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HYPERFUSE: A HYPERVELOCITY INERTIAL CONFINEMENT SYSTEM FOR
FUSION ENERGY PRODUCTION AND FISSION WASTE TRANSMUTATION*†

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Parametric system studies¹ 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 to 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., Cs¹³⁷, Sr⁹⁰, I¹²⁹, Tc⁹⁹, etc. The 14-MeV fusion neutrons released during the pellet burn cause transmutation reactions (e.g., (n,2n), (n, α), (n, γ), 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. The transmutation parametric studies conclude that the design of the hypervelocity projectiles should emphasize the achievement of high densities in the transmutation regions (greater than the DT fusion fuel density), as well as the DT ignition and burn criterion ($\rho R=1.0$ to 3.0) requirements. These studies also indicate that masses on the order of 1.0 grams at densities of $\rho \geq 500.0$ g/cm³ are required for a practical fusion-based fission product transmutation system. The large mass requirements, make it difficult, if not impossible, to achieve the desired conditions with laser or heavy-ion drivers due to the very large driver energy required to compress the mass. This suggests transmutation involving inertial fusion requires impact fusion schemes, which can more readily achieve large driver energies.

INTRODUCTION

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 Fusion² 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,^{3,4} 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 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 flow sheet of the HYPERFUSE 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^{137} , transuranics, etc.). They 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 ($\rho R = 1.0$ to 3.0 etc.) requirements. A spherical implosion 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-ray 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.

The problem of satisfactorily disposing of fission product waste is often felt to be a major obstacle to the development of nuclear power. There is much disagreement as to the best method and what sites should be used.

Over the past few decades transmutation of radioactive fission products to stable isotopes has been often proposed as a way of eliminating the problem of waste disposal. Numerous studies have investigated transmutation using fission reactors, accelerator driven spallation neutron sources, and fusion reactors. While some of the concepts that have been proposed appear marginally feasible, there are great difficulties in achieving a practical system.

Transmutation in fission reactors, for example, requires impractically high fluxes (i.e., 10^{16} to 10^{17} n/cm²-sec) to reduce the half-life of the most objectionable fission products, Cs^{137} and Sr^{90} , by a significant amount. The very high fluxes demand impractically high heat transfer rates in the reactor core.

Accelerator beam driven neutron sources can probably achieve the flux levels required, but the input power to generate the necessary proton or deuteron beam requires a large fraction ($\sim 10\%$) of the output power generated by the nuclear reactors that it services, and the effective half-life reduction factor is at best 100, but can be as low as 2.0 as in the case of Cs^{137} . The cost of an accelerator driven transmutation system will thus be relatively high.

Fusion reactors appear promising at first glance, since the energy input requirements to obtain fusion neutrons can be very small for certain fusion confinement approaches, and the very high energy 14-MeV neutrons from DT reactions would be very effective for transmutation.

However, heat transfer and radiation damage limitations prevent one from achieving first wall loads of more than a few MW(th)/m² with conventional fusion blankets. This is too low for effective transmutation of fission products like Cs¹³⁷ and Sr⁹⁰, though destruction of transuranics in such blankets has been studied and appears practical. Very high wall load (~100 MW(th)/m²) fluid blanket approaches, such as LINUS, have been proposed for transmutation of fission products. The technology of such devices appears very difficult, however, and half-life reduction factors are too low for economic practicality.

A new approach for the transmutation of fission products is proposed in this paper. Fission products would be incorporated into the fuel pellets for impact fusion ICF reactors. The large mass, very high fuel, and fission product densities and neutron fluences accompanying pellet micro-explosions should result in a high transmutation efficiency, and the transmutation reactor will also produce net power efficiently with a reasonable cycle efficiency. The heat transfer and radiation damage conditions on the fusion blanket will be similar to those projected for other inertial fusion reactor concepts. The principal distinction between such a transmutation inertial fusion reactor and a power only inertial fusion reactor will be the requirement that unburnt fission products and transmutation daughters be recovered from the pellet debris. The unburnt fission products would then be separated and recycled for another exposure to transmutation neutrons.

The possibility of economic fission product and transuranic transmutation with a fusion device appears most likely with impact fusion. This potential capability should be weighed when comparative assessment of different fusion approaches are being made.

PARAMETRIC STUDIES OF HYPERFUSE PERFORMANCE

A conservative, simplified analytical model was constructed in order to carry out the transmutation 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.

In previous work,¹ a set of model equations has been formulated. Restating the results below, the total number of transmutation reactions for a given Y_0 , f_B , ρ_{DT} , ρ_{FP} , m_{FP} , the yield, burn fraction, fusion fuel density, fission product density, and fission product mass, respectively, in units of GJ, g/cm³, and g, and for the appropriate cross sections σ (cm²), (Table 1.0) is given by:

$$N_{TR} = \left(\frac{Y_O N_A}{652 A_{DT}} \right) \left(\frac{\Sigma_A^{FP}}{K_{FP}} \right) \left(1 - e^{[R_B - R_f] K_{FP}} \right) e^{-K_{DT} R_B} \quad (1)$$

$$K = \frac{\rho}{A} N_A \sqrt{3 \sigma_{ABS} \left(\sigma_T - \sigma_S \left(\frac{2}{3A} \right) \right)} \quad (2)$$

$$\Sigma_a = \frac{\rho}{A} N_A \sigma_{ABS} \quad (3)$$

$$R_B = \left[\frac{3 Y_O}{4 \pi \times 326 f_B \rho_{DT}} \right]^{1/3} \quad (4)$$

$$R_f = \left[\left(\frac{Y_O}{326 f_B \rho_{DT}} + \frac{m_{FP}}{\rho_{FP}} \right) \frac{3}{4 \pi} \right]^{1/3} \quad (5)$$

A parametric study has been conducted in order to investigate, and predict the optimum performance of the HYPERFUSE concept. A computer code has been written utilizing the above stated equations. This computer code (HPRBNL), calculates the transmutation ratio f_{FP} , the support ratio R_{SUP} , the neutron utilization ratio f_n , N_{TR} , and $N_{TR}(TOT)$, the total number of transmutations per HYPERFUSE plant. The calculations are normalized for a 3-GW thermal power plant with a duty factor $D_F=0.8$, assuming a burnup of 30,000 MW/T, a fuel loading of 100.0 T/fission plant (e.g., an LWR), and the same thermal-to-electric conversion efficiencies for the fission and fusion power plants. The relevant ratios are defined below, where (WASTE) is defined as the total mass in grams of the high-level wastes (e.g., Sr^{90} , Cs^{137} , Kr^{85} , etc.) produced in one 3-GW thermal LWR. If the fraction of high-level waste is assumed to be 10% of the total fission wastes produced then (WASTE) = 8.76×10^4 grams/LWR/year.

$$f_{FP} = \frac{\text{No. of transmutations of FPs}}{\text{No. of fission product atoms present}} = \frac{N_{TR} A_{FP}}{m_{FP} N_A} \quad (6)$$

$$R_{SUP} = \frac{\text{No. LWR}}{\text{No. HYPERFUSE}} = \frac{N_{TR}(TOT) A_{FP}}{\text{WASTE} \times N_A} \quad (7)$$

$$f_n = \frac{\text{No. of transmutations of FPs}}{\text{No. neutrons produced in fusion burn}} = \frac{N_{TR} (652 A_{DT})}{Y_O N_A} \quad (8)$$

$$\begin{aligned} N_{TR}(TOT) &= \frac{\text{TOT No. of pellet shots}}{\text{year}} \times N_{TR} \\ &= \frac{3.0}{Y_O} \times D_F \times N_{TR} \times 3.15 \times 10^7 \frac{\text{sec}}{\text{year}} \end{aligned} \quad (9)$$

Assuming that Sr^{90} cross sections are characteristic of all other high-level fission product cross sections, the parameters Y_O , f_B , ρ_{DT} ,

ρ_{FP} , m_{FP} have been varied as described in Table 2.0. This assumption is justified by the fact that most fission products have a threshold (n,2n) or (n,3n) at ≈ 14.0 MeV of $\geq 1b$ (refer to Table 1.0 for examples). Transuranics, on the other hand, have very high fission cross sections over the ranges of down-scattered DT neutron energy considered here, and therefore, have at least an order of magnitude higher integrated cross section than Sr^{90} for transmutation. The fission product mass, m_{FP} , has been defined in these calculations in such a manner that the number of FP atoms present for a point calculation varies from 0.1 to 100.0 times the number of neutrons released in the fusion reaction for a given Y_o , f_B , and $(\rho R)_{DT}$.

The study is conducted for three different fusion fuel (e.g., DT) absorption cross section, σ_A , assumptions given below.

$$\begin{aligned}\sigma_{ABS}(1) &= \sigma_{DT}(n,\gamma) \\ \sigma_{ABS}(2) &= \sigma_{DT}(n,2n) \\ \sigma_{ABS}(3) &= \sigma_{DT}(TOT)\end{aligned}\tag{10}$$

The assumed σ_{ABS} values for the (n, γ) and (TOT) cross sections provide upper and lower bounds for the parameters of interest. The $\sigma(n,2n)_{DT}$ cross section value serves as a good middle ground and provides results which agree reasonably well with a detailed analysis.⁵ A flowchart of the current calculational procedure is found in Figure 2.0.

Repetition rate considerations lead us to examine the 3 to 10 GJ yield range and for the simplicity of demonstration, a yield of 5 GJ has been used throughout most of the parametric studies. A number (NFP/NDT) ratio of 10.0 has been found to be optimum for the ratio of fission product atoms in the irradiated shell of fusion neutrons produced. Number ratios greater than 10 produce excessive non-transmuted fission wastes in the storage and reactor circuits while number ratios less than 10 produce rather low support ratios, but higher transmutation ratios and cleaner system operation.

The principal parameters of interest are f_n , the fraction of fusion neutrons that cause transmutation; f_{FP} , the fraction of FP in the shell that undergo transmutation; $(\rho R)_{DT}$, the density-radius product of the fuel region; ρ_{FP} and $(R_B - R_F)$, 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:

$$P_{FUS}/P_{FIS} \approx \left(\frac{20}{200}\right) \frac{g}{f_n} \approx 0.1 \frac{g}{f_n}\tag{11}$$

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), $g = 0.10$.

The neutron utilization factor, f_n , is determined primarily by $(\rho R)_{DT}$ 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 ~ 0.1 to 0.3 can be obtained for reasonable pellet conditions [$(\rho R)_{DT} \sim 1$ to 3 , $\rho_{FP} 10^2$ to 10^4 g/cm³; mass of FP in pellet ~ 0.1 to 5 g]. The upper limit to f_n is ~ 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 β 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 β decays to stable Ba^{136} with a 13-day half-life.

Other FP's of possible interest for transmutation include Sm^{151} , I^{129} , Kr^{85} , Tc^{99} , Eu^{154} , Zr^{93} , etc. However, in general, these materials are considerably less hazardous than Sr^{90} and 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 Cs^{137} and Sr^{90} then correspond to P_{FUS}/P_{FIS} of ~ 0.03 to 0.10 for f_n of 0.1 to 0.3 (Figure 3.0). 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 (η_D), and the gross efficiency of the power cycle (η_C). For nominal performance values of $G \sim 100$, $\eta_D \sim 0.2$, and $\eta_C \sim 0.4$, approximately half of the generated power is recirculated 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 even at relatively low neutron energies. Work examining laser fusion pellet transuranic transmutation⁶ has resulted in predictions of support ratios of ~ 10 and high integrity waste storage time reduction from 10^7 to 10^2 years. Transuranic transmutation by HYPERFUSE should be substantially better (about one order of magnitude) than laser fusion-based transmutation.

Reactor designs for HYPERFUSE have been examined, using the BAM liquid curtain concept.^{7,8} 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 nontransmuted 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^{7,8} were found to exceed 2.0 depending on reactor parameters; breeding ratios for the HYPERFUSE reactor can be well above 1.0 , if desired.

Nontransmuted 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 4.0).

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 5.0). 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 Sr, Y (generated by decay of radioactive Sr^{89} and Sr^{90}), and Ra (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 ~ 2 half-lives should be sufficient, or ~ 30 days for the cesium chloride product and ~ 100 days for the mixed oxide product. The Sr^{89} and Cs^{136} could be isotopically separated reducing inventory by an order of magnitude or more.

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. Typical inventories are shown in Table 3.0.

SUMMARY AND CONCLUSIONS

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., ~ 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. It should be noted, however, that these results are based on a parametric neutronic transmutation model and do not include a self-consistent pellet impact, implosion, compression, burn and transmutation analysis. In light of the conclusions drawn from this preliminary analysis, further in-depth self-consistent studies are needed.

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NOMENCLATURE

A = atomic number,

f_B = burn fraction of DT fuel,

f_n = neutron utilization ratio, the fraction of fusion neutrons that cause transmutation,

f_{FP} = transmutation ratio, the fraction of FP in the shell that undergo transmutation,

N_{TR} = number of transmutations per fusion burn (pellet micro-explosion),

$N_{TR}(TOT)$ = total number of transmutations per year,

N_A = Avogadro's number,

m_{FP} = mass of fission product in pellet, g,

σ_i = microscopic cross section (S = scattering; T = total; and
ABS = absorption), cm^2 ,

$(f_{FP})_i$ = fraction of i^{th} fission product in pellet shell that is
transmuted in a pellet explosion,

f = feed rate, g/sec,

y_i = fission yield of i^{th} isotope,

α_i = fraction of i^{th} isotope surviving decay in the nuclear
fuel processing cycle until HYPERFUSE is reached,

S = fission rate in 1000 MW(e) LWR, fission/sec,

$(P_{\text{HYP}}/P_{\text{FIS}})^{-1}$ = number of LWR reactors served by one HYPERFUSE reactor of
equivalent thermal rating (support ratio) $\equiv R_{\text{SUP}}$,

t_p = time to pass total liquid lead inventory through fission
product process system, sec,

$(t_H)_i$ = time in holding tank to allow for decay of transmutation
daughters of i^{th} isotope, sec,

R_B = outer radius of DT fuel (boundary of DT and FP), cm,

R_f = outer (final) radius of FP shell, cm,

ρ_{DT} = density of DT fuel, g/cm^3 ,

ρ_{FP} = density of fission product shell, g/cm^3 , and

Y_o = yield, GJ.

TABLE 1.0

Cross-Section Data*†‡ (barns) at 14.0 MeV

Material	$\sigma(n, \gamma)$	$\sigma(n, 2n)$	$\sigma(n, 3n)$	σ_{el}	σ_{Nel}	σ_S	σ_A	σ_T
† D	29.4×10^{-6}	0.2	0.0	0.6	0.175	0.775		0.8
† T	1.0×10^{-7}	0.045	0.001	0.9	0.05	0.950		1.0
† D-T(50%)	14.8×10^{-6}	0.123	0.0			0.863	0.123	0.9
□ Sr ⁹⁰	7.0×10^{-3}	1.30	0.0			1.7	1.3	3.0
□ Cs ¹³⁷		1.84	0.0					4.0
□ Kr ⁸⁵		1.36	0.0					5.0
▽ Eu ¹⁵⁴		1.91	7.48×10^{-4}					
▽ Sm ¹⁵¹		1.83	3.52×10^{-2}					
▽ Zr ⁹³		1.87×10^{-4}	1.75					
▽ Cs ¹³⁵		1.79	0.0					
▽ Tc ⁹⁹		1.27	0.0					
▽ Sn ¹²⁶		1.49	0.35					
▽ I ¹²⁷		1.64	0.0					
▽ Pd ¹⁰⁷		1.39	0.0					

* For fission products and transuranics $\sigma_S \equiv \sigma_T - \sigma_A$

In most cases $\sigma_A \equiv \sigma(n, 2n)$ or $\sigma_A \equiv \sigma(n, 3n)$

For (D + T) $\sigma_S = \sigma_{el} + \sigma_{Nel}$

□ Data obtained from "The Clean Breeder Machine (CBM)", Meyer Steinberg, et al., BNL 22114, March 1976 and BNL 11915, November 1967.

† Data obtained from BNL 325, D. J. Garber and R. R. Kinsey, January 1976.

▽ Data obtained from private communications with J. W. Davidson, University of Texas at Austin, Center for Energy Studies, Austin, Texas, August 21, 1979.

TABLE 2.0

Parameter Value Table

Parameter	Range of values in study
Y_o (CJ)	0.05 to 50.0
f_B	0.5, 1.0, $f_B = \frac{(\rho R)_{DT}}{6.3 + (\rho R)_{DT}}$
$(\rho R)_{DT}$ (g/cm^2)	0.1 to 11.0
ρ_{FP} (g/cm^3)	1.0 to 50,000.0
m_{FP} (g)	2.8×10^{-4} to 280.0

TABLE 3.0

Feed Rates and Radioactive Inventories in HYPERFUSE

P_{FIS}/P_{HYP}	Cs^{137}				Sr^{90}			
	60		30		60		30	
	<u>0.1</u>	<u>0.03</u>	<u>0.1</u>	<u>0.03</u>	<u>0.1</u>	<u>0.03</u>	<u>0.1</u>	<u>0.03</u>
f_{FF}								
$f, g/sec$	0.68	2.26	0.34	1.13	0.45	1.50	0.22	0.7
$(I_R), \text{curies}$	2.6×10^4	9.5×10^4	1.3×10^4	4.8×10^4	2.8×10^4	1.0×10^5	1.4×10^4	5×10^4
$(I_H), \text{curies}$	1.2×10^8	4.3×10^8	6×10^7	2.1×10^8	4.9×10^8	1.7×10^9	2.4×10^8	8.5×10^8

S = fission rate in 1000 MW(e) LWR = 1×10^{20} fission/sec

Sr^{90} = 137 curies/g [29 y half life]

Cs^{137} = 86.7 curies/g [30.1 y half life]

$(\alpha y)_{Cs^{137}} \approx (\alpha y)_{Sr^{90}} \approx 0.05$

t_p = processing time = 500 sec

t_H = $2 \times 13 = 26$ day for cesium stream

= $2 \times 50.5 = 101$ day for strontium stream

average inventory $\sim 4.8 \times 10^6$ curies Sr^{90}
 in 1000 Mw(e) LWR $\sim 4.7 \times 10^6$ curies Cs^{137}
 [1 1/2 years average residence time]

FIGURE 1.0 HYPERFUSE SYSTEM FLOW SHEET

FIGURE 2.0 FLOWCHART OF CALCULATIONAL
PROCEDURE IN HPRBNL CODE

KEY FOR FIGURES 3.0 AND 4.0

BURN FRAC $1.0 - f_B = \frac{(\rho R)_{DT}}{6.3 + (\rho R)_{DT}}$

$2.0 - f_B = 0.5$

$3.0 - f_B = 1.0$

—	$\rho_{FP} = 1\text{g/cm}^3$
O	5g/cm ³
Δ	10g/cm ³
+	50g/cm ³
X	100g/cm ³
◇	500g/cm ³
▽	1,000g/cm ³
⊠	5,000g/cm ³
*	10,000g/cm ³
◆	50,000g/cm ³

FIGURE 3.0 SUPPORT RATIO VS $(\rho R)_F$ FOR Sr^{90}
 HYPERFUSE BURNER PLANT ($P_{FUS/FIS}^{-1}$
 = SUPPORT RATIO)

FIGURE 4.0 TRANSMUTATION RATIO VS $(\rho R)_F$
 FOR Sr^{90} HYPERFUSE BURNER
 PLANT

FIGURE 5.0 A POSSIBLE HYPERFUSE NUCLEAR CHEMISTRY SYSTEM