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Composition of Products Formed by Thermal Neutron Fission of ^{235}U

III. Isotopic Composition and Atomic Weight of the Fission Product Elements

JAN PRAWITZ

Research Institute of National Defence, Dept. 1, Sundbyberg 4, and Institute of Inorganic and Physical Chemistry, University of Stockholm, Sweden

The isotopic composition and atomic weight of the fission product elements have been calculated for seven different irradiation times between one day and two years, two cooling times, 100 and 3 000 days, and three thermal neutron fluxes 10^{12}, 10^{13} and 10^{14} n cm^{-2} sec^{-1}. Some applications of the difference in composition between the natural and fission product elements are discussed.

Since more accurate nuclear data of the fission products are available, many calculations of their properties have appeared in the literature [1-12]. Most of these works only consider the radioactive isotopes. Calculations on the stable isotopes and their poisoning effect in thermal reactors have been performed by Blomeke and Todd [9], Robb *et al.*[7], Lock [3], and Walker [8]. Part II[12] of this series considers the fission products, both radioactive and stable, from a chemical point of view. Atomic weights of artificially produced elements in the transmercury region are discussed by Glass *et al.*[16]

At the moment of "shut down" of a reactor the fission fragments are highly radioactive, but after moderate cooling times the major part of them has become stable. After 100 days 80 % and after 10 years 90 % of the nuclei are stable or have half-lives longer than 10^{10} years. The fission product elements have other isotopic compositions and therefore also differing atomic weights than the natural elements. These two properties are functions of the irradiation and cooling time. Except for the effect of neutron absorption by the fission products themselves the isotopic composition is independent of the thermal neutron flux.

Presentation. In this paper the isotopic abundances in atomic per cent and the atomic weights have been calculated for all fission product elements for seven irradiation times, (1 and 7 days, 1, 2 and 6 months, 1 and 2 years) and two cooling times, 100 days, a practical moment for fuel reprocessing, and 3 000

Table 1. Isotopic composition of the fission product elements in atomic per cent for seven different irradiation times and two different cooling times. Thermal neutron flux $\leq 10^{14}$ n cm^{-2} sec^{-1}. In those cases where the neutron flux influences the results, values are given for three fluxes, 10^{12}, 10^{13}, and 10^{14} n cm^{-2} sec^{-1}, equal flux for values on the same line. If the compositions after 3 000 days cooling time are not independent of the irradiation time, values are given for two irradiation times: 7 days and depending on the neutron fluxes (10^{12}, 10^{13}, or 10^{14} n cm^{-2} sec^{-1}) 2 years, 6 months, or 1 month. Isotopic abundances of the natural elements are also given. In the half life column y stands for years, d for days, and h for hours.

Fission product										Natural element
Isotope	Half-life for radioactive isotope	Cooling time 100 days. Irradiation time							Cooling time 3 000 days Irradiation time $\leq$2 y	
		1 day	7 days	1 month	2 months	6 months	1 year	2 years		
1	2	3	4	5	6	7	8	9	10	11
^{3}He										10^{-4}
^{4}He		—	—	—	100	—	—	—	100	100
—										
^{70}Ge										20.55
^{72}Ge		—	—	—	0.6	—	—	—	0.6	27.37
^{73}Ge		—	—	—	4.0	—	—	—	4.0	7.67
^{74}Ge		—	—	—	16	—	—	—	16	36.74
^{76}Ge		—	—	—	80	—	—	—	80	7.67
—										
^{75}As		—	—	—	100	—	—	—	100	100
—										
^{74}Se										0.87
^{76}Se										9.02
^{77}Se		—	—	—	2.4	—	—	—	2.4	7.58
^{78}Se		—	—	—	5.1	—	—	—	5.1	23.52
^{79}Se	65 000 y	—	—	—	9.1	—	—	—	9.1	
^{80}Se		—	—	—	17.3	—	—	—	17.3	49.82
^{82}Se		—	—	—	66	—	—	—	66	9.19
—										
^{79}Br		7.9×	8.1×	9.0×	10×	15×	22×	36×10^{-5}	2.3×10^{-3}	50.52
^{81}Br		—	—	—	100	—	—	—	100	49.48
—										
^{78}Kr										0.354
^{80}Kr										2.27
^{82}Kr		—	—	—	0.058	—	—	—	0.060	11.56
		* —	—	—	14.1	—	—	—	14.5 14.6	
^{83}Kr		** 14.1	14.1	14.1	14.1	13.8			14.5 14.2	11.55
		*** 14.1	14.1	13.7					14.5 14.1	
		* —	—	—	25.8	—	—	—	26.6 26.7	
^{84}Kr		** 25.8	25.8	25.8	25.8	26.0			26.6 27.0	56.90
		*** 25.8	25.8	26.1					26.6 26.9	
^{85}Kr	10.27 y	7.43	7.43	7.42	7.34	7.31	7.23	7.01	4.5	
^{86}Kr		52.5	52.5	52.5	52.5	52.5	52.8	52.9	54.4	17.37

1	2	3	4	5	6	7	8	9	10	11
—										
^{85}Rb		28.8	28.8	28.8	28.9	28.9	29.0	29.2	31.3	72.15
^{87}Rb	6.2 × 10^{10} y	71.2	71.2	71.2	71.1	71.1	71.0	70.8	68.7	27.85
—										
^{84}Sr										0.56
^{86}Sr		2.9 ×	2.9 ×	2.9 ×	3.0 ×	3.2 ×	3.3 ×	3.4 × 10^{-4}	4.1 × 10^{-4}	9.86
^{87}Sr										7.02
^{88}Sr		33.5	33.7	34.2	34.8	36.4	37.5	38.3	46.8	82.56
^{89}Sr	50.4 d	12.5	12.1	10.6	9.04	5.25	2.72	1.40		
^{90}Sr	27.7 y	54.0	54.3	55.1	56.1	58.2	59.7	60.2	53.2	
—										
^{89}Y		65.5	66.8	70.6	74.6	84.7	91.2	95.3	99.97	100
^{90}Y	64.2 h	0.029	0.029	0.029	0.029	0.030	0.030	0.030	0.026	
^{91}Y	58.3 d	34.4	33.1	29.4	25.4	15.2	8.67	4.49		
—										
^{90}Zr		0.13	0.14	0.17	0.21	0.26	0.37	0.60	5.4	51.46
^{91}Zr		12.5	12.8	13.5	14.2	16.1	17.2	17.9	17.8	11.23
^{92}Zr		18.9	18.9	18.9	18.9	18.9	19.0	19.0	18.0	17.11
^{93}Zr	9.5 × 10^{5} y	20.3	20.3	20.3	20.3	20.3	20.4	20.4	19.4	
^{94}Zr		20.8	20.8	20.8	20.9	20.9	20.9	20.9	20.0	17.40
^{95}Zr	65 d	7.20	6.91	6.19	5.26	3.20	1.83	0.93		
^{96}Zr		20.0	20.0	20.0	20.1	20.1	20.1	20.1	19.2	2.80
—										
^{93m}Nb	3.65 y	2.6 ×	2.7 ×	3.1 ×	4.0 ×	8.7 ×	21 ×	63 × 10^{-5}	16	
^{93}Nb		5.4 ×	5.9 ×	6.9 ×	8.7 ×	19 ×	48 ×	159 × 10^{-5}	84	100
^{95m}Nb	90 h	0.12	0.12	0.11	0.11	0.10	0.09	0.09	~10^{-10}	
^{59}Nb	35 d	—	—	—	99.9	—	—	—	~10^{-7}	
—										
^{92}Mo										15.86
^{94}Mo										9.12
^{95}Mo		12.5	13.0	14.2	15.9	19.6	22.2	23.8	25.4	15.70
^{96}Mo		2.7 ×	2.7 ×	2.6 ×	2.6 ×	2.5 ×	2.4 ×	2.3 × 10^{-3}	2.3 × 10^{-3}	16.50
^{97}Mo		28.4	28.2	27.8	27.3	26.0	25.2	24.7	24.1	9.45
^{98}Mo		28.2	28.1	27.7	27.1	25.9	25.1	24.6	24.0	23.75
^{100}Mo		30.9	30.7	30.3	29.7	28.3	27.4	26.9	26.2	9.62
—										
^{99}Tc	2.12 × 10^{5} y	—	—	—	100	—	—	—	100	
—										
^{96}Ru										5.50
^{98}Ru										1.91
^{99}Ru										12.70
^{100}Ru										12.69
^{101}Ru		43.4	43.4	43.8	44.1	44.9	45.5	45.9	47.0	17.01
^{102}Ru		33.1	33.2	33.4	33.7	34.3	34.7	35.1	35.9	31.52
^{103}Ru	40 d	4.24	4.03	3.35	2.68	1.33	0.70	0.36		
^{104}Ru		15.8	15.8	15.9	16.1	16.3	16.5	16.7	17.1	18.67
^{106}Ru	366.6 d	3.52	3.51	3.46	3.39	3.09	2.66	2.02	0.01	
—										
^{103}Rh		—	—	—	100	—	—	—	100	100
—										
^{102}Pd										0.96
^{104}Pd										10.97
^{105}Pd		79	79	79	78	77	74	71	64	22.2
^{106}Pd		5	5	5	6	8	11	14	23	27.3
^{107}Pd	5 × 10^{6} y	—	—	—	10	—	—	—	9	
^{108}Pd		—	—	—	4	—	—	—	3	26.7
^{110}Pd		—	—	—	1	—	—	—	0.9	11.8

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<tr><td>^{124}Sn</td><td></td><td colspan="7">23</td><td>23</td><td>5.98</td></tr>
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1	2		3	4	5	6	7	8	9	10		11
^{124}Xe												0.096
^{126}Xe												0.090
^{128}Xe			—— 2×10^{-3} ——							2×10^{-3}		1.919
^{129}Xe												26.44
^{130}Xe												4.08
^{131}Xe		*	13.6	13.4	13.3	13.3	13.3	13.3	13.3	13.4	13.3	21.18
		**	12.8	12.0	11.9	11.8	11.7			12.0	11.7	
		***	11.8	11.0	10.5					11.0	10.5	
^{132}Xe		*	20.1	19.7	19.6	19.6	19.6	19.6	19.6	19.7	19.6	26.89
		**	18.9	17.7	17.5	17.5	17.4			17.7	17.4	
		***	17.5	16.2	16.5					16.2	16.5	
^{134}Xe		*	36.3	35.6	35.5	35.5	35.5	35.5	35.5	35.6	35.5	10.44
		**	34.2	31.9	31.6	31.6	31.5			31.9	31.5	
		***	31.6	29.3	29.0					29.3	29.0	
^{136}Xe		*	30.1	31.3	31.5	31.6	31.6	31.6	31.6	31.3	31.6	8.87
		**	34.0	38.4	39.0	39.1	39.2			38.4	39.2	
		***	39.1	43.6	44.2					43.6	44.2	
—												
^{133}Cs		*	45.2	37.2	36.1	35.9	35.8	35.9	36.1	39.5	38.1	100
		**	47.1	43.2	42.7	42.6	42.6			46.3	45.7	
		***	50.6	50.1	50.0					54.4	54.1	
^{134}Cs	2.19 y	*			0.01	0.03	0.09	0.16	0.33	—	0.002	
		**			0.1	0.3	1.0			—	0.008	
		***		~0.1	1.4					—	0.010	
^{135}Cs	2.1×10^{6} y	*	12.5	28.1	30.3	30.6	30.8	30.9	31.1	29.8	32.8	
		**	9.0	16.6	17.5	17.7	17.8			17.8	19.0	
		***	2.05	3.24	3.41					3.5	3.7	
^{137}Cs	30.0 y	*	42.1	34.7	33.6	33.5	33.3	33.1	32.9	30.7	29.0	
		**	43.9	40.2	39.8	39.7	39.6			35.9	35.3	
		***	47.2	46.7	46.6					42.2	42.1	
—												
^{130}Ba												0.101
^{132}Ba												0.097
^{134}Ba										* —	0.03	2.42
										** —	0.2	
										*** —	0.2	
^{135}Ba												6.59
^{136}Ba			0.088	0.088	0.088	0.088	0.087	0.087	0.086	0.077		7.81
^{137}Ba			0.54	0.56	0.62	0.70	1.0	1.5	2.5	13.0	14.0	11.32
^{138}Ba			99.2	99.2	99.2	99.2	98.9	98.4	97.3	87.0	85.7	71.66
^{140}Ba	12.8 d		0.37	0.32	0.19	0.11	0.04	0.02	0.01			
—												
^{138}La	2×10^{11} y											0.089
^{139}La			—— 100 ——							100		99.911
—												
^{136}Ce												0.193
^{138}Ce												0.250
^{140}Ce			36.3	36.5	37.1	37.8	40.0	41.4	43.9	51.1		88.48
^{141}Ce	32.8 d		4.34	4.26	3.41	2.63	1.23	0.72	0.35			
^{142}Ce	5.1×10^{15} y		34.8	35.0	35.4	36.0	37.8	39.5	41.9	48.8		11.07
^{144}Ce	284.5 d		24.4	24.4	24.0	23.6	21.5	18.5	13.9	0.03		

1	2		3	4	5	6	7	8	9	10		11
—												
^{141}Pr			99.30	99.40	99.64	99.79	99.93	99.96	99.98	100		100
^{143}Pr	13.95 d		0.70	0.60	0.36	0.21	0.07	0.04	0.02			
—												
^{142}Nd								*0.006	0.01	—	0.01	27.13
						** 0.005	0.02			—	0.02	
				*** 0.01	0.04					0.01	0.03	
^{143}Nd		*	36.0	36.0	35.8	35.5	34.5	33.2	31.5	28.6	28.3	12.20
		**	36.0	36.0	35.7	35.4	34.0			28.6	28.3	
		***	36.0	36.0	35.4					28.6	28.3	
^{144}Nd	2.2×10^{15} y	*	7.3	7.4	8.0	8.8	11.7	14.8	18.8	26.6	26.8	23.87
		**	7.3	7.4	8.0	9.0	12.3			26.6	27.1	
		***	7.3	7.4	8.4					26.6	26.9	
^{145}Nd			24.1	24.1	23.9	23.7	23.0	22.2	21.1	19.0		8.30
^{146}Nd			18.4	18.4	18.2	18.0	17.5	16.9	16.1	14.5		17.18
^{146}Nd	11.6 d		0.037	0.030	0.017	0.010	0.003	0.002	0.001			
^{148}Nd			10.2	10.2	10.1	10.0	9.7	9.4	8.9	8.0		5.72
^{150}Nd			4.0	4.0	4.0	3.9	3.8	3.7	3.5	3.2		5.60
—												
^{147}Pm	2.66 y		———	———	———	100	———	———	———	100		
—												
^{144}Sm												3.16
^{147}Sm	1.25×10^{11}y		6.9	7.0	7.9	8.8	12.4	17.3	24.6	52		15.07
^{148}Sm								* 0.1	0.2	—	0.1	11.27
						** 0.2	0.5			—	0.1	
					*** 0.3					—	0.2	
^{149}Sm		*	54.3	53.8	50.1	45.8	32.2	20.7	10.5	28	7	13.82
		**	54.2	50.1	30.1	17.6	5.8			26	3	
		***	53.6	33.5	9.0					17	5	
^{150}Sm		*	0.01	0.5	3.7	7.5	18.7	27.6	33.3	2	21	7.47
		**	0.1	4.2	23.7	45.1	45.1			2	25	
		***	0.8	20.8	44.8					10	23	
^{151}Sm	93 y	*	21.4	21.3	20.9	20.3	18.2	15.8	12.0	10	7	
		**	21.3	20.9	18.4	15.8	9.1			10	5	
		***	21.3	17.3	7.5					8	4	
^{152}Sm		*	13.7	13.8	13.9	14.1	14.4	15.2	16.0	7	10	26.63
		**	13.7	14.2	16.6	18.8	23.6			7	13	
		***	13.8	17.7	27.9					9	15	
^{154}Sm			3.70	3.70	3.67	3.63	3.47	3.29	2.98	1.9		22.53
—												
^{151}Eu			0.2	0.2	0.2	0.1	0.2	0.7	0.9	8.0	6.3	47.86
										8.0	3.7	
										6.7	3.1	
^{153}Eu			91	91	91	92	93	94	95	92	94	52.14
^{154}Eu	16 y	*	0.001	0.01	0.05	0.1	0.3	0.6	1.3	0.007	0.8	
		**	0.01	0.1	0.5	1.0	2.9			0.07	2	
		***	0.1	1	4.5					0.7	3	

1	2		3	4	5	6	7	8	9	10		11
^{155}Eu	1.7 y	*	8.4	8.4	8.1	7.6	7.0	5.8	4.2	0.3	0.1	
		**	8.1	8.0	7.0	5.9	3.4			0.3	0.1	
		***	7.9	5.7	2.5					0.2	0.1	
^{156}Eu	15.4 d	*	0.041	0.036	0.024	0.016	0.007	0.005	0.003			
		**	0.041	0.040	0.034	0.028	0.016					
		***	0.044	0.066	0.079							
—												
												0.20
^{152}Gd								* 0.2	0.4	—	2	
^{154}Gd										—	**3.8	2.15
										—	***5.8	
^{155}Gd		*	8.2	8.6	8.9	9.1	10.3	9.4	7.1	44	24	14.73
		**	8.1	7.5	6.1	4.4	2.3			42	16	
		***	7.5	4.5	1.6					30	12	
^{156}Gd		*	29	29	30	31	34	39	46	18	37	20.47
		**	30	31	38	43	54			19	44	
		***	32	42	59					31	48	
^{157}Gd		*	36	34	29	26	12	5.8	2.7	21	2	15.68
		**	34	24	8.1	3.8	1.1			15	1	
		***	25	5.2	0.9					4	0.8	
^{158}Gd		*	20	22	26	28	38	40	39	13	31	24.87
		**	21	31	42	43	38			19	31	
		***	30	42	37					31	30	
^{160}Gd		*	6.5	6.5	6.3	6.2	5.8	5.3	4.8	4		21.90
		**	6.4	6.4	5.8	5.4	4.5					
		***	6.3	5.5	4.4							
—												
^{159}Tb		*	100	100	100	100	99.99	99.99	99.99	100		100
		**	100	100	99.98	99.96	99.92					
		***	100	99.96	99.83							
^{160}Tb	72.3 d	*	10^{-5}	4.10^{-4}	0.002	0.004	0.008	0.011	0.013			
		**	10^{-4}	0.004	0.018	0.035	0.078					
		***	10^{-3}	0.036	0.17							
^{161}Tb	7.15 d		$20 \times$	$20 \times$	$8 \times$	$4 \times$	$1.4 \times$	$0.7 \times$	0.3×10^{-5}			
—												
^{156}Dy												0.0524
^{158}Dy												0.0902
^{160}Dy		*	10^{-4}	0.013	0.054	0.11	0.37	0.75	1.7	0.018	1.9	2.294
		**	0.001	0.13	0.54	1.08	3.5			0.18	4.5	
		***	0.01	1.2	4.8					1.6	6.9	
^{161}Dy		*	100	99.99	99.95	99.9	99.6	99.2	98.3	99.98	98.1	18.88
		**	100	99.9	99.5	98.9	96.5			99.8	95.5	
		***	99.99	98.8	95.2					98.4	93.1	
^{162}Dy												25.53
^{163}Dy												24.97
^{164}Dy												28.18

* Values on this line are calculated for a thermal neutron flux of 10^{12} n cm^{-2} sec^{-1}.

** Values on this line are calculated for a thermal neutron flux of 10^{13} n cm^{-2} sec^{-1}.

*** Values on this line are calculated for a thermal neutron flux of 10^{14} n cm^{-2} sec^{-1}.

days, a moment when the isotopic composition in most cases has become stabilized and independent of the irradiation times considered (See Part II[12], Fig. 8). In those cases where the thermal neutron flux influences the result three fluxes, 10^{12}, 10^{13} and 10^{14} n cm^{-2} sec^{-1}, have been considered. For the two higher fluxes the calculation has been limited to irradiation times up to 6 and 1 month, respectively, because the burn up makes longer times impractical.

The isotopic compositions are summarized in Table 1 together with the natural isotopic abundances taken from Strominger *et al.*[13]. If no value is given for an isotope after a time, the value is either very small or the isotope does not belong to the fission products. The calculated atomic weights are given in Table 2 together with the atomic weights (1955) of the natural elements. The atomic weights are independent of the irradiation time except for seven elements, which are to be found in Table 3.

For a few elements with highly neutron absorbing isotopes, the compositions are also after 3 000 days cooling time strongly dependent on the irradiation time. In these cases two values are given for 7 days, and depending on neutron flux, 2 years, 6 months, or 1 month.

Method of calculation. The number of atoms of the fission product isotopes were calculated for the different irradiation and cooling times and neutron fluxes mentioned above with the modified Rubinson [14] formulae given in Part II[12]. The calculations assume constant thermal neutron flux, constant fission rate, and no fission product removal during irradiation. The required data of fission yields, half-lives, and neutron absorption cross sections are taken from Part I[15]* of this series except for a few more recent data. The isotopic abundances within the elements are then easily computed. By multiplying the abundances of the isotopes of an element with their atomic masses, adding the results, and dividing by 1.000275 the atomic weight on the chemical scale of the element is obtained. Nuclide masses are taken from Wapstra and Duckworth [17]. For five isotopes, where no data are available, the integral mass numbers are used. This uncertainty is negligible because the difference between the integral mass numbers and the corresponding measured nuclide masses in the fission product region is <0.1 %, and the abundances of these elements are low. For some elements, monoisotopic both in Nature and as fission products, the atomic weights adopted for the natural elements have been used.

Errors. The accuracy of the results depends directly on the accuracy of the parameters used. In this work fission yields and cross sections give the largest contributions to the errors, while half-lives and nuclide masses have little influence. The best values of the abundances have a standard deviation of 1 %, while others may have 20 %. However, most values have a standard deviation better than 10 %. Such a deviation will in general only cause a minor deviation in the atomic weights, but is larger than the difference between the physical and the chemical scale, except in the case of elements consisting of mainly one isotope, where the small errors of the nuclide masses dominate.

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* This compilation is in good agreement with that of Katcoff [18], but uses a fission yield of 6.32 % for ^{140}Ba as a standard value instead of Katcoff's 6.44 %. However, the choice of standard value has no or little effect on calculated isotopic compositions.

DISCUSSION

The main difference in isotopic composition between the natural and the fission product elements is the lack of light stable isotopes for most of the fission product elements. The reason for this is that such a light isotope is shielded from build-up from beta-decaying radioactive fission products by a stable isobar with lower atomic number. These fission product elements, therefore, have higher atomic weights than the natural ones. Furthermore, long-lived radioactive isotopes not occurring in Nature due to too short half-lives cause considerable differences in the atomic weights. The elements Tc and Pm with no stable isotopes are included among the fission products. Zn and Ga are not considered here, because only short-lived isotopes of these elements belong to the fission products. The reported results for the element Dy may be of limited value, because the isotope ^{162}Dy not yet reported as a fission product, may be formed in quantities as large as 10 % of ^{161}Dy.

Some fission product elements differ from those in Nature by consisting of one isotope only. These isotopes are ^{81}Br, ^{99}Tc, ^{109}Ag, ^{115}In, and ^{139}La. Other pure isotopes may be produced by chemical separation at a moment when they, or their radioactive precursors, make up 100 % of a chemical element, or else by many consecutive separations at special moments. Such procedures will be investigated in a later work.

About 25 % of the fissions result in stable Xe-isotopes. If the known world reserve of uranium in ores (25 Mton [20]), *i. e.* both ^{235}U and ^{238}U, was burnt up

Table 2. Atomic weights of the fission product elements after an irradiation time $\leq$ 2 years. Cooling time 100 and 3 000 days. Thermal neutron flux $\leq 10^{14}$ n cm^{-2} sec^{-1}. Atomic weights of natural elements (1955) are included.

Element	Fission product Cooling time in days 100	 3 000	Natural element	Element	Fission product Cooling time in days 100	 3 000	Natural element
He	4.003		4.003	In	114.909		114.82
Ge	75.5		72.60	Sn	120		118.70
As	74.91		74.91	Sb	124.6	123.4	121.76
Se	81.0		78.96	Te	129.7	129.6	127.61
Br	80.9198		79.916	I	128.56	128.55	126.91
Kr	84.9		83.80	Xe	See Table 3		131.30
Rb	86.34	86.29	85.48	Cs	134.9	134.8	132.91
Sr	89.11	88.97	87.63	Ba	138.0	137.9	137.36
Y	See Table 3	88.92	88.92	La	138.92		138.92
Zr	See Table 3	93.0	91.22	Ce	See Table 3	140.89	140.13
Nb	94.911	92.910	92.91	Pr	140.92		140.92
Mo	See Table 3	97.3	95.95	Nd	See Table 3	144.7	144.27
Tc	98.911		—	Pm	146.920		—
Ru	102		101.1	Sm	150	148	150.35
Rh	102.91		102.91	Eu	153.0	152.8	152.0
Pd	105.4	105.6	106.4	Gd	157	156	157.26
Ag	108.909		107.880	Tb	158.93		158.93
Cd	See Table 3		112.41	Dy	160.98		162.51

Table 3. Atomic weights of seven fission product elements after various irradiation times. Cooling time 100 days. Thermal neutron flux $\leq 10^{14}$ n cm^{-2} sec^{-1}.

Element	Irradiation time						
	1 day	7 days	1 month	2 months	6 months	1 year	2 years
Y	89.60	89.57	89.50	89.42	89.22	89.09	89.00
Zr	93.4	93.4	93.4	93.3	93.2	93.2	93.2
Mo	97.9	97.9	97.9	97.8	97.7	97.6	97.5
Cd§	* 112.3	112.3	112.3	112.3	112.3	112.4	112.4
	** 112.3	112.3	112.4	112.4	112.5		
	*** 112.4	112.4	112.5				
Xe§	* 133.7	133.7	133.7	133.7	133.7	133.7	133.7
	** 133.8	134.0	134.0	134.0	134.0		
	*** 134.0	134.1	134.2				
Ce	141.63	141.63	141.62	141.60	141.53	141.45	141.31
Nd	144.9	144.9	144.8	144.8	144.8	144.8	144.7

§ The Cd and Xe values also hold for cooling times >100 days, but they depend upon the the thermal neutron flux.
* Values on this line are calculated for a neutron flux of 10^{12} n cm^{-2} sec^{-1}.
** Values on this line are calculated for a neutron flux of 10^{13} n cm^{-2} sec^{-1}.
*** Values on this line are calculated for a neutron flux of 10^{14} n cm^{-2} sec^{-1}.

and the Xe produced was distributed in the atmosphere, the natural atomic weight of Xe would not be notably changed. However, if the uranium in the oceans (2 100 Mton) was burnt up, the atomic weight of Xe would change from 131.3 to 131.5. As Xe belongs to the rare elements in Nature the above result indicates that fission products evenly distributed among the natural elements will not cause a change of the atomic weights. However, concentrated deposits may cause local variations.

If ^{12}C instead of natural O is used as standard value for the atomic weights, this will change the values for six fission product elements only (Br, Nb, Tc, Ag, In, and Pm).

Applications. Since the first self-sustaining nuclear reactor was realized in the Chicago Pile-1 on December 2, 1942 [19], large amounts of fission products have been accumulated. Their isotopic composition differs from the natural elements which means different and sometimes useful nuclear properties. Isotope dilution, activation, and nuclear magnetic resonance analysis methods are favoured, when the desired isotope is present in high concentration and especially when undesired isotopes are not present at all. Mo with high neutron absorption cross section and Pd with low may be useful in nuclear energy facilities. Another useful construction metal is Zr, and as a fission product (yield 35 %) it is completely free from Hf but slightly radioactive due to the isotope ^{93}Zr with 950 000 years half-life. The cross section of fission product Cd generated during 7 days irradiation at a neutron flux of 10^{13} n cm^{-2} sec^{-1} is

4 700 barns, while natural Cd has 2 550 barns. The fission product Ag, consists of 100 % ^{109}Ag, whereas in Nature only 49 % ^{109}Ag, may be useful for the production of 253 days ^{110}Ag. A detailed penetration of Table 1 would certainly show further applications similar to the examples above. Some other utilizations have been pointed out by Glueckauf [21].

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