PHOENIX TYPE CONCEPTS FOR THE TRANSMUTATION OF LWR WASTE MINOR ACTINIDES

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ABSTRACT

A number of variations on the original PHOENIX theme were studied. The basic rationale of the PHOENIX incinerator is making oxide fuel of the LWR waste minor actinides, loading it in an FFTF-like subcritical core, then bombarding the core with a high current beam of accelerated protons to generate considerable energy through spallation and fission reactions. As originally assessed, if the machine is fed with 1600 MeV protons in a 102 mA current, then 8 core modules are driven to transmute the yearly MA waste of 75 1000 MW LWRs into Pu238 and fission products; in a 2 years cycle the energy extracted is 100000 MWd/T.

This performance cannot be substantiated in a rigourous analysis. A calculational consistent methodology, based on a combined execution of the HERMES, MCNP, and KORIGEN codes, shows, nonetheless, that changes in the original PHOENIX parameters can upgrade its performance.

1. The original PHOENIX contains 26 tons MA in 8 core modules; the 1.15 m**3 mudule is shaped for 40% neutron leakage; with a beam of 102 mA the 8 modules are driven to 100000 MWd/T in 10.5 years, burning out the yearly MA waste of 15 LWRs; the operation must be assisted by grid electricity.

2. If the 1.15 m**3 module is shaped to allow only 28% leakage, then a beam of 102 mA will drive the 8 modules to 100000 MWd/T in 3.5 years, burning out the yearly MA waste of 45 LWRs. Some net grid electricity will be generated

3. If 25 tons MA are loaded into 5 modules, each 1.72 m**3 in volume and of 24% neutron leakage, then a 97 mA beam will drive the modules to 100000 MWd/T in 2.5 years, burning out the yearly MA waste of 70 LWRs. A considerable amount of net grid electricity will be generated.

4. If the lattice is made of metal fuel, and 26 tons MA are loaded into 32 small modules, 0.17 m**3 each, then a 102 mA beam will drive the modules to 100000 MWd/T in 2 years, burning out the yearly MA waste of 72 LWRs. A considerable amount of net grid electricity will be produced. A further utilization of the 44% neutron leakage can be contemplated.

INTRODUCTION

In recent years the idea of utilizing spallation reactions in subcritical cores has bred a number of accelerator-cores concepts {1 - 3}. Common to all these is the assumption that future accelerators will deliver protons of about 1600 MeV, in currents ranging from a few tens to a few hundreds of mA. Such high power proton beams will be required if the accelerator-core machines are to be used as practical transmuters of LWR waste isotopes.

The entry of a high energy proton into a target gives rise to a host of spallation reactions. The total neutron output per proton depends on the target volume, mass number of target nuclei, and proton energy. It is an increasing function of all three, and may reach 50. These neutrons emerge with a hard spectrum, hence their envisaged utilizations as transmutation agents proceed via two avenues, namely directly within the hard spectrum or after thermalization. The fractional transmutation rate of a nuclide, e.g. the percentage transmuted in a year, is proportional to the effective one-group absorption cross section of the nuclide and to the average total flux. Comparing hard with thermalized specrta, the former yield higher fluxes, the latter sustain higher cross sections.

An incineration machine combines a proton accelerator with a core. In most studies the core is divided into a 'target' and a 'blanket'. The former is usually the core center, made of high mass materials, target for the protons. The latter is the site where transmutation takes place. Such 'blankets' may contain also fuel, if fuel is utilized to enhance the flux of spallation neutrons streaming out of the target. In thermal concepts a moderator region intervenes between target and blanket.

In the PHOENIX concept, addressing the hazard of the long-lived minor actinides waste, the target and blanket are one and the same. The proton beam enteres an FFTF-type core, initiating the transmutation of americium and neptunium, the fuel in the core. By fission, capture and decay the Np and Am transform into Pu238 and fission products {3}.

A conistent calculational methodology for proton-driven subcritical cores {4} was used to recalculate the original PHOENIX. The resulting performance fall short of the performance claim of the originators. Built of mostly intermediate and low mass number materials, and shaped for high leakage, the original PHOENIX will deliver only 1/5 (to 1/3, if basic neutron data uncertainties are considered) of the claimed power and thus will serve a smaller LWR community than envisaged. Also in discord with the originators, the PHOENIX enjoys a very small reactivity swing during a 100000 MWd/T operation.

Varying design parameters in the original PHOENIX helps regain most of its envisaged performance. Reshaping the PHOENIX 1.15 m**3 module for minimum (28%) leakage increases the spallation neutron yield (below 20 MeV) from 20 to 30, and the B.O.C criticality from .825 to .880, resulting in a much shortened cycle. Utilizing a larger core module of 1.72 m**3 further increases the neutron yield and criticality to, respectively, 32 and .905, bringing the cycle period down to 2.5 years.

If one allows the options of metal fuel {5} and a proton beam splitup to many (a few tens of) small current beams, then with a core module as small as 0.17 m**3 the PHOENIX cycle can be trimmed down to 2 years, serving at the same time as a neutron source (each module with 44% leakage) for further incineration applications.

ELEMENTARY CONSIDERATIONS OF PROTON CURRENT REQUIREMENTS

The performance of a PHOENIX-type machine may be approximately assessed with the help of some elementary considerations. The number of protons in a current of I miliampers is

I(mA) <=> 6 (10**15) I   protons/sec

Let

n = number of spallation neutrons produced per one beam proton,
M = k/(1-k) = multiplication of the spallation source by fissions,
P = neutron production rate in the target

Then

P = 6 I n M (10**15),   neutrons/sec.

Let

f = average target flux, neutrons/cm2/sec
s = effecive microscopic 1G abs. xsection of the fuel, barns
N = number density of the fuel, 1/(barn*cc)
V = target volume, cc

Then also, from a simple balance, and neglecting leakage,

P = N s f V

Let

gl= fuel load in the target, gr

For simplicity assume a mass numer 240 for the fuel, then

gl= (240/0.6) N V = 400 N V

Let

dt = time period, sec
df = destruction fraction of the fuel in time period dt

from elementary considerations

df = 1. - exp{-(dt)(s)(f)}

if the destructed fraction is relatively small during dt, then

df = (dt)(s)(f)

for a period of dt = 1 Year one obtains

1Y df = 0.031sf , s in barns, f in units of 10**15

Let

gd= number of grams fuel transmuted in 1Y,

then

gd= 0.031 s f (400) N V = 12.4 N s f V = 12.4 P

Let

L = number of LWRs whose waste minor actinides is to be transmuted in the target in 1Y (the no. of LWRs 'serviced' yearly)
W = number of waste minor actinides grams per PWR per 1Y

If one fixes the number of grams M.A. transmuted in 1Y to equal the amount of M.A. appearing in 1Y in the waste of L LWRs, namely

gd= LW

then

12.4 (6) I n M = L W

from which, the current required is

I = 0.0134 L W /n/M

Simplifying next by equating the effective 1G target abs. mic. xsection with that of the fuel in the target (i.e., neglecting absorptions in other target componenets), one may proceed with some specifications as follows:

L = 100 , namely 100 LWRs are to be 'serviced' yearly
W = 35000 grams minor actinides waste per LWR per 1Y
n = 30   as an upper limit for the neutron yield per one beam proton in a large target whose volume is occupied mostly by materials of low and intermediate mass numbers
k = .85 to .95 as typical of the criticality range envisaged for an operation of a PHOENIX machine

These specifications, coupled with the last equation above, then yield

[---]
[estimated proton current required for the transmutation of the]
[minor actinides waste of 100 LWRs]
[ ]
[for k = 0.85 -> 240 mA]
[for k = 0.90 -> 160 mA]
[for k = 0.95 -> 80 mA]
[---]

As will become evident from the detailed analyses of PHOENIX variations below, these are reasonable estimates.

An estimation of the relation between proton currents and neutron fluxes may be obtained directly from the 'production-absorption' balance, namely

6 I n (M+1) (10**15) = N s f V

resulting in

= 6 (10**15) I n / { (1-k) V (Ns)} , n/cm2/sec

Specifying, for example,

n = 30
k = 0.9
V = 1000000 cc (1 meter cube)
Ns = 0.01 1/cm, as a typical value for hard spectra
then

a 10 mA current will result in a flux of 0.18 (10**16) n/cm2/sec
a 100 mA current will result in a flux of 1.8 (10**16) n/cm2/sec

Again, detailed results below for the various-type PHOENIX core modules show these to be reasonable flux estimates.

PHOENIX VARIANTS

The analysis of the following four PHOENIX-like machines was performed by a consistent methodology in which the codes HERMES,MCNP, and KORIGEN combine to enable burnup studies of proton driven subcritical cores. A detailed description of the methodology is given in reference 4.

1. In an effort to keep the number of parameters to a minimum the original box-shaped PHOENIX {3} was replaced with a cylindrer, the proton current entering through a base. The 1st cylinder analysed had the original volume of 1.15 meter cube; in order to keep also to the original 40% neutron leakage it had the dimensions of 48.5cm/174cm, height/diameter. Table 1 is a summary of the performance of this target-core. Due to the high leakage, coupled with the fact that most of the core is occupied with light and intermediate mass number materials, the number of neutrons produced by the spallation reactions below 20 MEV is just 20, not 50 as factored in the analysis of the PHOENIX originators. In a burnup of 100000 MWd/T the changes of material densities have both positive and negative effects on the core criticality. On the one hand Pu238 replaces 9% of the minor actinides, raising the k-eff; on the other hand the generation of fission products decreases criticality through increased leakage (smaller cross sections) and absorption. The balance is a very small reactivity swing, a most favorable operational feature. This is in contrast to the originators assessment of a very large swing, from about .80 to over 1.0.

The combination of a relatively weak spallation source with a low criticality renders the power generated by the original PHOENIX only about 1/5 of the claimed power. It means that the destruction of about 800 Kg MA in a PHOENIX module takes about 10 years rather than 2 years, or in other words that an 8 module PHOENIX machine can serve the MA incineration needs of about 15 LWRs, not 75 as claimed. Further, this original PHOENIX is a net consumer, not producer, of grid electricity.

The isotopics of the fuel at EOC is about as in the original PHOENIX report {3}. The MA isotopics at EOC and BOC are not much different so that the establishment of an equilibrium operation, waste MA replacing in the core the incinerated MA, can be safely assumed. This point was demonstrated in more detail by the PHOENIX originators.

2. To increase the power of the PHOENIX machine one has to minimize the leakage out of the core. Rouhgly, neutron leakage will be minimal for the minimal cylinder surface; therefore the 1.15 meter cube PHOENIX module was reshaped with equal diameter and height, hence a 28% leakage. Table 2 summarizes the performance of this module. It can be seen that the spallation neutron yield is 30, compared with 20 in the original 40% leakage module, and the BOC criticality is .88, not the original .83. As a consequence this variant is considerably more powerful, delivering net grid electricity and reaching 100000 MWd/T in 3.5 years. The higher power density is well below 1 MW/Liter, a reachable value for Na cooled pin structured lattices. The reactivity swing is, again, very small.

3. The above PHOENIX variant may be further upgraded if 5.0 tonnes of MA are loaded into a 1.72 meter cube module, compared with 3.3 tonnes loaded into a 1.15 meter cube core, as in the above variants. Now the neutron leakage is trimmed down to 24%, yielding a 100000 MWd/T cycle length of 2.5 years, with increased net grid electricity delivery. The criticality swings from a BOC .90 to a EOC .95. The reactivity gain in a Na voiding is 5%, therefore the module remains subcritical when coolant is lost. This PHOENIX variant is the closests approach the original 2 year cycle claim, without entering the regime of Na voided supercritical cores. A performance summary is given in Table 3.

4. A powerful PHOENIX variant can be envisaged if one considers metal fuel. Specifications for MA metal fuel can be found in ref. 5. volume fractions of the lattice components remain about the same as with oxide fuel, but the higher actinides density coupled with the harder neutron spectrum render this variant much more reactive than the oxide variants described above. As a result a small module of 0.17 meter cube has a high BOC criticality of .94, sustaining at the same time a high neutron leakage of 44%. The 100000 MWd/T cycle now takes 2 years, with a net production of grid electricity. There is a small downward reactivity swing during the cycle. A performance summary is given in Table 4.

SUMMARY

Some of the engineering and performance parameters of the four PHOENIX variants here studied are tabulated below. In all four variants the modules are FFTF type lattices (except that variant 4 has metal fuel). In each of the four machines the total minor actinides load is 26 tonnes. Due to uncertainties in basic interaction data the performance values quoted in the table cannot be considered accurate to better than 30%

PHOENIX variant	proton current mA	fuel type	no. of modules	module volume m3	RxH cmxcm	machine to grid <MW>	neutron leakage %	LWRs served yearly
original	102	oxide	8	1.15	87x48	- 640	40	15
2	102	oxide	8	1.15	57x113	+ 640	28	45
3	100	oxide	5	1.72	65x130	+2500	24	70
4	102	metal	32	0.17	30x60	+2200	44	72

REFERENCES

1. Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation
PSI Proceedings 92-02
PSI, Switzerland, March 1992

2. Workshop on Nuclear Transmutation og Long-Lived Nuclear Power Radioisotopes
Inst. of Nuclear Power Engineering, Obninsk, July 1991

3. G. J. Van Tuyle et al.
Accelerator-Driven Sub-Critical Target Concept for Transmutation of Nuclear Waste
BNL- 46365 Dec 1991

4. M. Segev
A Methcdology for Neutronic Analysis of Fission Cores Driven by Accelerated Protons
Sub. Nucl. Sci. Eng. 1993

5. T. Mukaiyama et al.
Conceptual Study of Actinide Burner Reactors
Proc. Reactor Physics Conf.
Jackson Hole USA 1988

TABLE 1. PHOENIX - OXIDE FUEL - 40% LEAKAGE (ORIGINAL DESIGN)

target	:	cylindrical, height/diameter = 48.5cm/174cm
lattice	:	FFTF
fuel mixture	:	oxide M.A. from the CURE process ('PHOENIX' fuel)
coolant	:	sodium
Kg. m.A. loaded	:	3330
leakage (BOC)	:	40.0 %
protons energy	:	1600 MeV
beam current	:	13 mA
beam requires	:	20.8 MW(protons)*8 = 166 MWth target power

	B.O.C.	730 d	3800 d	5530 d
n-spall	20.8	20.6	20.6	
k-eff	.825	.829	.833	
leakage	39.9 %	40.0 %	41.2 %	
flux	5.34+14	5.53+14	5.96+14	0.0
MW/Liter	.072	.075	.078	
trgt MW	83.5	86.3	90.3	
grid mW	-82	-80	-76	
MWd/T	0	18600	100000	

		Kg. in target			Kg. difference 5530d - BOC
He 4		6.353e-01	4.084e+00	4.468e+00	
O 16	4.442e+02	4.441e+02	4.439e+02	4.439e+02	
Ne 22		2.258e-04	3.606e-03	4.375e-03	
Na 22		7.788e-04	1.863e-03	1.093e-03	
Na 23	3.390e+02	3.390e+02	3.387e+02	3.387e+02	
Mg 24		1.027e-02	5.594e-02	5.596e-02	
Mn 55		1.027e-02	1.664e-01	2.025e-01	
Fe 55		3.687e-02	9.002e-02	5.389e-02	
Fe 56	1.930e+03	1.929e+03	1.925e+03	1.925e+03	
Fe 57		3.497e-01	1.902e+00	1.902e+00	
U 232		1.119e-05	1.171e-03	1.616e-03	
U 233		7.639e-04	3.283e-03	4.016e-03	
U 234		4.211e-01	1.211e+01	1.667e+01	
U 235		4.940e-03	3.618e-01	3.656e-01	
U 236		4.556e-04	1.612e-02	2.111e-02	
Np235		3.809e-03	4.742e-03	1.321e-03	
Np236		7.213e-02	2.813e-01	2.813e-01	
Np237	1.372e+03	1.316e+03	1.093e+03	1.097e+03	-275.
Pu238		5.928e+01	2.884e+02	2.940e+02	+294.
Pu239		2.834e-01	6.860e+00	6.916e+00	+ 6.9
Pu240		4.279e+00	2.175e+01	2.615e+01	+ 26.2
Pu241		1.841e-02	4.035e-01	3.673e-01	
Pu242		8.558e+00	3.905e+01	3.910e+01	+ 39.1
Am241	1.601e+03	1.512e+03	1.173e+03	1.169e+03	-432.
Am242m		5.892e+00	2.276e+01	2.253e+01	+ 22.5
Am243	2.884e+02	2.763e+02	2.293e+02	2.292e+02	- 59.2
Cm242		1.245e+01	1.057e+01	5.320e-01	
Cm243		5.891e-02	2.948e-01	2.808e-01	
Cm244	5.605e+01	5.769e+01	6.079e+01	5.632e+01	+ 0.3
Cm245	3.310e+00	3.637e+00	4.946e+00	4.945e+00	+ 1.6
Cm246		1.765e-02	1.104e-01	1.103e-01	
Cm247		8.815e-05	2.564e-03	2.564e-03	
(total)	6.034e+03	5.970e+03	5.678e+03	5.678e+03	
fis.prd	0.000e+00	6.190e+01	3.462e+02	3.462e+02	+346.

TABLE 2. PHOENIX - OXIDE FUEL - 28% LEAKAGE

target	:	cylindrical, height/diameter = 113cm/114cm
lattice	:	FFTF
fuel mixture	:	oxide M.a. from the CURE process ('PHOENIX' fuel)
coolant	:	sodium
kg. m.a. loaded	:	3330
leakage (BOC)	:	28.0 %
protons energy	:	1600 MeV
beam current	:	13 mA
beam requires	:	20.8 MW(protons)*8 = 166 MWth target power

	B.O.C.	365 d	730 d	1095 d	1300 d	2030 d
n-spall	30.2	30.6	30.3	30.4	30.0	
k-eff	.881	.888	.900	.907	.908	
leakage	28.0 %	28.8 %	29.2 %	29.8 %	30.0 %	
flux	1.47+15	1.59+15	1.81+15	2.00+15	2.03+15	0.0
MW/Liter	.180	.202	.230	.255	.257	
trgt MW	208	233	265	294	296	
grid mw	42	67	99	128	130	
MWd/T	0	24200	51500	82000	100000	

	Kg. in target						Kg. difference 2030d -BOC
He 4		5.316e-01	1.426e+00	2.419e+00	2.998e+00	3.803e+00	
O 16	4.442e+02	4.441e+02	4.440e+02	4.440e+02	4.439e+02	4.439e+02	
Ne 22		1.658e-04	6.237e-04	1.343e-03	1.855e-03	3.374e-03	
Na 22		1.192e-03	2.201e-03	3.153e-03	3.678e-03	2.159e-03	
Na 23	3.390e+02	3.390e+02	3.389e+02	3.388e+02	3.387e+02	3.387e+02	
Mg 24		1.385e-02	2.887e-02	4.596e-02	5.656e-02	5.661e-02	
Mn 55		7.514e-03	2.835e-02	6.116e-02	8.458e-02	1.548e-01	
Fe 55		5.617e-02	1.042e-01	1.497e-01	1.748e-01	1.047e-01	
Fe 56	1.930e+03	1.929e+03	1.928e+03	1.926e+03	1.925e+03	1.925e+03	
Fe 57		4.725e-01	9.832e-01	1.564e+00	1.925e+00	1.925e+00	
U 232		9.162e-06	7.840e-05	2.699e-04	4.501e-04	1.106e-03	
U 233		3.501e-04	6.712e-04	9.333e-04	1.065e-03	1.788e-03	
U 234		2.410e-01	1.068e+00	2.474e+00	3.486e+00	8.133e+00	
U 235		3.902e-03	2.226e-02	7.020e-02	1.171e-01	1.274e-01	
U 236		1.296e-04	6.240e-04	1.830e-03	3.075e-03	5.399e-03	
Np235		6.687e-03	1.034e-02	1.272e-02	1.373e-02	3.825e-03	
Np236		9.475e-02	1.763e-01	2.472e-01	2.814e-01	2.814e-01	
Np237	1.372e+03	1.293e+03	1.213e+03	1.127e+03	1.077e+03	1.080e+03	-292.
Pu236		1.207e-04	5.266e-04	1.242e-03	1.775e-03	1.092e-03	
Pu238		6.822e+01	1.514e+02	2.333e+02	2.765e+02	3.062e+02	+306.
Pu239		3.832e-01	1.696e+00	4.162e+00	6.087e+00	6.168e+00	+ 6.2
Pu240		2.254e+00	4.614e+00	7.047e+00	8.431e+00	1.382e+01	+ 13.8
Pu241		1.351e-02	5.472e-02	1.282e-01	1.850e-01	1.689e-01	
Pu242		1.139e+01	2.242e+01	3.342e+01	3.950e+01	3.958e+01	+ 39.6
Am241	1.601e+03	1.486e+03	1.371e+03	1.251e+03	1.182e+03	1.178e+03	-423.
Am242m		7.789e+00	1.456e+01	2.052e+01	2.343e+01	2.320e+01	+ 23.2
Am243	2.884e+02	2.722e+02	2.559e+02	2.388e+02	2.288e+02	2.288e+02	- 59.6
Cm242		2.734e+01	3.283e+01	3.499e+01	3.593e+01	1.677e+00	+ 1.7
Cm243		1.460e-01	3.967e-01	6.737e-01	8.311e-01	7.916e-01	
Cm244	5.605e+01	6.171e+01	6.686e+01	7.178e+01	7.437e+01	6.891e+01	+ 12.9
Cm245	3.310e+00	3.774e+00	4.304e+00	4.922e+00	5.307e+00	5.306e+00	+ 2.0
Cm246		2.421e-02	5.334e-02	9.026e-02	1.152e-01	1.151e-01	
Cm247		1.610e-04	6.965e-04	1.763e-03	2.669e-03	2.669e-03	
(total)	6.034e+03	5.948e+03	5.853e+03	5.744e+03	5.676e+03	5.676e+03	
fis.prd	0.000e+00	8.395e+01	1.764e+02	2.830e+02	3.494e+02	3.494e+02	+349.

TABLE 3. PHOENIX - OXIDE FUEL - 24% LEAKAGE

target	:	cylindrical, height/diameter = 130cm/130cm
lattice	:	FFTF
fuel mixture	:	oxide M.A. from the CURE process ('PHOENIX' fuel)
coolant	:	sodium
kg. M.A. loaded	:	5000
leakage (BOC)	:	23.6 %
protons energy	:	1600 MeV
beam current	:	19.5 mA
beam requires	:	31.2 MW(protons)*8 = 250 MWth target power

	b.o.c.	226 d	432 d	615 d	902 d	1632 d
n-spall	32.2	31.8	31.4	31.0	31.6	
k-eff	.904	.911	.921	.936	.954	
leakage	23.6 %	23.9 %	24.3 %	25.1 %	25.7%	
flux	2.16+15	2.39+15	2.71+15	3.38+15	5.12+15	0.0
MW/Liter	.255	.280	.316	.401	.603	
trgt MW	440	483	546	692	1040	
grid MW	190	233	296	442	790	
MWd/t	0	20000	40000	60000	100000	

			Kg. in 2/3 target				Kg. difference 1632d - BOC
He 4		3.509e-01	9.708e-01	1.636e+00	2.849e+00	4.019e+00	
O 16	4.442e+02	4.441e+02	4.441e+02	4.440e+02	4.440e+02	4.440e+02	
Ne 22		5.236e-05	1.870e-04	3.754e-04	8.185e-04	1.875e-03	
Na 22		6.178e-04	1.159e-03	1.651e-03	2.557e-03	1.501e-03	
Na 23	3.390e+02	3.390e+02	3.389e+02	3.389e+02	3.388e+02	3.388e+02	
Mg 24		1.273e-02	2.562e-02	3.860e-02	6.431e-02	6.440e-02	
Mn 55		2.639e-03	9.438e-03	1.897e-02	4.144e-02	9.553e-02	
Fe 55		3.237e-02	6.086e-02	8.685e-02	1.348e-01	8.067e-02	
Fe 56	1.930e+03	1.929e+03	1.928e+03	1.927e+03	1.926e+03	1.926e+03	
Fe 57		4.348e-01	8.732e-01	1.315e+00	2.189e+00	2.189e+00	
U 233		2.082e-04	4.221e-04	6.253e-04	1.051e-03	1.751e-03	
U 234		1.247e-01	5.062e-01	1.078e+00	2.397e+00	7.446e+00	
U 235		1.300e-03	6.623e-03	1.786e-02	5.894e-02	6.751e-02	
U 236		5.427e-05	2.577e-04	7.046e-04	2.762e-03	4.638e-03	
Np235		3.902e-03	6.519e-03	8.433e-03	1.132e-02	3.154e-03	
Np236		7.336e-02	1.339e-01	1.832e-01	2.529e-01	2.529e-01	
Np237	1.372e+03	1.300e+03	1.230e+03	1.164e+03	1.042e+03	1.046e+03	-326.
Pu238		5.639e+01	1.229e+02	1.856e+02	2.870e+02	3.376e+02	+338.
Pu239		2.901e-01	1.210e+00	2.737e+00	7.077e+00	7.182e+00	+ 7.2
Pu240		1.414e+00	2.776e+00	4.034e+00	6.084e+00	1.186e+01	+ 11.9
Pu241		7.887e-03	2.976e-02	6.305e-02	1.509e-01	1.380e-01	
Pu242		1.050e+01	2.013e+01	2.888e+01	4.369e+01	4.379e+01	+ 43.8
Am241	1.601e+03	1.497e+03	1.398e+03	1.306e+03	1.141e+03	1.137e+03	-464.
Am242m		7.224e+00	1.325e+01	1.822e+01	2.539e+01	2.514e+01	+ 25.1
Am243	2.884e+02	2.736e+02	2.596e+02	2.464e+02	2.226e+02	2.226e+02	- 65.8
Cm242		3.195e+01	4.401e+01	5.002e+01	5.822e+01	2.686e+00	
Cm243		1.458e-01	4.253e-01	7.385e-01	1.375e+00	1.310e+00	+ 1.3
Cm244	5.605e+01	6.199e+01	6.727e+01	7.193e+01	7.965e+01	7.381e+01	+ 17.8
Cm245	3.310e+00	3.742e+00	4.208e+00	4.698e+00	5.694e+00	5.693e+00	+ 2.4
Cm246		2.210e-02	4.668e-02	7.385e-02	1.350e-01	1.349e-01	
Cm247		1.343e-04	5.416e-04	1.229e-03	3.421e-03	3.421e-03	
(total)	6.305e+03	6.228e+03	6.150e+03	6.069e+03	5.908e+03	5.908e+03	
fis.prd		7.488e+01	1.516e+02	2.300e+02	3.076e+02	3.871e+02	+387.1

TABLE 4. PHOENIX - METAL FUEL - 44% LEAKAGE

target	:	cylindrical, height/diameter = 60cm/60cm
lattice	:	FFTF
fuel mixture	:	metal, M.A. from the CURE process ('PHOENIX' fuel)
coolant	:	sodium
kg. M.A. loaded	:	3330 (into 4 unites)
leakage (BOC)	:	44.2 %
protons energy	:	1600 MeV
beam current	:	13 mA (divided between 4 unites)
beam requires	:	20.8 MW(protons)*8 = 166 MWth target power (from 4 unites)

	B.O.C.	218 d	462 d	737 d	1467 d
n-spall	31.1	30.7	30.3	30.0	
k-eff	.942	.936	.930	.930	
leakage	44.2 %	44.7 %	45.5 %	45.5 %	
flux	2.85+15	2.62+15	2.37+15	2.40+15	0.0
MW/Liter	.746	.669	.592	.585	
trg MW *4	506	454	402	397	
grd MW *4	340	288	236	231	
MWd/T	0	33333	66667	100000	

	Kg. in 4 targets					Kg. difference 1467d - BOC
He 4		3.181e-01	9.625e-01	1.726e+00	2.473e+00	
Ne 22		5.043e-05	2.082e-04	4.819e-04	1.129e-03	
Na 23	1.994e+02	1.994e+02	1.994e+02	1.993e+02	1.993e+02	
Mg 24		6.731e-03	1.366e-02	2.075e-02	2.077e-02	
Mn 55		2.135e-03	8.832e-03	2.048e-02	4.834e-02	
Fe 55		2.712e-02	5.041e-02	6.940e-02	4.154e-02	
Fe 56	1.135e+03	1.135e+03	1.134e+03	1.134e+03	1.134e+03	
Fe 57		2.690e-01	5.448e-01	8.265e-01	8.265e-01	
Y 89		1.271e-03	2.605e-03	3.966e-03	3.989e-03	
Zr 90		6.599e-02	1.336e-01	2.027e-01	2.027e-01	
Zr 91	5.566e+02	5.563e+02	5.559e+02	5.555e+02	5.555e+02	
Zr 92		1.830e-01	3.705e-01	5.619e-01	5.619e-01	
U 233		1.967e-04	4.510e-04	7.759e-04	1.527e-03	
U 234		1.035e-01	4.998e-01	1.272e+00	4.243e+00	
U 235		1.604e-03	8.017e-03	2.239e-02	3.075e-02	
U 236		5.889e-05	3.394e-04	1.075e-03	2.561e-03	
Np235		6.120e-03	9.767e-03	1.142e-02	3.182e-03	
Np236		1.119e-01	2.038e-01	2.774e-01	2.774e-01	
Np237	1.372e+03	1.284e+03	1.199e+03	1.118e+03	1.122e+03	-250.
Pu238		4.861e+01	1.095e+02	1.688e+02	1.988e+02	+199.
Pu239		2.238e-01	9.467e-01	2.178e+00	2.243e+00	+ 2.2
Pu240		1.402e+00	2.960e+00	4.697e+00	9.496e+00	+ 9.5
Pu241		7.439e-03	2.884e-02	6.346e-02	5.831e-02	
Pu242		9.634e+00	1.837e+01	2.617e+01	2.623e+01	+ 26.2
Am241	1.596e+03	1.473e+03	1.357e+03	1.248e+03	1.244e+03	-352.
Am242m		6.624e+00	1.206e+01	1.642e+01	1.626e+01	+ 16.3
Am243	2.901e+02	2.728e+02	2.562e+02	2.404e+02	2.404e+02	- 49.7
Cm242		2.964e+01	3.670e+01	3.453e+01	1.596e+00	+ 1.6
Cm243		1.034e-01	2.850e-01	4.527e-01	4.312e-01	
Cm244	5.773e+01	6.141e+01	6.425e+01	6.621e+01	6.135e+01	+ 3.6
Cm245	3.410e+00	3.723e+00	4.047e+00	4.370e+00	4.370e+00	+ 1.0
Cm246		1.990e-02	4.147e-02	6.469e-02	6.467e-02	
Cm247		1.537e-04	6.155e-04	1.383e-03	1.383e-03	
(total)	5.211e+03	5.083e+03	4.954e+03	4.824e+03	4.824e+03	
fis.prd		1.241e+02	2.497e+02	3.763e+02	3.763e+02	+376.