

BASIC ASPECTS OF SUB-CRITICAL SYSTEMS USING THIN FISSILE LAYERS

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Abstract:

Through the use of thin layers of fissile material one can design near critical systems in which the absolute amount of fissile material is small (less than one critical mass in a fast neutron system) yet with very favourable heat transfer properties. In the present paper we present the results of a basic investigation of such systems. In addition, we describe an application of such a system based on these thin films, to boost neutron production in spallation sources.

Introduction

The critical mass M_c of a system scales as the inverse square of the density ρ of fissile material i.e. $M_c \propto \rho^{-2}$. Hence, for systems with low fissile material content the mass of material required to make the system near critical is large (for more details see [1]). Because of the low density of fissile material, such systems clearly have a low heat source density. Systems based on the use of nearly pure fissile material require the least amount of fissile material to make the system near critical but have the disadvantage that it is very difficult to remove the heat generated.

Through the use of thin layers of fissile material one can design near critical systems in which the absolute amount of fissile material is small (less than one critical mass in a fast neutron system) yet with very favourable heat transfer properties [2]. In the present paper we present the results of a basic investigation of such systems. In addition, we describe an application of a system based on these thin films, to boost neutron production in spallation sources.

The minimum thickness of layer required in such systems must, of course, be of the order of the mean free path, mfp, of the neutron - otherwise the layer is just transparent to the neutron. In pure U^{235} the fission mfp for a thermal neutron is approximately 300 μm . The equivalent fission mfp in $\text{Am}^{242\text{m}}$ is only 30 μm . The critical masses for thermal neutrons in U^{235} and $\text{Am}^{242\text{m}}$ are approximately 11 kg and 500 g respectively. Hence, the corresponding diameters of spherical thin shell systems, $D = (M_c/\pi\rho)^{0.5}$, are 0.5 m for $\text{Am}^{242\text{m}}$ and 0.75m for U^{235} .

Since thermal and fast neutrons generally have different cross sections, this implies that the mfps are also different. This suggest the possibility of "filtering" neutrons with different energies. Actually it is more than a filter. Fast neutrons will go through the layer without interaction. Thermal neutrons, however, will be trapped, and induce fast neutrons through the fission process. This idea can also be generalised. In pure fissile material, fission and capture reactions also occur on different scale lengths according to their mfps. "Switching" reactions on and off then corresponds to a suitable choice of layer thickness. For the particular case of pure U^{235} , the thermal fission and capture mfps are 300 and 2000 μm respectively. Hence, in layers of dimension approximately 300 μm , only fission reactions will occur. In a mixed system such as U^{235}/U^{238} , the fission cross section of U^{235} is 300 μm and the capture cross section in U^{238} is 70000 μm !. Hence in layers of thickness around 1mm, thermal neutrons will only "see" the fissile U^{235} atoms.

Criticality Properties of Thin Actinide Layers

A critical or near critical system based on the use of thin actinide films is shown schematically fig. 1. The fissile material constitutes a thin layer on the inner surface of a hollow cylinder of circular cross-section, made of a neutron moderator material such as graphite or beryllium. The thickness of the layer is typically in the micrometer range. This thickness depends upon the type of fissile material and its concentration in this layer. In any case it must be sufficiently small in order to allow fast neutrons to pass through without interaction, whereas thermal neutrons are trapped.

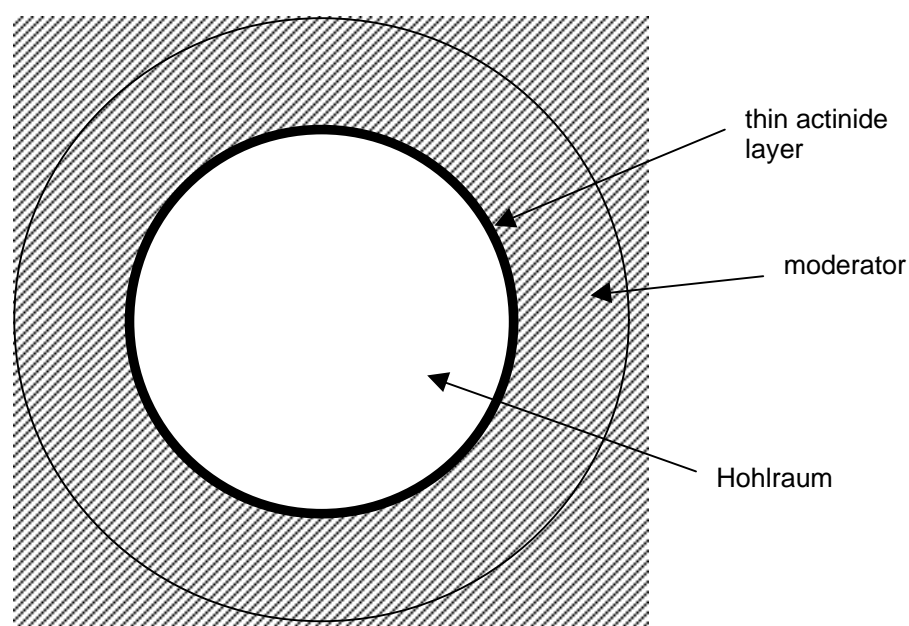


Fig. 1. A critical or near critical system based on a Hohlraum, a thin actinide layer and a moderator.

Neutrons in the Hohlraum may be thermal or fast. Thermal neutrons react immediately with the layer and generate fast neutrons whereas fast neutrons pass through without interaction. In both cases fast neutrons penetrate into the moderator and become thermalised. If these neutrons penetrate again into the thin fissile layer they cause more fissions. Those which escape from the cylinder at its outside constitute the output of the assembly.

In tables 1 and 2, the layer thickness of fissile material required to make the system critical ($k_{\text{eff}} = 1$), are given for Am242m and U235 for various cylinder diameters ϕ . The results refer to a cylinder having an inner diameter ϕ equal to its height. Also given is the mass of fissile material.

Table 1. Layer thickness of Am^{242m} metal and corresponding mass required for criticality for various cylinder diameters ϕ .

Diameter, Length (cm)	Critical Thickness (cm)	Critical Mass (kg)
0	2.2	1.3
10	0.4	2.6
20	0.063	1.6
30	5E-3	0.25
40	1E-3	0.1
60	4E-4	0.08

Table 2. Layer thickness of U²³⁵ metal and corresponding mass required for criticality for various cylinder diameters ϕ .

Diameter, Length (cm)	Critical Thickness (cm)	Critical Mass (kg)
0	4.4	10
10	2	14
20	0.8	20
40	0.15	14
60	0.023	5
100	0.007	4

The results from these tables are summarised in fig.2 where the critical mass is plotted as a function the layer thickness for Am^{242m} (small circles) and U²³⁵ (crosses). From fig. 2, for example, one can deduce that criticality is obtained with an Am^{242m} layer thickness of 4 μm on the inner surface (diameter 60 cm) of a graphite cylinder (axial length 60 cm). The overall critical mass of fissile material is under these circumstances only 80 g, which is considerably less than the (bare) critical mass of a solid sphere of the same material (4.7 kg). If a layer thickness below 4 μm is chosen then the arrangement will be subcritical.

The system shown in fig. 1 need not necessarily be of circular cross-section. The cross-section might be square or present an inner corrugated shape like a star. In this latter case the overall diameter of the cylinder can be reduced whilst maintaining the same surface area of fissile material.

In case that not a thermal neutron flux but a fast neutron flux is desired, the arrangement according to figure 1 can be extended, as shown in figure 3, by a further layer of fissile material on the outer surface of the graphite cylinder and optionally by a metal casing around this layer. This second layer is again transparent to fast neutrons as it interacts only with neutrons which have been thermalized in the graphite cylinder. These neutrons cause fission which result in fast neutrons. A part of these fast neutrons escapes through the casing whereas others return into the graphite cylinder and cause further fissions in one of the layers of fissile materials.

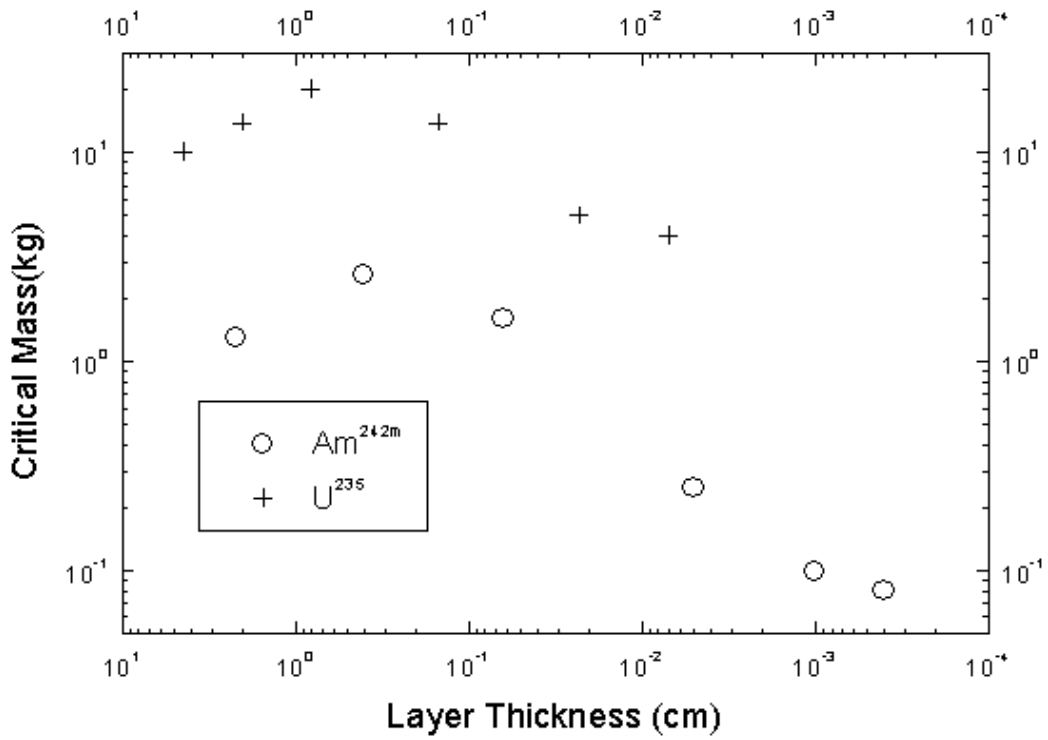


Fig. 2. Criticality masses of thin actinide layers vs. layer thickness

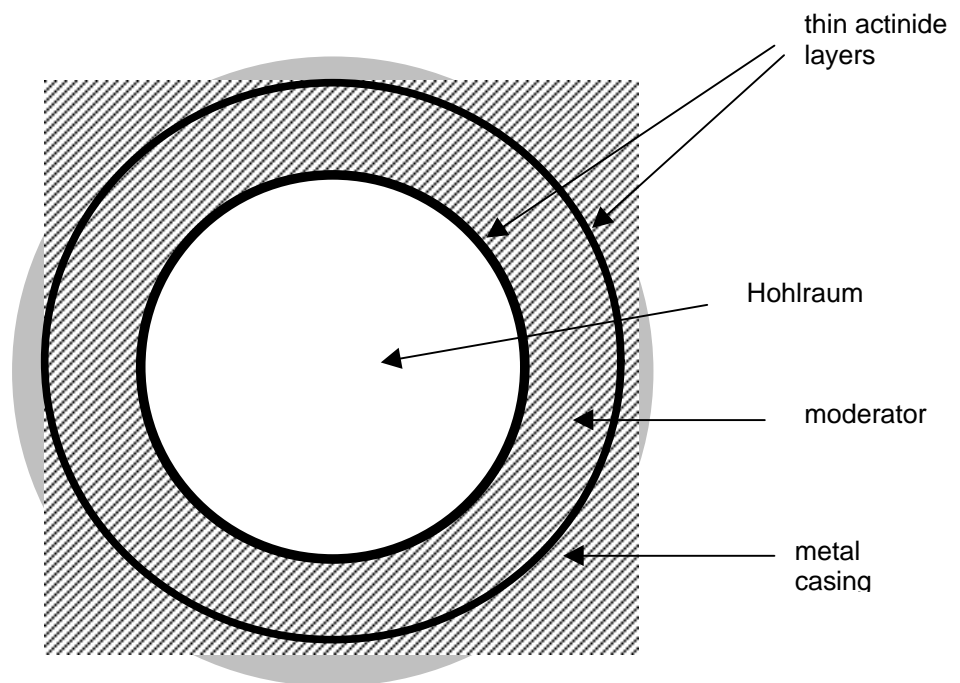


Fig. 3. A critical or near critical system for fast neutrons

Application to ADS: Boosted Spallation Sources

The basic idea is to surround the spallation target by a thin layer of fissile material which is sub-critical. This thin layer of fissile material acts as a neutron amplifier [3]. The consequence of this is that in ADS, one may be able to use a considerably less powerful proton accelerator to obtain the same neutron flux. Consider 1 GeV protons: through their interaction in the spallation target (Pb) each proton will produce approximately 30 neutrons. Alternatively, one can produce the same number of neutrons using 250-350 MeV protons (which gives rise to 2-3 neutrons per proton) on a spallation target which is surrounded by a thin film of fissile material with a k_{eff} of about 0.9 (gives a neutron multiplication factor of about 10). Alternatively, for a given proton energy, one could reduce the proton current in such systems. Hence such systems would demand much less powerful (and cheaper, less window damage etc.) accelerators, but in addition, considerably reduce the proliferation problem associated with high power accelerators. A schematic design of such a booster unit for spallation targets is shown in fig. 4.

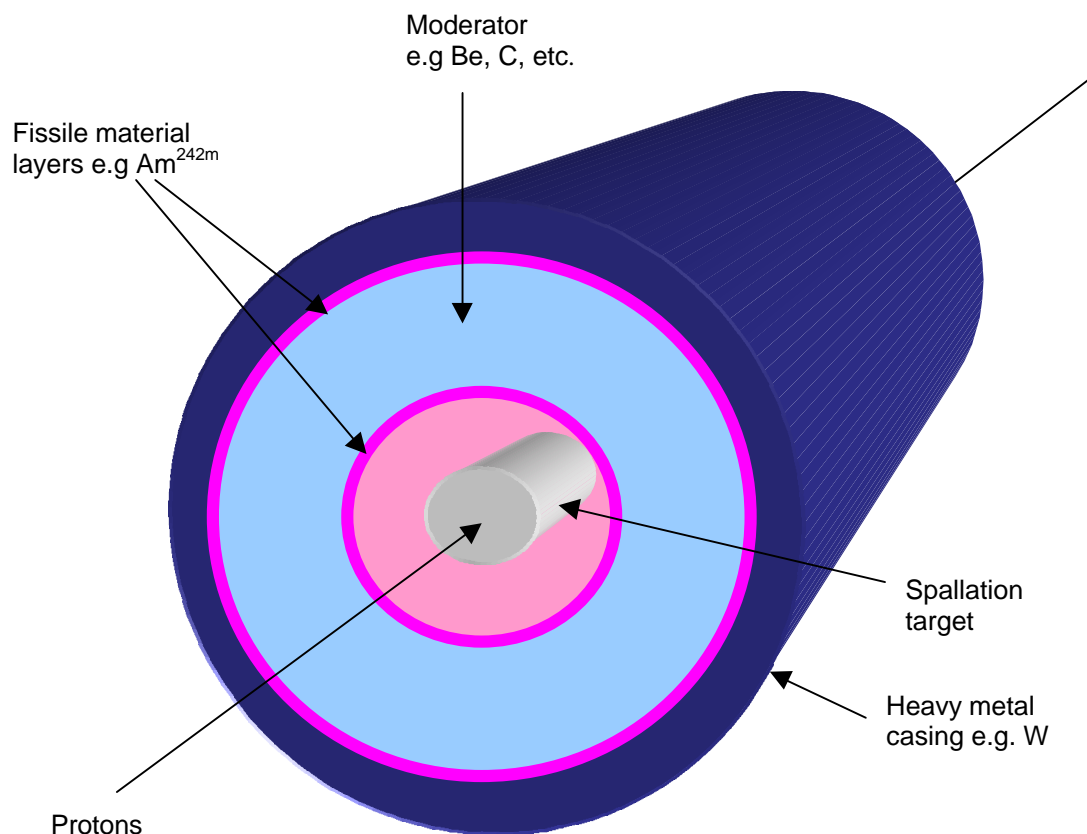


Fig. 4. Booster unit for spallation targets

The innermost layer is of fissile material. The dimensions of this layer are in the range 10-100 μm (this dimension depends on the fissile material, and the desired multiplication factor) such that fast neutrons pass through without interaction and thermal neutrons are trapped and

cause fission. Notice that the mean free path for thermal fission is about 30µm whereas the mean free path for a fast neutron is approx. 1m). A neutron starting in the Hohlraum (where the spallation target is) has two possibilities:

- a. If it is thermal, it will react immediately with the fissile layer generating fast neutrons. These neutrons either go into the Hohlraum or into the moderator. Those that go into the moderator will gradually diffuse through the moderator (some will also go back to the inner fissile and cause more fissions).
- b. If it is fast, it will not "see" the inner fissile layer but only the moderator. In the moderator the neutrons will diffuse. Some will diffuse to the outer fissile layer and some which have been thermalised can interact with the inner fissile layer causing fissions and fast neutrons.

In the moderator layer the neutrons will be thermalised such that when they reach the outer fissile layer they will immediately fission and cause fast neutrons. These fast neutrons will then diffuse outwards through the heavy metal casing with little loss of energy. At the outer surface of the metal casing there will be fast neutrons. Fast neutrons can, in addition propagate back through the moderator towards the inner fissile layer. They will of course be thermalised in this process. On reaching the inner fissile layer they will cause fissions and again fast neutrons etc.

Main problem which needs to be addressed is the coupling of two sub-critical systems i.e. system 1 is the booster unit and system 2 is the sub-critical blanket. This needs a detailed study.

How much heat is produced in the layer? Consider a single Am layer with a diameter 0.6 m, length 0.6 m, thickness 4 µm. This layer has a mass of 80g and is slightly sub-critical. Consider, in addition, an accelerator with the following characteristics: Proton energy = 150 MeV, proton current = 2 mA (i.e. power = 300 kW). Hence the proton generation rate is 1.25×10^{16} protons per second. Since the number of protons per neutron is approximately unity at 150 MeV, the neutron generation rate is also 1.25×10^{16} per second. If the k_{eff} of the booster unit is 0.95, the neutron multiplication factor will be approximately 20. Hence the neutron intensity is 2.5×10^{17} per sec. If we assume every neutron passing through the thin fissile layer causes fission, then the maximum heat generation rate is

$$2.5 \times 10^{17} \text{ s}^{-1} \cdot 200 \text{ MeV} = 2.5 \times 10^{17} \cdot 2 \times 10^8 \cdot 1.6 \times 10^{-19} \text{ J} = 8 \text{ MW}$$

This is not a lot of heat when one considers that a 1 GeV, 10 mA beam will generate around 10 MW in a considerably smaller volume. Also the heat generation in an assembly in a PWR (dimensions 20x20x370cm) is approximately 15 MW.

What is the lifetime of such a layer in this high neutron flux? The atom density in Am is $N \cong 5 \times 10^{22} \text{ cm}^{-3}$. The volume of the thin layer is $V = \pi D H \tau$ where D is the diameter, H the height, and τ is the layer thickness i.e. $V = 4.5 \text{ cm}^3$. Hence total number of atoms is $5 \times 10^{22} \cdot 4.5 = 2.3 \times 10^{23}$. The layer lifetime is then $2.3 \times 10^{23} / 2.5 \times 10^{17} \text{ s}^{-1} =$ about 10 days. So the booster unit should be exchanged every 10 days. This is still quite reasonable and justifies further investigation.

Conclusions

In the present work, some interesting properties of thin layers of fissile materials have been presented. From the point of view of neutrons, such systems can be made critical with very small quantities of material. Because of the effective large surface area, heat removal should not present any major difficulties. A variety of applications are under investigation. In this paper, one such application is described i.e. the design of a booster unit for spallation sources. Through the use of such a unit, one may be able to design accelerator driven systems with considerably less powerful accelerators.

References

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