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# Preliminary Study for Reactor Kinetics Modeling

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## 1. INTRODUCTION

This study introduced the simulation results of a draft computer program, Reactivity-X, to model the behavior of the pulse type reactivity insertion. Parameters such as power, reactivity, and temperature have been calculated as a function of time. The calculation model is developed as preliminary study for shot-time reactivity insertion behavior. In this study, from arbitrary experimental data, calculation results is compared. In this study, from the experiment results of reference 1 ~ 7, Reactivity-X program's performance is introduced for preliminary modeling of reactivity. All data is referenced from APR (Army Pulse Reactor) Core Design Summary report and Army Pulse Radiation Facility Reactor of ORNL report documents [1-5]. For preliminary study, Reactivity-X module is extracted from ORNL report's algorithm. In this study, simply, reference data and Reactivity-X module calculation are compared in the case of agreement in each other. Compared results is checked and Reactivity-X module's performance is reviewed.

## 2. CALCULATION METHODOLOGY

### *2.1 Calculation Theory of Reactivity-X*

The kinetics equations for a point-kinetics model are as follows:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\ell} n + \sum_i \lambda_i C_i \tag{1}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\ell} n - \lambda_i C_i \tag{2}$$

where: n is reactor power, ρ is the reactivity, ßi is the delayed neutron fraction of delayed neutron precursor *i*, *λi* is the delayed neutron decay constant for parental nuclide isotope *i*, *li* is the neutron generation time, and *Ci* is the delayed neutron population. The sum of all six ßi is ß. Slow transients in a fast reactor requires the solution of systems of equations containing very short time constants. Using the integral form of these equations will allow a numerical solution. Reactivity-X computer code can control the time step by many procedures. The integrals are evaluated analytically using the assumption that power follows the form: n(t) $e^{At}$.

Substitute the integral form for C from the second equation into the first equation, and integrate to obtain an equation for power as below:

$$n(t) = n_0 + \frac{1}{\ell}\int_{t_0}^{t} \rho(t')n(t')dt' + \sum_i \lambda_i C_{i0} \int_{t0}^{t} e^{-\lambda_i (t'-t0)} dt' - \sum_i \frac{\beta_i}{\ell} \int_{t0}^{t} n(t') e^{-\lambda_i (t'-t0)} dt' \tag{4}$$

The equation for reactivity has the form as below:

$$\frac{d\rho}{dt} = \alpha n(t) \tag{5}$$

$$\rho(t) = \rho_0 + \alpha \int_{t0}^{t} n(t')dt' \tag{6}$$

and with the assumption:

$$n(t) = n_0 e^{At}, \rho(t) = \rho_0 + \frac{\alpha n_0}{A}\left(e^{A(t-t_0)} - 1\right) \tag{7}$$

where: n, in units of W-sec, is the negative reactivity coefficient, which in this case includes the conversion of reactor power into heat generation. Substituting this result and our assumption into the power equation, we can integrate to get an equation that can be solved numerically:

$$n(t) = n_0 + \frac{\rho_0 n_0}{\ell A}\left(e^{Ah} - 1\right) + \frac{\rho_0 n_0^2}{\ell A^2}\left[\frac{1}{2}\left(e^{2Ah}+1\right) - e^{Ah}\right] - \sum_i C_{i0}\left(e^{-\lambda_i h} - 1\right) - \sum_i \frac{\beta_i n_0 e^{-\lambda_i h}}{\ell(A+\lambda_i)}\left(e^{(A+\lambda_i)h} - 1\right) \tag{8}$$

where: h is t-$t_0$.

A computer code, Reactivity-X, was written to solve the equation for A for a small time increment, h.

After A has been determined, reactor power and reactivity are easily calculated. These values are then used as the basis for the next time increment.

In this study, the safety block drop time of 200 ms was selected from test records. This test value is referenced from APR Core Design Summary reports [1-2]. Reactivity-X module is made [1-4]. But the module is introduced in the reference 1~2. In this study, the module source has converted txt and changed C++ source. And then the txt file is compiled by C++compiler in this study. The compiled calculation module can calculate the pulsed reactivity insertion [1-2]. Reactivity-X module and input/output is introduced in Appendix 1 and 2. For simplicity of this study, the safety rod block was removed linearly, $1 every 10 ms up to 150 ms for a total of $15. The actual removal of the safety rod block would start slow and proceed quicker with time.

Reactivity worth of $15 for the safety block and which is reported as $20 by the APRF Safety Analysis Report [1].

## 3. RESULTS AND DISCUSSIONS

According to reference 1 and reference 4, the safety block drop test method was used in analyzing the timing of the pulse rod. The time from the scram signal to the movement of the pulse rod was measured to be 160 ms. The drop time for the pulse rod to be completely out of the core was measured to be 360 ms. In this study, Reactivity-X program calculation is carried out in the same input conditions, $0.0353 every 30 ms up to 360 ms.

A comparison of calculation versus measurements for various reactivity insertions are presented in Table 1. The data presented here have been calculated out to 30 seconds. The data indicate that pulse-width-at-half-maximum (PWHM) from reference 1 and 2 can be resulted with very high accuracy for large pulses.

Table 1. Calculated and reference data in pulse insertion parameters

| Reactivity | Integrated Power | | Period, psec | | PWHM, psec | | Temp. Change, °C | |
|---|---|---|---|---|---|---|---|---|
| | M | C | M | C | M | C | M | C |
| 102 | 7 | 9.3 | 135 | 74 | 600 | 278 | 25 | 26 |
| 104 | 14.5 | 14.7 | 73 | 44 | 175 | 129 | 48 | 42 |
| 105 | 19 | 17.5 | 48 | 29 | 125 | 109 | 66 | 49 |
| 106.5 | 28 | 21.5 | 32 | 22 | 80 | 82 | 93 | 60 |
| 109 | 54 | 28 | 21.5 | 16 | 56 | 56 | 175 | 79 |
| 109.6 | 62 | 29.5 | 21 | 15 | 55 | 55 | 210 | 83 |

M: Reference data from reference 2 and reference 5
C : Calculated results in this study.

Table 2 shows a comparison of calculated values against the theoretical values of Wimett [3]. For this comparison, the calculated values have been converted into the units in Wimett's report. Furthermore, Wimett only calculated the fission yield under the spike; thus the total fission yield is not presented. As expected, the program's results are very close to theoretical values.

Table 2. Reactivity Pulse insertion parameters in Calculation and Wimett's theory

| Reactivity | Peak Power, $/sec | | Fission Yield, $ | | PWHM, psec | |
|---|---|---|---|---|---|---|
| | Wimett | Code* | Wimett | Code* | Wimett | Code* |
| 102 | 135 | 126 | 0.04 | 0.041 | 261 | 278 |
| 104 | 541 | 500 | 0.08 | 0.079 | 130 | 129 |
| 106.5 | 1413 | 1370 | 0.13 | 0.129 | 81 | 82 |
| 109 | 2813 | 2640 | 0.18 | 0.179 | 56.3 | 56 |

Code*) : Reactivity-X Calculation results

Table 3 lists different measured reactivity insertions correlated to a computed reactivity insertion using the new value for heat capacity. Using this value, and a reactivity insertion of $1.23, which would be a very large pulse in reality, the program will calculate a temperature change.

Table3. Reactivity Insertion Comparison

| Reactivity Insertion | | AT | Calculated AT at 120 Seconds | | |
|---|---|---|---|---|---|
| M | C | M | Norm | No Scram | PR Scram |
| 102 | 102 | 25 | 26 | 664 | 164 |
| 104 | 105 | 48 | 49 | 684 | 217 |
| 106.5 | 111 | 93 | 93 | 725 | 301 |
| 109 | 123 | 175 | 180 | 806 | 435 |

M: Reference data from reference 2 and reference 5
C : Calculated results of Reactivity-X in this study.

Results of the calculated temperatures after 30 seconds for these reactivity insertions with delayed scrams at 1, 5, and 10 seconds are listed in Table 4. The temperatures are initially 25 °C, which is the normal for reactor operations prior to initiating a pulse. Notice that for a normal scram, set point is 10 kW, the pulse below prompt critical has no temperature change. This is comparable to a mini-pulse operation where no temperature change is observable.

From Table 4, the peak fuel temperature change for any of the above pulses where the scram occurs at 1 second would not reach 350 °C. Note again that the temperatures calculated would be indicated temperatures; thus, using the conservative 1.43 peak to measured ratio, the safety limit of 650 °C would not be exceeded if the reactivity insertion is at or below 101 cents and the scram occurred at 10 seconds or less. Furthermore, a pulse-less tail operation is similar to a very wide pulse, in that the thermal stresses generated would be much less than the thermal stress generated in a high yield pulse, which the 650 °C safety limit has been established to prevent.

Table 4. Calculated Temperatures with various scrams using Reactivity-X

| Reactivity | Plateau Power | Temperature at 30 Seconds | | | |
|---|---|---|---|---|---|
| | | 10kW-Scram | Scram-1 sec | Scram-5 sec | Scram-10 sec |
| 99 | 2.3 MW | 25 | 106 | 319 | 432 |
| 100 | 3 MW | 30 | 138 | 336 | 444 |
| 101 | 4 MW | 43 | 152 | 347 | 454 |
| 102 | 6 MW | 51 | 163 | 357 | 462 |

Table 5 provides calculated temperatures for the same set of insertions with the scram occurring at 5 and 10 seconds; however, for these insertions the safety block is assumed to fail to drop and the pulse rod is the only scramming mechanism. By this table, no permanent damage will occur if the pulse rod drops, and if the pulse rod drops at 5 seconds, the safety limit of 650 °C will not be exceeded.

Table5. Calculated Temperature Pusle Rod with SCRAM in APRF report condition.

| Temperature at 30 Seconds | | |
|---|---|---|
| Reactivity | 5 sec | 10 sec |
| 99 | 414 | 491 |
| 100 | 430 | 503 |
| 101 | 441 | 512 |
| 102 | 451 | 521 |

## 4. CONCLUSIONS

A computer code was written using a point kinetics reactor model to calculate the pulse type reactivity insertion from data of pulse reactivity test document. The Reactivity-X code calculations have been compared to previous theoretical and reference empirical data to check the performance. Their results are in good agreement with the reference data. The pulse-less tail operation was investigated for delayed scrams at 1, 5, and 10 seconds. This revealed that for reactivity insertions exactly at prompt critical. A safety limit would not be exceeded for an operation up to a 101-cent insertion with a scram delayed up to 10 seconds.

## REFERENCES

[1] G. Breidenbach, APR Core Design Summary, United Nuclear Corporation SPAS 66-14, July 1966
[2] A. H. Kazi, H. A. Kurstedt, and V. E. Gazzillo, Preliminary Analysis of the Effect of Youngs Modulus on Fast Pulse Reactor Behavior, Memo for Record 78-68, August 1968.
[3] J. T. Mihalczo, Static and Dynamic Measurements with the Army Pulse Radiation Facility Reactor, ORNL-TM-2330, June 1969.
[4] H. A. Kurstedt, D. E. Glasgow, and T. E. Tipton, Analysis and Monitoring of a Fast Pulse Reactor Core, BRL contract report number 82, August 1970.
[5] H. Kazi, Army Pulse Radiation Facility Reactor Core III Startup Test Summary Report, March 1971.
[6] D. L. Hetrick, Dynamics of Nuclear Reactors, University of Chicago Press, 1971.
[7] S. Glasstone, and A. Sesonske, Nuclear Reactor Engineering third edition, Krieger Publishing Company, 1981.

## APPENDIX

### Reactivity-X input & output

```
INPUT FILE DATA:
      0.0002584   0.0127
      0.0014484   0.0317
      0.0012784   0.115
      0.0027676   0.311
      0.0008704   1.40
      0.0001768   3.87
      0.04683          -0.3         1.0e-8            25
         0.0           1.e-5          1.05        0.001
         1.e-3         1.e-3          0.00
         50.0e-3       1.0e-3        -0.05
         52.5e-3       1.0e-3        -0.10
         55.0e-3       1.0e-3        -0.10
         57.5e-3       1.0e-3        -0.25
         60.e-3        1.0e-3        -0.5
         70.e-3        1.0e-3        -1.0
         80.e-3        1.0e-3        -1.0
         90.e-3        1.0e-3        -1.0
         100.e-3       1.0e-3        -1.0
         120.e-3       1.0e-3        -1.0
         130.e-3       1.0e-3        -1.0
         140.e-3       1.0e-3        -1.0
         150.e-3       1.0e-3        -1.0
         160.e-3       1.0e-3        -1.0
         170.e-3       1.0e-3        -1.0
         180.e-3       1.0e-3        -1.0
         190.e-3       1.0e-3        -1.0
         200.e-3       1.0e-3        -1.0
         210.e-3       1.0e-3        -1.0
         0.5           1.0e-2         0.00
         1.00          0.1            0.00
         10.0          1.0            0.00
         30

BEGIN OUTPUT DATA:
     time        power (kW)       temp          rho         1/period       delta-t
 0.000000e+000 1.000000e-003 2.500000e+001 7.140000e-003
 1.000000e-005 9.503938e-003 2.500000e+001 7.140000e-003 1.054957e+005 2.242261e-008
 2.000000e-005 2.145182e-002 2.500000e+001 7.140000e-003 6.572550e+004 3.672489e-008
 3.000000e-005 3.823869e-002 2.500000e+001 7.140000e-003 5.178624e+004 4.905765e-008
 4.000000e-005 6.182468e-002 2.500000e+001 7.140000e-003 4.501189e+004 5.867678e-008
 5.000000e-005 9.496391e-002 2.500000e+001 7.140000e-003 4.115234e+004 9.312402e-008
 6.000000e-005 1.415261e-001 2.500000e+001 7.140000e-003 3.881214e+004 1.282834e-007
 7.000000e-005 2.069484e-001 2.500000e+001 7.140000e-003 3.729766e+004 1.203567e-007
 8.000000e-005 2.988707e-001 2.500000e+001 7.140000e-003 3.627950e+004 1.930491e-007
 9.000000e-005 4.280272e-001 2.500000e+001 7.140000e-003 3.559906e+004 1.649125e-007
 1.000000e-004 6.095005e-001 2.500000e+001 7.140000e-003 3.511921e+004 2.366062e-007
 1.100000e-004 8.644826e-001 2.500000e+001 7.140000e-003 3.479718e+004 2.246515e-007
 1.200000e-004 1.222749e+000 2.500000e+001 7.140000e-003 3.456455e+004 4.432042e-007
```