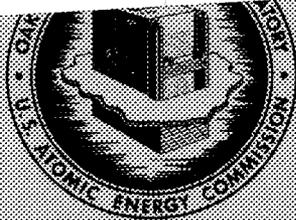


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PERFORMANCE CAPABILITY OF ADVANCED FUELS AND FAST BREEDER REACTORS

T. N. Washburn and J. L. Scott

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PERFORMANCE CAPABILITY OF ADVANCED FUELS AND FAST BREEDER REACTORS

T. N. Washburn and J. L. Scott

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PERFORMANCE CAPABILITY OF ADVANCED FUELS FOR FAST BREEDER REACTORS

T. N. Washburn J. L. Scott

ABSTRACT

The boundary limits of fuel performance are shown on plots of specific power (W/g) against linear power (kW/ft). For (U,Pu)₂O₂ fuels, these boundaries form a triangle with borders of about 100 W/g minimum specific power, about 0.200 in. minimum fuel diameter, and a maximum linear power of about 12 kW/ft for the core average or about 19 kW/ft for the highest rated fuel pin. For (U,Pu)C and (U,Pu)N fuels, the minimum specific power and minimum fuel diameter are the same as for the oxides. However, the higher thermal conductivity of these advanced fuels permits linear powers to about 30 kW/ft core average and about 45 kW/ft for the highest rated pin, when a sodium bond is used between the fuel and cladding to prevent excessive fuel temperatures and to provide space to accommodate fuel swelling. There is substantial economic advantage in operating fuel at these highly rated conditions, but a large amount of development work and irradiation testing must be performed with both the carbides and nitrides to permit an absolute comparison of their worth relative to oxides.

INTRODUCTION

The goal of the Fast Breeder Reactor (FBR) Program is to develop a source of both economic electric energy and additional fuel (i.e., bred plutonium) for expanding the supply of energy. Achievement of this goal is enhanced if the FBR fuel is capable of achieving extended burnup while operating at high linear and specific powers. Increasing the burnup of the fuel reduces the requirements for reprocessing and refabrication, while increasing the linear heat rate reduces the length of fuel that must be fabricated and as well permits design of either smaller or shorter cores. Increasing the specific power reduces the inventory of fuel required to produce a given amount of energy and thereby reduces the time required to double the fuel inventory. The principal advanced ceramic fuels are the carbides and nitrides of uranium-plutonium which have a thermal conductivity about five times that of the oxide.¹⁻³ This high thermal conductivity permits operation of fuel pins at higher linear and specific powers and enables design flexibility for optimization of both the cost of energy and fissile doubling time.

Fuel performance is a relative factor, and to illustrate the potential advantage of carbides and nitrides, we have first summarized the limitations of the oxide fuel. The technology of the oxide fuel system is much more developed than that of either the carbide or nitride. Therefore, it is obvious that the oxide is the only feasible candidate fuel for use in the Fast Test Reactor (FTR), the demonstration plants, and probably the initial commercial LMFBR's. However, once the technical feasibility of LMFBR operation is demonstrated, the major criterion for utilization of these reactors is economics, which is strongly influenced by fuel performance.

PERFORMANCE LIMITATIONS OF OXIDE FUEL

The performance boundaries or limitations of the oxide fuel are illustrated in Fig. 1 in terms of the relationship between specific power, linear power, and fuel pin diameter. The specific power boundary is shown at 100 W/g,* since below this approximate level of specific power, doubling time becomes excessively long because of the large amount of fuel required in the fissile inventory. Due to its low thermal conductivity, the oxide fuel reaches its melting temperature at a linear power of about 19 kW/ft, the exact value depending upon the fuel density, stoichiometry, and surface temperature. This establishes a linear power boundary, with the assumption that operation with molten fuel is unacceptable. The cladding diameter boundary is set by the excessive fuel fabrication costs generally encountered in making pins with a very small diameter.⁴ We have selected 0.200-in. cladding inside diameter as the minimum size pin practical to fabricate. This boundary is also not an absolute value; and though each reactor designer may select a slightly different minimum size, 0.200 in. is a reasonable value, and the specific value selected does not change our basic illustration. The cladding diameter is expressed as the inside dimension since at a given fuel smear density, the relationship between linear and specific power can be plotted without specifying pellet dimensions or densities, fuel-cladding diametral gaps, or cladding wall thickness.

Thus, for our assumptions regarding limitations on the fuel pin diameter and fuel center-line temperature, a maximum linear power of

*Specific power in this paper is expressed as W/g of (U+Pu).

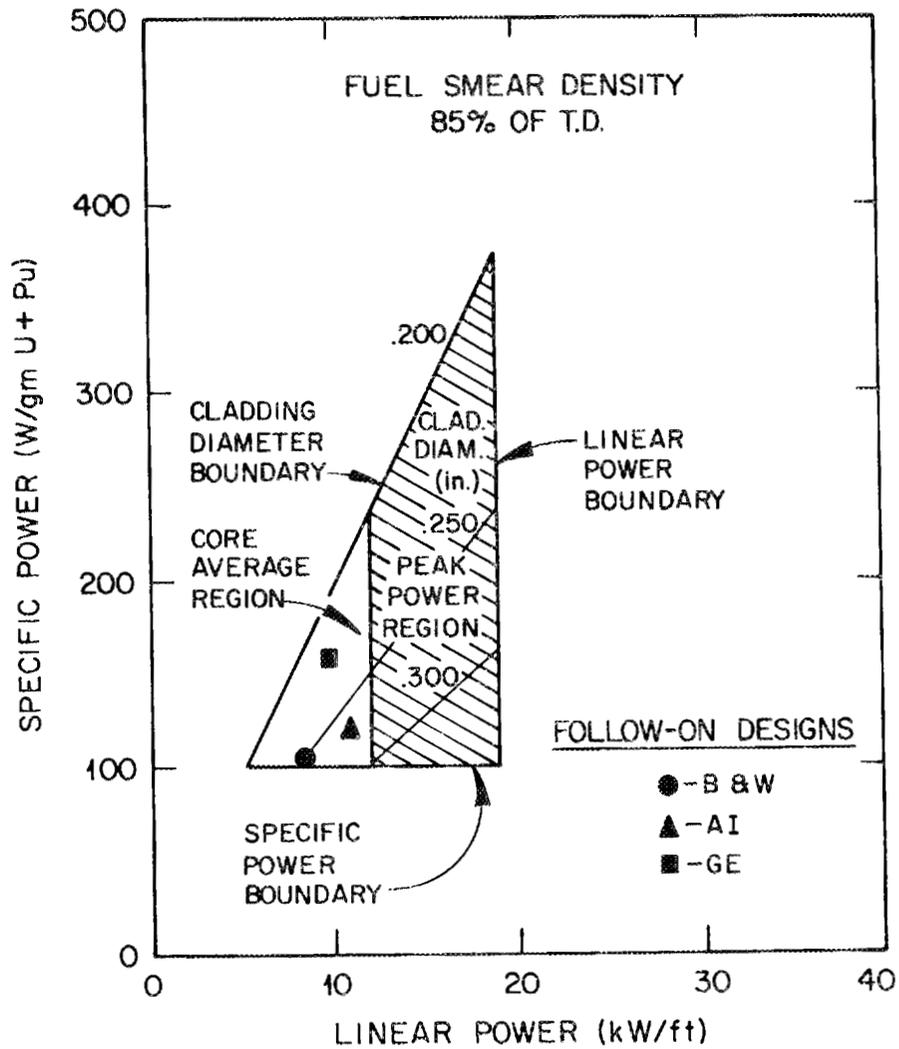


Fig. 1. Performance Boundaries of Stainless-Steel-Clad, Helium-Bonded $(U,Pu)O_2$ Fuel Pins in an LMFBR.

19 kW/ft would produce specific powers of 100 to about 375 W/g. However, this is for the maximum operating condition of any pin in the reactor core, and the average power conditions will be somewhat less. The ratio of peak to average power in a reactor core will be approximately 1.5. Thus, if the peak linear power rating is limited to about 19 kW/ft to prevent fuel melting, the core average will have a maximum of about 12 kW/ft. Thus, the oxide fuel core must be designed with a pin diameter between 0.200 and 0.300 in., with a maximum achievable average specific power of about 225 W/g.

With oxide fuel, the reactor core designer is left with little design flexibility. The average linear heat rate cannot be increased significantly above 12 kW/ft without fuel melting in the highest rated fuel pin. The average specific power can be increased only by reducing the fuel pin diameter; and, as the fuel pin diameter is decreased, the fuel fabrication costs increase substantially. The reduction in doubling time that can be achieved by increasing the specific power is counterbalanced by increased fuel fabrication costs and, thus, higher fuel cycle costs. The relatively small size of the core average region of the design boundary triangle in Fig. 1 leaves little opportunity to optimize the design for either economical power costs, short doubling time, or some compromise solution between these two.

We have plotted in Fig. 1 the location of the three oxide-fuel reactor designs from the LMFBR follow-on studies.⁵⁻⁷ The General Electric (GE) design had the smallest fuel pin diameter of 0.230-in.-ID, operated at an average linear power of 9.6 kW/ft, had the highest specific power of 157 W/g, and had the shortest doubling time of seven years.

The Babcock & Wilcox (B&W) design had a cladding inside diameter of 0.260 in., operated at an average linear power of 7.8 kW/ft and a specific power of 102 W/g, and had a doubling time of 10.4 years. Each of these two design studies assumed an average fuel burnup of 100,000 MWd/metric ton with vented fuel pins. The Atomics International (AI) design had a larger fuel pin diameter and operated at a higher linear power and an intermediate specific power. However, AI assumed a lower fuel burnup, 67,000 MWd/metric ton, which resulted in a doubling time of 13 years.

PERFORMANCE LIMITATIONS OF CARBIDES AND NITRIDES

In Fig. 2 we have plotted for the uranium-plutonium carbide fuel the same type of boundary conditions as previously discussed for the oxides. The plot for the nitride is essentially identical to that of the carbide. We have assumed the same minimum fuel cladding inside diameter of 0.200 in. and the same minimum specific power boundary limitation of 100 W/g. The linear power boundary has been extended to 45 kW/ft for the maximum rated fuel pin. This linear power boundary has not been well established for either the carbide or the nitride fuel and was selected because the corresponding fuel center-line temperature of the sodium-bonded carbide fuel would reach 1300 to 1400°C. Current data suggest that the fuel swelling becomes excessive at about this temperature.^{8,9} For the carbides and nitrides the cladding heat flux establishes a fourth boundary condition. In this case we have assumed 2×10^6 Btu hr⁻¹ ft⁻² as the maximum cladding heat flux. This limitation in a specific reactor design will be determined by the cladding

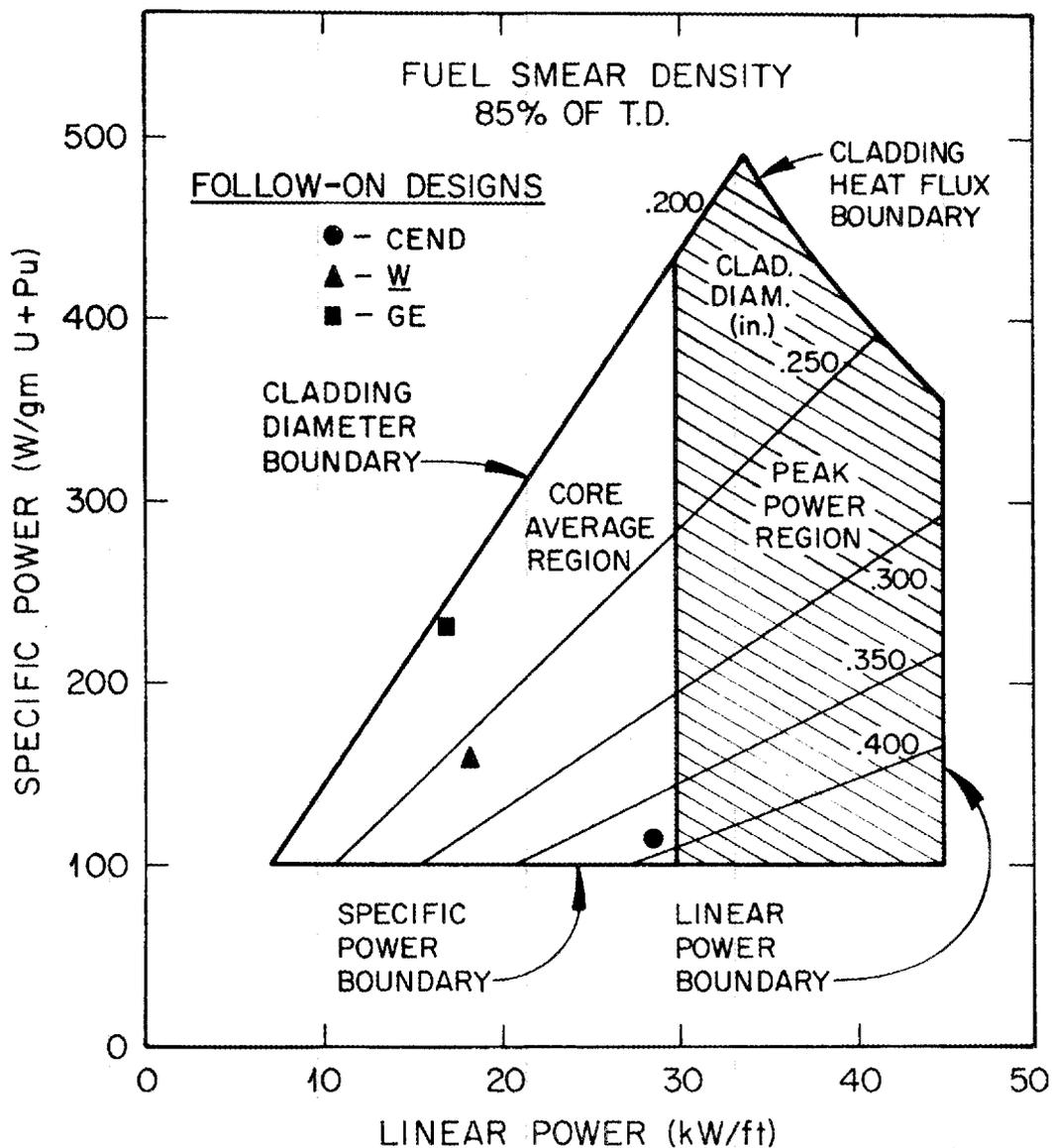


Fig. 2. Performance Boundaries of Stainless-Steel-Clad, Sodium-Bonded (U,Pu)C Fuel Pins in an LMFBR.

temperatures achieved, the thermal stresses in the cladding, and the sodium pumping requirements for removing heat at a high rate. These boundary conditions for linear power and cladding heat flux are peak pin operating conditions, and the reactor power gradients require significant reduction in the average core design parameters.

We have used the same ratio of peak to average power of 1.5 as used for the oxides, and this establishes the maximum average linear heat rate at 30 kW/ft. Therefore, for the carbides and the nitrides, the fuel cladding inside diameter could be varied between 0.200 and 0.400 in. and average specific powers of 100 to 425 W/g could be achieved. Thus, with the higher thermal conductivity materials, a much wider range of design parameters can be manipulated to achieve the desired compromise between short doubling time and economical electric power generation.

In Fig. 2 we have also plotted the sodium-bonded mixed carbide designs from the LMFBR Follow-On Studies.^{5,10,11} The GE core was designed with the smallest diameter pin (0.202 in. ID) and operated at 16 kW/ft average to achieve a specific power of 235 W/g. With an assumed burnup of 110,000 MWd/metric ton, a doubling time of 4.4 years was predicted. The Combustion Engineering (CEND) design, on the other hand, used the largest diameter pin (0.378 in. ID), operated at 28.5 kW/ft average, had a specific power of 118 W/g, and with an assumed burnup of 100,000 MWd/metric ton, achieved a doubling time of 8 years. The Westinghouse (W) design was intermediate to these two designs.

In Fig. 3 we have plotted the relative performance boundaries of the oxide and the carbide or nitride. Both these plots represent the core average design boundaries. While this graph is a dramatic comparison of the performance potential of the carbides and nitrides relative to the oxide, we would point out that the design limitations for the oxide are quite well established. On the other hand, insufficient work has been done on either the carbide or the nitride to firmly establish their design boundary limits. For example, the effect of fuel temperature on fuel swelling may be found to significantly increase or decrease the maximum permissible linear power of these advanced fuels from our assumed limits.

PRESENT STATUS OF CARBIDES AND NITRIDES

In spite of the obvious design potential of carbides and nitrides as discussed previously, there is not yet enough information on these fuels to allow an intelligent choice between these fuels and oxides. Important aspects of these fuels are compared with oxides in Table I. The need for a greatly increased level of effort on advanced fuels is indicated.

Most of the present techniques for fabricating both carbide and nitride fuels are prohibitively expensive, even if the economies of large-scale operations are considered. To form the stoichiometric compounds, expensive U-Pu alloy is reacted with carbon or nitrogen. The compounds are generally ground to form a sinterable powder, after which pellets are fabricated and sintered by conventional methods.^{12,13} Another major reason for the high fabrication costs of advanced fuels

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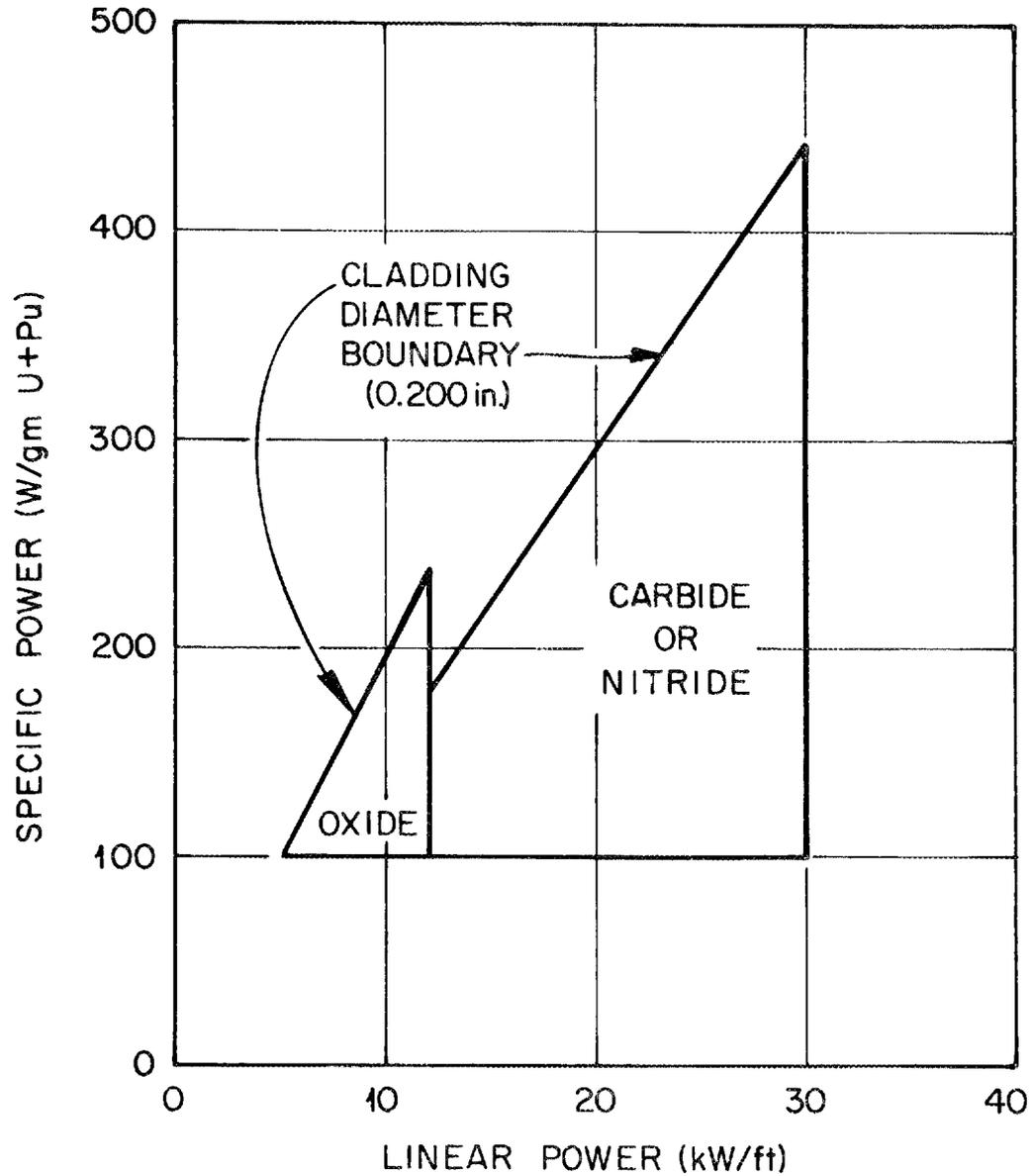


Fig. 3. Relative Performance Boundaries of Oxides and Carbides or Nitrides-Core Average.

Table I. Important Aspects of LMFBR Fuel

Characteristics	Relative Rating		
	Oxide	Carbide	Nitride
Fabrication Costs	Low	High	Medium
Control of Stoichiometry	Moderate	Difficult	Easy
Sodium Bonding	Not acceptable	Acceptable	Acceptable
Performance			
Fuel swelling and gas release	Acceptable	Acceptable ^a	Acceptable
Fuel-cladding compatibility	Reacts	Reacts	Minor reaction
Fuel-cladding mechanical interactions	Probable	Possible	Possible
Transient behavior	Acceptable	Acceptable	Unknown
Loss of sodium bond	Not applicable	Problem	Problem
Fission product redistribution	Occurs	Slight	Unknown
Burnup limitations	Acceptable	Unknown	Unknown

^a Provided fuel is stoichiometric or hyperstoichiometric.

is their chemical reactivity with air. Very high-quality glove boxes and inert gases are required to produce these materials in pure form. These features lead to more rigid specifications for fabrication lines and higher installation costs. However, once the line is built operating costs are probably not much greater for advanced fuels than for conventional oxide fuels. Fabrication methods involving uranium-plutonium alloy are not likely to be used for commercial production of advanced fuels. Extensive work has been reported on the carbothermic reduction of mixed oxides to produce the carbide^{14,15} and some work has been done on the nitride.¹⁶ These processes look attractive economically, but irradiation results are limited for this type of carbide¹⁷ and are nonexistent for the nitrides.

Control of stoichiometry is a serious problem during fabrication and for the performance of the carbide. If the carbon content of the carbide fuel is below 4.8 wt %, free metal will be present, resulting in excessive fuel swelling rates under irradiation. Conversely, if the carbon content is above 4.8 wt %, then higher carbides will be present and carbon may be transferred from the fuel to the cladding, degrading properties of the cladding. The presence of dicarbide appears to be more deleterious than the sesquicarbide, and this carbon transfer is enhanced when sodium bonding is used.¹⁸

The addition of buffering agents has been considered as a solution to the problem of performance of nonstoichiometric (U,Pu)C. These agents include iron or Cr_2C_6 for hypostoichiometric (U,Pu)C and chromium for hyperstoichiometric (U,Pu)C. The gains hoped for with these additions were not borne out in irradiation tests.¹⁹

It is relatively easy to produce single-phase (U,Pu)N. Since the nitrogen pressure in equilibrium with (U,Pu)N plus metal is about ten orders of magnitude lower than that in equilibrium with UN plus U_2N_3 , single-phase mononitride is stable over a wide range of pressures. Below 1500°C the mononitride will dissociate only at a nitrogen pressure less than 10^{-5} torr. Such pressures are easily avoided during fabrication and are not likely to occur during irradiation. Formation of the U_2N_3 phase can be avoided by always maintaining the nitrogen pressure below that defined by the mononitride-sesquinitride phase boundary.

Sodium bonding is needed to assure good heat transfer between carbide or nitride fuel and cladding and also accommodates fuel swelling. The sodium bond leads to inherently more expensive fabrication and the need for careful inspection of the bond quality. The performance of sodium-bonded pins in the event of loss of bond is unknown at present and can be answered only by irradiation tests. One possible problem with both sodium-bonded carbides and nitrides has been the breakup of fuel pellets and an apparent mechanical interaction producing ovality in the cladding.^{19,20}

CONCLUSIONS

In conclusion, advanced fuels for the LMFBR promise marked design advantages, which should result in both capital and fuel cycle cost reductions as well as reduced doubling time for the fissile material. An extensive development program, including irradiation testing of large numbers of pins, will be required before these advantages can be realized. The economic potential of the advanced fuels certainly

justifies these research and development efforts. The marked advantages of advanced fuels were illustrated in the recent 1000 MW(e) LMFBR follow-on studies. Of the three oxide-fueled designs the lowest doubling time was seven years, with a 0.38-mill/kWhr fuel cycle cost.⁵ The sodium-bonded carbide-fueled replacement core for this design⁵ reduced the doubling time to 4.4 years and the fuel cycle cost to 0.11 mill/kWhr. This fuel cycle cost reduction of 0.27 mill/kWhr is equivalent to a \$2 million annual saving for each 1000 MW(e) LMFBR plant fueled with an advanced fuel instead of oxide. Other studies^{21,22} have shown even larger fuel cycle cost advantages for carbide over oxide fuel. Another study²³ has indicated that the economic potential of the nitrides would be similar to the carbides.

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