HYPERFUSE: 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 each other or a target block 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., $(n, 2n)$, $(n, \alpha)$, 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.

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The proposed reactor concept "HYPERFUSE", has the following features:

- A single HYPERFUSE reactor can transmute either Cs or Sr fission products from a large number of conventional LWR reactors, e.g., 30 to 60.

- The power output and cycle efficiency of a HYPERFUSE reactor will be comparable to that of a conventional LWR.

- Only stable transmutation products would be discharged from HYPERFUSE.

- There will be a substantial inventory of fission products in isolated holding vessels at the HYPERFUSE reactor site to allow short-lived transmutation daughters to decay.

The recent workshop on Impact Fusion\(^{(2)}\) identified a number of promising accelerator concepts for propelling pellets to the velocity range required for impact fusion, i.e., \(\sim 100\) to \(300\) km/sec. These include rail guns\(^{(3,4)}\), coaxial induction drivers, plasma pinch impulse drivers, etc. The rail gun approach appears particularly promising. Velocities of \(\sim 6\) km/sec have been achieved with \(\sim 1\) g 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.

Figure 1.0 is an overall schematic flowsheet of the Hyper-fuse Concept. Roughly speaking, the accelerated pellets will contain fusion fuel (DT) inside a metallic shell of the material to be transmuted (e.g., Sr\(^{90}\), Cs\(^{136}\), transuranics, etc.). They
TARGET INJECTOR
FLOW DISTRIBUTOR
LIQUID WALL
TARGET BLOCK INJECTOR
REACTOR VESSEL
FLOW COLLECTOR

STEAM GENERATOR

FISSION PRODUCTS STABLE WASTE
AND TRANSURANICS

FEED

FIGURE 1.0 HYPERFUSE System Flowsheet
would be accelerated to hypervelocities by a rail gun or inductive mass driver. The hypervelocity pellets would then impact each other or on a target block inside a large reactor vessel, heating the fuel to fusion temperatures in a few nanoseconds. A rapid fusion reaction would occur before the pellet could disassemble and a substantial fraction of the generated fusion neutrons would then cause transmutations in the surrounding fission product shell. The design of the hypervelocity projectiles should emphasize the achievement of high densities in the FP and/or TU regions (greater than the DT fusion fuel density) as well as fusion ignition and burn criterion (\(\rho R = 1.0 - 3.0\) etc.) requirements. A spherical implosion, therefore, is not necessary for the success of the Hyperfuse Concept, although for simplicity the analysis in this paper assumes spherically symmetric compressions.

The energy released by the fusion reaction will appear as kinetic energy of the fusion neutrons and pellet debris, as well as x and gamma radiation. The x-rays and pellet debris will be stopped on the first wall (or inner surface) of the reactor vessel while the neutrons and gamma rays would penetrate deeply into the blanket that surrounds the exploding pellet.

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; $(\rho R)_F$, the density-radius product of the fuel region; $\rho_{FP}$ and $(R_{FP} - R_F)$, 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:

$$\frac{P_{FUS}}{P_{FIS}} \approx \frac{20}{200} \frac{G}{f_n} \approx 0.1 \frac{G}{f_n} \quad (1)$$
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, Sr$^{90}$ ($t_{1/2} = 29$ years) and Cs$^{137}$ ($t_{1/2} = 30.2$ years), $g \approx 0.10$.

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 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 [$(\rho R)_F \sim 1$ to 3, $\rho_{FP} \sim 10^2$ to $10^4$ g/cm$^3$; mass of FP in pellet $\sim 0.1$ to 5 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 Sr$^{90}$ is the $(n, 2n)$ reaction, resulting in Sr$^{89}$, which $\beta$ decays to stable Y$^{89}$ with a 50-day half-life. Reaction cross-sections for Cs$^{137}$ appear comparable to those of Sr$^{90}$, leading to similar neutron utilization factors. The dominant transmutation reaction for Cs$^{137}$ is also the $(n, 2n)$ reaction resulting in Cs$^{136}$, which $\beta$ decays to stable Ba$^{136}$ with a 13-day half-life.
Other FP's of possible interest for transmutation include $^{151}$Sm, $^{99}$Tc, $^{154}$Eu, $^{93}$Zr, etc. However, in general these materials are considerably less hazardous than $^{90}$Sr and $^{137}$Cs, 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 $^{137}$Cs and $^{90}$Sr then corresponds to $P_{\text{FUS/FIS}}$ of $\sim 0.03$ to $0.10$ for $f_n$ of 0.1 to 0.3 (Figure 2.0). 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 driver ($n_D$), 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 transuranic (TU's) has not been examined in detail for HYPERFUSE, however, reaction cross-sections are larger than those for FP destruction and remain high to relatively low neutron energies. Work examining laser fusion pellet transuranic transmutation $^{5}$ has resulted in predictions of support ratios of $\sim 10$ and high integrity waste storage time reduction from $10^7$ to $10^2$ years. TU transmutation by HYPERFUSE should be substantially better (about one order of magnitude) than laser fusion based transmutation.
KEY FOR FIGURES 2.0 AND 3.0

\[ 1.0 - f_B = \frac{(\rho R)_{DT}}{6.3 + (\rho R)_{DT}} \]

- 2.0 - \( f_B = 0.5 \)
- 3.0 - \( f_B = 1.0 \)

\[ \rho_{FP} = 1\text{g/cm}^3 \]
- 0 - 5\text{g/cm}^3
- \( \Delta \) - 10\text{g/cm}^3
- \( + \) - 50\text{g/cm}^3
- \( \times \) - 100\text{g/cm}^3
- \( \diamond \) - 500\text{g/cm}^3
- \( \triangledown \) - 1,000\text{g/cm}^3
- \( \square \) - 5,000\text{g/cm}^3
- \( * \) - 10,000\text{g/cm}^3
- \( \Phi \) - 50,000\text{g/cm}^3
FIGURE 2.0 Support Ratio vs (pR) for Sr$^{90}$ Hyperfuse Burner Plant ($P_{FUS/FIS}^{-1}$ = Support Ratio)
Reactor designs for HYPERFUSE have been examined, using the BAM liquid curtain concept (6). The liquid lead curtain (≈ 0.5 m 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 the BAM reactor chambers with diameters in the range of 3 to 5 meters. Tritium breeding ratios for the BAM reactor concept (6) 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 3.0).

A variety of processing concepts have been considered, including fused salt contacting, wet chemistry, etc. An attractive option, discussed below, deals only with Cs\(^{137}\) and Sr\(^{90}\) fission products (Figure 4.0). Similar process flow would apply for transmutation of other fission products and transuranics.

A fraction of the liquid lead coolant flow would be drawn off and pass through a two-stage recovery unit. First, a CO\(_2\) sparge of the liquid lead would convert dissolved Sr, Y (generated
FIGURE 3.0 Transmutation Ratio vs (\(\rho R\))_F for Sr\(^{90}\)

Hyperfuse Burner Plant
FIGURE 4.0 Proposed HYPERFUSE Nuclear Chemistry System
by decay of radioactive Sr$^{89}$ and Sr$^{90}$, and Ba (generated by decay of radioactive Cs$^{136}$ and Cs$^{137}$) to oxides, which would then be skimmed off.

In the second stage, dissolved Cs$^{137}$ and Cs$^{136}$ would be converted to the chlorine-bearing compound, e.g., HCl and then be skimmed off. Following the second stage treatment, the purified liquid lead coolant would be returned to the main coolant circuit.

The recovered oxides and chlorides would then be stored in a holding tank until most of the (n, 2n) transmutation daughters, i.e., Cs$^{136}$ and Sr$^{89}$, had decayed to stable elements (Ba$^{136}$ and Y$^{89}$). A holding time of $\sim 2$ half-lives should be sufficient, or $\sim 30$ days for the cesium chloride product and $\sim 100$ days for the mixed oxide product.

Stable elements (Y$^{89}$, Ba$^{136}$) would then be separated by wet chemistry from the remaining Cs and Sr and sent to waste disposal. The Cs and Sr would be reduced to metal, probably by fused salt electrolysis, and recycled to the HYPERFUSE reactor for further transmutation.

In conclusion, a new concept for the transmutation of fission products and transuranics is proposed. This concept, termed "HYPERFUSE", allows one inertial reactor to transmute the most objectionable fission products (Cs$^{137}$ and Sr$^{90}$) from a large
number (e.g., \( \sim 30 \)) of LWR fission reactors, while at the same
time generating electric power from the HYPERFUSE plant at a
reasonable net plant efficiency (e.g., \( \sim 30\% \)). The cost of
transmutation should be relatively low due to the high support
rate (number of fission reactors per HYPERFUSE reactor) and the
effective generation of power by the HYPERFUSE reactor.

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