MASTER

THE BREEDING PERFORMANCE OF CARBIDE AND NITRIDE FUELS IN 2000 MWe LMFBRs

PART IV: IMPACT OF A PRESSURE DROP CONSTRAINT ON BREEDING PERFORMANCE AND PIN DIAMETER OPTIMIZATION IN 5000 MWt LMFBRs USING SODIUM-BONDED CARBIDE FUELS

by

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July 1976

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ABSTRACT

Impact on pin diameter optimization and breeding performance from either a constant coolant velocity (25 ft/sec) constraint or a constant fuel bundle pressure drop (40 psi) constraint has been evaluated, and comparisons of these results are given. The 40 psi fuel bundle pressure drop was chosen not to imply a limit of pump technology, but because it corresponds to acceptable coolant velocities in the range of 25 ft/sec to 35 ft/sec for various pin diameters and linear heat ratings. The results for the constant coolant velocity constraint were obtained from a previous study.¹

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I. INTRODUCTION

Studies^{1,2} had been carried out for breeding performance evaluation and pin diameter optimization of a 5000 MW(th) sodium bonded carbide LMFBRs with a maximum coolant velocity of 25 ft/sec as one of many imposed constraints.³ The coolant velocity constraint is useful in limiting corrosion and pin vibration, and avoiding cavitation. However, fuel bundle pressure drop, thus pump power requirements will vary when pin size and linear heat rating are changed. To normalize pump power requirements, another meaningful approach is to use a constant fuel bundle pressure drop constraint. Since there is a direct correlation between coolant velocity and fuel bundle pressure for each design, these two constraints are not entirely independent of each other. For example, a given coolant velocity is a valid constraint only if it does not result in an excessive fuel bundle pressure drop, thus excessive pump power requirements. Conversely, a given fuel bundle pressure drop should not correspond to a coolant velocity which may cause cavitation, or excessive corrosion and pin vibration.

This study gives results of fuel pin, subassembly, and reactor core designs with consistent nuclear, thermal, and mechanical design assumptions.⁴ Breeding performance evaluations are obtained for various pin diameters, linear heat ratings, and residence times. A constant fuel bundle pressure drop of 40 psi is imposed. The corresponding coolant velocity is in the

range of 25 ft/sec to 35 ft/sec. This 40 psi fuel bundle pressure drop is chosen not to imply a limit in pump technology, but for the reason that it corresponds to a meaningful range of coolant velocities in terms of limiting corrosion and pin vibration and avoiding cavitation. A comparison with results for a 25 ft/sec coolant velocity constraint is given.

II. DESIGN ASSUMPTIONS

The basic nuclear, thermal and mechanical design assumptions are given in Table 1, 2, and 3. More detailed descriptions may be obtained in Ref. 4. In this study, a constant 40 psi fuel bundle pressure drop and residence times of 300, 600, and 900 full power days were used. The NAPIN code⁵ was used to carry out pin design. For a given pin diameter, clad thickness, and operating conditions such as temperature, coolant velocity, burnup, fast fluence and residence time, NAPIN employs the swelling characteristics of fuel and clad to compute gap size, which will close at the end of its residence time. Due to uncertainty in the swelling data, a conservative approach using 65% clad swelling and 135% fuel swelling was used. Since fluence and burnup from previous optimization studies⁶ were used as a first guess, an update will be made after the completion of breeding performance evaluations. The fuel subassembly design is carried out by NIFD.⁷ As NIFD computes pressure drop with coolant velocity as an input, some iterations were necessary to obtain the same pressure drop for various designs with different pin diameters and heat ratings.

Table 4 tabulates the diametric gap sizes, maximum fuel centerline temperature, and maximum clad mid-wall temperature as computed from NAPIN for three different residence times: 300, 600, and 900 full power days. A minimum diametric gap size of 10 mils was assumed for manufacturing allowance. The trend from Table 4 indicates that diametric gap size

increases as linear heat rating is increased, as residence time is increased, or as pin diameter is decreased. Also as expected, the maximum fuel centerline temperature and maximum clad mid-wall temperature are higher for a design with a smaller pin diameter, at a higher linear heat rating, or with a longer residence time. There is no data for the 0.30 in. diameter pins at 35 kW/ft rating at 900 fpd. The corresponding peak fast fluence for this design would have been as high as 5×10^{23} nvt, necessitating a diametric gap almost as large as the pin itself, and causing fuel centerline temperature to be higher than the melting point of the fuel.

Fig. 1 presents the fuel bundle pressure drop vs. coolant velocity for various pin diameters and linear heat ratings. At a constant 40 psi fuel bundle pressure drop, the corresponding coolant velocities are in the range of 25 ft/sec to 35 ft/sec.

III. BREEDING PERFORMANCE EVALUATIONS

A 5000 MWt sodium-bonded carbide reactor with a two-zone core was mocked up in 2-D R-Z geometry for breeding performance study. First, for a given pin diameter, maximum linear heat rating, and resident time, the optimal enrichment splits between the inner and outer core which optimize power peakings was determined iteratively according to the formalism developed by M. J. King.⁸ The code SYNURN⁹ in 2-D R-Z geometry was used to carry out burnup calculations. Power peakings at BOC and EOC, burnup, fast fluence, and breeding gains were determined. The compound system doubling time, CSDT, detailed in Ref. 4, Appendix A, was computed and used as a figure of merit for evaluating various designs.

1. Fast Fluence, Burnup, and Smeared Density

The fast fluence ($E > 0.1$ MeV) at end of life for various designs with 600 full power days residence time is shown in Fig. 2. It shows fast fluence

decreases as pin diameters are increased, or as linear heat ratings are decreased. The peak fast fluence at 600 fpd is in the range 1.3×10^{23} nvt to 3.4×10^{23} nvt for various pin diameters and linear heat ratings. Here, the issue of what the peak fast fluence limit should be is not directly addressed. The rationale of not setting a peak fast fluence limit at this stage is as follows. First, it will be shown later in this report that optimal pin diameters at various linear heat ratings have peak fast fluence near the acceptable range of 1.5×10^{23} nvt to 2.5×10^{23} nvt. Secondly, in order to optimize designs with respect to compound system doubling time, it is necessary to collect data for a wide range of pin diameters and linear heat ratings.

A similar plot for burnup is given in Fig. 3. Smaller pins at higher linear heat ratings have higher burnup. Here, for the same reasons given in the fast fluence study, no consideration is given to what the burnup limit is. It will be shown later that, for the optimal pin diameter with an optimal residence time, the peak burnup is about 96,000 MWD/T.

The smeared densities for various designs at different linear heat ratings, which depends only on the theoretical pellet density and diametric gap sizes, are shown in Fig. 4. The theoretical density assumed in this study is 95%. Larger pins with low linear heat ratings, thus smaller gap sizes, have higher smeared densities. Combining Figs. 3 and 4 gives a curve, correlating smeared density with burnup, in Fig. 5. The smeared density decreases monotonically as burnup is increased.

2. Updating Fast Fluences and Burnups as Input to NAPIN

As a first step in the basic fuel pin design, the NAPIN code was used to compute the diametric gaps, maximum fuel centerline temperature and clad mid-wall temperature, with the fast fluences and burnups as input. These fast fluence and burnup data are obtained from previous

designs⁶ as a first guess, and may not necessarily agree with the new predictions of SYNBURN. Therefore, it is desirable to investigate the effect of design iterations on these two important input parameters, namely the fast fluence and burnup, and how they affect breeding performance and pin diameter optimization. An iteration scheme employing successive updating of the fast fluence and burnup is shown in Fig. 6. First, the fast fluence and burnup data from previous design optimizations⁶ are inputted into the NAPIN code, which is used for basic fuel pin design. After assembly designs using the NIFD code, and core designs and breeding performance evaluations by the SYNBURN model, a fast fluence and burnup pair is obtained. This new pair of fast fluence and burnup is then fed back into the NAPIN code as input, starting the iteration. The 0.30 in. pin diameter at 30 kW/ft and 35 kW/ft was studied for 2 iterations: a first guess and a subsequent update. The results are tabulated in Table 5. The fast fluence to burnup ratios remain nearly unchanged for the first guess and for the update, indicating the first guess based on previous optimization studies are probably very close to the true value. Secondly, the compound system doubling time is rather insensitive to the update. Based on the observation that the uncertainty in the compound system doubling time calculations is about 0.5 to 1 year,⁴ it can be concluded that it is appropriate to use fast fluence and burnup data from the previous optimization studies⁶ for the basic fuel pin designs under a 40 psi fuel bundle pressure drop, though these data were developed for a 25 ft/sec coolant velocity constraint.

3. Compound System Doubling Times vs. Residence Times

Figs. 7, 8, and 9 show the compound system doubling time as a function of pin diameter and maximum linear heat rating, respectively at residence time of 300, 600, and 900 full power days. As a general trend, the CSDT improves when both pin diameter and maximum linear heat rating are increased. At 300 fpd residence time, the CSDT for the designs studied are in the

range of 8 to 15 years. The lowest CSDT is 8.6 years for 0.35 in. pin diameter at 35 kW/ft. However, such a short residence time may dictate a large fabrication cost penalty. Thus, an additional figure of merit, such as fuel cycle cost may be necessary. When the residence time is increased to 600 fpd, the lowest CSDT for the range of pin diameters and ratings considered is again 8.6 years, with the corresponding optimal pin diameter at 0.35 in. with a linear heat rating of 30 kW/ft. The second lowest CSDT is 8.7 years, corresponding to the 0.40 in. pin diameter with a rating of 35 kW/ft. Due to the uncertainty in the calculations, it is fair to assume both 0.35 in. pin diameter with 30 kW/ft rating and 0.40 in. pin diameter with 35 kW/ft have the lowest CSDT.

At 900 fpd residence time, the CSDT are less sensitive to changes in pin diameter and maximum linear heat rating, relative to the shorter residence time. It is also worthwhile to note that smaller pin designs are no longer feasible at 900 fpd because of extremely high fluence at the end of life. For example, at 900 fpd smaller pins (0.30 in. to 0.35 in. pin diameter) at various linear heat ratings have fast fluence in the range of 3×10^{22} nvt to 5×10^{23} nvt, which causes excessive swelling in the fuel and clad, and a higher-than-melting fuel centerline temperature (in the case of 5×10^{23} nvt).

Fig. 10 illustrates how the compound system doubling time changes as residence time is varied. Fig. 11 shows the optimal compound system doubling times with respect to residence time for various pin diameters and linear heat ratings. For larger pins at low linear heat ratings, e.g., 0.45 in. diameter pins at 25 kW/ft, the optimal residence times with respect to breeding performance are longer than 600 full power days. Also smaller pins at high linear heat ratings, e.g., 0.30 in. diameter pins with ratings from 25 kW/ft to 35 kW/ft, and 0.35 in. diameter pins at 35 kW/ft, have optimal residence time shorter than 600 full power days. However, for

pin diameters in the range of 0.35 in. to 0.40 in., with various linear heat ratings from 25 kW/ft to 35 kW/ft, 600 full power days is the optimal residence time.

In optimizing the residence time, the improvements in compound system doubling time are larger (9 years) for smaller pins at higher linear heat ratings (e.g., 0.30 in. pins at 35 kW/ft from 600 fpd to 300 fpd) than that (0.6 year) for larger pins at lower linear heat ratings (e.g., 0.45 in. pins at 25 kW/ft from 600 fpd to 900 fpd).

The CSDT as a function of fuel volume fraction at 300 and 600 fpd residence time are plotted in Figs. 12 and 13. Both figures show somewhat scattered data, and the optimal fuel volume fraction is in the range 0.33 to 0.35.

It is worthwhile to point out that the peak fast fluence and burnup for the optimal pin diameter is within the commonly acceptable range of values. From Fig. 2, for the optimal pin diameter of 0.35 in. at 30 kW/ft (compound system doubling time being 8.6 years), the peak fast fluence is 2.5×10^{23} nvt at 600 full power days. For the near-optimal pin diameter of 0.40 in. at 35 kW/ft (compound system doubling time being 8.7 years), the peak fast fluence is 1.5×10^{23} nvt. From Fig. 3, the burnup at 600 full power days is 96,000 MWD/T for the optimal pin diameter of 0.35 in. at 30 kW/ft rating. For the near-optimal pin diameter of 0.40 in. at 35 kW/ft rating, the burnup is 86,000 MWD/T.

IV. COMPARISONS WITH RESULTS FOR A 25 ft/sec COOLANT VELOCITY CONSTRAINT

In comparison to the results for a 25 ft/sec coolant velocity constraint,¹ reproduced in Figs. 14-18, the optimal pin diameters at various ratings under a constant 40 psi fuel bundle pressure drop constraint shift to smaller sizes. For linear heat ratings of 25 kW/ft to 35 kW/ft, the reductions in optimal pin diameters are in the range of 0.02 in. to 0.05 in. For example, the optimal pin diameter at 30 kW/ft with a 600 full power

days residence time is 0.40 in. under the 25 ft/sec velocity constraint, and shifts to 0.35 in. under the 40 psi fuel bundle pressure drop constraint. Furthermore, the optimal doubling times are shorter by 0.5 to 1 year for cores constrained by a 40 psi fuel bundle pressure drop relative to cores constrained by a 25 ft/sec coolant velocity. These results are consistent with the observations in a recent report on the effect of increase of coolant velocity on pin diameter optimization.¹⁰

In optimizing the fuel residence time, it was found again that 600 full power days is the optimal residence time for pin diameters in the range 0.35 in. to 0.40 in. at linear heat ratings 25 kW/ft to 35 kW/ft. The reductions in compound system doubling time are larger for smaller pins at higher linear heat ratings (e.g., 0.30 in. pins at 35 kW/ft) than that for larger pins at lower linear heat ratings (e.g., 0.45 in. pins at 25 kW/ft).

V. SUMMARY AND CONCLUSIONS

When constrained by a constant fuel bundle pressure drop of 40 psi, the optimal pin diameters shift to smaller sizes relative to those obtained under a constant coolant velocity constraint of 25 ft/sec. Furthermore, the compound system doubling times are 0.5 to 1 year shorter as compared to those with a 25 ft/sec velocity constraint. For example, the optimal pin diameter at 30 kW/ft is 0.40 in. for a 25 ft/sec coolant velocity constraint. It shifts to 0.35 in. for a 40 psi fuel bundle pressure drop constraint. The optimal residence times are again near 600 full power days for pin diameters varying from 0.30 in. to 0.40 in. at linear heat ratings of 25 kW/ft to 35 kW/ft. However, larger pins at lower ratings may have optimal residence times longer than 600 full power days. Conversely, smaller pins at higher ratings may have optimal residence time shorter than 600 full

power days. The improvement of compound system doubling time due to optimization of fuel residence time is larger for smaller pins at high linear heat ratings than for larger pins at low linear heat ratings.

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Table 1. Nuclear Design Assumptions

Total power, MW	5000
Total power peaking factor	1.65
Radial power peaking factor	1.375
Core height, ft.	3
Axial blanket length	
Upper axial blanket, in.	15
Lower axial blanket, in.	15
Axial reflector, in.	5
Rows of radial blankets	1
Blanket composition	LMFBR Demo
Control assembly composition	LMFBR Demo
Pin array	triangular
Number of pins/fuel assembly	169
Cycle length, fpd	300
Fuel residence time, fpd	300,600,900
Radial blanket residence time, fpd	60,1200,1800
Number of control rods	12-36
Volume ratio inner core to outer core zone	~ 60/40

Table 2. Thermal Design Assumptions

Inlet temperature, °F	750
Mixed mean outlet temperature, °F	1050
Subchannel pressure drop, psi	40
Max. sodium velocity, ft/sec	Computed
Ratings for sodium-bonded fuel, kW/ft	25, 30, 35*
Spacer concept	grids

*Maximum nuclear linear heat ratings.

Table 3. Mechanical Design Assumptions

Fuel pin diameter, in.	0.3, 0.35, 0.4, 0.45
Cladding thickness	
Sodium-bonded fuel, in.	0.015*
Bond thickness	
Sodium-bonded fuel, in.	calculated with a minimum of 0.010
Core fuel pellet density, % T.D.	95
Cladding material	SS316CW
Duct material	SS316CW
Duct thickness	calculated**
Interassembly gap	calculated***
Fuel pitch	triangular
Duct shape	hexagonal
Stress limit on duct, psi	15,800
Strain limit on cladding (thermal component), %	0.5
Plenum length	
Sodium-bonded fuel, in.	30
Plenum location	top

*This is an effective cladding thickness used for nuclear calculations and includes a 0.003 in. perforated shroud which surrounds the fuel pellets.

**Determined such that the duct wall stresses stay below the stress limit.

***Allowance was calculated for swelling, creep and handling.

Table 4a. Diametric Gap Max. Fuel Centerline Temperature,
and Max. Clad Mid-wall Temperature at 300 fpd

Max. Linear Rating Kw/ft	Pin Diameter, inch			
	0.30	0.35	0.40	0.45
25	10.0	10.0	10.0	10.0
	2369	2280	2220	2180
	1202	1191	1182	1175
30	10.0	10.0	10.0	10.0
	2737	2600	2503	2439
	1219	1205	1194	1186
35	14.2	12.4	11.1	10.0
	3218	2975	2818	2745
	1241	1219	1206	1197

Legend: xxx Diametric gap in mils

xxx Max. Fuel Centerline Temperature, °F

xxx Max. Clad Mid-wall Temperature, °F

Table 4b. 600 fPD Residence Time

Max. Linear Rating Kw/ft	Pin Diameter, inch			
	0.30	0.35	0.40	0.45
25	10.0	10.2	10.0	10.0
	2635	2460	2346	2268
	1203	1191	1182	1175
30	18.7	13.7	12.1	11.8
	3283	2916	2728	2609
	1219	1205	1195	1187
35	34.4	23.4	17.8	13.0
	4408	3568	3192	2941
	1239	1218	1206	1197

Table 4c. 900 fPD Residence Time

Max. Linear Rating Kw/ft	Pin Diameter, inch			
	0.30	0.35	0.40	0.45
25	15.3	14.3	12.9	11.5
	2985	2691	2498	2376
	1201	1190	1182	1175
30	35.6	21.6	17.2	15.6
	4231	3329	3007	2798
	1216	1204	1193	1185
35	--	46.7	28.7	21.0
	--	4479	3693	3308
	--	1217	1205	1196

Table 5. Fast Fluence and Burnup Update Case History

0.30" O.D. Pin, 30 Kw/ft 600 fPD					
	<u>Fast fluence, nvt</u>	<u>Burnup, MWD/T</u>	<u>Fluence/Burnup Ratio, $\frac{nvt}{MWD/T}$</u>	<u>Fuel Volume Fraction</u>	<u>CSDT, Yrs.</u>
Input (NAPIN)	28.0×10^{22}	112,000	25.0×10^{17}	--	--
Output (SYNBURN)	29.4×10^{22}	132,000	22.3×10^{17}	0.2587	11.74
Input Update (NAPIN)	29.4×10^{22}	132,000	22.3×10^{17}	--	--
New Output (SYNBURN)	32.0×10^{22}	134,000	23.8×10^{17}	0.2500	12.00

0.30" O.D. Pin, 35 Kw/ft 600 fPD					
	<u>Fast fluence, nvt</u>	<u>Burnup, MWD/T</u>	<u>Fluence/Burnup Ratio, $\frac{nvt}{MWD/T}$</u>	<u>Fuel Volume Fraction</u>	<u>CSDT, Yrs.</u>
Input (NAPIN)	30.0×10^{22}	136,000	22.0×10^{17}	--	--
Output (SYNBURN)	34.0×10^{22}	157,000	21.7×10^{17}	0.2197	19.78
Input Update (NAPIN)	34.0×10^{22}	157,000	21.7×10^{17}	--	--
New Output (SYNBURN)	36.5×10^{22}	167,000	21.8×10^{17}	0.2090	20.50

Fig. 1. Fuel bundle pressure drop vs. coolant velocity.

Fig. 2. Peak fast fluence vs. pin O.D. and linear heat rating (40 psi fuel bundle Δp and 600 fpd residence).

Fig. 3. Peak burnup vs. pin O.D. and linear heat rating (40 psi fuel bundle Δp and 600 fpd residence).

Fig. 4. Smeared fuel density, planar nominal (40 psi fuel bundle Δp and 600 fpd residence).

Fig. 5. Smeared density vs. burnup (40 psi fuel bundle Δp and 600 fpd residence).

Fig. 6. Iteration scheme for fast fluence and burnup updating.

Fig. 7. Compound system doubling time for a 5000 MWt sodium-bonded carbide LMFBR with a 40 psi fuel bundle pressure drop and 300 fpd residence time.

Fig. 8. Compound system doubling time for a 5000 MWt sodium-bonded carbide LMFBR with a 40 psi fuel bundle pressure drop and 600 fpd residence time.

Fig. 9. Compound system doubling time for a 5000 MWt sodium-bonded carbide LMFBR with a 40 psi fuel bundle pressure drop and 900 fpd residence time.

Fig. 10. Compound system doubling time vs. residence time:
40 psi fuel bundle pressure drop constraint.

Fig. 11. Compound system doubling time for a 5000 MWt sodium-bended carbide LMFBR with a 40 psi fuel bundle pressure drop and optimal residence time.

Fig. 12. Compound system doubling times vs. fuel volume fraction (40 psi fuel bundle Δp and 300 fpd residence time).

Fig. 13. Compound system doubling times vs. fuel volume fraction
(40 psi fuel bundle Δp and 600 fpd residence time).

Fig. 14. Compound system doubling time vs. pin O.D.
(25 ft/sec coolant velocity and 600 fpd residence).

Fig. 15. Compound system doubling time vs. linear heat rating (25 ft/sec coolant velocity and 600 hr residence).

Fig. 16. Compound system doubling time vs. residence time
(25 ft/sec coolant velocity and 25 kW/ft rating).

Fig. 17. Compound system doubling time vs. residence time (25 ft/sec coolant velocity and 30 kW/ft rating).

Fig. 18. Compound system doubling time vs. residence time (25 ft/sec coolant velocity and 35 kW/ft rating).