

FISSION-SUPPRESSED FUSION, THORIUM-CYCLE BREEDER AND NONPROLIFERATION

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Fusion reactors can be designed to breed fissile material for startup and makeup fuel for fission reactors while suppressing fissioning, thereby enhancing safety. Each fusion reaction can release about 2.1 times the 14 MeV neutron's energy in the blanket in this fission-suppressed design while producing 0.6 fissile atoms, which is 2660 kg/1000 MW of fusion power for a full power year. The revenues would be doubled from such a plant by selling both fuel at a price of \$60/g and electricity at \$0.05/kWh for $Q=P_{fusion}/P_{input}=4$. Fusion reactors could also be designed to destroy fission wastes by 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 dedicated to fissioning wastes with some of their neutrons. The design for safety and heat removal is already accomplished with fission reactors; however, fusion reactors have geometry that compromises safety with a complex and thin wall separating the fusion zone from the fission blanket zone. Fusion is unique compared to fission in that its high-energy 14 MeV neutron can generate up to 0.05 ²³²U atoms for each ²³³U atom produced from thorium, about twice the IAEA standards of "reduced protection" or "self protection."

I. INTRODUCTION

Mixing ²³³U with ²³⁸U can enhance nonproliferation. Also nonproliferation is enhanced in three typical fission-suppressed designs [1] by generating up to 0.05 ²³²U atoms for each ²³³U atom produced from thorium, about twice 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 ²³³U with 2.4% ²³²U one year after chemical separation of daughter products [2]. With 2.4% ²³²U, high explosive material is predicted to degrade owing to ionizing radiation after a little over ½ 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 ²³³U 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 ²³²U that comes along with making ²³³U, has a strong gamma ray associated with its daughter products. Reactions leading to ²³²U 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 ²³²U whereas fission has less than 3% of its neutrons above 6 MeV as shown in Fig. 1.

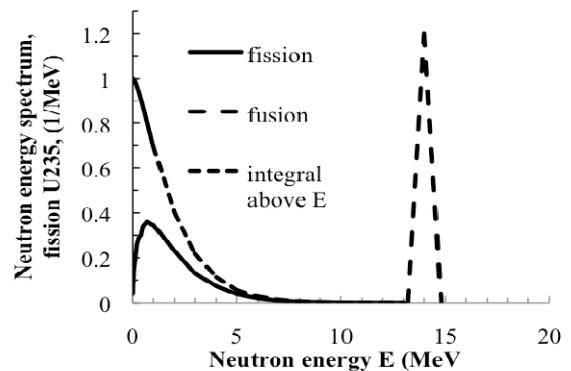
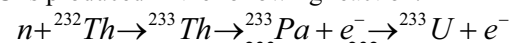


Fig. 1. Neutron source spectra for fission and fusion.

II. PRODUCTION OF ²³²U AND ²³³U

²³³U is produced in the following reaction.



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

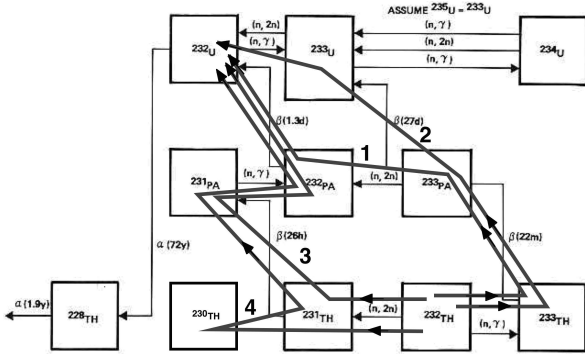


Fig. 2. Reaction paths that lead to ²³³U and ²³²U

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

- 1 $n + {}^{232}\text{Th} \rightarrow {}^{233}\text{Th} \rightarrow {}^{233}\text{Pa} + e^-$
 $n + {}^{233}\text{Pa} \rightarrow 2n + {}^{232}\text{Pa} \rightarrow {}^{232}\text{U} + e^-$
 (fast-neutron reaction)
- 2 $n + {}^{232}\text{Th} \rightarrow {}^{233}\text{Th} \rightarrow {}^{233}\text{Pa} + e^- \rightarrow {}^{233}\text{U} + e^-$
 $n + {}^{233}\text{U} \rightarrow 2n + {}^{232}\text{U}$
 (fast-neutron reaction)
- 3 $n + {}^{232}\text{Th} \rightarrow 2n + {}^{231}\text{Th} \rightarrow {}^{231}\text{Pa} + e^-$
 (fast-neutron reaction)

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

- 4 $n + {}^{232}\text{Th} \rightarrow 3n + {}^{230}\text{Th}$ (fast-neutron reaction)
 $n + {}^{230}\text{Th} \rightarrow {}^{231}\text{Th} \rightarrow {}^{231}\text{Pa} + e^-$
 $n + {}^{231}\text{Pa} \rightarrow {}^{232}\text{Pa} \rightarrow {}^{232}\text{U} + e^-$

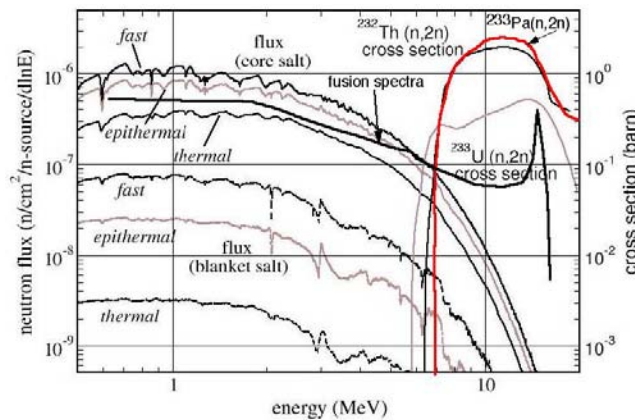


Fig. 3. Threshold cross-sections for producing ²³²U, [5]. The fusion neutron spectrum is superimposed but not to scale vertically.

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

Since ²³¹Pa accumulates, the first set of reactions depends on exposure time even after ²³³U is removed. Long exposure times are useful and the Pa needs to be left in during processing to remove ²³³U. The second reaction also depends on time during which the ²³³U accumulates to the value limited by the processing rate to remove the produced material.

As the concentration of ²³²U in ²³³U 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) 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% ²³²U / ²³³U

$$127 \text{ rem/h} \times \frac{2.4\%}{1\%} \times \left(\frac{0.5}{1.0}\right)^2 = 76.2 \text{ rem/h}$$

This discrepancy is a topic to be resolved in the future.

III. SPECIFIC FISSION-SUPPRESSED ²³³U FUSION BREEDING BLANKETS USING MOLTEN SALT

This breeding blanket is a well-documented design in [7,8] and shown in Fig. 4 & 5. 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 ²³²U production. The cylindrical shell blanket is 127 m long and fusion power is 3000 MW. The neutron wall load is 2 MW/m² and blanket energy multiplication at beginning of life is 1.6. Fission especially of ²³³U seems to increase 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% BeF₂+ 18% ThF₄, 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; uses helium cooling of beryllium pebbles to multiply neutrons and molten salt slowing flowing through tubes to both breed tritium and ²³³U. Producing ²³³U from thorium has both proliferation advantages and concerns. ²³²U that inevitably accompanies ²³³U production makes the

material undesirable but not impossible for use in fission weapons.

TART [10] neutron transport calculations were done for this blanket with results projected in time, shown in Fig. 6. The blanket energy multiplication climbs from 1.6 to 2.1 as shown in Fig. 7 for the fluorination process rate of $10 \text{ m}^3/\text{d}$ 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 safe storage tanks. As mentioned in the previous section the Q should be >8 for a first approximation of economics. Typical parameters of this blanket are given in Table 1.

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. 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 .

Another blanket design in Ref. [1] uses ^7Li for neutron multiplication followed by a molten salt zone and gives similar results as those in Fig. 6 with Be; the $^{232}\text{U}/^{233}\text{U}$ ratio levels off at 5% however, $M=1.3$.

TABLE 1. Be/molten salt blanket parameters.

	Beginning	Steady state
P_{nuclear} , MW	4440	5640
P_{fusion} , MW	3000	3000
$P_{\text{alpha particle}}$, MW	600	600
P_{blanket} , MW	3840	5040
P_{electric} , MW	1380	1860
$P_{\text{wall load}}$	2 MW/m^2	
Length of blanket	127 m	
First wall radius	1.5 m	
T	1.1	
F_{net}^*	0.6	
M^*	1.6	2.1
Fissile production	6380 kg $^{233}\text{U}/\text{yr}$ at 80% capacity factor	
Total cost	\$4870 M (1982\$)	

* F_{net} is the fissile atoms bred/triton consumed. M is the energy released in the blanket per triton consumed divided by 14 MeV. More recent studies gives $M=2.1$. Previously fission of ^{233}U must have been ignored or a much higher processing rate used.

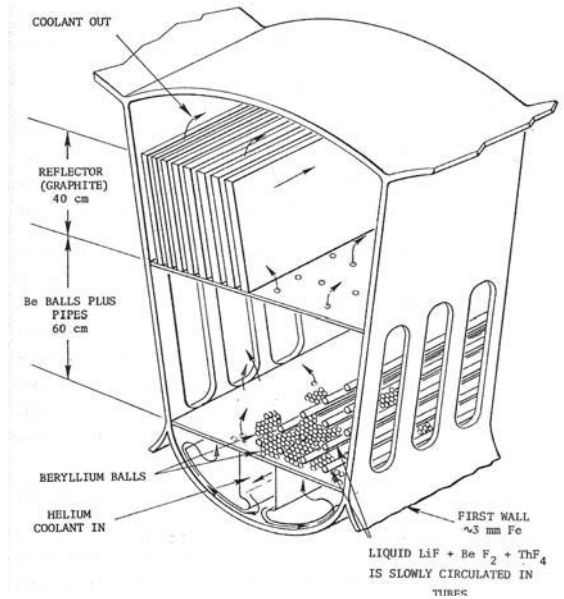


Fig. 4. shows a blanket submodule designed both for a tandem mirror [7,8] and a tokamak [9] with pebbles and helium cooling.

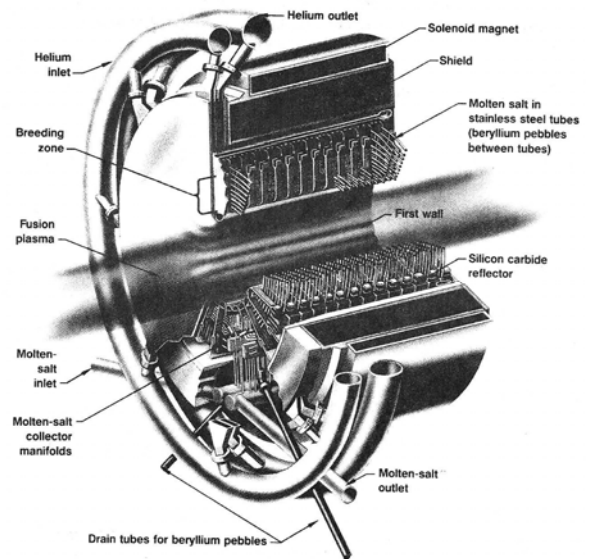


Fig. 5. shows the submodule adapted to mirror geometry making an integrated package of first wall, blanket, shield and solenoidal magnet.

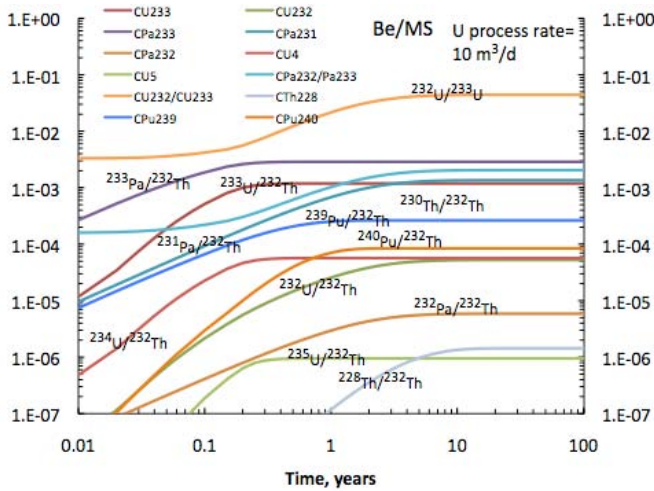


Fig. 6. Concentration ratios versus exposure time for the Be/MS case.

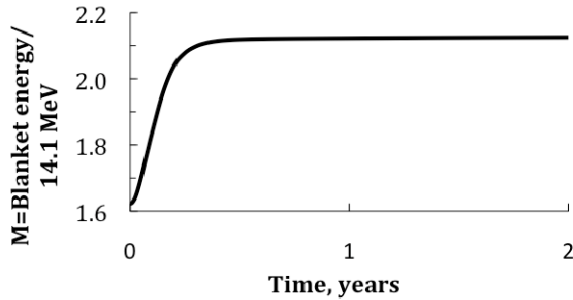


Fig. 7. Blanket multiplication increases with burn time.

IV. ²³²U NONPROLIFERATION FEATURES

In this section we describe in some detail the several features of ²³²U that tend to discourage use in ²³³U weapons. These are strong gamma rays at 2.6 MeV, 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 ²³²U. We assume at time zero the ²³²U has just been separated and therefore the ²²⁸Th content is zero. Notice that the heat rate is finite at the beginning but the gamma rate starts at zero while the ²²⁸Th 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.

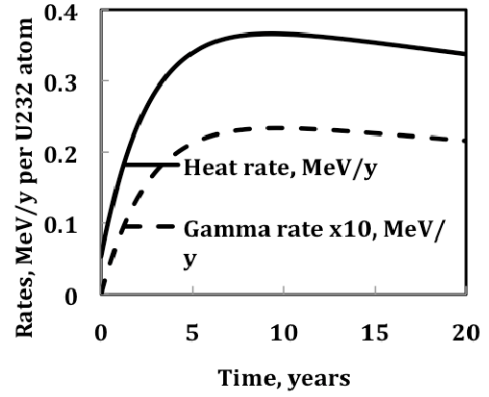


Fig. 8. Gamma rate in Mev per atom of ²³²U.

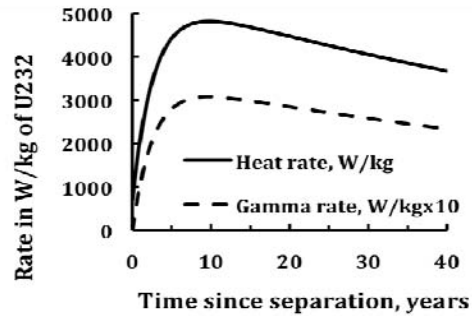


Fig. 9. Heat rate of ²³²U in watts per kg.

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

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

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

The heat rate of ²³²U is like that of ²³⁸Pu 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 1.0×10⁸ r [11]. 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 $^{232}\text{U}/^{233}\text{U}$ on gamma dose rate from a sphere of ^{233}U of 5 kg reflected by beryllium that would be just critical. At $^{232}\text{U}/^{233}\text{U} = 0.024$ 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.

$$\text{Dose} = \int_0^t \frac{NRa224}{\tau_{224}} E_{\text{gamma}} dt$$

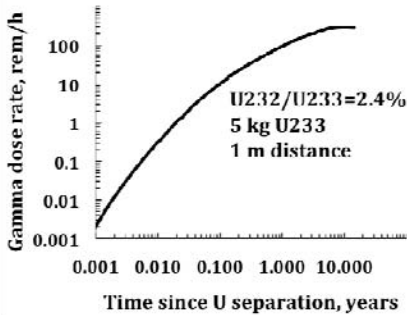


Fig. 10. Gamma dose rate from 5 kg of ^{233}U with 2.4% ^{232}U .

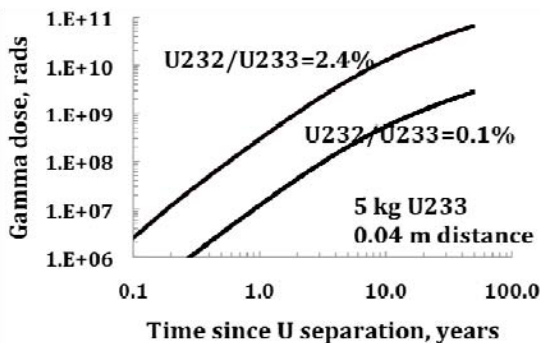


Fig. 11. Contact dose in rads from 5 kg with 0.1% & 2.4% ^{232}U versus time.

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, 25, 60 130 and 430 kg corresponding to isotopic enrichment, $^{233}\text{U}/(^{232}\text{U} + ^{238}\text{U})$ of 0.13, 0.2, 0.5 and 1, we calculate the heat generation rate shown in Fig. 12 and 13.

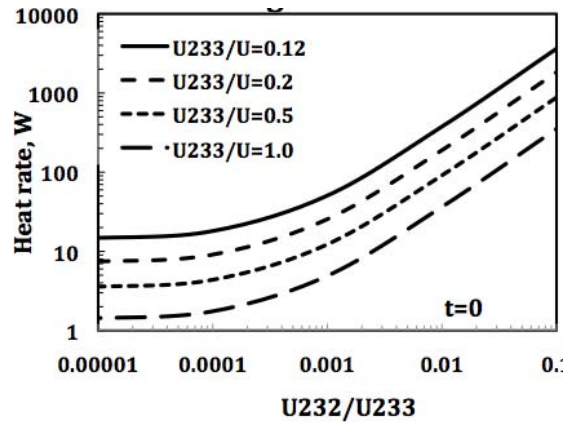


Fig. 12. Heat rate in watts from a critical mass versus ^{232}U concentration at time of separation of uranium.

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 & 13 gives the results shown in Fig. 14.

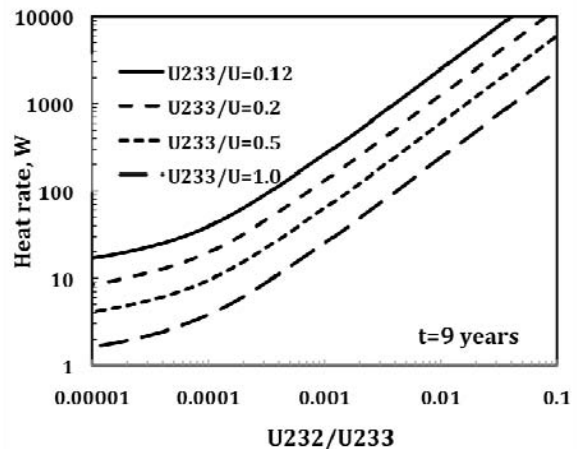


Fig. 13. Heat rate in watts from a critical mass versus ^{232}U concentration nine years after separation of uranium.

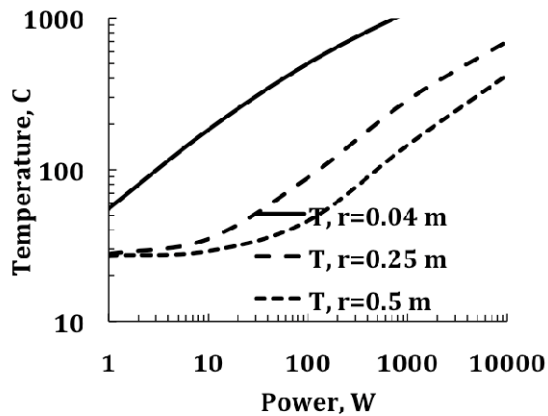


Fig. 14. Surface temperature for radiation heat transfer.

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 [12]. 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 kg ^{233}U /GW \cdot y (for $\eta_{\text{Th}}=0.4$ this is 74 kg ^{233}U /GW $_{\text{nuclear}}\cdot$ y) with a conversion ratio, 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 kg ^{235}U /GW $_{\text{nuclear}}\cdot$ y) makeup fuel. Thorium burning reactors can be designed with CR varying up to 1 or slightly higher. Makeup fuel is proportional to 1-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 fusion breeder is 2660 kg/1000 MW $_{\text{fusion}}\cdot$ y. The ratio of nuclear power to fusion power is 1.88, so the production becomes 1420 kg/GW $_{\text{nuclear}}\cdot$ y. One such fusion breeder can fuel 19 equal nuclear power molten salt reactors with CR=0.8.

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}U /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. SUMMARY AND DISCUSSION

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.

VIII. CONCLUSIONS

Fusion's 14 MeV neutrons, being well above the 6 MeV threshold for producing ^{232}U , makes it unique in enabling the thorium cycle with strong nonproliferation features.

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 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 for a fatal dose at $^{232}\text{U}/^{233}\text{U} = 2.4\%$.

Not so well known is the damage to high explosive material placed near the critical mass 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.

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