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Fission-Suppressed Fusion Breeder on the Thorium Cycle and Nonproliferation

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Abstract. Fusion reactors could be designed to breed fissile material while suppressing fissioning thereby enhancing safety. The produced fuel could be used to startup and makeup fuel for fission reactors. Each fusion reaction can produce typically 0.6 fissile atoms and release about 1.6 times the 14 MeV neutron's energy in the blanket in the fission-suppressed design. This production rate is 2660 kg/1000 MW of fusion power for a year. The revenues would be doubled from such a plant by selling fuel at a price of 60/g and electricity at \$0.05/kWh for $Q=P_{\text{fusion}}/P_{\text{input}}=4$. Fusion reactors could be designed to destroy fission wastes by transmutation and fissioning but this is not a natural use of fusion whereas it is a designed use of fission reactors. Fusion could supply makeup fuel to fission reactors that were dedicated to fissioning wastes with some of their neutrons. The design for safety and heat removal and other items is already accomplished with fission reactors. Whereas fusion reactors have geometry that compromises safety with a complex and thin wall separating the fusion zone from the blanket zone where wastes could be destroyed. Nonproliferation can be enhanced by mixing ^{233}U with ^{238}U . Also nonproliferation is enhanced in typical fission-suppressed designs by generating up to 0.05 ^{232}U atoms for each ^{233}U atom produced from thorium, about twice the IAEA standards of "reduced protection" or "self protection." With 2.4% ^{232}U , high explosive material is predicted to degrade owing to ionizing radiation after a little over $\frac{1}{2}$ year and the heat rate is 77 W just after separation and climbs to over 600 W ten years later. The fissile material can be used to fuel most any fission reactor but is especially appropriate for molten salt reactors (MSR) also called liquid fluoride thorium reactors (LFTR) because of the molten fuel does not need hands on fabrication and handling.

Keywords: Hybrids, thorium, U-233, fusion fuel breeder, nonproliferation

PACS: 28.52.70

I. INTRODUCTION

Mixing ^{233}U with ^{238}U can enhance nonproliferation. Also nonproliferation is enhanced in three typical fission-suppressed designs [1] by generating up to 0.05 ^{232}U atoms for each ^{233}U atom produced from thorium, about twice the IAEA standards of "reduced protection" or "self protection" due to ionizing radiation set at a dose rate of 100 rem/h (1 Sv/h) 1 m from 5 kg of ^{233}U with 2.4% ^{232}U one year after chemical separation of daughter products [2]. With 2.4% ^{232}U , high explosive material is predicted to degrade owing to ionizing radiation after a little over $\frac{1}{2}$ year. The heat rate is 77 W just after separation and climbs to over 600 W ten years later.

The fissile material can be used to fuel most any fission reactor but is especially appropriate for molten salt reactors (MSR) [3] also called liquid fluoride thorium

reactors (LFTR) [4] because the molten fuel does not need hands on fabrication and handling that otherwise would be expensive owing to the 2.6 MeV gamma emission.

A fusion system can produce unusually large quantities of fissile material, for example ^{233}U from thorium, because the 14 MeV neutrons can be multiplied to give the extra neutrons needed. A nonproliferation feature of thorium, and one of the reasons it has not been desired for making nuclear weapons, is partly because the contaminant ^{232}U that comes along with making ^{233}U , has a strong gamma ray associated with its daughter products. Reactions leading to ^{232}U need neutrons well above approximately 6 MeV threshold. Fusion is unique compared to fission in having all its source neutrons produced at 14 MeV, well above the 6 MeV threshold for producing ^{232}U whereas fission has less than 3% of its neutrons above 6 MeV as shown in Fig. 1.

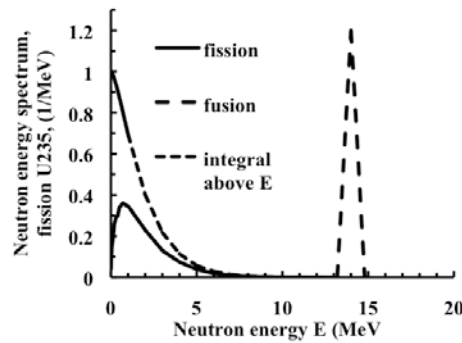
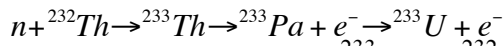


FIGURE. 1. Neutron source spectra for fission and fusion.

II. PRODUCTION OF ^{232}U AND ^{233}U

^{233}U is produced in the following reaction.



The reaction paths that lead to ^{233}U and ^{232}U are shown in Fig. 2.

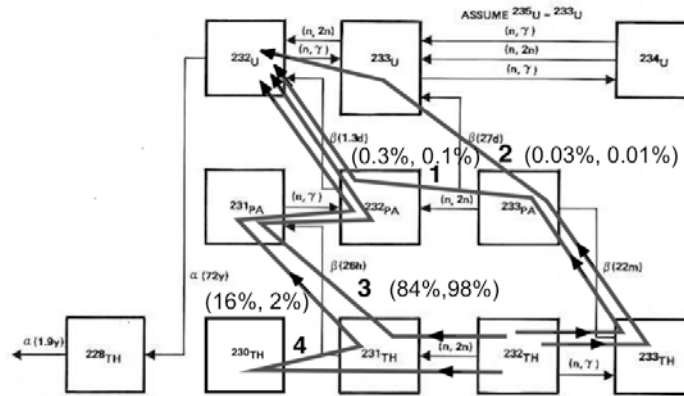
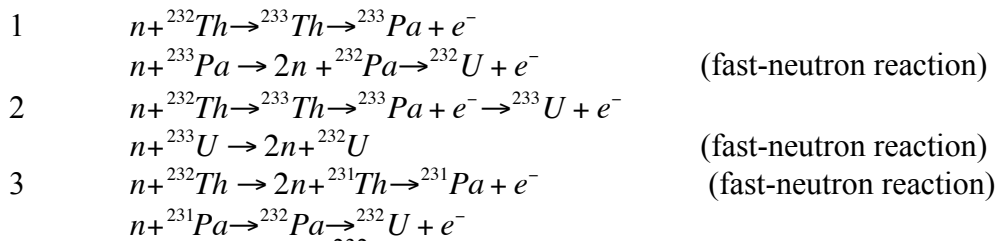


FIGURE. 2. Reaction paths that lead to ^{233}U and ^{232}U . The numbers in parentheses are the Li/MS and Be/MS percentages of each route leading to ^{232}U .

Four routes to producing ^{232}U shown in Fig. 2 are enabled by the three threshold reactions in the following two-step set of reactions whose cross sections are shown in Fig. 3:



Other reactions ending in ^{232}U are possible, such as the following three step-reactions:

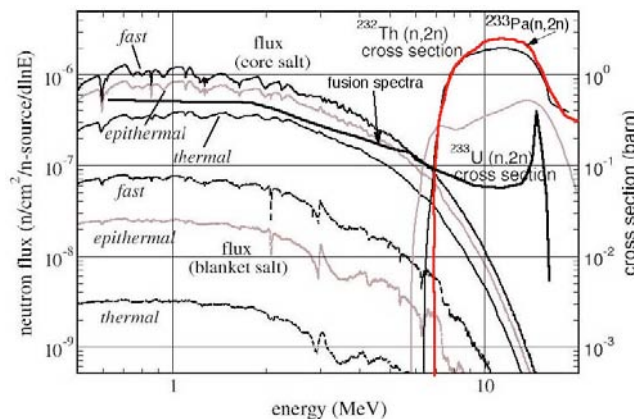
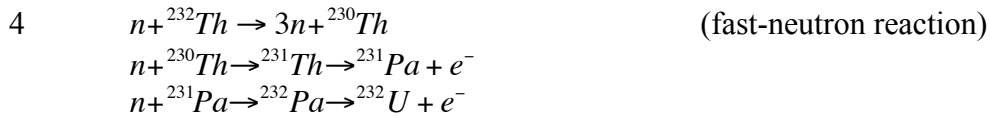


FIGURE 3. Threshold cross-sections for producing ^{232}U , [5]. The fusion neutron spectrum is superimposed but not to scale vertically.

These reactions cannot take place with neutrons below 6 MeV. The production of ^{232}U therefore can be much greater for fusion sources than for fission sources of neutrons.

Since ^{231}Pa ($T_{1/2}=33,000$ yr) accumulates, the third set of reactions depends on exposure time even after ^{233}U is removed. Long exposure times are useful and the Pa needs to be left in during processing to remove ^{233}U . The second set of reactions also depends on time during which the ^{233}U accumulates to the value limited by the processing rate to remove the produced material.

As the concentration of ^{232}U in ^{233}U builds up, detection becomes easier owing to the 2.6 MeV gamma activity as can be seen in later figures. As the concentration reaches several hundred ppm, proximity to a quantity of uranium such as 5 kg becomes dangerous. Above 2.4% (24,000 ppm) the activity becomes high enough that the IAEA's standard for reduced physical-protection or "self-protection" requirements (>100 rem/hr = 1 Sv/hr at 1 meter for 5 kg) one year after chemical separation of daughter products are met [Ref. 6, Table 2]. If we scale their result to 1 m we get 76.2

rem/h rather than 100 rem/h as quoted for 2.4% ^{232}U / ^{233}U , a discrepancy that should be resolved in the future. $127 \text{ rem/h} \times \frac{2.4\%}{1\%} \times \left(\frac{0.5}{1.0}\right)^2 = 76.2 \text{ rem/h}$

III. SPECIFIC FISSION-SUPPRESSED ^{233}U FUSION BREEDING BLANKETS USE EITHER LITHIUM OR BERYLLIUM AS A NEUTRON MULTIPLIER AND MOLTEN SALT AS A BREEDER

A liquid lithium cylindrical annulus extends from 2.5 m to 3.0 m radius contains 0.92% Li-6 and 99.08% Li-7. This zone multiplies neutrons and produces about half the needed tritium. The second zone consists of molten salt, ^7LiF 72%+ BeF_2 16%+ ThF_4 12% from 3.01 to 3.5 m where the rest of the tritium breeding occurs and ^6Li in the molten salt zone $\sim 10^{-7}$ that of ^7Li . A blanket module is shown in Fig. 4.

Another well-documented design [7,8], shown in Fig. 5, uses beryllium as a neutron multiplier. A similar blanket design was done for a tokamak example [9] and could work equally well for other fusion concepts such as inertial fusion energy. These old studies calculated but did not emphasize ^{232}U production. The cylindrical shell blanket is 127 m long and fusion power is 3000 MW. The neutron wall load is 2 MW/m². Fission, especially of ^{233}U , increases the blanket energy multiplication. The first wall is at radius 1.5 m, 0.01 m of iron, the blanket extends from $r=1.51$ m to 2.1 and consists of 10 mm diameter beryllium spheres with molten salt circulating in steel tubes of 17 mm diameter. The molten salt is 70%LiF + 12% BeF_2 + 18% ThF_4 , a 10 mm Fe wall extends to 2.11 m, graphite extends to 2.41 m. The blanket zone consists of 50vol% beryllium, 10% tubes, 0.8% Fe. The volume of molten salt inside the blanket is 85 m³. We assume the volume outside is the same. The amount of thorium is 358 tonnes.

Fission-suppressed fuel producing hybrids maximize safety and the amount of fuel production. Beryllium pebbles are used to multiply neutrons and molten salt slowing flowing through tubes breed both tritium and ^{233}U . Producing ^{233}U from thorium has both proliferation advantages and concerns. ^{232}U that inevitably accompanies ^{233}U production makes the material undesirable but not impossible for use in fission weapons.

TART [10] neutron transport calculations were done for these blankets with results projected in time, shown in Fig. 6. The blanket energy multiplication climbs from 1.6 at the beginning of life for the Be/MS design to 2.1 as shown in Fig. 7 for the fluorination process rate of 10 m³/d chosen. The performance of this blanket is 0.6 ^{233}U atoms produced for each fusion event. Safety is enhanced by fission being suppressed, producing fewer fission products, and in the event of a failure the molten salt is passively drained to passively cooled storage tanks. The assumption is the ^{233}U and ^{232}U are continuously removed by the fluorination process to keep the fission rate of ^{233}U suppressed for both designs. However, it is important to allow ^{231}Pa to

accumulate, as reaction path #3 of Fig. 2 is the overwhelmingly dominant route to making ^{232}U .

For the Li/MS design the calculation assumes a processing rate of $14.4 \text{ m}^3/\text{d}$ (80 days to process the entire inventory for uranium). The $^{232}\text{U}/^{233}\text{U}$ ratio levels off at 5% (for both designs) and M starts at 1.2 and levels off at 1.4. The breeding rate is estimated at $0.5 \text{ }^{233}\text{U}$ /fusion event.

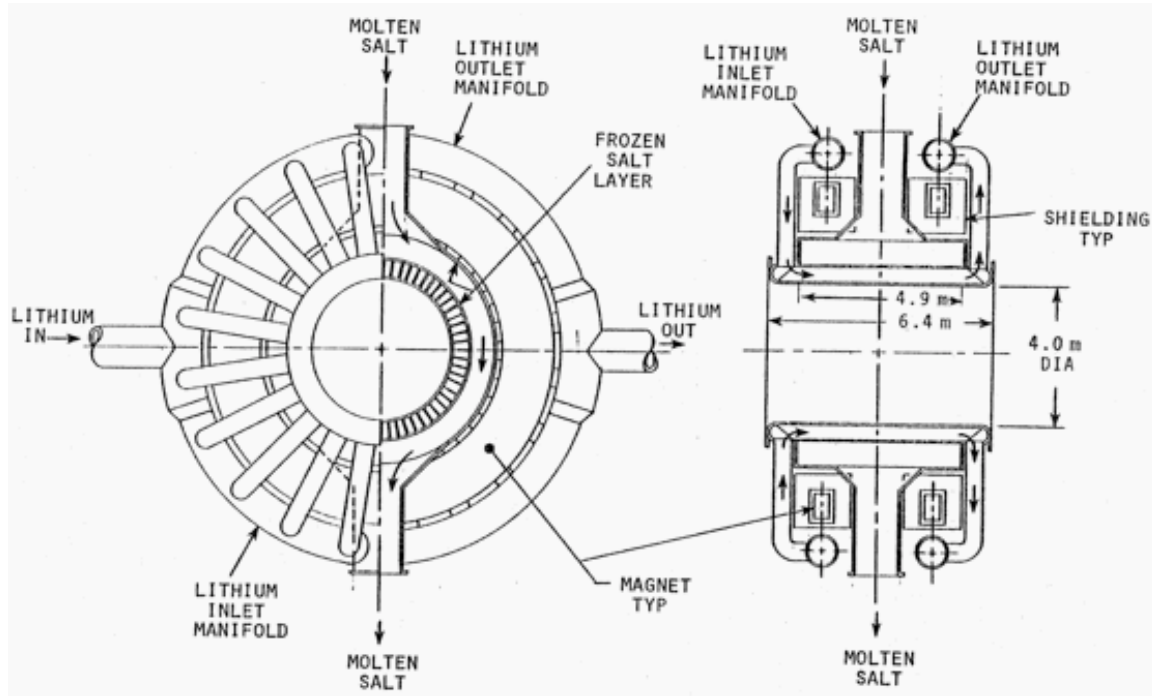


FIGURE 4. Two zone lithium neutron multiplier blanket with a molten salt second zone for the breeding media [11] (Li/MS).

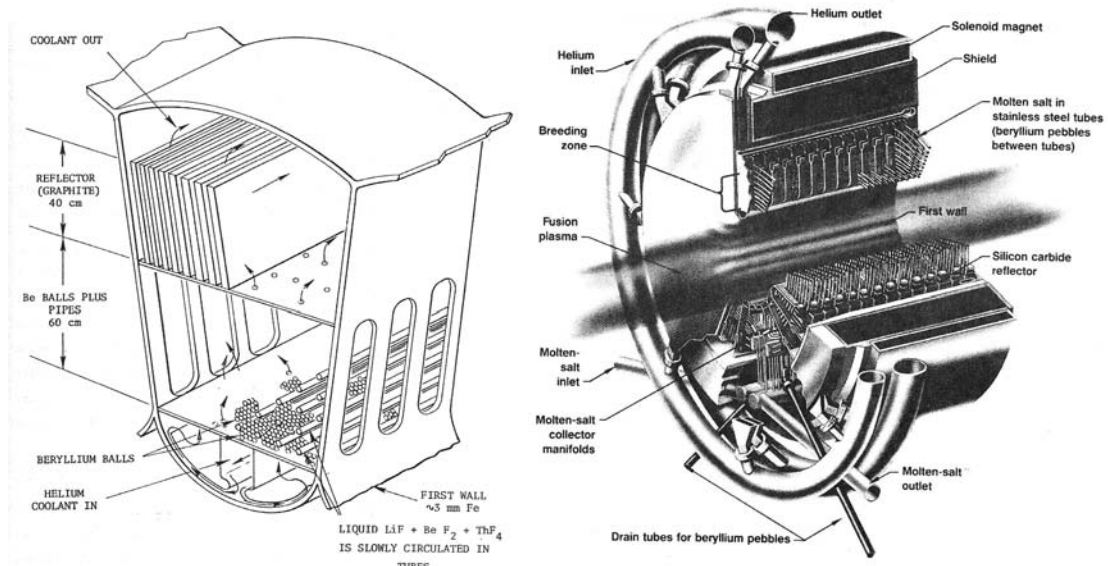


FIGURE 5 shows a blanket submodule designed both for a tandem mirror [7,8] and a tokamak [9] with pebbles and helium cooling the submodule adapted to mirror geometry making an integrated package of first wall, blanket, shield and solenoidal magnet (Be/MS).

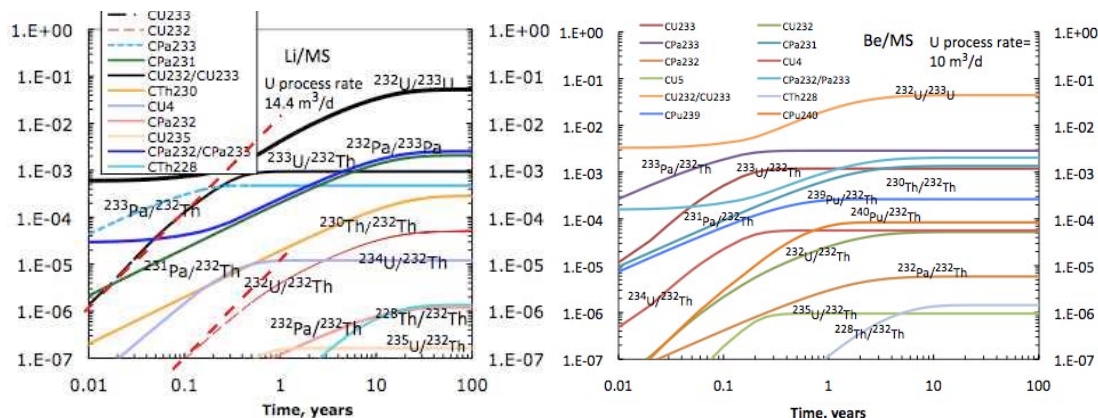


FIGURE 6. Concentration ratios plotted versus exposure time for the Li/MS and Be/MS cylindrical mirror fusion case, uranium processing only.

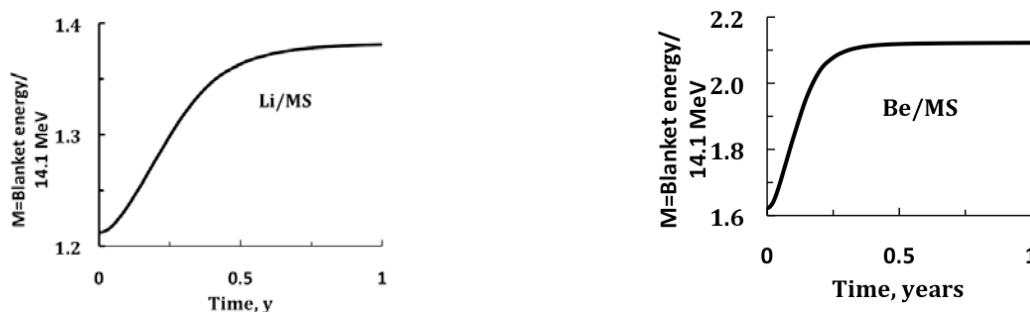


FIGURE 7. Blanket multiplication increases then saturates with burn time.

IV. ^{232}U NONPROLIFERATION FEATURES

In this section we describe in some detail the several features of ^{232}U that tend to discourage use in ^{233}U weapons. These are strong 2.6 MeV gamma rays, strong decay heat from alpha decay, gamma rays degrading high explosive and possibly other effects.

The heat rate and gamma rate are shown in Fig. 8 & 9. They are based on one atom of ^{232}U . We assume at time zero the ^{232}U has just been separated and therefore the ^{228}Th content is zero. Notice that the heat rate is finite at the beginning but the gamma rate starts at zero while the ^{228}Th builds up to a peak in about nine years. The gamma rate peaks at 0.023 MeV/y and the heating peaks at 0.39 MeV/y.

The half-life of ^{233}U is 159,000 years and its energy release is 4.9 MeV. The heat rate of pure ^{233}U is 0.28 W/kg as is shown:

$$\begin{aligned}
 P &= (\text{heat rate in MeV/atom} \cdot \text{year}) \times \left(\frac{M(\text{kg} \text{U}233)}{233.04 \times 1.66054 \times 10^{-27} \text{ kg/atom}} \right) \\
 &\quad \times \left(\frac{1.6021 \times 10^{-19} \text{ J/eV} \times 10^6 \text{ eV/MeV}}{365.25 \times 24 \times 3600 \text{ s/y}} \right) \\
 &= \frac{4.9 \text{ MeV/atom}}{159,000 \text{ y} / 0.693} \left(\frac{1}{233.04 \times 1.66054 \times 10^{-27} \text{ kg/atom}} \right) \times \left(\frac{1.6021 \times 10^{-19} \text{ J/eV} \times 10^6 \text{ eV/MeV}}{365.25 \times 24 \times 3600 \text{ s/y}} \right) \\
 &= 0.28 \text{ W/kg}
 \end{aligned}$$

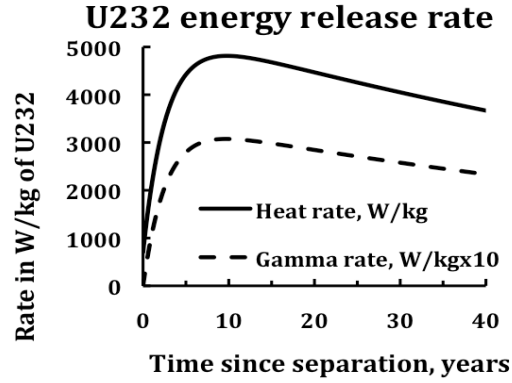
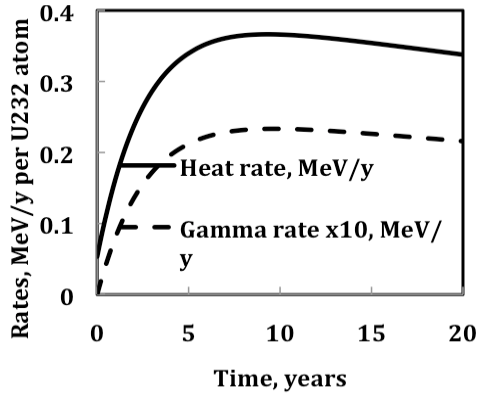


FIGURE. 8. Gamma rate in MeV per atom of ^{232}U . FIGURE. 9. Heat rate of ^{232}U in watts per kg.

The amount of ^{232}U to produce the same heat as that of ^{238}Pu is 9.4 times less after 9 years of build up because ^{238}Pu has one alpha in its decay chain, whereas ^{232}U has six alphas.

The heat rate of ^{232}U is like that of ^{238}Pu on steroids!

heat rate / kg of U232 ÷ heat rate of Pu238 =

$$\frac{238}{232} \left[\frac{NU_{232}}{\tau_{232}} E_{232} + \frac{NTh_{228}}{\tau_{228}} (E_{total} - E_{232}) \right] / \left[\frac{NPu_{238}}{\tau_{238}} E_{238} + \frac{NTh_{228}}{\tau_{228}} E_{238} \right]$$

V. RADIATION DAMAGE TO HIGH EXPLOSIVE (HE)

The high explosive HMX commonly used in nuclear explosives can withstand up to 1.0×10^8 r [12]. The effects of this radiation dose are gas evolution, crumbling and other undesirable effects. A r (roentgen) is equal to 0.00877 J/kg. 100 rad = 1 gray (Gy) = 1 J/kg. 1 r = 0.877 rad = 0.00877 gray. 100 rem = 1 Sv. For our purposes a rad, a rem and an r are pretty closely equal for gamma radiation.

We now discuss the consequences of various levels of ^{232}U / ^{233}U on gamma dose rate from a sphere of ^{233}U of 5 kg reflected by beryllium that would be just critical. At ^{232}U / ^{233}U = 0.024 the dose rate at 1 m is 100 rem/h after 1 year from separation [6]. We have normalized the dose rate of Fig. 2 to 100 rem/h at 1 year and plotted the result in Fig. 10.

At 0.04 m (contact) the dose rate would be $100/0.04^2 = 6.3 \times 10^4$ rad/h assuming a rem=rad shown in Fig. 11. High explosive can tolerate about 100 Mr before degradation. $10^8 / 6.3 \times 10^4 = 1600$ hours to accumulate the tolerable dose for 1 year after separation of ^{232}U . At nine years the dose rate is 2.9 times that at 1 y. The time to degrade or shelf life would be 550 hours (Fig. 11).

A more proper way to assess the dose required to damage high explosive (HE) is to integrate the function of Fig. 8, which is shown in Fig. 10 and 11.

$$\text{Dose} = \int_0^t \frac{NRa_{224}}{\tau_{224}} E_{\text{gamma}} dt$$

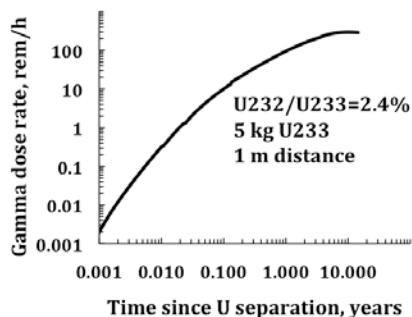


FIGURE 10. Gamma dose rate plotted versus time since separation.

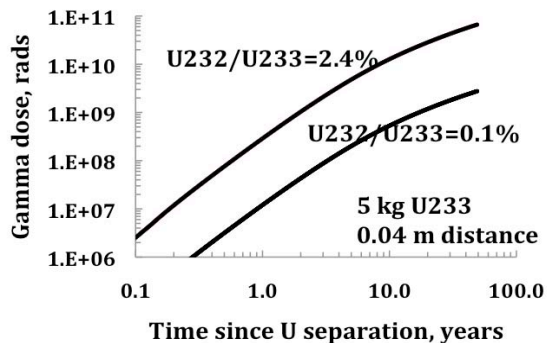


Figure 11. Contact dose in rads with 0.1% & 2.4% ^{232}U plotted versus time since separation.

The HE damages in 3.4 and 0.58 years for 0.1 and 2.4% ^{232}U from Fig. 11. The ^{232}U concentration ratio is proportional to gamma dose or damage for a fixed time.

Heat Generation

Based on the work of Kang and von Hippel [6] for critical mass 5 and isotopic enrichment, $^{233}\text{U}/(^{232}\text{U} + ^{238}\text{U})$ of 1, we calculate the heat generation rate shown in Fig. 12 and 13. The heat rate is 77 W just after separation and climbs to over 600 W ten years later.

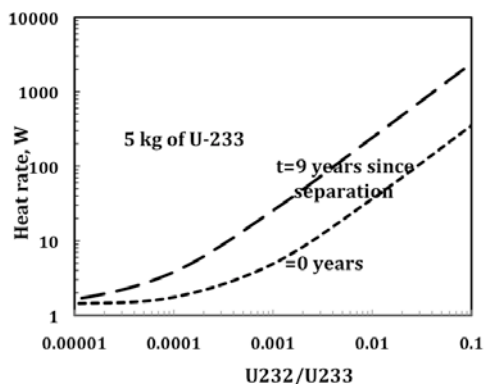


Figure 12. Heat rate in watts from a critical mass versus ^{232}U concentration.

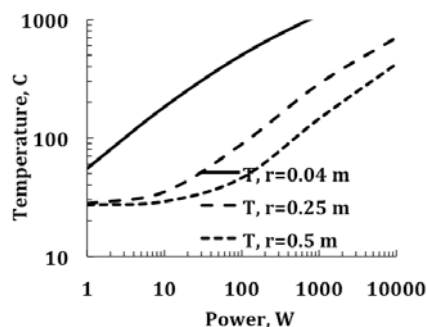


Figure 13. Surface temperature for radiation heat transfer.

We calculate the surface temperature of a sphere containing 5 kg of ^{233}U by two heat transfer mechanisms, convection in air and radiation. The sphere is chosen to be 0.05 and 0.5 m radius for two cases. For a ^{233}U bare sphere at 10 W heat release and 0.05 m radius the temperature is warm to the touch. Above 100 W the temperature is high and rising almost linearly with increasing power. With a sphere of radius 0.5 m surrounding the same mass of U the surface temperature rise would be small. Radiation heat transfer using the heat rates shown in Fig. 12 gives the results shown in Fig. 13.

The gamma radiation to personnel, damage to HE and heat generation all argue against use in nuclear weapons, especially at high concentrations of $^{232}\text{U}/^{233}\text{U} > 2.4\%$. Another effect to be considered is the ejection of particulates caused by alpha particle emitter recoil [13]. Six alphas for each ^{232}U compared to one for ^{238}Pu makes this phenomenon six times stronger.

VI. NUMBER OF FISSION REACTORS SUPPORTED BY EACH FUSION BREEDER

The MSR-LFTR make up fuel is $185 \text{ kg } ^{233}\text{U} / \text{GWe}\cdot\text{y}$ (for $\eta_{\text{Th}}=0.4$ this is $74 \text{ kg } ^{233}\text{U} / \text{GW}_{\text{nuclear}}\cdot\text{y}$) with a conversion ratio, $\text{CR}=0.8$ appropriate to a Th- ^{233}U cycle that would rely on safeguards to address proliferation issues as well as being supplied with fuel spiked with $^{232}\text{U}/^{233}\text{U} \sim 5\%$. An MSR operated with ^{235}U fully denatured with ^{238}U required $85 \text{ kg } ^{235}\text{U} / \text{GW}_{\text{nuclear}}\cdot\text{y}$ makeup fuel. Thorium burning reactors can be designed with CR varying up to 1 or slightly higher. Makeup fuel is proportional to $1-\text{CR}$.

The Th- ^{233}U cycle would rely on safeguards to address proliferation issues as well as being supplied with fuel spiked with $^{232}\text{U}/^{233}\text{U}$ up to 5%.

The fuel production from the fission-suppressed Be/MS fusion breeder is $2660 \text{ kg} / 1000 \text{ MW}_{\text{fusion}}\cdot\text{y}$ and for the fission-suppressed Li/MS fusion breeder is $2220 \text{ kg} / 1000 \text{ MW}_{\text{fusion}}\cdot\text{y}$. The ratio of nuclear power to fusion power is 1.88 for Be/MS and 1.32 for the Li/MS, so the production becomes $1400 \text{ kg} / \text{GW}_{\text{nuclear}}\cdot\text{y}$ for Be/MS and $1700 \text{ kg} / \text{GW}_{\text{nuclear}}\cdot\text{y}$ for Li/MS. One Be/MS fusion breeder can fuel 19 equal nuclear power molten salt reactors with $\text{CR}=0.8$ and 23 for the Li/MS fusion breeder.

The startup inventory of ^{233}U for MSR is typically 1.5 to 3 kg/MWe. At $\eta_{\text{Th}}=0.4$ this is 600 to 1200 kg $^{233}\text{U} / \text{GW}_{\text{nuclear}}$. The fusion breeder could supply with initial fissile inventory each year between 2.2 and 4.4 molten salt reactors of the same nuclear power.

VII. CONCLUSIONS

Fusion's 14 MeV neutrons, being well above the 6 MeV threshold for producing ^{232}U , makes it unique by producing large amounts of ^{232}U in concentrations of $^{232}\text{U}/^{233}\text{U} = 5\%$ resulting in strong nonproliferation features while enabling the thorium cycle by making ^{233}U in large quantities. The radiation associated with the thorium fuel cycle is well known and is one of the reasons it is not used in nuclear reactors, especially since hands-on fabrication of solid fuel is precluded. This radiation also argues against ^{233}U from thorium use in nuclear weapons because of the dose to workers near the explosive. The allowed time of exposure is 300 hours after chemical separation of daughter products for a fatal dose at $^{232}\text{U}/^{233}\text{U} = 2.4\%$ at 1 m. This concentration satisfies the IAEA standards of "reduced protection" or "self protection" set at a dose rate of 100 rem/h (1 Sv/h) 1 m from 5 kg of ^{233}U with 2.4% ^{232}U one year after chemical separation of daughter products. Not so well known is the damage to high explosive material placed near the critical mass of 5 kg owing to ionizing

radiation. The estimated shelf life for high explosive damage is about $\frac{1}{2}$ year after separation for $^{232}\text{U} / ^{233}\text{U} = 2.4\%$. The heat generation at the time of separation is 77 W and rises in nine years to 600 W. The temperature rise owing to this heat generation rate for a bare sphere is estimated to be 84 °C and 450 °C at time of separation and after 9 years, respectively.

Fusion's first and early application could be to produce fuel to start up thorium cycle molten salt fission reactors and supply makeup fuel for over 20 fission plants of equal nuclear power. In this paper we have shown the role that ^{232}U can play in nonproliferation of the thorium fuel cycle. However, it is far from perfect and strong safeguards should be fully employed with the thorium fuel cycle. The molten salt state of the fuel in both the fusion and the fission system lend themselves to processing at low rates to keep excess fissile material to a minimum, which should aid nonproliferation. Another feature of molten salt is that under a wide variety of adverse conditions the fuel can be drained to passively-cooled holding tanks.

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