reactor cycles where the minor actinides (MA's) can be fully or partly recycled along with the plutonium [10]. This would allow the MA's to be burnt further than in a conventional fast reactor fuel cycle. This is just one aspect of the very high degree of flexibility fast reactor cycles make possible.

6. SUSTAINABLE BENEFITS OF CLOSED FUEL CYCLES COMPARED TO DIRECT DISPOSAL

Several themes have been discussed in the above paper, which address issues within the open and closed fuel cycle. From the LCA model of open and closed fuel cycles it is evident that reprocessing compared to, mining and milling, has the lowest impact for all non-active burden categories, except ozone depletion which relates to the UK energy mix rather than the actual process. Mining and milling for a range of ore grades exhibiting substantially higher burdens. When this comparison is extended over the whole of the fuel cycle indications are that the burdens between open and closed cycles are broadly equal.

Burdens assessed in terms of a new LCA category 'human irradiation' also indicates that recycling, compared to mining and milling, has a 82.86% lower risk than mining. Although both levels of risk are insignificant, risks within the nuclear industry normally being rounded up to 10^{-6}, because of the uncertainties of calculating risks below this level. This does demonstrate however, that the impact associated with recycling is comparable to mining and milling. It also demonstrates the value of assessing impact in risk terms rather than total activity, as recycling has a higher associated total activity. Extending the assessment to the full cycle results in the risk for open and closed cycles being comparable, in the order of 10^{-9}.

This shows that recycling can make a positive contribution in terms of non-active burdens and as a minimum, is no more detrimental than mining and milling in human irradiation terms.

Recycling further contributes to sustainability in that it enables energy resources to be recovered, which would otherwise be lost through direct disposal. This not only conserves resources of uranium, but if used to displace other forms of energy generation can contribute to the reduction of greenhouse gases in the form of CO_2. Savings per TJ are in the region of 91% for gas and 96.5% for coal. Moving to Fast Reactor cycles dramatically increasing the energy value of this resource base.

Extension of the cycle to incorporate a percentage of MOx within the core, leads to a reduction in the volumes of mining waste of 12.5% (Pu recycle) and 25% (U and Pu recycle) and a shift in the proportions of HLW and ILW. HLW being a factor of 10 lower for the closed cycle, reducing the quantity of heat generating waste, which requires the most careful handling, storage and disposal.

A strategy of recycling plutonium rather than storage or direct disposal, into MOx cycles also benefits the cycle in that there is a reduction of about 50% in the total plutonium over that of the open cycle. The use of the plutonium as a fissile species in fuel also constitutes a "free" resource as it is generated within the uranium oxide cycle, displacing the need to produce enriched uranium. The overall activity is also reduced through the conversion of plutonium atoms (other than ^{241}Pu) into short lived fission products, resulting in a overall reduction in activity, in the medium to long term of over 30%. Values for ITP are also reduced, beyond 500 years due to the lower levels of plutonium, which dominate toxicity in the medium to long term, leading to a reduction in ITP of up to 35% by 100,000 years.

Extending the closed fuel cycle to include entire thermal MOx cores or moving towards fast reactor cycles would further extend these benefits. Fast reactors with a breeding ratio of more than 1.0, allow the full energy potential of ^{238}U to be realised. Activity and the ITP of wastes can also be reduced by fissioning the MA's in fast reactors, rather than accumulating them, as occurs in a thermal

reactor. Further there are fast reactor cycles where MA's can be recycled along with plutonium to be burnt further than in conventional fast reactor fuel cycles.

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