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DEVELOPMENT OF THE GAS COOLED FAST REACTOR CONCEPT*

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SUMMARY

Following the work on gas cooling for fast reactors reported at Geneva, a year's subsequent study has strengthened confidence in the system, and indicated prospects of considerable further performance advances.

With steel-canned carbide fuel and CO₂ cooling at 2000 psi, fuel ratings and power densities of the order of 1.75 Mw/kg and 600 kw/litre appear possible, while producing high enough gas temperatures to yield 41.5% over-all plant efficiency and retaining less than \$1 reactivity swing for a 100,000 Mwd/tonne maximum burnup. The corresponding over-all conversion ratio is 1.6, leading to total system doubling times of around 4 yr and to substantially zero fuel cycle cost (with 4-3/4% fuel use and 10% working capital charges).

Use of thorium instead of depleted uranium blankets (but with U-238 left as fertile material in the core) could further reduce fuel cycle costs by about 0.2 mill/kw(e)-hr.

In desalting applications, the system offers the interesting prospect of achieving as good economy in a single purpose plant as is obtainable in combined electric and desalting applications employing thermal reactors.

INTRODUCTION

Some information and preliminary conclusions from early studies on gas cooled fast reactors have already been published.¹ The purpose of the present paper is to report on more recent work (partly under AEC sponsorship) in this field at General Atomic, which has included both more detailed conclusions and a wider extension of application.

For clarity, it is desirable firstly to recapitulate very briefly the essential characteristics of the system we have been studying, and to refer again to our general reasons for interest in the gas cooling of fast reactors, for these have not changed and are basic to the design philosophy adopted.

WHY GAS COOLING?

The original reasons for looking at gas cooling for fast reactors arose from a wish to explore an alternate to sodium technology which might offer practical engineering attractions, and also some important inherent safety advantages.

While a desire to avoid use of an active and highly combustible primary coolant requiring rigorous isolation and completely blind core manipulation procedures is understandable enough, some important considerations affecting the issue are not so self-evident, so it is perhaps worthwhile to comment on these at once.

Fundamentally, these considerations stem from the side effects of interaction between the coolant and the nuclear behavior of the core, which can have undesirable consequences on the design of sodium systems, particularly in application to large scale plants. The problem is that reduction in the moderating influence of the coolant consequent on its loss, or the development of core void, tends to increase reactivity. It is true that the coolant presence has also an opposite effect, via its influence on core neutron leakage, but making this latter effect predominate in large systems involves sacrifice of internal conversion ratio and acceptance of either increased burnup reactivity allowance or greatly shortened refueling intervals. Alternately, safety dictates that having any considerable positive void coefficient requires the provision of a sufficiently high Doppler coefficient for its prompt override, and securing this can involve sacrifice of over-all conversion if deliberate spectrum softening is needed to get it.

As a result, large sodium cores, designed to rigorous inherent safety requirements, can have disappointingly short refueling intervals (in spite of postulated long total fuel exposure), and practical total conversion ratios can be far below the 1.65 or so that a good hard spectrum could give with plutonium fuel and a passive coolant.²

*Work supported in part under USAEC Contract AT(04-3)-167.

The alternate gas cooled designs aim at complete elimination of partial reloads, with less than \$1 reactivity swing during burnup, and at the hardest spectrum that the fuel material (carbide or oxide) will allow. The degree of cooling aimed at is such as ultimately to combine this with a fuel rating in the 1.5 Mw/kg range, yielding doubling times as short as 4 yr, which really qualifies the fast reactor for an expanding program.

PARTICULAR FEATURES OF THE GENERAL ATOMIC SYSTEM

Four basic features distinguish the particular gas cooled fast reactor designs we are discussing and require recognition in drawing comparison with other schemes which might be proposed:

1. Incorporation of resonance absorbers in the fuel to ensure reactivity decrease consequent on water or steam admission, allowing also underwater inspection and long-term shutdown heat removal by natural convection.
2. Total enclosure of the primary circuit by a prestressed concrete containment.
3. Use of partially roughened can surfaces to aid heat transfer, in regions where required.
4. Use of a type of core assembly minimizing structure and dead void space.

Also of great significance are the common design ground rules adopted, among which are:

1. Maintenance of temperatures within the present established capability of steel cans and the particular fuel used (oxide or carbide).
2. Provision of high enough gas outlet and inlet temperatures to supply a steam plant in the 40% efficiency range in power applications.
3. Restriction of gas pressures and pumping powers to the capability of a pressure vessel and circulators presently considered practical.
4. Selection of helium as the reference coolant, although CO₂ would yield improved performance. If it can be demonstrated that a molecular coolant such as CO₂ is sufficiently stable in the intense fast neutron and irradiation field characteristic of a fast reactor, then this would become the preferred coolant. Cases involving both coolants are reported here.

SCOPE OF MORE RECENT WORK

Essentially, the work reported in the Geneva paper had to do more with feasibility than with optimization, and its nature justified adoption of comparatively crude analysis in some areas and neglect in others. For instance, as an approximation to the requirement for long

refueling periods, unity core internal conversion ratio was specified as the determining factor in setting enrichment, rather than use of more sophisticated burnup calculations. Also, fuel fabrication costs were based on use of a simple fixed charge per unit length of fuel element, based on available information on similar constructions. Areas not studied included the use of carbide fuel and the search for better resonance absorbers than the one first selected (indium).

The general areas in which recent work has been most concentrated are as follows:

1. Burnup studies leading to adoption of single batch fuel management as a practical and useful specification.
2. Further water flooding studies.
3. Carbide fuel performance.
4. More sophisticated fuel cycle cost analysis, leading to core optimization.
5. Further thought on over-all plant proportions.
6. Application extension, including desalting.

These studies have, in fact, led to our talking now about ratings of 1-1/2 Mw/kg and over, of doubling times of as short as 4 yr, and even of negative over-all fuel costs--steps very considerably beyond what was originally speculated. We will now deal with these areas in more detail.

BURNUP STUDIES

The variations in nuclide compositions that occur during irradiation have been studied in some detail to evaluate the feasibility of obtaining long burnups without large reactivity loss. These studies consisted of machine calculations in which broad-group cross sections were obtained from a B₁ spectrum calculation utilizing a 99-group library, these cross sections then being used in several different one-dimensional burnup codes. Changes in composition during irradiation were determined for the following nuclides: U-235, U-236, U-238, Np-239, Pu-239, Pu-240, Pu-241, Pu-242, Mo-95, Tc-99, Rh-103, Xe-131, Cs-133, Nd-143, Pm-147, Sm-149, Sm-151, Eu-153. Other fission products were assumed nonsaturating, and other materials such as coolant, structural materials, and resonance absorbers were assumed non-burning. Neutron absorption in these materials was, of course, accounted for.

Figure 1 shows typical reactivity lifetime relations for cores of several initial internal conversion ratios, using mixed plutonium-depleted uranium oxide fuel (with plutonium isotopic content corresponding roughly to that obtained from low enriched uranium irradiated to

10,000 Mwd/tonne, i. e., Pu-239:Pu-240:Pu-241:Pu-242::78:13:8:1). Other than the plutonium to uranium ratio, these cases correspond to the reference oxide case of Table 1.

Figure 1 Keff Versus Core Lifetime for Various Initial Core Conversion Ratios

It will be seen that an initial internal conversion ratio of about 1.1, rather than unity, is needed to get lifetime burnup with less than \$1 reactivity swing, and that the result is very sensitive to this number. With an internal conversion ratio of 1.04, partial reloading every 200 days is required. The severe penalty for going much below unity is noteworthy and is illustrative of the consequences of settling for a low internal conversion ratio in any fast reactor.

To raise the internal conversion ratio requires an increase in fuel volume, owing to the corresponding lower fissile density, so the interaction of this factor with the heat transfer had to be looked at also. The conclusion of this study was, however, that the penalty (in terms of reduced available fuel rating or of increased coolant pumping requirement) was outweighed by the operational advantage of the improved reactivity lifetime, and the safety feature of low reactivity change. Consequently, all subsequent work was confined to cores specified in the 1.04 to 1.10 internal conversion ratio range. A side

benefit of these high figures was ability to flatten the reactor power distribution over the whole core lifetime, a feature which led to the specification of only a 1.2 to 1 radial maximum-to-mean heat distribution in recent performance studies, which was achievable with a three-zoned core.

Table 1

REPRESENTATIVE GAS COOLED FAST REACTOR
DESIGN AND PERFORMANCE (OXIDE FUEL
AND HELIUM COOLING)
(5000 - LITRE CORE)

CORE PROPORTIONS

LENGTH	100 CM
DIAMETER	250 CM
FUEL ELEMENT DIAMETER	1.1 CM
NUMBER OF FUEL BOXES (OF 100 ELEMENTS EACH)	256

OPERATING CONDITIONS

WORKING PRESSURE	1000 PSI
PUMP POWER	2-1/2% THERMAL OUTPUT
GAS TEMPERATURE	
IN	300°C (ALLOWS 38% NET
OUT	598°C EFFICIENCY)
MAX ELEMENT TEMPERATURE	
CAN SURFACE	660°C
FUEL AXIS	2100°C

PERFORMANCE

POWER DENSITY	222 KW(1)/LITRE
FUEL RATING	0.87 MW(1)/KG FISSILE
DOUBLING TIME	10.1 YR
CONVERSION RATIO	
INTERNAL	1.04
OVER-ALL	1.50

FUEL CYCLE COST

10% WORKING CAPITAL, 4-3/4% USE	0.292 MILL/KW(e)-HR
10% WORKING CAPITAL, 10% USE	0.748 MILL/KW(e)-HR

NET ELECTRIC POWER

463 MW

FURTHER WATER FLOODING STUDIES

The effect of water entry on reactivity was evaluated by means of detailed calculations in which both energy and spatial self-shielding of absorption resonances in fertile material and resonance absorbers were accounted for (using methods described by L. W. Nordheim³). For the oxide reference design, it appears that gadolinium is a suitable poison, since the loss in conversion ratio at dry operating conditions could be held to less than 0.05. A somewhat better poison, from the neutronic standpoint, would consist of a mixture of gadolinium, indium, samarium, europium, and other materials because of the reduced self-shielding and the enhanced absorption in the partially flooded cases. Investigation of this "witches brew" was not pursued, since gadolinium by itself proved acceptable. Figure 2 shows the decrease in criticality factor as a function of water content for the chosen gadolinium loadings. It is seen

that the reactivity is negative for any degree of water flooding, and this characteristic leads to the considerable operational and safety advantages which have been mentioned previously.

Figure 2 Effective Multiplication as a Function of Percent of Helium Space Flooded

CARBIDE FUEL

The potential advantage of carbide fuel over oxide rests on three features:

1. Increased conductivity.
2. Increased heavy metal density.
3. Decreased moderating effect.

In sodium systems, only effect (1) is of real significance, and this gain is somewhat offset by decreased allowable fuel temperature. With gas cooling, the ability usefully to employ a harder spectrum and the increased premium on available coolant passage cross section together make the latter two effects dominant.

The improved conductivity of the carbide over the oxide may allow the peak heat extraction per foot length of fuel element to be raised from 20 kw to around 40 kw, but to make full use of this gain requires that this improved internal heat transfer be accompanied by a corresponding surface dissipation improvement.

Our optimization studies indicate that whereas a 1000 lb/in.² working pressure gave a good balanced design for the oxide, raising this to 2000 lb/in.² was desirable with the carbide.

Helium cooled reference designs have been established at 1000 psi, with the pressure primarily limited by problems associated with handling and storage. CO₂, on the other hand, can be liquified or exhausted to the atmosphere under controlled conditions, and therefore higher coolant pressures have been assumed with CO₂. Actually, these coolants are quite interchangeable and yield comparable performance when helium pressure is about 20% above CO₂ pressure.

Tables 1 and 2 show comparative performances of two 5000 litre core reference designs for oxide and carbide fuels, respectively, which clearly illustrate the very big improvement in rating, doubling time, and fuel cycle cost resulting from the change to carbide. Each case has about the same can temperature, but the fuel axis temperature is appropriate to the limits of the fuel (2100°C for oxide, 1430°C for carbide).

Table 2

REPRESENTATIVE GAS COOLED FAST REACTOR
DESIGN AND PERFORMANCE (CARBIDE FUEL
AND CO₂ COOLING)
(5000 - LITRE CORE)

CORE PROPORTIONS	
LENGTH	100 CM
DIAMETER	280 CM
FUEL ELEMENT DIAMETER	0.88 CM
NUMBER OF FUEL BOXES (OF 100 ELEMENTS EACH)	354
OPERATING CONDITIONS	
WORKING PRESSURE	2000 PSI
PUMP POWER	2-1/2% THERMAL OUTPUT
GAS TEMPERATURE	340°C (ALLOWS NET PLANT
IN	815°C EFFICIENCY OF 41.5%)
OUT	
MAX ELEMENT TEMPERATURE	890°C
CAN SURFACE	1430°C
FUEL AXIS	
PERFORMANCE	
POWER DENSITY	800 KW(1)/LITRE
FUEL RATING	1.75 MW(1)/KW FISSILE
DOUBLING TIME	4.4 YR
CONVERSION RATIO	
INTERNAL	1.10
OVER-ALL	1.80
FUEL CYCLE COST	
10% WORKING CAPITAL, 4-3/4% USE	0.013 MILL/KW(e)-HR
10% WORKING CAPITAL, 10% USE	0.227 MILL/KW(e)-HR
NET ELECTRIC POWER	1364 MW

Of particular interest are the substantially zero net fuel cycle costs of the leased fuel carbide case, which includes 10% working capital charges, but only 4-3/4% fuel use charge. The question of how such low fuel cycle cost arises is therefore of prime interest and will be dealt with next.

FUEL CYCLE STUDIES

In looking at the fuel cycle cost estimates of any reactor system--particularly one yet to be realized--it is obvious that there is plenty of scope for presenting optimistic claims by suitable choice of assumptions and ground rules, which are often incompletely stated.

It is therefore worthwhile to attempt to clarify the situation to the extent of mentioning some of the factors which might be expected to lead to differences between gas and sodium coolant performance in this area.

Basically, the influence of reactor design on fuel cycle cost is through:

1. The fuel rating (Mw/kg fissile), affecting mainly inventory charges.
2. The over-all conversion ratio, affecting fuel buy-back returns.
3. The maximum linear heat load (kw/ft), affecting fabrication charge, and determined mainly by the nature of the fuel.
4. The fineness of fuel subdivision (pin size), affecting fabrication charge.
5. The degree of power flattening.
6. The maximum burnup (Mwd/tonne).
7. The plant efficiency.

In comparing systems aimed at the same burnup and capable of the same order of plant efficiency (as we are doing), we are substantially concerned only with changes in items (1) and (2) that may result from the nature of the coolant, and changes in item (3) that may come from changes in the kind of fuel (oxide or carbide). It is therefore of interest to show the effect on fuel cost of arbitrary variation of conversion ratio and fuel rating. We are furthermore interested in seeing this repeated for linear heat loadings typical of oxide and carbide fuels (20 kw/ft and 40 kw/ft, respectively). In this way, we get a preview of what to expect from design changes.

Figure 3 shows the effect of the conversion ratio on the fuel cycle cost for the oxide and carbide reference designs based on the following ground rules:

1. Energy yield (including U-238 fission) at 22,700 Mw(t)-hr/kg fissile destroyed.
2. Net thermal efficiency at 0.415 for carbide and 0.38 for oxide fuel.

3. Other parameters as given in Table 3.

Referring to Figure 3, the base point, at ordinate zero, is for the reference design cases of Tables 1 and 2. The conversion ratios at these points were obtained from burnup calculations and include reductions due to parasitic absorption in fission products, core and blanket structural material, resonance absorbers, control rods, leakage, etc.

Figure 3 Variation in Fuel Cycle Cost as a Function of Conversion Ratio

Table 3

ECONOMIC BASIS FOR THE FUEL CYCLE COST

MAXIMUM BURNUP	100,000 MWD/MT
PRE-REACTOR HOLDUP TIME	0.50 YR
POST-REACTOR HOLDUP TIME	0.50 YR
FABRICATION COST	(SEE EQ. (6) IN TEXT)
SHIPPING COST	6 \$/KG FUEL
REPROCESSING CHARGE	23,000 \$/DAY (AEC REPROCESSING RATES)
BATCH RELOADING OF CORE AND AXIAL BLANKET, 1/3 OF RADIAL BLANKET RELOADED EVERY CORE LIFETIME	
INSTALLED CAPACITY SERVED BY FABRICATION PLANT	
FABRICATION PLANT	3000 MW (e)
WORKING CAPITAL CHARGE ON FUEL	10% OR 4.75 %
WORKING CAPITAL CHARGE ON FABRICATION AND REPROCESSING	10 %
FISSILE PLUTONIUM	9.00 \$/G

The maximum conversion ratios shown are theoretical upper bounds attainable only in an infinite medium of pure fissile and fertile material. Conversion ratios less than that at the base point would be obtained if liquid metal or other moderating coolant were substituted for gas, and Figure 3 can be used to estimate the corresponding increase in fuel cycle cost. It is seen that a decrease of 0.10 to 0.15 in conversion ratio gives an increase of 0.1 mill/kw-hr in fuel

cycle cost.

The object of the foregoing is to illustrate the order of fuel cycle cost advantage from high conversion ratio and high rating, and to explain that these factors are mainly responsible for the very low fuel cycle costs that we are getting from carbide fuel, gas cooled systems. With this in mind, we will proceed to a more detailed cost consideration.

FABRICATION COST ESTIMATE

In the present fuel cycle study, the nuclear, thermal, and economic characteristics of the gas cooled fast reactor have been appropriately accounted for to determine the fuel cycle cost in terms of the principal variables. One of these variables is the fuel element fabrication cost, which is sometimes expressed in dollars per kilogram of fuel and sometimes in dollars per centimeter of rod. Neither of these values, when maintained constant throughout a reactor study, properly recognizes the dependence of the fuel fabrication cost on the rod size and on the fuel element fabrication plant throughput. To more accurately represent this dependence, the fabrication cost, E, can be conveniently broken down into three terms:

$$E(\$/\text{yr}) = B(\$/\text{metric tonne (MT) of fuel}) Q \left(\frac{\text{tonnes}}{\text{year}} \right) + C(\$/\text{rod}) R \left(\frac{\text{rods}}{\text{yr}} \right) + A(\$/\text{yr}) \quad (1)$$

The first term, BQ, includes capitalization, cladding materials, and labor costs for the nitrate conversion into oxide or carbide. The second term, CR, covers costs associated with unit rather than volume operation, e. g., pelletizing, encapsulation. The constant term, A, is a fixed charge per year to operate a plant of a given size.

Using the relationship

$$Q = \frac{\pi}{4} D^2 \rho L R 10^{-4}, \text{ tonnes fuel per year,} \quad (2)$$

where ρ = the fuel density in g/cm^3 ,
L = the fuel active length in meters,
D = the fuel element inside diameter in cm,
R = the number of fuel rods processed per year,

and dividing both sides of equation (1) by $Q \times 10^3$, we get the fuel element fabrication cost in $\$/\text{kg}$ fuel:

$$F_C(\$/\text{kg fuel}) = B \times 10^{-3} + \frac{10C}{\frac{\pi}{4} D^2 \rho L} + \frac{10A}{\frac{\pi}{4} D^2 \rho L R} \quad (3)$$

It is further assumed that the unit rates A, B, and C are dependent on fuel fabrication plant size and rod throughput in the following manner:

$$A = A_o \left(\frac{Q}{Q_o} \right)^p, \quad B = B_o \left(\frac{Q_o}{Q} \right)^m, \quad C = C_o \left(\frac{R_o}{R} \right)^n \quad (4)$$

When the relations in equation (4) are substituted into equation (3) and the constant terms grouped, the fuel element fabrication cost formula takes the form

$$F_C(\$/\text{kg}) = \frac{M}{Q^m} + \frac{N}{(\rho L)^{1-n} D^{2-2n} Q^n} + \frac{P}{Q^{1-p}} \quad (5)$$

M, N, and P being a new set of constant terms.

A survey of published PuO_2 - UO_2 and PuC - UC sintered fuel fabrication costs⁴ indicates that the value of the exponents are approximately $m = n = 0.5$ and $p = 1$. The constants M, N, and P are then derived from several detailed cost analyses made on different pin sizes for the core and blanket,⁴ and for the purpose of this study we have used the following values:

Region	Fuel	M	N	P
Core	PuC-UC	146	1380	10
Core	PuO_2 - UO_2	101	1380	10
Ax. blk.	Depl. UO_2	20.6	150	0
Rad. blk.	Depl. UO_2	133	560	1

It is evident that the fuel element fabrication plant size as determined by its throughput, Q, has an important bearing on the fabrication cost, F_C . This throughput is obtained from an assumed total electrical output capacity $H(\text{Mw(e)})$ installed and an average fuel burnup, β , in Mwd/MT through the relationship

$$Q_i \left(\frac{\text{MT}}{\text{yr}} \right) = \frac{365 H L a_i}{\eta \beta_i} \quad (6)$$

where the subscript, i, refers to the core zone or blanket region and a_i is the percentage of the total power generated in zone i having a burnup β_i . η and L are the over-all thermal efficiency

and load factor, respectively. The over-all reactor fuel element fabrication cost (core and axial blanket) as a function of pin diameter is given in Figure 4, based on the above assumptions. The fabrication plant throughput of 31.33 MT/yr of 9% enriched $\text{PuO}_2\text{-UO}_2$ and 28.60 MT/yr of depleted uranium are typical of a 3000 Mw(e) capacity, 0.80 load factor, and 70,000 Mwd/MT (mean burnup) gas cooled fast reactor. These fabrication costs are applicable to stainless steel clad elements and include the conversion of plutonium nitrates to oxide or carbide.

Figure 4 Core and Axial Blanket Fuel Element Fabrication Cost; Fabrication Plant throughput of 31.33 MT/yr of $\text{PuO}_2\text{-UO}_2$ (9% Pu Enrichment) and 28.60 MT/yr of Depleted Uranium

RESULTS OF FUEL CYCLE STUDIES

The above fuel element fabrication cost formulas were used in a broad fuel cycle cost survey. The reactor size was maintained constant at 5000 litres as was the 2.5% pumping power fraction in the core and axial blanket. The coolants considered were CO_2 and helium at pressures of 1000 and 2000 psia over a wide range of maximum cladding temperature and gas inlet temperature. For each case the fissile density and fuel volume fraction in the core were determined to ensure an internal conversion ratio of 1.04 or 1.10 for two types of fuel, i.e., oxides and carbides in pellet form, sintered and pressed to 90% of their theoretical density. A thermal analysis performed on each core provided the specific power in Mw/kg fissile used in the fuel cycle cost. The economic basis for the cost determination is given in Table 3.

A typical plot of the fuel cycle cost in mills/kw(e)-hr as a function of specific power in Mw(t)/kg fissile is shown in Figure 5. The different curves are for the oxide and carbide fuels, an internal conversion ratio of 1.04, and two different gas inlet temperatures, 300°C and 340°C. When the oxide core is cooled with CO_2 at 2000 psig, it is possible to obtain for this oxide fuel a specific power of 1.38 Mw(t)/kg fissile for a maximum cladding temperature of 690°C and 2.5% fractional pumping power for the core and axial blanket. This specific power and the 1.92 Mw/kg fissile for the similar carbide case are indicated in Figure 5.

Figure 5 Fuel Cycle Cost as a Function of Specific Power

The oxide and carbide reference designs outlined in Tables 1 and 2 are capable of operating at specific powers of 0.67 and 1.75 Mw(t)/kg fissile, respectively. The fuel cycle costs for these two reference designs are detailed in Table 4.

An additional useful observation which resulted from this broad survey is that all the fuel cycle costs obtained for different coolants and coolant pressures, core shapes, internal conversion ratios, and maximum cladding temperatures can be correlated within a few percent as a function of two variables only, i.e., the specific power in Mw(t)/kg fissile and the over-all conversion ratio. This statement applies for a specific type of fuel (oxides or carbides) and requires that the same economic bases be used. It is seen from Figure 5 that in the range of

specific power realized by gas cooling, the fuel cycle cost is a weak function of specific power. In other words, there is little to be gained by substituting some other coolant for the gas, CO_2 , in an attempt to increase the specific power.

Table 4

FUEL CYCLE COST FOR THE OXIDE AND CARBIDE REFERENCE DESIGNS
(MILLS/KW (e)-HR)

	YEARLY CHARGE ON FUEL			
	OXIDE FUEL ^a		CARBIDE FUEL ^b	
	10%	4.75%	10%	4.75%
DEPLETION	-0.521	-0.521	-0.572	-0.572
FABRICATION	0.222	0.222	0.238	0.238
REPROCESSING AND SHIPPING	0.161	0.161	0.140	0.140
SUBTOTAL	-0.138	-0.138	-0.194	-0.194
FUEL WORKING CAPITAL	0.870	0.414	0.408	0.194
NON-FUEL WORKING CAPITAL	0.016	0.016	0.013	0.013
NET WORKING CAPITAL	0.886	0.430	0.421	0.207
NET FUEL CYCLE COST	0.748	0.292	0.227	0.013

^a ICR = 1.04, TCR = 1.50, HELIUM COOLANT AT 1000 PSIA, 38% EFFICIENCY.

^b ICR = 1.10, TCR = 1.60, CO_2 COOLANT AT 2000 PSIA, 41.5% EFFICIENCY.

On the other hand, use of liquid coolants leads to spectrum degradation and a corresponding lower conversion ratio. More specifically, let us consider the conservative reference design for oxide fuel, helium cooled at 1000 psia, and a specific power of 0.67 Mw/kg fissile. An attempt to raise the specific power to the oft-quoted value of 1000 kw/kg fissile would result in a gain of approximately 0.16 mill/kw(e)-hr. If a liquid metal coolant were used, this gain apparently would be offset by the reduction in the conversion ratio, e.g., from 1.5 to 1.25,* and a corresponding increase in the fuel cycle cost of 0.21. The result is a net increase in the fuel cycle cost of 0.05 mill/kw(e)-hr.

The net increase in fuel cycle cost for choosing a liquid metal coolant can be as high as 0.35 mill/kw(e)-hr in a more highly rated design such as the carbide, CO_2 , 2000 psia reference case.

Before finally leaving the question of fuel cycle costs, it is worth noting that we have thus far only considered the case of simple U-238 blankets. In fact, if thorium were substituted here (but not in the core), 13\$/g U-233 instead of 9\$/g plutonium could be produced in the blankets without other significant change to

* This value is taken from reference 2.

performance. This would result in approximately a further 0.2 mill/kw-hr reduction in fuel cycle cost in all cases. Also, further, as yet unexplored, reductions in blanket inventory and reprocessing cost could result from use of moderator material sandwiched in blankets, so the present discussed economics by no means represents limiting cases.

MECHANICAL DESIGN

Figure 6 shows a perspective sketch of the form taken by a 500 Mw(e) version of the gas cooled fast reactor, as presented in the Geneva paper.

Figure 6 Sketch of 500 Mw(e) Version of Gas Cooled Fast Reactor

Very briefly, features of this initial study are that the fuel is accommodated in roughly 4-1/2 in. square boxes of 100, 1 cm diameter, steel clad oxide elements. These fuel boxes, comprising an active length of 4-1/2 ft, with 18 in. top and bottom reflector sections, and a top 3 ft length of fission gas void space, are secured to a single, very deep, top grid plate by

a single top nut, in effect providing built-in support over a 4 ft length, confined to the constant (inlet) temperature region of the core.

Bottom loading (i. e., fuel elements not passing through the grid plate) is used to allow close enough box pitch in the working zones to avoid the need for coolant bypass prevention baffles, thus relieving the flat box walls of pressure differential load. This feature minimizes core structure and space wastage. Another feature contributing to effective performance is the use of roughened fuel element surfaces over part of their length, where needed.

The boiler system is mounted over the core in a shielded compartment, allowing access on shutdown. The central region (over the core and blanket) in the boiler space is baffled off from the main gas flow path, allowing access, with the main circulators running (with either helium or air) during shutdown.

As already mentioned, all the studies reported thus far related to reactors capable of driving a high efficiency steam plant, and they accepted the gas temperatures that this ground rule implied. This feature is referred to here because it considerably affects plant proportions; yet the question of just how high a plant efficiency should be aimed at to minimize total power cost is one which would require much further study to settle positively. All that can be said now is that the inherently low fuel cost of the system and the dominance of boiler size, rather than reactor core size, in determining pressure vessel volume would probably bias optimum design in the direction of accepting somewhat lower plant efficiency in return for the reduced boiler and pressure vessel dimensions and cost that would go with a larger allocation of temperature differential to heat transfer.

That the plant dimensions accompanying even the high efficiency plant are quite modest is best seen from Figure 7, which shows, to the same scale, outlines of the French EDF-4 natural uranium reactor (representing present concrete vessel technology), an advanced HTGR type, and the GCFR, all sized for 500 Mw(e).

Noticeable features are the relative dominance mentioned of boiler dimensions in the present case, and the fact that we are talking of quite modest vessel structure size compared with the requirements of the type of natural uranium thermal system which has until now been the main application of concrete vessels. This feature should be remembered when we speak of our higher working pressures.

Figure 7 Primary System Proportions of Three 500 Mw(e) Reactors

DESALTING APPLICATIONS

As a final example of the sort of extension to the earlier work that there is space to consider here, we would like to mention some interesting desalting applications.

Of particular interest was the possibility of applying the system to evaporative desalting as a single purpose plant. The thought here was that, without the compromise necessary to secure sufficient in and out gas temperatures to drive an efficient electric plant, a remarkable reactor performance seemed likely, which might avoid the previously considered necessity of a combination plant to achieve acceptable economy. This would, it was felt, in many ways represent an ideal application of gas cooling, since it would permit full exploitation of the ability to employ large temperature differences to effect heat transfer surface economy.

Table 5 shows the result of preliminary design studies, in the form of typical reference design core performances. It will be seen that with carbide fuel and 1000 psi CO₂ cooling, the original 5000 litre core that would have given some 500 Mw(e) at the same pressure and can temperature as an efficient electric plant heat source now gives over 3700 Mw(t) of heat, with essentially zero fuel cycle cost. Furthermore, it does this with an outlet temperature still over 500°C, allowing very effective heat transfer.

Nor is this the whole attraction. A main reason for the comparatively high capital cost of an evaporative desalting plant lies in the normal

need to reduce heat requirements by use of extensive regenerative heat exchangers. A typical efficient cascade evaporator system uses as little as 80 Btu of heat per pound of water product (compared with 950 Btu of heat in simple evaporation). However, to do this typically requires a capital charge of 15 to 20¢ per million gallons of water. With zero or negative fuel cycle cost as here, obviously some reoptimization is called for, whereby the sum of reactor and evaporator costs is minimized without regard to efficiency. It seems very likely that such study might lead not only to great plant simplification, but to water cost reduction beyond what might be expected just from the direct contribution of low fuel cost.

Table 5

SINGLE PURPOSE DESALTING APPLICATIONS FOR GAS COOLED FAST REACTOR
(5000 LITRE CORES, CO₂ COOLED)

FUEL	COOLANT PRESSURE (PSI)	SPECIFIC POWER (MW/KG FISSILE)	TOTAL POWER (MW(t))	TIME (YR)		FUEL CYCLE COST (¢/10 ⁶ BTU)	
				CORE LIFE	SYSTEM DOUBLING	10% USE CHARGE, 10% WORKING CAPITAL	4-3/4% USE CHARGE, 10% WORKING CAPITAL
CARBIDE	1000	2.0	3700	1.3	4.1	2.4	-0.03
	2000	3.8	7200	0.69	3.0	1.3	-0.06
OXIDE	1000	1.2	2300	2.1	6.4	3.1	1.9
	2000	2.3	4400	1.1	4.4	3.6	1.8

CONSTANT CONDITIONS

MAXIMUM CAN TEMPERATURE, 660°C
MAXIMUM FUEL TEMPERATURE:
OXIDE, 2100°C;
CARBIDE, 1950°C;
PUMP POWER, 2-1/2%
INLET TEMPERATURE, 150°C.
FABRICATION AND REPROCESSING PLANT, 7500 MW(t) CAPACITY.

CONCLUSIONS

Starting from a mere wish to see whether liquid metals were as essential to fast reactor cooling as was generally supposed, we have in fact been led to an advocacy of the gas cooling alternative which, at the outset, was quite unexpected.

Not only does it appear that all the cooling needed can be got very economically this way, but there appears a surprising number of direct and side benefits for gas cooling--particularly in large systems.

It is particularly important to note that these conclusions are based on studies of fuel materials selected for our present familiarity with them, rather than for their ultimate potential, and that, in line with this outlook, plant design has centered around maximum use of equipment development for other reactor types--particularly the HTGR systems.

For these reasons, although the idea of a gas cooled fast reactor may seem a novelty, we see no reason to associate this with big development outlay (by the standards that an entirely

new system might imply). Rather, it is felt that this type of reactor is an avenue for the unexpected further utility of large sums that have already been spent.

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