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REACTIVITY CAPACITY OF NPR CONTROL SYSTEMS

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D. E. Simpson

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REACTIVITY CAPACITY OF NPR CONTROL SYSTEMSINTRODUCTION

The reactivity control capacity of the N-reactor control systems has been calculated by methods which take into account the absorption of epithermal as well as thermal neutrons. Earlier calculations were made using a method which is satisfactory in control calculations for the existing Hanford reactors but which largely neglects the epithermal absorption. The new calculations were undertaken because of recent evidence that the epithermal absorption is more important to the NPR control strength and because of some concern regarding the margin between previously calculated control strength and anticipated control requirements.

The calculational methods used in the present study and the resulting calculated control capacities are reported in this document.

SUMMARY

The control capacities calculated in this study are substantially higher than those previously obtained. This result gives a more comfortable margin of safety between control strength and expected control requirements, but it does not indicate any incentive to reduce appreciably the capacity of the designed control systems.

The calculated NPR control strengths are tabulated in Table I; also included are the strength of a K-reactor ball 3X channel and an EGCR (enriched gas-cooled reactor) control rod which were used for comparison of calculational and experimental results. The NPR ball 3X values reported are for steel balls containing 1.5 percent boron by weight; the samarium-oxide poisoned ceramic balls expected to be used have about 92 percent of the reactivity strength of boron-steel balls.

TABLE I
CALCULATED REACTOR CONTROL CAPACITY

<u>Reactor</u>	<u>Operating Condition</u>	<u>Local Control Strength (mk)</u>		<u>Full Pile Capacity (mk)</u>	
		<u>HCR</u>	<u>3X*</u>	<u>HCR</u>	<u>3X*</u>
NPR	cold-green	94-120 88-112 (dry rods)	84-101	80-102	79-95
	cold-ripe	90-115	80-96	76-98	75-90
	hot-ripe	104-132	94-113	88-112	88-106
	accident**	---	76-88	---	71-83
		<u>Local Strength</u>			
		<u>Calculated</u>	<u>Measured</u>		
K 3X	cold-green	96	88 ± 9		
EGCR (rod)	cold-green	310	290 ± 30		

* 1.5 percent boron-steel balls.

** Calculated for the incredible situation of cold water in the process tubes of the hot reactor plus flooding of all channels with exactly the amount of water in exactly the right location to reach the maximum calculable lattice reactivity.

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DISCUSSION

Nearly all past calculations of Hanford reactor control strengths have employed two energy group neutron diffusion theory but have been limited to the assumption that all significant neutron absorption occurs in the thermal energy group. The only experimental data available for comparison with calculations are the results of the rather imprecise control strength measurements performed during initial reactor startup tests. While these comparisons are not entirely satisfactory, the calculated control strengths have been shown to be at least in the right neighborhood.

During preparation of the NPR design bases, the original calculations of NPR control system strengths were performed.(1, 2) At that time there were no data available on the relative magnitudes of the thermal and epithermal fluxes and it was assumed that the ratio would be about the same as for a K-reactor. As in calculations for the existing reactors, the absorption of epithermal neutrons was neglected except for an attempt to account for the moderation and subsequent absorption of epithermal neutrons in the water-cooled horizontal control rods. The results of these calculations were reported in reference 2.

More recently the relative thermal and epithermal fluxes have been calculated for NPR and for a K-reactor, showing the NPR epithermal flux to be relatively higher than at K.(3) Also recently an experiment not directly related to NPR was performed in the Hanford PCTR in which the local control strength of a boron-carbide poisoned control rod was measured in the graphite and enriched uranium lattice of the prototype enriched gas-cooled reactor (EGCR); the measured strength was about twice that calculated on the basis of thermal absorption only. According to available design data the EGCR neutron age and diffusion length are similar to those of NPR; hence the flux spectrum must be at least somewhat similar.

With these two indications that epithermal neutron absorption would contribute more significantly to the control strength of the NPR than of the older reactors, calculations were undertaken to re-evaluate the NPR control capacity. In considering the epithermal neutron absorption the problem of calculating an effective control element blackness to neutrons in the widespread slowing down energy range was immediately encountered. The multi-group weighting relationship chosen, which is justified primarily by its apparent success in calculating the strength of the EGCR control rod and a K-reactor ball 3X channel, is

$$\bar{\beta}_{c1} = \frac{\sum_{i=1}^{16} \beta_{ci} (2 - \beta_{ci}) \phi_i}{\sum_{i=1}^{16} (2 - \beta_{ci}) \phi_i}$$

where

$\bar{\beta}_{c1}$ = effective epithermal control channel blackness

β_{ci} = control channel blackness to neutrons in the i^{th} energy group

ϕ_i = relative flux in the i^{th} group in the absence of control

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The ϕ_1 were taken from the results of earlier calculations reported in reference 3. Note that the blacknesses here are evaluated at the control channel surface, not necessarily the control rod or poison material surface.

In setting up the proper boundary conditions on the neutron flux at the control channel surface, it is necessary to know the neutron mean free path in the surrounding medium. For reactors of the existing type at Hanford it is satisfactory to use the mean free path of neutrons in graphite; for a lattice like NPR's, however, it is not clear whether one should use the average lattice mean free path or the graphite mean free path, and in either case whether or not a streaming correction should be applied because of the void spaces in the lattice. In view of this uncertainty, calculations were made using the more conservative mean free path in graphite, both with and without a streaming correction. It is expected that the actual control strength will fall between the values calculated for the two cases.

The linear extrapolation distance of the flux at the surface of a control channel is⁽⁴⁾

$$d = \frac{4\lambda}{3\beta_c} + \lambda(d' - 4/3)$$

(See Appendix I for notation.) Subject to the boundary conditions that the slope of the flux be zero at the edge of the control region and that the linear extrapolation distance be as given above, the material buckling, μ^2 , of the region surrounding a control element is found from the equation:

$$\begin{vmatrix} X - d_1 X' & Y - d_1 Y' \\ X - d_2 X' & \frac{S_2}{S_1} (Y - d_2 Y') \end{vmatrix} = 0$$

where

$$X = - \frac{Y_1(\mu R)}{J_1(\mu R)} J_0(\mu r_1) + Y_0(\mu r_1)$$

$$Y = \frac{K_1(\nu R)}{I_1(\nu R)} I_0(\nu r_1) + K_0(\nu r_1)$$

$$\text{and } \phi_1 = A X + C Y$$

$$\phi_2 = S_1 A X + S_2 C Y$$

These equations are derived and discussed in Appendix I.

The material buckling of the region is the change in buckling equivalent to insertion of the control element. This is related to the equivalent change in k_{∞} by

$$\Delta k_{\infty} = \mu^2 M^2$$

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The local strengths of the NPR ball 3X channels (containing 1.5 percent boron-steel balls) and HCR channels were calculated for various operating conditions in the N-reactor loaded with nominal 22 lb/ft fuel elements of 0.947 percent initial enrichment.

The ratio between full pile capacity and local strength, taken from the earlier calculations of reference 2, is about 0.94 for the ball 3X system and 0.85 for the HCR system assuming installation of the spare process tubes at the top and bottom of the reactor. The calculated ranges of control strengths are shown in Table I in the Summary; also included for comparison are the results of K and EGCR calculations and measurements. Details of these calculations are given in Appendix II.

The control system strengths are reported as ranges of values rather than as single values because of the theoretical ambiguity concerning the neutron mean free path. The most important other uncertainty in the actual calculations is the epithermal control element blackness; the thermal blackness of the HCR's is also somewhat uncertain. In addition there is a possibility of error in the input data, that is in the values of τ and L^2 obtained from lattice calculations. For the ball 3X system at least, the mean free path uncertainty is probably predominant; therefore, while the lower value reported for the system strength is not exactly a lower bound, there is very little likelihood of a lower actual value. It is also unlikely that the control strength of the HCR system will be less than the lower value reported, but the degree of assurance is not as great.

It is not the purpose of this report to discuss in any detail the expected NPR control requirements. Recent studies in this area have been made, and are continuing, by R. O. Gumprecht, C. W. Allen, C. E. Bowers, and others. Many of the results of these studies have not been reported (however, see HW-64755)(5); by and large they indicate that, while control requirements under the same conditions are not greatly different from those calculated earlier by C. A. Mansius(1,6) the previously reported control capacities would provide an uncomfortably slim margin above the requirements and might perhaps place some undesirable restrictions on operating procedures. The substantially higher capacities of the present study appear to remedy this situation but there is no indication that the strength of the designed control system should be reduced appreciably.

D. E. Livingston

Reactor & Systems Design Analysis
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Attachments

APPENDIX I TWO-GROUP CONTROL THEORY

The following notation is used in this appendix and, except as separately defined, in the rest of this report:

ϕ	neutron flux
D	diffusion coefficient
Σ	cross section for removal from group
Σ_a	absorption cross section
Σ_{sd}	slowing down cross section
$\nu \Sigma_f$	fission cross section times neutrons produced per fission
τ	neutron age
L^2	neutron diffusion length squared
$M^2 = L^2 + \tau$	
k	lattice multiplication factor
d	linear extrapolation distance
λ	neutron mean free path
$\bar{\beta}_c$	mean control channel blackness
β_c	control channel blackness

$$\beta_c = \frac{r_o \beta}{r_1}$$

where β = control rod or ball column blackness

r_o = radius of rod or column

r_1 = radius of channel

R radius of control cell

Subscripts

- 1 epithermal neutron group
- 2 thermal neutron group
- 1th group of the 16 groups used in multi-group calculations of epithermal blackness

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The two energy group neutron diffusion equations may be written

$$D_1 \nabla^2 \phi_1 - \Sigma_1 \phi_1 + \frac{k}{p} \Sigma_2 \phi_2 = 0$$

$$D_2 \nabla^2 \phi_2 - \Sigma_2 \phi_2 + p \Sigma_1 \phi_1 = 0$$

These are the equations given by Glasstone and Edlund⁽⁷⁾, chapter VIII, except for the added parameter, p. Following Glasstone and Edlund we find that

$$\phi_1 = AX + CY$$

$$\phi_2 = S_1 AX + S_2 CY$$

where $\nabla^2 X + \mu^2 X = 0$

$$\nabla^2 Y - \nu^2 Y = 0$$

$$\text{and } \mu^2 = 1/2 \left[- \left(\frac{1}{\tau} + \frac{1}{L^2} \right) + \sqrt{\left(\frac{1}{\tau} + \frac{1}{L^2} \right)^2 + \frac{4(k-1)}{\tau L^2}} \right]$$

$$-\nu^2 = 1/2 \left[- \frac{1}{\tau} + \frac{1}{L^2} - \sqrt{\left(\frac{1}{\tau} + \frac{1}{L^2} \right)^2 + \frac{4(k-1)}{\tau L^2}} \right]$$

When k is close to unity,

$$\mu^2 \approx \frac{k-1}{L^2 + \tau}$$

$$-\nu^2 \approx - \left(\frac{1}{\tau} + \frac{1}{L^2} \right)$$

$$\text{and } \frac{S_2}{S_1} \approx - \frac{\tau}{L^2}$$

Now the boundary conditions for the fluxes at the edge of the control cell (radius $r = R$) are that both the thermal and epithermal currents are zero. This may be satisfied by requiring the derivatives of X and Y to vanish at that radius. Now solving for X and Y and applying this condition, we have

$$X = - \frac{Y_1(\mu R)}{J_1(\mu R)} J_0(\mu r) + Y_0(\mu r),$$

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$$Y = \frac{K_1(\nu R)}{I_1(\nu R)} I_0(\nu r) + K_0(\nu r);$$

for the cases of interest the first term of Y is nearly zero.

The boundary conditions at the surface of the control channel are

$$\phi_1(r_1) = d_1 \left. \frac{d\phi_1}{dr} \right|_{r_1}$$

$$\phi_2(r_1) = d_2 \left. \frac{d\phi_2}{dr} \right|_{r_1}$$

where the linear extrapolation distance is⁽⁴⁾

$$d = \frac{4\lambda}{3\beta_c} + \lambda(d' - 4/3).$$

Applying these conditions we have

$$A(X - d_1 X') + C(Y - d_1 Y') = 0$$

$$A(X - d_2 X') + C \frac{s_2}{s_1} (Y - d_2 Y') = 0$$

The determinant of the coefficients of A and C must vanish for a non-trivial solution; hence

$$\begin{vmatrix} X - d_1 X' & Y - d_1 Y' \\ X - d_2 X' & \frac{s_2}{s_1} (Y - d_2 Y') \end{vmatrix} = 0$$

This may be solved by trial and error for the buckling, μ^2 , from which the change in control cell k_{∞} equivalent to insertion of the control element is found:

$$\Delta k_{\infty} = \mu^2 M^2$$

A more accurate expression of the two-group diffusion equations than that used above is

$$D_1 \nabla^2 \phi_1 - (\Sigma_{a1} + \Sigma_{sd1}) + \frac{1}{k} (\nu_1 \Sigma_{f1} \phi_1 + \nu_2 \Sigma_{f2} \phi_2) = 0$$

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$$D_2 \nabla^2 \phi_2 - \Sigma_{a_2} \phi_2 + \Sigma_{sd_1} \phi_1 = 0$$

in which k is an eigenvalue required for a steady state solution and in the case under consideration is equivalent to the k_{∞} of the control cell. From these equations the buckling is expressed by

$$B^4 + B^2 \left\{ \frac{\Sigma_{a_2}}{D_2} + \frac{\Sigma_{a_1} + \Sigma_{sd_1} - \frac{1}{k} \nu_1 \Sigma_{f_1}}{D_1} \right\} + \frac{\Sigma_{a_2} (\Sigma_{a_1} + \Sigma_{sd_1} - \frac{1}{k} \nu_1 \Sigma_{f_1}) - \frac{1}{k} \nu_2 \Sigma_{f_2} \Sigma_{sd_1}}{D_1 D_2} = 0$$

and μ^2 and $-\nu^2$ are the two values of B^2 .

One NPR control calculation was made using the values of μ^2 and $-\nu^2$ obtained this way and using the corresponding value of S_2/S_1 . The values of the constants were taken from the three-group calculations of reference 8. The control strength agreed with that calculated by the previously outlined procedure within three percent so the simpler method was employed in all other calculations.

As noted before, the calculation of the linear extrapolation distance at the surface of the control channel involves the control channel blackness and the neutron mean free path in the surrounding medium. In the thermal energy range the blackness corresponding to the average thermal energy cross sections is satisfactory; in the epithermal range, however, it is necessary to average the blackness over the entire range.

It is immediately apparent that the blackness over an energy range in which β may go from near unity to near zero cannot be determined simply by spectrally averaging the control element cross sections over this range and finding the corresponding blackness. If, for example, the absorption cross section were extremely high over a narrow energy range, the blackness so obtained would be close to one even if the absorption probability over most of the energy range were small. It does seem, however, that if the blackness itself is known as a function of energy that this should be weighted by the incident neutron spectrum to obtain the proper average.

If this is true, there still remains the problem of determining the incident neutron spectrum. This is not the same as the equilibrium flux spectrum in the absence of the control. The absorption of neutrons of a particular energy in the control element reduces the flux of neutrons of that energy near the control rod and to a somewhat lesser extent reduces the incident current at that energy. No theoretical expression for this effect has been found but the expression $J_{inc}(2 - \beta_c)\phi$ does have the property of indicating a reduced current where the blackness is large. Empirically, this expression used as a weighting function for control element blackness seems to give satisfactory results for the epithermal neutron absorption in a K-reactor ball 3X channel and in the EGCR control rod. Primarily on this basis, the weighting equation used to estimate epithermal blackness of NPR control elements was

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$$\bar{\beta}_{cl} = \frac{\sum_{i=1}^{16} \beta_{c_i} (2 - \beta_{c_i}) \phi_i}{\sum_{i=1}^{16} (2 - \beta_{c_i}) \phi_i}$$

The mean free path of neutrons in graphite-moderated reactors of the existing Hanford type is, for most practical purposes, the mean free path in graphite. For NPR, however, the lattice contains an unusually large quantity of water and of fuel as well as a large proportion of void space. For such a lattice, it is not clear whether the appropriate mean free path for control calculations should be the average value for the lattice or the value for the graphite, and in either case, whether or not it should include a streaming correction because of the void spaces. Intuitively it seems that since the control elements are immediately surrounded by graphite that the use of the average lattice mean free path could be perhaps unjustified. It turns out furthermore that the lattice mean free path, if taken to be three times the diffusion coefficient, which includes a streaming correction, is about midway between the graphite mean free path determined with and without the streaming correction. Based on these observations it is expected that the actual control strength will lie between the values calculated using the graphite mean free path both with and without a streaming correction.

APPENDIX II
DETAILS OF THE CONTROL CALCULATIONS

In order to find an average epithermal blackness it was first necessary to evaluate the blackness of the control elements to neutrons in each of the 16 energy groups used in the calculations of reference 3. For the ball 3X channel this was relatively straightforward and consisted of finding in APEX-515, the multi-group cross sections for the control materials and from these determining the blackness. The blackness was evaluated from the tabulated values of collision probabilities in ANL-5800⁽¹⁰⁾, (Section 3.7.1) or from blackness curves calculated by the method of successive generation.⁽¹¹⁾

For the HCR the situation was rather more complex since it was necessary to consider the reflecting action of the outer water annulus, the moderating effect of the inner water channel, and the absorption in the hollow cylinder of boron-carbide. Consideration of all of these leads to the expression

$$\beta_c = \frac{r_{w1}}{r_1} (1 - R) \frac{r_p}{r_{A1}} \left[\beta_p + (1 - \beta_p) \beta_w \frac{r_{w2}}{r_p} \right]$$

where

β_c = rod channel over-all blackness

β_p = blackness of the hollow cylinder of B₄C

β_w = effective blackness of inner water channel; i.e., the probability that a neutron entering this channel would be slowed down enough to be captured on the way out

R = reflection probability of outer water annulus

r_1 = radius of control channel

r_{w1} = outer radius of outer water annulus

r_p = outer radius of B₄C annulus

r_{A1} = inner radius of outer water annulus

r_{w2} = radius of inner water channel

The blackness β_p was determined from cross section data of APEX-515⁽⁹⁾ plus the techniques described in ANL-5800⁽¹⁰⁾ (Section 5.2) and KAPL-1262.⁽¹²⁾ The inner water blackness was estimated at a constant 20 percent. The water reflection probability was calculated by the thin region theory of Wachspress⁽¹³⁾ using the transport cross section of water as Σ_s .

The various control rod component radii are the same as reported in reference 2; however, due to a change in the rod channel design, the channel radius, r_1 ,

was taken as 6.5 cm. In this range the rod strength is insensitive to changes in this radius anyway.

Pertinent multi-group blackness data are tabulated below:

NPR CONTROL ELEMENT MULTI-GROUP BLACKNESS

<u>Group</u>	<u>Lethargy</u>	<u>Ball 3X</u>	<u>HCR</u>			<u>ϕ</u>
		<u>β_c</u>	<u>(1-R)</u>	<u>β_P</u>	<u>β_c</u>	
1 - 9	< 7.0	0	.91	0	.08	.474
10	8.0	0	.91	.15	.11	.115
11	10.0	.05	.91	.50	.23	.111
12	12.0	.25	.91	.83	.35	.107
13	14.0	.60	.91	.93	.38	.072
14	15.5	.80	.90	.97	.39	.049
15	16.5	.92	.89	1.0	.40	.038
16	17.5	.96	.87	1.0	.39	.035

$\bar{\beta}_c$ (epithermal)

Ball 3X 0.13

HCR 0.19

The thermal group blacknesses were taken as 0.97 for the ball 3X channel and $(r_{w2}/r_1)(1 - R) = 0.36$ for the HCR channel. It may be noted that the maximum HCR blackness occurs at a lethargy of 16.5 or an energy of about 0.7 ev; the reason for this is the large decrease in the scattering cross section of water for neutrons above thermal energies.

Following the same procedure the blacknesses of the K-reactor ball 3X channel and the EGCR channel were calculated to be:

$\bar{\beta}_c$

<u>Control</u>	<u>Thermal</u>	<u>Epithermal</u>
K 3X	1.10*	0.17
EGCR	0.81	0.22

* The thermal blackness here is greater than 1.0 because of the scheme used to convert the square channel to an equivalent circle. It is assumed that the control element, in this case the column of balls, is equivalent to a circle of equal perimeter while the channel is equivalent to a circle of equal area. Thus the control element radius is greater than the channel radius and the channel blackness can be effectively greater than one.

The following values of neutron mean free path were used

<u>Reactor</u>	<u>Thermal</u>	<u>Epithermal</u>
NPR		
(no streaming)	3.4 cm	3.8 cm
(streaming)	4.76	5.3
K	2.7	3.0
EGCR	2.6	3.0

One exception to these values for NPR was the case of the flooded graphite stack. In this case, the calculated values of $\bar{\tau}$ and L^2 were substantially smaller than in the other cases, and λ was assumed to be reduced in proportion to L . Because water fills about 15 percent of the graphite void space under these conditions, the values of $\bar{\tau}$ and L^2 were further reduced to correspond to a streaming correction of 1.34 instead of 1.4; therefore, the λ with the streaming correction is only 1.34 times that with no streaming correction.

Using the procedure described in Appendix I, the local control strengths of the NPR control rods and ball 3X channels, and the strength of the K ball 3X and EGCR control rod, were finally calculated. The following table includes the more important intermediate quantities and the results of these calculations.

TABLE II
CONTROL CALCULATION DATA

NPR Ball 3X

3.81
45.86
0.13
0.97

r_1
 R^1
 β_{c1}
 β_{c2}

τ
 L^2
 M^2

s_2/s_1
 ν
 ν^{r_1}
 Y
 Y'

λ_1
 λ_2

d_1
 d_2

$Y-d_1 Y'$

$(s_2/s_1)(Y - d_2 Y')$

Crit. Eq.

μ^2

Δk_{00}

<u>Hot Ripe</u>		<u>Cold Ripe</u>		<u>Cold Green</u>	<u>Max. React.</u>	
462		417		417	318	
194		157		169	145	
656		574		586	463	
-2.38		-2.66		-2.47	-2.19	
.08555		.09363		.09119	0.10021	
.3259		.3567		.3474	0.3818	
1.300		1.216		1.240	1.156	
-0.238		-0.234		-0.235	-0.231	
<u>No Strmg.</u>	<u>Strmg.</u>	<u>No Strmg.</u>	<u>Strmg.</u>	<u>No Strmg.</u>	<u>No Strmg.</u>	<u>Strmg.</u>
3.4	4.76	3.4	4.76	3.4	3.0	4.0
3.8	5.3	3.8	5.3	3.8	3.4	4.6
37.4	52.6	37.4	52.6	37.4	33.4	45.4
3.19	4.68	3.19	4.68	3.19	2.79	3.85
10.20	13.82	9.97	13.52	10.03	8.871	11.643
-4.903	-5.745	-5.219	-6.147	-4.915	-3.943	-4.479
X-14.30X'=0	X-18.75X'=0	X-14.94X'=0	X-19.65X'=0	X-14.44X'=0	X-12.21X'=0	X-15.39X'=0
173 μb	144 μb	168 μb	139 μb	172 μb	191 μb	164 μb
113 mk	94 mk	96 mk	80 mk	101 mk	88 mk	76 mk

TABLE II (Cont.)

NPR HCR		K 3X		EGCR
6.5 48.64 0.19 0.36		5.37 58.80 0.17 1.10		5.08 34.39 0.22 0.815
Hot Ripe		Cold Ripe		
462 194 <u>656</u> -2.38 0.08555 0.5561 0.838 -0.123		417 157 <u>574</u> -2.66 0.09363 0.6086 0.767 -0.120		455 149 <u>604</u> -3.05 0.09439 0.4795 0.960 -0.161
No Strmg.	Strmg.	No Strmg.	Strmg.	
3.4 3.8 24.84 10.90 3.893 -5.186	4.76 5.3 35.0 15.45 5.143 -6.516	3.4 3.8 24.84 10.90 3.748 -5.520	4.76 5.3 35.0 15.45 4.967 -6.972	2.6 3.0 16.72 2.97 3.652 -4.386
X-18.86X'=0 202 μ b 132 mk	X-26.38X'=0 159 μ b 104 mk	X-19.20X'=0 200 μ b 115 mk	X-26.87X'=0 156 μ b 90 mk	X-10.47X'=0 515 μ b 311 mk

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HW-65753

r_1
 R
 $\bar{Q}$ c1
 $\bar{Q}$ c2

χ
 I^2
 M^2
 S_2/S_1
 ν
 ν_{r_1}
 Y
 Y_1

λ_1
 λ_2

d_1
 d_2

$Y - d_1 Y_1$

$(S_2/S_1)(Y - d_2 Y_1)$

Crit. Eq.

ν^2
 ΔK_{∞}

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