HYPER-FUSE: A NOVEL INERTIAL CONFINEMENT SYSTEM UTILIZING HYPERVELOCITY PROJECTILES FOR FUSION ENERGY PRODUCTION AND FISSION WASTE TRANSMUTATION*

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Parametric system studies(1) of an inertial confinement fusion (ICF) reactor system to transmute fission products from an LWR economy have been carried out. The ICF reactors would produce net power in addition to transmuting fission products. The particular ICF concept examined is an impact fusion approach termed "HYPERFUSE", in which hypervelocity pellets, traveling on the order of 100 - 300 km/sec, collide with a target in a reactor chamber and initiate a thermonuclear reaction. The DT fusion fuel is contained in a shell of the material to be transmuted, e.g., Cs$^{137}$ or Sr$^{90}$. The 14 MeV fusion neutrons released during the pellet burn cause transmutation reactions [e.g., (n, 2n), (n, α), etc.] that convert the long lived fission products (FP's) either to stable products or to species that decay with a short half-life to a stable product.

A conservative, simplified analytical model was constructed in order to carry out the parametric studies. The model assumed one-group diffusion transport of 14 MeV neutrons from the center of the pellet through the compressed, high density fuel region and the surrounding compressed, high density shell. Neutrons which experience significant energy loss through down-scattering, inelastic, or particle reaction events are assumed to be effectively lost and unable to cause transmutation reactions in the FP shell. Thus, the transmutation rate predicted by the model is a lower-bound since: a) the actual distance of neutron travel in the fuel is substantially less than the distance assumed in the model (i.e., the radius of the fuel region), and b) fusion neutrons can still cause transmutation even after losing some energy.

The principal parameters of interest are found to be $f_n$, the fraction of fusion neutrons that cause transmutation; $f_{FP}$, the fraction of FP in the shell that undergo transmutation; $(pR)_P$, the density-radius product of the fuel region; $p_{FP}$ and $(R_{FP} - R_P)$, the density and thickness of FP in the shell; $Y$, pellet yield; and $G$, pellet gain (delivered ratio of yield to driver input energy to pellet).

For a combined LWR/ICF system in which the ICF reactors transmute FP from the LWR's, the ratio of fusion thermal power to LWR fission thermal power is given by

$$\frac{P_{FUS}}{P_{FIS}} \approx \left( \frac{20}{200} \right)^n \approx 0.1 \frac{G}{f_n}$$

(1)

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where \( g \) atoms of FP are cycled to the ICF reactors for transmutation (per fission event in the LWR reactors) and the term \( (20/200) \) approximates the relative energy releases for fusion and fission. For the case where the two worst FP are transmuted, \( \text{Sr}^{90} \) \((t_\frac{1}{2} = 29 \text{ year})\) and \( \text{Cs}^{137} \) \((t_\frac{1}{2} = 30.2 \text{ year})\), \( g = 0.10 \).

The neutron utilization factor, \( f_n \), is determined primarily by \((\rho R)_F\) and the density and thickness of the FP shell since neutrons are parasitically lost either by down-scattering or \((n, 2n)\) reactions in the fuel region or by leakage out of the pellet. Parametric studies with \( \text{Sr}^{90} \) shells indicate that values of \( f_n \) in the range of \( \sim 0.1 \) to 0.3 can be obtained for reasonable pellet conditions \([\rho R] \sim 1 \text{ to } 3, \rho_{FP} \sim 10^2 \text{ to } 10^4 \text{ g/cm}^3; \text{mass of FP in pellet} \sim 0.1 \text{ to } 5 \text{ gms}]\). The upper limit to \( f_n \) is \( \sim 0.4 \) because of inelastic and down-scattering processes for neutrons in the FP shell. The dominant transmutation reaction for \( \text{Sr}^{90} \) is the \((n, 2n)\) reaction, resulting in \( \text{Y}^{89} \), which \( \beta \) decays to stable \( \text{Y}^{89} \) with a 50-day half-life. Reaction cross-sections for \( \text{Sr}^{90} \) appear comparable to those of \( \text{Sr}^{90} \), leading to similar neutron utilization factors. The dominant transmutation reaction for \( \text{Cs}^{137} \) is also the \((n, 2n)\) reaction resulting in \( \text{Ba}^{136} \), which \( \beta \) decays to stable \( \text{Ba}^{136} \) with a 13-day half-life.

Other FP's of possible interest for transmutation include \( \text{Sm}^{151}, \text{Tc}^{99}, \text{Eu}^{154}, \text{Zr}^{93} \), etc. However, in general these materials are considerably less hazardous than \( \text{Sr}^{90} \) and \( \text{Cs}^{137} \), and it may not be desirable to transmute them. The fusion to fission thermal power ratio is proportional to \( g \), the number of atoms to be transmuted per fission event. A \( g \sim 0.10 \) for transmutation of \( \text{Cs}^{137} \) and \( \text{Sr}^{90} \) then corresponds to \( P_{\text{FUS/FIS}} \sim 0.03 \) to 0.10 for \( f_n \) of 0.1 to 0.3, Figure 1.0. A low power ratio of this order is desirable, since it minimizes the investment in new technology. The HYPERFUSE reactors will produce some net electric power. The amount will depend on the pellet gain performance \( (G) \), the efficiency of the drive \( (n_D) \), and the gross efficiency of the power cycle \( (n_C) \). For nominal performance values of \( G \sim 100, n_D \sim 0.2, \) and \( n_C \sim 0.4 \), approximately half of the generated power is recirculated to the driver with the remainder delivered to an electric grid.

Transmutation of transuranics \((\text{TU}'s)\) has not been examined in detail; however, reaction cross-sections are larger than those for FP destruction and remain high to relatively low neutron energies.

Reactor designs for HYPERFUSE have been examined, using the BAM liquid curtain concept\((2)\). The liquid lead curtain \( \sim 0.5 \text{ meter thick} \) attenuates blast effects from exploding fusion pellets, acts as a neutron multiplier through \((n, 2n)\) reactions, and absorbs pellet debris, including both the transmuted and non-transmuted FP's. Pellet yields up to 10 GJ can be handled in BAM reactor chambers with diameters in the range of 3 to 5 meters. Tritium breeding ratios for the BAM reactor concept\((2)\) were found to exceed 2.0 depending on reactor parameters; breeding ratios for the HYPERFUSE reactor can be made well above one, if desired.

Non-transmuted FP's can be extracted from the liquid lead circuit and recycled to a fabrication facility to be incorporated into new pellets. The transmutation per pass through a pellet explosion is in the range of 0.01 to 0.10, depending on pellet parameters, Figure 2.0.

A variety of processing concepts have been considered, including fused salt contacting, wet chemistry, etc. An attractive option appears to be the
addition of lead oxide to a liquid lead side stream with subsequent skimming (perhaps with the addition of some non-radioactive scavenger) to remove Cs and Sr oxide reaction products. These would be electrolyzed and Cs and Sr metal recycled to the pellet fabrication facility (Figure 3.0 and Figure 4.0).

The recent workshop on Impact Fusion\(^{(3)}\) identified a number of promising accelerator concepts for propelling pellets to the velocity range required for impact fusion, i.e., ~100 to 300 km/sec. These include rail guns\(^{(4,5)}\), coaxial induction drivers, plasma pinch impulse drivers, etc. The rail gun approach appears particularly promising. Velocities of ~6 km/sec have been achieved with ~1 gm projectiles using a 3 m rail. Recent studies indicate that the hypervelocity range can be reached with relatively short rails, on the order of 20 m in length. A conceptual design for a rail gun accelerator has been conducted in the course of the study.

REFERENCES


5. Devices for Launching 0.1-g Projectiles to 150 km/s or more to Initiate Fusion, Part 2, Railgun Accelerators, R.S. Hawke, UCRL-52778 Part 2, July 6, 1979.
<table>
<thead>
<tr>
<th>BURN FRAC</th>
<th>1.0 - f_B = \frac{(\rho R) DT}{6.3 + (\rho R) DT}</th>
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<tr>
<td></td>
<td>2.0 - f_B = 0.5</td>
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<td>3.0 - f_B = 1.0</td>
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- \( \rho_{FP} = 1 \text{g/cm}^3 \)
- \( 0 - 5 \text{g/cm}^3 \)
- \( \triangle - 10 \text{g/cm}^3 \)
- \( + - 50 \text{g/cm}^3 \)
- \( X - 100 \text{g/cm}^3 \)
- \( \Diamond - 500 \text{g/cm}^3 \)
- \( \triangledown - 1,000 \text{g/cm}^3 \)
- \( \blacksquare - 5,000 \text{g/cm}^3 \)
- \( * - 10,000 \text{g/cm}^3 \)
- \( \blacklozenge - 50,000 \text{g/cm}^3 \)
Fig. 1.0 Support Ratio vs $(\rho R)_T$ for Sr$^{90}$ Hyperfuse Burner Plant

YIELD = 5.000  NFP/NDT = 10.00
BURN FRAC = 2.00  SIG(N,2N)
Fig. 2.0 Transmutation Ratio vs \((\rho R)_F\) for Sr\(^{90}\) Hyperfuse Burner Plant

YIELD = 5.000  NFP/NDT = 10.00
BURN FRAC = 2.00  SIG(N,2N)
Ce AND Sr FISSION PRODUCTS

NUCLEAR FUEL PROCESSING

ISOTYPE SEPARATION

STABLE Ce AND Sr ISOTOPES

NON Ce AND Sr FISSION PRODUCTS

Ce AND Sr METAL

Pellet Fabrication

Hyperfuse Reactor

LIQUID LEAD CIRCUIT (P, FES, ETC.)

Cs and Sr METAL

PROCESSING SIDE STREAM

MAIN CIRCUIT

137 Cs90, Cs136
Sr90, Sr89

CO2 SPARCE

HOLDING DECAY TANK (~100 DAYS)

OXIDE SKIMMING

CHLORIDE SKIMMING

REDUCTION TO METAL

WET CHEMICAL SEPARATION

REDUCTION TO METAL

WET CHEMICAL SEPARATION

STABLE 89Y, Ba136

STABLE Ba136

CHLORINATION

SKIMMING

89Sr

89Sr

HOLDING DECAY TANK (~30 DAYS)

STABLE Ba136

137 Cs90, Cs136
Sr90, Sr89

f---

89Ba136

HOLDING DECAY TANK (~30 DAYS)