Breeding Performance of Carbide and Nitride Fuels in 5000 MWt LMFBRs

The breeding performance of carbide and nitride fuels in 5000 MWt LMFBRs has been analyzed. The nuclear, thermal and mechanical design assumptions are listed in Tables I, II and III. Both fuel types were analyzed with either sodium- or helium-bonding to the cladding. In case of nitride fuel, the effect of enriching nitrogen in N^{15} on the breeding performance was analyzed, too.

Some of the results of a recently completed study of the breeding performance of advanced fuels are summarized in Table IV and Figs. 1-8. Figs. 1 and 2 show the breeding ratio as a function of fuel pin diameter for carbide fuel, Figs. 4 and 5 show the same dependence for nitride fuel. Figs. 3 and 6 show the breeding ratios as a function of fuel pellet volume fraction. Fig. 7 shows the breeding ratio as a function of fuel residence time and Fig. 8 shows how the fuel volume fraction depends on the design residence time of the fuel assembly.

The breeding ratios BR were calculated according to

$$BR = \frac{\text{production of fissile material during an operating cycle}}{\text{destruction of fissile material during an operating cycle}}$$

In calculating the breeding ratios the destruction of ^{235}U in the depleted uranium was neglected, the decay of ^{241}Pu during one operating cycle was taken into account and found to be very significant.

The following trends can be observed:

1. As the pin diameter increases so does the breeding ratio.

2. The higher the linear heat rating the lower the breeding ratio for the same pin diameter. The reason for this decrease is the larger amount of sodium required to remove the heat.

3. By plotting the breeding ratio against the fuel pellet volume fractions, the fuel pins lose their identity with respect to the linear heat rating.

4. The maximum achievable breeding ratios for helium-bonded fuel are lower than for sodium-bonded fuel. Because helium-bonded fuel pins require thicker claddings than sodium-bonded fuel to accommodate fuel-cladding interaction, the parasitic absorption in helium-bonded fuel LMFBRs are higher than in sodium-bonded fuel LMFBRs. Typically, the volume fraction of structural material in an LMFBR with sodium-bonded fuel is of the order of 10-12% whereas the volume fraction of structural material in helium-bonded fuel LMFBRs is of the order of 20% and more.

5. The highest breeding ratios were obtained for sodium-bonded carbide fuel, next ranked helium-bonded carbide fuel, followed by sodium-bonded nitride fuel and helium-bonded nitride fuel.

6. The breeding ratios for cores using sodium-bonded nitride fuel fully enriched in N^{15} are nearly the same as for sodium-bonded carbide fuel.

7. While the breeding ratio increases steadily with increasing fuel volume fraction the lowest doubling times are obtained for fuel volume fractions in the range of 37-40%.

General comments about the results and expected modifications:

1. The design of the helium-bonded fuel pins was based on the fuel lifetime code UNCLE. Recent irradiation data on helium-bonded carbide fuel seem to indicate that pellet densities of less than 90% T.D. might be required to assure a residence time of 600 fpd. This finding would tend to decrease the breeding ratio for helium-bonded fuel somewhat.
2. No elaborate control analysis was performed in assessing the breeding potential of advanced fuels. In general, the analysis so far shows that cores with small fuel pins will lose reactivity over a burn cycle and cores with larger fuel pins will gain reactivity. Therefore, for a given pin size, a more extensive control analysis might lead to either a slight increase or decrease in fuel volume fraction because of a change in the number of control assemblies. This will affect the homogenized fuel volume fraction for the core and those for breeding.
3. The breeding performance of sodium-bonded fuel will improve slightly by using pellet densities of 97-98% T. D. which seem to be now achievable.
4. A further increase in breeding ratio arises as the blanket thickness is increased. No blanket optimization has been performed yet.

5. The current breeding assessment of the advanced fuels was based on CW316SS as a structural material. Because this is a high swelling alloy, large interassembly gaps had to be provided consistent with the "kiss-of-death" design criterion. In some instances these gaps were in excess of 0.600 inches and represented more than one-third of the total sodium volume fraction in the core. A substantial reduction of the sodium-volume fraction can be obtained by using the socalled "advanced alloys", which are essentially nickel-base alloys (like PE-16) and ferritic alloys which exhibit low swelling and high-temperature strength properties superior to that of CW316SS. Though the higher nickel content (and in some instances also molybdenum content) will tend to decrease the breeding ratio, the reduced duct wall and cladding thickness together with the reduction in the sodium volume fraction will lead to a net increase in breeding ratio.

6. In addition to core size and composition, blanket size and composition, the breeding ratio depends on the fuel residence time. As shown for the cores with sodium-bonded nitride fuel at 30 kW/ft, the breeding ratio decreases as the residence time increases. The obvious reason is the higher concentration of fission products, the reduction in the ^{238}U concentration and the required higher enrichment. But another reason for this decrease is the reduction in the fuel volume fraction as the residence time increases. For longer residence times, larger interassembly gaps are required because of the higher fluence and thus increased swelling of the structural material.

Table I. Nuclear Design Assumption

Total power, MWt	5000
Core height, ft	3
Axial blanket length, in.	
upper axial blanket	15
lower axial blanket	15
Axial reflector length, in.	5
Rows of radial blankets	1
Blanket composition	LMFBR Demo
Control assembly composition	LMFBR Demo
Number of pins/fuel assembly	169
Operating cycle length, fpd	300
Fuel residence time, fpd	600
Radial blanket residence time, fpd	1200
Number of control rods	12-36
Number of enrichment zones	2
^{235}U content in depleted uranium, %	0.2
Pu composition (feed), %	
^{239}Pu	67.84
^{240}Pu	19.44
^{241}Pu	10.26
^{242}Pu	2.46

Table II. Thermal Design Assumption

Inlet temperature, °F	750
Mixed mean outlet temperature, °F	1050
Max. sodium velocity, ft/sec	25
Maximum nuclear heat ratings, kW/ft	
sodium-bonded fuel	25, 30, 35
helium-bonded fuel	14.8, 18.5, 22.2

Table III. Mechanical Design Assumptions

Fuel pin diameter, in.	0.3, 0.35, 0.40, 0.45
Cladding thickness, in.	
helium-bonded fuel	calculated*
sodium-bonded fuel	0.015
Bond thickness, in.	calculated**
Core fuel pellet density, % T.D.	95
Cladding material	CW316SS
Duct material	CW316SS
Duct thickness	calculated****
Interassembly gap	calculated***
Fuel pitch	triangular
Duct shape	hexagonal
Stress limit on duct, psi	15,800
Plenum length, in.	
helium-bonded fuel	40
sodium-bonded fuel	30
Plenum location	bottom

*The cladding thickness was assumed to be proportional to the pin diameter with a reference pin of 0.31 in. and a cladding thickness of 0.020 in.

**The bond thickness was based on fuel lifetime calculation. In case of the sodium-bonded fuel, the gap was determined such that the fuel touches the cladding after 600 fpd. The gap for the helium-bonded fuel was sized such that the thermal component of the strain on the cladding did not exceed 0.5%. For both helium- and sodium-bonded fuel, the minimum gap size was 0.005 inches.

***The duct thickness was calculated based on the stress limit and the coolant pressure drop.

****The gap between assemblies was determined in such a way that two fuel assemblies bond each other not earlier than after 600 fpd of operation. In sizing the gap, irradiation induced swelling, duct rounding and a duct handling allowance were taken into account.

Table IV. Integrated Breeding Ratio for Two-Batch Equilibrium Cycle

Bond Material	Linear Heat Rating kW/ft	Pin O. D. inches	Breeding Ratio: Carbide	Breeding Ratio: Nitride	Breeding Ratio: Fully Enriched Nitride
He	14.8	0.30	1.37	1.32	
He	14.8	0.35	1.45	1.39	
He	14.8	0.40	1.49	1.42	
He	14.8	0.45	1.52	1.44	
He	18.5	0.30	1.30	1.26	
He	18.5	0.35	1.40	1.35	
He	18.5	0.40	1.46	1.39	
He	18.5	0.45	1.50	1.42	
He	22.2	0.40	1.43	1.37	
He	22.2	0.45	1.48	1.41	
Na	25	0.30	1.30	1.27	
Na	25	0.35	1.43	1.39	
Na	25	0.40	1.52	1.45	
Na	25	0.45	1.58	1.52	
Na	30	0.30	1.22	1.16	1.25
Na	30	0.35	1.39	1.33	1.41
Na	30	0.40	1.48	1.41	1.50
Na	30	0.45	1.55	1.47	1.57
Na	35	0.30	1.13	1.08	
Na	35	0.35	1.34	1.27	
Na	35	0.40	1.45	1.38	
Na	35	0.45	1.52	1.44	

Figure 1

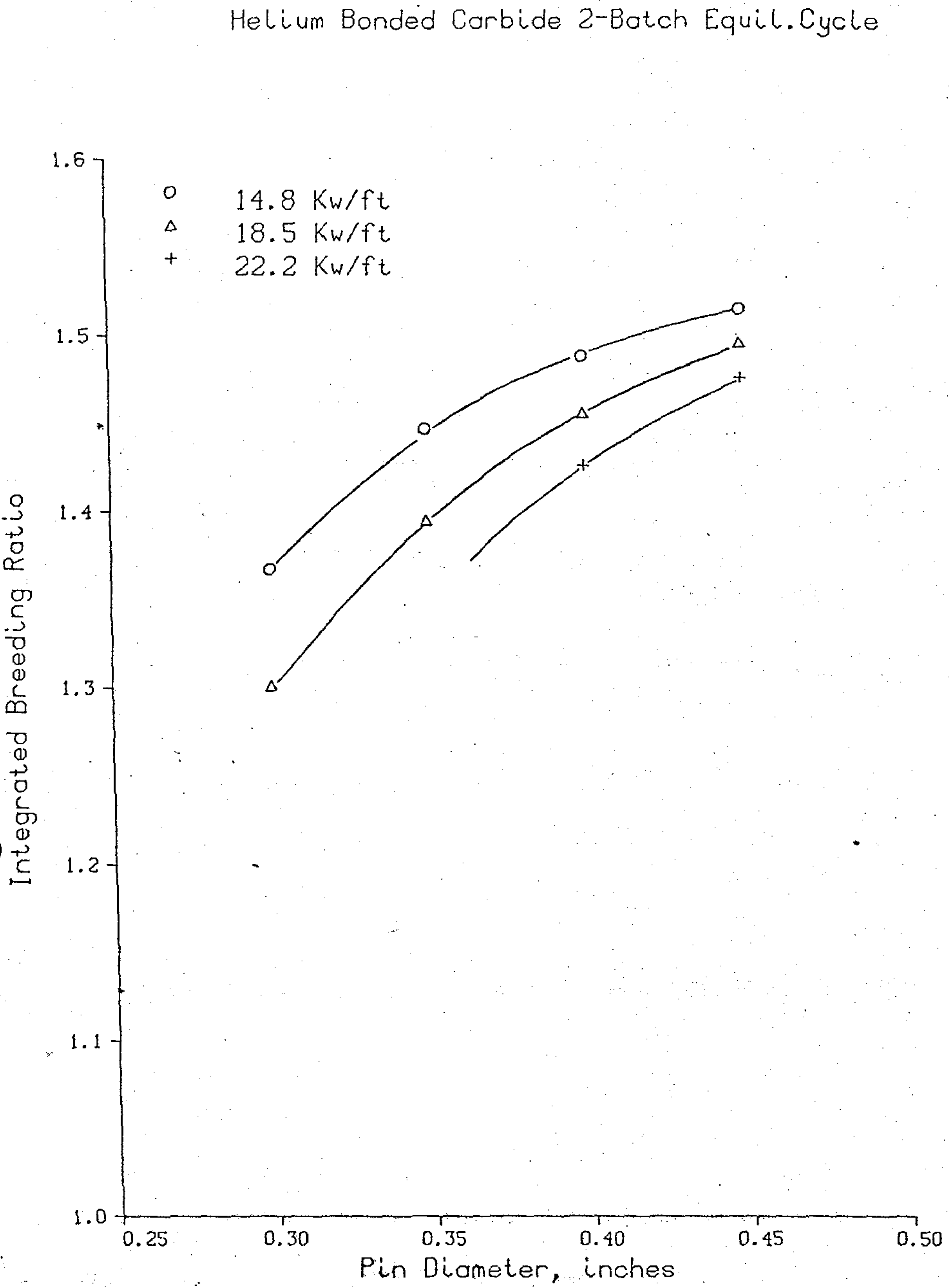

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Figure 2

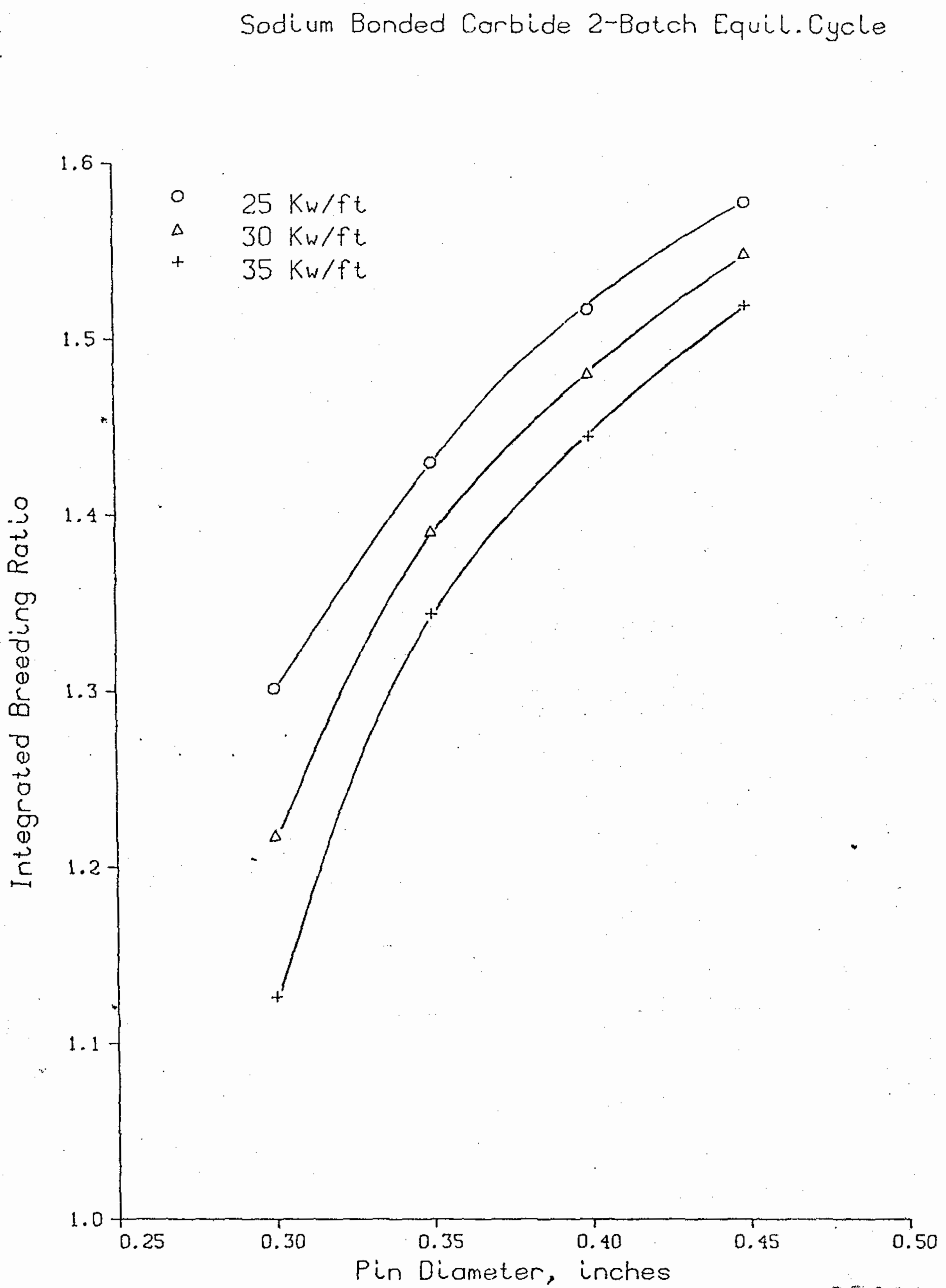

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Figure 3

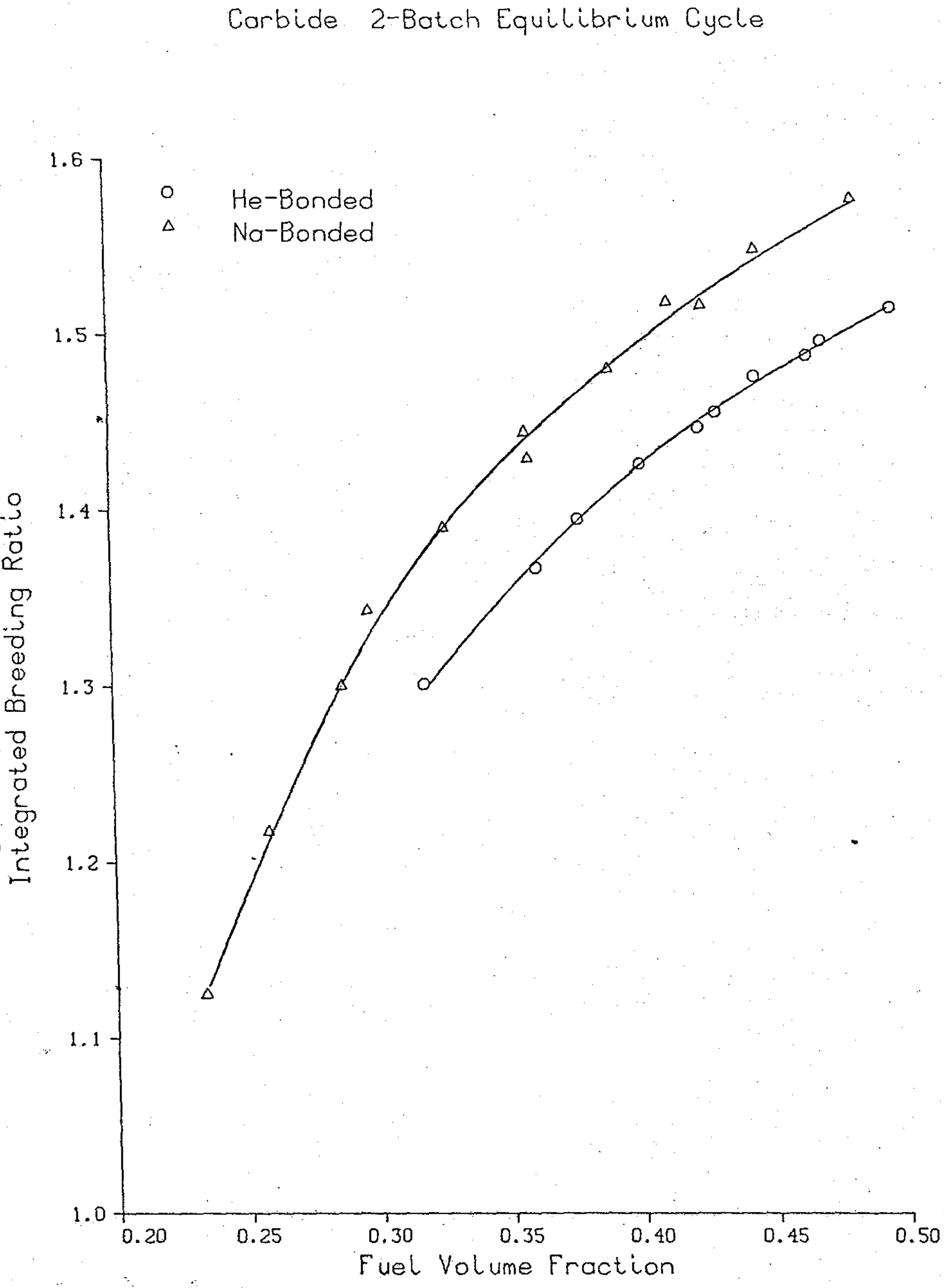

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Figure 4

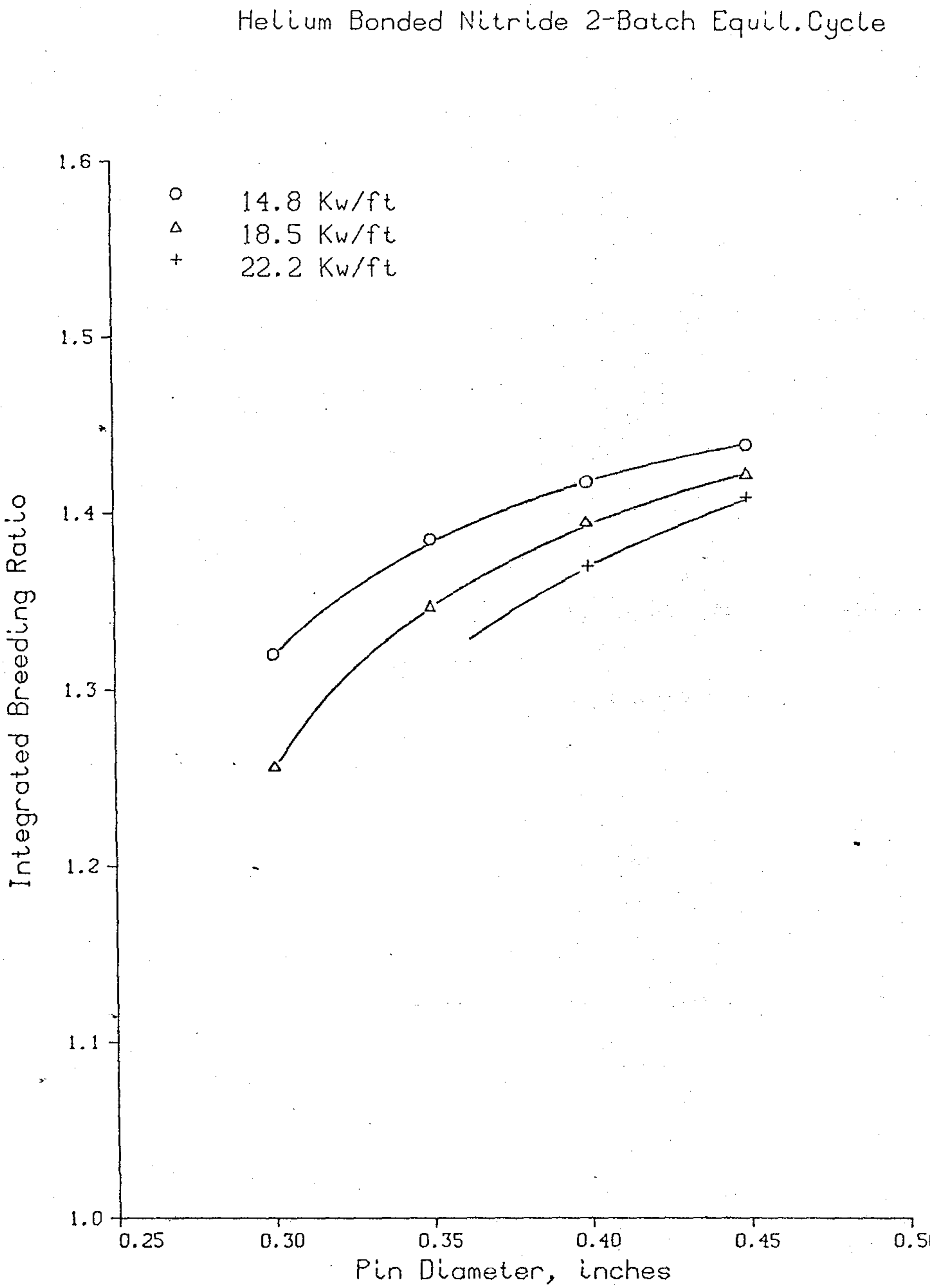

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Figure 5

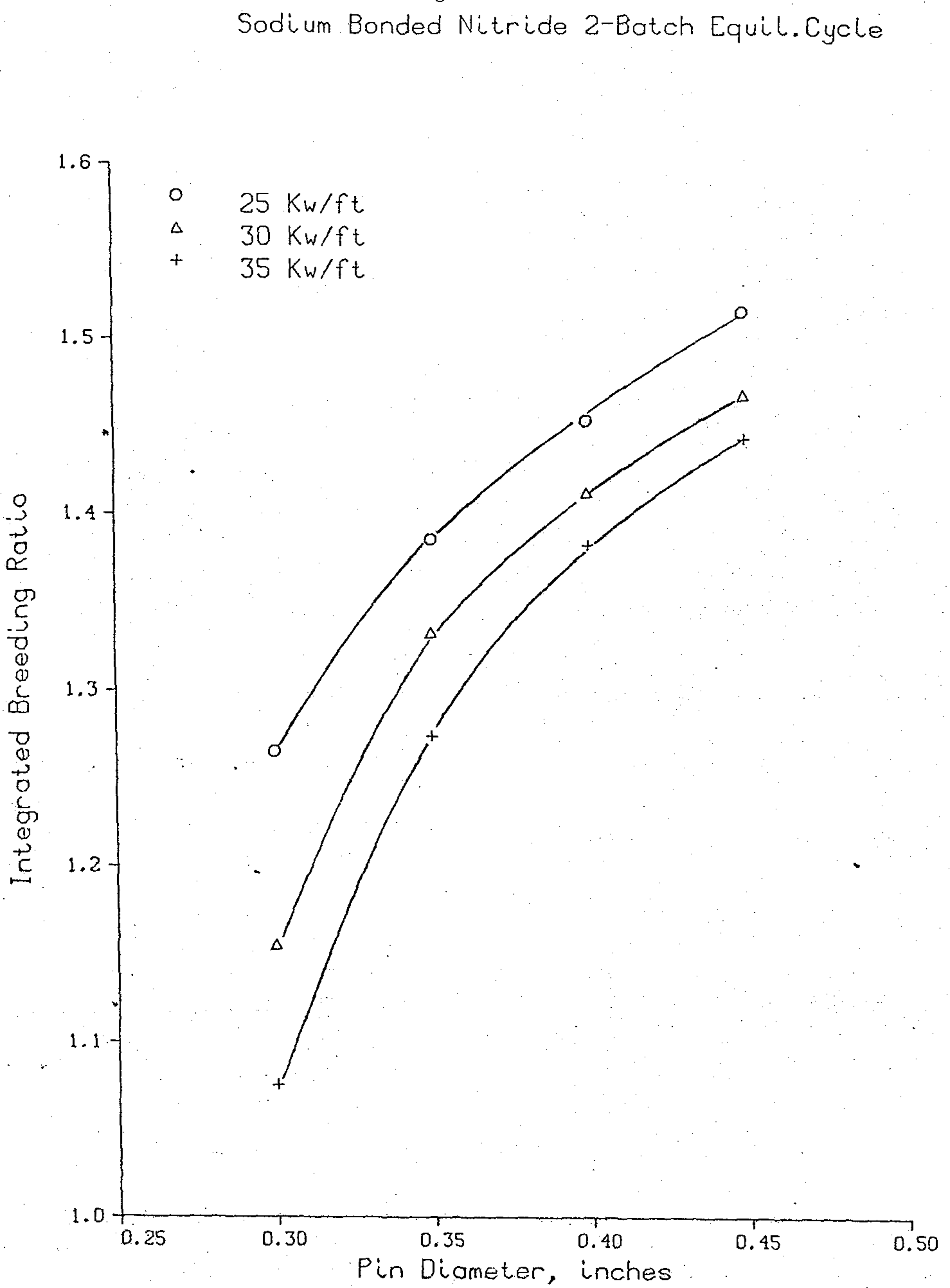

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Figure 6

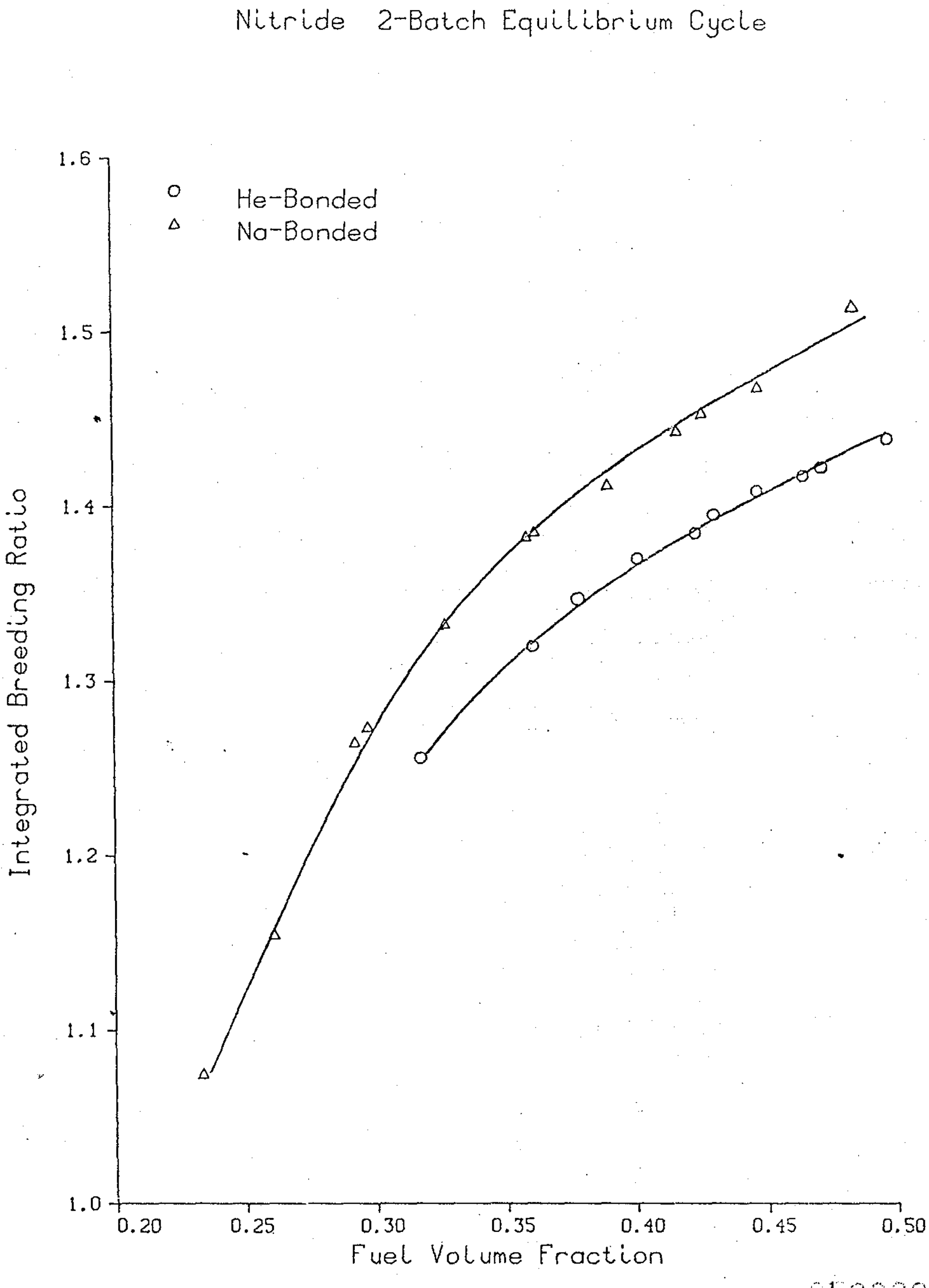

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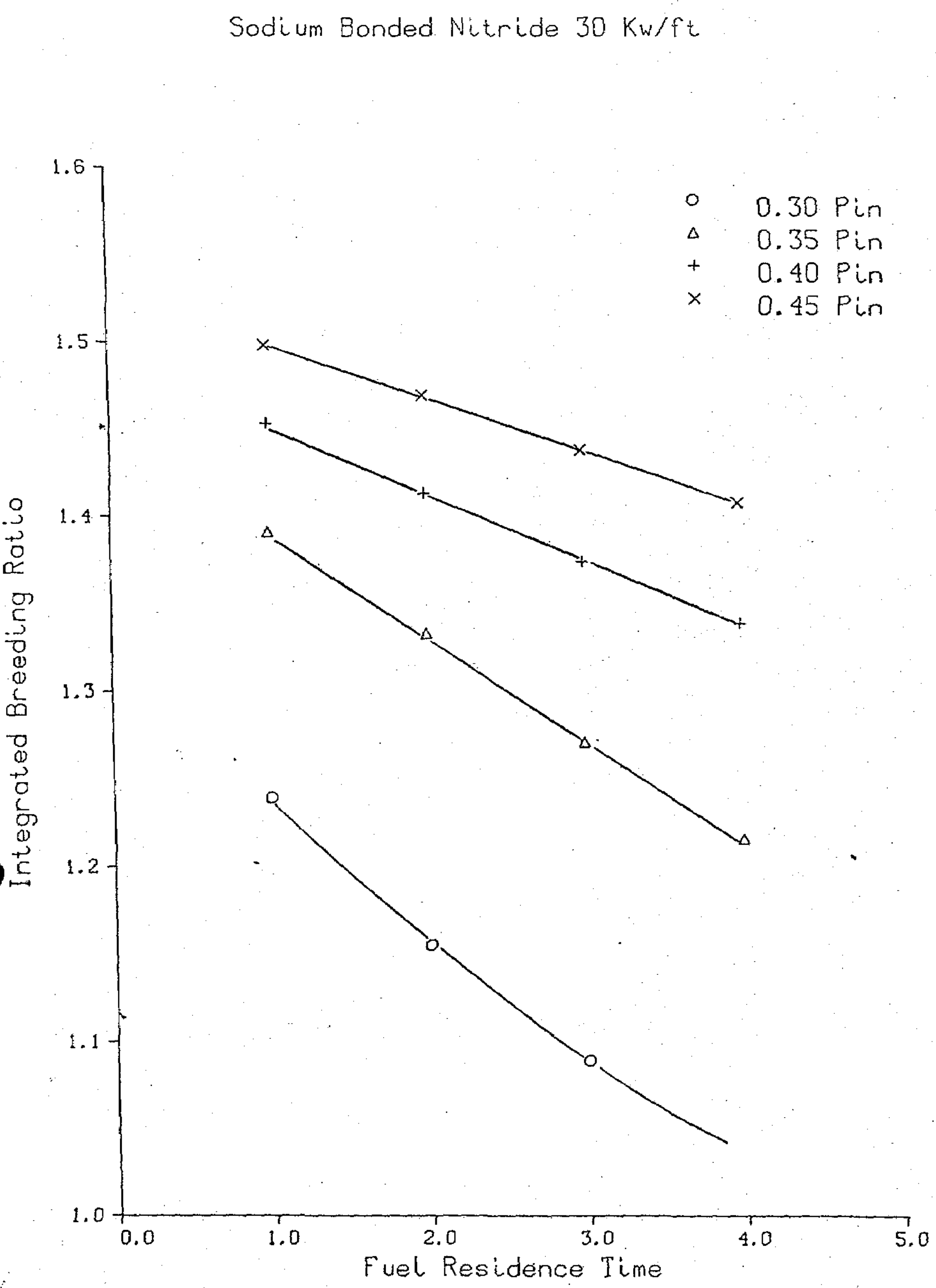
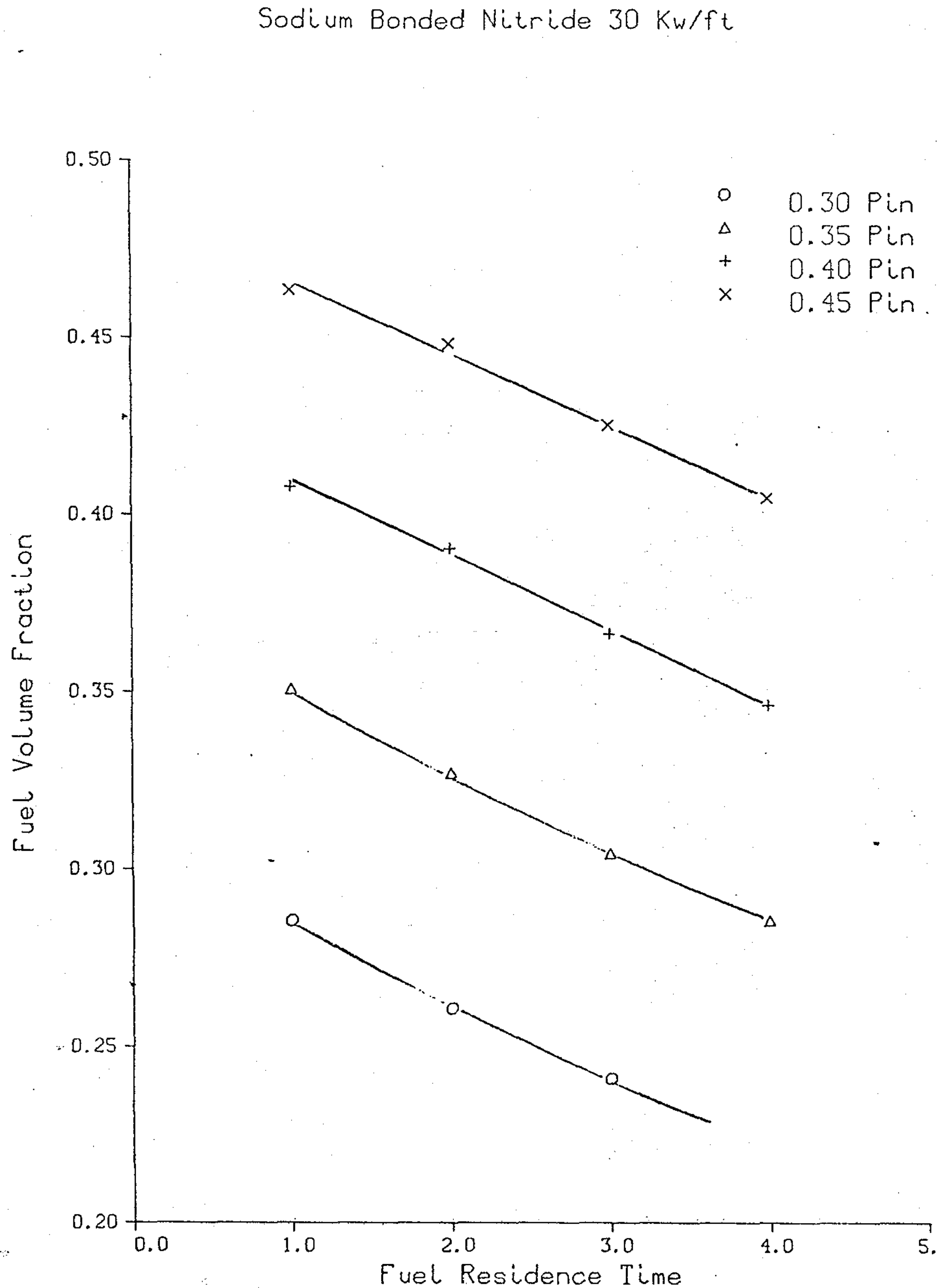
Figure 7



Sodium Bonded Nitride 30 Kw/ft
1.6
1.5
1.4
1.3
1.2
1.1
1.0
Integrated Breeding Ratio
0.30 Pin
0.35 Pin
0.40 Pin
0.45 Pin
0.0
1.0
2.0
3.0
4.0
5.0
Fuel Residence Time

Figure 8



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