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AEC RESEARCH AND DEVELOPMENT REPORT

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

ACCIDENT AND TRANSIENT CHARACTERISTICS OF KIWI-B REACTORS

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LAMS-2542
C-86, NUCLEAR ROCKET AND
RAM-JET ENGINES
(M-3679, 24th Ed.)

This document consists of 52 pages

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LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT COMPILED: April 6, 1961

REPORT DISTRIBUTED: July 10, 1961

ACCIDENT AND TRANSIENT CHARACTERISTICS OF KIWI-B REACTORS

by

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ABSTRACT

This report is a compilation of six preliminary memoranda describing accident and transient studies applicable to Kiwi-B reactors. The work was done primarily to determine an optimum control rod system from the standpoints of good system performance and good safety characteristics. Two control rod systems were considered. One was the usual combination of slow shim rods to establish the quiescent operating level, and a small number of fast regulating rods to obtain good system performance for small perturbations. In the second system all rods were identical. Various combinations of maximum rod velocities were considered for both systems.

Memoranda N-4-719, "Reactor Transient Calculations -- IBM 704"; N-4-723, "Kiwi-B Accident Studies, Part I"; N-4-747, "Kiwi-B Ramp Reactivity Transients"; N-4-771, "Kiwi-B Ramp Reactivity Transients - II"; and N-4-777, "Kiwi-B Accident Studies (Part 2)" contain digital and analog computer data for various combinations of accidents and control rod systems. N-4-784U, "Kiwi-B-1 Control Vane Velocity Limiting", contains a summary of this work and the conclusions which were reached.

REACTOR TRANSIENT CALCULATIONS - IBM 704

19 September 1960

The neutronics code ROK permits the representation of reactivity as a power series in time plus a constant-frequency harmonic. This has been modified (and called ROL) by the author to permit instead the representation of reactivity proportional to $\sin^2(\theta/2)$.

Reactivity is represented as a constant C_o plus

$$C_1\left\{\sin^2\left[\frac{\pi}{2}(t - C_2)/C_3\right] - \left[\sin^2 \frac{\pi}{2}\frac{C_2}{C_3}\right]\right\}$$

$$+C_4\left\{\sin^2\left[\frac{\pi}{2}(t - C_5)/C_6\right] - \left[\sin^2 \frac{\pi}{2}\frac{C_5}{C_6}\right]\right\}$$

where C_1 and C_4 represent the positive or negative reactivity worth of regulating and shim systems, C_3 and C_6 the respective full travel times, and C_2 and C_5 the initial position (in time) to permit a non-zero time problem start.

Power transients from a constant power start have been computed for a total regulating and shim system worth of \$1.4 and \$7.0 respectively (at beta = 0.0065), and a neutron lifetime of 32 microseconds.

Control element travel was such that full motion of the regulating rod system took 0.5 second, and that for the shim either 18 seconds or 2 seconds.

Initial starting points for the excursions were varied as follows:

(a) $\theta_0 = 90^{\circ}$. This permits starting an excursion at the maximum reactivity removal rate (approximately 1.8 times the "average" rate). For example, at 0.5 and 18 second reactivity removal and shim removal rates, C_2 and C_5 are 0.25 and 9.0 seconds.

(b) 0.3 second from the full out position. This starts the excursion at a lower reactivity removal rate, but also insures that when the scram motion commences the reactivity insertion rate will be small, resulting in a slower decrease from the scram power level. At 0.5 and 18 second rates, C_2 and C_5 are 0.2 and 17.7 seconds.

(c) - (d) 0.25 and 0.2 second from full out. The last three cases are of course not to be reasonably expected unless there is some drastic miscalculation or misfortune in setting the operating positions of the control system, but still cannot be disregarded.

Starting then at these various positions, power transients were computed, and curves of P vs t plotted from which typical scram signals were selected. These included relative power levels of 1.2, 1.5, and 2.0 times the initial power, and periods of 300, 200 and 100 ms. Additionally in a few instances relative power level scrams of 1.0 were selected to give a base point or minimum power rise and heat generation.

To the time at which each scram signal occurred, a suitable delay time (20 or 100 ms) was added. Conditions existing at that new time were recorded, and used as starting conditions for scram. Full travel scram times were generally 0.5 second, although some runs at 0.25 second were made.

[redacted]

TEMPERATURE RISE

The area under the power profile (rise plus scram) was then assumed to represent an unwanted excess of power above the previously constant power. Flow rate was assumed to remain unchanged during this excursion. Therefore temperature of the fuel elements was assumed to continue rising until power level fell back to the initial constant value, after which it would start to decrease. Taking peak temperature rise as the determining factor, calculations were not continued beyond that point.

A simple code (TVP — Temperature vs Power) was written which calculates average temperature rise and peak temperature rise vs time, as well as an exponentially attenuated peak temperature rise at the end of the excursion. The average temperature rise at any time is taken as

$$\Delta \bar{T} = \sum_{t} \frac{\Delta p \times \Delta t}{m \times c_p}$$

The rise in peak temperature was taken to be a constant times the rise in average temperature, where that constant was determined from a KIB calculation performed by O. Farmer. For constant flow rates, and power constant at 90, 100, 110 and 120% of full power, the ratio of the change in peak temperature of the loaded fuel element to the change in average temperature was found to be constant at 1.28.

The rise in peak temperature during each time interval was also attenuated exponentially from that interval to the end of the excursion, with a 3 second time constant.

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Other constants used were: c_p, specific heat of 0.52 Btu/lb - °F, m, mass of 545 kg, and Δt, average time intervals of 10 ms, initial power of 1000 MW, and fraction of power locally deposited of 0.98.

RESULTS

Figures 1 and 2 show rise in average temperature vs power level when scram starts, for the 18 second and 2 second full travel shim withdrawal times. The ordinate is plotted in order to permit the arbitrary mixing of scram signals and delay times.

Figures 3 and 4 show power profiles. Used with Figures 1 and 2, they permit this arbitrary mixing to be estimated.

Figures 5 and 6 show rise in average temperature vs power level when scram is signalled, for 18 second and 2 second shim full travel times, and for 0.10 and 0.02 second delay times.

A comparison of Figures 3 through 6 shows the following —

18 second shim travel: for approximately 1/4 second, the relative power profile for the theta equals 90° start slightly exceeds that for the 0.3 sec from full out start, the two curves being nearly parallel. Therefore a given power level scram signal would cause an earlier scram for the 90° case than for the 0.3 sec case and, since the curves are nearly parallel, the longer-running case (0.3 sec start) will show the greater temperature rise because of a greater net area under the power profile, MW-seconds (see Figures 3 and 5).

2 second shim travel: at all times, the power profile for the theta equals 90° start exceeds that for the 0.3 sec-from-full-out-position start. For small (0.02 sec) delay times, at low power level scrams (1.5), the curves have not diverged greatly, and as before, the temperature rise is

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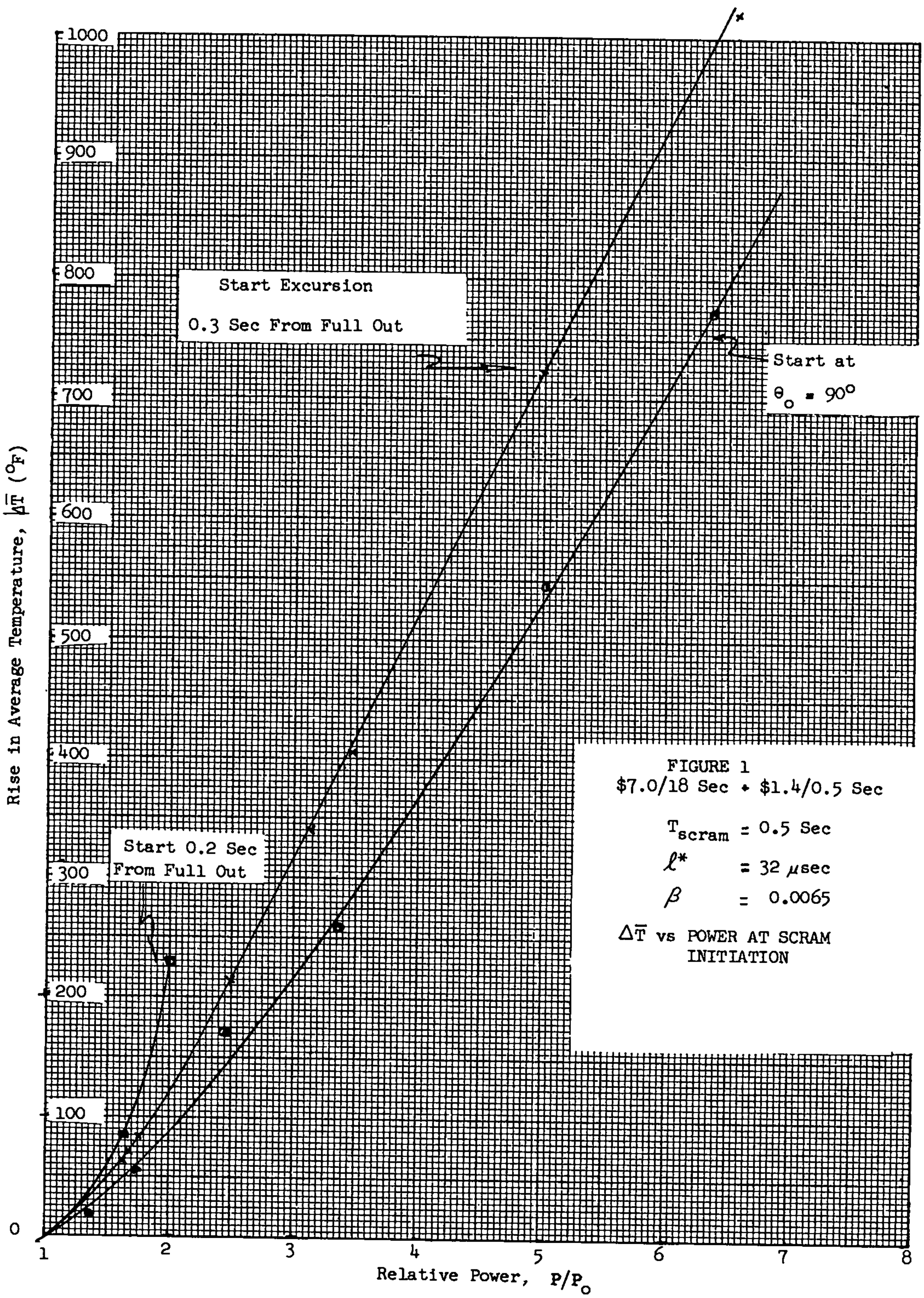
1000
900
800
700
600
500
400
300
200
100
0
Start Excursion
0.3 Sec From Full Out
Start at
θo = 90°
FIGURE 1
$7.0/18 Sec + $1.4/0.5 Sec
Tscram = 0.5 Sec
ℓ* = 32 μsec
β = 0.0065
ΔT̄ vs POWER AT SCRAM INITIATION
Start 0.2 Sec
From Full Out
Rise in Average Temperature, ΔT̄ (°F)
1
2
3
4
5
6
7
8
Relative Power, P/Po

[redacted]

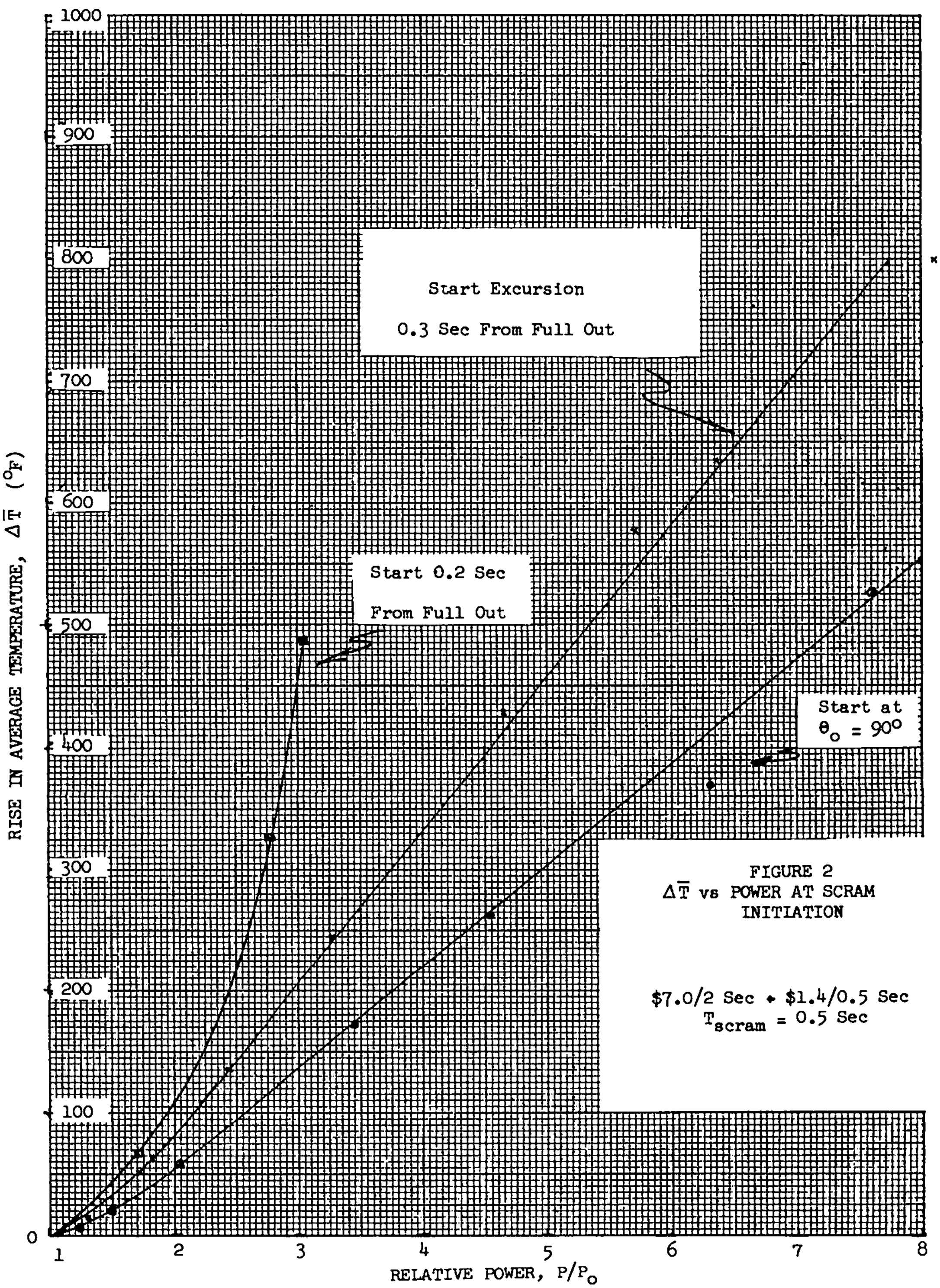

FIGURE 2
$\Delta\bar{T}$ vs POWER AT SCRAM INITIATION

\$7.0/2 Sec + \$1.4/0.5 Sec
$T_{scram} = 0.5$ Sec

[redacted]

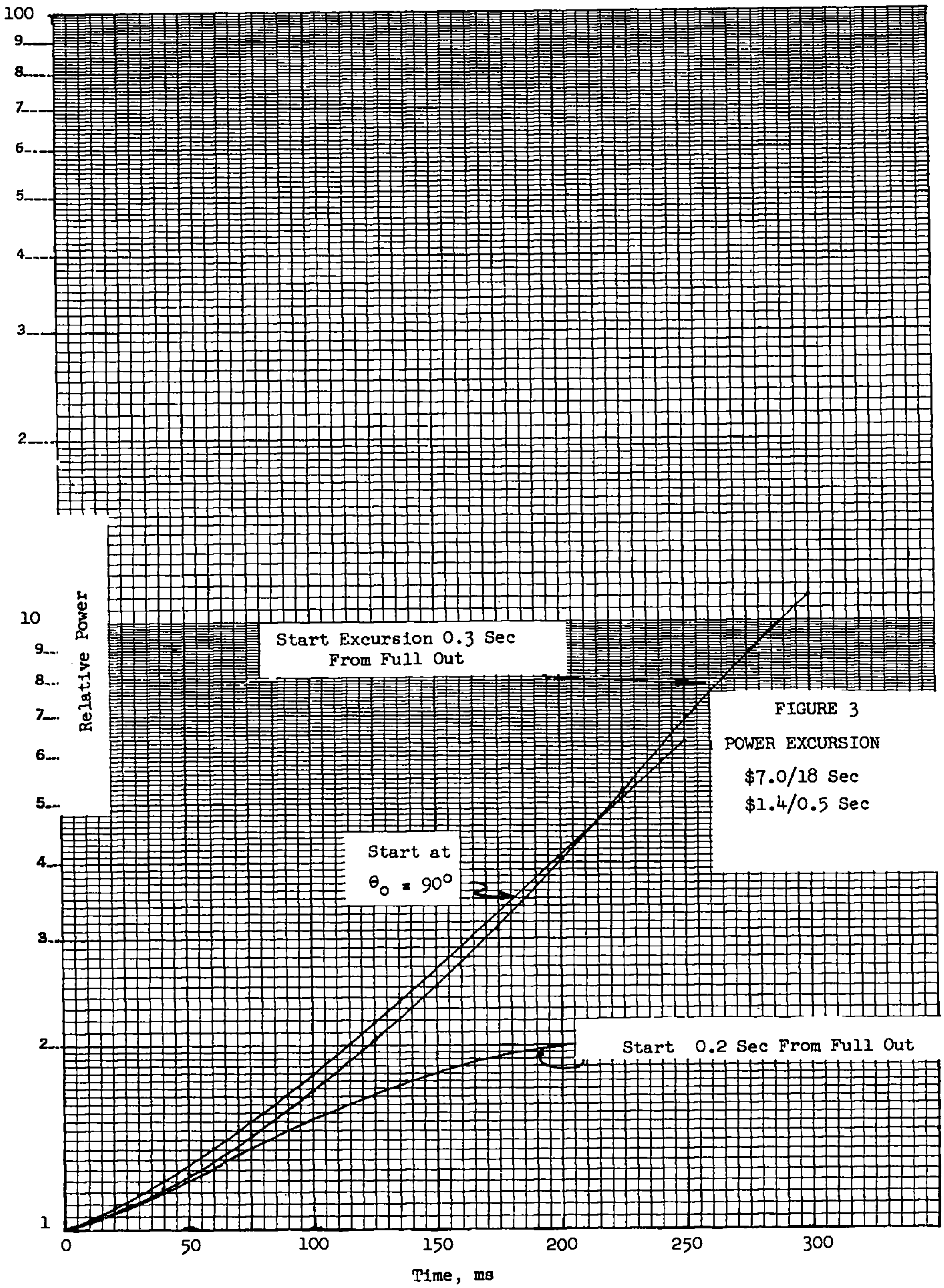

FIGURE 3

POWER EXCURSION

\$7.0/18 Sec

\$1.4/0.5 Sec

[redacted]

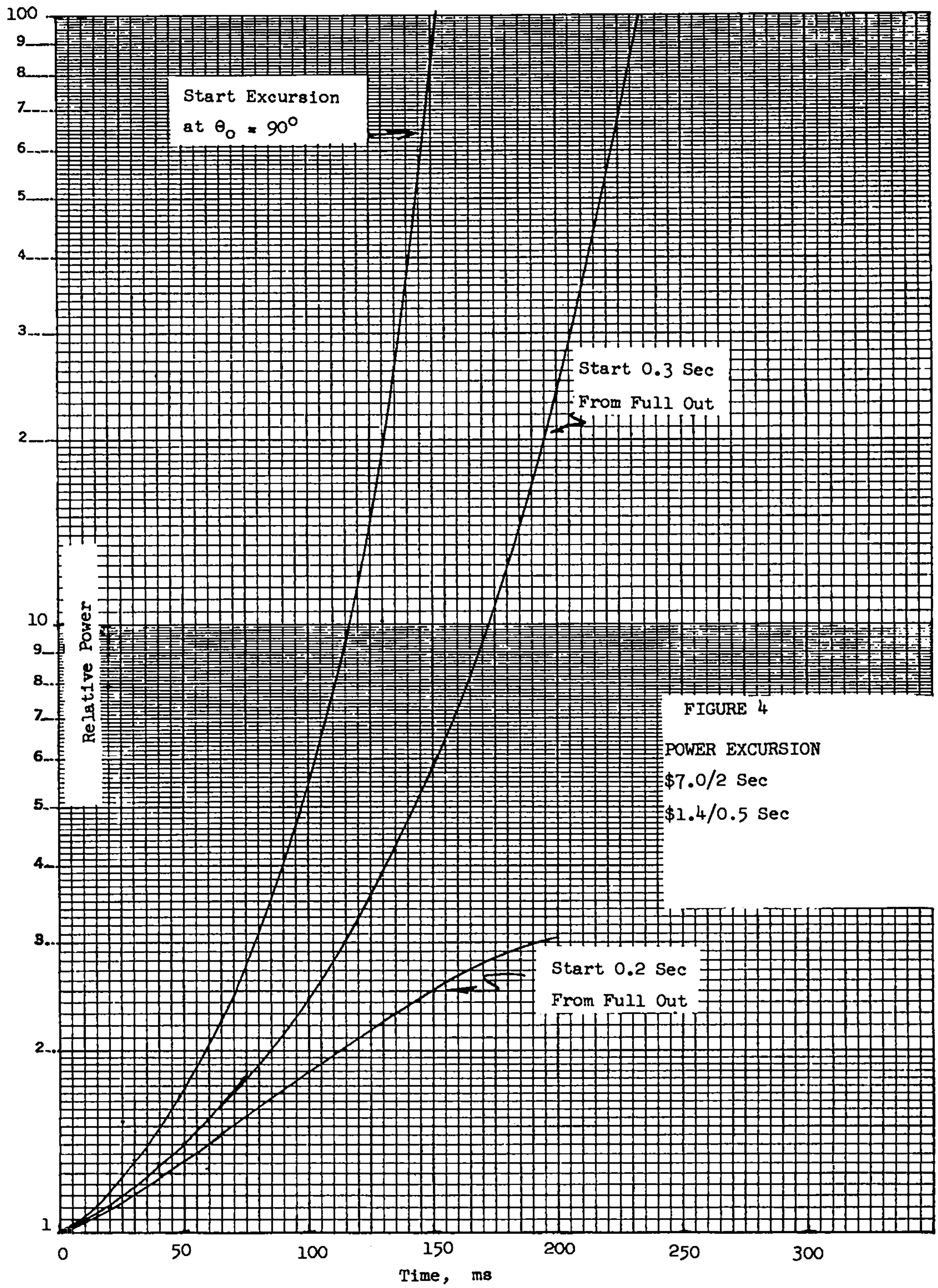

FIGURE 4

POWER EXCURSION
\$7.0/2 Sec
\$1.4/0.5 Sec

[redacted]

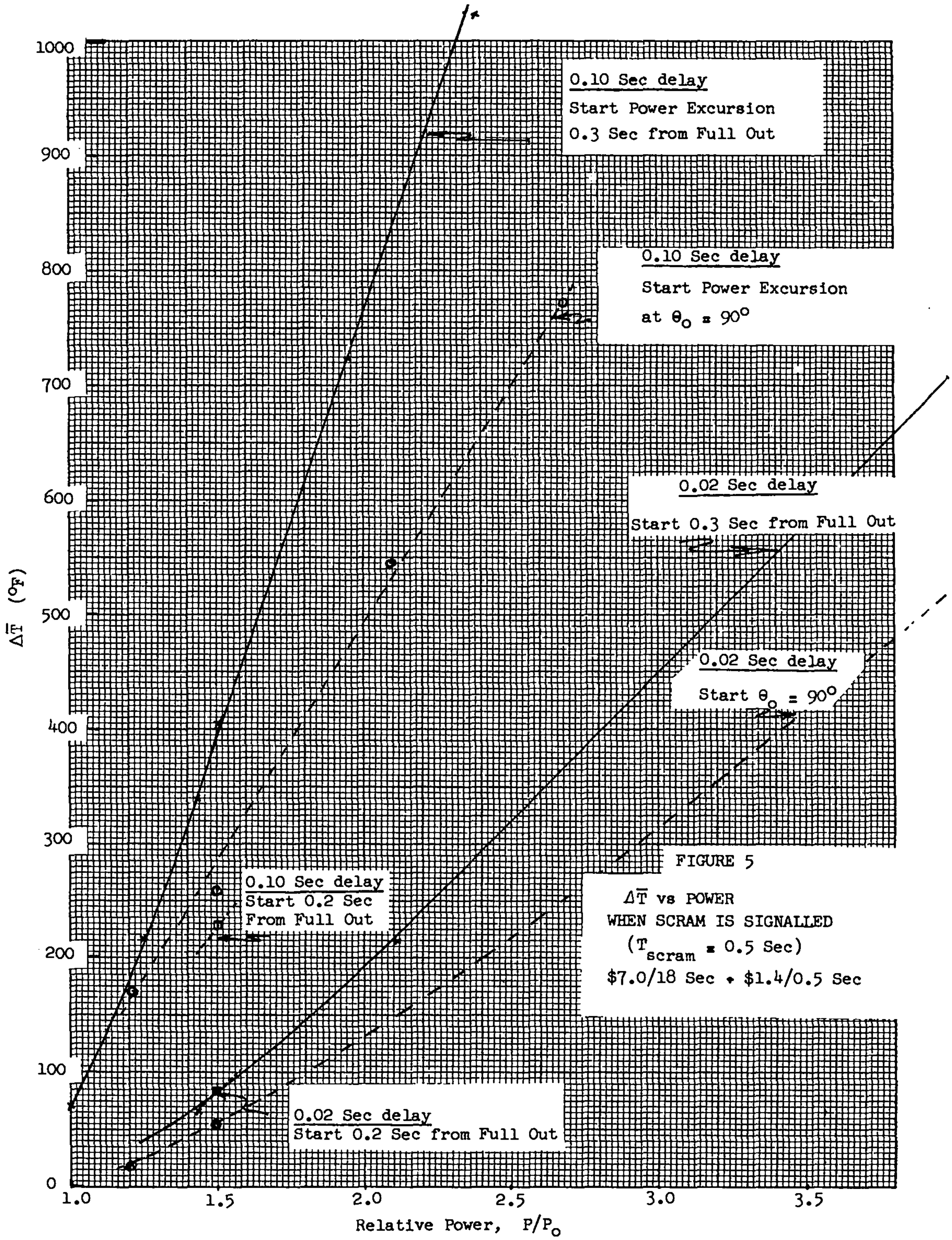

FIGURE 5

$\Delta\overline{T}$ vs POWER
WHEN SCRAM IS SIGNALLED
($T_{scram} = 0.5$ Sec)
\$7.0/18 Sec + \$1.4/0.5 Sec

[redacted]

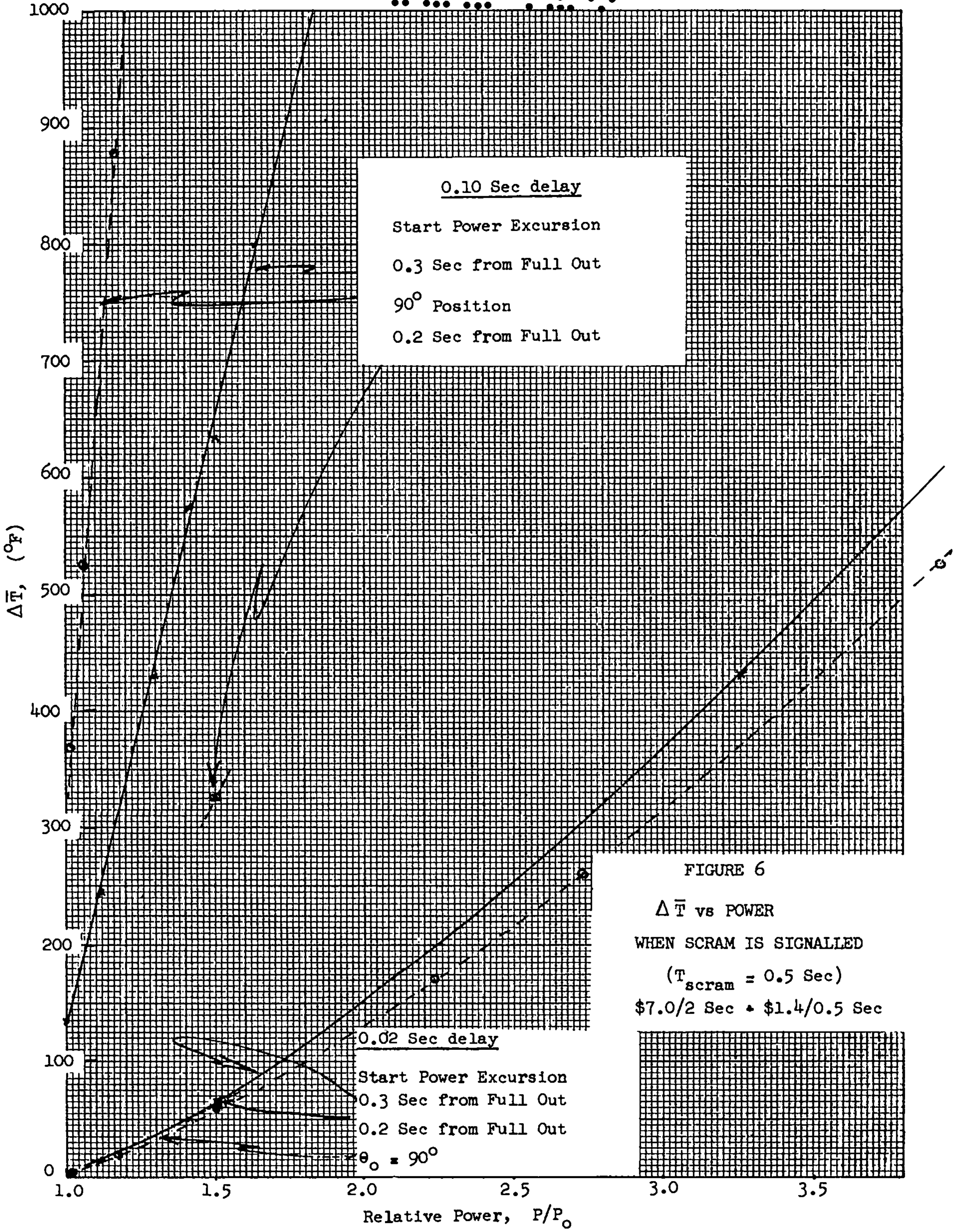

FIGURE 6

$\Delta \overline{T}$ vs POWER

WHEN SCRAM IS SIGNALLED

(T_{scram} = 0.5 Sec)

\$7.0/2 Sec + \$1.4/0.5 Sec

[redacted]

greater for the 0.3 sec case. However, for large delay times, the 90° case power rises so very much faster than the 0.3 sec case that, even though the latter takes a longer time to reach scram initiation and the end of the excursion, the area under the former power profile (MW-seconds) causes a much greater temperature rise.

The tables below indicate the temperature rises found for various cases, where in all instances,

(1) Regulating system = \$1.4

(2) Shim system = \$7.0

(3) Regulating system full travel withdrawal time = 0.5 sec

(4) P_o = 1000 MW

(5) c_p = 0.52

(6) m = 545 Kg

(7) Time constant = 3 sec

(8) Peak-to-average temperature rise = 1.28

(9) Fraction of power locally deposited = 0.98

CONCLUSIONS

Excursions start: more cases should be examined. Nevertheless, for the 18 second shim withdrawal condition, since the shims are removing poison much more slowly than are the regulating rods, regulating rod position is dominant; and for the regulating rod, there is little difference among the cases of 0.3, 0.2 and 0.25 ($\theta_o = 90°$) second from full out. For the two second shim withdrawal case, where shim reactivity rates are comparable to regulating rod rates, the $\theta = 90°$ (mid-position start and highest withdrawal rate) is the worst of those considered.

TABLE I: 18 SEC SHIM WITHDRAWAL TIME (FULL TRAVEL)

t_{start}	Scram	t_{scram}	t_{delay}	t_{in}	$\frac{P}{P_0}(t_{in})$	T_{scram}	$\Delta\bar{T}$	ΔT_{pk}	$\sum\Delta T_{pk}e^{-t/3}$
0.3 sec from full out position (shim and regulating)	300 ms	0.075 s	0.10 s	0.1[illegible] s	3.14	0.5 s .25	340 F 271	435 F 348	421 F 339
	↓	↓	.02	.095	1.63	.5 .25	63 51	81 66	80 65
	1.0 Power	0	.10	.10	1.68	.5	72	93	91
	1.5	.085	.10 .02	.185 .105	3.46 1.75	↓	405 84	518 108	500 106
	2.50 4.99	.150 .220	0	.150 .220	2.50 4.99	↓	216 723	277 925	269 889
	6.53 8.06	.245 .265	↓	.245 .265	6.53 8.06	↓	1020 1430	1310 1830	1250 1750
0.2 sec from full out	1.5 Power	0.10	0.10	0.20	2.00 (Max)	0.5 .25	228 193	292 247	281 240
	↓	↓	.02	.12	1.63	.5 .25	85 67	109 86	106 84
θ_0 = 90° (shim and regulating in mid-positions)	300 ms	0.04	0.10	0.14	2.47	0.5 .25	171 134	219 171	215 169
	↓	↓	.02	.06	1.63	.5 .25	18 17	23 23	22 22
	1.5 Power	.075	.10 .02	.175 .095	3.36 1.73	.5	260 55	333 71	326 70
	5.02 6.37	.220 .250	0	.220 .250	5.02 6.37	↓	545 773	698 990	677 958

TABLE II: 2 SEC SHIM WITHDRAWAL TIME (FULL TRAVEL)

t_{start}	Scram	t_{scram}	t_{delay}	t_{in}	$\frac{P}{P_o}(t_{in})$	T_{scram}	$\Delta\bar{T}$	ΔT_{pk}	$\sum \Delta T_{pk} e^{-t/3}$
0.3 sec	300 ms	0.02 s	0.10 s .02	0.12 s .04	3.26 1.30	0.5 s	245 F 14	314 F 17	307 F 17
from full out	200 ms	.05	.10 .02	.15 .07	5.71 1.71		576 52	737 67	717 66
position (shim and	1.5 power	.055	.10 .02	.155 .175	6.38 1.81		635 63	813 81	791 80
regulating)	2.44 4.65	.10 .14	0	.10 .14	2.44 4.65		137 430	176 550	172 535
	8.11	.165		.165	8.11		801	1026	966
0.2 sec from full out	1.5 Power	0.07	0.10	0.17	2.77	0.5 .25	327 263	418 336	404 328
			.02	.09	1.72	.5 .25	67 55	86 71	84 70
	3.06	.20	0	.20	3.06 (Max)	.5	487	586	562
$\theta_0 = 90°$	300 ms	0.005	0.10 .02	0.105 .025	6.31 1.24	0.5	369 6	473 8	465 8
(shim and regulating	200 ms	.02	.10 .02	.12 .04	11.75 1.50		879 20	1125 26	1103 25
in mid-	1.5 Power	.04	.10 .02	.14 .06	37.52 2.04		3570 58	4570 75	4450 74
positions)	3.45 4.54	.085 .095	0	.085 .095	3.45 4.54		172 262	220 336	216 331
	7.61	.110		.110	7.61		526	674	661

[redacted]

<u>Delay time</u>: as expected, this is perhaps the most significant factor. If a 20 ms delay time can be guaranteed, then the two second shim withdrawal full travel time is quite acceptable.

<u>Scram time</u>: for the cases considered, the difference in rise in peak temperature caused by a 1/4 sec vs a 1/2 sec scram is negligible, in most instances.

<u>LIMITATIONS</u>

Where possible, it was decided to err on the conservative side (i.e., higher power rise). For example, reactivity temperature coefficient is not included; in general the transients are over in a few hundred milliseconds. Specific heat and peak-to-average temperature rise were considered constant over the temperature range encountered.

It is realized the conditions considered here represent but a few of many possible variations. Other shim and regulating rod withdrawal (and perhaps scram) rates should be considered, as well as other excursion starting points. This can be done easier with an analog computer, but it is hoped these calculations will serve as useful checkpoints.

As an estimate of computer (704) time required, we have:

(a) One power excursion carried out for 300 milliseconds (a long time) - approximately 10 seconds.

(b) From the resulting curve of P vs t, various scram initiation times were selected, and the power scrammed. One such scram computation carried out for 100 milliseconds (generally a long time) - approximately 30 seconds.

(c) Computation of temperature rise - approximately 4 seconds.

[redacted]

KIWI-B ACCIDENT STUDIES (Part 1)

23 September 1960

PURPOSE

Kiwi-B shim actuator velocity limit and scram rate has not been resolved at the present time. Also, the maximum permissible scram delay time has not been determined. The purpose of this study is to determine effects of these variables on wall temperature overshoot and determine optimum values.

DISCUSSION

A simplified simulation of Kiwi-B (**Figure** 1) was used to obtain accident study data. The simulation consists of a fairly accurate representation of regulating and shim vane dynamics (G.E. Actuators). The neutronics simulation is a ladder type simulator with mean neutron lifetime (ℓ^*) of 3.3×10^{-5} sec (Neutronic Simulator, A. G. Bailey, 12/21/59). The heat exchanger is represented by a simple lag of 1.6 sec as determined by mass heat capcity of core, maximum power level and maximum flow rate. A temperature reactivity of $1.5 per 5050°F was used. Propellant mass flow rate and reactivity due to hydrogen were assumed to be constant during all runs.

All computer runs were made a maximum power and maximum flow rate conditions with a power level scram at 150% of maximum power. The accidents assumed were: all shim vanes moving out at their velocity limited rate with regulating vanes fixed and all vanes, shim and regulating, moving out at their maximum rates. Scram delay time, shim vane velocity limit and shim vane scram speed were varied in computer runs. Power level maximum wall temperature, change in maximum wall temperature, regulating vane position, shim vane position and total reactivity were recorded.

Figure 2 shows the effect of varying shim vane scram speed on maximum wall temperature overshoot while maintaining a constant 18° per second shim vane velocity limit. Figure 2 also shows the effect of having shim vane velocity limit equal to the scram speed. All computer runs shown in Figure 2 used a 20 ms scram delay.

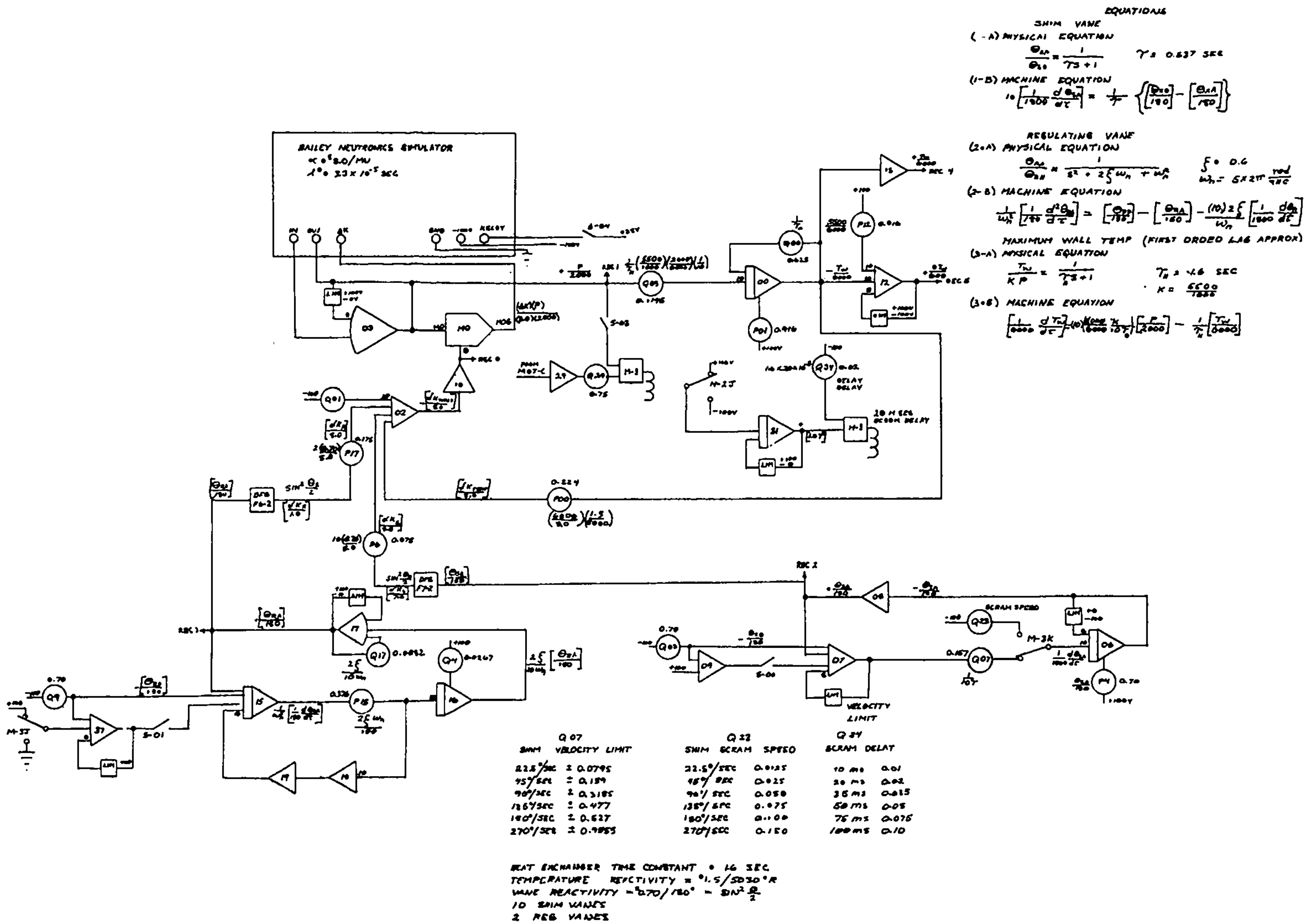

FIGURE ONE - KIWI-B ACCIDENT STUDY ANALOG SIMULATION PACE COMPUTER

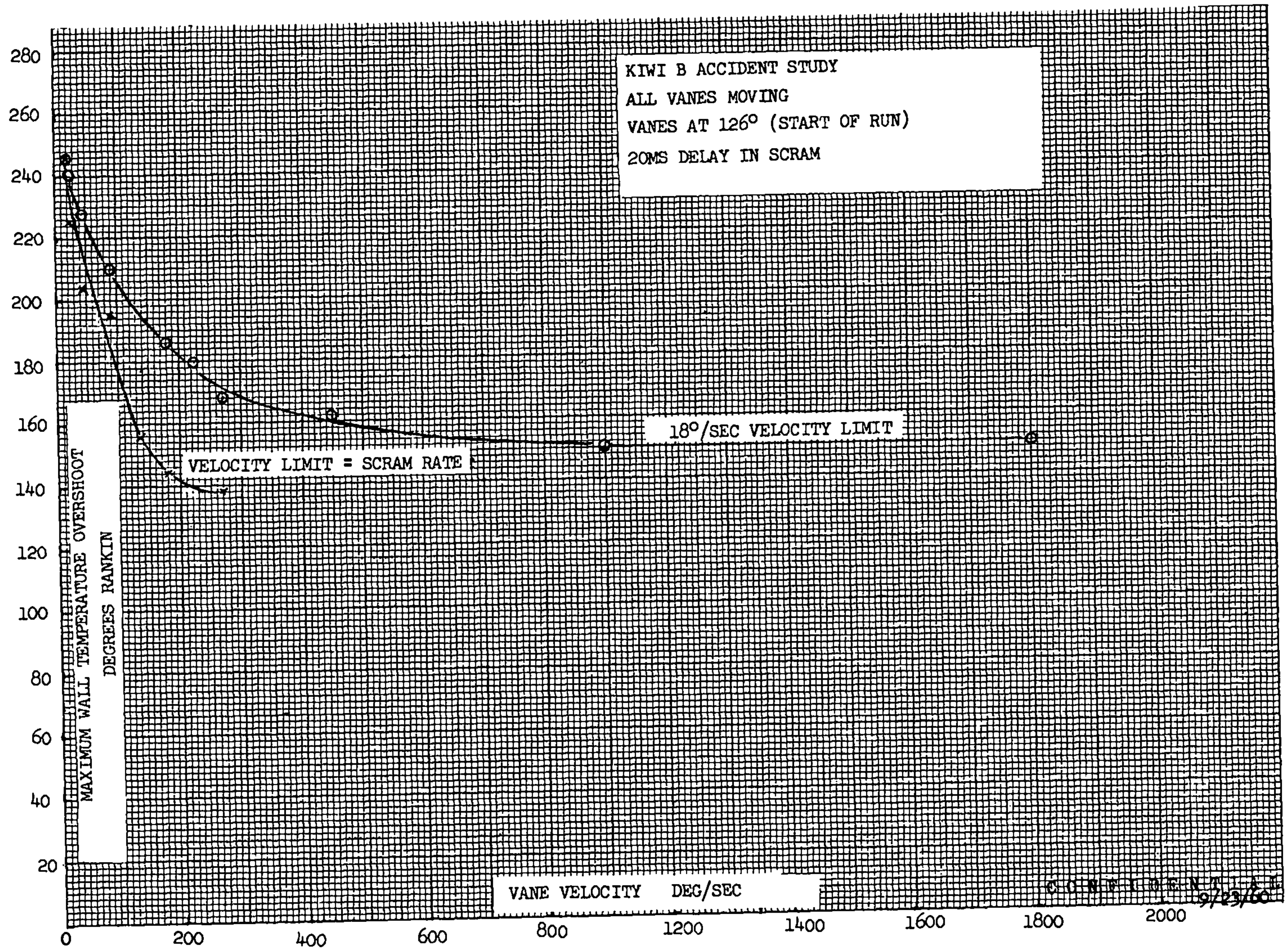
KIWI B ACCIDENT STUDY
ALL VANES MOVING
VANES AT 126° (START OF RUN)
20MS DELAY IN SCRAM
18°/SEC VELOCITY LIMIT
VELOCITY LIMIT = SCRAM RATE
MAXIMUM WALL TEMPERATURE OVERSHOOT
DEGREES RANKIN
VANE VELOCITY DEG/SEC
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
200
400
600
800
1200
1400
1600
1800
2000
CONFIDENTIAL
9/23/60

FIGURE TWO

[redacted]

The effect of scram delay time on wall temperature overshoot is shown in Figure 3. Three curves, 45°/sec velocity limit and scram rate, 90°/sec velocity limit and scram rate, and 18°/sec velocity limit with a 90°/sec scram rate, plot maximum wall temperature overshoot vs scram delay time. Vanes were all set at 126° at the start of each computer run. Regulating vane maintained a constant position during all runs.

Figure 4 is the same as Figure 3 except that the regulating vane was included in the accident study.

Figure 5 is a repetition of the 90°/sec and 18°/sec shim vane velocity limit curves of Figures 3 and 4 with all vanes starting at 90° instead of 126°.

<u>CONCLUSIONS</u>

Figure 2 shows that increasing the scram speed beyond 200°/sec does not decrease temperature overshoot significantly during an accident. Figure 2 also shows that an increase in velocity limit actually causes a decrease in temperature overshoot with a 20 ms scram delay.

Figures 3 and 4 indicate that if scram delay time is less than 35 ms a 45°/sec velocity limit and scram or a 90°/sec velocity limit and scram is better than a 18°/sec velocity limit with a 90°/sec scram.

Figure 5 shows that an accident at 90° vane starting position and a 90°/sec velocity limit, produces higher temperature overshoots, when delay is long (75 ms), than does the same accident at 126° vane starting position. It also shows, however, that temperature overshoot is within design tolerances if scram delay time is kept below 35 ms.

[redacted]

APPROVED FOR PUBLIC RELEASE

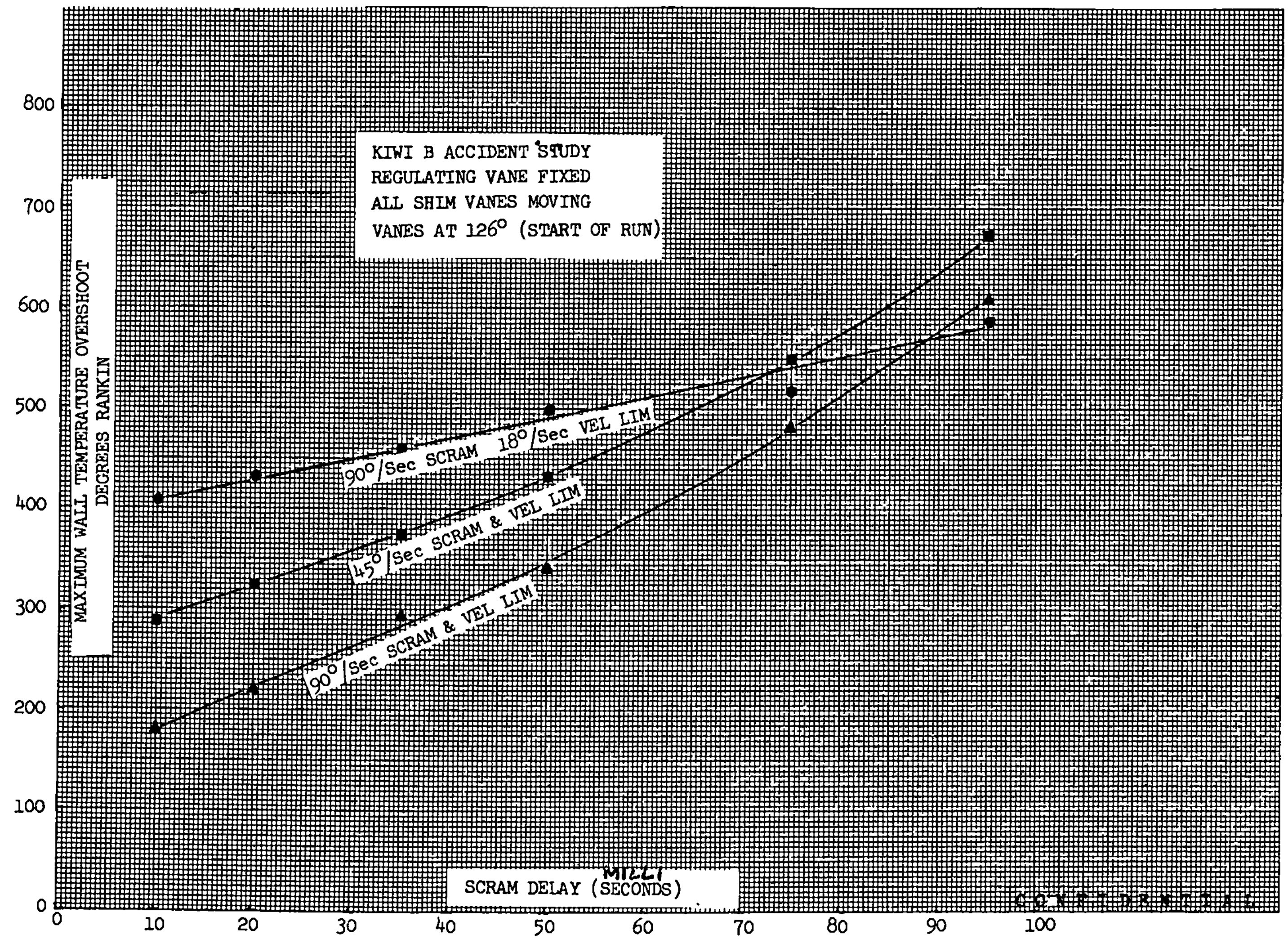

FIGURE THREE

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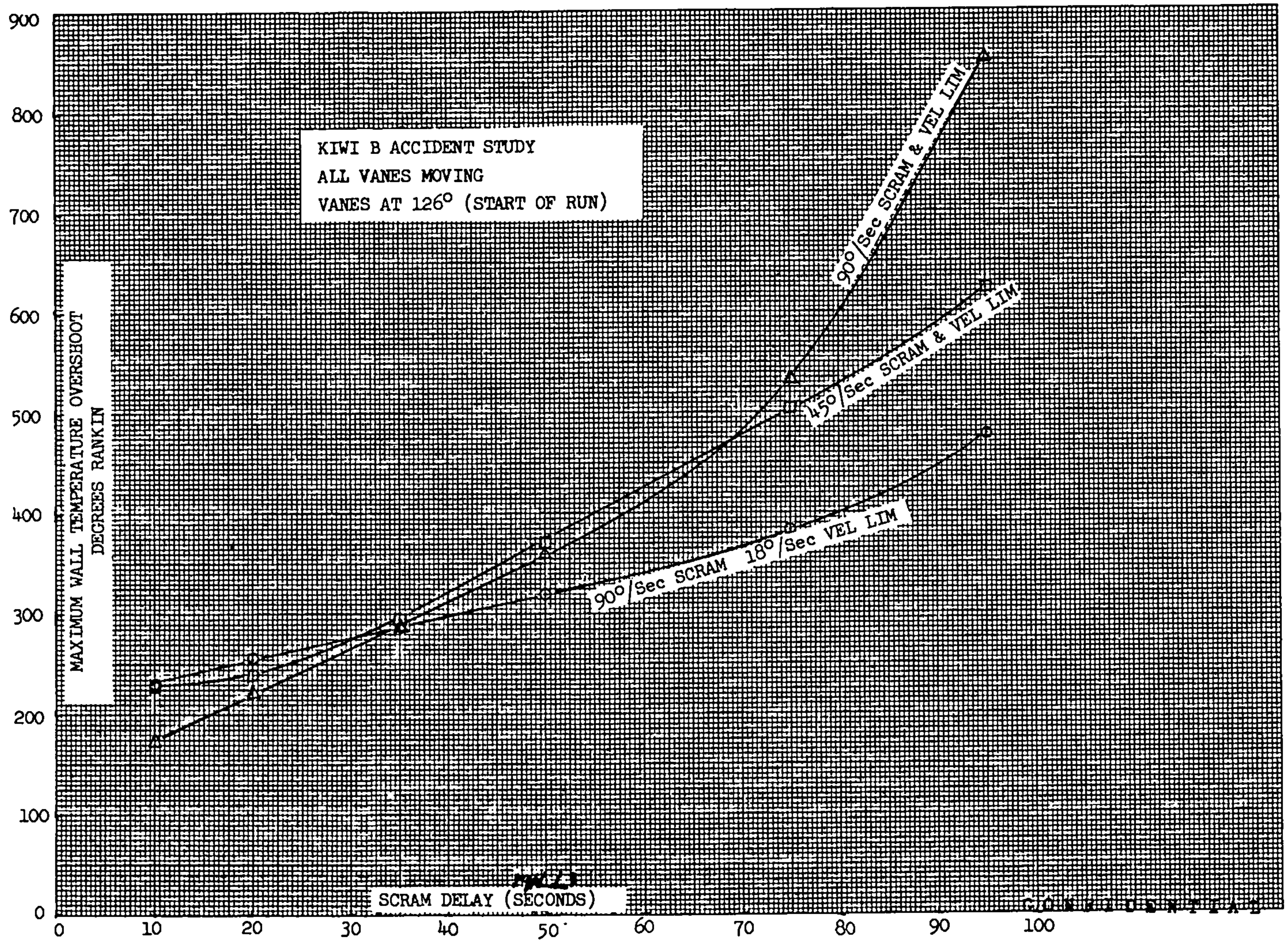


FIGURE FOUR

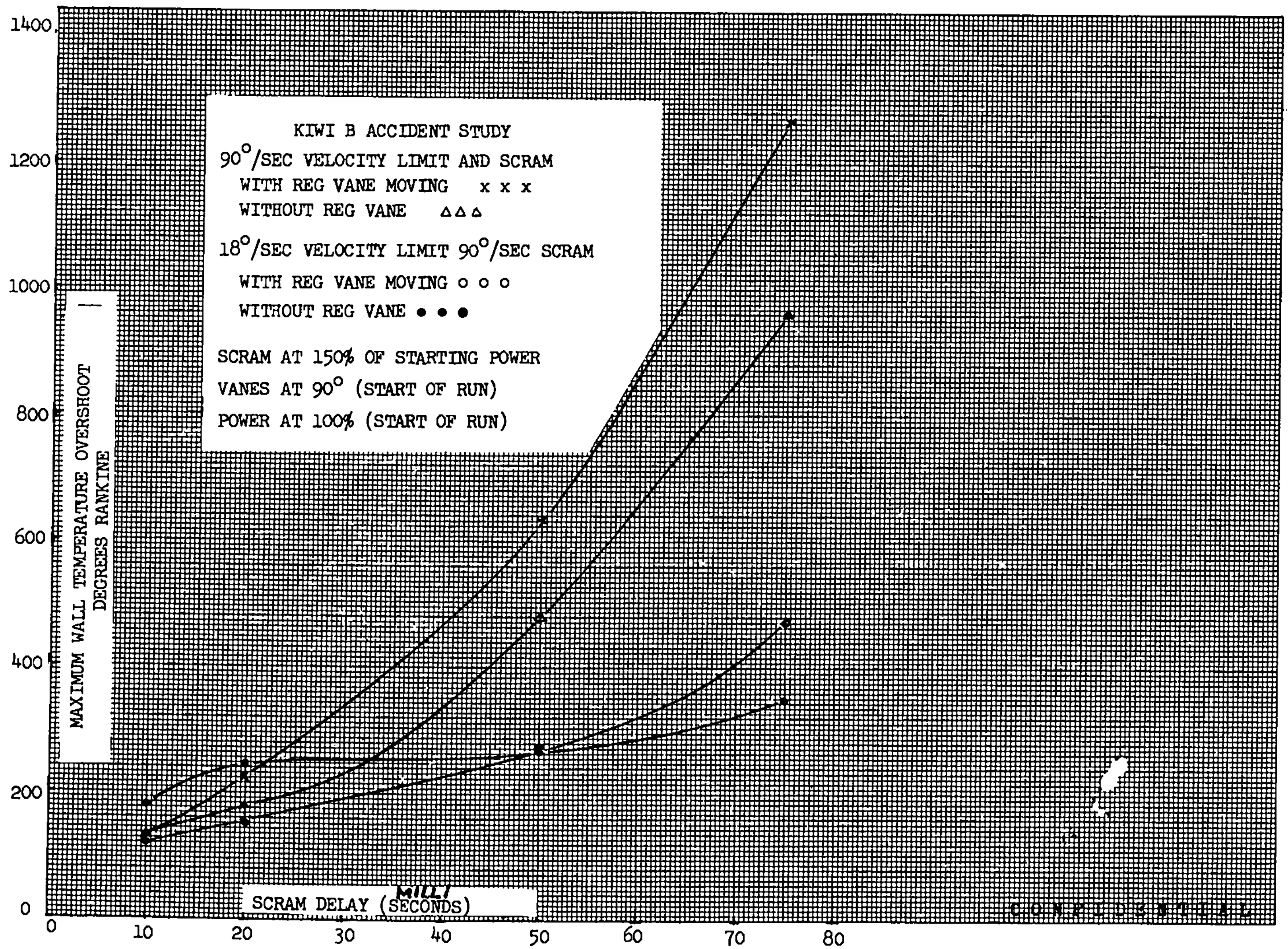


FIGURE FIVE

25

[redacted]

KIWI-B RAMP REACTIVITY TRANSIENTS

27 October 1960

The September monthly progress report and this report, "Reactor Transient Calculations -- IBM 704" describe the calculation of power transients using the ROK neutronics code, and the computation of the resulting temperature rise using the TVP code. These previous calculations were based upon reactivity excursions caused by control element motion, and simulated the approximate $\sin^2 \frac{\theta}{2}$ reactivity dependence.

Subsequently, calculations have been initiated to determine the effects of ramp reactivity additions, in order to estimate reactor behavior in regions near prompt critical under severe accident conditions.

Because it may be possible to mechanically adjust control vane motion such that reactivity rates are nearly constant (Δk proportional to time rather than $\sin^2 \frac{\theta}{2}$), scram was simulated as a negative ramp.

Accidents are postulated as follows:

(1) From an initially constant power level, positive reactivity additions commence, and power curves are plotted as a function of time.

[redacted]

[redacted]

(2) At the instant of scram initiation, twelve 70¢ control elements start to insert poison at a linear rate dependent upon full stroke scram time, T_{scram}. Travel is limited to the insertion of only one half the total worth, in order to simulate more realistic conditions.

(3) Before, during and after this scram action, the positive ramp reactivity addition is postulated as still occuring. This reduces the control element scram effectiveness and also gives an indication of whether the system can be shutdown completely.

Table I (on page 28) indicates relative power level as a function of time (neglecting temperature coefficient) for positive reactivity ramps, where $\ell^* = 32\ \mu sec$ and $\beta = 0.0065$. PC = prompt critical. (Table I)

The $10/sec rate was selected as representative of a severe accident, and for various scram signals and delay times the system scrammed. Representative full stroke scram times used were 0.5, 0.35, 0.25 and 0.1 second, while the corresponding scram motions were permitted to last 0.25, 0.175, 0.125 and 0.05 seconds.

The core was simulated as 545 kg of loaded fuel elements, with a specific heat of 0.52 Btu/lb-°F, and a peak-to-average temperature ratio of 1.28 to 1. The rise in average loaded fuel element temperature, in peak fuel element temperature,

[redacted]

TABLE I

Δk Rates

t	$2/sec	$ $5/sec	$10/sec	$ $20/sec	$40/sec
0	1.0	1.0	1.0	1.0	1.0
25 ms	1.04	1.11	1.24	1.59	2.85 (PC)
50	1.10	1.29	1.75	4.07 (PC)	73.0
75	1.17	1.53	2.83	28.3	151000.
100	1.24	1.87	5.92 (PC)	1390.	
125	1.32	2.41	20.2		
150	1.42	3.31	162.		
175	1.53	5.01	4090.		
200	1.66	8.89 (PC)			
225	1.82	20.2			
250	2.01	66.7			
275	2.24	365.			
300	2.52	3580.			
400	4.86				
500	17.3 (PC)				
600	350.				

and the rise in peak fuel element temperature at the end of the excursion (P/P_0 returned to 1.0) attenuated with a 3 second time constant were computed. Some results are tabulated in Table II.

These results indicate that for a severe accident situation such as the $10/sec reactivity ramp, where the possibility exists of approaching or exceeding prompt critical, a short scram time is necessary. Depending on the severity of the accident expected, scram delay times, and scram worth, it appears that full travel scram times in the order of 1/4 second would be desirable.

Still to be calculated are conditions obtaining as a result of a positive reactivity ramp starting from some positive period rather than steady state. This should yield still more stringent requirements for the scram system.

TABLE II

SCRAM SIGNAL	DELAY TIME	t_{scram}	$\frac{P}{P_o}(t_{scram})$	T_{scram}	$\Delta\bar{T}$	ΔT_{Pk}	$\sum(\Delta T_{Pk} e^{-\frac{\Delta t}{3}})$
$\frac{P}{P_o}$ = 1.2	20 ms	45 ms	1.62	0.5 s	54 F	70 F	68 F
1.2	20	45	1.62	0.25	29	37	37
1.2	100	125	20.2	0.5	Cannot shutdown		
1.2	100	125	20.2	0.25	1840	2360	2310
1.2	100	125	20.2	0.1	991	1270	1250
Prompt Critical	0	100	5.92	0.5	855	1100	1040
Prompt Critical	0	100	5.92	0.35	524	671	653
Prompt Critical	0	100	5.92	0.25	389	498	489
Prompt Critical	0	100	5.92	0.1	259	332	328
Prompt Critical	40	140	62.2	0.25	Cannot shutdown		
Prompt Critical	40	140	62.2	0.1	3050	3910	3860

[redacted]

KIWI-B RAMP REACTIVITY TRANSIENTS -- II

28 November 1960

Reference is made to "Reactor Transient Calculations -- IBM 704", dated 19 September 1960 and "Kiwi-B Ramp Reactivity Transients", dated 27 October, 1960.

The former section outlines the technique of simulating $\sin^2\theta/2$ reactivity variations in the ROK neutronics code, and the method of calculating temperature rise with the TVP code. Temperature rises were computed for power excursions due to control elements alone, starting from steady state power, and scramming on period or power level. Only a limited number of cases were considered -- 18 second, and 2 second shim withdrawal times, and 1/2 second regulating system withdrawal time ($7.0 and $1.4, respectively). Excursions were started 0.3, 0.25 and 0.2 seconds from the full out position. Delay time was found to be the most important factor, with full travel scram time playing a relatively minor role. It was determined that if the delay time could be limited to no more than 20 ms, then a two second shim withdrawal full travel time would be acceptable. For example, control element, runaway and 300 ms scram signal, 0.5 second full travel scram yields a 470°F change in peak fuel temperature, where m = 545 kg, c_p = 0.52 Btu/#°F, ratio of peak to average temperature change = 1.28, and time constant = 3 seconds.

The second section describes some ramp reactivity transients. Starting from an initially constant power level, positive ramps of $2, $5, $10, $20, and $40/sec were added. The system was then scrammed linearly at various scram signals. The results indicate that for a severe accident such as a $10/sec reactivity ramp coupled with a <u>simultaneous</u> control system failure such that only scram action is available for reactor poisoning, a short scram time is necessary. Depending on the severity of the accident expected, scram delay times and scram worth, it appears that full

[redacted]

[redacted]

travel scram times of about 1/4 second would be desirable (e.g., a scram at prompt critical with zero delay time occurring 1/10 second after $10/sec is started), $10/sec positive reactivity still being added during scram, and a 1/4 second full travel scram time, results in a 500°F rise in peak fuel element temperature.

Because comments have been made to the effect that the above accident is too severe (postulating simultaneous positive reactivity ramps and control system failure), some less serious situations have been investigated. These accidents consist of an initial positive reactivity, on which there is superimposed a control system failure permitting control element withdrawal at the velocity-limited rate, until a scram signal is reached, a delay time allowed to elapse, and the system scrammed (either at the same velocity-limited rate, or a faster one). All control element motions are presumed to be linear with time, rather than $\sin^2\theta/2$ to simplify the problem; this can be pursued in further detail on the analog computer if it seems desirable.

The reactor (again a 32 μsec mean neutron lifetime, 12 - 70¢ control elements) is initially placed on a positive period by the addition of a 50¢ step at 1/10 of full power. This serves the purpose of developing a stable reactor period of about 4.8 seconds, after the knee of the power-time curve is passed (at about 50 ms, or 20% of full power), a somewhat realistic situation. Note that a 75¢ step would result in a much shorter period, about 1 1/2 seconds, and too steep a power rise for this high an absolute power level.

It was then assumed that this almost 5 second period rise would be permitted to continue for several seconds, and a power-time curve plotted. At 2 seconds after the step, $p/p_o = 3.4$, or $p = 340$MW, several positive ramp reactivities were added. These were $8.40 per 10 seconds, 4 seconds and 2 seconds (18°/s, 45°/s and 90°/s respectively).

Power curves paralleling the programmed 4.8 second period curve were plotted at 1.2, 1.5 and 2.0 times programmed power. The intersection of the three excursion curves with each of these three relative power curves was recorded and assumed to signal a scram. Delay times of 20 or 35 ms were added, and the system scrammed. The energy (MW-seconds) represented by the rise above the programmed power level (the five second period curve) represents energy added and was used to compute temperature rise.

[redacted]

Because even the most severe of the excursions considered did not result in an excessive rise in peak loaded fuel element temperature, only they were calculated and listed below:

TABLE I

POSITIVE $8.40 RAMPS SUPERIMPOSED

UPON A +50¢ REACTIVITY

τ Full Travel	Degree/ Sec.	Additional Time Elapsed After Initiation of Excursion, for P/P_{start} = 1.2	1.5	2.0
10 sec	18°/s	108 ms	197 ms	291 ms
4	45	52	91	132
2	90	32	52	74

TABLE II

TEMPERATURE RISE

τ Full Travel out	Degr/ Sec	Scram Signal	Delay Time	τ Full Travel Scram	Degr/ Sec	ΔT	ΔT_{Pk}	$\Delta T_{Pk} e^{\frac{-\Delta T}{3}}$
10 sec	18°/s	2.0	35 ms	0.5s	360°/s	96F	123F	119F
4	45	2.0	35	0.5	360	66	85	83
4	45	2.0	35	4	45	146	187	176
2	90	2.0	35	0.5	360	82	106	104
2	90	2.0	35	2	90	176	226	217

CONCLUSIONS:

If it is agreed that the worst accident expected is a control system velocity-limited runaway starting from about 35% of full power on a 5 second period, then it appears a similarly velocity-limited control element insertion with a floating 2.0 power level scram and a 35 ms delay time can adequately limit the reactor temperature rise. Note that the first section discussed the full power, constant power start situation and came to about the same conclusion.

[redacted]

If it is felt that faster accidents are possible, it is not clear that this system will suffice. Rather, short scram times (perhaps 1/4 second or less) appear to be desirable.

[redacted]

KIWI-B ACCIDENT STUDIES (Part 2)

10 December 1960

PURPOSE:

Section Two , "Kiwi-B Accident Studies, Part 1", gives analog computer results when using a ladder type neutronics simulator, a simple 1.6 sec lag for heat exchanges and simulated vanes. This report, "Kiwi-B Accident Studies, Part 2", discusses accident study results using more accurate problem simulation. Its purpose is to extend present Kiwi-B accident studies to the extent that more firm specifications for shim vane characteristics may be made.

DISCUSSION:

Ramps in vane motion, and the associated effect on reactor power level and core temperature are considered in this study. These vane ramps are used to simulate simultaneous failure and withdrawal of the entire shim gang at various shim velocity limits.

Table I shows the effect of vane velocity limit on reactor power overshoot if an accident occurs at a low power level (10 MW) and when the reactor is on a short period (0.5 sec). All vanes are considered to have the same characteristics with a total worth of $8.4. A reactor power level scram at 15 MW with a 20 ms delay in vane response was used in all runs. Computer setup (Fig. 1) consisted of simulated vanes, the Kiwi-B heat exchanger, the logarithm type Kiwi-B neutronics simulator, and the scram relay network.

[redacted]

Solenoid bypass valve, which bypasses velocity limiting orifice in scram mode, was considered to have a 45 ms delay in the simulation. Simulated propellant mass flow rate was set at 1.0 lb/sec for all runs. Final stage wall temperature was found to remain constant (approx. 275°R) in every run.

The effects of shim vane accidents at 950 MW and full propellant flow rate when reactor is on a 5 second period are shown in Table II. Power overshoot and final stage wall temperature overshoot are given for various vane velocity limits. Figure 1 again shows the computer setup for this data except that a ladder type Kiwi-B neutronics simulator with an ℓ^* of 3.5×10^{-5}sec was used in place of regular logarithm type Kiwi-B neutronics simulator. A scram at 1500 MW with a 20 ms delay in vane response was used in all runs.

Table III gives results of accidents occurring at 500 MW and full propellant flow rate when the reactor is on a 5 second period. Figure 2 shows the simulation setup in which an actual vane and actual solenoid orifice bypass valve were used. The ladder type neutronics simulator was used in these runs. The solenoid delay was determined to be about 110 ms by experimentation at the time in which data were taken. At the present time this 120 ms operating time has been reduced to approximately 40 ms. Scram signal occurred at 750 MW.

Table IV shows the results of accidents at 1000 MW steady state with a 1500 MW scram level. Figure 2 shows the simulation setup for these runs also. A logarithm type neutronics simulator was used to represent the Kiwi-B neutronics for the 90°/sec vane velocity limit data. The ladder type neutronics simulator was used for the 18°/sec vane velocity limit data.

[redacted]

TABLE I (0.5 sec period, 10 MW)

VELOCITY LIMIT SIMULATED VANES	SCRAM SOLENOID SIMULATED VALVE	OVERSHOOT Power MW	OVERSHOOT Power %
18°/sec	Bypass used (45 ms delay)	8.2 MW	82%
45°/sec	Bypass used (45 ms delay)	8.2	82
45°/sec	Bypass not used	9.3	93
90°/sec	Bypass used (45 ms delay)	14.	140
90°/sec	Bypass not used	14.	140

TABLE II (5 sec period, 950 MW)

VELOCITY LIMIT SIMULATED VANES	SCRAM SOLENOID SIMULATED VALVE	OVERSHOOT Power MW	OVERSHOOT Power %	OVERSHOOT Wall Temp
18°/sec	Bypass used (20 ms delay)	632 MW	66%	175°R
45°/sec	Bypass used (20 ms delay)	790	83	127
45°/sec	Bypass not used	885	93	262
90°/sec	Bypass used (20 ms delay)	1100	116	132
90°/sec	Bypass not used	1200	126	200

[redacted]

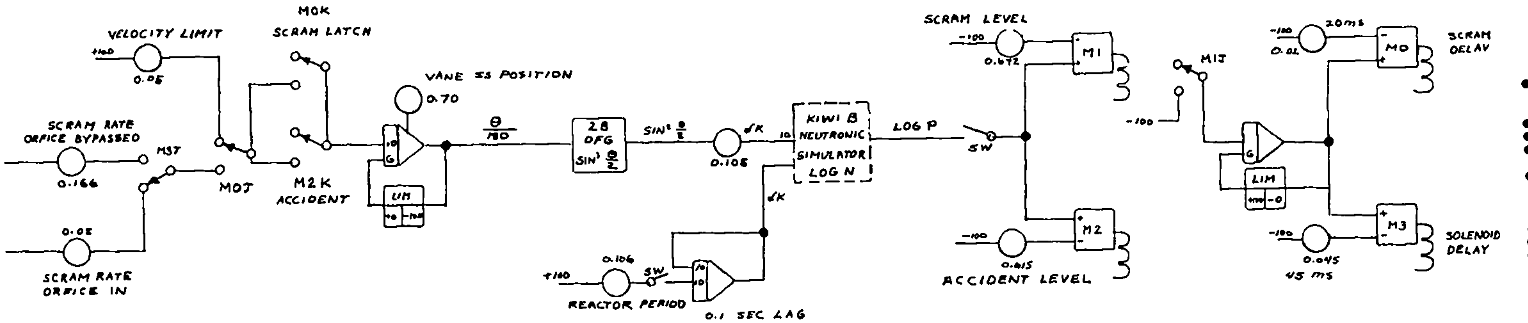
TABLE III (5 sec period, 500 MW)

VELOCITY LIMIT ACTUAL VANES	SCRAM SOLENOID ACTUAL VALVE	OVERSHOOT		
		Power MW	Power %	Wall Temp
18°/sec	Bypass used	316 MW	63.2%	110°R
90°/sec	Bypass used	730	146	84
90°/sec	Bypass not used	758	152	90

TABLE IV (Steady State, 1000 MW)

VELOCITY LIMIT ACTUAL VANES	SCRAM SOLENOID ACTUAL VALVE	OVERSHOOT		
		Power MW	Power %	Wall Temp
18°/sec	Bypass used	570 MW	57%	100°R
90°/sec	Bypass used	800	80	80
90°/sec	Bypass not used	820	82	85

[redacted]



VANE SCRAM RATE OR VANE VELOCITY LIMIT	POT SETTING
18°/SEC	0.01
45°/SEC	0.025
90°/SEC	0.05
300°/SEC	0.166

ALL RELAY CONTACTS SHOWN IN DEENERGIZED POSITION

FIGURE 1. ACCIDENT STUDIES KIWI-B

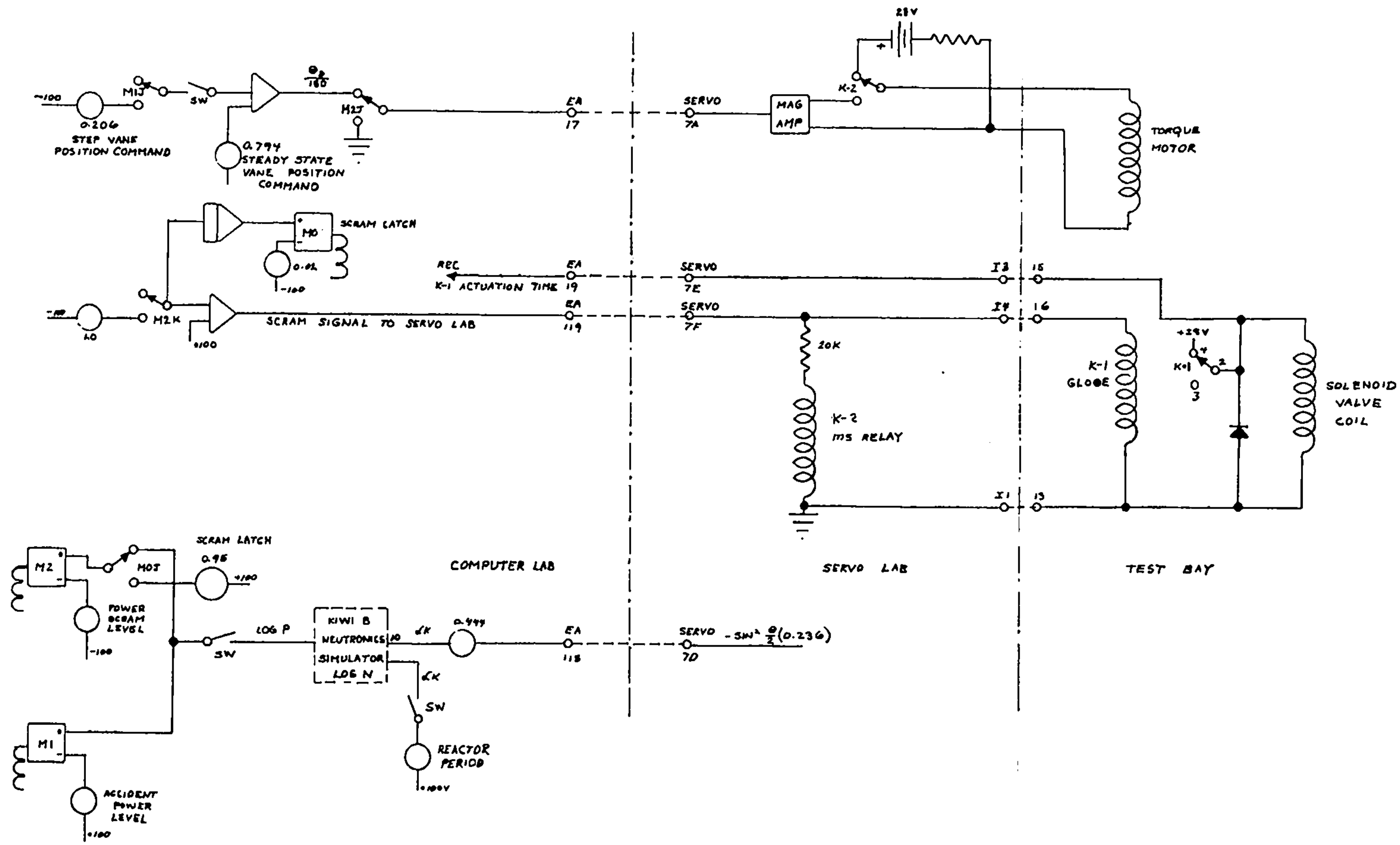


FIGURE 2. ACCIDENT STUDIES KIWI-B

KIWI-B-1 CONTROL VANE VELOCITY LIMITING

19 December 1960

A study has been conducted to investigate the feasibility of replacing the shim and regulator vane control package with a package containing only one type of vane servo. This servo would have a velocity limited vane, but the limit could not be less than approximately 45°/second to provide the same dynamic reactivity capability that can be obtained with two unlimited regulator vanes. Secondary objectives of the study were to obtain a better understanding of the effects of vane scram velocity and the scram system time delays on the ability of the power control system to minimize temperature overshoot during accidents.

Two preliminary assumptions were reached during meetings with N-2 personnel. First, the best protection from non-vane-generated accidents can be achieved with high vane velocity limits if the power control system operates properly. The upper limit on vane velocity is then established by the ability of the scram system to prevent damage due to vane-generated accidents. N-3 suggested the use of 500°R as the maximum allowable temperature rise at full power. The second assumption was that vane scram velocities in the order of 360°/second are desirable to reduce the effects of non-vane-generated accidents producing faster than prompt critical periods. This assumption is heavily influenced by the scram system time delay.

The term vane velocity limit refers to the maximum velocity of a vane when its actuator is driven through the torque motor. Scram velocity indicates the vane velocity, after a scram signal, when the actuator velocity limiting orifice has been bypassed or a scram spring has been released. This action is accomplished with a scram solenoid. Two parallel sequences occur when a scram signal is generated. First, a small signal relay impresses a battery voltage across the torque motor. This starts the vanes in at their velocity limited rate. A parallel signal operates the scram solenoid which increases the velocity of the vanes to the scram rate. The torque motor scram time delay, the time from scram signal

[redacted]

generation at the control building until the vane starts in, is approximately 20 milliseconds. The scram time delay through the solenoid has been in the order of 60 to 100 milliseconds on past reactors, but it is hoped that this figure can be reduced to something like 30 to 40 milliseconds for future systems.

Two independent accident studies were conducted by A. W. Charmatz and P. B. Erickson. The digital time-solution study done by Charmatz is reported in memoranda N-4-719 and N-4-771. Erickson's investigation was done with the analog computer and, in some cases, an actual Kiwi-B1-A rod servo. Erickson's work is described in memoranda N-4-723 and N-4-777. The data were obtained over several months of time with varying assumptions, initial conditions and simulation equipment. Therefore, it is difficult to correlate the data numerically. Gross numerical correlations are evident; however, and the general conclusions are consistent.

Common assumptions for all data are a Kiwi-B1 core configuration with an ℓ^* of 30 microseconds. The thermal time constant of the loaded portions of the fuel elements was assumed to be either 3 or 3.2 seconds. The worth of each vane was assumed to vary as the square of the sine of one-half the vane angular position relative to the maximum negative reactivity position. The worth of each vane was assumed to be 70¢. Temperature reactivity was considered in the analog study but not in the digital work.

Figures 1, 2, 3 and 4 show some of the early analog computer data with digital data points plotted where comparable assumptions exist. For these figures the rod package was assumed to consist of ten shim vanes and two regulator vanes. The accident studied consisted of either the shim vanes or all vanes going out at their velocity limited rates with the reactor operating at full power. The analog simulator consisted of a linear neutronic kinetics representation and a one-lump simple lag heat exchanger. The data shown in Figures 1 through 4 indicate the following:

1. Improvement in scram characteriestics can be realized by increasing the scram velocity to approximately 360°/second if the velocity limit is 18°/second and the scram delay time is 20 ms. The advantages of high scram velocities generally reduce with increasing scram time delays or velocity limits.

2. Vanes velocity limited to either 45°/second or 90°/second give better scrams than 18°/second vanes for scram time delays less than approximately 30 milliseconds.

[redacted]

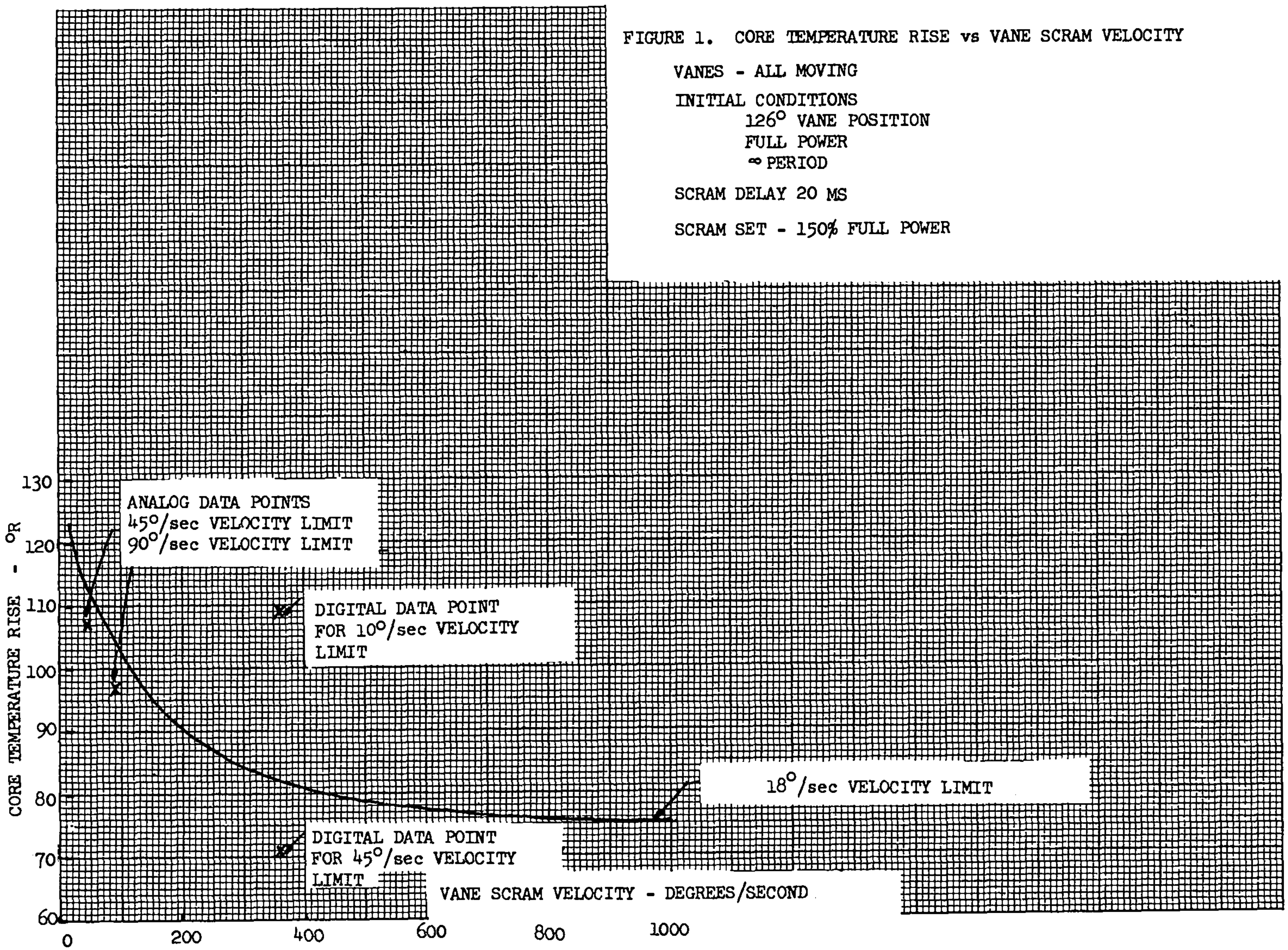
FIGURE 1. CORE TEMPERATURE RISE vs VANE SCRAM VELOCITY

VANES - ALL MOVING

INITIAL CONDITIONS
126° VANE POSITION
FULL POWER
∞ PERIOD

SCRAM DELAY 20 MS

SCRAM SET - 150% FULL POWER



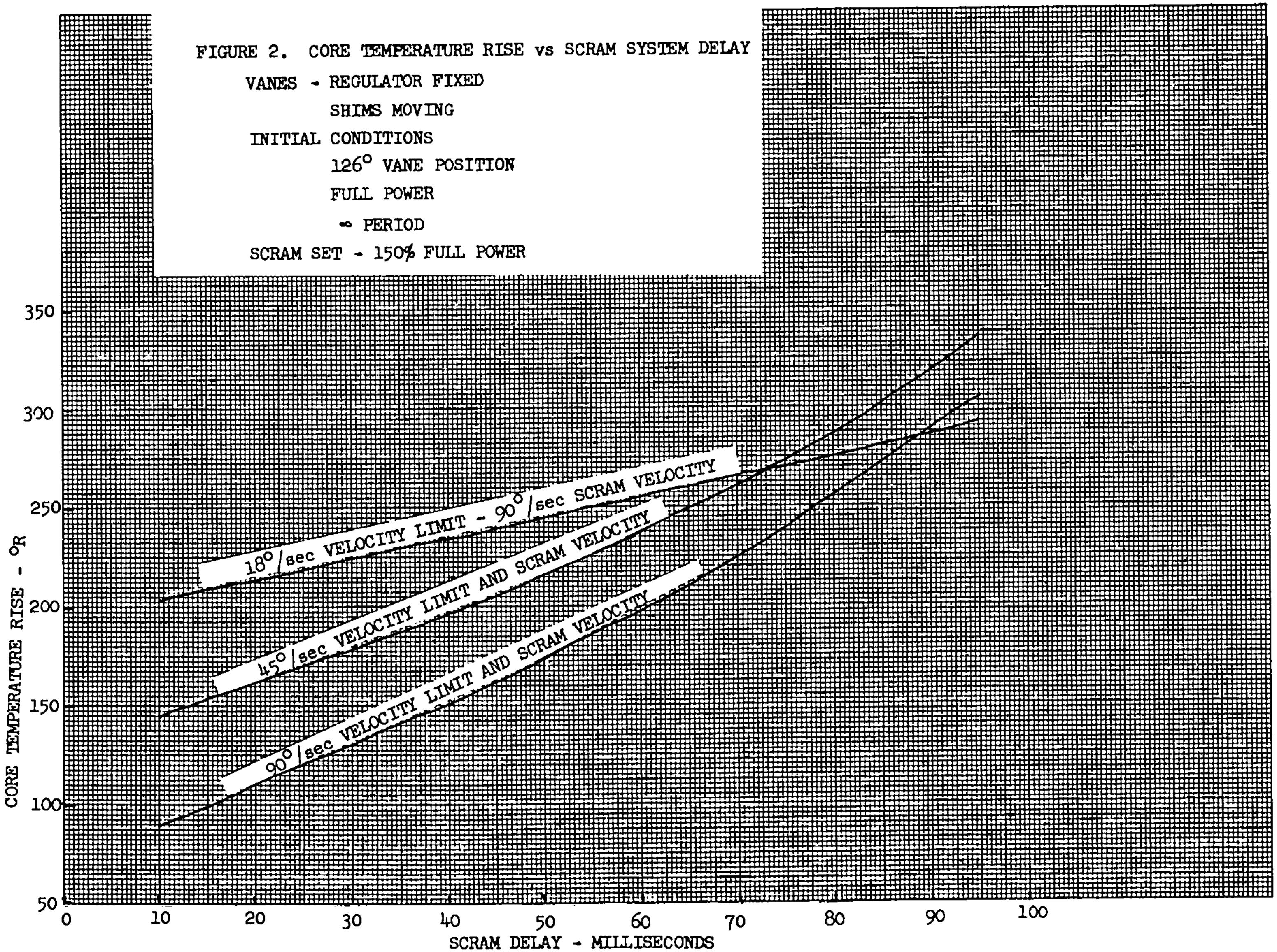


FIGURE 2. CORE TEMPERATURE RISE vs SCRAM SYSTEM DELAY

VANES - REGULATOR FIXED
SHIMS MOVING

INITIAL CONDITIONS
126° VANE POSITION
FULL POWER
∞ PERIOD

SCRAM SET - 150% FULL POWER

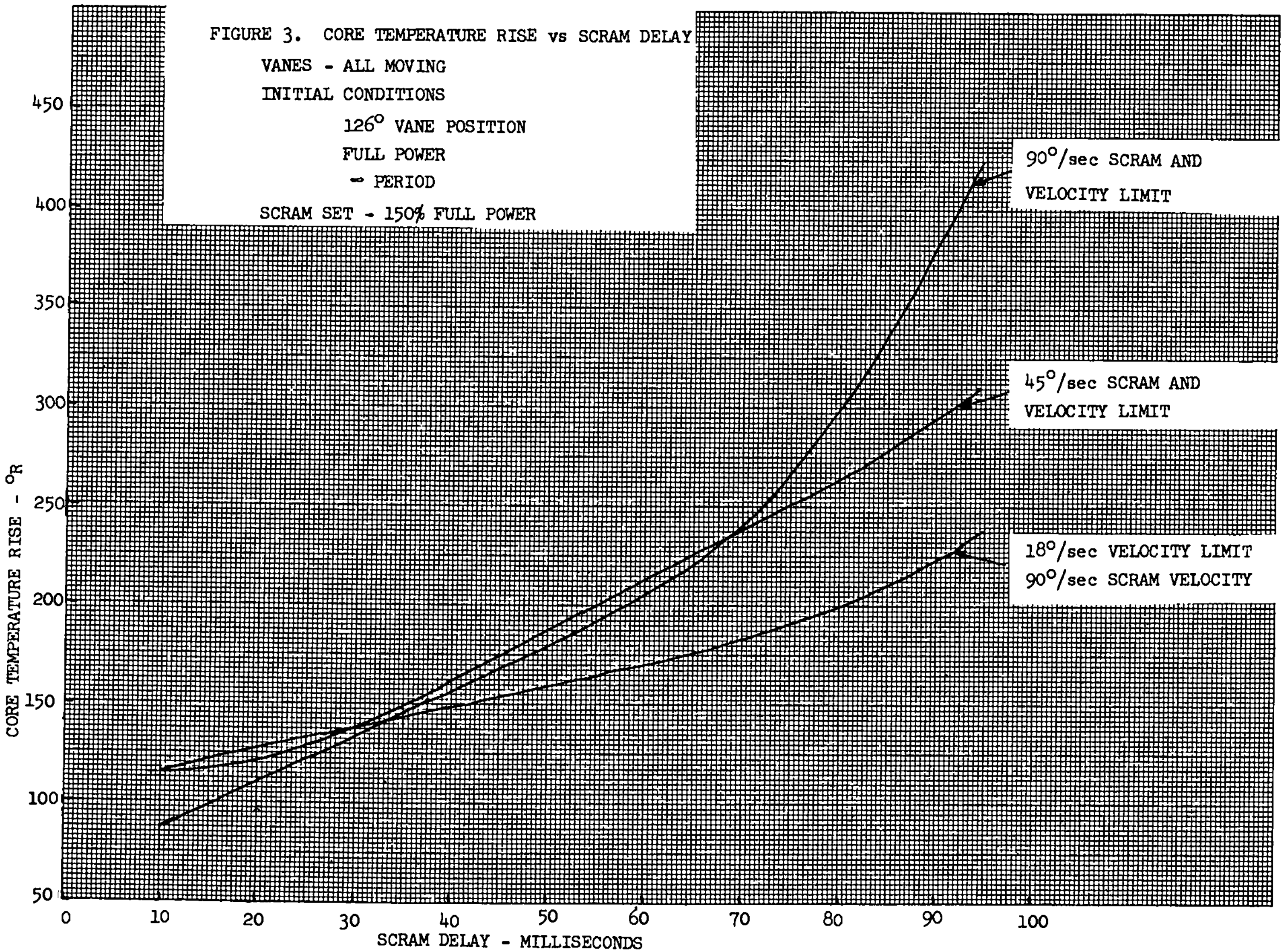


FIGURE 3. CORE TEMPERATURE RISE vs SCRAM DELAY

VANES - ALL MOVING

INITIAL CONDITIONS

126° VANE POSITION

FULL POWER

∞ PERIOD

SCRAM SET - 150% FULL POWER

[redacted]

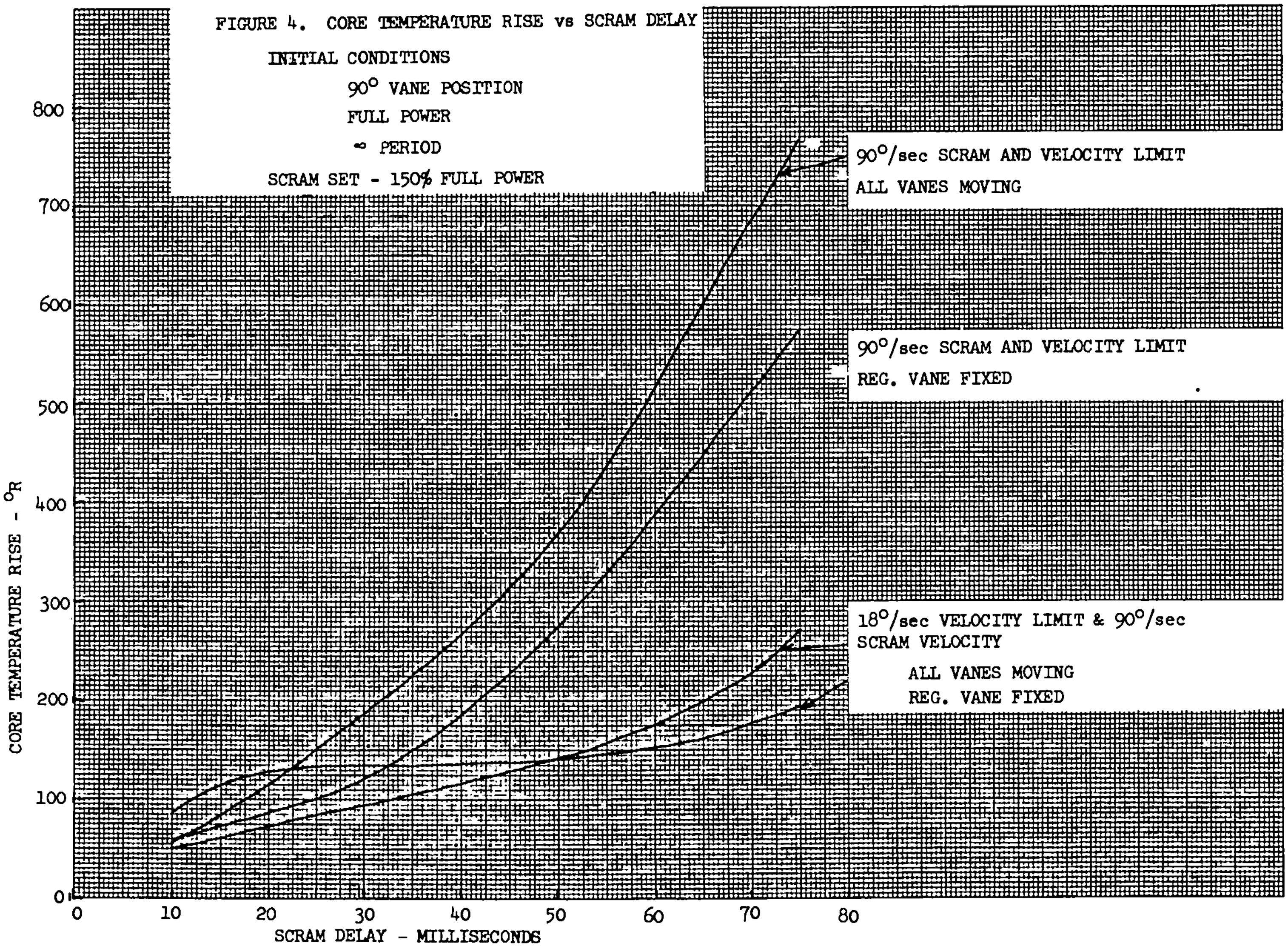


FIGURE 4. CORE TEMPERATURE RISE vs SCRAM DELAY

[redacted]

3. If the scram delay time can be kept below approximately 50 milliseconds, it is highly unlikely that any of the rod generated accidents considered during the early phases of the study would damage the core.

The data obtained during the first phase of the velocity limit study did not reveal any prohibitive characteristics associated with velocity limits up to 90°/second; therefore, it was decided to continue the work with a control package having all identical vane servos. At the suggestion of N-2, it was also decided to consider rod accidents with the reactor at various power levels and periods approximating fast start-up conditions. The complete Kiwi-B heat exchanger and neutronic kinetics simulators were used for this portion of the study. In addition, an actual Kiwi-B vane servo was used part of the time.

Tables I through V summarize the data obtained during the last phase of the velocity limit study. These data support the earlier conclusion that in all the cases studied either 45°/second or 90°/second velocity limiting gives better protection than 18°/second velocity limiting for realistic scram delay times. The data also show that a 90°/second velocity limited system would not require a higher scram velocity to control rod-generated accidents. However, unreported data indicate that scram velocities up to 360°/second provide considerable additional protection against high-speed non-vane-generated accidents if the scram solenoid delay time can be trimmed to less than approximately 35 milliseconds. It is felt that the high scram velocity characteristic should be retained.

If the high-speed, all identical vane servo system is adopted it is recommended that the velocity limit be approximately 90°/second. The 45°/second and the 90°/second systems have about the same vane accident probability and the 90°/second system has a better capability for controlling non-vane-generated transients and accidents.

Advantages which could be realized by using a 90°/second, all identical vane servo system rather than ten 18°/second shim vanes and two unlimited regulator vanes are as follows:

1. Core temperature rises caused by reactivity transients and accidents would be smaller.

2. Loss of up to possibly five vanes during a run would cut down the power system bandwidth slightly, but it would not stop the test unless the failure generated a scram. If an integral shim controller is used with the 18°/second system, the power control loop will become either unstable or marginally stable if the regulator vanes are lost.

[redacted]

[redacted]

TABLE I

VANE ACCIDENT DATA AT 1% OF FULL POWER ON A 0.5 SECOND PERIOD

Velocity Limit °/Second	Scram Velocity °/Second	Core Temp. Rise °R
18	300	0
45	300	0
45	45	0
90	300	0
90	90	0

Analog data

Vane accident at 1% of full power
Scram set -- 1.5% of full power
Simulated rod
Initial conditions
    Sustained 0.5 second period
Torque Motor Scram Delay -- 20 milliseconds
Scram solenoid delay -- 45 milliseconds

TABLE II

VANE ACCIDENT DATA AT HALF POWER ON A 5 SECOND PERIOD

Velocity Limit °/Second	Scram Velocity °/Second	Core Temp. Rise °R
18	310	110
90	310	84
90	90	90

Analog data

Vane accident at 50% of full power
Scram level set at 75% of full power
Actual vane servo and scram circuits
Initial conditions
    Sustained 5 second period

[redacted]

TABLE III

VANE ACCIDENT DATA AT
FULL POWER ON A 5 SECOND PERIOD

Velocity Limit °/Second	Scram Velocity °/Second	Core Temp. Rise °R
18	300	175
45	300	127
45	45	262
90	300	132
90	45	200

Analog Data

Vane accident at full power
Scram set -- 150% of full power
Simulated vane
Torque motor scram delay -- 20 milliseconds
Scram solenoid delay -- 20 milliseconds
Initial conditions
    Sustained 5 second period

TABLE IV

VANE ACCIDENT DATA AT
FULL POWER ON INFINITE PERIOD

Velocity Limit °/Second	Scram Velocity °/Second	Core Temp. Rise °R
18	310	100
90	310	80
90	90	85

Analog data

Scram level -- 150% of full power
Actual vane servo and scram circuits
Initial conditions
125° Vane position
    Full power
    ∞ period

TABLE V

VANE ACCIDENT DATA AT
33% OF FULL POWER ON A 5 SECOND PERIOD

Velocity Limit °/Second	Scram Velocity °/Second	Core Temp. Rise °R
18	360	123
45	360	85
45	45	187
90	360	106
90	90	226

Digital data

Vane accident at 33% of full power
Scram set -- 66% of full power
Torque motor and solenoid scram delay -- 35 milliseconds
Initial conditions
Sustained 5 second period

3. Pneumatic actuator size, weight, cooling gas requirements and technical difficulties would be reduced. These changes generally improve reliability.

4. The use of only one type of vane servo would reduce the power controller complexity, thus increasing reliability.

5. Control package field modifications and maintenance would be simplified.

The study failed to reveal any advantages of the shim and regulator vane system with 18°/second velocity limiting over the 90°/second system. However, both have a characteristic which conceivably could cause the destruction of a reactor core. If one assumes a simultaneous failure of the automatic scram system and the vane positioning system such that the vanes move out at maximum velocity, the core would be destroyed. Three solutions to this problem have been proposed. One is that the accident has such a low probability of occurrence that reasonable protection can be provided by using redundant circuits and highly reliable components. A good example is the use of two parallel scram systems between the control building and the test cell. The second proposal is to provide a circuit to automatically scram the vanes if excessive errors appear between demanded and actual vane positions for a predetermined period of time. The third solution is more a proposal for a different vane package than a solution to the 90°/second velocity limited package. It involves the use of a shim and regulator vane package with the shim vanes velocity limited to approximately 2°/second. With this system an alert operator possibly could scram the reactor manually before the core was damaged. This assumes that the automatic scram system failure was not between the operators scram button and the reactor. An arrangement of this type probably would use only one regulator vane because it is unlikely that an operator could stop a two-vane accident in time to prevent damage to the core. The shim and regulator vane system with 2°/second velocity limiting has not been studied; however, it appears to have a few disadvantages which must be weighed against the general feeling that reactor controls should be slow. Some of these are as follows:

1. The 2°/second system would require temperature or fast personnel scrams in addition to power scrams to protect the core. For example, consider the single accident of all shim rods going out at their limited rates. Power would remain constant for approximately 5 seconds until the regulator vane hit the full in stop. At this time the automatic power system would lose control and power would rise to the scram level in

a few seconds and scram the reactor. At this relatively slow rate of power increase the integral of the power excursion would be sufficient to overheat the core. Effective use of a temperature scram system to stop slow accidents of this type requires a temperature scram level only 5% to 10% above the operating temperature. Inadvertent scrams may be a problem under these conditions.

2. The system capability to control unanticipated reactivity transients would be reduced considerably. It is felt that this is an important factor for the low thermal time constant of the Kiwi-B1 core.

In conclusion, the study indicates that a control package consisting of all identical vane servos velocity limited to 90°/second is feasible. Compared to the 18°/sec system with two regulator vanes it would permit the use of a simpler, more reliable power control system with less probability of core destruction due to accidents. However, if multiple failures should result in the destruction of a core, it is possible for the destruction to be more violent with the 90°/second vane system.

It is not possible at this time to make a quantitative comparison between the 90°/second system and the shim and regulator vane package having shim vanes velocity limited to 2°/second. Qualitatively, it is felt that the 90°/second system would be better because the 2°/second package would degrade the power system dynamic performance and require either temperature or operator scrams in addition to power scrams.