IMPACT-FUSION MOLTEN-SALT BREEDER (IFMSB) USING SHAPED-PROJECTILE AND AXIALLY SYMMETRIC MASS DRIVER

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ABSTRACT

A new design concept for fissile material production breeder is proposed. The key technologies are (1) a shaped-projectile, which has a built-in imploding mechanism with a DT fuel-pellet eliminating a fuel target injection in fine alignment, (2) an axially symmetric mass driver, which is based on a rapid Z-pinch discharge between the cylindrical electrodes expecting positionally stable acceleration of the projectile, and (3) a molten-salt target/blanket technology, which is similar to that of Accelerator Molten-Salt Breeder having a big salt bath with deep vortex but now adding He bubbles. The target salt including $^{235}$U prepared in IFMSB could be supplied to Molten-Salt Fission Power Stations, integrally constituting an idealistic molten salt fuel cycle system.

INTRODUCTION

In the rational, economical and safer nuclear fission energy system, the power stations of several sizes (utility facilities) and the fissile-fuel breeders (process plants) should be separated and coupled by a simple molten-fluoride fuel cycle. Already Accelerator(Spallation) Molten-Salt Breeder(AMSB) and Inertial-confined Fusion Molten-Salt Breeder(IHMSB) were proposed (1)(2), and now another idea will be presented.

Impact fusion (3) is one of the approaches to produce controlled thermonuclear power using hypervelocity impact of a target made of deuterium-tritium (DT) ice. This concept is as follows: Small projectiles with a mass of 0.1g designed by appropriate materials are accelerated to a velocity of $V \sim 10^7$ cm/sec. They collide with a DT target, and their kinetic energy is abruptly converted into thermal energy ($\sim 10$ keV per nucleon, temperature $\sim 10^8$ K) which is inertially-confined in the shocked region. To achieve an uniform acceleration $\alpha$ of a small projectile, a non-relativistic accelerator will have a length

$$x = \frac{V^2}{2\alpha}. \quad [1]$$

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The differential or tidal stresses caused by an accelerating force $F$ acting on a projectile with characteristics of size $L$ are in the order of $\sim F/L^2$. If these stresses are not to exceed the yield stress $S$ of the projectile, the minimum length of the accelerator must be

$$x_{\text{min}} \sim \frac{\rho L^2}{S}$$

for a projectile of density $\rho$ and mass $\rho L^3$, because the relation between $S$ and $\alpha$ is

$$\rho L \alpha = S.$$ 

The criterion (3) for a net gain in impact fusion is approximately $L \rho \sim 0.1 \text{g/cm}^2$. With a reasonable value for the yield stress of $S \sim 10^{10} \text{dyne/cm}^2$, it is found that the minimum accelerator length is $x_{\text{min}} \sim 1 \text{km}$. This result is generally acceptable and applicable to any kind of accelerators. A shorter accelerator would require a material with a larger yield stress $S$.

In order for impact fusion to have a reasonable hope of practical application, the maximum length of the accelerator should be of the order of 10 m. This can be achieved by adopting shaped-targets, as proposed in the literature (4). In this case, the necessary velocity of the small projectiles is $V \sim 10^7 \text{cm/sec}$, which gives an accelerator length $x_{\text{min}}$ described by [2] as

$$x_{\text{min}} \approx 10 \text{m},$$

even taking a standard value of the yield stress,

$$S \approx 10^{10} \text{dyne/cm}^2.$$

In this report, the following three key technologies are applied for the breeding of $^{233}$U utilizing neutrons generated from the impact fusion.

[I] The first is the choice of the shaped-projectile (5) instead of the shaped-target (4). It has a built-in imploding mechanism with a fuel-pellet, and now a fuel target pellet injection in fine alignment is not necessary.

[II] The next is the development of the mass driver system. By the choice of the shaped-projectile the aspect ratio $d/h$, of the shaped-projectile must be as small as possible in order to reduce the mass of the projectile. In this case, the positional stability of the projectile becomes an important problem in the course of accelerating the projectile. This means that the position of accelerating disk-like projectile should be stabilized by its spinning motion and that the accelerator must be axially symmetric in order to minimize the perturbation to the spinning disc. We are thus naturally lead to the investigation of the totally axial-symmetric accelerator system developed by one of the authors (K.I.) (6).

[III] The third is the application of the molten-salt target/blanket technology, which is similar to that of the Accelerator (Spallation) Molten-Salt Breeder (AMSB), which was developed by one of the authors.
A big molten-salt bath including Thorium fluoride will effectively work for the several purposes such as

(a) non-destructive permanent target system,
(b) collision- and reaction-heat removal system,
(c) blanket material for fissile $^{233}\text{U}$ production by the neutron absorption of $^{232}\text{Th}$ in salt, and
(d) chemical processing medium.

In chap. II we review the accelerator system. In chap. III the functions of the components composing the breeding system including the shaped-projectile are analyzed in order to decide the breeder parameters. The necessary data base for the impact fusion breeder will be discussed in chap. IV.

A REVIEW OF THE AXIALLY SYMMETRIC ABLATION MASS DRIVER

The electro-magnetic acceleration of projectile in axially symmetric geometry is thoroughly described in the literature (7). The mechanism for accelerating the projectile is based on a rapid Z-pinch discharge between the cylindrical electrodes shown in Fig. 1.

Consider a Z-pinch between a pair of long hollow electrodes whose axes of symmetry are on a common straight line. We can expect a plasma column between the electrodes like that in an ordinary Z-pinch in a plane electrode geometry. In the case of a Z-pinch in the hollow electrode geometry, however, a pair of plasma disks are formed at both ends of the plasma column which propagate along the cylinder axis, down to both ends of the cylindrical electrodes because of the force unbalance across the plasma disk, where the disk plasma is called the "plasma brim". If the projectile with an ablator is loaded in a cylindrical electrode in front of a plasma brim, as shown in Fig. 1, the projectile will be accelerated by the interaction of the current through the disk with the self-magnetic field.

The equation of motion of the projectile in the barrel is

$$\frac{d}{dt} \left( M \frac{dZ}{dt} \right) = \frac{\mu_0 I^2}{2 \pi R} g,$$

where $I$ is the total current in the plasma brim, $M$ is the mass of the projectile including ablator and the plasma brim, and $g$ is a constant of the order unity, depending on the current distribution in the plasma brim. The quantity $\mu_0$ is the magnetic permeability of the vacuum.

The acceleration of projectiles to hypervelocity in a single pair of long cylindrical electrodes is questionable from various viewpoints, such as the stability of the long plasma column, the energy dissipation by the resistive loss in the long cylindrical electrode, etc., These problems are reduced if the accelerator is formed by many short cylindrical electrodes. A schematic diagram of the accelerator system with a
segmented electrode is shown in Fig. 2. An important point for mentioning in this case is that it may not be necessary to use switches to close the circuit because the switching is automatically provided by the plasma brim following the projectile.

The two-stage accelerator was built to test this accelerator concept at Texas Tech University in 1986 (8), and it was confirmed that the automatic switching mechanism worked.

The advantages of this axial-symmetric accelerator compared with the standard rail gun are as follows: In the axial-symmetric case, (a) the plasma spilling over the nose of the projectile is inhibited because there is no gap for the plasma to penetrate past the projectile in the cylindrical electrode arrangement, (b) there is another acceleration force by the rocket effect from the flowing-out plasma through the field-null-line of the azimuthal magnetic field in the direction opposite to the projectile acceleration, and (c) the break-down voltage along the insulator surface between the electrodes does not depend on the size of the projectile, although the diameter of the projectile is the distance of the rails in the case of rail gun so that the small projectile is rather hard to accelerate by the rail gun because of the low flash-over voltage along the short insulator surface.

In the next section we consider the Impact Fusion Molten-Salt Breeder (IFMSB) under the assumptions that every stage of the Z-pinchess, except the first one, is triggered automatically by Z-pinch following after the projectile, and that the velocity of the projectile is attained over a value required for the impact fusion to be triggered by the hypervelocity impact of the shaped-projectile.

**IMPACT FUSION MOLTEN-SALT BREEDER (IFMSB)**

With a shaped-projectile

In order to trigger the thermonuclear fusion based on the hypervelocity impact of the shaped-projectile with the molten salt, the structure of the shaped-projectile should have a built-in imploding mechanism as schematically shown in Fig. 3.

Once the velocity of the projectile becomes over 200 km/sec, the implosion of thermonuclear fuel-pellet in the cavity could be expected by black body radiation generated by the hypervelocity impact of a thin and high-atomic-weight material covering in front of the cavity with the liquid(molten salt) target.

The schematic drawing of the Impact Fusion Molten-Salt Breeder (IFMSB) is shown in Fig.4 with a shaped projectile made of the frozen salt and thorium metal. The hypervelocity shaped-projectile is injected into the center of voltex of molten salt target/blanket bath, and the generated neutrons by the thermonuclear fusion penetrate deep in the
target salt to produce $^{233}$U from $^{232}$Th (or $^{239}$Pu from $^{238}$U).

This molten-salt system is essentially similar to AMSB (1) except the addition of He bubbler, which is not clear about suitable length yet. He bubbles will be helpful for the relaxation of mechanical and thermal shock by injection and reaction (cf. Fig. 4). The size of target salt bath is about 4 m in diameter and 10 m in depth. Inside of the reactor vessel made by Hastelloy N (Ni-Mo-Cr alloy) is covered by thick graphite blocks for neutron reflection. The target salt is circulated in flow-rate of about 5 m$^3$/sec by a free-surface type centrifugal pump. The inlet and outlet temperatures of salt in reactor vessel will be 560 and 680 °C. The generated heat is transferred to the coolant salt NaF-NaBF$_4$ through the intermediate heat exchanger from target salt circuit, and is used for electric power generation applying essentially same technology, which is developed for Molten-Salt Breeder Reactor by ORNL USA (9), except the improvement of the electric conversion efficiency to 46% or more by the application of recent ultra-supercritical steam turbine technology.

The composition of target/blanket salt is chosen from the several candidates of Th or U containing fluoride salts, as presented in the papers of AMSB or IHMSB (1) (2). At moment one of the most interesting composition will be

$$\text{LiF-BeF}_2-\text{ThF}_4-^{233}\text{UF}_4 \ (64-18-17.5-0.5 \text{ mol\%}),$$

which has the melting point of about 540 °C.

The shaped-projectile is composed of frozen glassy salt such as

$$\text{LiF-BeF}_2-\text{ThF}_4 \ (64-18-18 \text{ mol\%})$$

eluded by Th metal. The DT fuel-pellet accommodated in it will be a Th metal sphere of inner diameter 8 mm.

**ESTIMATION OF IFMSB PERFORMANCE**

We are not understanding yet the detailed phenomena in impact fusion in practice. However, the following scenario will be predicted: The fuel-pellet of about 10 g including 67 mg DT will be injected into target salt once in every 2.5 sec. The electric power required for projectile acceleration will become about 820 MWe, assuming the conversion efficiency of about 10 %.

Assuming the thermonuclear reaction efficiency of 10 %, the annual yield of neutron is about 33,800 mol/year. If the isotope composition of Li in target salt of composition [7] is chosen as about 40 % $^6$Li, the production of tritium will become self-sufficient for continuous reaction operation, and the production of $^{233}$U will be about 3.0 ton/year, by the estimation from the neutronic calculation results in the case of IHMSB (2). However, if the salt composition is changed to the composition shown in [6], the $^{233}$U production will become about 4.4 ton/year increasing about 50 % [cf.(1)].
The heat generations in target salt are (1) thermalization of kinetic energy of projectile: about 82 MW corresponding to 10% of electric power consumed for acceleration and (2) thermonuclear reaction heat: 1820 MW produced from 10% burning. The total 1902 MWth will reproduce the electric power of 874 MWe, which will be able to compensate the consumed electric power.

DISCUSSIONS

Already the three ideas on the fissile breeder facilities have been proposed:

[A] AMSB: Accelerator(Spallation) Molten-Salt Breeder

[B] IHMSB: Inertial-confined Fusion Hybrid Molten-Salt Breeder

[C] IFMSB: Impact Fusion Molten-Salt Breeder.

A is the most reliable concept depending on the sound theoretical bases. However, we have to widely search the alternative methods. B is more ambitious but not clear on technological feasibility. Many injection holes are necessary, which will introduce several engineering difficulties. C has only one injection hole as same as A, and is based on further ambitious, simple but crude technologies. Their technical parameters were chosen in some conservative side as shown in previous chapter, expecting the higher performances of IFMSB from the following reasons.

(1) Many Molten-Salt Fission Power Stations will be operated by the direct supply of the target salt including $^{233}$U from IFMSB. Careful design of Molten-Salt Converter Reactors(MSCR) could guarantee its self-sufficient operation, that means the no fissile consumption in stationary operation except the initial stage. For example, even the small 155 MWe MSCR (named FUJI-I, -II) has the conversion ratio of about 95% or more. The possible shortage of electric power for acceleration will be solved by the electric power from these power stations.

(2) The recovery of electric power from the electric loss of about 737 MWe in the accelerator should be expected in the amount of 150〜250 MWe.

(3) The separation technology of tritium from molten-fluoride system was experimentally established by ORNL. This is depending on the tritium trapping by the water content of secondary coolant salt after permeating through the tube wall of intermediate heat exchanger. However, the total tritium amount handling in reactor system is huge such as 2.3 Kg/day. IFMSB is connected with the accelerator vacuum through the injection hole. To minimize the tritium inventory in IFMSB, the improvement of tritium burning efficiency is essential, and the production participation in outside of breeder will be preferable. IFMSB can choose the lower isotope concentration of $^6$Li, and the partial tritium production will be performed in the other closed MSCRs consuming $^{233}$U(or $^{239}$Pu) (12), in which $^6$Li composition is increased than the ordinary MSCR, and the tritium permeation to atmosphere will be perfectly protected.
ted by Mo or oxide plating of vessel and components.

(4) The Th content in the projectile is useful for compensation of Th consumed in target salt, and the excess Th tips will be collected by strainer. IFMSB has no any fine structures feasible for blockage.

(5) The engineering of injection port is one of the most ambiguous problems. However, the number of injection port is only one as same as AMSB and might be closed among the interruption of injection.

CONCLUSIONS

The concept of the Impact Fusion Molten-Salt Breeder (IFMSB) is outlined. The key technology of IFMSB is to develop highly efficient accelerators, one of which is being developed by one of the authors (K.I.). Once the required velocity is attained, the molten salt target/blanket concept developed by modification of that of the Accelerator Molten-Salt Breeder (AMSB) will provide an ideal technology for breeding 233U or other fissile materials.

Many unknown phenomena exist in this concept, and the estimation of several important technical parameters is in low reliability still. However, if these points are solved in sound basis, IFMSB might be expected to become one of the most powerful fissile breeder, which target salt would be supplied as the fuel salt of Molten-Salt Fission Power Stations, integrally constituting one of the most idealistic energy systems for the next century.

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**Fig. 1.** Mechanism of the electromagnetic acceleration of a projectile in a cylindrical electrode. The interaction between the plasma brim and the self-magnetic field gives the forward thrust to the projectile.
Fig. 2. Schematic drawing of the ablation mass driver system. In order to give the initial velocity to the projectile without the use of an additional injection system, the second ablator, i.e., ablator 2, is loaded in the first electrode with length $L_0$.

Fig. 3. A shaped projectile with built-in thermonuclear pellet and the liquid target. Heavy metal foil is a thin and high-atomic weight material covering the cavity.
Fig. 4. Impact Fusion Molten-Salt Breeder system with a projectile made of frozen salt.