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INFLUENCE OF CONTROL ROD WORTH INTERACTIONS ON LMFBR CONTROL SYSTEMS DESIGN*

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LMFBR control rod systems serve both a safety and an operational function, providing shutdown capability as well as the control of reactivity for startup, power transitions, and for burnup compensation. Two independent control systems are utilized in order to provide redundant and diverse safe shutdown capability. One system (the primary system) must have sufficient worth at any time in the reactor operating cycle, assuming failure of any single active component (i.e. a stuck rod), to shut the reactor down from any planned operating condition and to maintain subcriticality over the maximum range of system (coolant) temperatures expected. Allowance is made for the maximum reactivity fault associated with any anticipated occurrence. In addition, the primary control system is designed to compensate for the excess reactivity in the fuel enrichments for fuel burnup and operational requirements for each cycle as well as to compensate for criticality, reactivity feedback and refueling worth uncertainties. The other control system (the secondary system) serves only the redundant safety function. This system must have sufficient reactivity worth to shut the reactor down to zero power at the hot standby temperature, assuming a single stuck rod, with allowance for the maximum reactivity fault.

These design criteria are interpreted to define the reactivity worth requirements for the primary and secondary control systems in terms of the minimum control systems capability under faulted conditions which will assure that the reactor can be safely shut down. The faulted conditions are postulated to occur upon the simultaneous failure of one of the redundant safety control systems to scram, a stuck rod in the scramming

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system, and a reactivity insertion resulting from the uncontrolled withdrawal of the highest worth control rod inserted in the reactor. The resulting positive reactivity insertion from the rod runout envelopes other postulated operational faults and is imposed on the shutdown requirements of both the primary and secondary control systems.

In order to determine the minimum shutdown capability, an evaluation is made of the worst combination of control rod runout (reactivity fault) and stuck rod worth. In the primary control system, a group (bank) of rods are partly or fully inserted in the reactor to suppress the excess reactivity loaded for fuel burnup requirements. The postulated reactivity fault is based on one of these rods being withdrawn from its furthest insertion to the full out position. This same control rod is then assumed to be stuck in the fully withdrawn position. The requirement is then to demonstrate a safe shutdown reactivity balance with the remaining primary control rods inserted in the presence of this positive reactivity fault.

In a heterogeneous LMFBR, like the Clinch River Breeder Reactor Plant, flux redistribution and the resulting control rod worth interactions between banks of rods and between individual rods in a given bank, substantially increase the reactivity worth of the faulted rod-runout/stuck rod combination. Table 1 shows the worths of several asymmetric control rod patterns measured by ANL in ZPPR-7[1] using the subcritical source multiplication technique. ZPPR-7 (Figure 1) is a pre-Engineering Mockup Critical mockup of the CRBRP heterogeneous core containing a total of 15 control rods; 3 rods at 120° intervals in row 4 simulating the parked CRBRP primary control rods, 6 rods in row 7 at the corners of the hex (designated R7C) simulating the CRBRP operating primary control rod bank, and 6 rods in Row 7 on the hex flats (R7F) simulating the CRBRP withdrawn secondary control rod bank. Expected shutdown configurations involve the R4 plus R7C banks or the R7F bank.

Insertion of only a single R7C rod results in a reactivity worth insertion of only about 70% of the average-rod worth in the bank. Of particular importance in the development of the minimum shutdown margin is the worth

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(1) P. J. Collins, H. F. McFarlane and S. G. Carpenter, "Control Rod Interactions in ZPPR-7G, A Heterogeneous LMFBR Benchmark Assembly," <u>Trans. Am. Nucl. Soc.</u>, <u>28</u>, 782-3 (June 1978).

of a single rod withdrawn from a fully inserted R7C bank (rod runout). Table 1 shows that this value exceeds the worth of the average rod in the bank by a factor of 2.3. That is, the combination of rod runout and stuck rod removes effectively 2.3 rods from the available primary shutdown worth.

In the secondary control system, under the worst combination of circumstances with a rod runout in the primary control system leaving 5 of 6R7C rods partly inserted, and with the stuck secondary control rod occurring adjacent to the runout rod, the apparent worth of the stuck secondary rod in the local flux peak is three times the average worth in the bank. This is in contrast to a stuck secondary control rod on the opposite side of the core from the faulted primary rod, in which case the interactions approximately cancel.

Table 1 also indicates that the large, asymmetric control rod interactions (ratios of control rod worths) can be predicted with good accuracy using standard LMFBR design methods (9-group, 2 dimensional diffusion theory).

TABLE 1

REACTIVITY WORTHS OF ASYMMETRIC CONTROL ROD PATTERNS IN ZPPR-7G

CONTROL CONFIGURATION INSERTED	MEASURED WORTH ($)*	INTERACTION FACTOR+	
		MEASURED	CALCULATED
6R7C	17.08		
1R7C	2.03	0.71	0.73
5R7C	10.44 (6.64)	0.73 (2.33)	0.73 (2.34)
6R7F	11.57		
1R7F	1.53	0.79	0.82
6R7F + 6R7C	28.83		
5R7F + 5R7C (adjacent)	16.22 (12.61)	0.68 (2.62)	0.68 (2.58)
5R7F + 5R7C (opposite)	20.22 (8.61)	0.85 (1.79)	0.84 (1.82)
6R7F With 6R7C	11.75		
5R7F with 5R7C (adjacent)	5.78 (5.97)	0.59 (3.05)	0.61 (2.97)
5R7F with 5R7C (opposite)	9.78 (1.97)	1.00 (1.01)	1.01 (0.97)

*Worth with respect to all rods out, β eff = 0.00334. (ANL-RDP-66, Feb. 1978).

+Interaction factor defined as worth with respect to worth in equivalent symmetric bank. Values in ( ) represent rods withdrawn from bank.

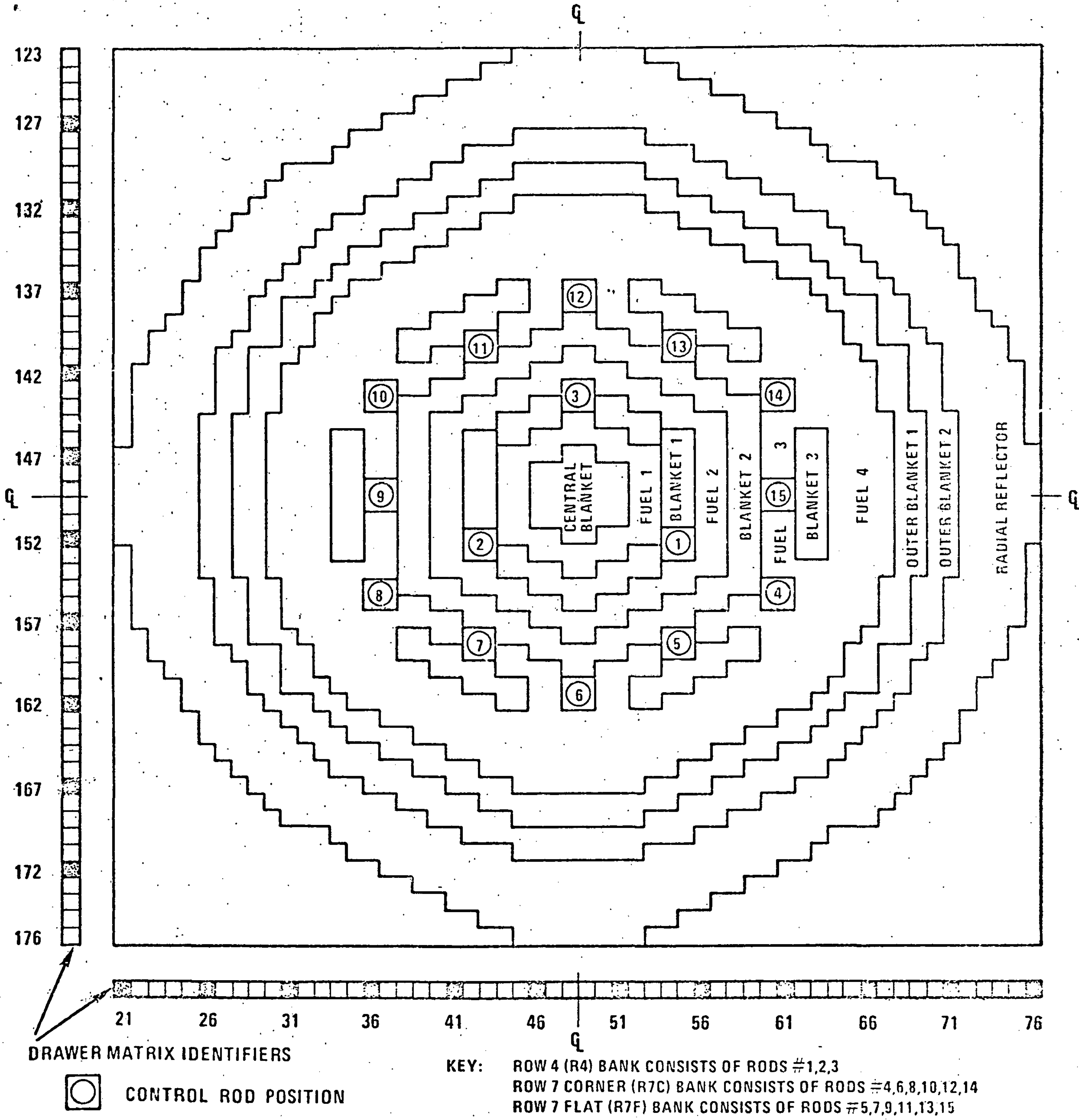

Figure 1. ZPPR Assembly 7, Phase G Configuration.