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THE FAST DILUTE REACTOR, AN INTERIM PROGRESS REPORT

John R. Menke

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The Fast Dilute Reactor, An Interim Progress Report

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ABSTRACT

In the planning of a breeding program fast dilute piles constitute one of the interesting domains for design study. A few families of fast dilute reactors have been surveyed and these indicate reasonable feasibility with moderate performance. High temperature heat rejection and doubling times of 5 - 10 years seem to be attainable with critical masses of 100 - 200 kgs.

[redacted]

THE FAST DILUTE REACTOR, AN INTERIM PROGRESS REPORT

John R. Menke

[redacted]

Introduction

In planning a breeding program for fissile material and power production there are, of course, many regimes which may prove more or less feasible; for instance, Dr. Wigner has discussed the breeder problem before the reactor development group on October 17, 1947. Fast dilute piles constitute one of the interesting domains for design study. Soodak (CF-3107) has treated the family of plutonium piles diluted with normal uranium and Snyder (A-4248) has given some detailed attention to the critical problem of a single high dilution lead - uranium-235 pile. The author, originally infected with Dr. Zinn's enthusiasm for the field, has also considered some aspects of the problem.

This paper written, somewhat by force of circumstance, before the study is complete presents results obtained in a survey of the field motivated by the need to outline the regions of most promising feasibility. No attempt at design of specific piles is made, the scattered calculations serving only to lend definiteness. Such surveys accomplish the additional purpose of emphasizing again the large areas wherein we remain ignorant of physical properties and methods of evaluation.

A representative fast dilute pile as an example might have the following dominant characteristics:

[redacted]

Critical mass: $\sim$100 kgs U^{233} in pile [redacted]

Holdup outside pile: Unknown, probably at least one more critical mass

Breeding gain: $\sim$ 0.3 for U^{233}

Specific Power: $\sim$1000 watts/gm^{233} in pile

Doubling time for material in pile: $\sim$ 9 years

Controllability: Neutron lifetime $\sim$ 1/10 of that in thermal pile achieved by $\sim$ 1/10 thermal fissions in "mixed" portion of pile

Coolant temperature in: 185° C (365° F)

out: 550° C (1300° F)

This is by no means an optimum fast dilute pile (for instance Pu is superior to U^{233} as a breeder material) but is cited because some of the details have been worked out.

A few of the important areas where unknown physical properties forestall more complete studies can well be repeated here. Probably foremost among the unknowns is the behavior of α (1) with neutron energy. (Plutonium α is receiving attention now by the General Electric Company.) Moreover, data on the inelastic and transport scattering properties of the diluents are sparse. We are in a somewhat better position with respect to the fast absorption cross sections. Furthermore, data on the high-diluent, fissile alloy systems are not good. Thus the low-

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(1) $$\alpha \equiv \frac{\sigma_{\text{radiative capture}}}{\sigma_{\text{fission}}}$$

[redacted]

plutonium end of the plutonium alloy systems are almost totally unknown to us. Many of the uranium alloy phase diagrams are available, but without much information on the alloy physical properties. To conclude with by no means the least important region of ignorance, we know almost nothing of the damaging effects of radiation on these materials (with the possible exception of the aluminum and uranium systems).

The plan of the report is as follows: first, the design constraints are listed; second, the available materials are surveyed; third, a somewhat detailed description of one family of piles is given; and fourth, several families of piles are compared.

Discussion

I. The Bases for Design

We shall limit our attention to the discussion of large, stationary, landbased reactor installations for breeding or converting and for the production of power by fast fissions. We may consider the chief design constraints as falling into the following major categories:

1. Nuclear
2. Thermal
3. Metallurgic and Chemical
4. Economic

This is one convenient arrangement; many others might suit.

The chief nuclear constraints upon reactor design involve the critical size, the neutron economy, the controllability, and the susceptability to radiation damage. For the survey purposes of this

[redacted]

paper, only first-order, crude approximations to critical size have been considered worthwhile. This size has been examined as a function of dilution with inert materials and as a function of various reflector arrangements. The neutron economy has been considered somewhat more carefully, especially in its relationship with the specific power. These two constraints, the first indicating smaller, and the second, greater dilutions, lead to an optimum dilution which has been given before[1] by Young. The parasitic absorption of the diluents and the extent of the fast fission effect in the fertile materials largely differentiate the neutron economics of the various fast piles. The controllability of fast reactors is dependent primarily upon two quantities; the fraction of neutrons which are delayed and the average neutron lifetime. Contrary to some early indications it has been recently demonstrated that the fraction of delayed neutrons from fast fission of U^{235} and Pu^{239} is very nearly the same as that due to thermal fission. If it is desired, the average neutron lifetime of a simple fast pile can be increased by perhaps a factor of 10^3 in a composite pile by the addition of a thermal region for say 10% of the fissions. This "safety factor" also serves the useful purpose of reducing the critical size at a small cost to the neutron economy[2,3]. Susceptability to radiation damage is probably reduced by increased dilution in the solid phase and is probably nearly absent in the liquid phase.

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1. Pile Technology, Lecture #24.

2. CLM-JRM-2.

3. Mon P-412.

[redacted]

The chief thermal constraints upon reactor design (which make up the reactor thermal characteristics; the specific power and the available temperature potential) may be noted as follows: the specific heat per unit of fissile material, the total of three temperature differences available and needed to remove the fission energy, the feasible temperatures, stresses, dimensions, pressures, and velocities of the reactor materials and the practicable pumping power. The specific heat per unit of fissile material obviously determines the time rate of temperature rise on a fluctuation in either the heat removal or production. In highly concentrated reactors this may become a very rapid rate indeed. The total temperature drop available to remove the fission energy let us say, in the heterogeneous, liquid-metal cooled pile, will normally be somewhat less than the difference between the melting point of the coolant and the first phase change in the solid phase material. This available temperature potential will be used to move the heat energy; first, out of the solid phase material, second, into the coolant stream, and third, to accumulate the energy along the coolant stream and out of the reactor. The first drop which we call the plate drop indicates plate thicknesses which impose thermal paths less than, say several millimeters. Porous construction may reduce this component even further. The second, the film drop or better, the drop into the stream is minimized by thin, turbulent streams of high thermal conductivity fluids. The remaining potential, the drop along the stream is governed by the coolant volumetric specific heat and velocity and by the pile size. The plate drop together with the solid's physical properties also governs the thermal stresses. These

 [redacted]

are minimized by small thermal paths in ductile materials of high conductivity. There may be some question about the ability of materials in high radiation fluxes to accept large mechanical stresses which could limit the pile pressure level. The velocities and pumping power are determined by normal engineering considerations.

The chief metallurgic and chemical constraints (i.e. atomic or molecular constraints) upon reactor design involve the corrosion problem, the alloy possibilities and physical properties, the reprocessing problem, and, one may list again, the radiation damage difficulties. In all-metal designs the corrosion problem reduces to the problems of controlling or excluding foreign substances, especially oxidants, and of choosing mutually insoluble coolant and plate materials. Perhaps the problem of inducing coolant wetting should be included here. The natural alloy systems constitute severe constraints upon the diluent-fertile-fissile dilutions which are possible. It may be, however, that where a natural alloy does not exist, one may nevertheless construct an artificial "alloy" by powder metallurgy or other new technics. Even where the natural alloy does exist the material (such as an intermetallic compound) may be totally impractical to use alone because of its extreme brittleness and low thermal conductivity. The reprocessing problem and its ramifications are enormous and cannot be adequately treated here. However, it is clear that an expendable diluent is preferable to an expensive one which must be retrieved at each cycle. Furthermore, there may be some advantages in having a more chemically active diluent (such as Al) than fissile material to avoid the separate reduction of radioactive

 [redacted]

fissile material. Little is known yet about the influence of metallurgic state upon radiation damage.

The economic constraints upon reactor design have been almost totally neglected. Nevertheless, such considerations as the installed cost per unit of power and breeding, the operating and reprocessing cost, and the reprocessing frequency will eventually count heavily in the evaluation of the worth of any given installation.

With some of the basic design constraints in hand we can now turn to the next step - a survey of the materials of which such a stationary, fast pile might be constructed.

II. Survey of Materials

We choose to divide the materials of construction into two major groups, the fissile and fertile materials, and the diluent materials. From LA-520 we can write down the major characteristic of the fissile materials, their neutron fission cross section in barns in Table 1.

Table 1

Energy in mev.	0.1	0.4	1.0	1.5	2.0	3.4	4.8	5.85
$_{90}Th^{232}$						0.17	0.17	0.17
$_{92}U^{233}$	2.87	2.5	2.1			1.84	1.8	1.76
$_{92}U^{235}$	1.92	1.46	1.35			1.32	1.32	1.32
$_{92}U^{238}$				0.25	0.42	0.58	0.65	0.66
$_{94}Pu^{239}$	1.95	1.94	1.94			1.94	1.94	1.93

 [redacted]

Other important characteristics of the fissile group available to us are summarized in Table 2.

Table 2

	mols/cm^3	$\sigma_a(n-\gamma)$ 1 mev	$\xi\left(\frac{2}{A}\right)\sigma^*_{tr}$(1.5 mev)	σ^*_{inel}(1.5→.5 mev)	ν	k (thermal cond.)
$_{90}Th^{232}$	0.0495	~ 0.15	0.0086			
$_{92}U^{233}$	0.0785	-	0.0086		2.65	~ 0.05
$_{92}U^{235}$	0.0785	-	0.0085	4.9	1.3	2.5	~ 0.05
$_{92}U^{238}$	0.0785	~ 0.15	0.0084	4.3	1.6		0.05
$_{94}Pu^{239}$	~ 0.067		0.0084			2.95	~ 0.02

* $\begin{cases} \text{LA-274} \\ \text{LA-169} \end{cases}$

Considerations other than suitability to the reactor design will of course contribute to the choices of fissile and fertile materials.

We attempt next to list the most likely diluent materials and their major characteristics, including both solids and liquids (coolant and plate materials) in Table 3. The low atomic weight elements have been omitted because of their high elastic slowing-down power. Other, high atomic weight elements have been omitted because of their indicated high parasitic capture cross sections for neutrons. Many of the capture cross sections used are about three times larger than those given by Hughes in order to adjust for the probable pile energy spectrum. Late indications from Los Alamos are that these may still be too low by about a factor of two.

[redacted]

Table 3

	mols/cm^3	ξ	σ_a	*σ_{tr}	*σ_{inel}	Radiation Damage	Alloy Information with U	with Pu	k (thermal cond.)
Na	0.041	0.09	0.003			prob. O.K.			0.365
Mg	0.07	0.082	0.006						0.376
Al	0.10	0.072	0.009	1.9	0.0	good	good	some	0.48
Si	0.085	0.071					fair		0.20
P	~0.07	0.065	high						low
S	~0.06	0.062	0.003						low 10^{-3}
K	0.021	0.051							0.237
Ca	0.04	0.05							high
Ti	0.09	0.041							
V	0.11	0.039	0.0075						high
Cr	0.13	0.038					poor		0.165
Mn	0.13	0.036	0.010						high
Fe	0.14	0.035	0.015	2.2	0.0		fair	little	0.18
Co	0.149	0.034	0.027	2.2	0.0				0.165
Ni	0.149	0.034	0.021	2.3	0.0		fair	little	0.14
Cu	0.14	0.031	0.027	2.2	0.3		fair	some	0.92
Zn	0.11	0.030	0.060						0.268
Ga	0.085	0.0284	0.075			prob. O.K.	some,		low
Rb	0.0175	0.023	0.090			prob. O.K.			high
Sr	0.0296	0.023	low?						high
Y	0.062	0.022	low?						
Zr	0.07	0.022	low?				some		0.13
Cb	0.092	0.021	0.100				good		high
Mo	0.106	0.0205	0.050				fair	some	0.35
Te	0.049	0.0155	0.030						0.014
Cs	0.014	0.015	low?			prob. O.K.			high
Ba	0.025	0.0145	0.010						
La	0.044	0.0144	low?						low
Ce	0.048	0.0143	low?						low
Pr	0.047	0.0142	low?						low
W	0.105	0.0108	0.070	4.7	0.9				0.476
Hg	0.068	0.01	0.090			prob. O.K.	fair		0.02
Tl	0.058	0.0098				prob. O.K.			0.093
Pb	0.055	0.0097	0.005	3.4	0.0	prob. O.K.			0.083
Bi	0.047	0.0096	0.005			prob. O.K.	some		0.02
Th	0.05	0.0086	0.150						
U	0.0785	0.0084	0.150	4.3	1.6	bad, so far		fair	~0.056

* LA-274

$\xi \cong \frac{2}{\text{atomic wt.}}$ = log energy loss per collision

σ_a = barns, values used are two to three times those indicated by Hughes to adjust for pile spectrum.

σ_{tr} = barns, representative value, at 1.5 mev.

σ_{inel} = barns, representative value, 1.5 mev. neut. degraded to 0.5 mev.

 [redacted]

Table 3 gives some graphic evidence of the extent of our ignorance of properties.

There is clearly no rigorous, analytic approach possible to weld the many constraints into an absolute criterion for the choice of reactor materials. The contraints can only be used as guides in the exercise of technical judgment. For our examples we have chosen to illustrate the iron-uranium systems cooled with lead-bismuth alloys. The region of the periodic table from titanium through the transition elements is interesting and was chosen because the parasitic capture cross sections are low; the metals have high atomic density; their alloy systems with uranium are partially known; their fast scattering properties are partially known and favorable; and finally, because they are articles of commerce and cheap.

III. Description of Some Iron-Uranium 233 Piles

Assuming that α is 0.06 for pile neutron energy spectrum averaging near 0.5 mev and using a simple optimum criterion for dilution:

$$\text{Atomic Dilution} \cong \frac{\sigma_{\text{fission}}}{\sigma_{\substack{\text{absorption } (n-\gamma) \\ \text{diluent}}}} \left[\frac{\eta - 2}{\eta + 2} \right]$$

one arrives at an indicated dilution of one U^{233} atom for about 16 iron atoms. We have, therefore, chosen to investigate a series of three piles (Table 4) with the following atomic ratios in the core:

 [redacted]

Table 4

		Pile #1	Pile #2	Pile #3
fissile atoms	(U^{233})	1.0	1.0	1.0
fertile	(U^{238})	0.0	1.0	2.0
diluent	(Fe)	8.0	14.0	20.0
coolant	(Pb Bi)	3.3	6.0	9.0
gms U^{233}/cm^3 pile		1.67	0.91	0.64

In each case the volume of coolant is about equal to the volume of solid. Some derived quantities are given below in Table 5 for a system of two reflectors in series, 3 cm of beryllium followed by 27 cm of normal uranium (no credit taken in critical size for slowing down in Be or for fast fissions in fertile materials). We have purposely avoided refined critical calculations as being only of second phase importance in a survey.

Table 5

	Pile #1	Pile #2	Pile #3	
Critical mass	~50 kgs	~100 kgs	~160 kgs	
Critical radius	~20 cms	~30 cms	~40cms	
Breeding gain	0.36	0.27	0.19	
Specific power	(1.2kw/cm^3)	(1.kw/cm^3)	(0.85kw/cm^3)	
	730 kw/kg	1100 kw/kg	1330 kw/kg	
Inlet temp. (m.p. Bi-Pb eutectic = 125 °C)	185 °C	185 °C	185 °C	(365 °F)
Max. plate temp. (first phase change Fe-U system = 910 °C)	700 °C	700 °C	700 °C	(1300 °F)
Rate of temp. rise for 100% increase in heat production (or zero coolant velocity)	435 °C/sec	360 °C/sec	307 °C/sec	
Plate thickness	3 mm	3 mm	3 mm	
Coolant velocity	3 m/sec	3 m/sec	3 m/sec	(~10 ft/sec)
Fast flux (n's/cm^2 sec)		~$5x10^{15}$		
Breeding gain x specific power	255	297	252	
Doubling time for material in pile	10.8 yrs.	9.2 yrs.	10.9 yrs.	
Normal uranium in reflector		~14 tons		

 [redacted]

Hansen reports the solubility of bismuth in iron as less than 10^{-5}. The project Chicago handbook gives the iron-uranium phase diagram. In the iron-rich region there is an intermetallic compound (UFe_2) at 67% iron and a eutectic at 84% iron melting at 1080 °C (with a prior phase change at 910 °C). We have remained on the iron-rich side of the eutectic. Probably, one would "clad" both sides of the fissile-alloy with uranium free sheets 1/4 - 1/2 mm thick.

In an over-all sense we have described a small family of piles of moderate performance characteristics in a domain of design less well-known than that of thermal piles but perhaps more well-known than that of resonance piles. The construction is of nearly standard materials with fairly normal fabrication characteristics for which there exists some experience. The size of a single installation is not excessive (Pile #2 $\cong$ 100,000 kw. of heat). The piles would probably have a continuous reprocessing schedule; the lifetime of fissile material being of the order of 100 days.

IV

The only other survey of this field known to us is given by Soodak in CF-3107. It may be valuable in conclusion to attempt a comparison of the fields of these two surveys even though a rigorous comparison is not reasonable. Soodak dealt primarily with plutonium piles diluted with normal uranium.

[redacted]

Table 6

Piles	atoms solid diluent / atoms fissile matl.	kgs. rough crit. mass	years doubling time	
$Pu + U^{238}$ (CF-3107)	1	35	9.1	
$Pu + U^{238}$ (CF-3107)	4	90	4.6	
$Pu + U^{238}$ (CF-3107)	10	390	3.8	optimum dilution only at infinite crit. size.
$U^{233} + Fe$ (this survey)	8	50	10.8	
$U^{233} + Fe$	14	100	9.2	optimum dilution
$U^{233} + Fe$	20	160	10.9	
$Pu + Fe$ (this survey)	8	50	5.7	
$Pu + Fe$	14	100	4.4	
$Pu + Fe$.	20	160	4.1	optimum dilution

The table is drawn with adjustment made for similar cooling conditions as far as this was possible. It indicates the advantages gained by fast fissions in the normal uranium diluent in CF-3107 which is paid for in comparison by larger critical sizes.

In conclusion the realm of fast dilute piles is apparently attractive enough to warrant further study.

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