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Title: ACCELERATOR-DRIVEN MOLTEN-SALT BLANKETS: PHYSICS ISSUES

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# Accelerator-Driven Molten-Salt Blankets: Physics Issues

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**Abstract.** A number of nuclear physics issues concerning the Los Alamos molten-salt, accelerator-driven plutonium converter are discussed. General descriptions of several concepts using internal and external moderation are presented. Burnup and salt processing requirement calculations are presented for four concepts, indicating that both the high power density externally moderated concept and an internally moderated concept achieve total plutonium burnups approaching 90% at salt processing rates of less than 2 $m^3$ per year. Beginning-of-life reactivity temperature coefficients and system kinetic response are also discussed. Future research should investigate the effect of changing blanket composition on operational and safety characteristics.

## INTRODUCTION

Accelerator-driven molten-salt blankets are being considered for numerous applications, primarily plutonium destruction and nuclear waste transmutation. Blanket safety and performance should be optimized for each application, as the blanket is a major component of the overall system, and optimal blanket design will vary with the purpose of the system. The overall safety and performance of any target/blanket (T/B) concept depends on the nuclear physics, thermal-hydraulic, mechanical design, and other features of that system. The research reported in this paper focuses on the nuclear physics of subcritical molten-salt blankets designed for burning weapons-grade plutonium.

Two types of multiplying molten-salt blankets are under consideration: blankets with an internal graphite moderator and blankets with no internal moderator. These two concepts are used to highlight the important physics issues relevant to selecting a concept for conceptual design. Each blanket type has advantages and disadvantages. The difference in the performance of these two blankets is primarily caused by differences in neutron spectrum and leakage. Specific physics issues used to compare these two concepts include safety, blanket multiplication, blanket reactivity temperature coefficients, attainable blanket plutonium burnup, blanket control, and blanket neutron spectrum.

In selecting one concept for further design, maximum attainable burnup and safety (usually as related to the blanket reactivity temperature coefficient) are used in the initial screening process. Engineerability, waste stream generation, and other factors are used in the final selection process. Additional analyses are performed for point designs, including blanket flux distributions and the effect of various reactivity insertions. Reactivity insertion effects are evaluated by performing kinetics calculations that estimate blanket power, temperature, and reactivity throughout the transient. Reactivity effects of cooling and over-temperature accidents are also evaluated, as are methods for ensuring blanket shutdown.

## TARGET/BLANKET DESCRIPTION

As previously mentioned, two blanket arrangements were initially screened for their attractiveness in terms of performance and safety. For both concepts, the T/B system consists of a molten lead target radially centered in the multiplying blanket, with the axial position optimized to produce the maximum effective number of neutrons for every incident proton. Salt enters at the bottom of the blanket and is pumped upward through the blanket. After exiting the active region, heat is transferred from the primary salt to a non-fissioning secondary salt. Various fission products are removed from the salt through an active helium gas sparge system and metal fission product plateout at the heat exchangers. The volume of the active region ranges from 2 $m^3$ to 80 $m^3$, depending on design specifics and whether external or internal moderation is used. The first configuration, termed internally moderated (IM), is very similar to the reactor core of the ORNL molten-salt breeder reactor [1]. In this configuration the active blanket is comprised of 90% graphite and 10% molten fuel salt. Typical blanket dimensions are 5 m in diameter by 5 m tall, with the fuel salt traveling upwards through small (1- to 2-cm-diameter) circular channels cut directly into the graphite. A more detailed description of this concept can be found elsewhere [2,3]. The second configuration, termed externally moderated, consists of an all-fuel salt core surrounded by a stainless-steel-clad graphite vessel. A schematic of this configuration is shown in Figure 1. The size of this T/B is roughly 1.4 m in diameter and 1.4 m tall.

## BURNUP

Burnup analyses were performed for four design concepts using a coupled Monte Carlo neutronic (MCNP) and depletion code (ORIGIN2) system. The first concept is a reference internally moderated design, described in reference [1]. The active region for this concept has a volume of approximately 80 $m^3$ (8 $m^3$ of fuel salt), and consists of salt flowing through channels in graphite blocks. The second concept is a low power density, externally moderated system (LPD/EM). The active region for this concept has a volume of 9 $m^3$, and consists entirely of fuel salt. A 1-m-thick graphite reflector/moderator surrounds the blanket, softening the neutron spectrum. The third concept is a high power density, externally moderated system (HPD/EM) with an active region (pure molten salt) volume of only 2 $m^3$. The fourth concept is a low power density system with no graphite reflector/moderator (LPD/NM). The active region for this concept has a volume of 9 $m^3$, and consists entirely of fuel salt.

In performing burnup calculations, several fission product classes are removed during operation, including noble gases (Kr and Xe), seminoble metals (Zn, Ga, Ge, and As), and noble metals (Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, and Sb). Maximum burnup is limited by reactivity and solubility considerations. Reactivity limits are caused by the need to maintain a specified blanket multiplication (based on accelerator size and other factors). Solubility limits are caused by the need to ensure that plutonium and lanthanides remain dissolved in the salt during all operating conditions. Two solubility limits were considered: 75% of the solubility limit at the lowest projected blanket operating temperature (0.3 moles/liter at 850 K), and the solubility limit at the near freezing temperature of the salt (0.1 moles/liter at approximately 725 K).

Table 1 gives a summary of the results for the four systems evaluated. Burnup and cycle time for each of the four systems are shown for three conditions: at a total plutonium and lanthanide concentration of 0.1 moles/liter, at a total plutonium and lanthanide concentration of 0.3 moles/liter, and at peak burnup or 10 full power years (FPY). Table 1 contains several interesting results. First, the LPD/EM and LPD/NM systems achieve significantly lower peak burnups than the other two systems. Second, the peak attainable single-pass burnup (without the use of supplemental fissile material) is quite high (90%). Third, the IM and HPD/EM systems have very similar peak burnups, although this burnup is reached in less than half the time by the HPD/EM system. The decision on whether to use the IM or HPD/EM system will be made based on factors other than burnup. In Table 1, cycle time refers to the time at which the concentration limit is reached for the system.

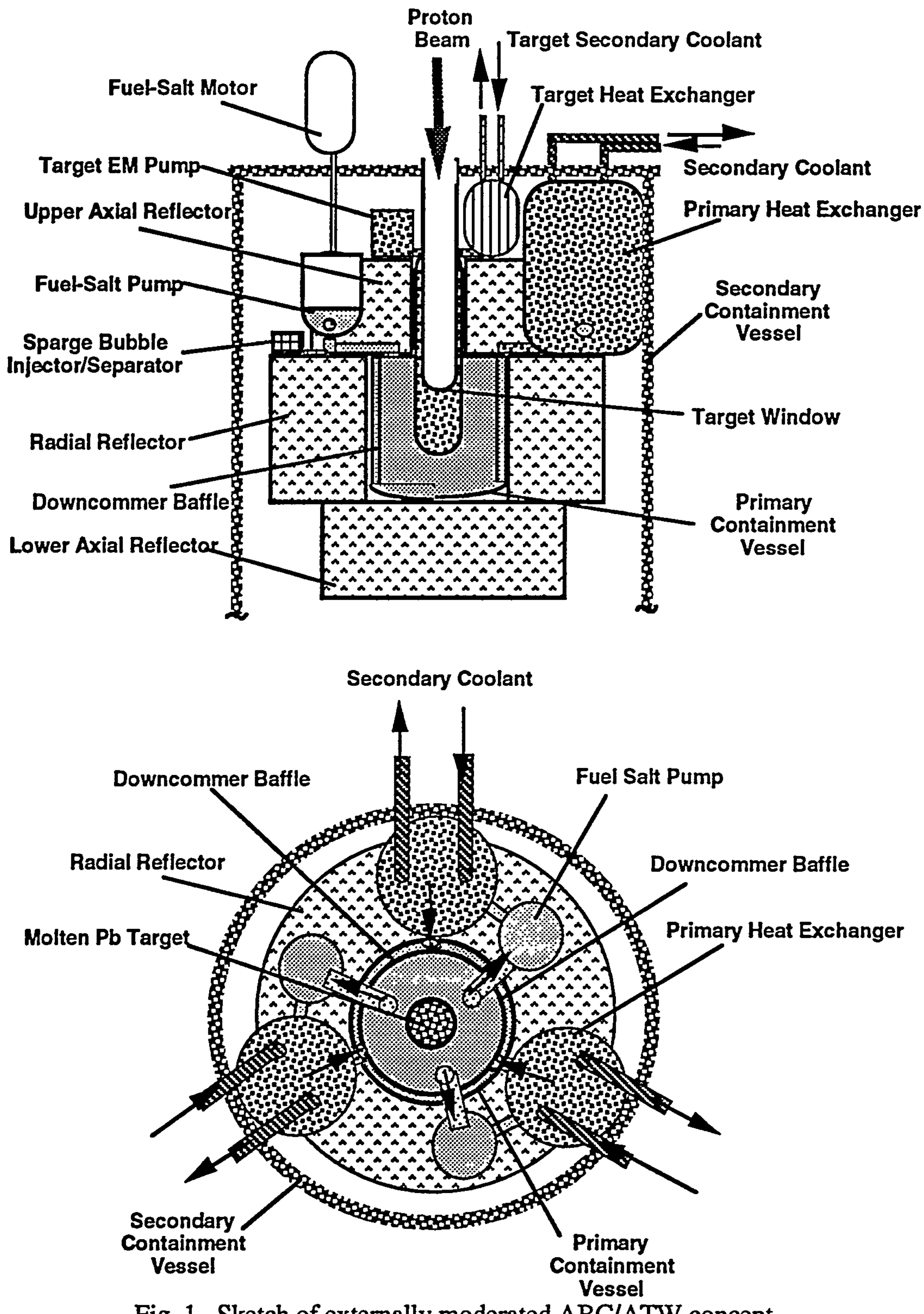


Fig. 1. Sketch of externally moderated ABC/ATW concept.

**Table 1. Summary of plutonium burnup and cycle time for the four cases studied.**

| System | At 0.1 mole/liter Pu BU (%) | At 0.1 mole/liter Cycle Time (yr) | At peak or 10 FPY Pu BU (%) | At peak or 10 FPY Cycle Time (yr) | At 0.3 mole/liter Pu BU (%) | At 0.3 mole/liter Cycle Time (yr) |
|---|---|---|---|---|---|---|
| IM | 81 | 3.2 | 88 | 10 | ~90 | ~12 |
| HPD/EM | 82 | 1.5 | 88 | 5.1 | 88 | 5.1 |
| LPD/EM | 76 | 2.3 | 80 | ~5.5 | 78 | 7.1 |
| LPD/NM | 69 | 1.9 | 73 | ~4.5 | 73 | 6.0 |

IM - Internally Moderated
EM - Externally Moderated
HPD - High Power Density
LPD - Low Power Density

Another parameter of interest is the salt processing requirement, summarized in Table 2. The rate at which salt must be processed will effect operating costs and other parameters. As shown in Table 2, the required salt processing rate for the HPD/EM system is slightly lower than for the other systems, especially at peak burnup.

**Table 2. Summary of salt processing capacity requirement for the four cases studied.**

| System | At 0.1 mole/liter Salt Processing ($m^3$/yr) | At peak or 10 FPY Salt Processing ($m^3$/yr) | At 0.3 mole/liter Salt Processing ($m^3$/yr) |
|---|---|---|---|
| IM | 5.81 | 1.86 | 1.55 |
| HPD/EM | 5.33 | 1.57 | 1.57 |
| LPD/EM | 6.04 | 2.53 | 1.96 |
| LPD/NM | 7.31 | 3.09 | 2.32 |

Salt Processing Capacity = cycle time x salt volume

## REACTIVITY TEMPERATURE COEFFICIENTS

Another distinguishing factor between blanket concepts is the temperature coefficient of reactivity. This coefficient (RTC) will impact both safety and operation because if the RTC is either highly positive or highly negative, accidental criticality could result from overheating or overcooling accidents, respectively. The most desirable RTC is probably one that is near zero or slightly negative. Effects of burnup on the RTC are also very important as the composition of the fuel salt is changing as a function of operating history. This effect is currently being assessed.

The temperature coefficient of reactivity is strongly dependent on the neutron spectrum, making it dependent on plutonium concentration and the degree of neutron moderation. At the beginning of its life, the internally moderated system has a strong positive RTC, whereas the externally moderated systems have coefficients either near zero or negative. Temperature coefficients for the internally moderated system are as high as +1.0e-4 dk/k/C, whereas temperature coefficients for systems with no additional moderator (internal or external) can be set at -1.5e-4 dk/k/C or below.

## KINETICS

Unlike critical systems, subcritical multiplying blankets require an external neutron source to produce significant power. If the external source (accelerator) is turned off, the fission power in the blanket rapidly drops, and the decay of fission products becomes the only significant source of heat. In the systems being studied, the accelerator beam can be removed from the target quite rapidly (milliseconds), enabling rapid shutdown of the subcritical multiplying system.

Kinetics calculations have been performed on several point designs, and several observations have been made. First, from a criticality safety standpoint, even large positive temperature coefficients are acceptable, as long as $k_{eff}$ does not approach unity at the maximum blanket temperature. Large positive temperature coefficients may also be acceptable from an overall safety standpoint if it is possible to rapidly remove the neutron source (by turning the accelerator off or directing the beam away from the target). However, from a safety and operational standpoint it appears most desirable to design a system with a near-zero or negative RTC. Scoping studies have shown that it is possible to design a system with a beginning-of-life RTC ranging from strongly positive to strongly negative. It may be possible to set the RTC at a desired value throughout the system life.

Subcritical multiplying blankets are characterized by a very benign response to reactivity insertion accidents. For example, in a plutonium-based multiplying blanket operating at a $k_{eff}$ of 0.96, an instantaneous reactivity insertion of 5$ results in an increase in blanket power of less than 40% (assuming negligible feedback), which could be accommodated until the neutron source was removed. In contrast, a reactivity insertion of 5$ into a critical system could result in a severe accident, especially if there is no strong source of negative reactivity feedback. It should be possible to design a system that limits the maximum accidental reactivity insertion to values much lower than 5$, in which case the response of the subcritical multiplying blanket would be even more benign. General comments concerning the response of subcritical systems to reactivity insertions can be found in a companion paper [4].

## SUMMARY

Accelerator-driven transmutation is a viable option for utilizing excess weapons plutonium. Two conceptual designs have been produced that allow plutonium burnups approaching 90% in a single pass. Plutonium extraction from the salt and other methods could be used to allow burnups exceeding 99%. Considerable future physics research is required to further develop blanket designs. First, blanket operating characteristics as a function of burnup must be determined.

## REFERENCES


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