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SAFETY CHARACTERISTICS OF POTENTIAL WASTE TRANSMUTATION SYSTEMS*

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ABSTRACT

For nuclear waste transmutation to alter significantly the need for geologic disposal of spent fuel from U.S. Light-water reactors (LWRs), about 1.4% of the spent fuel (by mass) must be separated and transmuted. This includes the plutonium, the minor actinides, and four fission products: iodine, technetium, cesium and strontium. Regarding the actinides, fissioning of the plutonium, neptunium, americium, and curium generates a great deal of heat, so much so that most of the plutonium should be used to produce power. However, these actinides have some undesirable neutronic characteristics, and their utilization in reactors or subcritical (proton-accelerator) targets requires either a fast neutronic spectrum or a very high thermal-neutron flux. Transmutation of the fission products is generally by neutron capture, although this is difficult in the case of cesium and strontium. In this paper, various proposed means of transmuting the actinides and fission products are discussed, with the main focus being on the safety characteristics of each approach.

I. INTRODUCTION

Once one assumes the effective separation of nuclear waste stream elements, there are several options available for the transmutation of problem elements, each with its own advantages and disadvantages. In selecting the best options for the transmutation processes, the safety characteristics will be a key discriminator. This is the result of some hazardous characteristics of the high-priority candidates for transmutation, as well as the low-risk (at least over the short term) alternative of simply storing the materials.

Because of some of the physical characteristics of the minor actinides, the designer has four clear choices: [fast or high thermal flux] and [reactors or accelerators]. Each option carries some inherent safety advantages and challenges, and the designers are faced with some difficult choices. In this paper the four options will be discussed, along with example systems that are currently proposed by three DOE laboratories, the Argonne, Brookhaven, and Los Alamos National Laboratories.

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II. THE LWR SPENT FUEL COMPONENTS

If one starts with typical spent fuel from a LWR, and then allow for a ten-year decay period, one obtains the isotopic composition described in Westinghouse Hanford's CURE Report.[1] At that time, the spent fuel contains about 95.6% uranium and 3.00% short-lived or stable fission products. Since the uranium is of low enrichment (perhaps 0.8% U-235) and low toxicity, disposal should not be a major challenge (and partial recycle may be an option). Similarly, stable fission products are mostly harmless, and storage of the short-lived ones long enough to render them harmless should be achievable. Thus, after 10 years of decay, 98.6% of the spent fuel is comparatively easy to dispose of. The remaining 1.4% is composed of plutonium (0.87%), minor actinides (0.11%) technetium (0.08%), iodine (0.02%), cesium (0.24%), and strontium (0.08%). It is these components that require longer-term retention, and drive the requirements for effective geological disposal, and the elimination of these materials would largely resolve the technical aspects of the nuclear waste disposal problem.

The Actinide Buildup/Decay Chain pertinent to the potential transmutation of LWR spent fuel is shown in Figure 1. Once the uranium and plutonium are stripped away, and after ten years of cool-down, the remaining actinides include about 42% Np-237, 48% Am-241, 9% Am-243, and less than 2% Curium (mostly Cm-244). All of these isotopes are quite toxic and have long half-lives.

Of the many fission products, only a few have sufficiently long half-lives to cause problems for burial. Seven such fission products are shown in Figure 2. The ^{90}Sr and ^{137}Cs are problems over the near term, i.e., a few hundred years, as they are highly active and contribute significantly to both toxicity and heat loading. The other five isotopes in Figure 2 are approximately equivalent when judged by half-life and toxicity. However, the ^{99}Tc and ^{129}I are much more mobile and thus more likely to leach into the groundwater. Therefore, it is these four fission products, Sr, Cs, Tc, and I, that are the highest priority for elimination.

III. SYSTEM OBJECTIVES

The predicted throughput of the spent fuel from one hundred 1000 MWe light water reactor power plants running at

about 75% capacity is illustrated in Figure 3. Since the U.S. LWRs are not currently running at that capacity or that efficiency, these mass flow rates are higher than the actual throughput from today's system, probably by 20 to 30%. Regardless, it is the proportions that are most important.

The Separations Facility is nominally aqueous-based to achieve the indicated separations. If pyro-processing were used, the minor actinides would most likely remain with the plutonium and the fission products would not be separated to the same degree. However, the comparable pyro-processing system is based on a reactor that can run on the actinide mixture, and the fission products are placed in more stable forms via chemistry. Therefore, the pyro-based equivalent to Figure 3 is much simpler, but could ultimately achieve many of the same objectives. The discussion here, however, will be based on the aqueous system. If one fissions (transmutes the plutonium "waste" from the roughly 100 large (1000 MW electric) light-water reactors (LWRs), enough energy is produced to run another 17 large (1000 MWe) nuclear power plants. Therefore, the first component of a nuclear waste transmutation system is advanced power reactors that can operate on plutonium (or a mix of uranium and plutonium). This is achievable in either thermal spectrum reactors, possibly variations on our current plants, or in fast spectrum ("breeder") reactors. Because plutonium's neutronic performance improves as the spectrum hardens (faster neutrons), plutonium usage as a fuel poses some safety challenges, but there exist viable means for using plutonium safely.

If the minor actinide throughput from the 100 large LWRs is fissioned, about two additional LWRs' heat load will be generated. Therefore, one has the option of either factoring the minor actinides into some advanced U-Pu-Minor Actinide fuel for power reactors, or designing and building two large waste transmutation machines. If the dedicated waste burner is chosen, the options are small inventory, high thermal flux (and power density) devices or large inventory, fast spectrum devices. In addition, one may choose to operate either a critical device (a reactor), by supplementing the minor actinides with plutonium to achieve criticality (this adds to the scope of the mission), or a subcritical device augmented by spallation neutrons created when accelerated protons are driven into a heavy metal target (lead, tungsten, or the actinides themselves). There are several safety issues associated with each option, and it may be necessary to first develop each option to a degree where informed decisions may be made.

Transmutation of the fission products, i.e., the iodine, technetium, cesium, and strontium, is simpler in principle, although perhaps not in practice. The iodine-129 and technetium-99 isotopes are very likely to absorb thermal neutrons and convert to stable xenon and ruthenium isotopes, respectively. If one salvages the extra neutrons produced by fissioning the minor actinides, one could transmute most of the iodine throughput, but only a fraction of the technetium. Thus, a scheme to transmute the technetium must involve fissioning plutonium and/or uranium, probably in a power reactor. Since technetium and ruthenium are solids well above 2000°C, their addition to a critical device is acceptable, as they are very unlikely to escape the core (adding reactivity in the process). In contrast, one would like to transmute the iodine (xenon) in a subcritical device if possible, or converted to some chemically stable form for transmutation in reactors.

Transmutation of the cesium and strontium isotopes is far more challenging, due to the presence of multiple isotopes and small cross sections. In addition, two of the most important isotopes decay with half-lives in the 30-year range, and thus are not long-term disposal problems. If one is going to transmute cesium and/or strontium successfully, this would likely require very high neutron fluxes and possibly isotopic separations.

IV. TRANSMUTATION PHYSICS

Fissioning of the plutonium waste stream is not difficult, technically (although the political problems are formidable). The one significant problem is that plutonium fissions even better in a fast spectrum, which can lead to safety concerns when one postulates overheating with failure to shut down the reactor neutronically.

Fissioning of the minor actinides is more difficult because the isotopes that are produced (and not fissioned) in the LWRs (mostly Np-237, Am-241, Am-243) will capture thermal neutrons rather than fission. Once they capture neutrons they are briefly fissile, as Np-238, Am-242, and Am-244 (see Figure 1). However, these isotopes are short-lived, and within a day or two (see Table 1) have decayed to Pu-238, Cm-242, and Cm-244, which are again much more likely to capture neutrons than to fission. If these isotopes then capture a neutron and go to Cm-243 or Cm-245, then a subsequent fission event becomes very likely. However, this implies one is investing 3 neutrons per fission, and gets only about 2.6 in return. In the low neutron fluxes in most power reactors, the minor actinides are thus acting as poisons, i.e., they hurt the reactor performance. However, in a high neutron flux, one can hope to fission the Np-238, Am-242, and Am-244 before they decay to non-fissile isotopes. If one uses this approach to fission the minor actinides, one must have a high neutron flux and most likely a high power density, but one can get by with a small inventory of minor actinides since the thermal neutron cross sections are fairly large.

One can estimate the thermal flux required to fission the Am-242 as rapidly as it decays ($\lambda N = \phi \sigma N$) as 5.7×10^{15}, using the numbers in Table 1. This is more than an order of magnitude above the flux in an LWR, and implies very high power densities if all of the neutrons are produced via fission.

Table 1. Half-Lives of Key Short-Lived Fissile Actinides

Isotope	σ_f	Half-Life (hrs.)
Np-238	211 + 900	50.8 hrs
Am-242	2100	16.0 hrs. (Note 1)
Am-244	2300	0.43 hrs. (Note 2)

Note 1: 90% Created in Ground State; Assumed 100%
Note 2: 95% Created in Isometric State; Assumed 100%

A second method of fissioning the minor actinides takes advantage of the relative likelihood of a fast neutron causing a fission (as opposed to a capture event). However, because the

cross sections for fast neutrons are relatively small, a fast spectrum reactor requires a large inventory. In addition, because the likelihood of fissioning the minor actinides increases strongly as the spectrum hardens, there are safety concerns in terms of large positive reactivity feedbacks and the associated reactor stability issues.

The transmutation chains for iodine and technetium are shown in Figure 4. While there is no real advantage to converting the ^{127}I, it is 24% of the iodine and will therefore be present to divert some of the neutrons that could be better used to convert the ^{129}I. In the case of all three base isotopes, ^{99}Tc, ^{129}I, and ^{127}I, the absorption of one neutron cross sections are generally between 10 and 100 barns, creates a stable isotope, and the absorption of subsequent neutrons has little impact, except for wasting neutrons.

The situations regarding cesium and strontium are far more complex, as indicated by the numbers in Table 2. For Sr-90, the small neutron absorption cross section means a very high neutron flux would be required to reduce the effective half-life below 29.1 years. For cesium, the stable Cs-133 isotope will capture most of the neutrons, and very few neutrons would convert the Cs-137. There may be other options for transmuting the cesium and strontium, but one cannot simply place the elemental strontium or cesium in a neutron flux and expect to significantly improve on the 30-year decay times.

Table 2. Cesium and Strontium Isotopes in Spent Fuel (10 Yrs.)

Isotope	Fraction Present	Half-Life (yrs.)	σ (barns)
Sr-88	.454	Stable	.006(+.06)
Sr-90	.545	29.1	.014
Cs-133	.475	Stable	33.6(+3900)
Cs-135	.123	2.3×10^6	8.7(+62)
Cs-137	.400	30.2	.11

Note: Resonance Absorption Cross-Sections Indicated Parenthetically

V. FOUR OPTIONS FOR WASTE "BURNERS"

As previously mentioned, fissioning of the plutonium will produce a great deal of power (at least 15000 MWe), and machines dedicated to this task should be considered power plants ("advanced reactors"). In contrast, fissioning the minor actinides in a reactor requires either a hard spectrum (fast reactors) or a high flux thermal spectrum, as well as some plutonium feed to achieve criticality.

The accelerator option provides additional "spallation" neutrons to the process, and gives some extra design options, including subcriticality and higher fluxes at lower power densities. However, there are higher costs associated with the accelerator, and some materials issues are raised regarding proton damage.

The iodine and technetium could be transmuted using any of the options, although a major consideration is the number of excess neutrons that can be used. On a per-fission basis, the fast spectrum machines require fewer neutrons to sustain the fission process, and the neutrons can be slowed outside the region where the fission process is ongoing. On a per-machine basis, the accelerator driven machine should make additional neutrons. However, without the accelerator, plutonium make-up is needed, so there will be more machines, more fissions, and more neutrons.

A. The Fast Spectrum Reactor

The sodium cooled fast spectrum reactor has been under development for many years in several countries, and has been designed from the outset to run on plutonium. The focus until recently has been to breed more plutonium than is consumed, using breeding "blankets" with high U-238 content. However, it can be adapted to burn-off plutonium by leaking off the excess neutrons rather than capturing them in the blankets.

If one could achieve a very hard (fast) neutron spectrum, one could operate the reactor on minor actinides alone. However, this is not practical, so one must add plutonium to achieve criticality. This then leads to the question of whether one is making more minor actinides in the plutonium feed than is being transmuted at the same time.

In the U.S., the reference sodium cooled fast reactor is known as the Integral Fast Reactor (IFR), and is based on metallic fuel.[2] The commercial version, known generally as the Advanced Liquid Metal Reactor (ALMR) or more specifically PRISM, is developed by General Electric with funding by the U.S. DOE.[3] The reference commercial ALMR plant utilizes nine 471 MWt reactor modules (see Figure 5) to produce a total of 1440 MWe from three identical 480 MWe power blocks employing a superheated steam cycle.

The ALMR design team's approach to providing safety related functions with passive rather than active systems has been quite successful. Design features which help accomplish this include: a completely passive shutdown decay heat removal system; passive safety grade containment cooling; and the use of gravity and/or battery driven shutdown systems which are backed up by passive (temperature and flow rate driven) negative feedbacks within the core which in the unlikely event of a failure to scram provides a transition to a safe stable condition.

One of the areas where there exist open safety issues[4] is in the area of positive reactivity feedbacks. If the sodium coolant in the center of an LMR core boils, there is the potential for a reactivity insertion and power excursion, a situation often referred to as the "positive sodium void worth". The other potentially positive feedback is fuel relocation, which requires a melt condition or some other severe condition, including large seismic events. Accidental control rod withdrawal can also add reactivity, which could then trigger the positive feedbacks. The reactor designer has various choices, and may choose to flatten or "pancake" the core to reduce the sodium void worth.[5] However, this can increase the burnup reactivity swing and force

the use of higher-worth control rods. This in turn could make the control rod withdrawal accident much worse.

When the minor actinides are substituted for plutonium in the ALMR, the reactivity feedbacks can get much worse.[4] This is because the minor actinides fission so much better with faster neutrons, so the removal of any moderating component (sodium) will boost reactivity significantly. In theory, the ALMR could probably run with as high as 90% minor actinides (10% plutonium needed to go critical). However, positive reactivity feedbacks would lead to very significant questions about the stability of such a reactor. The more conservative approach is to feed the ALMR the mix of plutonium and minor actinides present in the waste stream from light water reactors (LWRs). The impact on the sodium void worth and Doppler (fuel temperature dependence) feedbacks are significant but probably manageable. However, by running the ALMR on the mix from LWRs, one starts producing almost as much minor actinide content as is burned off.

B. The High-Flux Thermal Spectrum Reactor

In general, the minor actinides will act as poisons in thermal spectrum reactors, absorbing more neutrons than they produce via fission. As was discussed in Section IV, they will perform much better in a high flux thermal spectrum, and criticality can be achieved with a reasonable level of plutonium feed. However, the flux needs to be much higher than that in LWRs, which implies very high power production per unit mass of fuel. While there are few options for such reactors, there exists at least one design that could operate with such a high power density, the Particle Bed Reactor (PBR) under design at BNL.[6] The fuel is in the form of small (800 microns) graphitic particles containing plutonium or minor actinides, which can withstand very high temperatures. Many such particles are packed between thin "frits", which are placed into a reactor vessel containing graphite and/or D_2O moderator (see Figure 6). Heat is normally removed from the fuel particles by the helium coolant. The heat is then used to run a steam cycle and produce electric power.

Plutonium feed is used to achieve criticality, with about twice as much plutonium feed as minor actinide feed. The amount of fission per unit fuel mass is roughly 20 times higher than that in LWRs, leading to a 20 day fuel cycle. At that time, roughly half the plutonium and half the minor actinides will have been fissioned. It is believed the particle fuel form will perform adequately at the high temperature and high burnup levels (operating temperature $< \sim$ 1/3rd of the melting temperature) satisfactorily.

Since the plutonium feed is to be only as required to remain critical, the PBR would be operated as a minor actinide burner. However, the actinide (including Pu) throughput would be about 3 times higher than the minor actinides alone. There would also be some capability to transmute iodine or technetium using the PBR, but the number of excess neutrons would be much less than those from a fast spectrum reactor. Since between 2 and 3 neutrons are needed for each minor actinide fission event, most excess neutrons would be due to the presence of plutonium.

The main safety issue for the PBR is the after heat removal, which is made somewhat higher by the comparatively hot minor actinide isotopes. With the high power density, back-up heat removal systems will require pumping, as natural circulation cooling would be inadequate.

C. Accelerator-Driven Fast Spectrum Target

With increased development of particle accelerators for applications ranging from research, to materials production and modification, and to the Strategic Defense Initiative, these machines have become larger, more powerful, and more efficient. The basic physics that results when high-energy charged particles are driven into targets of heavy elements has been known for several years. While empiricisms remain regarding the precise features of the intranuclear cascade process, there exist sufficient data and supporting theory to make reasonably accurate (approximately $\pm$ 15%) predictions for protons of a given energy level having an impact on an actinide nucleus.

Figures 7 and 8 indicate current best estimates, based on data and calculations, of the number of transuranic nuclides spalled and the number of neutrons ultimately released, as a function of the incident proton energy in large targets. For an incident proton at 1.6 GeV, five or six nuclides of neptunium, americium, or curium (they will be very similar) will be spalled. More importantly, $\sim$ 50 neutrons will be knocked free as the proton penetrates the lattice, most of these resulting from "evaporation". In a subcritical target, the neutrons that are released via spallation lead to far more transmutations than come directly from the proton interaction (Figure 7). It has been shown[7] that:

$$\#\ \text{Transmutations} = \#\ \text{Spallations} + N_s \left[\frac{1}{1-k}\right] / \nu$$

where N_s is the number of neutrons initially released via spallation, k is the reactivity multiplier for the lattice (k, effective from reactor physics), and ν is the number of neutrons released per fission event (on average). An effective multiplication factor of 0.9 results in the 50 neutrons becoming 450 neutrons. Most of these neutrons result from the fission of $\sim$ 167 nuclides. In combination with the spalled nuclides, the single proton results in the destruction of 172 target nuclides. Should the multiplication factor be 0.95, the same proton could trigger destruction of 357 of the transuranic nuclides.

The PHOENIX Concept[7] uses a large linear proton accelerator (linac) to drive and control one or more subcritical lattices of minor actinides (neptunium, americium, and curium). One 3600-MW (thermal) machine would transmute the neptunium, americium, curium, and much of the iodine produced by $\sim$ 75 LWRs and would generate a net of $\sim$ 850 MW (electric) for the electrical grid, as indicated in Figure 9.

The PHOENIX Concept assumes a large linac that can produce a 104-mA beam of 1.6 GeV protons. While such an accelerator is an extension of current technology, an even larger machine producing 250 mA of 1.6-GeV protons was recently

designed and evaluated for use in a concept for producing tritium.[8,9]

A multiple module (modular) concept was developed for the PHOENIX subcritical lattice. Each module resembles the core of the Fast Flux Test Facility[10] (FFTF), with the minor actinides formed into oxide fuel rods, replacing the uranium and plutonium in the FFTF fuel. The fuel rods are cooled using liquid sodium and are bundled into 217 pin assemblies, with 124 such assemblies making up a 450-MW (thermal) target module.

The accelerator provides two major benefits for the PHOENIX Concept. First, the target lattice does not have to be critical at the beginning of life, since the accelerator can drive a sub-critical target. This allows a throughput of 2.6 tonnes per year of minor actinides without any plutonium feed. Second, the positive reactivity feedbacks that result from the use of minor actinides in a fast spectrum machine are not very important, as long as the machine will shut down when the accelerator is shut off. Note, however, that those feedbacks will dictate how closely k_effective should be allowed to approach 1.0.

While the accelerator feature essentially resolves an important safety issue for fast spectrum machines, it re-introduces a problem that is generally avoided in sodium-cooled reactors. Because sodium burns in air and reacts strongly with water, almost all sodium cooled reactors use double vessels to retain the coolant. As a result, most such reactors are not vulnerable to loss-of-coolant events. In the case of a spallation target, it is necessary to minimize structures in the proton beam in order to maximize neutron production. Additionally the materials damage from high energy protons is not well known.. As a result, the PHOENIX Target materials and structures would be more vulnerable to loss of coolant events than is usually the case with many sodium cooled systems.

D. Accelerator Driven High-Flux Thermal Systems[11]

In this case, all accelerator and spallation discussions from Section C apply. However, in order to minimize the inventory in the target (larger cross-sections), a thermal spectrum is used. And, as was the case in Section B, a highly efficient moderator such as heavy water is used and a high neutron flux is necessary.

The Los Alamos Accelerator Transmutation of Nuclear Waste (ATW)[11] concept consists of four principal systems: accelerator, neutron spallation target, blanket (moderating region surrounding the target), and chemical separation. The base-case design is an aqueous system that uses heavy water (D_2O) for the target coolant, blanket moderator, actinide slurry carrier fluid, and fission product solution.

ATW uses high-energy protons from a linear accelerator, which are directed onto a high-atomic-number target material to produce neutrons that are then moderated in a surrounding D_2O blanket. The neutrons are slowed to thermal energy in the moderator and are absorbed in the fission product waste or they are used in the fission and transmutation of actinides. Because of the high-flux levels, dilute mixtures in the blanket region can be used, which therefore reduce the potential for criticality accidents and power excursions. The transmutation isotopes are continuously transported through the blanket region, through heat exchangers, and into separation process loops.

The blanket consists of a low-pressure aluminum moderator tank that contains the structure to support the target zircaloy tubes that contain the technetium fission-product solution, and double-walled tubes that contain the actinides. Because of its excellent neutronics properties, D_2O was chosen as the blanket moderator and the slurry and solution carrier fluid.

The purposes of the slurry heat-transport system are to burn up the actinide waste and to remove the heat generated due to the nuclear-fission processes. The amount of heat generated in the actinide slurry is similar to a small conventional nuclear-reactor system (~ 1540 MW) and requires that the actinide slurry be pumped in a loop containing the heat-exchanger equipment. The technetium fission product is transported through the blanket in a lithium-pertechnetate solution. The small amount of heat absorbed in the solution is removed by a separate heat exchanger that is located outside the blanket.

Clearly, ATW is the most ambitious of the four waste transmutation devices described here. It is also the one which is evolving the most rapidly, and is therefore the most difficult to assess regarding safety. Instead, there are certain issues that are likely to remain regardless of how the design evolves. First, a high flux implies either an enormous number of spallation neutrons (expensive in terms of electricity) or a high fission rate per mass of actinides. Economics will likely drive the designers toward higher fission rates, and make after-heat removal an issue. Second, when problems develop in the target, blanket, or coolant systems, this must be recognized and the accelerator must be shut down quickly. Detection of the problem will be the challenge. Third, the use of various hazardous materials in slurries raises various issues about pipe breaks or varying concentrations. And fourth, the system complexity is an issue by itself, since it is difficult to anticipate all the interactions which may occur.

VI. SUMMARY AND CONCLUSIONS

There are at least four viable means of transmuting the actinides and key fission products, namely, fast reactors, high flux thermal reactors, accelerator-driven fast subcritical targets, and accelerator-driven high-flux thermal-subcritical targets. Four examples were provided, spanning the four technological options. It is quite possible that superior options are available, but it is very likely such options would fit into one of these four categories of machines.

The reactors must be run critical and require some plutonium feed to accomplish this. They may also have some vulnerability to reactivity accidents, due to some undesirable characteristics of the minor actinides. The accelerator-driven machines will be more expensive and cost more to operate. However, because there is little need for plutonium feed, fewer machines would be required. While these machines would be relatively immune to reactivity accidents, there will be materials

concerns and the need to turn off the accelerator if something goes wrong in the target.

The fast-spectrum machines require large inventories of actinides, and require coolants such as sodium. In addition, the presence of minor actinides introduces some stability issues. The thermal spectrum machines need a high flux, which means a lot of power per unit mass of fuel. However, a relatively small amount of fuel is needed, improving the safety situation in the case of an accident.

Of the four technologies, the ALMR is the most mature, and has the advantage of being a viable candidate for plutonium and waste transmutation. At this time, its safety systems are the most mature, but the problem of undesirable reactivity feedbacks will always be an issue. The Particle Bed Reactor provides a high throughput of actinides and can survive high temperatures. However, after-heat removal will be a challenge. The PHOENIX Concept can bypass the reactivity issues present with the ALMR, but issues related to structures and materials damage may lead to questions regarding loss-of-coolant scenarios. Lastly, ATW could evolve into the safest of the foursome, but a strong engineering effort will be needed to deal with some of the inherent complexities of the system.

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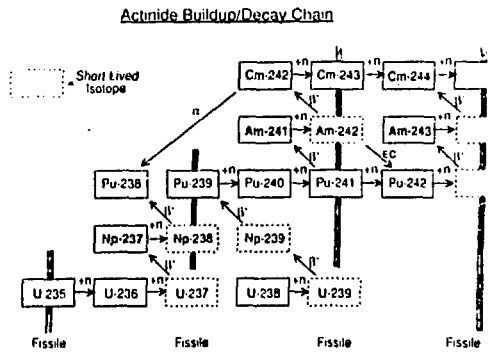

Figure 1 - Actinide Buildup/Decay Chain

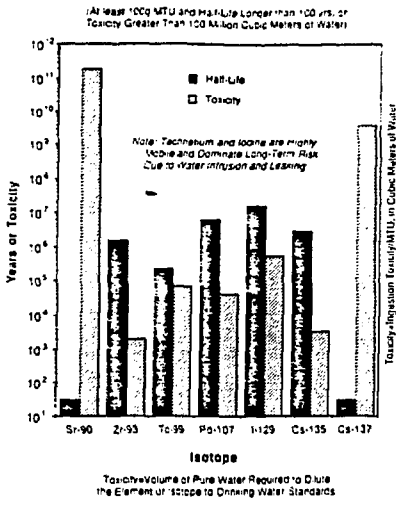

Figure 2 - Characteristics of Key LWR Fission Products. (Technetium and Iodine are Highly Mobile and Dominate Long-Term Risk Because of Water Intrusion and Leaking.)

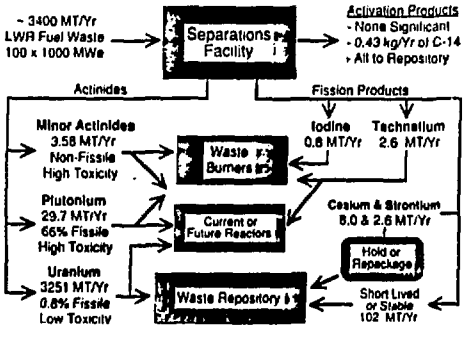

Figure 3 - Predicted Mass Flows from One Hundred 1000 MWe Plants

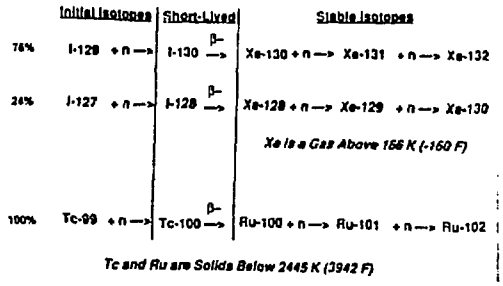

Figure 4 - Transmutation Chains for Iodine and Technetium

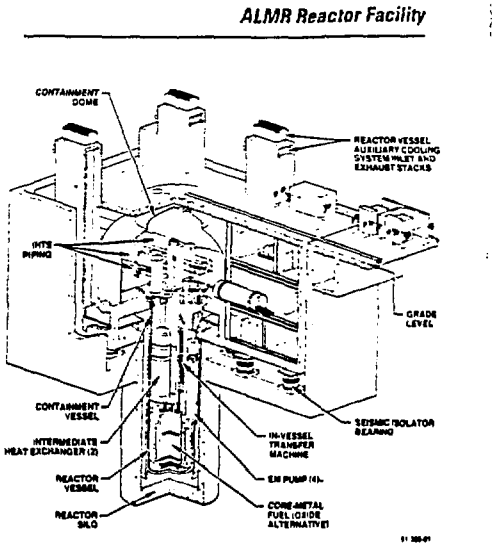

Figure 5 - ALMR Reactor Facility

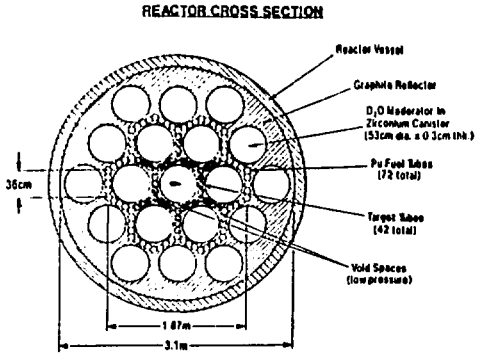

Figure 6 - Reactor Cross Section

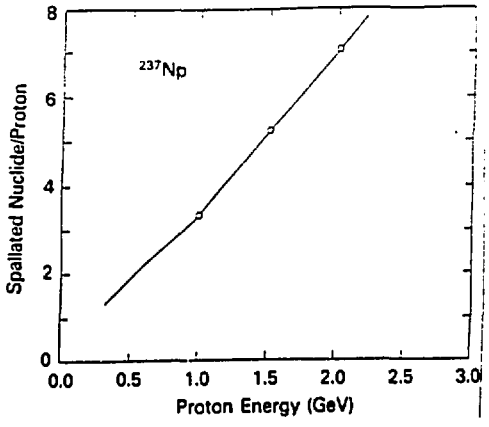

Figure 7 - Number of Nuclides Spallated per Incident Proton Energy

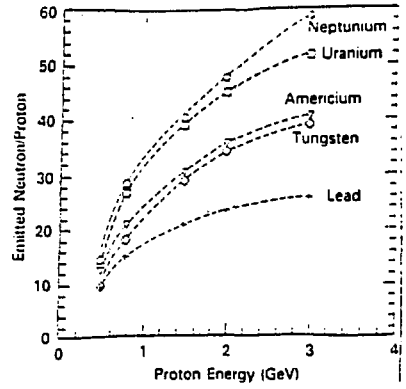

Figure 8 - Number of Neutrons Produced per Incident Proton Energy

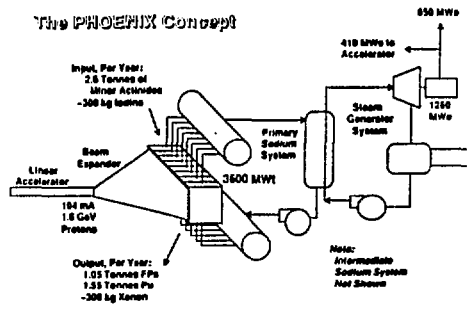

Figure 9 - The PHOENIX Concept (Intermediate Sodium System Not Shown)

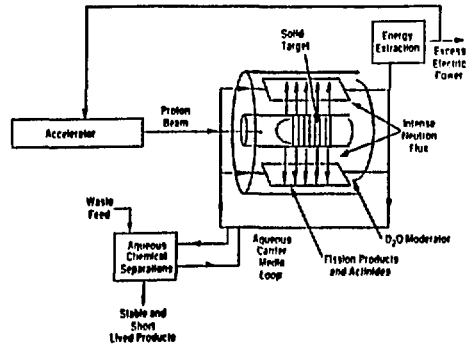

Figure 10 - Accelerator Transmutation of Waste (ATW) Target System