Commercial Value of Used Nuclear Fuel Reprocessed with Elements Separated, Purified and Reduced to Metals

By
Edwin D. Sayre,
Engineering Consultant,
408 356 2769,
pbmpilot@comcast.net

Introduction

Most people due to a complete lack of knowledge of what comprises used nuclear fuel and due to the antinuclear misinformation in the public media think it is dangerous waste to be safely stored away forever. The truth is it is a very commercially valuable material that can be properly processed for use.

Nuclear energy is critical to the future of the US. It is absolutely necessary that the US develop a reprocessing and recycling program for the used nuclear fuel and a development program for the fast breeder reactor that can use all the used fuel and the Uranium 238 that is stored after removing the Uranium 235 for weapons. The fast breeder reactor used fuel can be used in the thermal reactors that are the future energy sources for the US and the rest of the world. The purpose of this paper is to provide the commercial value of the used nuclear fuel. It is essential to undertake a study to determine the cost of reprocessing and separating out the isotopes of future commercial value.

This paper is based upon reprocessing one metric ton of used fuel, originally enriched to 3.2% U235, that has been stored for 50 years after providing 33,000 megawatt days of thermal energy (10560 megawatt days of electricity). This used fuel consists of about 3% fission products with a balance of mostly U238 with about 2.1% of other actinides including 1.3% U235 All the transuranic actinides provide enrichment for a fast reactor.

The used fuel element and isotope content data was provided by Tang Wu at GE Nuclear Energy Div, (1 Wu). The fifty year aged fuel is used for this evaluation because most of the fuel going to reprocessing in the U S will be stored that long Also, the advantage of storing used fuel that long before reprocessing is that most of the highly radioactive isotopes that have short enough half lives will be decayed by then thus making the reprocessing much easier and less costly. It will also make more of the elements have better commercial value.

In Table 1, the composition of the used fuel is separated into various categories for ease in explanation of what they are and their commercial use and value. The subsequent category tables list the isotopes, their half life, radiation, amount, and commercial value. The commercial value is based upon catalog cost in 2008. As indicated in Table 1 the commercial value for one metric ton of reprocessed fuel with metals purified and reduced for commercial use is $651,540. The commercial value of the used fuel from a 1000 MW power plant operating at 32% efficiency and 90% capacity factor for one year is $20,269,708.

Determination of Commercial Value

Most of the used fuel, 96.6% is made up of actinide elements with about 2.1% actinides not including U 238, but are including 1.3% U 235. All the transuranic actinides provide enrichment for a fast reactor.

The value of the actinides was established by the value of natural uranium on the market. The extra value of the transuranics has not been determined Most of the metal values were published in the 2008-2009 Alfa Aesar Catalog for Research Chemicals, Metals and Materials, (2 Alfa). The Commercial Value column on the left for one metric ton of fuel fissioned for 33,000 megawatt days of thermal production. The data input for the right hand column value is for one year of used fuel from one 1000 MW nuclear power plant with 32% efficiency for electrical conversion and a 90% capacity factor.

Table 1 Categories of the Elements in Used Fuel to be Separated

Category	**Amount** gr.	**Value** 1 metric ton	**Value 1000 MW Nuc Plant** for 1 year
Actinides	965,933	$138,138	$ 4,297,473
Fuel Cladding Zirconium Isotopes	3,878	$11,826	367,907
Technetium for Commercial use	771	7,710	239,858
Highly Radioactive Heat Sources	2,316	4,634	144,163
Natural Elements with Stable Isotopes	8,510	335,792	10,446,489
Natural Elements With Radioactive Isotopes	8,057	16,299	507,062
Elements with Natural Radioactive + Fission Isotopes	797	1,594	49,589
Stable Elements with Small Quantities of Manmade Radioactive Isotope	1,935	124,870	3,884,706
Gases in The Fission Products	5,644	10,677	332,161
Isotopes to be processed for storage	398	0000	0000
Total	**998,235**	**$651,540**	**$20,269,708**

The Processes for Separation, Purification of Elements & Reduction to Metal

There are two basic processes that have been used for reprocessing used nuclear fuel. They are the PUREX process which is a chemical solution separating process and an electrometallurgical process. The chemical solution process dissolves the fuel in a chemical solution and separates the elements by element compound solidification and separation from the fluid. The electrometallurgical process dissolves the fuel in molten salt and the elements are separated by various voltages for reduction of the metals on an electrode. After separation the elements are put through the standard commercial processes for purification to meet commercial requirements and are then reduced to pure metals.

In order to save them the gases are removed from the solution first. Then the actinides are removed to significantly reduce the bulk for the separation of the fission products. The highly radioactive heat source elements are separated next followed by removal of the highly radioactive waste elements to allow the rest of the elements to be separated in a very low radiation environment which will help reduce the cost of processing the non-radioactive and very low level radioactive metals. There will be minute quantities, in parts per million of other elements from the fuel in the metals, which should not have any effect on many of their uses.

Actinides

In this group are the uranium isotopes and the transuranic elements, Neptunium, Plutonium, Americium and Curium. All of these elements will eventually be used in the recycled fuel. The uranium isotopes can be reused in thermal reactors and the plutonium isotopes can be used for enrichment in the thermal reactors. All of the other actinides can be separated and recycled into fuel for fast breeder reactors. Because of their small amounts the following actinides will not be listed for value, U233, 0.009gr., U232, 0.001 gr., Th232, 0.006 gr., Th230, 0.03 gr.Pu244, 0.02 gr., Am242, 0,5 gr., Cm242, 0.001 gr., Cm243, 0.1 gr., Cm245, 0.85 gr., Cm246, 0.1 gr. The actinides are listed in table 2

Table 2 Actinides

Isotopes	**Amount Grams**	**Half life Years**	**Radioactivity Mev**	**Commercial Value 1 Metric ton of used fuel**	**Commercial Value Used fuel from 1000 MW Nuc. Plant for 1 Yr.**
U 238	944,100	4.47E9	α 4.2, γ.0496 SFw	Total of	
U 236	3,971	2.34E7	α 4.5, γ.0494 SFw		
U235	7,974	7.04E2	α 4.4, γ.657 SFw	all actinides is valued at	
U234	225	2.45E5	α 4.8, γ.0532 SFw		
Np237	503	2.14E6	α 4.7, γ.0294		
Pu242	454	3.76E5	α 4.8, γ.0449 SFw	$163 per Kg	
Pu241	111	14.35	α4.9, γ.1485		
Pu240	2,302	6.56E3	α5.2, γ.5424 SFw		
Pu239	5,025	2.41E4	α5.2, γ.0516 SF		
Pu238*	95	87.74	α5.5, γ.0435 SFw .		
*Heat energy 0.56 watts per gram					
Am241	1,084	432	α5.5, γ.0595		
Am243	85	7.37	α5.3, γ.0747 SFw		
Cm244*	4	18,11	α5.8, γ.0428 SFw		
*Heat energy 2.44 watts per gram					
Total	**965,933**			**$138,138**	**$4,397,473**

The actinides should be removed from the solution first in order to reduce the volume of the elements to be further separated, purified and reduced for commercial use.

Fuel Cladding, Zirconium Isotopes

The pure zirconium isotopes from the Zircalloy cladding are all stable except for Zr93 and it has very low level radiation. Much of the beta radiation is absorbed in the metal and the gamma is low enough that the metal could be reused for cladding on the recycled fuel. The value is based on a solid metal slug with isotopes listed in Table 3

Table 3 Fuel Cladding Zirconium Isotopes

Isotopes	Amount gr.	Half life Years	Radioactivity Mev	Commercial Value 1 Metric ton of used fuel	Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Zr96	798	Stable	None		
Zr94	741	Stable	None		
Zr93	718	1.5E6	β0.060, γ .0305		
Zr92	639	Stable	None		
Zr91	590	Stable	None		
Zr90	391	Stable	None		
Total	**3,878**			**$11,826**	**$367,907**

Fission Products

When fissile elements fission they break into lower mass elements. The following categories include stable elements and radioactive elements of various levels.

Technetium for Commercial Use

Technetium 99 has very low radiation and is ideal for many commercial uses, (3Sayre) It is a sister element of rhenium which is lower in radiation level, Rhenium is 62.6% Re187 which has a half life of 4.5E10 and radiation of β0.0026 Mev and no γ. Technetium isotopes are listed in Table 4.

Table 4 Technetium for Commercial Use

Isotopes	Amount gr.	Half life Years	Radioactivity Mev	Commercial Value 1 Metric ton of used fuel	Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Tc98	0.006	4.2E6	β 0.40, γ 0.7454		
Tc99	770	2.3E5	β 0.293 γ 0.090		
Total	**771**			**$7710**	**$239,859**

Highly Radioactive Heat Sources

These fission products decay with fairly short half lives and release energy in the form of heat which can be utilized for electrical energy production for remote places on the Earth, the Moon and Mars. Sr87, 0.003 gr. And Sr86, 0.4 gr. are included in the fission products but are not considered for value. Since about half of the strontium is stable that cuts the heat output for the mass at 0.47 watts per gram. Since only 20% of the cesium is heat producing the net for the mass is 0.084 watts per gram. The Isotopes are listed in Table 5. These isotopes should be removed first from the fission products to reduce the heat and radioactivity of the solution for ease in further processing.

Table 5 Highly Radioactive Heat Sources

Isotopes	Amount gr.	Half life Years	Radioactivity Mev	Commercial Value 1 Metric ton of used fuel	Used fuel from 1000MW Nuc Plant for 1 Yr.
Sr90*	391	29	β0.546, no γ		
*Heat energy 0.93 watts per gram				Ave	
Sr88	350	stable	none		
Cs137*	377	30.17	α0.512, γ 0.662	Value	
*Heat energy 0.42 watts per gram					
Cs135	300	3E6	β 0.21 no γ	$2.00/gr.	
Cs233	1,125	stable	none		
Total	**2,316**			**$4,634**	**$144,163**

Natural Elements with Stable Isotopes

The stable elements include many common metals that have everyday common use and rare earth metals that have continuing market value as new technologies grow. There are such small quantities of Lithium, Germanium Arsenic. Erbium and Thulium that they are not included below. Cadmium is naturally radioactive with 12% Cd113, however in this fission product Cadmium only 0.2% is Cd113 so it is considered non radioactive. Natural elements are listed in Table 6.

Table 6 Natural Elements with Stable Isotopes

Isotopes	Amount gr.	Half life Years	Radioactivity Mev	Commercial Value 1 Metric ton of used fuel	Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Bromine	21.6	stable	none	$ 22	$ 684
Molybdenum	3,345	stable	none	860	26,754
Ruthenium	2,177	stable	none	99,663	3,100,556
Silver	76.2	stable	none	152	4,727
Cadmium	107.8	stable	none	215	6.687
Barium	2,311	stable	none	1,295	40,275
Terbium	2.6	stable	none	78	2,425
Dysprosium	1.4	stable	none	7	218
Rhodium	467	stable	none	233,500	7,264,163
Total	**8,509.6**			**$335,792**	**$10,446,489**

Elements with Natural Radioactive Isotopes

There are several elements in the fission products that are the rare earth elements that are naturally radioactive. They have some isotopes that are stable and some that are radioactive with very long half lives. These elements are not radioactive enough to be any physical hazard in their common usage by society. There are many commercial applications for the rare earth metals. There are commercial processes for separating these elements from chemical solutions and reducing them to pure metals. These elements are listed in Table 7. All natural elements with radioactive isotopes are listed in Table 12 for comparison with the radioactive isotopes coming from the fission products.

Elements with Natural Radioactive + Manmade Fission Isotopes

Some of the elements in the fission products are naturally stable with some natural radioactive isotopes. In the fissioning process some manmade radioactive isotopes are made and added to the natural element. In some cases the amount of manmade radioactivity from the element is not significant compared to the natural radioactivity. In these cases the elements should be satisfactory for commercial use. These elements are listed in Table 8.

Stable Elements with Small Quantities of Manmade Radioactive Isotope

There are some elements that are mostly stable with some small percentage of manmade radioactive isotopes that are so low level that they are safer to use than some other natural elements with natural radioactive isotopes. A good example is Palladium which has only 16 % of Pd107 with a half life of 6.5E6 with radioactivity of only β 0.033 Mev. This is much weaker radioactivity than many of the elements with natural radioactivity that have many commercial uses. There should be many commercial uses of this Palladium metal.

The Yttrium in the fission products has only 0.004 % of the radioactive isotope Y90 mixed in the stable isotope after the 50 year ageing. With the 64 hour half life the amount will decline to an insignificant amount by the time it is separated and purified for commercial use. By that time there will be little or no measurable radioactivity. These elements are listed in Table 9.

Gasses in the Fission Products

There are four gases in the fission products, tritium and three noble gasses, Helium, Xenon and Krypton. Tritium is H3 which is radioactive, Xenon is made up of all stable isotopes and Krypton has one radioactive isotope Kr 85, which is 0.2 % of the total. The gasses will have to be removed from the used fuel together and then separated. There are commercial applications for all three gases. These gases should be removed first to keep from losing them.
These gases are listed in Table 10.

Isotopes to be Processed for Storage

There is a small amount of fission product isotopes that have no current commercial value. Those that we think may have potential economic value in the future should be separated, purified and stored for easy recovery. Those with short enough half live to store for about 200 years and then put back safely into the environment should be stored. Those that have long half lives and could not be aged in a reasonable time should be put back into reactors and transmuted to either stable elements or isotopes with short enough half lives to be stored to age for release to the environment. These isotopes are listed in Table 11. If all the energy used by people in the US is generated by nuclear fission, including heat, transportation, electricity, commercial and industrial is produced by nuclear power the amount of waste isotopes to be processed for storage every year is less than the size of one M&M candy.

Conclusion

The commercial value of the elements in the used fuel as indicated in Table 1 is a big surprise for most people. The commercial value of over twenty million dollars a year for each 1000 MW reactor is based on today's value for the rare metals in the fission products and the fissile metals to be recycled in fuel. The accelerated use of these elements with future technology will probably make them worth more than double that commercial value in 2050.

The United States should be interested in determining the cost of reprocessing the used fuel and preparing the elements for commercial use. It is estimated roughly that there will be a considerable profit in the processing of the elements in the used fuel. DOE is supporting technical proposals for the Advanced Fuel Cycle Initiative (AFCI) for computing and simulating the operations required for processing the used fuel and separating out the commercial elements to determine the cost. There will be further programs to optimize the technology for the processing and establishing the required facilities. It would be economically ideal to start up the first reprocessing facilities by 2020 to start using the used fuel with over 50 years of aging.

Many other countries are moving forward in the reprocessing and recycling the actinides in fast breeder reactors to make fuel from all low enriched fuel for the future use in the thermal reactor power plants. There is enough used nuclear fuel and the uranium 238 stored away to meet all of the US energy requirements for the next 500 years with the proper technical planning and program operation.

Table 7 Natural Elements with Radioactive Isotopes

Element	Amount gr.	Isotope	Percent	Half Life Years	Radioactivity Mev	Commercial 1 Metric ton of used fuel	Value Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Rubidium	365	Rb87	66.8	4.89E10	β 0.273, no γ	$ 4,300	$ 133,773
Tellurium	484.58	Te123	0.0017	1.3E13	e?	675	20,999
Lanthanum	1215	La138	0.0004	1.05E11	β0.26, γ 1.44	2.187	68,032
Neodymium	3,487.5	Nd144	38	2.1E15	α 1.83	7,671	238,645
		Nd145	19,2	>6E16	α?		
Indium	2.6	In115	92	4.4E14	β 0.48	26	809
Cerium	2,355	Ce142	47.	5E16	α~1.5?	662	20,595
Gadolinium	141.6	Gd152	0.12	14E14	α 2.14	778	24,204
Τοταλ	**8,057**					**$16,299**	**$507,057**

Table 8 Elements with Natural Radioactive + Manmade Fission Isotope

Element	Amount Total	Natural Radioactive Isotope	Manmade Radioactive Isotope	% of total	Half Life Years	Radioactivity Mev	Commercial 1 Metric ton of used fuel	Value Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Samarium	797	Sm147		25	1.06E11	α 2.23		
		Sm148		21	7E15	α1.96		
		Sm149		0.3	>1E16	α 1.8?		
			Sm151	1.1	90a	β 0.076, γ 0.0216		
	Sm152 & Sm154 stable isotopes			52.6				
Total	**797**						**$1,594**	**$49,589**

Table 9 Stable Elements with Small Quantities of Manmade Radioactive Isotope

Element	Amount Total gr	Manmade Radioactive Isotope	% of total	Half Life Years	Radioactivity Mev	Commercial 1 Metric ton of used fuel	Value Used fuel from 1000 MW Nuc. Plant for 1 Yr.
Palladium	1370.6	Pd107	16	6.5E6	β 0.033, no γ	$113,710	$ 3,537,516
Yttrium	455.94	Y90	0.009	64 hr.	β 2.28, γ 1.8 weak	4,560	141,866
Europium	110.04	Eu152	0.002	13.4	β 0.727, γ 0.0.122	6,600	205,324
		Eu154	0.62	8.5	β 0.56, γ 0.123		
		Eu155	0.0009	4.73	β 0.44, γ 0.087		
Total	**1,935.23**					**$124,870**	**$3,884,706**

Table 10 Gasses in The Fission Products

Element	Amount Total gr	Manmade Radioactive Isotope	% of total	Half Life Years	Radioactivity Mev	Commercial 1 Metric ton of used fuel	Value Used fuel from 1000 MW Nuc' Plant for 1 Yr.
Hydrogen	0.0034	tritium H3	100	12.5	β 0.0156, no γ	$ 1,000	$ 31,110
Helium	2.89	H4	100	Stable		5	156
Krypton	308.18	Kr85	0.2	10.72	β 0.687, γ 0.514	616	19,164
Xenon	5,332	stable	100	Stable		9,050	281,546
Total	**5,643.0734**					**$10,677**	**$331,976**

Table 11 Isotopes to be Processed for Storage

Isotopes	Quantity	Half Life/Yrs	Radioactivity	Storage or Transmute
Be10	0.000015	1.6E6	β 0.557 no γ	Store & transmute*
Se70 + stable	56	6.5E4	β 0.16 no γ	Transmute
Nb93m,94,95	0.0174	d & long	high average	Store & Transmute*
Sn114/126	90	d & long	medium	Transmute
Sb 125/121/125	18	Sb125 2.76	β 0.0302, γ 0.4278	Store
I127/129	234	I129 6E7	β 0.15, γ 0396	Transmute
Ho165/166m	0.144	Ho166m 26hr	β 1.855, γ 0.0805	Store &Transmute*
Total	**398.16142**			

*** Store & collect to gather enough to transmute**

Table 12. Natural Elements With Radioactive Isotopes – to Compare

Elements	Radioactive Isotopes	% of Total	Half Life Years	Radioactivity Mev Alpha	Gamma	Beta
Hydrogen	H3	???	12.3	0	0	0.0186
Carbon	C14	???	5730	0	0	0.1560
Potassium	K40	0.0117	1.25E8	0	1.4608	1.3800
Vanadium	V50	0.250	3.9E17	0	1.554	0.7330
Rubidium	Rb87	27.830	4.69E10	0	0	0.2730
Cadmium	Cd113	12.22	9E15	?	?	?
Indium	In116	95.7	4.4E14	0	0	0.490
Tellurium	Te123	0.908	1.3E13	0	0	E
Lanthanum	La138	0.09	1.6E11	0	1.4358	0.2600
Neodymium	Nd144	23.80	2.1E15	1.83	0	0
Neodymium	Nd145	8.30	6E16	?	0	0
Samarium	Sm147	15.0	1.06E11	2.23	0	0
Samarium	Sm148	11.3	7..0E15	1.86	0	0
Samarium	Sm149	13.8	1E16	1.8?	0	0
Gadolinium	Gd152	0.20	1.1E14	2.14	0	0
Dysprosium	Dy156	0.20	>1E16	?	?	?
Lutetium	Lu176	2.60	3.7E10	0	0.570	0.3069
Hafnium	Hf174	0.16	2E15	2.5	0	0
Tantalum	Ta180	0.012	2.8E12	0	0	?
Rhenium	Re187	62.60	4.5E10	0	0	0.0026
Osmium	Os186	1.58	2E15	0	0	~0.275
Platinum	Pt190	0.01	7E11	3.180	0	0
Bismuth	Bi209	100	7E19	3.07?	0	0
Radium	Ra226	100	1600	0.7845	0.4862	0
Thorium	Th232*	100	1.4E10	4.01	0.0590	0
Polonium	Pa231	~100	3.28E4	5.01	0.0275	0
Radon	Rn222	~100	3,842days	5.480	0.510	0
Uranium	U234*	0.0055	2.45E5	4.775	0.0532	0
Uranium	U235*	0.7200	7.04E8	4.401	0.1857	0
Uranium	U238*	99.2745	4.468E9	4.196	0.0496	0

* Self fissile weak

References

1, Wu, personal letter from Tang Wu, 3-06-96

2, Alfa, Alfa Aesar, A Johnson Matthey Company, Research Chemicals, Metals and Materials Catalog, 2008-2009

3, Sayre, Sayre, E. D. "Technetium, A Manmade Sister Element and Backup Alloying Element For Rhenium," Rhenium and Rhenium Alloys, Edited by Boris D. Bryskin, Proceedings of National Symposium on Rhenium and Rhenium Alloys, February 9-13, 1997, Orlando, FL, Published by TMS, The Minerals, Metals and Materials Society, 420 Commonwealth Drive, Warrendale, PA,15086