A Design Framework for Compact Fusion Systems to Burn Fission Product Wastes

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I. Introduction

It seems that a sequence of events have brought us to a confluence of enormous problems of our own making. These are (i) The emergence of strong global warming from our own greenhouse gas emissions, (ii) The plateau in cheap oil production and its impending decline, (iii) The relentless rise of populations due to better access to clean water, abundant food ,improved health care and continued poverty. (iv) The failure to press development of new energy sources, especially fission and fusion. Radical action is required for the very survival of our civilisation, though that is now hindered by the global financial collapse. We need to reliably electrify our transport systems, manufacturing, mining and home heating and services to a high degree, around 75%. This is an immense change to be achieved this century. Only coal has large enough reserves to supply all this high quality energy, but its use must be discontinued to evade large global warming. The use of carbon capture and storage is very expensive, almost doubling the energy costs, and the CO^2 storage must be almost perfect for a thousand years. It is not safe to continue or expand the use of coal until this technology is fully proven. [McNamara I]. We waste about 30% of our energy after it is generated by careless and profligate usage, so energy conservation is a critical contribution.

Predictions that Iraq has a further 300Gb of oil or that the USA has recently 'discovered' enough natural gas for a 100 years are spurious. The real numbers are still 150Gb of oil and 25 years of natural gas. Resources such as tar sands and oil or gas shales have an embarrassingly low energy return and can only add to the total greenhouse gas emissions and extensive environmental damage. There are no 'silver bullet' solutions.

Renewable energy systems based on Wind, Wave and Solar power will have a place in our new energy supplies but cannot handle the totality of our energy needs. Nuclear energy resources are clearly sufficient to run the planet for many thousands of years but deployment is now needed on a huge scale. The known and accessible Uranium supplies are insufficient to support the needed reactor build rate, to 3500 reactors by 2050, beyond about 2035 and the fast reactors which would have solved that problem still need a great deal of development and are now too late. Fusion has been running for 25 years on subsistence funding and appears too late also. However, progress has been sufficient for us to be able to now build Compact Fusion reactors of low power with existing technologies and materials. Their neutron output is sufficient to fill the critical gaps of breeding fresh Plutonium from Depleted Uranium (DU) and to burn the long lived Fission Product wastes (FP) which are the major public objection to the whole nuclear power programme [Galvao et al.]

. The latter is one of the simplest applications and, for industry, the most valuable early mission for Compact Fusion. The version we choose is the Spherical Tokamak which has shown remarkable success in its plasma performance. The basic case we discuss here is for burning Technetium waste and leads directly to a range of commercially viable applications of Fusion. We also examine the case of Caesium which requires other technologies like Laser Isotope Separation (LIS), to be advanced to an industrial scale.

Here we estimate the design parameters for burning radioactive Technetium -99 by transmutation to Ruthenium-100 in a blanket with thermal neutrons. It reveals a significant energy release from the burn which makes the Fusion Core + Blanket self sufficient in energy, lifting the system energy gain factor, Q, from 3.0 for the Fusion Core to 6 with the burning blanket. The process is extremely safe as the radiation drops promptly to the small natural output from Tc-99 when the core turns off , there is no radioactive decay heat and no possibility of a meltdown. We also examine the prospects for a Hot Neutron Blanket to take advantage of the large resonant capture of hot neutrons. The recycling technology needed to periodically separate the Ruthenium from Technetium is much simpler than that for reprocessing spent nuclear fuel.

We briefly review the radiation hazards of long lived waste to show why such processing is necessary and to highlight the care needed in the remote handling of the far more active short lived wastes.

The case of Caesium is more difficult, requiring Laser Isotope Separation of the long lived isotope, Cs-135 to make the process as simple as that for Tc-99. The highly active isotope, Cs-137, has a half-life of 30 years and so could be stored as it is produced. We consider cold neutron blankets which have much larger neutron capture rates to make the burning of Cs-137 more feasible.

II. Fission Product Wastes

Fission reactors produce two classes of radioactive materials which are not found in nature. A Gigawatt-electric power plant produces about 1 tonne of such materials per year, dispersed as 5% of the spent nuclear fuel. The other 95% is unburned Uranium which may be recovered to make up fresh fuel. The two classes of radioactive materials are:

I. Plutonium and other trans-Uranic elements, all of which fission readily or are transmutable by neutrons into fissionable isotopes. These are all part of our nuclear fuel inventory.

II. Fission Products or fragments of the fissioned fuel. Almost all of these decay by a factor of 1000 in about 10 years, a few last to 50 years and only ten last for thousands of years and constitute a long term radioactive waste hazard . These can be separated and burned with a suitable neutron flux. This is the technical solution to the nuclear waste problem.

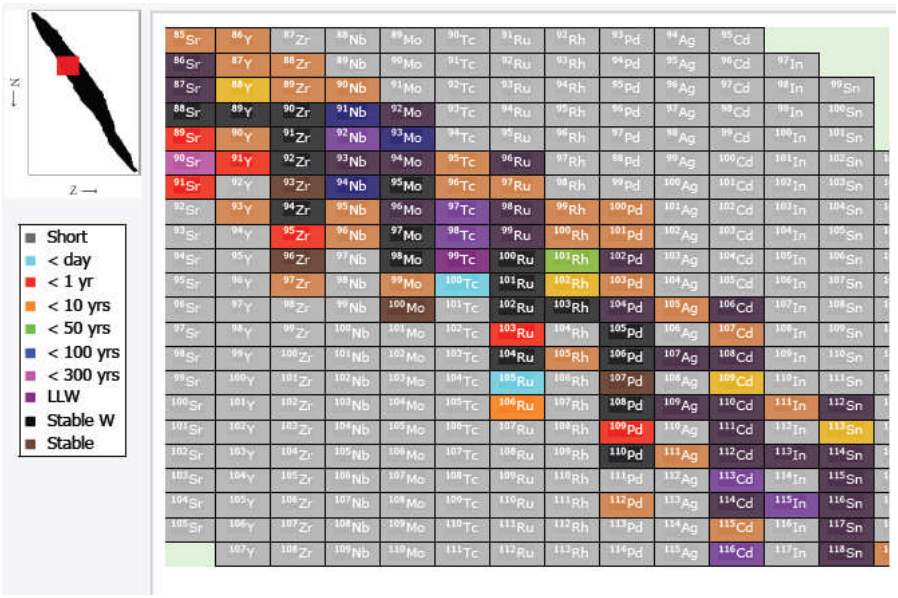


Chart I: All possible Isotopes between Strontium and Tin

This a primary area for Fission Product Waste. The Black and Dark Brown isotopes are stable. The others are all radioactive with 95% decay times as shown.

Fission of Uranium and Plutonium does not split the nuclei in half , but around a 40:60 ratio. Chart 1 above shows all possible Isotopes between Strontium and Tin, colour coded by the rates at which they decay by 96% in a day (gray), year, decade, and finally fall into the canyon of stability (black or brown) with a cosmic lifetime. [Zeleny]. Most are gone in a day and only a few of these are directly produced by fission.

Technetium, element 43, has no stable isotopes at all and only exists from fission somewhere. Technetium-99 dominates the very long term radioactivity burden but is also the simplest to separate and burn. It is named as the man made element. Notice that fission does not produce Silver or Gold but does produce Palladium and Rhodium.

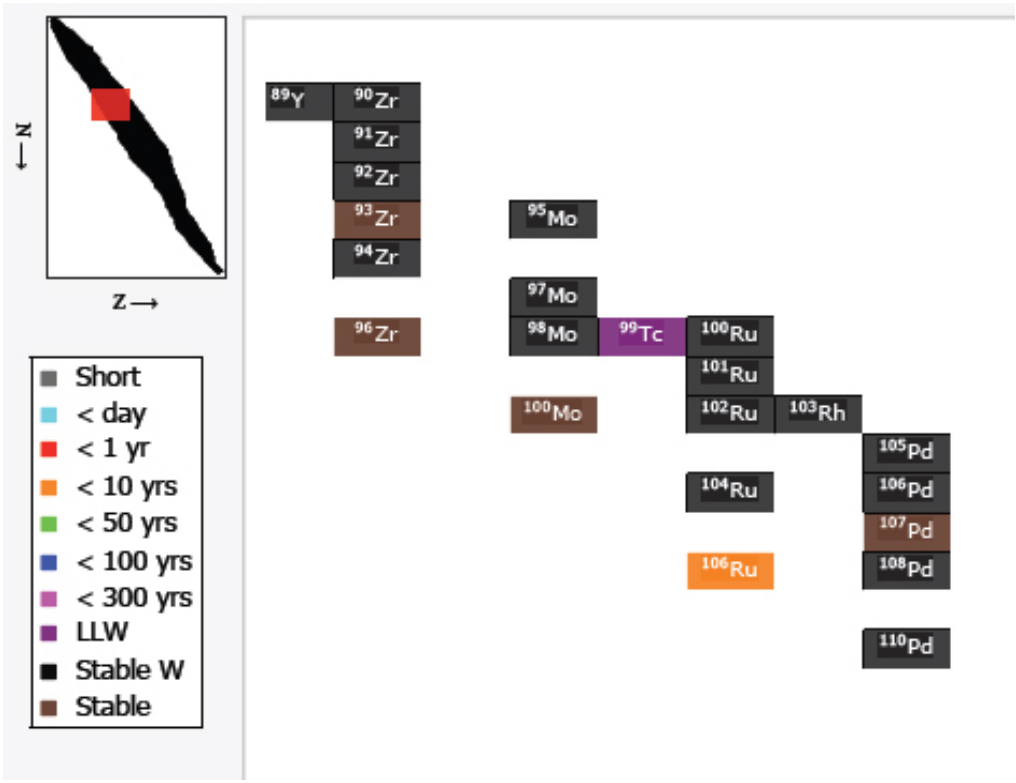


Chart II: Fission Product Waste from Uranium and Plutonium after 1 year of cooling.

None of the other isotopes shown in Chart 1 are present in spent nuclear fuel.

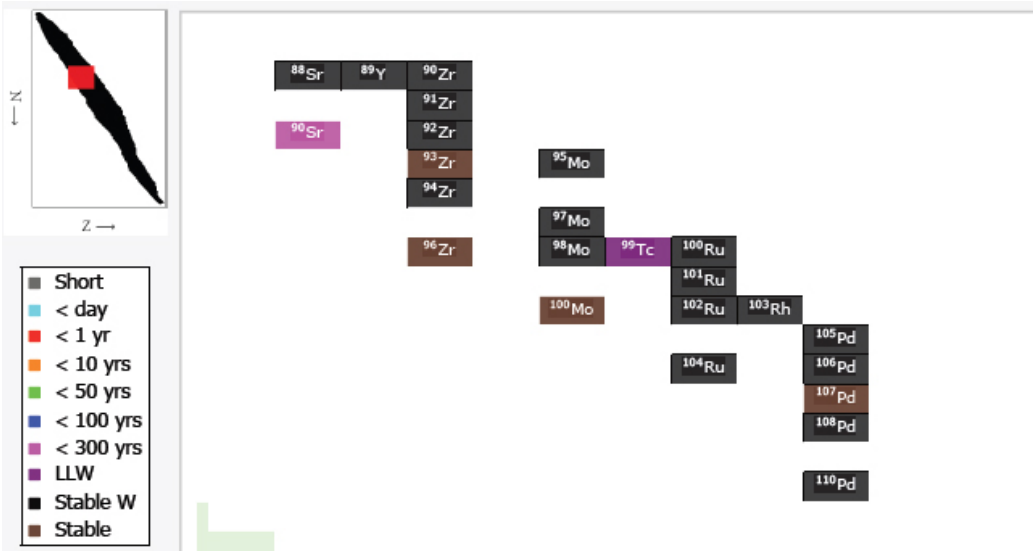
Nuclear fuel starts life as a mix of Uranium and Plutonium as metal, Oxides, Fluorides Nitrides or Carbides, depending on the chosen fuel form. Chart II shows all the isotopes in range in spent fuel, none of the others from Chart I being produced. Spent fuel is extracted as about 20t of fuel containing 5% of highly radioactive FP waste. It is normally cooled for about 10 years, though there is lots of legacy spent fuel up to 50 years old.

This can be reprocessed by say, the UREX method which divides it into 4 streams – (i) Uranium (ii) Trans-Uranics including Plutonium (iii) Solid Fission products (iv) Gaseous FPs like Krypton and Argon. This is one process which separates out over 95% of the Technetium at a stage where it evaporates as Tc Fluoride gas. The longer lived radioactive contents of the Fission Product waste are up to 6% of each tonne: Technitium-99 (61kg.), Zirconium-93 (55 kg.), Palladium-107 (1.2kg.), Tin 126 (1 kg.), and Strontium-90 (45 kg). Similar amounts of their stable isotopes are also produced.

All these elements can be separated chemically, with varying degrees of difficulty, to be burned separately or together in Compact Fusion machines. As we will see, the irradiation of these isotopes can add up to 60% more power output to the Fusion system, so they really do burn.

Radioactive isotopes emit very powerful radiation so very tiny amounts are detectable. However, every year, decade, and century reduces most of them by another factor of 100. By 300 years only the few long lived radioactive isotopes remain a problem.

Chart III: Fission Waste after 10 years cooling
leave only Sr-90, Zr-93 and TC-99 for treatment.



III. The Destruction of Technetium.

Figs. 1,2 Physical states of Technetium and Ruthenium

Technetium – a silvery white metal.

Ruthenium – a hard white Platinate metal in powder form.

The natural units for nuclear processes are the electron Volt (**eV**) at 1.6 10^{-19} Joules of energy, the atomic mass unit **u** at 1.66 10^{-27} kg., and the cross sectional area of a nucleus, a **barn**= 10^{-28} cm^2 . Since a kilo of Technetium contains 6 10^{24} atoms the results all scale up to the familiar engineering units of kW., kg., and m^2.

The neutronics of this system is a particularly simple example of how the Compact Fusion machines work. Tc-99 decays with a half life of 211,000 years by beta (β) emission at 0.293MeV , a very hot electron,. This is a tiny but steady energy output of about 60 milli-watts per kilo, a 4.5cm. cube of Tc-99 metal, but still dangerous to the biosphere as discussed later.

Capture of a single thermal neutron lifts TC-99 (absorption cross section of 20 barns) to an excited state of Tc-100 which promptly emits a spectrum of gamma (γ) rays to settle into its ground state. The energy emitted is calculated by the difference in mass between a Tc nucleus plus the neutron and the mass of the final Tc-100 nucleus. A typical measure for radiative neutron capture is about 6MeV. The final Tc-100 nucleus then has a half life of about 15 seconds, decaying to stable Ruthenium-100:

Tc-99 + n → Tc-100*

→ Tc-100 + γ (6.76 MeV)

[16 Sec.] → Ru-100 + β (3.2 MeV)

The γ spectrum is mostly at energies of 172, 240, and 299 keV and is 95% absorbed in 2cm. of Tc-99 or a similar mass of other materials. Each D-T fusion reaction in the core produces a 3.5 MeV alpha particle and a 14.1MeV neutron. The neutron deposits most of its energy into the cooling system or other blanket layers to become a thermal neutron in a Maxwellian spectrum at the ambient blanket temperature.. With the burn energy of the Tc-99, the total yield is therefore 27.6MeV per fusion reaction, a 57% gain on the 17.6 MeV from the fusion core. The ratio, Q, of the total fusion energy produced to the input of the energy and particle beams which drive the fusion core is estimated to be about 3.0. The Tc burn takes this to Q=4.6 for the total system.

There is a miniscule chance that the Tc-100 can capture another neutron in its 16 sec. half-life, but this leads to Tc-101 which also decays quickly with a 14 min half-life. There is very little net production of such higher Tc isotopes. The Ru-100 can also capture a neutron leading to Ru-101, then to Ru-102, both of which are stable. Ruthenium capture cross sections are a quarter that of Tc-99 and their buildup beyond Ru-100 is very slow. The essentials of the neutronics of a Tc-99 metal blanket are just in the reaction shown above.

It is important to notice that the process is driven entirely by fusion neutrons entering the system. When the fusion power is switched off all reactions stop leaving the 15 sec. decay of Tc-100 and the tiny background output from the natural decay of Tc-100 as the only energy output. Unlike a fission reactor, there is no significant afterheat and no possibility of a meltdown or even overheating of the machine in the case of a loss of coolant.

Ruthenium has similar physical properties to Technetium and indeed can form an alloy with it. As the Tc-99 burns this is essentially what happens. Their chemical properties are different and so separation of the Ruthenium, which oxidises rapidly, from unburned Tc-99 is straightforward. The Tc-99 can be recycled back to the Burner blanket.

IV. Blanket design

A complete blanket design requires a 3D computation of the neutron flows through the steel first wall of the reactor, into the blanket, its cooling system, cladding of burnable material, and structural components. Here we give a simple evaluation of neutron transport parameters, such as absorption and diffusion lengths, which is sufficient to estimate the size of the structures and the general performance to be expected. This gives an upper limit on performance but identifies the Design Space for full computational design.

We simplify the blanket structure to an infinite sheet of iron for the first wall, water coolant to absorb most of the energy of the fusion neutrons, some Zirconium cladding that is almost transparent to neutrons with a cross section of 0.01b, and Tc-99 metal, as shown below. Over 80% of the thermalised neutrons will be absorbed in the first couple of cm. of Tc-99 so the layer would actually be built as two layers to simplify the extraction and recycling process for Ruthenium. Note that an external source of Tritium is required to fuel the fusion Core.

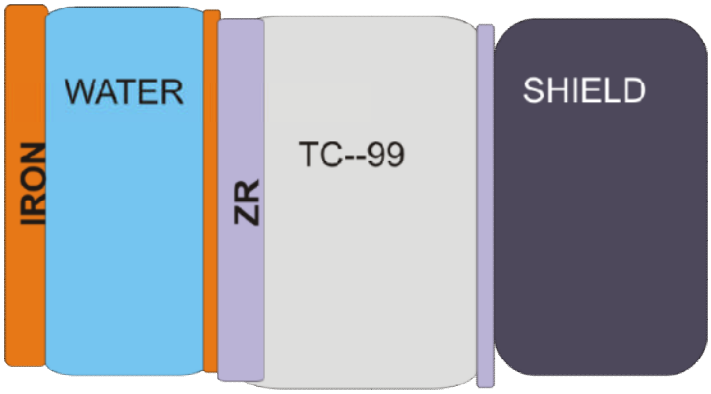


Fig. 3 Sketch of blanket layers from the first wall to final γ ray shielding.

Cladding

The Tc metal must be clad for safe handling and to eliminate contamination of the blanket structures. One option could be Zirconium cladding, which has tiny neutron absorption ~0.01b , as an alloy with manganese, Zircalloy, which has good structural strength. This is the cladding used for fuel rods in PWR reactors. In this form there can be no escape of Tc-99 atoms and the blanket modules remain uncontaminated as in the recommended Enclosed Radioactive Materials System (ERMS) [McNamara II].

Zirconium-93 is also a radioactive Fission Product, with a low neutron absorption of 2.2b and a long life of 1.53My against decay at 0.091MeV. Having a low activity it is not unreasonable to use this FP Zirconium supply to clad the Tc-99 , giving some additional benefit through the slow destruction of Zr-93. Manufacturing complex parts from materials with even low radioactivity is a challenging task. We could contemplate the electroplating of cast Tc-99 ingots with Zirconium until fully robotic manufacturing can be developed.

Neutronics

We need only take account of neutron collisions, which cause diffusion in the materials, and neutron capture in the target nuclei. The effective cross sections of the nuclei for each of these processes determine their rate . Metallic Tc-99 is very dense at ρ = 11200 kg/m^3 , and so it absorbs thermal neutrons readily, allowing for quite a thin blanket. The melting temperatures are high so the blanket remains solid.

Neutron flows are determined by the macroscopic cross sections of materials which are just the product of the number density of atoms and their microscopic cross sections, for collisions and capture. The collision rates determine the diffusion rate and the capture rate determines the reduction length of neutron flux from the source. In this example, the absorption length of 1.1 cm. dominates and diffusion can be ignored in making our estimates – though not in a full computer model. This gives a mass of Tc of some 650kg./m^2 , about 10 years output from a fission reactor. The natural decay energy of the Tc-99 generates only 17 Wm^{-2} of blanket and is not a significant cooling problem.

The following Table I gives the relevant data for all the blanket components and the consequent thicknesses required. We assume that the neutron flux corresponds to 0.25 MW/m of blanket or 9.125 10^{16} neutrons s^{-1} m^{-2} at the first wall. The maximum rate of destruction of Tc-99, if all neutrons were captured by Tc-99 would be 0.47 kg./m^2/year. A 25MW Compact Fusion Burner reactor of this elementary design could therefore dispose of 47 kg/year, most of the full output of a 1000 GWe fission reactor. This is still a small fraction of the Tc-99 in the blanket which may continue to be burned for many years.

Table I. Neutronics properties of the Technetium layer.

ISOTOPE	Tc-99	Tc-100	Ru-100	Ru-101	Tc Layer
PROPERTIES					
Z - protons	43.0	43.0	44.0	44.0	
Weight - At. Mass Units, u.	98.91	99.91	99.90	100.91	
Solid Density - kg/m^3	11200.0	11200.0	11200.0	11200.0	
Melt Pt. - C	2157		2334		
Blanket Temperature ^oC	350.0	350.0	350.0	350.0	
CROSS SECTIONS - barn					
Elastic Maxwellian at 0.253 eV	3.4		6.5	3.7	
Rad. Capture @ Blanket Temp 350 ^oC	16.0		4.5	2.7	
Capture Γ Spectrum MeV	6.8		6.8		
Rad Capture Res integral b	311.6		11.2	100.2	
β decay half life - secs.	6.66E+12	15.8	inf.	inf.	
β energy - MeV	0.3	3.2	0.0	0.0	
Radiation dose Sieverts/(kg. hr.)	0.22				
MACROSCOPIC CROSS SECTIONS					Tc Layer
% Tc-99 & Burn products	99.0	0.1	0.8	0.1	**100.0**
Elastic Scattering - 1/m	23.1	0.1	43.2	24.7	**23.2**
Rad. Capture @ T -blanket - 1/m	107.5	0.0	0.2	0.0	**107.8**
Scatt. Mean free path m.	4.30E-02	1.49E+01	2.30E-02	4.02E-02	**4.31E-02**
Absorption length at T-blanket - m	9.30E-03	1.64E+03	4.12E+00	6.12E+0 1	**9.28E-03**
Capture Fraction @ T-blanket	9.98E-01	5.65E-06	2.25E-03	1.52E-04	
Diffusion Coeff - m.					**3.09E-03**
Diffusion Length,to absorption - m					**1.15E-02**
BLANKET PARAMETERS					
Mass m^{-2} of blanket kg	639.8	0.6	5.2	0.6	**646.3**
Neutron flux/sec. at 250 kW.m^{-2}	9.13E+16				
γ outputs kW/m^2	98.7		0.2		
β outputs kW		46.7			
Tc-99 Annual Burn rate. –kg. m^{-2}	0.47				

At a burnup of 10% the capture fraction for Tc-99 is still 97%, only 3% being captured by Ru-100. The blanket can be burned for a long time without recycling.

A Hot Neutron Blanket

Neutron capture is very sensitive to the neutron energy. The cross section at 0.0253 eV, 20 ^oC, is 19.6 barns. This reduces inversely with the neutron velocity, hence the average cross section for a Maxwellian spectrum at the blanket temperature of 350 ^oC is only 16.0 barns, as listed. At 14MeV the cross section is around 2b and our Tc-99 layer is almost transparent to fusion neutrons.

At energies between 8 eV and 800 eV (11,000 to 0.88 million ^oK) the capture shows a closely spaced set of huge resonances as the neutron connects with internal structure of the Tc-99 nucleus, as shown below [Korean

Atomic Energy Inst.]. The Resonant Integral across the range is 311.6 b as listed in Table I. However, the neutrons do not slow down smoothly but in discrete steps at each collision. The fraction of energy lost at each collision depends only on the mass of the target and is 4% for Tc-99. This ranges from 32 eV to 0.32 eV for a head-on collision across the range so the resonances can be missed in the average 42 collisions it takes to cross the range.

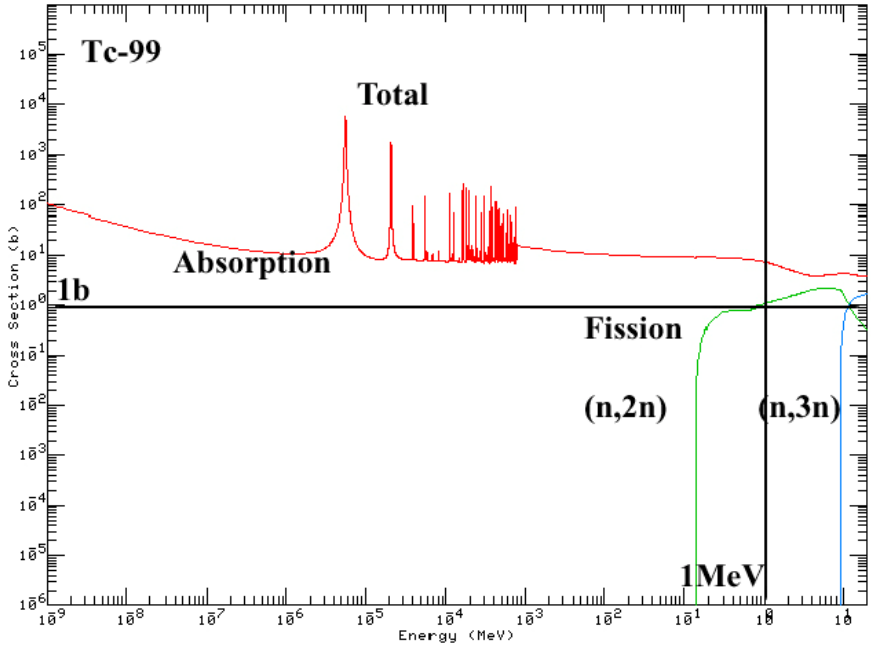


Chart IV. Radiative capture cross sections for Tc-99
and neutron multiplication cross sections for multi-MeV (n,2n) and (n,3n) reactions.

A water coolant layer is an excellent medium for slowing down or moderating neutron energies, absorbing 75% of a neutron's energy per collision with a Hydrogen nucleus. Simple estimates show that a thickness of ~2cm. of water could slow the fusion neutron flux down just enough to form a hot neutron spectrum in this range. Monte Carlo computations are needed to verify this and examine the effects of resonant capture in a thinnerTc-99 layer where the energy loss per collision is far smaller. A hot neutron spectrum could be valuable for other blanket applications. Another factor to be explored computationally is the modest, but useful, 2 barn cross sections for neutron multiplication by multi-MeV neutrons.

Compact Fusion Waste Burner options.

Our principal proposals for a Compact Fusion machine include other inner blanket layers to increase the number of neutrons in the system by reactions with neutron multiplier materials like Beryllium. This absorbs about 3MeV into the Helium nuclei produces but can yield up to 1.6 times as many neutrons [Moir]. These would increase the Tc burn rate by 60% and enhance the total system energy gain to about 46MW, a Q of 5.5, and enough to make it close to the energy self sufficient value of Q=6 with a 33% efficiency of electric power generation and a 50% efficiency of the input power systems.

Another intermediate layer, before the Tc layer, containing Lithium could breed a steady replacement supply of the fusion fuel, Tritium. This would leave only 60% as many neutrons as the simple Tc burner case, a lower Tc burn and less electrical energy generated. With the burn energy released from the Tc-99 the total Q becomes 5.6 at 40MW from a 25MW fusion core.

Clearly, a 1MW Compact Fusion system would provide an acceptable demonstration of all the technologies for this waste destruction process. There are many thousands of tonnes of separated Fission Product Waste already produced by recycling plants, from which sample load of Tc-99 has already been extracted.

V. Radioactive Waste Hazards

The β and γ radiation emitted is all ionizing in the human body , though most of the energy is deposited as heat. The ionizations cause cell damage which is dangerous when β emitters are ingested. The more dangerous form is γ radiation which is highly penetrating and needs heavy shielding when γ emitters are transported.

The measure of radiation dose is the Sievert, 1 Joule/sec. absorbed times an effectiveness factor which is 1.0 for these types of radiation. The annual limit for human exposure is very small at 500 mSv per year for whole body radiation and **1mSv** to a foetus or reproductive cell. This means that homes and workplaces must be scrupulously free of radiation to humans.

Natural radioactivity comes from widely dispersed sources and even then, like the Radon released through spontaneous decay of Uranium, can collect to damaging levels in homes built over granite – as I found to my cost in Princeton. The standard goal set for each kilo of waste processed is to have an output below that of natural Uranium which is regarded as safe because it is already part of our environment. The radiation energy from Tc-99 is about 500 times that from natural Uranium. The radioactivity from the one tonne/yr of nuclear waste produced annually by a 1GWe reactor is millions of times more than Uranium and 20 times more again when separated. The separated volumes are minute by comparison with normal industrial and chemical wastes but this is no reason not to handle them with exceptional care.

In our systems, large quantities of radioactive materials must be handled in small batches and all procedures must be fully robotic so that no human contact with even minute samples is either possible or required. This should also apply to associated nuclear R&D laboratories. Machines may corrode or break but at least they will always follow procedures.

A kilo of Tc-99 produces 0.224 Sv/hr. in β radiation, which would be readily absorbed by a few metres of air or 1 cm. .of Perspex or .2 cm. of Tc-99. It is therefore very dangerous if dispersed in your environment or, like Radium, used to be sold as a healthy drink, but can be handled with simple precautions and shielding. Even stored as pure metal, there can be no guarantee it will not disperse in some way on a 200,00 year timescale. In our Tc-99 burner it is the only naturally radioactive element being handled during the cycle. The β and γ radiation flux from neutron capture and decay of Tc-100 in the blanket is enormously greater but stops in seconds when the fusion core turns off.

Neutrons cause transmutations wherever they go. All the reactor materials are chosen for their low neutron absorption which eventually produces very small amounts of their radioactive isotopes. However, none of these is long lived and the valuable materials can all be recycled after decommissioning within about 100 years of storage in suitable reclamation vaults.

VI. Other Wastes & Caesium

The burning of Technetium is, as we have seen, straightforward. The other long lived wastes to be burned have other problems in separation and choice of the chemical form for the blanket. The blanket modules will vary accordingly. We only mention some typical issues here.

Iodine-129 has a half life of 17 Myrs with a β emission at 0.191 MeV and so is far less active than Tc-99. However, it poses a much more serious biohazard because of the solubility of its salts and its tendency to concentrate in the thyroid gland if ingested. This makes it, and the other such isotopes, a potential source of energy for small devices or for medical uses, but the quantities are minute. Iodine is volatile in many mixtures and it is not permitted to vent it to atmosphere.

Caesium

Fission product waste is about 20% Caesium in three main isotopes whose nuclear properties raise special problems for their transmutation and burning. Caesium is a major contributor to the radioactivity of spent fuel. The elastic collision cross sections are similar for all, but the capture cross sections drop rapidly from 23.58b for the only stable isotope, Cs-133, to 0.2b for the most radioactive isotope, Cs-137, as shown in Table III and the accompanying Chart VI. All the natural β decays lead to stable Barium isotopes.

Our objective is to destroy the long lived Cs-135, t-half=2.3Myrs. If the mixture is burned as is then the Cs-133 captures 77% of the neutrons, transmuting to Cs-134. Unfortunately, this has a 2 yr. half life and a relatively huge capture cross section, so most of this transmutes again into Cs-135 before it can decay. Burning the mixture as is only creates more of the isotope we are trying to destroy. The tiny capture cross section for Cs-137 means that little of it is burned and it is generally hard to destroy.

TABLE II. Parameters for Caesium waste.

PARAMETER / ISOTOPE	Cs-133	Cs-134	Cs-135	Cs-136	Cs-137	Cs-138	TOTALS
M Mass no.	133	134	135	136	137	138	
N - neutrons	78	79	80	81	82	83	
CROSS SECTIONS - barns							
Elastic Maxwellian at 0.253 eV	4.294	22.65	4.85	3.5	3.53	3.53	
Rad. Capture @ Blanket Temp	23.58	113.09	7.06	10.55	0.20	0.20	
EMISSION ENERGIES - MeV							
Γ Emission from capture	6.89	8.76	6.83	8.28	4.41	3.00	
Res. Rad Capture Integral	396.2	105.3	62.44	3.5	3.53	3.53	
Γ from excited Barium-m					0.6617	0	
β decay half life secs.	Stable	6.5E+07	7.3E+13	1.1E+06	9.5E+08	2.0E+03	
β energy		2.059	0.269	2.548	1.176	5.373	
Cs in SPENT FUEL & WASTE							
Yield kg/ tonne U235 fissioned.	67.02	0.00	65.33	0.00	62.69	0.00	195.0
Separated Cs %	34.36	0.00	33.50	0.00	32.14	0.00	100.0
Natural Emission Energies							
Sieverts nat decay kW/kg	0.00	1.6E+01	1.8E-06	1.1E+03	9.4E-01	1.3E+06	
From Separated Cs WASTE kW/kg		5.5E-05	6.1E-07	5.6E-04	3.0E-01	6.6E-06	0.3
kW/tonne Spent fuel @5% waste		2.8E-11	2.0E-06	2.8E-09	9.5E-01	3.3E-16	0.9
EMISSIONS FROM NEUTRON FLUX							
γ outputs kW/m^2	9.4E+01	5.8E-03	**2.7E+01**	7.4E-05	**4.7E-01**	5.1E-12	121.7

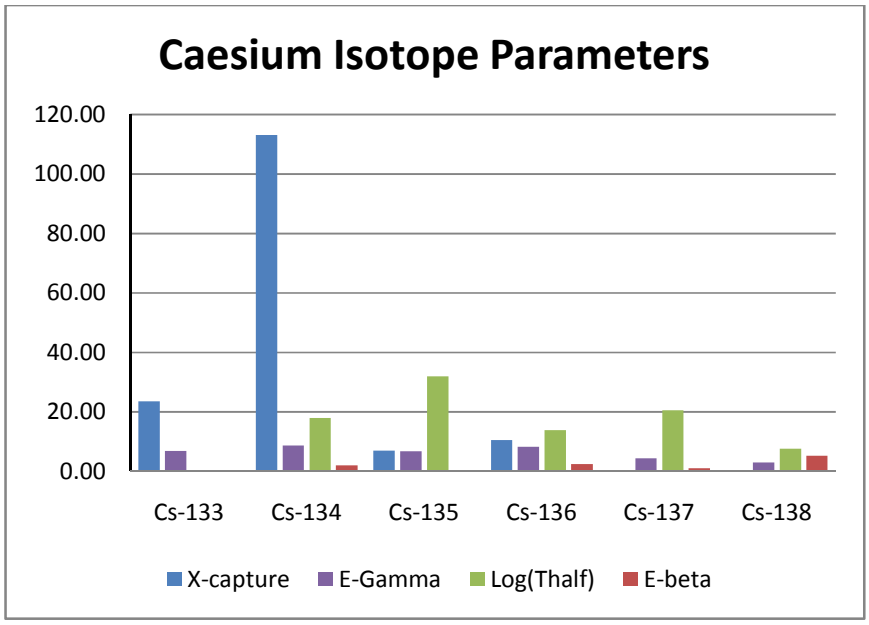
The Cs-135 has a low activity because of its long half-life, though this does not mean it is not dangerous to human life. The amount to be stored would grow remorselessly, and a fleet of 1000 reactors would produce 32,500 tonnes every 500 years. The Cs-137 produced from the same fleet, with a half-life of 30 years, balances out with this decay to a steady level of 40 times the annual production, about 2,520 tonnes However, this is half a million times more active with a total radiation energy output of 2.5MW.

Finally, the γ radiation energy from neutron captures at 0.25MW/m^2 of fusion neutrons into a blanket is shown. The total output is about 0.120MW/m^2 and a handsome addition to the energy output. This seems to have gone unnoticed in many calculations where blankets contain fissile materials with their outputs of 200MW/fission.

In the second part of the table we show the fission yield per tonne of Uranium burned and the fraction of each isotope in separated Caesium waste. The radiation output from β-decays and a γ emission from the Cs-137 decay is shown as the activity per kg. of each isotope, the output from separated waste, and the output from a tonne of untreated spent fuel. This highlights the need for increasing precautions as the materials become more concentrated.

Chart V. Parameters for Caesium isotopes from spent fuel.

Neutron Capture cross section – barns, γ emission energy from capture – MeV, Log(Half-life to β decay – secs.), β emission energy from natural decay.



It seems that laser isotope separation of the Cs-133 is necessary before the transmutation of Cs-135 can be effective. There are a number of experimental studies of the process using highly tuneable dye lasers. This concentrates all the radioactive isotopes in the target material, but once again it is the lower Cs-135 isotope which is burned. The transmutation product, Cs-136, has a short life of 13 days and so little of this transmutes onwards to Cs-137. The process then runs as shown by Table IV and the Chart VII.

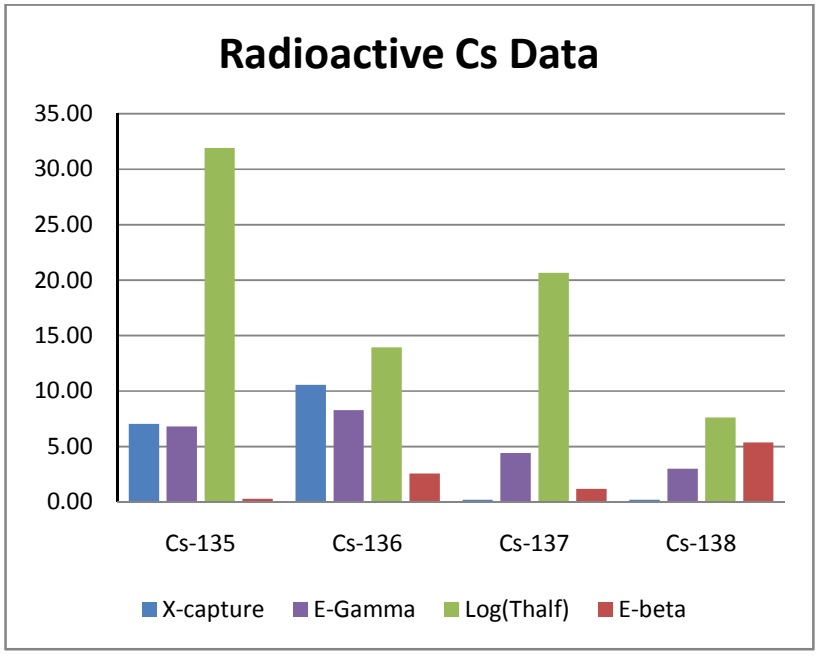
The waste steadily burns to Barium which must be periodically removed in a secondary cycle. Detailed calculations may show that a preliminary laser separation of the Cs-137 would be more economical, allowing for a higher blanket concentration of the much weaker radiation source, Cs-135, and a smaller blanket thickness. This reduces the radiation problems in destroying long lived Caesium waste to the same level as our Tc-99 burner.

TABLE III. Parameters for burning Radioactive Isotopes only from Caesium waste.

PARAMETER / ISOTOPE	Cs-135	Cs-136	Cs-137	Cs-138	TOTALS
Cs in SPENT FUEL & WASTE					
Separated Cs135,137 %	51.03	0.00	48.97	0.00	100.0
Natural Emission Energies					
From Separated Cs WASTE kW/kg	9.3E-07	1.7E-03	4.6E-01	1.0E-05	0.5
EMISSIONS FROM NEUTRON FLUX					
Capture Fraction @ T-blanket	9.7E-01	2.2E-06	2.6E-02	4.2E-13	
γ outputs kW	**117.9**	6.5E-04	**2.4E+00**	2.2E-11	120.3

Chart VI. Parameters for the radioactive Caesium isotopes.

Neutron Capture cross section – barns, γ emission energy from capture – MeV, Log(Half-life to β decay – secs.), β emission energy from natural decay.



This simplified analysis assumes that the 0.25MW of fusion neutrons is all absorbed by these neutron captures. This burns about 0.8kg./yr of Cs-135 turning it mostly into Cs-137. A 25MW Compact Fusion unit would keep up with the annual Cs-135 output of a 1000MWe fission plant. However, we have not identified a suitable chemical form here for the target Caesium and this is not a blanket design for this task. A liquid form would simplify the engineering of a batch system in which each batch would be irradiated for no more than 3 months in two years, allowing the Cs-136 to decay and reducing the overall production of Cs-137.

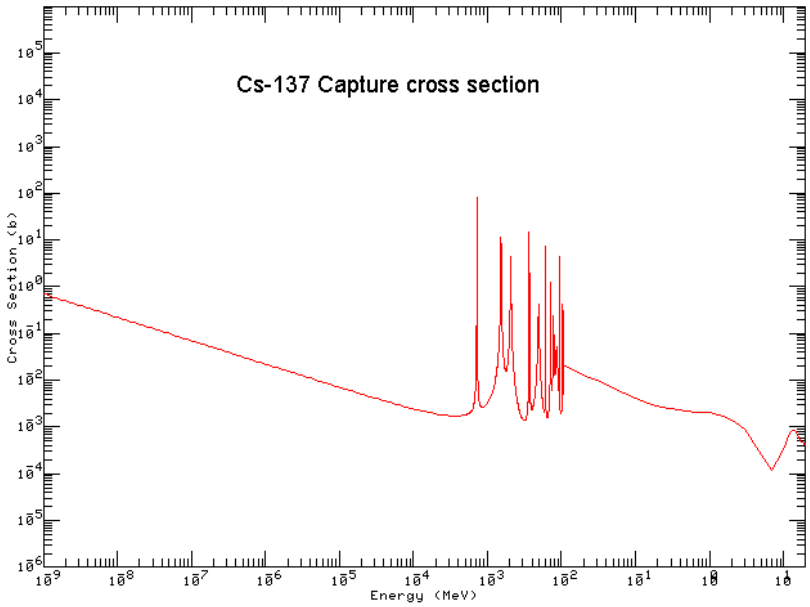
Cold Blankets

Larger Compact Fusion systems, especially those with a fissile power producing blanket, could have a sufficient excess of neutrons that several tasks can be carried out together, allowing for the slow burn of Cs-137.

There is one way to increase the capture cross section of Cs-137 which declines inversely with the neutron velocity at energies below the resonant region at 300eV, Chart VIII. Liquid nitrogen temperature is 77^{o} K, or $6.6\ 10^{-9}$ MeV where the capture cross section is nearly 0.5b instead of 0.2b at the blanket temperature of 620 K. The Compact Fusion reactor system already requires a large superconducting coil in the centre of the fusion core, so cooling an outer blanket region to liquid nitrogen temperatures is quite feasible. This would reduce the blanket volume by a factor of 2.5 to more realistic proportions. If the blanket could be engineered to run at liquid Helium temperature, the cross section goes to a more useful 5b.

Chart VII. The low Capture cross sections for Cs-137.

Even the resonances are low and sharp, giving a small average there. At fusion energies it is far below the 1-2 barns which is more normal.



Burning Cs-135 is a necessary task for the nuclear industry if million year waste dumps are not to litter the planet. The difficulty in burning the very active Cs-137 requires some further ingenuity. The volumes of Cs-137 to be managed in storage are small compared with the spoil heaps from other industries. The real danger lies in the trust to be placed in employees, contractors, managers and governments, so burning is still preferable to storage.

Conclusions

This Design Framework shows that Compact Fusion machines could burn Technetium wastes effectively and recover energy from them in a very safe fashion . Problems and possible solutions have been identified for what may the most difficult element to handle, Caesium.

A demonstration version of this machine would be of immediate value to the nuclear industry, removing the greatest obstacle to public acceptance of nuclear energy. Storage of these wastes is proving very expensive and there is no belief that it can be done on geological time scales. This solution is necessary and undoubtedly cheaper. The high costs of site cleanup show that we cannot afford to pollute a large number of sites with practices that lead to these problems.

We envisage a sequence of machines which can enter service in quick succession:

1. A very low power 1-5MW machine to demonstrate the principles and provide real world data on the neutronics, engineering and design issues of the blankets discussed here. Laboratories with such a facility can then explore the ancillary technologies for recycling Fission Product waste and the safe handling of these radioactive materials on a commercial scale. The radioactivity from Tc-99 is far less than that from the Plutonium and higher Actinides in spent fuel, so this level of reprocessing is entirely simpler and safer than that in the fuel reprocessing cycle. This gives an outstanding opportunity to develop safety and security systems for an ERMS approach to handling nuclear materials which is crucial to the long term success of nuclear energy. Much of the engineering and chemistry developments required may be done without the use of radioactive materials. Caesium processing needs the highest levels of robotic materials control.
2. A machine with a 25MW fusion core is capable of burning the annual Tc output of a large power station and breeding its own fusion fuel, Tritium. This would promptly be used to start the destruction of existing waste stockpiles. Such machines with various blanket modules could be installed for every nuclear recycling plant.
3. Fusion systems with 50MW of output would be capable of breeding the annual Plutonium top-up needs of a 1GWe fission plant from by neutron capture in Depleted Uranium so fission is largely suppressed. The process also benefits from the production of 6.8MeV of gamma energy with each transmutation. Compact Fusion Breeders could free many nuclear energy countries from the need for mined Uranium. Again, the reprocessing of irradiated DU will be far simpler and safer than for reprocessing spent fuel. This would be the cleanest process on the planet for producing fresh Plutonium reactor fuel.
4. Still more powerful reactors, 100MW+, could provide a fusion core to a sub-critical fission reactor blanket to produce nuclear power on a smaller, safer and more buildable scale – 200-300MW total – than the giant PWR base plants under construction today. The strong neutron multiplication from fission can also provide neutrons for nuclear waste disposal in outer blankets, as developed in our earlier machines.

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