243
9-9-75
UC 79 d,e
plus UK, & Japan
summary

Dec. 16 13

HEDL TME 75-79
UC 79 d,e

A METHOD FOR DETERMINING
DETAILED ROD WORTH PROFILES
AT LOW POWER IN THE
FAST TEST REACTOR

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
A Subsidiary of Westinghouse Electric Corporation

P.O. Box 1970 Richland, WA 99352

MASTER

Prepared for the U.S. Energy Research and Development
Administration under Contract No. AT(45-1)-2170

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the U.S. ERDA, nor any of their employees, nor any of their contractors, sub-contractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$ 4.00; Microfiche \$2.25

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

A METHOD FOR DETERMINING
DETAILED ROD WORTH PROFILES
AT LOW POWER IN THE
FAST TEST REACTOR

by
R. A. Sevenich

August 1975

Hanford Engineering Development Laboratory

Operated by the
**Westinghouse
Hanford Company**

A Subsidiary of
Westinghouse Electric
Corporation

for the United States
Energy Research and
Development Administration
Contract No. AT(45-1)2170

,

,

,

,

A METHOD FOR DETERMINING DETAILED ROD
WORTH PROFILES AT LOW POWER IN THE
FAST TEST REACTOR

R. A. Sevenich

ABSTRACT

A method for obtaining a detailed rod worth profile at low power for a slow control rod insertion is presented. The accuracy of the method depends on a preparatory experiment in which the test rod is dropped quickly to yield, upon analysis, the magnitude of the rod worth and an effective source value. These numbers are employed to initialize the inverse kinetics analysis for the slow insertion. Corrections for changes in detection efficiency are not included for the simulated experiments.

r

s

.

v

CONTENTS

	<u>PAGE NO.</u>
1. INTRODUCTION	1
2. DESCRIPTION OF CALCULATIONAL MODEL	2
2.1 INVERSE KINETICS	2
2.2 IKRD SIMULATION	3
2.3 IKRRI SIMULATION	5
3. RESULTS OF SIMULATIONS	8
3.1 IKRD RESULTS	8
3.2 IKRRI RESULTS	9
3.3 UNCERTAINTY ASSESSMENT FOR IKRRI RESULTS	11
4. CONCLUSIONS	15
REFERENCES	16
APPENDIX A	A-1-6
APPENDIX B	B-1-11
APPENDIX C	C-1-8

FIGURES

<u>Figure No.</u>		<u>Page No.</u>
1	IKRD Simulation Flow Chart	4
2	IKRRI Simulation Flow Chart	6
3	Relative Reactivity as a Function of Relative Rod Insertion for IKRRI Simulation Input	7
4	Logic Diagram for IKRRI Experiment with Estimate of Uncertainty in Rod Worth Profile	13
5	Uncertainty Envelope for Output Reactivity Profile from IKRRI Simulation	14

TABLES

<u>Table No.</u>		<u>Page No.</u>
I	Inferred Reactivities from Three Independent Detectors Compared to Input Reactivities for an IKRD Simulation	8
II	Inferred Reactivities with Estimated Standard Deviations for a Thirty Detector IKRD Simulation	9
III	IKRRI Results Output Reactivity Profile Averaged from Three Independent Detectors	11

1. INTRODUCTION

An evaluation has been made of the possibility of employing an inverse kinetics technique to obtain accurate control rod calibration curves for the Fast Test Reactor (FTR) of the Fast Flux Test Facility (FFTF). This investigation is based on the analysis of simulated low-power reactor experiments. The proposed method is akin to inverse kinetics rod drop (IKRD) with the important distinction that in this method the control rod is slowly inserted into the reactor rather than dropped. It is convenient to use the acronym, IKRRI (inverse kinetics rod run-in) for this slow insertion experiment.

In its present form the IKRRI analysis assumes that changes in detection efficiency are insignificant. Future work incorporating a correction for such efficiency changes in situations where they are important will hopefully generalize this method and make its usefulness more universal.

It is illuminating to compare IKRRI to IKRD. The latter relies on rapid rod insertion for an accurate value of total rod reactivity, while the IKRRI technique requires the slower rod insertion to uncover the reactivity worth profile. The accuracy of IKRD experiments in the absence of significant detection efficiency changes has been firmly established⁽¹⁾. It has been suggested that the relative inaccuracy of the IKRRI analysis might be ameliorated by initializing the IKRRI experiment by a preparatory IKRD experiment⁽⁵⁾. This report shows that expectation to be justified.

This method can be used for calibration of control rods in the FTR reactor if the Low Level Flux Monitor (LLFM) positions have only small detection efficiency changes. Preliminary indications⁽⁵⁾ suggest that this will be the case for the two LLFM locations in trisectors other than the one corresponding to the test rod position. Data from even the third LLFM position can be employed for reactivity insertions of small enough magnitude so that the detection efficiency changes are insignificant.

2. DESCRIPTION OF CALCULATIONAL MODEL

2.1 Inverse Kinetics

The inverse kinetics analyses discussed here are rooted in the point reactor equations,

$$\frac{dn}{dt} = (\rho - \beta) \frac{n}{\Lambda} + \sum_i \lambda_i c_i + q$$

$$\frac{dc_i}{dt} = \beta_i \frac{n}{\Lambda} - \lambda_i c_i ,$$

where n = average number of neutrons/volume
 t = time
 ρ = reactivity
 Λ = prompt neutron generation time
 c_i = number/volume of type i precursors
 β_i = fraction of neutrons from precursor type i
 q = source term
 $\beta = \sum_i \beta_i$.

Six precursor groups are usually adequate so that the index i runs from 1 to 6. The point reactor equations are, of course, approximate. In particular, there is no mention of the spatial dependence of the parameters involved. A careful derivation of these equations from transport theory indicates the precise nature of the approximations involved^(6,7). For the purposes of this discussion it is sufficient to note that the equations are useful when the reactor is near critical with no large localized perturbations in the flux shape.

Inverse kinetics solves these equations for $\rho(t)$ after relating $n(t)$ to the count rate from the neutron detectors. If q is known, the equations are quite simply coded for computer calculation. However, q is typically unknown and the solution for $\rho(t)$ is less straightforward. In the method developed by Cohn⁽¹⁾ the reactivity for times after rod motion had stopped was fitted to the function $A + Bf(t)$. Arguing that the reactivity must be constant after

the cessation of rod motion, a search was made for a source value yielding $B = 0$. A conceptually similar approach was advanced by Yang and Albrecht⁽⁴⁾. Their scheme involved solving the point reactor equations for the source term and fitting it to a curve $a+bZ(t)$. Because the source term is constant over the time period of the experiment, a minimization scheme is applied to b by finding the value of final reactivity giving $b = 0$.

In principle, codes such as the Cohn or Yang-Albrecht algorithms could be used whether the rod is inserted quickly or slowly. However, in both algorithms the minimization and search schemes are based on the count rate data after rod motion has stopped. In the case of a slow rod insertion these late data are at such a low count rate that the noise level seriously interferes with the minimization and search schemes. As mentioned in the introduction, this difficulty can be partly overcome by using an IKRD experiment to find an accurate source value and then performing the IKRRI experiment. When done in this fashion the inverse kinetics code needs no minimization and search capability because the source value is now known.

2.2 IKRD Simulation

For simulation of either IKRD or IKRRI experiments, count rate data characteristic of the reactivity insertion must be simulated. Such data were prepared for these applications by use of a direct kinetics subroutine. A derivation of such an algorithm from the point reactor equations appears in Appendix A. Detection noise to be superimposed on the data was constructed employing the pseudo random number generating function called RANF, available as a FORTRAN function. RANF yields pseudo random numbers distributed uniformly on the interval 0 to 1. These numbers were then converted to a Gaussian distribution characteristic of the nuclear counting statistics.

Figure 1 presents a flow chart for the IKRD simulation. The 'input' parameters include an effective source value, the initial reactivity characterizing the slightly subcritical equilibrium state of the reactor before the rod drop, and the final reactivity after the drop. In an actual experiment the degree of initial subcriticality is chosen to maximize the detector count rate without exceeding the dynamic range of the detection system and

Figure 1. IKRD Simulation Flow Chart.

without introducing significant counting losses. Such a choice lessens the effect of detection noise. The direct kinetics subroutine employs the input parameters to generate the corresponding noisy count rate profile. The inverse kinetics code then analyzes this simulated profile yielding as 'output' parameters the initial reactivity, the final reactivity, and an effective source value. Comparison of the input to the output parameters completes the IKRD simulation.

A derivation of the inverse kinetics code is available elsewhere⁽⁸⁾ and is not presented here. The code chosen is the Yang-Albrecht algorithm because of its demonstrated lack of bias. A Fortran listing of the code appears in Appendix B.

2.3 IKRRI Simulation

Figure 2 is a flow chart for the IKRRI simulation. The input reactivity profile is of the form

$$\rho = Ax + Bx^2 + Cx^3$$

where A, B, and C are coefficients and x is the distance the rod is inserted into the reactor. It is assumed that the test rod is inserted at a constant speed so that x varies linearly with time. If ρ is normalized to the net worth of the rod and if x is normalized to the full insertion length then both ρ and x vary from 0 to 1 as the rod is inserted. This convenient normalization would therefore require that $A + B + C = 1$. Figure 3 displays the $\rho(x)$ dependence chosen for the simulation. This dependence is used to drive the direct kinetics subroutine which generates the simulated count rate data. These data are then analyzed with inverse kinetics. Note that the inverse kinetics code has available to it the effective source value gleaned from the IKRD experiment. Consequently the inverse kinetics employed in the IKRRI experiment is simpler than that needed for the IKRD analysis. This simpler inverse kinetics algorithm is derived in Appendix A. The reactivity values inferred by inverse kinetics are then fit to the functional form

$$\rho = A'x + B'x^2 + C'x^3 + D'x^4 .$$

Figure 2. IKRRI Simulation Flow Chart.

Figure 3. Relative Reactivity as a Function of Relative Rod Insertion for IKRRI Simulation Input

In the absence of noise on the simulated data one finds

$$A' \approx A, B' \approx B, C' \approx C, \text{ and } D' \approx 0.$$

In the presence of noise such close matching of input to output reactivity coefficients does not occur, but the point-by-point comparison of the input-to-output reactivity profiles is favorable.

3. RESULTS OF SIMULATIONS

3.1 IKRD Results

A Fortran listing of the Yang-Albrecht code employed for IKRD analysis appears in Appendix B. To exploit the advantages of statistics it would be desirable to measure the test rod with a high number of rod drop experiments. Because of the high value of reactor time this is not possible in practice. If detection noise is the principal cause of drop-to-drop variation then the use of several independent detection systems can partly alleviate the need for a large number of drops. FTR, for example, has three independent low level detection systems and one rod drop results in three count rate profiles with independent detection noise statistics.

Table I presents results for the simulated analysis of count rate profiles from three detectors looking at the same rod drop.

Table I
Inferred Reactivities from Three Independent
Detectors Compared to Input Reactivities
for an IKRD Simulation

	Input to Direct Kinetics	Inferred from Detector 1	Inferred from Detector 2	Inferred from Detector 3	Average from all 3 Detectors
Initial Reac- tivity	-.01\$	-.00991\$	-.010005\$	-.010002\$	-.00997\$
Final Reac- tivity	-3.95\$	-3.941\$	-3.946\$	-3.942\$	-3.943\$

To examine the statistical spread to be expected in such simulations a computer run for thirty such detectors was made. The results appear in Table II with the estimated standard deviations for the initial and final reactivities. In both Tables I and II the input reactivity to the direct kinetics sub-routine is presented so comparisons can be made. The accuracy of the results is enhanced as the initial count rate is made larger. On the other hand, if the initial count rate is too high it may exceed the range of the detection system or get into a region where counting losses become significant. For this analysis the initial count rate at one cent subcritical was taken to be approximately 2.6×10^5 cps.

Table II
Inferred Reactivities with Estimated Standard
Deviations for a Thirty Detector IKRD Simulation

	<u>Input to Direct Kinetics</u>	<u>Average from 30 Detectors with Estimated Standard Deviation</u>
Initial Reac- tivity	-.0100\$	-.009995\$ ($1\sigma = .000035\%$)
Final Reac- tivity	-3.9500\$	-3.9476\$ ($1\sigma = .0056\%$)

3.2 IKRRI Results

A Fortran listing of the IKRRI analysis appears in Appendix C. The direct kinetics code is driven by a reactivity dependence

$$\rho_{in} = Ax + Bx^2 + Cx^3$$

where $A = .06$,
 $B = 2.82$, and
 $C = -1.88$.

Detection noise is then superimposed on the simulated count rate data. The inverse kinetics code, initialized by the IKRD experiment, then infers a reactivity versus time profile which is converted to a reactivity versus rod length inserted profile. The latter profile is then fitted in a least squares manner to the dependence

$$\rho_{out} = A'x + B'x^2 + C'x^3 + D'x^4.$$

The 4th order dependence allows for sufficient detail in the reactivity profile. In an actual measurement ρ_{in} would be unknown so that choice of a 3rd order dependence for ρ_{out} was not made, to avoid deceptively good results.

To assess the ability of the code to extract the $\rho(x)$ dependence a noise-free simulation was carried out and yielded

$$\begin{aligned} A' &= .0607 \\ B' &= 2.8185 \\ C' &= -1.8758, \text{ and} \\ D' &= -.003437 \end{aligned}$$

matching the input A, B, and C rather well.

With detection noise present the match of the ρ_{out} coefficients to the ρ_{in} coefficients suffers, but a point-by-point comparison of the ρ_{out} and ρ_{in} profiles still shows excellent agreement. Such a comparison is shown in Table III. Note that all entries in that table are dimensionless. The fractional differences at various points between the ρ_{out} and ρ_{in} profile appear in the third column. All the fractional differences are quite small. Incidentally, the extremely small fractional difference at the end of the table results from the constraint on the fitting routine that the relative rod worth be unity when the relative rod insertion reaches unity. Thus the IKRRI analysis is quite reasonable for extracting the reactivity profile in the presence of noise on the count rate data.

Table III
IKRRI Results
Output Reactivity Profile
Averaged from Three Independent Detectors

<u>Input Relative Reactivity Profile</u>	<u>Output Relative Reactivity Profile</u>	<u>Fractional Difference</u>	<u>Relative Rod Insertion</u>
.2312963-02	.238822E-02	-.325396E-01	.200000E-01
.133459E-01	.134954E-01	-.111977E-01	.600000E-01
.323200E-01	.324736E-01	-.475160E-02	.100000E+00
.585133E-01	.586349E-01	-.207802E-02	.140000E+00
.912038E-01	.912865E-01	-.906813E-03	.180000E+00
.129670E+00	.129731E+00	-.473305E-03	.220000E+00
.173189E+00	.173266E+00	-.446443E-03	.260000E+00
.221040E+00	.221186E+00	-.658358E-03	.300000E+00
.272500E+00	.272777E+00	-.101368E-02	.340000E+00
.326849E+00	.327324E+00	-.145306E-02	.380000E+00
.383363E+00	.384105E+00	-.193654E-02	.420000E+00
.441320E+00	.442395E+00	-.243507E-02	.460000E+00
.500000E+00	.501463E+00	-.292591E-02	.500000E+00
.558680E+00	.560574E+00	-.338990E-02	.540000E+00
.616637E+00	.618987E+00	-.380966E-02	.580000E+00
.673151E+00	.675957E+00	-.416838E-02	.620000E+00
.727500E+00	.730736E+00	-.444880E-02	.660000E+00
.778960E+00	.782568E+00	-.463235E-02	.700000E+00
.826811E+00	.830695E+00	-.469819E-02	.740000E+00
.870330E+00	.874353E+00	-.462229E-02	.780000E+00
.908796E+00	.912773E+00	-.437609E-02	.820000E+00
.941487E+00	.945182E+00	-.392495E-02	.860000E+00
.967680E+00	.970802E+00	-.322603E-02	.900000E+00
.986654E+00	.988850E+00	-.222521E-02	.940000E+00
.997687E+00	.998538E+00	-.852922E-03	.980000E+00
.100000E+01	.100000E+01	-.142109E-13	.100000E+01

3.3 Uncertainty Assessment for IKRRI Results

It is desirable to obtain good estimates for the uncertainty in the rod worth profile resulting from the IKRRI analysis. Classical propagation-of-error techniques have been successfully applied to IKRD experiments analyzed with the 'three-point method⁽⁹⁾.' However, an IKRRI experiment corresponds to a reactivity which varies slowly with time and the inverse kinetics do not yield a simple closed form for the dependence of inferred reactivity on the

observed count rate. This lack of simplicity is compounded by the fact that the statistical error in count rate values changes with the count rate as the rod is inserted. For these reasons a classical propagation-of-error analysis becomes intractable for an IKRRI measurement. Consequently, an intuitively equivalent scheme of error analysis has been devised to estimate uncertainties. This method would employ data from an experimental rod run-in to construct many quantitatively equivalent simulations from which estimates of standard deviations in the reactivities are calculated. It should be emphasized that these multiple simulations do not correspond to multiple experiments but rather are constructed from information generated by a single rod run-in experiment.

Figure 4 is a logic diagram of this uncertainty estimation scheme for a situation in which the rod run-in is observed by three independent detection systems. Figure 5 displays the uncertainty band corresponding to the $\rho_{out}(x)$ discussed in Section 3.2 of this report. The uncertainty band is the $\pm 2\sigma(x)$ envelope about $\rho_{out}(x)$ where $\sigma(x)$ is the estimated standard deviation of $\rho_{out}(x)$. The listing of the IKRRI code in Appendix C includes this uncertainty analysis. The coefficients A, B, C, and D are found from each of the detector count rate profiles. Each of the three coefficient sets is then used to create a population sample of noisy count rate profiles. Next a reactivity profile is calculated from each count rate profile via inverse kinetics. The resulting set of reactivity profiles provides a basis for calculating estimates for the standard deviations for each reactivity point on the rod worth curve. As mentioned in Section 3.2, the rod worth curve itself is constructed using the average A, B, C, and D values from the three coefficient sets from the three detectors.

Figure 4. Logic Diagram for IKRRI Experiment with Estimate of Uncertainty in Rod Worth Profile.

HEDL 7507-43.1

Figure 5. Uncertainty Envelope for Output Reactivity Profile from IKRRI Simulation

4. CONCLUSIONS

The IKRRI technique discussed in this report is capable of recovering reactivity profile detail from noisy count rate data. It must be recalled that in its present form it cannot handle significant changes in detection efficiency. However, corrections for such changes are under study and it may be feasible to incorporate such modifications into the technique. The relatively high accuracy of the IKRRI technique is a direct result of the suggestion⁽⁵⁾ that the inverse kinetics be initialized by a preparatory IKRD experiment.

REFERENCES

1. C.E. Cohn, "Experience with Subcriticality Determination by Rod Drop in the FTR-3 Critical Experiments," Trans. Am. Nucl. Soc., 14, 29, 1971.
2. S.G. Carpenter and R.W. Goin, "Rod-Drop Measurements of Subcriticality," Applied Physics Division Annual Report, July 1, 1969 to June 30, 1970, ANL-7710, pp. 206-209.
3. D.H. Shaftman, "Estimation of Degree of Subcriticality of ZPR Fast-Criticals Configurations by Methods of Neutron Source Multiplication," Argonne National Laboratory, ZPR-TM-102, April 1972.
4. C.Y. Yang and R.W. Albrecht, "Subcriticality Determination by a Novel Inverse Kinetics Technique," Trans. Am. Nucl. Soc., 16, 297, 1973.
5. R.M. Fleischman, J.W. Upton, Jr., and R.A. Bennett, "Subcritical Reactivity Surveillance Procedures for the Fast Flux Test Facility," HEDL-TME 73-43, May 1973.
6. G.I. Bell and S. Glasstone, "Nuclear Reactor Theory," Van Nostrand Reinhold Co., Ch. 9, 1970.
7. D.L. Hetrick, "Dynamics of Nuclear Reactors," Univ. of Chicago Press, Chs. 1 and 8, 1971.
8. C.Y. Yang and R.W. Albrecht, "Inverse Kinetics Determination of Subcriticality," Nucl. Technol. 22, 323, 1974.
9. J.W. Allen, J.C. Robinson, and N.J. Ackermann, Jr., "Statistical Errors in Subcritical Reactivity Inferred from Inverse Kinetics Rod Drop Measurements Using the Three-Point Method," Nucl. Technol. 22, 315, 1974.

APPENDIX A
Derivation of Direct Kinetics Equations
and Derivation of Inverse Kinetics
Equations With Known Source

The point reactor equations previously mentioned in Section 2.1 are

$$\frac{dn}{dt} = (\rho - \beta) \frac{n}{\Lambda} + \sum \lambda_i c_i + q \quad (A-1)$$

and

$$\frac{dc_i}{dt} = \beta_i \frac{n}{\Lambda} - \lambda_i c_i, \quad i=1, \dots, 6. \quad (A-2)$$

Let $N(t)$ be the number of counts during a time interval Δt ending at t . The efficiency $\epsilon(t)$ can be defined by

$$N(t) = \epsilon(t) \frac{n(t)}{\Lambda}. \quad (A-3)$$

Our assumption of constant detection efficiency allows us to rewrite this as

$$N(t) = \frac{1}{\alpha} n(t) \quad (A-4)$$

where α is constant. Rewriting the point reactor equations in terms of $N(t)$ yields

$$\Lambda \frac{dN}{dt} = (\rho - \beta) N + \sum \lambda_i C_i + S \quad (A-5)$$

and

$$\frac{dC_i}{dt} = \beta_i N - \lambda_i C_i, \quad (A-6)$$

where we have defined the parameters C_i and S by

$$C_i = \frac{\Lambda}{\alpha} C_{i0} \text{ and } S = \frac{\Lambda}{\alpha} q.$$

For either an IKRD or an IKRRI experiment the reactor is initially in a slightly subcritical equilibrium state. Designating that initial state by the subscript 0 and noting that the time derivatives in Eqs. (A-5) and (A-6) vanish, it then follows from those equations that

$$(\rho_0 - \beta)N_0 + \sum \lambda_i C_{i0} + S = 0 \quad (A-7)$$

and

$$0 = \beta_i N_0 - \lambda_i C_{i0} = 0. \quad (A-8)$$

Solving for C_{i0} and S gives

$$C_{i0} = \frac{\beta_i}{\lambda_i} N_0 \quad (A-9)$$

and

$$S = -\rho_0 N_0. \quad (A-10)$$

Equations (A-9) and (A-10) comprise important information for a direct kinetics algorithm.

To obtain direct kinetics equations it is convenient and sufficiently accurate to employ the zero lifetime approximation which holds when

$$\Lambda \left| \frac{dN}{dt} \right| \ll \left| (\rho - \beta) N \right|.$$

Qualitatively, this requires that Λ be quite small, that ρ be less than and not too near β , and that no fast transients occur. These conditions are easily met by the IKRD and IKRRI experiments proposed for low power physics tests in the FTR, for example. In this approximation, Eqs. (A-5) and (A-6) become

$$0 = (\rho - \beta) N + \sum \lambda_i C_i + S \quad (\text{A-11})$$

and

$$\frac{dC_i}{dt} = \beta_i N - \lambda_i C_i. \quad (\text{A-12})$$

Solving Eq. (A-11) for $N(t)$ gives

$$N(t) = \frac{S + \sum \lambda_i C_i(t)}{\beta - \rho(t)}. \quad (\text{A-13})$$

Now in direct kinetics $\rho(t)$ is known, so according to Eq. (A-13), $N(t)$ can be generated if the $C_i(t)$ can be determined.

To obtain the $C_i(t)$, Eq. (A-12) is rewritten as

$$\frac{d}{dt} \left[e^{\lambda_i t} C_i(t) \right] = e^{\lambda_i t} \beta_i N(t). \quad (\text{A-14})$$

Integrating from t to $t + \delta t$ results in

$$C_i(t + \delta t) = C_i(t) e^{-\lambda_i \delta t} + \beta_i e^{-\lambda_i(t + \delta t)} \int_t^{t + \delta t} e^{\lambda_i t'} N(t') dt'. \quad (\text{A-15})$$

If δt is chosen to be small enough so that $N(t')$ varies little over the interval of integration then $N(t')$ can be approximated by $N(t)$ and slipped out of the integral. The integral can then be performed yielding

$$C_i(t+\delta t) = C_i(t)e^{-\lambda_i \delta t} + \frac{\beta_i}{\lambda_i} N(t) \left[1 - e^{-\lambda_i \delta t} \right]. \quad (A-16)$$

All the ingredients of the algorithm now are present. Equations (A-9) and (A-10) comprise the starting equations. Equation (A-16) is next employed to generate the first nonequilibrium C_i which is then employed in Eq. (A-13) to generate the subsequent N value. The loop through Eqs. (A-16) and A-13) is then continued until the desired $N(t)$ profile is generated. Thus the necessary equations for the direct kinetics algorithm, gathered together, are

$$C_{i0} = \frac{\beta_i}{\lambda_i} N_0$$

$$S = -\rho_0 N_0$$

$$C_i(t+\delta t) = C_i(t)e^{-\lambda_i \delta t} + \frac{\beta_i}{\lambda_i} N(t) \left[1 - e^{-\lambda_i \delta t} \right]$$

$$N(t+\delta t) = \frac{S + \sum \lambda_i C_i(t+\delta t)}{\beta - \rho(t+\delta t)}.$$

In both appendices B and C the algorithm entitled, DRKIN, is based on these equations. It is worth noting that in that subroutine the experimental time interval for counting is called, DT , while the calculational time interval corresponding to δt is called TL , which equals DT divided by an integer chosen to legitimize the approximation used to obtain Eq. (A-16).

Equations (A-11) and (A-12) can also provide the basis for the inverse kinetics algorithm. However, to allow for the possibility of perceiving some transient behavior, it was decided to employ the point reactor equations in their less approximate form using Eq. (A-5) rather than (A-11). Recall Eq. (A-15), and to allow for a more rapid time variation, assume

$$N(t') = N(t)e^{-\gamma(t'-t)} \quad (A-17)$$

so that after integration, Eq. (A-15) becomes

$$C_i(t+\Delta t) = C_i(t)e^{-\lambda_i\delta t} + \frac{\beta_i}{\lambda_i-\gamma} [N(t+\delta t) - N(t)e^{-\lambda_i\delta t}] \quad (A-18)$$

$$\text{with } \gamma(t) = \frac{1}{\delta t} \ln \frac{N(t)}{N(t+\delta t)} . \quad (A-19)$$

Combining Eqs. (A-5) and (A-17) results in the form

$$-\gamma\Delta N(t) = \left[\rho(t) - \beta \right] N(t) + \sum \lambda_i C_i(t) + S \quad (A-20)$$

which when solved for $\rho(t)$ gives

$$\rho(t) = \beta - \gamma(t)\Delta - \frac{\sum \lambda_i C_i(t) + S}{N(t)} . \quad (A-21)$$

Gathering together the equations needed for the inverse kinetics subroutine gives the list

$$C_{i0} = \frac{\beta_i}{\lambda_i} N_0$$

$$\rho_0 = -S/N_0$$

$$C_i(t+\delta t) = C_i(t)e^{-\lambda_i\delta t} + \frac{\beta_i}{\lambda_i-\gamma(t)} \left[N(t+\delta t) - N(t)e^{-\lambda_i\delta t} \right]$$

$$\rho(t) = \beta - \lambda \gamma(t) - \frac{\sum \lambda_i C_i(t) + S}{N(t)}$$

$$\text{with } \gamma(t) = \frac{1}{\delta t} \ln \left[\frac{N(t)}{N(t+\delta t)} \right].$$

These equations are the basis for the subroutine called RHOPRO appearing in Appendix C.

APPENDIX B
IKRD Fortran Listing

```

COMMON/AXX/BETA(6),YAMBDA(6),PNG,TBETA,TA(6),TB(6),REFER,
$  W(7),A(7),NW
COMMON/REG/FLUX(2000)
DIMENSION JDATA(2000),REAC(50),BREAC(50),SRCE(50)
DIMENSION YBETA(6),Y(6),B(6),GF(6),      XINT(6)
REAL JDATA

C
C-BETA,LAMBDA AND PNG VALUES
READ(4,60) (BETA(I),I=1,6),(YAMBDA(I),I=1,6),PNG
60 FORMAT(6E12.6)
WRITE(5,61)
61 FORMAT(18H BETAS AND LAMBDA S)
WRITE(5,62) (BETA(I),YAMBDA(I),I=1,6)
62 FORMAT(2E12.6)
WRITE(5,63) PNG
63 FORMAT(24H NEUTRON GENERATION TIME,E12.6)
REFER=YAMBDA(4)
TBETA=0.
RHOIH=0.
DO 30 I=1,6
TBETA=TBETA+BETA(I)
RHOIH=RHOIH+BETA(I)/(1.+3600.*YAMBDA(I))
30 YBETA(I)=BETA(I)/YAMBDA(I)
RHOIH=(PNG+3600.*RHOIH)/3600.
DCLLAR=TBETA/RHOIH
CALCULATING CONSTANTS OF INHOUR EQUATION -- TA(6) AND TB(5)
DO 31 I=1,5
TA(I)=0.
31 TB(I)=0.
TA(6)=YAMBDA(1)
DO 32 K=2,6
32 TA(6)=TA(6)+YAMBDA(K)
DO 105 I=1,6
TA(1)=TA(1)+YAMBDA(I)
TA(5)=TA(5)+TA(6)/YAMBDA(I)
TB(1)=TB(1)+BETA(I)*YAMBDA(I)
TB(2)=TB(2)+BETA(I)*YAMBDA(I)**2
105 TB(5)=TB(5)+BETA(I)*TA(6)/YAMBDA(I)
DO 110 I=1,5
LJ=I+1
DO 115 J=LJ,6
TA(2)=TA(2)+YAMBDA(I)*YAMBDA(J)
115 TA(4)=TA(4)+TA(6)/(YAMBDA(I)*YAMBDA(J))
110 CONTINUE
DO 120 I=1,4
L1=I+1

```

```

      DO 123 J=L1,5
      L2=J+1
      DO 126 K=L2,6
126  TA(3)=TA(3)+YAMBDA(I)*YAMBDA(J)*YAMBDA(K)
123  CONTINUE
120  CONTINUE
      DO 130 I=1,6
      DO 133 J=1,5
      IF(J.EQ.I) GOTO 133
      LJ=J+1
      DO 136 K=LJ,6
      IF(K.EQ.I) GOTO 136
      TB(3) =TB(3) +BETA(I)*YAMBDA(I)*YAMBDA(J)*YAMBDA(K)
      TE(4) =TB(4) +BETA(I)*TA(6)/(YAMBDA(J)*YAMBDA(K))
136  CONTINUE
133  CONTINUE
130  CONTINUE
C - LIMITS OF ERRORS USED FOR TESTING THE CONVERGENCE.
      LFR1=1.E-07
      LFR2=2.E-04
      DRFDS=2.E-05/ERR1
      NT=3
      DT=0.3
      DT2=DT/2.
      NP=2000
      RHO1=-.01
      RHO2=-3.95
      CALL DRKIN(RHO1,RHO2,DT,NT,NP)
      SFCE(1)=0.
      MZ=3
      DO 611 MM=1,MZ
      DO 205 I=1,NP
      SIG=SQRT(FLUX(I))
      AVER=FLUX(I)
      205  JDATA(I)=RANUM(SIG,AVER)
      NP1=NP-1
C
C-INVERSE KINETICS CALCULATION BEGINS
C
C-DETERMINE THE ROD DROP TIME -- JFH
      JFH=40
      DJ=0.
      DO 160 I=1,JFH
160  DJ=DJ+JDATA(I)
      DJ=DJ/JFH
      DDJ=0.
      DO 155 I=1,JFH
155  DDJ=(JDATA(I)-DJ)**2
      DDJ=SQRT(DDJ)/(JFH-1)

```

```

DSC=DJ-DDJ
JF1=JFH+1
JC=0
DO 153 I=JF1,NP
IF(DSC-JDATA(I))151,151,152
152 JC=JD+1
IF(JD.GE.40) GOTO 154
GOTO 153
151 JD=0
153 CONTINUE
154 JR=I-39
JJR=JR+80
IF(JJR.LE.NP) GOTO 158
WRITE(5,159)
159 FORMAT(21HFAILURE TO FIND DROP)
GOTO 611
158 CONTINUE
JR1=JR+1
C-SELECT THE STARTING TIME FOR IK CALCULATION
JS=JR+NT
DO 33 I=1,6
Y(I)=YAMBDA(I)*DT
33 B(I)=EXP(-Y(I))
FLUX0=0.
DO 100 J=1,JR
100 FLUX0=FLUX0+JDATA(J)
FLUX0=FLUX0/FLOAT(JR)
ANO=FLUX0/DT
DO 34 I=1,6
34 GF(I)=ANO *YBETA(I)
C-THE FIRST TWO TRIAL VALUES FOR THE FINAL REACTIVITY, RHO2
DKF1=0.
DKF2=-.003
NN=1
DKF=DKF1
RHOF=-TBETA*2.
NKF=1
C - ITERATIONS UNTIL ALL LOOPS ARE CONVERGED
1 CALL INHOUR(RHOF)
IH=1
SUM1=0.
SUM2=0.
SUM3=0.
NK2=1
3 SUM4=0.
SUM5=0.
DO 36 I=1,6
36 XINT(I)=0.

```

```

R2=JDATA(J+1)
AT=ALOG(R2/FLUX0)
T=0.
DO 230 J=JR1,NP1
R3=JDATA(J+1)
A2=ALOG(R3/R2)/DT
T=T+DT
AKL=R2*FUNC(AT)
IF(J.GT.JS) GOTO 5
DO 37 I=1,6
37 XINT(I)=B(I)*(XINT(I)+AKD*BETA(I)/FUNC(AT+Y(I)))
IF(J-JS) 10,4,5
4 X1=R2/DT*EXP(A2*DT2)*PNG
DO 38 I=1,6
38 X1=X1+GF(I)*EXP(-YAMBDA(I)*T)+XINT(I)
GOTO 10
5 X2=R2/DT*EXP(A2*DT2)*PNG
DO 39 I=1,6
XINT(I)=B(I)*(XINT(I)+AKD*BETA(I)/FUNC(AT+Y(I)))
39 X2=X2+GF(I)*EXP(-YAMBDA(I)*T)+XINT(I)
SDT=X2-X1-DKF*R2
Z=EXP(W(1)*T)
DO 40 K=2,NW
40 Z=Z+A(K)*EXP(W(K)*T)
IF(IH.GT.1) GOTO 9
SUM1=SUM1+1.
SUM2=SUM2+ Z
SUM3=SUM3+ Z*Z
9 SUM4=SUM4+ SDT
SUM5=SUM5+ SDT*Z
X1=X2
10 R2=R3
AT=A2*DT
200 CONTINUE
IF(IH.GT.1) GOTO 11
SUMD=SUM1*SUM3-SUM2*SUM2
11 SLOPE=(SUM1*SUM5-SUM2*SUM4)/SUMD
CONVERGENCE TEST NO.1. IF NOT SATISFIED, REVISE VALUE OF DKF
IF(ABS(SLOPE)-ERR1) 16,15,12
12 IF(NK2.GT.1) GOTO 15
IF(NN.LE.1) GOTO 41
DKF2=-ABS(DKF-SLOPE*DKFDS)
41 SLOPE1=SLOPE
DKF=DKF2
IH=IH+1
NK2=NK2+1
GOTO 3
15 IF(NK2.GT.4) GOTO 16

```

```

      IF(SLOPE .EQ. SLOPE1) GOTO 16
      DKFDS=(DKF-DKF1)/(SLOP.-SLOPE1)
      DKF1=DKF
      SLOPE1=SLOPE
      DKF=JKF -SLOPE * DKFDS
      NK2=NK2+1
      GOTO 3
16  RHOFC=DKF
      NN=2
      EE=(RHOFC-RHOF)/RHOFC
CONVERGENCE TEST NO. 2. IF NOT SATISFIED, REVISE VALUE OF RHOF
      IF(ABS(EE)-EKR2) 20,20,19
19  IF(NKF.GT.4) GOTO 20
      NKF=NKF+1
      RHOF=RHOFC
      GOTO 1
20  SDTCAL=(SUM3*SUM4-SUM2*SUM5)/SUMD
      RH01=-SDTCAL/(FLUX0*RHOIH)
      RH02=DKF/RHOIH
      LRHO=RHO2-RH01
      SS3=RH01/DOLLAR
      SS4=RH02/DOLLAR
      WRITE(5,620) MM
620  FORMAT("RUN NUMBER IS",I5)
      WRITE(5,621) SS3,SS4
621  FORMAT("INITIAL AND FINAL REACTIVITIES ARE",2E15.6)
      BRHO1=RH01
      REAC(MM)=RH02
      BRHO1=0.
      FRHO1=0.
      DO 610 I=1,MM
      BRHO1=BRHO1+BREAC(I)
610  FRHO1=FRHO1+REAC(I)
      BRHO1=BRHO1/MM/DOLLAR
      FRHO1=FRHO1/MM/DOLLAR
      SRCE(MM+1)=SRCE(MM)+SDTCAL
611  CONTINUE
      SRCC=SRCE(MZ+1)/FLOAT(MZ)
      WRITE(5,745) SRCC
745  FORMAT(18H0 AVERAGE SOURCE IS,E12.5)
      BREACT=0.
      REACT=0.
      DO 613 MM=1,MZ
      BREACT=3 REACT+BREAC(MM)
613  REACT=REACT+REAC(MM)
      FRHOF=REACT/MZ
      BRHO=BRREACT/MZ
      STD=0.
      STLEV=0.

```

```

      DO 615 MM=1,MZ
      STL=STL+(BRHO-BREAO(MM))**2
615  STDEV=STDEV+(FRHOF-REAO(MM))**2
      STL=SQRT(STL/(MZ-1))/DOLLAR
      STDEV=SQRT(STDEV/(MZ-1))/DOLLAR
      BRHO=BRHO/DOLLAR
      FRHOF=FRHOF/DOLLAR
      WRITE(5,617)
617  FORMAT(42H0 AVERAGE FINAL RHO AND STANDARD DEVIATION)
      WRITE(5,619)FRHOF,STDEV
      WRITE(5,618)
618  FORMAT(42H0 AVERAGE INITIAL RHO AND STANDARD DEVIATION)
      WRITE(5,619)BRHO,STD
619  FORMAT(2L13.6)
620  STOP
      END
      SUBROUTINE DRKIN(RHO1,RHO2,DT,NT,NP)
      COMMON/AXX/B(6),L(6),PNG,BETA
      COMMON/RLG/PNR(2000)
      DIMENSION R(1600),C(6),NR(1600)
      PEARL L
COMMENT      DIRECT KINETICS CALCULATION OF NOISY DATA.0 LEFTM
C      APPROXIMATION IS USED.
      IFG=0
      IPR=40
      ITS=IPR*NP
      IF=NI+40
      ST=FLOAT(NT)
      PG=263674.*DT
      AL=.06  $BC=2.82  $CC=-1.88  $DD=0.
      FC=PG/FLOAT(IPR)
      SOURCE=-P0+BETA*RHO1
      WRITE(5,209) P0
209  FORMAT(30H0INITIAL SIMULATED COUNT VALUE,=12.5)
      WRITE(5,203) SOURCE
203  FORMAT(17H0SOURCE FOR DRKIN,=12.5)
      TL=DT/FLOAT(IPR)
      WRITE(5,201)
201  FORMAT("C1PG,IR,ITS,AND IPR FOR DRKIN")
      WRITE(5,2)IPG,IR,ITS,IPR
      2  FORMAT(4I8)
      X=0.
      DX=1./ST
      DO 1 I=1,40
      NR(I)=IPR*I
      1  R(I)=RHO1*BETA
      DO 19 I=41,15
      X=X+DX
      W=AC*X+BC*X**2+CC*X**3+DD*X**4

```

```

      R(I)=RH01*BETA+W*(RH02-RH01)*BLTA
19  NR(I)=IPR*I
      PF=0.
      DO 50 I=1,IPG
50  C(I)=P0*B(I)/L(I)
      NPCH=0
      R1=R(1)
      DO 500 J=1,ITS
      DO 80 M=1,IR
      IF(NR(M) .NE. J) GO TO 80
      R1=R(M)
      GO TO 90
80  CONTINUE
90  CONTINUE
      P1=0.
      DO 120 I=1,IPG
      P1=P1 + L(I)*C(I)/(BETA-R1)
120 CONTINUE
      P1=P1+SOURCE/(BETA-R1)
      DO 150 I=1,IPG
      C(I)=TL*B(I)*P1+C(I)*(1.-L(I)*TL)
150 CONTINUE
      PP=PP+P1
      IF(MOD(J,IPR)) 500,302,500
302  NPCH=NPCH+1
      PWR(NPCH)=PP
      PP=0.
500  CONTINUE
      DO 7 I=1,IR
      7  R(I)=R(I)/BETA
      P0=P0*FLOAT(IPR)
      RETURN
      ENDS
      SUBROUTINE INHOUR(RHOF)
C - TO SOLVE THE INHOUR EQUATION
      COMMON/AXX/BETA(6),YAMBDA(6),PNL,TBETA,TA(6),TB(6),REFER,
      $  W(7),A(7),NW
      DIMENSION XCOF(8),COF(8),ROOTR(8),ROOTI(8),G(7)
      TBERHO=TBETA-FHOF
      M=7
      COEFFICIENTS OF THE SEVENTH ORDER INHOUR POLINOMIAL
      XCOF(8)=1.
      XCOF(7)=TA(1)+TBERHO/PNL
      XCOF(6)=TA(2)+(TBERHO*TA(1)-TB(1))/PNL
      XCOF(5)=TA(3)+(TBERHO*TA(2)-TB(1)*TA(1)+TB(2))/PNL
      XCOF(4)=TA(4)+(TBERHO*TA(3)-TB(3))/PNL
      XCOF(3)=TA(5)+(TBERHO*TA(4)-TB(4))/PNL
      XCOF(2)=TA(6)+(TBERHO*TA(5)-TBETA*TA(5)+TB(5))/PNL
      XCOF(1)=-RHOF*TA(6)/PNL
      CALL POLET(XCOF,COF,M,ROOTR,ROOTI,IER)

```



```

C - ROOTS OF INHOMO EQUATION, ROOTR(J)
C - COEFFICIENTS OF TRANSIENT COMPONENTS, D(J)
  GO 200 J=1,M
  WX=0.
  GO 205 I=1,6
205 WX=WX+3ETA(I)*YAMBD(I)/(ROOTR(J)+YAMBD(I))**2
  L(J)=RHO/((ROOTR(J)*(FNL+WX))
200 CONTINUE
  NW=1
  W(1)=ROOTR(1)
  MK=1
  GO 300 J=2,M
  IF(W(1)-ROOTR(J)) 320,300,300
320 W(1)=ROOTR(J)
  MK=J
300 CONTINUE
  DMK=D(MK)
  GO 400 J=1,M
  D(J)=D(J)/DMK
400 CONTINUE
  A(1)=D(MK)
  GO 500 J=1,7
  IF(J.EQ.MK) GOTO 500
  IF(-ROOTR(J)-REFLE) 71,71,500
  71 NW=NW+1
  W(NW)=ROOTR(J)
  A(NW)=D(J)
500 CONTINUE
  RETURN
  END

SUBROUTINE POLRT(XCOF,COF,M,ROOTR,ROOTI,IEF)
C - TO SOLVE A M-TH ORDER POLYNOMIAL WITH REAL COEFFICIENTS
  DIMENSION XCOF(8),COF(*),ROOTR(8),ROOTI(8)
  IFIT=0
  N=M
  IER=0
  IF(XCOF(N+1)) 10,20,10
10 IF(N) 15,15,32
15 IEF=1
20 RETURN
25 IER=4
  GOTO 20
30 IEF=2
  GOTO 20
32 IF(N-30) 35,35,30
35 NX=N
  NXX=N+1
  N2=1
  KJ1=N+1

```

```

      DO 40 L=1,KJ1
      MT=KJ1-L+1
40  COF(MT)=XCOF(L)
45  X0=.00500101
      Y0=0.01000101
      IN=0
50  X=X0
      X0=-10.0*Y0
      Y0=-10.0*X
      X=X0
      Y=Y0
      IN=IN+1
      GOTO 53
55  IF IT=1
      XFR=X
      YFR=Y
59  ICT=0
60  UX=0.0
      UY=0.0
      V =0.0
      YT=0.0
      XT=1.0
      U=COF(N+1)
      IF(U) 65,130,65
65  DO 70 I=1,N
      L =N-I+1
      TEMP=COF(L)
      XT2=X*XT-Y*YT
      YT2=X*YT+Y*XT
      U=U+TEMP*XT2
      V=V+TEMP*YT2
      FI=I
      UX=UX+FI*XT*TEMP
      UY=UY-FI*YT*TEMP
      XT=XT2
70  YT=YT2
      SUMSQ=UX*UX+UY*UY
      IF(SUMSQ) 75,110,75
75  DX=(V*UY-U*UX)/SUMSQ
      X=X+DX
      DY=-(U*UY+V*UX)/SUMSQ
      Y=Y+DY
78  IF(ABS(DY)+ABS(DX)-1.0E-05) 100,80,80
80  ICT=ICT+1
      IF(ICT-500) 60,85,85
85  IF(IFIT) 100,90,100
90  IF(IN-5) 50,95,95
95  IER=3

```

```

      GOTO 20
100 DO 105 L=1,NXX
      MT=KJ1-L+1
      TEMP=XCOF(MT)
      XCOF(MT)=COF(L)
105 COF(L)=TEMP
      ITEM=N
      N=NX
      NX=ITEM
      IF(IFIT) 120,55,120
110 IF(IFIT) 115,50,115
115 X=XPR
      Y=YPR
120 IFIT=0
122 IF (ABS(Y)-1.0E-4*ABS(X)) 135,125,125
125 ALPHA=X/X
      SUMSQ=X*X+Y*Y
      N=N-2
      GOTO 140
130 X=0.0
      NX=NX-1
      NXX=NXX-1
135 Y=0.0
      SUMSQ=0.0
      ALPHA=X
      N=N-1
140 COF(2)=COF(2)+ALPHA*COF(1)
145 DO 150 L=2,N
150 COF(L+1)=COF(L+1)+ALPHA*COF(L)-SUMSQ*COF(L-1)
155 RCOFI(N2)=Y
      RCOFI(N2)=X
      N2=N2+1
      IF(SUMSQ) 160,165,160
160 Y=-Y
      SUMSQ=0.0
      GOTO 155
165 IF(N) 20,20,-5
      END
      FUNCTION FUNC(XA)
CALCULATES X/(EXP(X)-1.) FOR PROPOSED ALGORITHM
      X=XA
      XB=ABS(X)
      IF(XB-24.3)2,2,1
1 IF(X)3,3,4
3 FUNC=-X
      RETURN
4 FUNC=X/EXP(X)
      RETURN
2 IF(XB-.2)6,6,5

```

```

5 FUNC=X/(EXP(X)-1.)
  RETURN
6 FUNC=1.-X*(.5-X*(.083333333333-(X*X)*( .00138888888869
$ -.00003306878307*(X*X))))
  RETURN
  END
  FUNCTION EXPP(XA)
C - TO AVOID UNDERFLOW (OR OVERFLOW) CALCULATIONS
  IF(XA+30. ) 1,1,2
1 EXPP=0.
  RETURN
2 LXPP=EXP(XA)
  RETURN
  END
  FUNCTION RANNUM(SIG,AVER)
C POLAR GENERATION OF NOISY FLUX REF P.104 KNUTH
4 V1=2.*RANF(-1)-1.
  V2=2.*RANF(-1)-1.
  S=V1*V1+V2*V2
  IF (S.GE.1.) GOTO 4
  RANNUM=AVER+SIG*V1*SQRT(-2.*ALOG(S)/S)
  RETURN
  END

```

APPENDIX C
IKRRI Fortran Listing

```

PROGRAM IKRRI(INPUT,OUTPUT,TAPE4=INPUT,TAPE5=OUTPUT)
COMMON/CSQ/RRHC(1800),RIN(1800),NT,B11,B12,B13,B21,B22,
*B32,B33,B23,B31
COMMON/AXX/BETA(6),YAMBDA(6),TBETA,JDATA(2500),PNG,FLUXO,
*NP,DT,REAC(2500),NP1,RHOIH
COMMON/REG/AC,BC,CC,DC,X5,X6,X7,X8
DIMENSION STDV(1800),PAC(50),PBC(50),PCC(50),PDD(50)
DIMENSION AK(30),BK(30),CK(30),DK(30),FLUP(2500),FLUX(2500)
REAL I11,I12,I13,I21,I22,I23,I31,I32,I33
REAL JDATA
C-BETA,LAMBDA AND PNG VALUES
READ(4,60) (BETA(I),I=1,6),(YAMBDA(I),I=1,6),PNG
60 FORMAT(6E12.6)
WRITE(5,61)
61 FORMAT(13H BETAS AND LAMBDA S)
WRITE(5,62) (BETA(I),YAMBDA(I),I=1,6)
62 FORMAT(2E12.6)
WRITE(5,63) PNG
63 FORMAT(24H NEUTRON GENERATION TIME,E12.6)
TBETA=0.
RHOIH=0.
DO 30 I=1,6
TBETA=TBETA+BETA(I)
30 RHOIH=RHOIH+BETA(I)/(1.+36CC.*YAMBDA(I))
RHOIH=(PNG+3600.*RHOIH)/3600.
DOLLAR=TBETA/RHOIH
C DT IS THE TIME INCREMENT FOR EACH COUNTRATE VALUE.
DT=0.3
C NP IS THE TOTAL NUMBER OF COUNTRATE VALUES TO BE ANALYZED.
NP=2000
NP1=NP-1
COMMENT. NT IS TIME INCREMENTS TAKEN UP BY ACTUAL ROD MOTION.
NT=800
WRITE(5,72) NT
72 FORMAT(31H TIME INCREMENTS FOR ROD MOTION,I5)
C IFP IS THE NUMBER OF INDEPENDENT DETECTORS.
IFP=3
KJK=8
DO 200 I=1,NT
200 RIN(I)=FLOAT(I)/FLOAT(NT)
X1=0.
X2=0.
X3=0.
X4=0.
X5=0.
X6=0.
X7=0.

```

```

X8=0.
DO 4 J=1,NT
X1=X1+RIN(J)
X2=X2+RIN(J)**2
X3=X3+RIN(J)**3
X4=X4+RIN(J)**4
X5=X5+RIN(J)**5
X6=X6+RIN(J)**6
X7=X7+RIN(J)**7
4 X8=X8+RIN(J)**8
A11=X2-2.*X5+X8
A12=X3-X5-X6+X8
A13=X4-X5-X7+X8
A22=X4-2.*X6+X8
A23=X5-X7-X6+X8
A33=X6-2.*X7+X8
A21=A12
A31=A13
A32=A23
B11=A22*A33-A32*A23
B12=A32*A13-A12*A33
B13=A12*A23-A22*A13
C=A11*B11+A21*B12+A31*B13
B11=B11/D
B12=B12/D
B13=B13/D
B21=(A31*A23-A21*A33)/D
B22=(A11*A33-A13*A31)/D
B23=(A21*A13-A11*A23)/D
B31=(A21*A32-A31*A22)/D
B32=(A12*A31-A11*A32)/D
B33=(A11*A22-A21*A12)/D
I11=A11*B11+A12*B21+A13*B31
I12=A11*B12+A12*B22+A13*B32
I13=A11*B13+A12*B23+A13*B33
I21=A21*B11+A22*B21+A23*B31
I22=A21*B12+A22*B22+A23*B32
I23=A21*B13+A22*B23+A23*B33
I31=A31*B11+A32*B21+A33*B31
I32=A31*B12+A32*B22+A33*B32
I33=A31*B13+A32*B23+A33*B33
WRITE(5,3)
3 FORMAT('DCHECK INVERSION')
WRITE(5,22) I11,I12,I13,I21,I22,I23,I31,I32,I33
22 FORMAT(3E16.5)
C THE FOLLOWING PARAMETERS ARE USED IN THE DIRECT KINETICS.
RHC1=-.01
RH02=-3.95
FLUX0=263674.*DT

```

```

      AC=.06 $ BC=2.82 $ CC=-1.88 $ DD=0.
C   DRKIN IS THE DIRECT KINETICS SUBROUTINE.
      CALL DRKIN(RH01,RH02,NT)
      DO 329 I=1,NP
329  FLUX(I)=JDATA(I)
C   RH01,RH02,AND SOURCE FROM PRECEDING ROD DROP
      RH01=-.01009
      RH02=-3.9506
      SDTCAL=2.6801
      JFH=40
      JF1=JFH+1
      IR1=NT+40
      IR2=IR1+1
      ST=FLOAT(NT)
      DX=1./ST
      DO 804 I=1,50
804  STDV(I)=0.
      DO 888 IM=1,IPP
C   RANNUM SUPERIMPOSES RANDOM GAUSSIAN NOISE ON THE COUNTRATE.
      DO 205 I=1,NP
      SIG=SQRT(FLUX(I))
      AVER=FLUX(I)
      205 JDATA(I)=RANNUM(SIG,AVER)
C-DETERMINE THE ROD DROP TIME -- JR
      DJ=0.
      DO 160 I=1,JFH
160  DJ=DJ+JDATA(I)
      DJ=DJ/JFH
      FLUX0=DJ
      DDJ=0.
      DO 155 I=1,JFH
155  DDJ=DDJ+(JDATA(I)-DJ)**2
      DDJ=SQRT(DDJ)/(JFH-1)
      DSC=DJ-DDJ
      JF1=JFH+1
      JD=0
      DO 153 I=JF1,NP
      IF(DSC-JDATA(I))151,151,152
152  JD=JD+1
      IF(JD.GE.40) GOTO 154
      GOTO 153
151  JD=0
153  CONTINUE
154  JR=I-39
      JJR=JR+80
      IF(JJR.LE.NP) GOTO 158
      WRITE(5,159)
159  FORMAT(21HFAILURE TO FIND DROP)
      GOTO 800

```

```

158 CONTINUE
    WRITE(5,501) JR
501  FORMAT(19HOFIRST TRY AT JR IS,I5)
    FL1=0.
    FL2=0.
    JR3=JR-20
    DO 301 I=JR3,JR
    FL1=FL1+JDATA(I)
301  FL2=FL2+JDATA(I+20)
    FL1=FL1/20.
    FL2=FL2/20.
    JR=JR-INT(40./(FL1-FL2)*SQRT(FL1))
    WRITE(5,1) JR
    1  FORMAT(15HADJUSTED JR IS,I5)
    JR1=JR+1
COMMENT. RHOPRO IS THE INVERSE KINETICS ROUTINE.
COMMENT. SDTCAL IS THE EFFECTIVE SOURCE.
    CALL RHOPRO(SDTCAL)
    DO 201 J=1,NT
    201 RRHO(J)=(PEAC(J+JR)-REAC(JR))/(RH02-RH01)/DOLLAR
COMMENT. LSG SMOOTHS RRHO.
    CALL LSG
    WRITE(5,221)
    221 FORMAT('OFIT COEFFICIENTS,FIRST THROUGH FOURTH ORDER')
    WRITE(5,222) AC,BC,CC,DD
    222 FORMAT(4E12.5)
    AC=AC  $BG=BC  $CG=CC  $DG=DD
    AK(IM)=AC  $BK(IM)=BC  $CK(IM)=CC  $DK(IM)=DD
    DO 204 I=1,NT
    204 RRHO(I)=AC*RIN(I)+BC*RIN(I)**2+CC*RIN(I)**3+DD*RIN(I)**4
COMMENT. NOW RRHO IS THE SMOOTHED RELATIVE ROD WORTH.
    DO 223 I=1,NT
    223 RRHO(I)=RRHO(I)*(RH02-RH01)
    WRITE(5,224)
    224 FORMAT('DROD WORTH ARRAY')
    WRITE(5,225)(RRHO(I),I=1,NT,KJK)
    225 FORMAT(10E12.5)
    CALL DRKIN(RH01,RH02,NT)
    DO 328 I=1,NP
    328 FLUB(I)=JDATA(I)
    MZ=30
    MZ1=MZ-1
    DO 199 MM=1,MZ
    DO 172 I=1,NP
    SIG=SQRT(FLUB(I))
    AVER=FLUB(I)
    172 JDATA(I)=RANUM(SIG,AVER)
C-DETERMINE THE ROD DROP TIME -- JR
    JFH=40

```



```

      DJ=0.
      DO 560 I=1,JFH
550  DJ=DJ+JDATA(I)
      DJ=DJ/JFH
      FLUXD=DJ
      DDJ=0.
      DO 555 I=1,JFH
555  DDJ=DDJ+(JDATA(I)-DJ)**2
      DDJ=SQRT(DDJ)/(JFH-1)
      DSC=DJ-DDJ
      JF1=JFH+1
      JD=0
      DO 553 I=JF1,NP
      IF(DSC-JDATA(I))551,551,552
552  JD=JD+1
      IF(JD.GE.40) GOTO 554
      GOTO 553
551  JD=0
553  CONTINUE
554  JR=I-39
      FL1=0.
      FL2=0.
      JR3=JR-20
      DO 701 I=JR3,JR
      FL1=FL1+JDATA(I)
701  FL2=FL2+JDATA(I+20)
      FL1=FL1/20.
      FL2=FL2/20.
      JR=JR-INT(40./(FL1-FL2)*SQRT(FL1))
      CALL RHOPRO(SDTAL)
      DO 173 J=1,NT
173  RRHO(J)=(REAC(J+JR)-REAC(JR))/(RHO2-RHO1)/DOLLAR
      CALL LSQ
      PAC(MM)=AC $ PBC(MM)=BC $ PCC(MM)=CC $ PDD(MM)=DD
199  CONTINUE
      ZZ=0.
      DO 179 I=1,50
      ZZ=ZZ+.02
      S=0.
      DO 175 J=1,MZ
      S1=(AG-PAC(J))*ZZ
      S2=(BG-PBC(J))*ZZ**2
      S3=(CG-PCC(J))*ZZ**3
      S4=(DG-PDD(J))*ZZ**4
175  S=S+(S1+S2+S3+S4)**2
179  STDV(I)=SQRT(S/MZ1)+STDV(I)
888  CONTINUE
      DO 803 I=1,50
803  STDV(I)=STDV(I)/FLOAT(IPP)

```

```

      WRITE(5,801)
831  FORMAT('ESTIMATED STANDARD DEVIATIONS')
      WRITE(5,802)(STDV(I),I=1,50)
902  FORMAT(2E14.6)
      AC=0.  $BC=0.  $CC=0.  $DD=0.
      DO 10 IM=1,IPP
      AC=AC+AK(IM)
      BC=BC+BK(IM)
      CC=CC+CK(IM)
10   DD=DD+DK(IM)
      AC=AC/IPP
      BC=BC/IPP
      CC=CC/IPP
      DD=DD/IPP
      WRITE(5,302)
302  FORMAT('DAVERAGE FIT COEFFICIENTS')
      WRITE(5,303)AC,BC,CC,DD
303  FORMAT(4E12.5)
      DO 307 I=1,NT
      RRHO(I)=AC*RIN(I)+BC*RIN(I)**2+CC*RIN(I)**3+DD*RIN(I)**4
307  RRHC(I)=RRHO(I)*(RHO2-RHC1)
      WRITE(5,309)
309  FORMAT('DAVERAGE EXPERIMENTAL REACTIVITY ARRAY')
      WRITE(5,311)(RRHO(I),I=1,NT,KJK)
311  FORMAT(10E12.5)
800  STOP
      END
      SUBROUTINE RHOPRO(SDTCAL)
CALCULATES REACTIVITY PROFILE
      COMMON/AXX/B(6),Y(6),BETA,P(2500),PNG,POW,KK,DT,
      *RHO(2500),NP1,RIH
      DIMENSION C(6)
      S=SDTCAL
      N=KK-1
      DO 10 I=1,6
10   C(I)=B(I)*POW/Y(I)
      DO 1 I=1,N
      IF((ABS(P(I)/P(I+1))-1.).EQ.0.) GOTO 2
      G=ALOG(P(I)/P(I+1))/DT
      GOTO 3
2    G=0.
3    CONTINUE
      T1=0.
      DO 4 J=1,6
      C(J)=C(J)*EXP(-Y(J)*DT)+B(J)/(Y(J)-G)*
      1(P(I+1)-P(I)*EXP(-Y(J)*DT))
4    T1=T1+C(J)*Y(J)
1    RHO(I+1)=BETA-G*PNG-(S+T1)/P(I+1)
      RHC(1)=-S/POW

```

```

DO 33 I=1, KK
33 RHO(I)=RHO(I)/RIH
RETURN
END
SUBROUTINE LSO
COMMON/CSQ/RRHO(1800),RIN(1800),NT,B11,B12,B13,B21,B22,
*B32,B33,B23,B31
COMMON/REG/AC,BC,CC,DD,X5,X6,X7,X8
S1=0.
S2=0.
S3=0.
S4=0.
DO 1 J=1,NT
S1=S1+RRHO(J)*RIN(J)
S2=S2+RIN(J)**2*RRHO(J)
S4=S4+RRHO(J)*RIN(J)**4
1 S3=S3+RRHO(J)*RIN(J)**3
S1=S1-X5*X8-S4
S2=S2-X6*X8-S4
S3=S3-X7*X8-S4
AC=B11*S1+B12*S2+B13*S3
BC=B21*S1+B22*S2+B23*S3
CC=B31*S1+B32*S2+B33*S3
DD=1.-AC-BC-CC
RETURN
END
SUBROUTINE DRKIN(RHO1,RHO2,NT)
COMMON/AXX/B(6),L(6),BETA,PWR(2500),PNG,PC,NP,DT
COMMON/REG/AC,BC,CC,DD
DIMENSION R(1600),C(6),NR(1600)
REAL L
IPG=6
IPR=3
ITS=IPR*NP
IR=NT+40
ST=FLCAT(NT)
PD=PD/FLOAT(IPR)
SOURCE=-PD*BETA*RHO1
WRITE(5,209) PD
209 FORMAT(30H0INITIAL SIMULATED COUNT VALUE,E12.5)
WRITE(5,203) SOURCE
203 FORMAT(17H0SOURCE FOR DRKIN,E12.5)
TL=DT/FLOAT(IPR)
WRITE(5,201)
201 FORMAT('0IPG,IR,ITS,AND IPR FOR DRKIN')
WRITE(5,2)IPG,IR,ITS,IPR
2 FORMAT(4I8)
X=0.
DX=1./ST

```

```

      DO 1 I=1,40
      NR(I)=TPR*I
1    R(I)=RH01*BETA
      DO 19 T=41,IR
      X=X+DX
      W=AC*X+BC*X**2+CC*X**3+DD*X**4
      R(I)=RH01*BETA+W*(RH02-RH01)*BETA
19   NR(I)=TPR*I
      PP=0.
      DO 50 T=1,IPG
50   C(I)=PD*B(I)/L(I)
      NPCH=0
      R1=R(1)
      DO 500 J=1,ITS
      DO 80 M=1,IR
      IF(NR(M).NE.J) GO TO 80
      R1=R(M)
      GO TO 90
80   CONTINUE
90   CONTINUE
      P1=0.
      DO 120 I=1,IPG
      P1=P1 + L(I)*C(I)/(BETA-R1)
120  CONTINUE
      F1=P1+SOURCE/(BETA-R1)
      DO 150 T=1,IPG
      C(I)=TL*B(I)*P1+C(I)*(1.-L(I)*TL)
150  CONTINUE
      PP=PP+P1
      IF(MOD(J,IPR)) 500,302,500
302  NPCH=NPCH+1
      PWR(NPCH)=PP
      PP=0.
500  CONTINUE
      DO 7 I=1,IR
      7  R(I)=R(I)/BETA
      PD=PD*FLOAT(IPR)
      RETURN
      END
      FUNCTION RANNUM(SIG,AVER)
C    FCLAR GENERATION OF NOISY FLUX    REF P.104 KNUTH
      4  V1=2.*RANF(-1)-1.
      V2=2.*RANF(-1)-1.
      S=V1*V1+V2*V2
      IF (S.GE.1.) GOTO 4
      RANNUM=AVER+SIG*V1*SQRT(-2.*ALOG(S)/S)
      RETURN
      END

```

DISTRIBUTION

UC-79 Basic List (204)

UC-79d Physics (18)

UC-79e Reactor Core Systems (21)

ERDA-RL (2)

A.G. Fremling

R.M. Poteat

ERDA-FFTFPO-RL (1)

R.L. Ferguson

Westinghouse Hanford Company (17)

R.A. Bennett (2)

J.W. Daughtry

R.A. Harris

R.W. Harmsen

D.L. Johnson

T.A. Mangelsdorf

R.E. Peterson

R.A. Sevenich (2)

G.A. Worth

Central Records and Files (5)

Publications Services (2)