50-255

DESCRIPTION OF IN-CORE ANALYSIS

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OPERATION OF THE INCA PROGRAM

The INCA computer code is used by the Palisades Reactor Engineer to set alarm limits on the rhodium self-powered neutron detectors and to give information on the reactor power distribution. Included as Attachment A of this letter is part of a procedure describing the input and output of the INCA computer code. Attachment B of this letter is a portion of the Combustion Engineering INCA User's Manual which relates some of the theory behind the INCA code.

Detector Signal Conversion and Library Usage

Input to the code is supplied by plant personnel and consists of various plant data and a paper tape containing the incore detector raw millivolt signals and the sensitivity and background correction factors to correct the millivolt signals. This paper tape is punched by the Varian Datalogger, an on-line computer at the plant. After reading in the data on the paper tape, INCA makes sensitivity and background corrections to the millivolt signals. In order to make the millivolt-to-power conversion of the detector signals, INCA finds the current exposure distribution from a computer file generated by a previous INCA run. This exposure distribution is used as the independent variable in a linear interpolation of the data in the INCA library to find the correct burn-up dependent conversion factors. INCA then uses the exposure distribution in a similar manner to find a set of one pin peaking factors, a set of coupling coefficients and a theoretical power distribution for each axial region of the core as defined by the position of the control rods.

Full Core Routine

Once a theoretical power distribution has been found, the code goes into the full core routine. The routine takes the detector power signals before any signal checking has been done and divides them by the theoretical power distribution. The ratios are then normalized to an average of 1.0. If any ratio deviates from the average by more than an input value (15%), the signal with the largest deviation is zeroed out and the rest are renormalized. This process is repeated until all remaining ratios are within the acceptance criterion.

Then, through linear least squares and for each detector level, the code finds coefficients to a fitting function that is a function of bundle location. INCA then multiplies this interpolating function by the theoretical power distribution to get a "measured" power distribution. This radial power distribution is weighted by the average of all the functional detectors in that level. The full core integrated power map is found by quadrature integration of the weighted detector level power distributions on a bundle-by-bundle basis. The full core quadrant tilt is the sum of the bundle powers in the highest quadrant of the integrated power distribution divided by the sum of the bundle powers in an average quadrant.

Detector Signal Checking

From the full core routine INCA goes back to the original set of detector power signals and makes the first pass at checking the signals by replacing bad signals with symmetric partners if any are available. The code then does an axial ratio check and a radial coupling coefficient check and flags detectors that don't pass the radial test. Once again bad detectors are replaced by symmetric partners if any are available. Other bad signals are replaced by using a neighboring detector's signal by use of the coupling coefficients. The signals are passed through the axial and radial checks again to verify that the synthesized signals are acceptable.

Sensitivity Overcheck

INCA then does an overcheck of the Varian Datalogger sensitivity updates. The Datalogger must periodically update the sensitivity of each detector to account for rhodium depletion. The change in sensitivities from one update to the next divided by the current background corrected millivolt signal is approximately the same for all detectors. This assumes only small changes in the power distribution. If the averaging is done by detector level, the deviations are typically less than one percent. The code looks for and flags zero and negative updates and large deviations from the average. This part of the code compares detector failures to any flags set in the sensitivity check and to the failed detectors in the previous INCA run. Note that a failed detector has been replaced in one of three ways in the code: a) by hand input; b) by replacement with a symmetric partner; c) by generating a signal with the coupling coefficients.

Tilt Routines

At this time INCA calls on the tilt routines. The first one is the azimuthal zenon tilt routine which is described in the CE Users Manual on page III-10. The value of S is found in a least squares manner to the fitting function of $J_1(\alpha_{11}, r)/J_0(\alpha_{01}, r)$ with only 3 or 4 detectors at a time going into the fit. Once an average value of S and tilt angle have been found by averaging 16 sets of detectors, the half core tilt, quarter core tilt and maximum tilt at the edge of the core are calculated. The other tilt routine is still experimental. It takes symmetric pairs of detectors and linearly extrapolates any tilt they measure to the edge of the core and averages the results.

Power Distribution

INCA now calculates an octant power distribution for use in setting alarm limits. After the final detector signal checks there is a set of detector power signals for each of the 28 octant locations. The signals are then curve fit in the axial direction as described in the CE Users Manual on pages III-4 and III-5. The 51 axial nodes are collapsed to 25 nodes before any alarm limits calculations. The core power from this calculated power distribution is adjusted to match the core thermal power as indicated by a heat balance. INCA uses this power distribution to update the exposure distribution and to accumulate control rod exposure. Included as Attachment C is a comparison of an Exxon PDQ7 calculation and an INCA power map at 10,500 MWd/MT of core burnup. The maximum bundle power as measured by INCA is very close to the prediction.

Alarm Limits

INCA changes this power distribution to a heat flux distribution to calculate the detector alarm limits. This distribution has factored into it the Technical Specification's uncertainty factors and the maximum quadrant power factor computed by the full core routine. This has the effect of lowering the alarm limits. The code ratios the maximum allowable heat flux over the calculated heat flux and searches for the minimum ratio in nodes 1 to 8 for detector level 1, 8 to 13 for detector level 2, 13 to 18 for detector level 3 and 18 to 25 for detector level 4. The maximum allowable heat flux in any given node depends on the axial location of the node. The limiting heat flux is from either DNBR or ECCS analysis[1], whichever is more restrictive. Once the code has found a minimum ratio for each detector level it calculates alarm limits for each detector by multiplying the background

corrected millivolt signal by the minimum ratio for that detector's level. The code also calculates peak pin power and peak assembly power and prints out the fraction of the limit for each, but, does not set any alarms on these values. The limits on pin power and assembly power are based on limiting radial peaking factors assumed in the LOCA and DNBR analysis. The DNBR calculation as described on pages III-8 and III-9 of the CE Users Manual is outdated.

Library Generation

The INCA library contains exposure dependent data for calculating coupling coefficients, millivolt-to-power conversion factors and one pin peaking factors. It is created by simulating burnup of the Palisades core with fine mesh quarter core PDQ7s. Input to PDQ7 is generated by the computer codes EXPOSE and HAMMER. The results are verfied by comparison to cycle 2 zero power physics tests and rod worths and by recalculating cycle 1 rod worths. The data necessary to the INCA library is extracted from the PDQ7 computer files and print files by a series of in-house computer codes.

1. Proposed Technical Specification Changes for Requested Power Increase, License DPR-20, Docket 50-255, Hoffman to Schwencer, dated August 12, 1977.

ATTACHMENT A

PALISADES IN-CORE DETECTOR ANALYSIS SYSTEM (INCA)

SECTION PROCEDURE

ORP-2

Rev 0 1/ 6/76
Rev 1 4/12/76
Rev 2 10/12/76
Rev 3 8/19/77

Operating Reactor Physics Section
Nuclear Activities Department
Bulk Power Operations
Consumers Power Company

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PROCEDURE
PALISADES IN-CORE DETECTOR ANALYSIS SYSTEM (INCA)

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PROCEDURE

PALISADES IN-CORE DETECTOR ANALYSIS SYSTEM (INCA)

1.0 PURPOSE

Define the various tasks in the INCA system.
Establish the responsibility of use and maintenance of the various tasks in the INCA system.
Provide the starting point for retrieving the documentation concerning the INCA system.

2.0 SCOPE

The procedure applies to the Operational Reactor Physics Section which has prime responsibility for the maintenance of the system and the Palisades Reactor Engineer who has prime responsibility for use of the system as called for by the Technical Specifications.

3.0 REFERENCES

Input provided by Palisades Plant personnel. Attached as an Appendix.
Description of the INCA output reports. Attached as an Appendix.
INCA production control manual. Attached as an Appendix.
INCA users manual - Combustion Engineering.
NAD-12 Procedure - Computer Program Control.
Palisades Nuclear Plant Engineering Manual.

4.0 DEFINITIONS

JCL - Statements required to initiate and control a computer job that is run on the General Office computer system.
Varian Data Logger or Data Logger - Computer device used as the interface between the in-core detectors and the General Office Computer system.

5.0 PROCEDURE

5.1 General System Definition

The in-core nuclear instrumentation, which is installed in the Palisades Nuclear Plant, is intended to provide a source of information concerning the gross power distribution within the reactor core. It plays no role in the Plant Engineered Safeguards System, since the out-of-core instrumentation is deemed adequate for this purpose.

The in-core alarm system is composed of self-powered neutron detectors, an analog to digital converter and a digital computer.

The neutron detectors generate electrical current signals proportional to the number of neutrons striking them. These analog signals are converted to digital signals and processed by a digital computer. The signals are used to produce information on the reactor power distribution.

For plant operations at high power, the in-core alarm system must be set to warn of abnormally high power in the fuel assemblies. The alarm set points are determined by the power distribution map obtained from an INCA calculation.

The alarm limits are compared to the detector signals within the digital computer. If a signal is greater than the limit, an alarm is sounded. If four or more valid alarms are received concurrently, the power is immediately decreased below the alarm set point and a power distribution map must be obtained. If the power map is not obtained within 24 hours, the power must be further reduced.

A power distribution map must be evaluated to set the alarms every week or more often as required by plant operations.

The INCA system also maintains a history of plant operations which is used for financial accounting and verifying plant design calculations.

5.2 Job Initiation

The plant reactor engineer is responsible for determining the need for the execution of an INCA run.

The Palisades Nuclear Plant Engineering Manual contains the procedures which require an INCA calculation. Specific procedures are:

EM-04-02	Quadrant Power Tilt
EM-04-03	Hot Channel Factors
EM-04-04	Power Ratio
EM-04-06	Administering In-Core Alarms
EM-04-07	Linear Heat Rate
EM-04-12	Core Physics Calculations
EM-04-13	Calibrate Out of Core Detectors
EM-04-14	INCA Power Distribution and Exposure Distribution

5.3 Computer Code Certification

Certified codes are required for this procedure.
The JCL procedure utilized by the Reactor Engineer assures the use of the current certified codes. Appendix M describes in detail the JCL required.

Each INCA run includes the name, modification level, and date of modification of each certified code. This allows the INCA output to be tied to the exact source code used to perform the calculations. Runs which predate this code identification system are difficult to tie to the applicable source. The operational reactor physics administrator (ORPA) is responsible for all code modifications.

Updates to any program, JCL, or permanent control cards must be logged in the INCA Auxiliary Program Execution and System Updates Log. This includes but is not limited to changes to computer system data sets CP.PGMLIB, CP.PROCLIB, and CP.PRODCONT.

The members of the above data sets that are vital to the INCA production are listed below.

CP.PGMLIB - Load Module Library

P411835T	Varian to IBM Format Data Translation
P411825I	Main Calculational Program
P411825B	Copy Exposure and Power Distribution File
P411825S	Copy Plant Inputs

CP.PROCLIB - JCL Procedure Library

P411825C	Main Procedure to Execute an INCA Case
P411825B	Backup Exposure History
P411825P	Reprint an INCA Case
P411825R	Restore Exposure Library
P411825E	Copy Exposure and Power Distribution File

CP.PRODCONT - Permanent Control Card Library

P411825B	Used by Proc P411825B
P411825F	Used by Proc P411825C

Other programs which may be classified as common usage utility programs are utilized by the INCA system to copy data sets and to create microfiche. These programs are not considered to be within the scope of NAD-12.

"Standard" methods of updating program load modules have been developed to make life a little easier for the programmer. Examples of how to update and file the compiles of P411825T and P411825I and the library are provided as samples only and are not represented as being the only way to update a program. The example JCL is not logically part of this procedure, but is located in an appendix for ease of reference.

5.4 Available Documentation

All available formal documentation is listed under 3.0 References of this procedure. Microfiche copies of all versions of the source of the certified codes are on file. Microfiche copies of all versions of the certified library are on file. Source and library versions which predate microfiche are available on paper.

ORPA is repsonsible for maintaining the documentation.

5.5 Computer Code Library Certification

A certified library is required for this procedure. The library is retrieved like the codes as described in 5.3 of this procedure. Use of the JCL procedure assures use of the current library. Cycle 2 and later libraries are self-identifying.

ORPA is responsible for maintaining the library. The types of data on the library are:

A. Factors used to calculate the power of an assembly given the millivolt signal of the detector.

   Includes effects of:

   Nearest Control Rod Insertion
   Burnup

B. Factors used to calculate heat flux and DNBR limitations. Include effects of:

   1 - Pin Peaking Factors

C. Factors used to calculate the theoretical power of an assembly.

   Include effects of:

   Adjacent Assembly Power
   Burnup

5.6 Input

INCA has seven sources of input data:

A. Varian Data Logger - The Varian data logger provides the primary input. The values of the in-core detectors and various plant parameters that describe the state of the primary coolant system are provided on the data logger paper tape.

   The plant reactor engineer is responsible for selecting the paper tape that most accurately represents reactor operations.

   The paper tapes are not machine dated or otherwise identified by machine readable code. Plant personnel must be careful to ensure the proper paper tapes are processed.

B. Keyed Data - Data keyed by plant personnel is used to specify program options and to override data logger values as needed. A description of the keyed data is in Input Provided by Palisades Plant personnel.

C. Library Data - A library of seldom changing plant parameters is provided separate from the program coding for ease of maintenance. The library is described in more detail in 5.5 of this procedure.

D. Exposure History - Exposure of fuel and control rods is kept on permanent computer readable storage. Each INCA run uses the previous exposure history as the independent variable of several linear interpolation schemes used in the code. Updating and retrieving exposure data is entirely by automated means.

The integrity of this data is important for correct operation of INCA. To insure against destruction of this data, backup and recovery procedures are used. Backup of this data is performed weekly by Computer Services. The INCA Production Control Manual section on Weekly Backup of INCA libraries describes in detail the JCL required. Restoration of backup is performed by ORPA. The INCA Production Control Manual section on restoration of INCA libraries describes in detail the JCL required.

Execution of the backup or restore procedure must be logged in the INCA auxiliary Program Execution and System Update Log.

E. Power Distribution History - The three dimension power distribution history is kept on permanent computer readable storage for possible future use. Backup and restoration of this file is performed with the exposure file as described in D above.

F. Full-Core Quadrant Tilt History - The tilt history file is kept on permanent computer readable storage and is plotted and updated for each exposure case.

G. Failed Detector History - The history of failed detectors is kept on permanent computer readable storage for comparison of previous INCA run to present INCA run.

5.7 Output

INCA has six output files:

A. The human readable reports are described in Description of the INCA Output Reports. A copy of these reports is printed at the plant. An archival microfiche copy is filed by ORPA in the Document Control Center.

B. The exposure history file is updated for use by the next INCA run. A description of this file is at 5.6.D of this procedure.

C. The power distribution history file is updated for possible future use. A description of this file is at 5.6.E of this procedure.

D. The full-core quadrant tilt file is updated for each exposure run.

E. The failed detector file is updated for each INCA run.

F. The detector signals divided by the theoretical power distribution is written out on machine readable storage for possible future use.

5.8 Hand Processing of Computer Results

One of the prime objectives of the INCA system is to calculate the alarm limits which are checked by the Varian Data Logger. Communication of the limits from INCA to the data logger is by a manual key process. Plant personnel are responsible for key entry of the alarm limits which appear on a printed report.

5.9 Limits of Applicability

INCA is designed to consider the reactor core as 1/8 symmetric. INCA will accommodate all control rods withdrawn and group four regulating control rod insertion only.

Most of the library input is expected to be unique to cycle two. Refueling will necessitate revision of the library and possibly portions of the code.

The calculated alarm limits are intended to reflect any limitations imposed by the Technical Specifications. Review of any license changes and subsequent code modifications will be made by ORPA.

APPENDIX A

INPUT PROVIDED BY PALISADES PLANT PERSONNEL

INCA INPUT PROVIDED BY PALISADES PLANT PERSONNEL

The primary input to INCA is the values of the in-core detectors and various plant parameters that describe the state of the primary coolant system. These data are produced in machine readable form by the Varian data logger system.

Parameters which control the execution of the INCA program and values which override erroneous data logger values may be keyed input by plant personnel.

Other inputs of a more permanent nature are stored and automatically retrieved within the computer system. Seldom changing plant and fuel design parameters and the automatically updated power history file are in this category. The description of these data is under another topic.

A brief description of the data logger generated input will be given. Details of this data are not necessary for a typical INCA run since the data is produced automatically.

Data Logger Items:

Flux Detectors
Background Correlation & Scaling Factors
Sensitivity Factor
Steam Generator Thermal Power Temperature, Flow, Pressure
Pressurizer Pressure
Primary Coolant Flow, Delta Temperature, Average Temperature
Electrical Power
Turbine Pressure
Condenser Vacuum
Charging Flow
Boronmeter Concentration
Reactor Period

Plant personnel may key input data. Program parameters control various input and output functions. Several data logger items may be overridden. Sensors may have failed or are deemed not accurate enough for a particular calculation. Control rod insertion must be input by key since that data is not available elsewhere.

Records are presented in order required for the computer run. Some records are optional and may not appear in a particular computer run.

KEYED INPUT LEGEND:

FIELD: First number designates record type. Second number designates sequence number of a unique piece of data on the record.

TYPE: A - Alphanumeric
R - Real Number
I - Integer Number

COLUMNS: Inclusive column number available for the data item.

VARIABLE: Name as it appears in the source program.

FORM: Format statement used in source program.

The following record is inserted in the computer run deck immediately following //DELETES DD *. The //DELETES may be omitted if there are no cases to delete.

1 Delete (Optional)

Any case which is considered as useless due to errors, should be marked as such by use of this record. If there are no cases to delete, do not input any cards.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
1-1	I	1-16	DELDTE	I6,I10	Date of the erroneous computer run.
1-2	A	17-64	DELCØM	12A4	Free format comments.
1-3	I	65-80	RUNDTE	I6,I10	Date of computer run that deleted the case. This field is normally supplied by the computer; no human action needed.

The following records are inserted in the computer run deck immediately following //CARDS DD *.

1 Title (Required)

The values of this record are used to create parts of the case title.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
1-1	I	1- 5	BLØCK	I5	Burnup case sequence number. Value not useful for nonburnup case.
1-2	I	6-10	IPTAPE	I5	Number of the paper tape used as input.
1-3	I	11-13	IPCTPW	I3	Percent power level.
1-4	A	14-26	DTEPAL	3A4,A1	Date of plant burnup or power distribution.

Format Required for Burnup Case

mm/dd-dd/yy

Format Required for Power Distribution

mm/dd/yy hhmm

mm	Month
dd	Day
dd-dd	Inclusive Days
yy	Year
hhmm	Military Time of Day - Hours and Minutes

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
1-5	A	27-64	COMENT	9A4,A2	Free format comments to appear on first line of the INCA output.
1-6	I	65-80	RUNDTE	I6,I10	Date of the computer run. This field is normally supplied by the computer; no human action needed.

2 Input/Output Options (Required)

Various input and output formats are controlled by values on this record.

2-1	I	1- 8	IPRIØ	I8	This field controls the optional output reports.

Most reports are printed for each run. Exposure reports only appear with an exposure update.

IPRIØ ≤ 0 Only standard reports are printed.

IPRIØ > 0 Additional reports include:

Detector Axial Locations
Detector x-y Locations
Core Normalized Power Distribution
Some of the Output From the Full-Core Routine

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
2-2	I	9-16	RØDSIN	I8	This field specifies the format of the control rod position input.

RØDSIN ≠ 1 Read individual control rod position - see Record 4.

RØDSIN = 1 Read control rod positions by symmetric groups - see Record 5.

2-3	I	17-24	IXCORE	I8	This field controls an optional read statement to read in the values of the excore detectors.

IXCØRE = 0 Don't read excore values.

IXCØRE ≠ 0 Read excore detector values - see Record 3.

3 <u>Excore Detector Values</u> (Use if IXCORE ≠ 0)

3-1 3-2 3-3 3-4 3-5 3-6 3-7 3-8	R	1- 8	XCØRE	8F8.1	Start with the upper excore in Quadrant 1 and list sequentially through Quadrant 4. Then do the same for the lower excores.

4 <u>Control Rod Positions by Individuals</u> (Use if RØDSIN ≠ 1)

4-1 4-35	R	1- 8	H	10F8.1	The 45 control rod positions are sequentially listed by ascending rod drive system index. Ten numbers per card, five cards needed in total. Units are inches from bottom of core - same as rod drive position indicating equipment. Since INCA assumes octant symmetry, the positions of symmetric control rods are averaged. See control rod index table.

5 <u>Control Rod Position by Group</u> (Use if RØDSIN = 1)

5-1	R	1- 8	RØDG	7F8.1	Control rod positions by group in order of Groups 1, 2, 3, 4, P, SA, SB. Units are inches from bottom of core - same as rod drive position indicating equipment. See control rod index table.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
6 Burnup and Plant Parameters (Required)					
Plant parameters specified on the record override the normal data logger input.					
6-1	R	1- 8	DT	F8.1	Energy to be distributed in MWHT. If value is zero or negative, no burn-up is considered. If value is positive, fuel and control rod burn is performed.
6-2	R	9-16	SCALE	F8.1	Boronmeter scale (multiples of 500 ppm boron).
6-3	R	17-24	SØLBØR	F8.1	Boron concentration in ppm. If zero, data logger boronmeter plus scaling is used.
6-4	R	25-32	CALPØW	F8.1	Calorimetric thermal power level in MWT. This should not include pump power. If zero, data logger value is used.
6-5	R	33-40	PSIA	F8.1	Pressure of the primary coolant system in psia. If zero, data logger value is used.
6-6	R	41-48	Ø(1)	F8.1	Core flow in 10^6 lbs/h. If zero, data logger value is used.
6-7	R	49-56	TIN	F8.1	Primary inlet temperature °F. If zero, data logger value is used.
7 Input and Calculational Control Parameters (Required)					
7-1	I	1- 8	N	I8	Number specifies how many Type 7 records follow. Negative or zero value indicates no hand overlaid signal.
7-2	I	9-16	IAVG	I8	Control averaging of symmetric detectors to determine value in an octant location.
IAVG = 1 Do not average symmetric detectors.					
IAVG = 0 Average symmetric detectors.					
7-3	I	17-24	IAXL	I8	Control axial ratio check.
IAXL = 1 Calculate and check axial ratios.					
IAXL ≠ 1 No axial ratio calculation and check.					

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
7-4	I	25-32	IRAD	I8	Control checking of radial ratios and replacement of bad detectors.

IRAD = 0 No radial checking.

IRAD = 1 Check radial ratios and replace bad detectors.

IRAD = 2 Check radial ratios but do not replace bad detectors.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
7-5	R	33-40	DEV1	F8.1	Percent deviation used for axial ratio check.
7-6	R	41-48	DEV	F8.1	Percent deviation used for radial check.
7-7	R	49-56	UNUSER	F8.0	Uncertainty factor by which the power distribution is to be multiplied. This factor affects the alarm limit calculations only and not the actual power and exposure distribution. May be used to specify a tilt factor.

UNUSER $\leq$ 0 The factor is not used (set to 1).

UNUSER > 0 The factor multiplies the power for alarm limit calculations.

8 Hand Overlay In-Core Signals (Use Repeatedly as Specified by N)

This record is used to replace detector signals as recorded by the data logger.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
8-1	I	1- 8	J	I8	Detector string number.
8-2	I	9-16	I	I8	Detector level number 1 is top of core.
8-3	R	17-24	E(J,I)	F8.1	Simulated data logger in-core detector signal in MV.

9 Date and Program Parameters (Required)

For burnup cases TSTART and TEND define the operation date of the burnup block. For power distribution cases, the applicable dates for that unique paper tape should be used.

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
9-1	I	1- 2	TSTART(1)	I2	Starting Month
9-2	I	3- 4	TSTART(2)	I2	Starting Day of Month
9-3	I	5- 6	TSTART(3)	I2	Starting Year
9-4	I	7-10	TSTART(4)	I4	Starting Time (Military - Hours in 1000s and 100s, Minutes in 10s and Units hhmm)
9-5	I	11-12	TEND(1)	I2	Ending Month
9-6	I	13-14	TEND(2)	I2	Ending Day of Month
9-7	I	15-16	TEND(3)	I2	Ending Year
9-8	I	17-20	TEND(4)	I4	Ending Time (Military hhmm)
9-9	I	21-36	RUNRQT	I6,I10	Computer run date of an exposure case that is to be used as the exposure base of a power distribution. If the requested case is not found or the field is blank (zero), the last exposure case on file is used, unless HISTAT=BOC.
9-10	A	37-40	HISTAT	A4	Controls switching of history file to a new data set and beginning of cycle initialization.

HISTAT = BØCb Assumes zero previous exposure. This option writes the burnup block with no validation of mating times and block sequence. b is blank.

HISTAT = bbbb Exposure read from file and new case written at end of same file. Normal value is blanks.

HISTAT = Anything Else Start new history file on FORTRAN Unit 10. This option also involves a JCL override.

Inclusion of the Unit 10 JCL automatically invokes this option without the need to change the HISTAT value.

10 Xenon Worth Calculation

Calculate reactivity worth of xenon and samarium depending on power vs time profile. Five step power changes within 100 hours may be specified.

Record 1 (Required)

Field	Type	Columns	Variable	Fortran Format	Description/Restrictions
10a-1	I	1- 8	IB	I8	Number of power level changes. Maximum number of five changes.

IB = Negative Number — Negative indicates the power level on next record is in MWTH. Absolute value is number of power level changes.

IB = 0 — No xenon calculation performed. Do not supply the next two records.

IB = Positive Number — Positive indicates the power level on next record is in fraction of the power level. Calculated from the in-core detectors.

Record 2 (Use If IB ≠ 0)

If the power is given in MWTH (IB is negative) the first power level is the equilibrium power and time must be 0. If power level is fraction of INCA power, equilibrium power is from INCA and first power level is a change. Power must be greater than zero.

10b-1	R	1- 8	PLEVEL(1)	F8.1	First power level.
10b-2	R	9-16	PLEVEL(2)	F8.1	Second power level.
10b-3	R	17-24	PLEVEL(3)	F8.1	Third power level.
10b-4	R	25-32	PLEVEL(4)	F8.1	Fourth power level.
10b-5	R	33-40	PLEVEL(5)	F8.1	Fifth power level.

Record 3 (Use If IB ≠ 0)

Times in hours from equilibrium time (time = 0). Each time corresponds to the end of a power level interval. Maximum time is 100 hours.

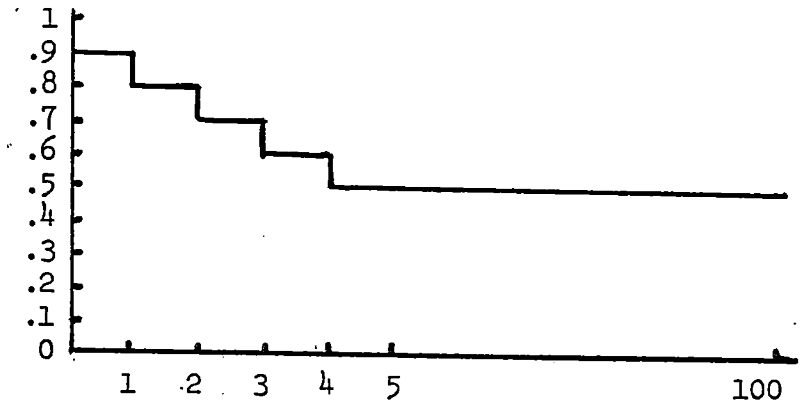
10c-1	R	1- 8	TIME(1)	F8.1	Time of first power level.
10c-2	R	9-16	TIME(2)	F8.1	Time of second power level.
10c-3	R	17-24	TIME(3)	F8.1	Time of third power level.
10c-4	R	25-32	TIME(4)	F8.1	Time of fourth power level.
10c-5	R	33-40	TIME(5)	F8.1	Time of fifth power level.

Example:

IB = 5
PLEVEL = .9, .8, .7, .6, .5
TIME = 1., 2., 3., 4., 5

Equilibrium Power Level = 1

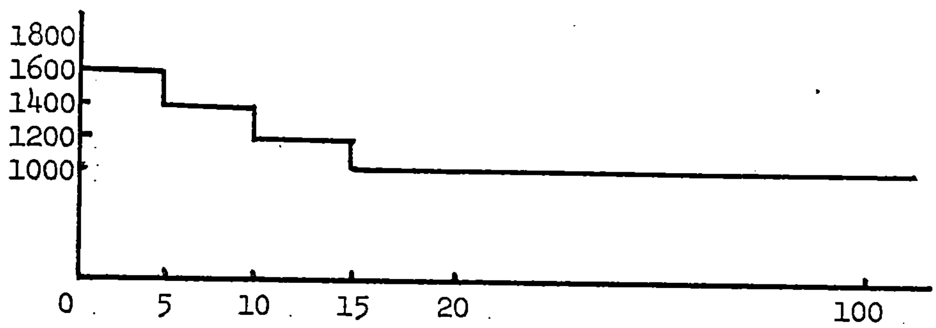
Fraction of INCA Power



IB = -5
PLEVEL = 1800, 1600, 1400, 1200, 1000
TIME = 0., 5., 10., 15., 20.

Equilibrium Power Level = 1800

Power in MWTH



APPENDIX J

DESCRIPTION OF INCA OUTPUT REPORTS

DESCRIPTION OF THE INCA OUTPUT REPORTS

The first page of the INCA output recaps the various inputs. The primary source of input to INCA is from the Varian data logger. Hand overlay cards may be input by plant personnel. The title of the case is listed as the first line of the first page and each page after. The second line of each INCA output describes the INCA version-brief summary of features of that version. The third line of the first page gives the PANVALET source program name, level, and date. This allows each INCA output to be tied back to the Fortran source program.

Fluid Properties

The reactor flow does not include any bypass flow. This field is input from the hand input by plant personnel. If left blank, the data logger value for core flow is used. The data logger value is listed under reactor flow in plant parameters.

Inlet enthalpy, liquid enthalpy, and vapor enthalpy are calculated from other fluid properties.

Reactor pressure is read from the plant input. If that is blank or zero, pressure is used from the data logger.

Power in steam generator 1 and power in steam generator 2 are taken from data logger. The reactor power is also taken from the data logger. It is usually the sum of the two steam generator powers.

Feed-water temperature and feed-water flow for the two steam generators are read from the data logger.

Steam flow and pressure of the two steam generators are read from the data logger.

Reactor pressure and reactor flow are read from the data logger. The reactor flow does not include any bypass flow.

T average and delta T for the two steam generators are read from the data logger. Megawatts electric gross, megawatts electric net, nuclear power channel 9, turbine stage 1 pressure, condenser vacuum, and charging flow are read from the data logger.

Boronmeter is read from the data logger. However, the boronmeter scale, which is the multiple of 500 ppm, is read from the hand input. Boron concentration is from hand input. If the hand input is blank or zero, the boronmeter reading plus scaling is used.

Core thermal power is the entire power output of the reactor; pump power is not included. This is considered to be the true power and the detector signals are scaled to match this power. See, also, the detector to calorimetric adjusted after the tilt calculations.

Core inlet temperature is input from the data logger.

The next portion of the INCA output describes a few of the options which may have been selected by plant personnel. The options are whether or not symmetrically located detectors were to be averaged. Another option is whether or not axial ratios were to be calculated and checked. The third option is whether or not radial signals were to be calculated and checked. If any hand overlayed signals were input, they are summarized towards the bottom of the first page. If no hand overlay signals were used, a message to that effect is output.

Mating or Rerun Case on File

These messages list the first case on file that could mate with the exposure of this case. All subsequent cases to the end of the file are also listed. The message EXPOSURE BLOCK RUN ON indicates which case is being used as the exposure base for this case.

Bias Applied to Belfab Sensitivities

Number that has been added to all Belfab sensitivities.

Bias Based on This Run

Bias seen by Reuter-Stokes and Belfab symmetric detectors. Values may be used to verify the actual bias applied. Values associated with failed detectors should be ignored.

Detector Axial Position

The detectors' position given in centimeters and feet from the core bottom are summarized on this page.

Instrument Core Location

A core map showing the orientation of the core and the position of each of the 45 detectors is printed. See detector numbering map.

Detector Signals Arranged in Groups of Symmetric Detectors

A summary of all of the detector signal inputs and their conversion to megawatts thermal is given. The signals are corrected for exposure depletion and background noise. The millivolt signals listed on this report include any hand overlayed signals. Any detector validation and subsequent replacement by symmetric or adjacent detectors is not indicated on this report.

Detectors which are treated as failed because they had zero input and have symmetric partners are listed in the next report. The detector numbers, the failed signal and the replacement signal is given. See octant locations map.

Rod Bank Regions

A summary of the position of all the control rods is given on this report.

Exposure Dependent Peaking Factors and Coupling Coefficients

A separate report is given for each rod bank region. The rod bank region number which appears in the title of each report is an indexing number internal to the INCA program. The reports are given in order of the regions listed under the rod bank regions report, that is, the first report corresponds to region 1, the second report corresponds to region 2. Bank is the index internal to the INCA program. Integ is the limits of the rod bank region in INCA indexing system. Bundle is the octant location number. Average exposure is the exposure in the rod bank region. One pin and four pin are the peaking factors associated with this rod bank region. The four couples, B bottom, R right, T top, and L left, are used to replace and check a detector with its four octant symmetry neighbors. The coupling consistency check verifies that a bottom couple corresponds to its neighbors up couple and that a left couple corresponds to a neighbors right couple.

The power distribution shown is generated from the coupling coefficients. This power distribution is not used in the INCA solution. It represents a precalculated power shape based on library values.

Full-Core

Detectors failed by coupling coefficient check are not failed for the rest of INCA. The symmetric coefficient matrix is the list of curve fit coefficients that are found by least squares analysis. The Measured/Theoretical Map is the curve fit with the detector values printed below the location of the detector. The reactor power map is the curve fit values with the theoretical distribution factored in to give a power distribution. The deviation from the average octant is the value in each octant location divided by the average value for that octant minus one. The collapsed octant map is the average value for each octant. The normalized integrated power map is produced by quadrature integration of the four detector level power maps.

Percent Deviation From Expected Detector Power

Detector power deviation from the value that would make the individual axial ratios as close as possible to the average axial ratio.

Sensitivity Update Check

The change in sensitivity divided by the millivolt signal should be a constant, assuming no large power distribution changes. Listed is the percent deviations from the average delta sensitivity divided by millivolt signal. The averaging is done by detector level. Asterisks denote detectors with a zero millivolt signal or a detector with no sensitivity update. This report will not be generated if all of the detectors have a zero sensitivity update.

Failed Detector Log

Detector failures compared to previous INCA's detector failures. L denotes detector had a large deviation in sensitivity check. N denotes detector had a negative sensitivity update. Z denotes detector had a zero sensitivity update. S denotes detector was failed in the previous INCA but not now failed (failed means +,X or *). C denotes a combination of S and L, S and N or S and Z. A +, X or * will cover up anything else. + denotes hand overlay; X denotes replaced by symmetric detector. * denotes replaced by coupling coefficients.

Coupling Coefficient Failures

A detector is compared to its theoretical power by coupling coefficients to its octant symmetry neighboring detectors. Any detector which exceeds an input deviation from its theoretical value is considered failed.

Symmetric Replacements

Detectors which have been failed through the various checks are then replaced by symmetric detectors.

Generated Replacements

Any detectors which are failed and have not been able to be replaced by symmetric detectors are replaced with their theoretical power. The failed signal in millivolts and the replacement power in megawatts is listed for each failed detector.

The axial ratio test is calcualted as before and the ratio results are again output. Any detectors which failed to pass the axial ratio test are again listed.

The detectors are again compared to their theoretical power based on coupling coefficients. Any deviations are again reported.

Azimuthal xenon tilt is calculated based on three sets of symmetric detectors. The average tilt amplitude and average tilt angle are calculated. This tilt may not be used to determine the quadrant tilt as required by the Technical Specifications.

Detector to Calorimetric Adjustment
Core Normalized Power Distribution

This report is by octant bundle. The normalization factor is (204 x 50)/core power. 204 is the number of bundles in the core. 50 is the number of axial nodes listed in this report. Nodes 1 and 51 each are weighted as a half node.

Bundle Normalized Axial Power Shape

The normalization factor for this report is 25. There are 25 axial locations in each bundle. They are integral quantities calculated from the 51 points in the above report. This indicates the power shape in each bundle, but it does not indicate how each bundle relates to other bundles.

Core average axial is the average axial profile based on the bundle normalized axial power shape weighted by the bundle powers.

Power Distribution (Peak kW/Ft With TILT Factor)

This report gives the power in kilowatts per foot at each axial location. These numbers are compared to the license limit.

Minimum Margin to Tech Spec Limits

These ratios are the comparison of the license limit with the above power distribution.

Core Extreme Values

A summary of the core extreme values, the kilowatts per foot (with tilt factor), and the margin to limit ratio is given. The alarm factors are calculated for each of the four levels of detectors. This report indicates the limiting conditions in the reactor. Values by detector are for the worst case "seen" by that detector. PLHGR and peak pin power are by fuel type. PLHGR and peak pin power given are the nearest to the limit (not necessarily maximum value) if the axial peak is above .75 core height. In that instance another message is printed giving all 28 octant locations limit. If any margin to limit (ratio), except the alarm factor (PLHGR) is less than 1.0, a message is printed on the core information page. Radial peaking factor is based on actual assembly power with pin peaking (times tilt factor).

Fuel Exposure Axial Distribution

Fuel exposure for each axial node in each bundle is given in MWD/MTU.

The data of the exposure and energy generated in MWHT is given at the end of the report.

Control Rod Exposure Axial Distribution

Control rod exposure for each axial node in each control rod is given in MWD of neighboring fuel bundles. See control rod numbering map.

Assembly Information

This is a series of reports listed in octant format.

Octant Numbering System

This report indicates the octant location number of each bundle.

Core Loading

The fuel type is given.

Integrated Power

The magawatts thermal generated in each bundle is given.

XY Normalized Power

The power of each bundle relative to its neighbors is given. The normalization factor is 204/core power.

Maximum Heat Flux

This is the maximum heat flux in the bundle.

Location of Maximum Heat Flux

This is the location of maximum heat flux as given in the above report.

Peak Pin Power kW (With TILT Factor)

This is the maximum nodal pin power in kilowatts per foot in each bundle.

Peak Linear Heat Generation Rate kW/Ft

PLHGR includes pin peaking factor but no uncertainty factors.

Current Control Rod Position

This is the position of the control rods in centimeters from the core bottom as input by plant personnel. Negative numbers indicate part length control rods.

Exposure (MWD/MTU)

Bundle average exposure.

Summary of Control Rod Exposure

Core Information

Total core power in megawatts thermal is the power as input by the data logger or plant personnel. This is the core power used in calculating the license limits. Core average exposure is the average of all the fuel exposure given in megawatt days per metric ton uranium. The power split is the power in the lower half of the core compared to the power in the upper half of the core.

Batchwise Information

The power fraction in the three batches of fuel is given. The exposure by fuel type is given.

Quadrant TILT Vs Core Average Exposure

The quadrant TILT from the full-core routine integrated power map is plotted against core average exposure. The plotted character denotes the quadrant in which the TILT occurred. This plot is only updated for an exposure run. Any data points above the maximum plot scale are plotted at the top with letters denoting the quadrant number.

Data Logger Readings and Alarm Limits

This report is the pertinent document for setting the alarms. The alarm limit for each detector is given. Failed detectors which should have no alarm limit are indicated by a +, X or * under the failed column at the left-hand side of the report. Although a nonzero value may be indicated for the alarm limit of a detector failed by X there really should be no alarm limit associated with that detector. The reading in millivolts and the background and sensitivity factors are listed as they were input from the data logger. The millivolts are not corrected for exposure, background, and .98 scaling. NV is units of flux neutrons/CM^2 -sec divided by 10^{12} and is corrected for exposure and background.

Number of Detectors Used

Report number of working detectors (as determined by INCA) by quadrant and axial level. A message is printed if the number of detectors is less than the number required by the Tech Specs.

Varian Data Logger Output

List of analog to digital counts and the values converted to engineering units.

List of Input Cards as Supplied by Plant Personnel

ATTACHMENT B

INCA-1.0

IN-CORE INSTRUMENT ANALYSIS SYSTEM FOR THE PALISADES PLANT

C-E COMBUSTION DIVISION

LEGAL NOTICE

The analysis methods presented in this document and developed at Combustion Engineering, Inc., have been discussed elsewhere in the open literature—hence, further distribution of this information is not restricted. This refers to Sections I, II, and III of this manual. However, the actual coding, whether it be a FORTRAN listing, a source deck, or any other form, and the values of the library coefficients and weighting factors are considered proprietary to Combustion Engineering, Inc., and are not to be distributed to persons other than the employees of the Consumers Power Company, Inc., or persons under a proprietary agreement with Combustion Engineering, Inc.. This refers to Section IV and the four appendices of this manual.

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IN-CORE INSTRUMENT ANALYSIS SYSTEM - INCA 1.0

I. INTRODUCTION

The in-core nuclear instrumentation which is being installed in the present generation of power reactors is intended to provide an auxiliary source of information concerning the gross power distribution within the reactor core. It plays no role in the protection of the reactor plant, since the out-of-core instrumentation is deemed adequate for this purpose. The design limits on control rod insertion, maneuvering rates, and other operational characteristics are determined during the design of the core, with a more-than-adequate margin. In addition, the in-core instrumentation is not felt to be necessary to the economic operation of the reactor. Nonetheless, it is desirable in a large reactor to have some additional and more detailed information concerning the irradiation of the fuel assemblies than can be obtained from the out-of-core instrumentation in order to provide a means of verifying the validity of the basic design calculations.

The instruments presently provided in Combustion reactors are Rh self-powered detectors which, of course, measure neither the flux nor the fission power, but the Rh activation. Consequently, it is necessary to apply theoretical corrections in order to convert the in-core instrument signals to more meaningful information. The INCA-1.0 code is intended to perform this information conversion operation in a systematic way and to present the results in a form which has direct significance to the reactor engineer. In essence, the code converts instrument signals into the integrated power in each fuel assembly at any point in core life, the maximum linear heat rate for any fuel rod in a given fuel assembly, and the minimum DNB ratio computed for the hottest channel in each fuel assembly. In addition, the accumulated exposure is provided on both an assembly-wise and batchwise basis.

The present handbook collects in one place the information on the detector system, the analysis methods, and the INCA code, so that the user may have a full understanding of both the instrument signals and their interpretation. Since the system is still undergoing evolution, the handbook is provided in a looseleaf form so that subsequent revisions and additions can be conveniently made.

II. DESCRIPTION OF THE IN-CORE DETECTOR HARDWARE

A. Introduction

The in-core instrument assemblies for the Palisades plant were manufactured by Reuter-Stokes of Canada. Each instrument assembly consists of two chromel alumel thermocouples, four rhodium self-powered neutron detectors, and either a vanadium self-powered neutron detector, a cobalt self-powered neutron detector, or a background detector (see Fig. II-1). The thermocouples are used to measure fuel assembly inlet and outlet coolant temperatures, while the neutron detectors are used to provide signals to produce information on the reactor power distribution.

B. Principles of Self-Powered Neutron Detector Operation

The principle of operation of self-powered neutron detectors involves conversion of the incident neutron radiation on the detector emitter material to energetic electrons which penetrate the solid insulation and come to rest on the collector or its surroundings. The deficiency of electrons in the emitter results in a positive charge on the center conductor of the coaxial cable attached to the emitter. The rate of positive charge production produces a current which is directly proportional to the rate at which radiation is being absorbed by the emitter.

1. Rhodium and Vanadium Detectors . The primary mechanism by which the incident neutron radiation in the rhodium and vanadium detector is converted to energetic electrons is through neutron capture in the emitter producing a capture product which decays through beta emission. Some of the beta particles are energetic enough to escape from the emitter resulting in a positive charge on the emitter.

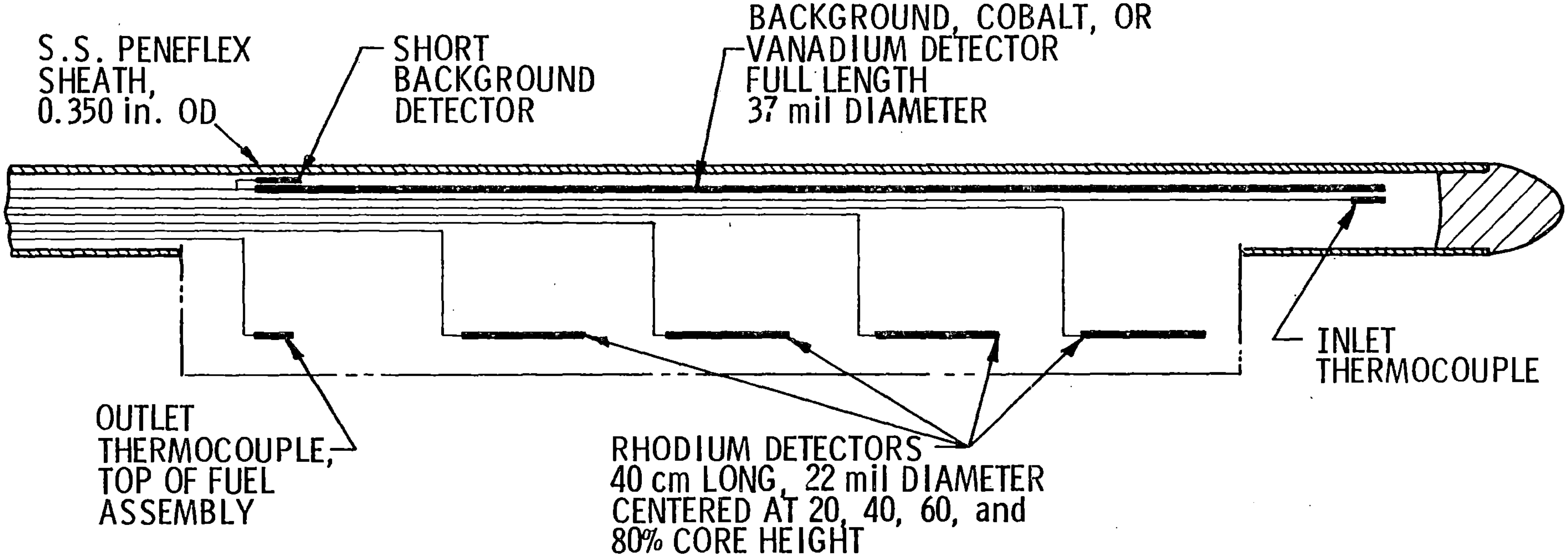
   The rhodium and vanadium emitters have reasonably large neutron capture cross sections and their capture products are beta emitting isotopes with short half-lives. Rhodium-103, for example, has a 150 barn 2200 m/sec cross section and its capture product (Rhodium-104) emits beta particles possessing an end-point energy of 2.4 Mev with a 42 second half-life*. Vanadium-51 has only a 5 barn 2200 m/sec absorption cross section and its capture product (Vanadium-52) emits beta particles having a 2.5 Mev end point energy. Since the cross section of the vanadium detectors is much less than rhodium, its sensitivity per unit length (and therefore its burnout rate) is much less than rhodium. However, the vanadium detectors are full core length while the rhodium detectors are only 40 cm long causing the total sensitivity (to 2200 m/sec neutrons) to be slightly greater than that of rhodium.

---

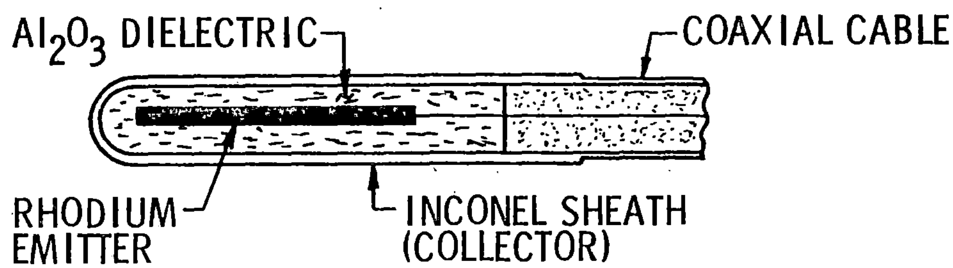
* An isomeric state, RH^{104m}, is also produced approximately 7.3% of the time with a 4.41 min. half-life.

Figure II.1

TYPICAL NEUTRON DETECTOR AND DETECTOR ASSEMBLY



TYPICAL INSTRUMENT ASSEMBLY



TYPICAL RHODIUM DETECTOR

2. Cobalt Detectors - The primary mechanism governing the operation of the cobalt detectors is neutron capture in the emitter producing capture gamma rays which are partly absorbed in the emitter itself, which produce compton and photo-electrons. Some of these are energetic enough to escape from the emitter resulting in a positive charge on the emitter. Normally, the emitter material in this type of detector should have a large neutron cross section and should not produce any interferring beta emitting capture products.

Cobalt, however, does have a beta emitting product with a very long half-life (5.26 years). This decay signal does produce a background. However, due to the long half-life, it is easily compensated for.

When neutrons are absorbed in the cobalt, the capture gamma rays emitted within 10^{-14} seconds are converted to compton and photo-electrons. The time response of these detectors is thus limited only by cable capacitance and the electronics. The sensitivity of the cobalt detectors used in Palisades is about one-fourth that of the vanadium detectors.

C. Detector Configuration

A sketch of the instrument assembly is shown in Figure II-1. Note that the "fifth" neutron detector in the assembly can be either a full core length cobalt detector, a full length section of cable for background detection, or a length of cable for background detection which terminates at the top of the core.

Table II-1 below give a comparison of various properties of the rhodium and vanadium detectors for a PWR.

TABLE II-1

COMPARISON OF PROPERTIES OF RHODIUM DETECTORS WITH THOSE OF VANADIUM DETECTORS

	PROPERTY	RHODIUM^{103} DETECTOR	VANADIUM^{51} DETECTOR
1.	Length	40 cm	321 cm
2.	Diameter	22 mils	37 mils
3.	Sensitivity	1.37×10^{-21} amp/nv-cm	1.87×10^{-22} amp/nv-cm
4.	σ_1 (PWR spectrum)	9 b	.06 b
5.	σ_2 (PWR spectrum)	75 b	2.7 b

TABLE II-1 (Cont.)

PROPERTY	RHODIUM103 DETECTOR	VANADIUM51 DETECTOR
6. Depletion Rate in 10^{13} n/cm^2-sec (Maxwellian)	0.23% per month	0.013% per month
7. Depletion Rate in PWR Spectrum $(\sigma_1 \varphi_1 + \sigma_2 \varphi_2) \times 1$ month	1.2% per month	0.03% per month

Note: The depletion rate in vanadium for Palisades is only about 2.5% that of rhodium.

D. Background Signal

The term, background, is used for the sum of all signals generated in the detector and cable which are not the result of neutron interaction with the emitter. The main contributors to the background signal are expected to be the following:

1. The cable "self" signal.
2. Detector-to-detector and detector-to-cable "cross talk".
3. The gamma sensitivity of the detector.

The first effect is due to the (γ, e) reaction with the sheath and the lead wire, the neutron activation of aluminum in the insulation, and the pickup of externally generated electrons such as from neutron activation of the manganese in the stainless steel Penflex sheathing. The sizes of the rhodium detector cable have been chosen so as to minimize the (γ, e) effect. The remaining self signal effects are expected to be small with the information from the background detectors used for compensation.

The second effect is the cross talk effect. This is due to the decay electrons in the vanadium and rhodium emitters impinging on adjacent detectors and cable lead wires. This effect is not expected to contribute much to the signals, since the detectors and cables are not bound tightly together. Again, information from the background detectors should provide information on this effect.

The last important background signal effect is the gamma sensitivity of the detector. This effect is due to gamma rays ejecting photo and compton electrons from the emitter and the sheath. At the present time, there is no way to experimentally determine the magnitude of this effect. However, since the gamma flux should be fairly proportionaly to local fission rate of power, the error incurred should be small.

E. Detector Readout

The output of the self-powered detectors is a low level current. This current flows through a lead resistor producing a voltage. The voltage is then measured by the data processor.

Under average flux conditions, the current from a rhodium detector will be about 2.6 microamperes. This current flowing through the load resistor of 10^5 ohms produces 260 millivolts. A signal of this magnitude is easily measured by the data processor.

To insure that essentially all of the detector current flows through the load resistor, the leakage resistance of the cable (this resistance is effectively in parallel with the load resistor) should be maintained at a value which is greater than 10^8 ohms. This value means that no more than 0.1% of the current flows through the leakage resistance.

F. Detector Layout in Palisades

Figure II-2 shows the layout of detectors in the Palisades reactor. There are 45 instrumented assemblies. All the instrument tubes contain a string of four rhodium detectors and two thermocouples; 12 contain a background detector; 6 contain a cobalt detector, and 45 - 12 - 6 = 27 contain a vanadium detector.

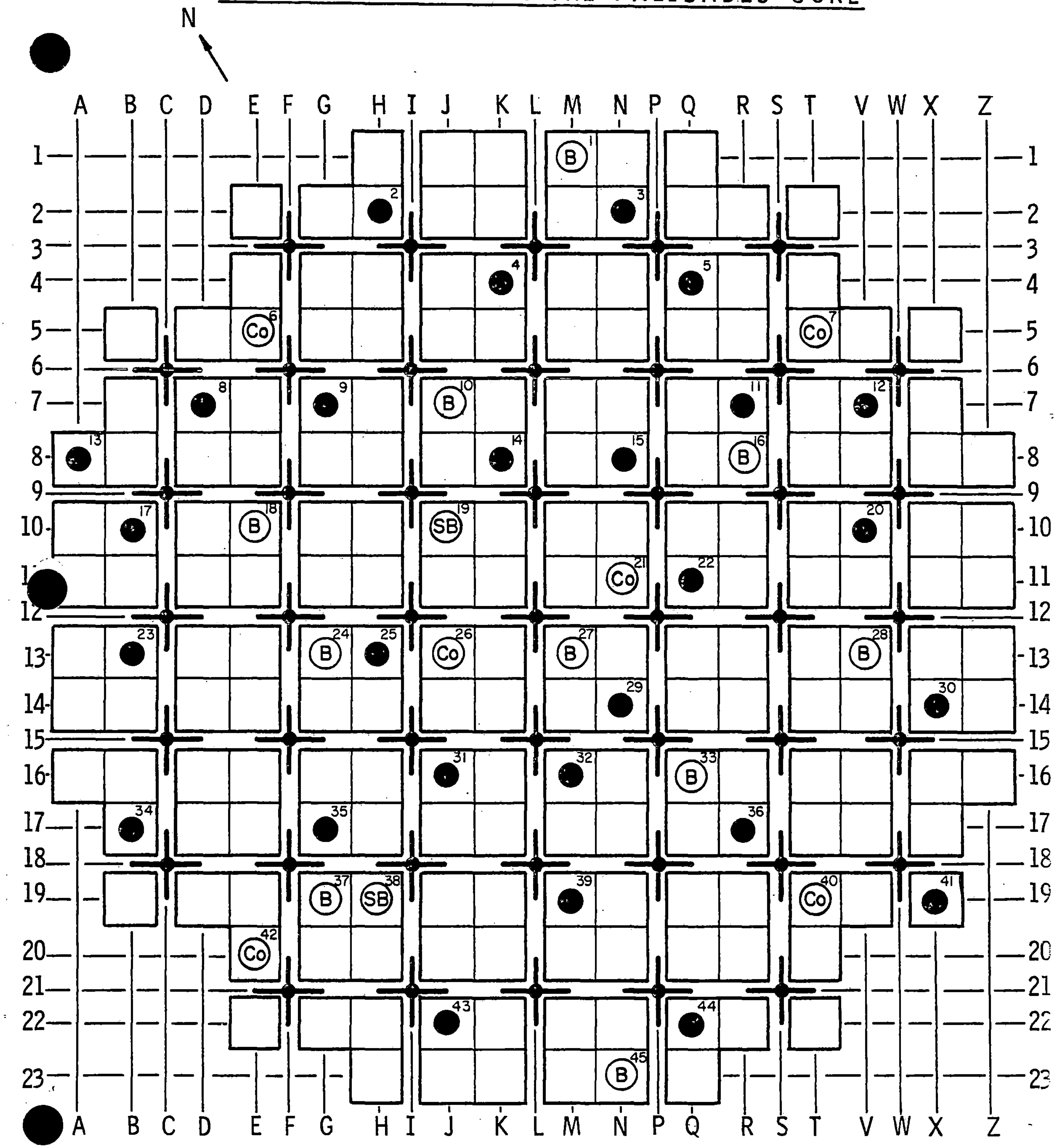
In Fig. II-2 "B" indicates a background signal cable terminating at the bottom of the active core. The fuel assembly locations are: M-1, J-7, R-8, E-10, G-13, M-13, V-13, Q-16, G-19, and N-23.

"SB" indicates a background signal cable terminating at the top of the active core. The fuel assembly locations are: J-10 and H-19.

"Co" indicates a cobalt detector. The fuel assembly locations are: E-5, T-5, N-11, J-13, T-19, and E-20.

Figure II.2

DETECTOR LAYOUT IN THE PALISADES CORE



III. THE INCA ANALYTICAL PROCEDURE

In essence, the method of performing the instrument signal analysis is similar to the synthesis techniques frequently used to approximate solutions to three-dimensional design problems. The signals from instruments along one channel are used to infer an average axial power shape in the surrounding fuel assembly. These shapes are then used in conjunction with a library of coupling coefficients to obtain the corresponding power profiles in fuel assemblies which are uninstrumented or contain inoperable detectors. These coupling coefficients are allowed to vary axially over the various vertical regions defined by differing control rod patterns. Thus, the axial power shapes in these assemblies are piecewise continuous linear combinations of the axial shapes in the adjacent instrumented fuel assemblies. Additional libraries, derived from standard reactor analysis calculations, are then employed to obtain the peak pin power and hot channel heat flux in each assembly. From the latter, the overpower safety margin of each fuel assembly is obtained by iterated DNB (departure from nucleate boiling) ratio calculations.

For the most part, the analysis assumes symmetrical operation of the core; that is, octant symmetry is employed to allow reflection of all the instruments into one octant of the core. The synthesis then proceeds for this chosen subset of assemblies. However, before the reflection, the presence of a tilted flux distribution is checked by comparing signals from the symmetrically located detectors, and information as to the amplitude and orientation of the tilt is printed in the output. A routine is also available which does not assume the octant symmetry and produces expanded, full core power maps.

A. Analysis of Instrumented Fuel Assemblies

1. Notation - In the following list of symbols, the integers e and m designate the x and y locations of both a fuel assembly and the control rod it contains in the plan view, while n (1, 2, 3, or 4) indicates the axial detector position. The axial coordinate is measured from the bottom of the core.

E_{emn} = rhodium detector signal from the n^{th} axial detector of fuel assembly em, corrected for rhodium depletion and any deviation from the nominal sensitivity.

P_{emn} = power in assembly em integrated only over the length of axial detector n.

$P_{em}(z)$ = power in assembly em per unit axial length at height z.

P_B = total power generated in a given batch of fuel assemblies.

P_{em} = total power generated in fuel assembly em.

$\langle P_{em} \rangle$ = average power per unit length in fuel assembly em.

$\langle P_B \rangle$ = average power per assembly per unit length for assemblies in a given batch B.

$\langle P_C \rangle$ = average power per assembly per unit length for all the assemblies in the core.

α_n = distance of the top of the n^{th} detector from the core bottom.

$A_{emn}, \cdots, D_{emn}$ = control and perturbation coefficients for detectors in assembly em

β_n = distance of the bottom of the n^{th} detector from the core bottom.

H_{em} = distance of the bottom of the control rod em from the core bottom

S_K = distance of the bottom of the k^{th} rod bank region from the core bottom ("rod bank region" will be defined in a later section).

$\bar{P}_{emk}$ = largest value of $P_{em}(z)$ with $S_{K-1} \leqslant z \leqslant S_K$.

$Q_{em}(z)$ = heat flux per unit length in hottest channel of fuel assembly em at z.

T_{emk} = maximum ratio of channel-heat-flux to xy integrated power in fuel assembly em and rod bank region k.

R_{emk} = maximum ratio of pin power per unit length to average pin power per unit length in fuel assembly em and rod bank region k.

w_{emn} = fractional insertion of control rod em into axial zone defined by the ends of detector n.

W_{emn} = power-to-signal coupling coefficient which relates the integrated power in assembly em over the length of detector n to the signal from detector n in the absence of control rods.

2. Conversion of Rhodium Activation to Assembly-Power Integrals - In the instrumented assemblies the volume integrated power is taken to be related to the rhodium signal E_{emn} and to the position of the control rods--primarily those which are adjacent (there are other small effects such as those due to the soluble boron in the water, the fuel burnup, and the power level, which are accounted for in the INCA code but will be neglected here for simplicity of discussion). Thus:

$$P_{emn} = \left[W_{emn} + A_{emn}\, w_{e-1,m,n} + B_{emn}\, w_{e+1,m,n} + C_{emn}\, w_{e,m-1,n} + D_{emn}\, w_{e,m+1,n} \right] E_{emn}$$

The fractional insertion of a full length control rod, W_{emn}, is given in terms of H_{em}, α_n and β_n, as shown in Fig. III-1.

$$0 \leqslant w_{emn} = \frac{\alpha_n - H_{em}}{\alpha_n - \beta_n} \leqslant 1$$

if $w_{emn} < 0$, it is set at $w_{emn} = 0$.
$w_{emn} > 1$, it is set at $w_{emn} = 1$.

For a part-length rod of length L, the corresponding expressions are somewhat more complex as can be seen from Fig. III-1.

$$\text{For } H_{em} + L < \alpha_n,\ 0 \leqslant w_{emn} = \frac{H_{em} + L - \beta_n}{\alpha_n - \beta_n}$$

$$\text{For } H_{em} + L \geqslant \alpha_n,\ 0 \leqslant w_{emn} = \frac{\alpha_n - H_{em}}{\alpha_n - \beta_n} \leqslant 1$$

As before, if W_{emn} is calculated to be out of the 0-1 range, it is set equal to either 0 or 1 by the previously given rule. In this formulation, it has been assumed that the control rod shaft above the active material has no effect on reactivity or the power distribution and that it can be treated as a water filled guide-tube.

The rhodium power to signal coupling coefficient is given by the following expression:

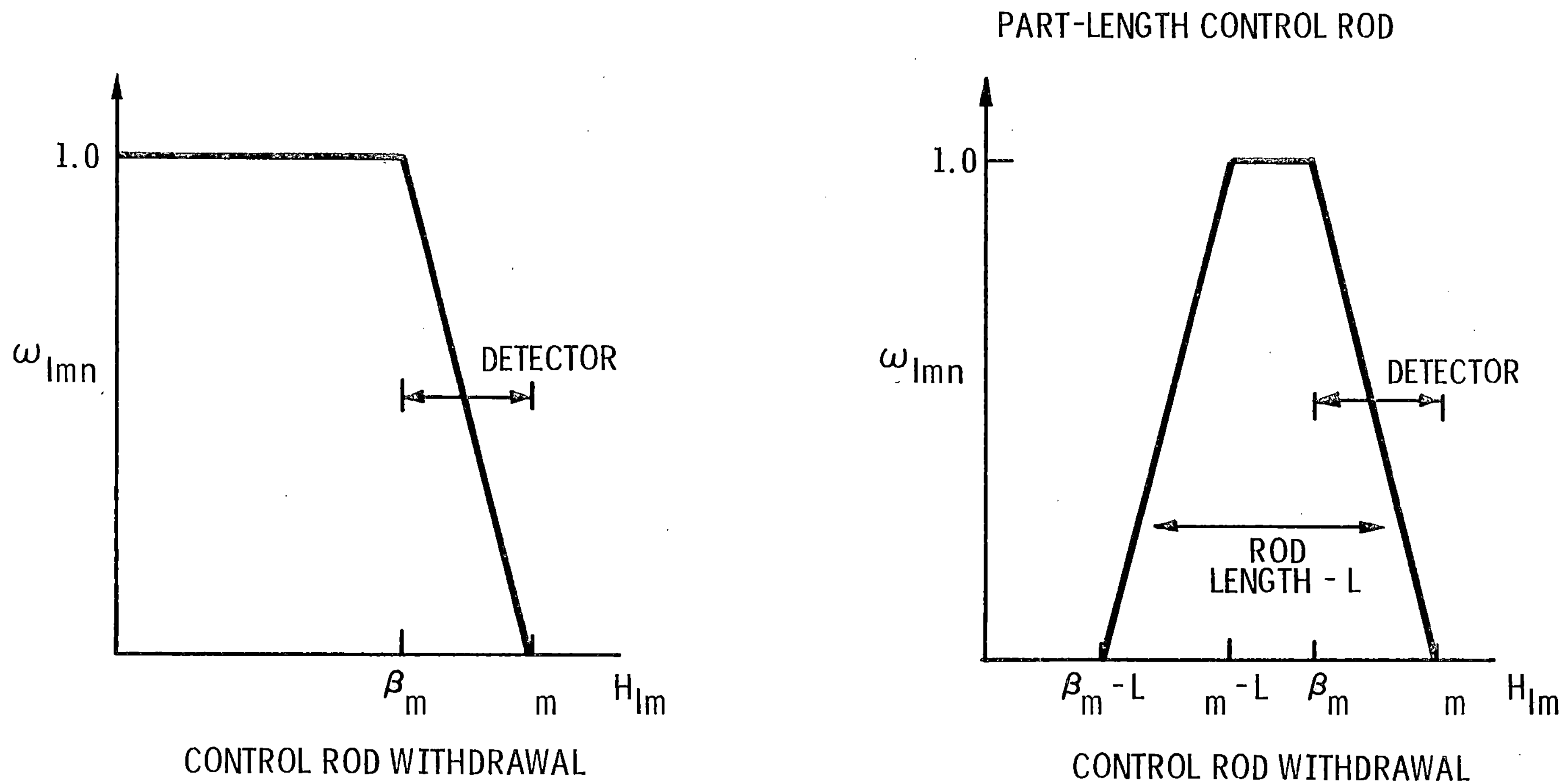
$$W_{emn} = \left[SENS_{emn} \right]^{-1} * CALIB * WPRIME_{emn}$$

$$= \left[\frac{1}{\text{amps/unit } \varphi_O \text{ MAXWELLIAN at the surface of the detector sheath}} \right] \left[\text{rhodium activation due to unit } \varphi_O \text{ MAXWELLIAN impinging on the detector sheath, per rhodium atom} \right] \left[\frac{\text{integrated power of assembly em over the length of the nth detector}}{\text{rhodium activation, per rhodium atom}} \right]$$

The first term simply contains the sensitivity factor obtained from the specifications supplied by the detector vendor and relates the detector current produced to the unit 2200 m/sec Maxwellian neutron flux at the surface of the

Figure III.1

AXIAL CONTROL ROD WEIGHTING FUNCTION



detector sheath. The second term relates the emitter activation to the unit φ_O MAXWELLIAN, and can be derived from a thermal multi-group calculation as indicated below:

$$CALIB \equiv \frac{\int_0^{Eo} \int_{rh} \sigma_a^{rh} (E, \bar{r})\, \varphi (E, \bar{r})\, d\bar{r}\, dE}{\varphi_{2200}^{SHEATH}}$$

The third term in the expression for W_{emn} simply relates the integrated assembly em power seen by detector n to the emitter activation. Conventional fine spatial mesh, two-dimensional, few-group diffusion calculations are utilized to obtain these ratios via the following expression:

$$WPRIME_{emn} \equiv \left[\frac{P_{assembly}}{\sigma_{a,}^{rh}\, \varphi_{,}^{rh} + \ldots\ldots + \sigma_{aG}^{rh}\, \varphi_G^{rh}} \right]_{emn}$$

where G indicates the number of energy groups in the calculation. The rhodium cross sections are derived from detailed multi-group lattice cell calculations using conventional rhodium cross sections and a single empirically determined resonance shielding factor to account for both the nuclear shielding effect and the difference between the thermal and resonance beta escape probabilities from the detector wire.

The spectral and spatial conversion coefficient for the vanadium detectors is given by an expression completely analogous to the above by substituting "vanadium" where ever "rhodium" appears. However, since vanadium has no important resonance, the semi-empirical treatment of the resonance shielding factors obviously does not apply.

3. Axial Power Distribution in Instrumented Assemblies - From the four power integrals which have now been determined for each instrumented fuel assembly, the axial distribution of the xy integrated power of fuel assembly em can be constructed by fitting to simple Fourier modes:

$$P_{emn} = \int_{\beta_n}^{\alpha_n} dz \left[a_{em} \cos B(z - \frac{H}{2}) + b_{em} \sin 2B(z - \frac{H}{2}) + c_{em} \cos 3B(z - \frac{H}{2}) \right]$$

$$= a_{em} f_n + b_{em} g_n + c_{em} h_n$$

where

$$f_n = \left[\sin B\, (\alpha_n - \frac{H}{2}) - \sin B\, (\beta_n - \frac{H}{2}) \right] / B$$

$$g_n = \left[-\cos 2B \ (\alpha_n - \frac{H}{2}) + \cos 2B \ (\beta_n - \frac{H}{2}) \right] \quad /2B$$

$$h_n = \left[\sin 3B \ (\alpha_n - \frac{H}{2}) - \sin 3B \ (\beta_n - \frac{H}{2}) \right] \quad /3B$$

In these expressions, the choice of the wave number B introduces the capability of adjusting the axial reflector savings to improve the fit of the data. For four axial detectors in each channel, there will be twelve numbers in the set (f_n, g_n, h_n) and these are fixed program constants.

Rather than attempt a fit of the entire axial distribution by a simple function of many terms, it is usually better to fit a simpler function over a shorter range. The procedure is to generate two functions, one for the lower half of the core described by the set $(a, b, c)_{em}$ and one for the upper half described by $(a^*, b^*, c^*)_{em}$. The lower coefficients are determined from data for the lower three detectors:

$$P_{em1} = af_1 + bg_1 + ch_1$$

$$P_{em2} = af_2 + bg_2 + ch_2$$

$$P_{em3} = af_3 + bg_3 + ch_3$$

Similarly, the starred set is determined from the upper three detector data:

$$P_{em2} = a^*f_2 + b^*g_2 + c^*h_2$$

$$P_{em3} = a^*f_3 + b^*g_3 + c^*h_3$$

$$P_{em4} = a^*f_4 + b^*g_4 + c^*h_4$$

Solution of these two sets of equations provides the required numerical values of the six coefficients which then completely specify the axial distribution of the xy integrated power in fuel assembly em, $P_{em}(z)$.

Using these coefficients, the axial power distribution is computed at 51 axial points and stored for later calculations:

$$P_{em}(z) = a_{em} \cos B(z - \frac{H}{2}) + b_{em} \sin 2B(z - \frac{H}{2}) + c_{em} \cos 3B(z - \frac{H}{2}), \ 0 \leqslant z \leqslant \frac{H}{2}$$

$$= a^*_{em} \cos B(z - \frac{H}{2}) + b^*_{em} \sin 2B(z - \frac{H}{2}) + c^*_{em} \cos 3B(z - \frac{H}{2}), \ H/2 \leqslant z \leqslant H$$

B. Extrapolation Procedure to Fuel Assemblies Containing Inoperable Detectors

Although it is expected that very few of the detectors will fail during the course of the fuel cycle, a procedure is provided whereby the power in an assembly containing an inoperable detector can be obtained by consideration of the neighboring assemblies.

Use of tables of nuclear design results is made to estimate the power distribution in these "uninstrumented" assemblies. This is done by simply dividing the core axially into regions where the regions are characterized by differing control rod patterns and then by relating the axial power profiles in these rod bank regions to the known shapes in the neighboring instrumented assemblies. This method of synthesis is simple in concept but somewhat cumbersome in practice since the resulting axial power distributions are piecewise continuous linear combinations of the distributions in adjacent assemblies.

1. Definition of Control Rod Bank Regions - Under normal operating conditions, there will be some multiple of four control rods, one in each quadrant, having their tips at some lowest level. By finding these sets, the entire control bank configuration can be specified in terms of the population of each set and its withdrawal, S_K as indicated in Fig. III-2.

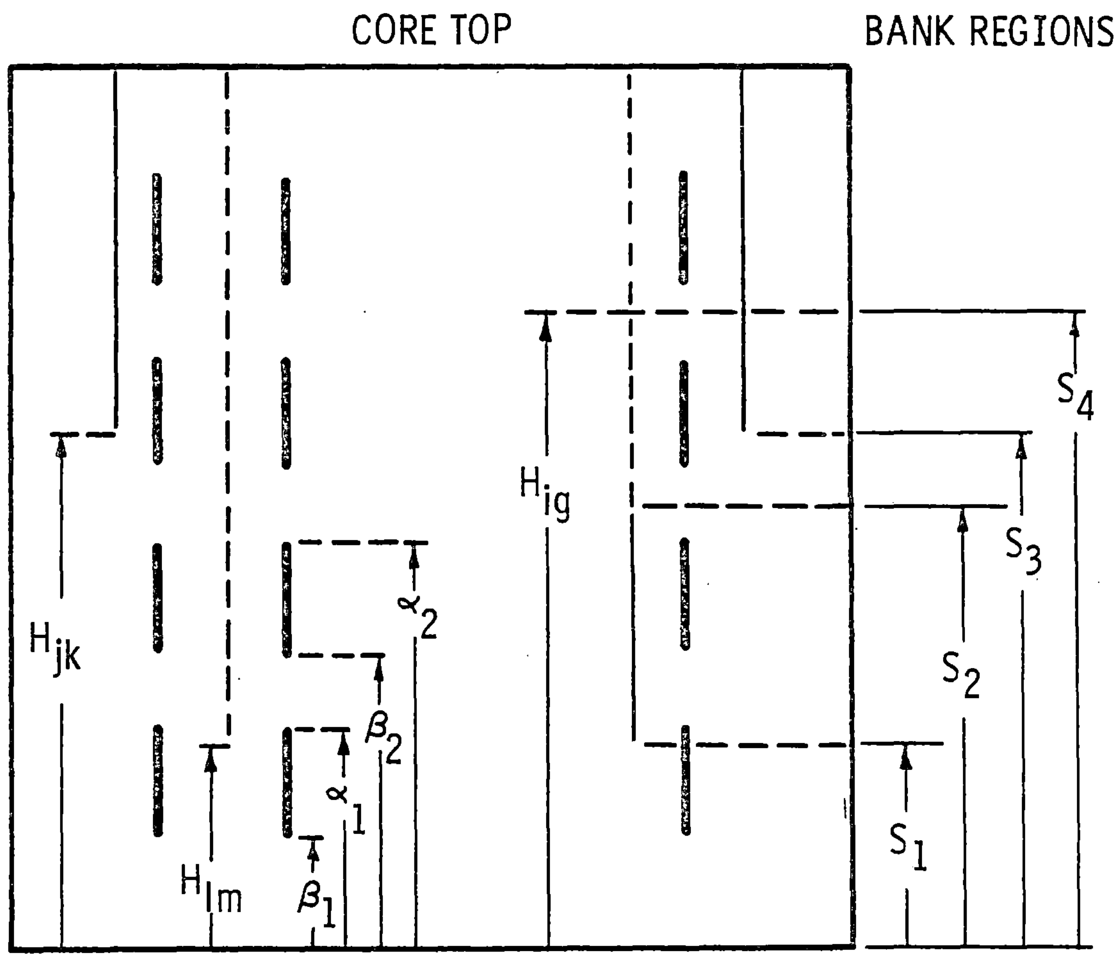
   To find the various bank sets, one scans all values of H_{em} to see which rods have their H_{em} within a specified dead-band δ about the first one examined. The process is then repeated for the remaining rods; etc. The members of a set, distinguished by their em indices, are then compared with the membership of certain banks known in the library and distinguished by indices j. From this procedure, the core configuration can be described completely as follows: the lowest axial region from 0 to S_1 is bank j^0 pattern, the next region from S_1 to S_2 is bank j^1 pattern, etc., until the height of the upper bank limit is equal to the full core height. Normally, it is expected that only two to four bank regions will be present and the total number of possible bank configurations in the library will be less than fifteen so the sorting among various alternatives is not too difficult.

   Part-length control rods require special treatment since both the top and bottom of the poisoned section define bank region limits. This can be done by adding to the array of rod withdrawal values the additional values $H_{em} + L$, where L is the length of the part-length rod in assembly em.

2. Calculation of Axial Power Distribution - The power distribution in these "uninstrumented" fuel assemblies is taken as proportional to the power in adjacent instrumented assemblies with coupling coefficients which are constant within a given control rod bank region:

Figure III.2

AXIAL CONTROL ROD AND DETECTOR ARRANGEMENT



$$P_{em}(z) = A_{emk} P_{e+1,m}(z) + B_{emk} P_{e-1,m}(z) + C_{emk} P_{e,m+1}(z) + D_{emk} P_{e,m-1}(z), \text{ for } S_{k-1} \leqslant z \leqslant S_k$$

For each "uninstrumented" assembly, $P_{em}(z)$ must be calculated over each control rod bank region. When all regions have been treated, the resulting 51 axial points are stored for later calculations.

The coefficients, A, B, C and D, are determined from an analysis of the dependence of the power in a given assembly to the power in its neighbors, as given by diffusion theory 2-D spatial calculations.

C. Total Fuel Assembly, Batch, and Core Powers

This completes the determination of the axial power distributions of the xy integrated powers; axial integration of each of these curves provides the total power generated in each assembly P_{em}; summation over the assemblies in a batch gives the batch power P_B and summation over the three provides the reactor power, P_C. Each of these numbers are multiplied by the time elapsed since the last calculation and the result added to the cumulative fuel assembly, batch and core exposure counters. These data will provide information for the most advantageous fuel management. It is also useful to compute the total power in the upper and lower halves of the core for comparison with the split out-of-core detectors.

D. Maximum Power Calculations in Each Fuel Assembly

From the axial distributions now available for each fuel assembly estimates can be formed of the maximum fuel power density, the maximum heat flux per unit area of fuel pin and the maximum heat flux into a channel by applying library values of the local factors appropriate to each of the control rod bank regions and fuel assemblies.

1. Pin Peak Power - The assembly pin peak power is found by taking the maximum value of $P_{em}(z)$ in each rod bank region k, designated as $\overline{P}_{emk}$, multiplying each of these numbers by the appropriate R_{emk} and taking the maximum value of the set of products. The assembly pin peak-to-average power can then be written as:

$$F_{em} = \underset{k}{\text{Max}} \left(R_{emk} \cdot \overline{P}_{emk}\right) / \langle P_{em} \rangle$$

Similarly, the peak-to-average power for a batch B or the entire core are found by searching the products $R_{emk} \cdot \overline{P}_{emk}$ for all rod bank regions and for all members of the batch or core to get for a batch:

$$F_B = \underset{k}{\text{Max}} \ (R_{emk} \cdot \bar{P}_{emk})_B / \ \langle P_B \rangle$$

and for the core:

$$F_C = \underset{k}{\text{Max}} \ (R_{emk} \cdot \bar{P}_{emk})_C / \ \langle P_C \rangle$$

In each of these cases, the values of emk corresponding to the maximum are recorded along with the peaking factor.

It is more desirable to record, instead of the peaking factors, the maximum pin power in each fuel assembly in units of kw/ft as this has more direct physical significance than the peaking factors. This is simply a listing of p Max $(R_{emk} \cdot P_{emk})_{em}$, where p is a constant converting the results to the desired units.

2. DNBR Calculation - The calculation of the minimum departure from nucleate boiling ratio (DNBR) for each octant assembly utilizes the standard W-3 correlation developed by Tong, et al. (1)

   In short, the values of

$$Q_{em}^{DNB,N}(z) \ / \ Q_{em}(z)$$

   are evaluated for each assembly and the minimum value is taken to be the minimum DNBR of assembly em. In this correlation, the $Q_{em}^{DNB,N}(z)$ is given by:

$$Q_{em}^{DNB,N}(z) = Q_{em}^{DNB,EU}(z)/F(z)$$

   where

   $Q_{em}^{DNB,EU}(z)$ ≡ equivalent uniform DNB heat flux

   $Q_{em}^{DNB,N}(z)$ ≡ DNB heat flux for the actual flux shape in the channel

   $F(z)$ ≡ shape factor

---

(1) L. S. Tong, "Prediction of Departure from Nucleate Boiling for an Axially Non-Uniform Heat Flux Distribution," Journal of Nuclear Energy, 21: 241-248, 1967.

Both $Q_{em}^{DNB,\ EU}(z)$ and F(z) are given by complicated expressions involving several empirically derived constants. See Ref. 1 for the details. The $Q_{em}(z)$ is found by the following equation:

$$Q_{em}(z) = G_{em}\ P_{em}(z)\ T_{emk}$$

where the value of T_{emk} is the value in the rod bank region k in which z is located. Note that this procedure may produce a hottest channel composed physically of segments of several channels, since the hottest channel in a particular assembly in rod bank region S_i may not be the same channel as the hottest channel in that assembly in another rod bank region, S_j. The method is, however, conservative.

An important parameter in the W-3 correlation is the mass velocity, G. Because of limitations imposed on the computer, INCA must use the closed channel thermal-hydraulic model instead of the open channel analysis used in standard design effort. Therefore, a correlation for an "equivalent mass velocity" was developed (and incorporated into INCA) which, when used in the closed channel calculations, produces open channel DNB ratios. This equivalent mass velocity, G_e, is related to the reactor parameters as follows:

$$\begin{aligned} G_e{*}10^{-6} = 1.890 &+ 0.02327\ (\%\ FLOW-100) \\ &- 0.22495\ (F_{\Delta H}^{N} - 1.94) \\ &- 0.12527\ (F_{\Delta H}^{N} - 1.94)^2 \\ &- 0.004933\ (\%\ POWER-100) \\ &- 0.00005667\ (\%\ POWER-100)^2 \\ &- 0.00485\ (T_{in} - 545) \\ &- 0.0001078\ (T_{in} - 545)^2 \\ &+ 0.0003595\ (PSIA-2100) \\ &- 0.0000009524\ (PSIA-2100)^2 \end{aligned}$$

where

$F_{\Delta H}^{N}$ = channel nuclear enthalpy rise factor

T_{in} = inlet temperature, °F

PSIA = primary system pressure

FLOW = pump flow, lb/hr

POWER = thermal power, MWth

As the inlet enthalpy is required in the correlation, the following linear expression is included for enthalpy as a function of inlet temperature:

$$H_{in} = 1.24{*}\ T_{in} - 134.44$$

E. Detection of Azimuthal Flux Tilt

Indications of any azimuthal flux tilting are obtained by comparing the signals from symmetrically located detectors. These signals are fitted to the functional form:

$$\phi(r,\theta) = \phi_o(r,\theta)\ [\ 1 + sg(r)\ \cos\ (\theta - \theta_o)\ ]$$

where the fundamental flux pattern is designated as ϕ_o, the amplitude of the tilt by s, and the orientation of the tilt by θ_o. The separable functional form in the second term of the equation has been suggested by examination of tilted flux shapes from diffusion theory representations of mild xenon oscillations. The functional g(r), which is given approximately by $J_1(\alpha_1, r)/J_o(\alpha_o, r)$, can be used to relate the tilt signals from different sets of detectors if no asymmetrically placed rods are inserted. In INCA, however, the analogous function to $J_1(\alpha_1, r)/J_o(\alpha_o, r)$ as obtained from two-dimensional diffusion calculations is used.

Signals from symmetrically placed rhodium detector strings are analyzed to obtain s and θ_o. One symmetrical set such as this gives four values of s and θ_o since there are four axially located detectors in each string.

In the Palisades core, there are four sets of such symmetrically located detector-strings. Since there are four detectors per string, this gives 16 values of the pair (s, θ_o). The average value of s and θ_o are then found as well as the respective standard deviations. A study of the standard deviations gives some insight into whether or not the average values of s and θ_o indicate a true flux tilt.

F. Accumulated Control Rod Exposure

In the Palisades core, each control rod can be associated through its indices to the adjacent fuel assemblies. If it is assumed that control rod exposure is proportional to the time-integrated power of the fuel assemblies, then it is possible to generate an axial exposure distribution for each control rod.

Let $EX_{em}(z)$ represent the accumulated exposure and $\Delta EX_{em}(z)$ be the incremental time interval Δt between INCA sweeps of the data. Then for full length rods

$$\Delta EX_{em}(z)\ \alpha\ P_{em}(z)\ \Delta t, \text{ where } H_{em} \leqslant z \leqslant H$$

and for part-length rods of length L_{em}

$$\Delta EX_{em}(z)\ \alpha\ P_{em}(z)\ \Delta t, \text{ where } H_{em} \leqslant z \leqslant H_{em} + L_{em}$$

are added to the values of $EX_{em}(z)$ already stored. In these equations, H_{em} is the distance from the bottom of the core to the bottom of the rod and H is the distance from the bottom of the core to the top of the core. An independent calculation will have been performed to decide for what $\int P_{em}(z)\, dt$ the active portion of the CEA should be replaced.

G. Xenon and Samarium Reactivity Effects

The core average equilibrium xenon and samarium concentrations and the reactivity effects thereof may be calculated based on the current power level of the core, assuming that equilibrium concentrations of xenon, iodine, promethium, and smarium are found via the following equations:

$$I_{EQ} = \frac{\gamma_I \, (P_{EQ}/E_R')}{\lambda_I}$$

$$XE_{EQ} = \frac{(\gamma_I + \gamma_{XE}) \cdot (P_{EQ}/E_R')}{\lambda_{XE} + (\bar{\sigma}_{a_{th}}^{xe} P_{EQ} C) / (E'_R \, \bar{\Sigma}_f^{th})}$$

$$PM_{EQ} = \frac{\gamma_{PM} \, (P_{EQ} / E_R')}{\lambda_{PM}}$$

$$SM_{EQ} = \frac{\gamma_{PM} \, (P_{EQ} / E_R')}{\bar{\sigma}_{a_{th}}^{SM}}$$

where $C = 1 - \dfrac{\bar{\Sigma}_F^{EPI} \, \bar{\varphi}_{EPI}}{\bar{\Sigma}_f^{EPI} \, \bar{\varphi}_{EPI} + \bar{\Sigma}_f^{th} \, \bar{\varphi}_{th}}$ derived from detailed diffusion theory calculations

$\bar{\Sigma}_f$ ≡ core flux weighted fission cross sections
$\bar{\varphi}$ ≡ average group flux
P_{EQ} ≡ equilibrium power level, watts/cc
E_R' ≡ watt sec/fission
γ_i ≡ fission yield of nuclide i
λ_i ≡ decay constant of nuclide i

The reactivity effects of the xenon and samarium are taken proportional to the number densities, i.e.,

$$\rho_{XE}^{EQ} = (GAMMA)\ (X_{E\,EQ})$$
$$\rho_{SM}^{EQ} = (DELTA)\ (S_{M_{EQ}})$$

INCA will also estimate near-term future xenon and samarium reactivity worths during proposed maneuvering transients. The method is based on a direct integration of the point reactor rate equations through the use of integrating factors. The following assumptions are made:

1. The core power level changes with time only in a step-function form. Note that ramp changes could also be incorporated, but it is found that the step response closely follows the ramp and that the additional formulation required to treat the ramp is not justified.

2. Since the fission cross section is independent of time over the intervals considered for xenon transients, and since the reactivity loss and gain due to xenon is compensated by control rod movement, the neutron fluxes vary as the power level.

The use of these assumptions lead to the following analytic solutions of the rate equations:

$$I(t) = \left(I_o - \frac{\gamma_I P(t)}{\lambda_I E_R'}\right) e^{-\lambda_I t} + \left(\frac{\gamma_I P(t)}{\lambda_I E_R'}\right)$$

$$X_E(t) = X_{E_o} - \left\{ \left[\frac{\lambda_I I_o - \gamma_I P(t) / E_R'}{(\lambda_{XE} - \lambda_I) + (\bar{\sigma}_{a_{TH}}^{XE} C P(t)) / (\bar{\Sigma}_f^{th} E_R')} \right] - \left[\frac{(\gamma_I + \gamma_{XE}) P(t) / E_R'}{\lambda_{XE} + (\bar{\sigma}_{a_{TH}}^{XE} C P(t)) / (\bar{\Sigma}_f^{TH} E_R')} \right] \right\} \exp \left[-\lambda_{XE} - \frac{\bar{\sigma}_{a_{TH}}^{XE} CP(t)}{\bar{\Sigma}_f^{TH} E_R'} \right]$$

$$+ \left[\frac{\lambda_I I_o - \gamma_I P(t)/E_R'}{(\lambda_{XE} - \lambda_I) + (\bar{\sigma}_{a_{TH}}^{XE} CP(t))/\bar{\Sigma}_f^{TH} E_R'} \right] \exp \left[-\lambda_I t \right]$$

$$+ \left[\frac{(\gamma_I + \gamma_{XE}) P(t)/E_R'}{\lambda_{XE} + (\bar{\sigma}_{a_{TH}}^{XE} CP(t))/\bar{\Sigma}_f^{TH} E_R'} \right]$$

$$P_M(t) = \left[P_{M_o} - \frac{\gamma_{P_M} P(t)}{\lambda_{P_M} E_R'} \right] \exp \left[-\lambda_{P_M} t \right] + \left[\frac{\gamma_{P_M} P(t)}{\lambda_{P_M} E_R'} \right]$$

$$S_M(t) = \left[S_{M_0} - \frac{\gamma_{P_M} \left(P(t)/E_R'\right)}{\bar{\sigma}_{a_{TH}}^{S_M} \, C \, P(t) / \bar{\Sigma}_f^{TH} \, E_R'} + \frac{\gamma_{P_M} \left(P(t)/E_R'\right) - \lambda_{P_M} P_{M_0}}{\bar{\sigma}_{a_{TH}}^{S_M} \dfrac{C \, P(t)}{\bar{\Sigma}_f^{TH} E_R'} - \lambda_{P_M}} \right] \exp\left[- \bar{\sigma}_{a_{TH}}^{S_M} \frac{C \, P(t)}{\bar{\Sigma}_f^{TH} E_R} \, t \right]$$

$$+ \left[\frac{\lambda_{P_M} P_{M_0} - \gamma_{P_M} P(t)/E_R'}{\bar{\sigma}_{a_{TH}}^{S_M} \dfrac{C \, P(t)}{\bar{\Sigma}_f^{TH} \, E_R'} - \lambda_{P_M}} \right] \exp\left[- \lambda_{P_M} t \right]$$

$$+ \left[\frac{\gamma_{P_M} \left(P(t)/E_R'\right)}{\bar{\sigma}_{a_{TH}}^{S_M} \dfrac{C \, P(t)}{\bar{\Sigma}_f^{TH} E_R'}} \right]$$

where all quantities have been defined before, except

I_0, X_{E_0}, P_{M_0}, S_{M_0}, = initial concentrations of the nuclides, most likely the equilibrium values as described previously.

The above equations are precisely those formulated into the XENON algorithms. Once the time dependence of the fission product poison concentrations are known, the reactivity effects thereof are calculated based on known values of reactivity worth (%) per absorber atom in equilibrium conditions, i.e.

$$\rho \, X_E(t) = (\text{GAMMA}) \, X_E(t)$$
$$\rho \, S_M(t) = (\text{DELTA}) \, S_M(t)$$

If equilibrium conditions are attained prior to the proposed power changes, the only data necessary as input to XENON are:

1. The initial core power (MWTH) (PCORE)
2. The number of step power changes to be made (IB) (IC = O)
3. The fraction of core power at the end of each power change, N(PLEVEL(N))
4. The time duration of each power change, N(TIME(N)).

The initial concentrations are then calculated via the equilibrium equations and the code uses these as input to solve the time dependent equations for every hour over the first step in the power history, i.e., over time interval a - b in Fig. III-3.

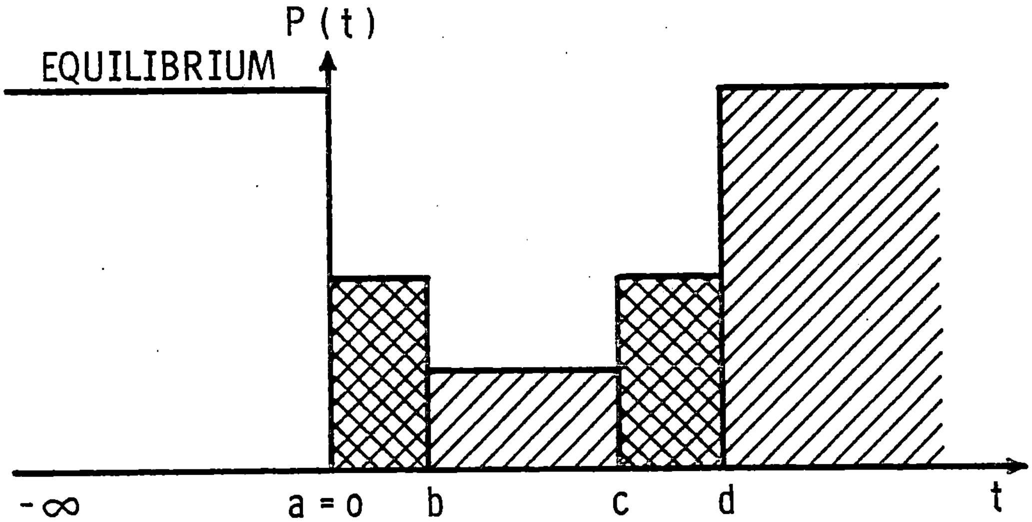


FIGURE III-3- TYPICAL POWER LEVEL HISTORY

If the power level then changes at time b+, the equations are solved for every additional hour till time c, using the predicted concentrations at time b as input. This procedure continues through the power cycles up to a maximum time of 100 hours.

If equilibrium conditions are not attained prior to the proposed power changes, or if one wants to extend the procedure beyond 100 hours or decides to change the proposed power changes, the initial concentrations can be input to the code through variables Q(1), XE(1), SA(1), PM(1). A plotting procedure is then available to display this information in an easily readable format.

All constants used in INCA for the XENON routines are listed in Table III-1.

TABLE III-1

CONSTANTS USED IN XENON FOR THE PALISADES CORE

VARIABLE	VALUE
λ_I	2.875×10^{-5} sec.$^{-1}$
λ_{XE}	2.092×10^{-5} sec.$^{-1}$
γ_I	0.061 at/fission U-235
γ_{XE}	0.003 at/fission U-235
E_R'	0.3167×10^{-6} sec.$^{-1}$
λ_{PM}	0.0113 at/fission U-235
C	.796835
$CFA = \dfrac{\bar{\sigma}_{a_{TH}}^{XE} \quad C}{\bar{\Sigma}_f^{TH} \quad E_R'}$	0.817943×10^{-6}
$CFB = \dfrac{\bar{\sigma}_{a_{TH}}^{SM} \quad C}{\bar{\Sigma}_f^{TH} \quad E_R'}$	0.286280×10^{-7}
$\bar{\sigma}_{a_{TH}}^{XE}$	1.50×10^{6} b
$\bar{\sigma}_{a_{TH}}^{SM}$	52,500 b
GAMMA	0.1401×10^{-14}% / (at Xe/cc)*
DELTA	0.4693×10^{-16}% / (at S_m/cc)*
CONFAC	0.0684324 (w/cc) / MWth

* These reactivity worths have been shown to be fairly independent of core burnup, and are thus assumed to be constant over lifetime.

H. Vanadium Detectors

Because vanadium has a smaller capture cross section than rhodium, the vanadium detectors have a lower sensitivity than the rhodium detectors. For this reason, the vanadium detectors run essentially the full length of the reactor core. Since they are the full length of the core, as opposed to being in the form of four short length instruments in a "string" as are the rhodium detectors, the vanadium detectors do not provide information about the vertical power distribution in the core. On the other hand, vanadium has certain merits as a detector material, namely the cross section is "1/v" and hence easy to analyze. Also, the fact that the cross section is relatively small makes the sensitivity change much less with detector depletion.

Because of these characteristics of the vanadium detectors, it is convenient to use them as a check on the rhodium detectors rather than as a means of obtaining new information. This is done in the following way:

The relationship between the power P and the detector signal E from a vanadium detector is:

$$P = W^V E$$

where W^V is referred to as the power to signal coupling coefficient. Thus:

$$E = \frac{P}{W^V}$$

or more precisely:

$$E_i(z) = \frac{P_i\ (z)}{W_i^V\ (z)}$$

where:

$P_i\ (z)$ = the power in assembly i per unit vertical distance at height z.

W_i^V = the coupling coefficient as given above which, for assembly i, relates the contribution to the current generated in the unit vertical distance at height z to the power in the assembly over the same vertical distance.

$E_i(z)$ = the contribution to the current generated in the vanadium wire in the unit vertical distance at height z.

In the INCA analysis of the rhodium signals the $P_i(z)$ will have been determined to be:

$$P_i\ (z) = a_i \cos B(z - \frac{H}{2}) + b_i \sin\ 2B(z - \frac{H}{2}) + c_i \cos 3B(z - \frac{H}{2})$$

in the lower half of the core and

$$P_i(z) = a_i^* \cos B(z - \frac{H}{2}) + b_i^* \sin 2B(z - \frac{H}{2}) + c_i^* \cos 3B(z - \frac{H}{2})$$

in the upper half.

The calculated vanadium signal is just:

$$\int E_i(z)\, dZ = \int \frac{P_i(z)}{W^V(z)}\, dZ$$

where the integration is over the length of the vanadium wire. This integration is performed numerically. The vanadium wire is assumed to be divided into N segments and W_i^V is assumed to be constant over each segment. Thus:

$$E_i = \sum_{n=1}^{N} \int E_i(z)\, d_z = \sum_{n=1}^{N} \frac{\int_n P_i(z)\, dz}{W_i^V}$$

where the integration, $\int_n$, is over the nth segment. N is usually taken to be 50.

The computed values of E_i are then printed out in INCA along with the measured values. Agreement between the calculated vanadium signals and the actual meter readings lends confidence that the overall instrumentation is working properly and that the INCA analysis of both the rhodium detectors and the vanadium detectors is adequate.

I. Expanded Power Map

An expanded power map is produced upon demand which makes explicit use of the azimuthal flux tilt calculations described in Section III.E. This routine will allow the extraction of useful information from the detector signals when a tilted power shape exists in the core.

The power distribution in the presence of a small tilt can be expressed as:

$$P_{emn} = P_{emn}^{o} \left[1 + S_n\, g_{em} \cos(\theta_{em} - \theta_n^{o}) \right]$$

where

P_{emn} = total power in assembly em integrated only over the length of axial detector n.

P_{emn}^{o} = fundamental mode power in assembly em integrated only over the length of axial detector n.

and the remaining terms are as previously described in Section III.E. The P_{emn} are obtained by the methods of Section III.A.2 for each instrumented assembly over all values of n. This tacitly assumes that the spectral and spatial conversion coefficients, W_{emn}, are approximately the same for both the fundamental and first harmonic modes.

After the average tilt amplitude, S_n and tilt orientation, Θ_n^o, have been calculated for each detector plane n, the ratio of the fundamental component of the power to the total power is obtained for the n slices of all 204 assemblies by the following equation:

$$\frac{P^o_{emn}}{P_{emn}} = \left[1 + S_n \; g_{em} \; \cos \; (\theta_{em} - \theta^o_n)\right]^{-1}$$

The next step is to reflect all instruments to the east northeasterly octant of the core, carrying along their respective values of em and Θ_{em}. One detector string for each instrumented assembly in the octant is then chosen. For this subset of detectors, the fundamental mode contribution, P^o_{emn}, is calculated. By utilizing the coupling coefficients as described in Section III.B, the n fundamental mode power integrals for all assemblies in the octant are easily obtained. Since P^o_{emn} possesses eighth-core symmetry, the full core power map of P^o_{emn} is actually found. Furthermore, by using the ratios of P^o_{emn} to P_{emn} already calculated, the complete set of P_{emn}'s for all 204 assemblies is available.

Finally, these n power integrals for each assembly can be used to produce axial power shapes via the procedures outlined in Sections III.A through III.D. Pin peaks, channel peaks, and DNBR calculations can then be performed.

J. Library Coefficients

As previously indicated, INCA is dependent on a large library of predetermined coefficients. These variables exhibit a strong dependence on both space and the fuel and rhodium depletion characteristics which must be properly incorporated in the INCA algorithms. The choice of coefficients depend, then, not only on control rod configuration and spatial location, but also upon the accumulated fuel and detector irradiations at each node in the core. Because of these added conditions, simplifying approximations are made in order to keep the program within convenient limits of size and complexity. This section of the report considers each type of coefficient and documents the simplifications utilized in the INCA system.

1. Spectral and Spatial Converison Factor - From Section III.A.2, the coefficient W_{emn} is defined as the power-to-signal coefficient relating the integrated power in assembly em over the length of detector n in the absence of any control rods to the detector output signal. This coefficient must properly account for the spatial variation of enrichment and fuel burnup in addition to the depletion of the rhodium emitter.

W_{emn} is written as a function of essentially four terms, i.e.,

$$W_{emn} = \left[WPRIME*WINITAL \right]_{emn} * BORON_{em} * MWTH_{em}$$

where

$WPRIME_{emn}$ = expression for the dependence of W_{emn} on the exposure level, normalized to unity at BOL.

$WINITAL_{emn}$ = initial value of WPRIME.

$MWTH_{em}$ = expression for the dependence of W_{emn} on the power level (about full power).

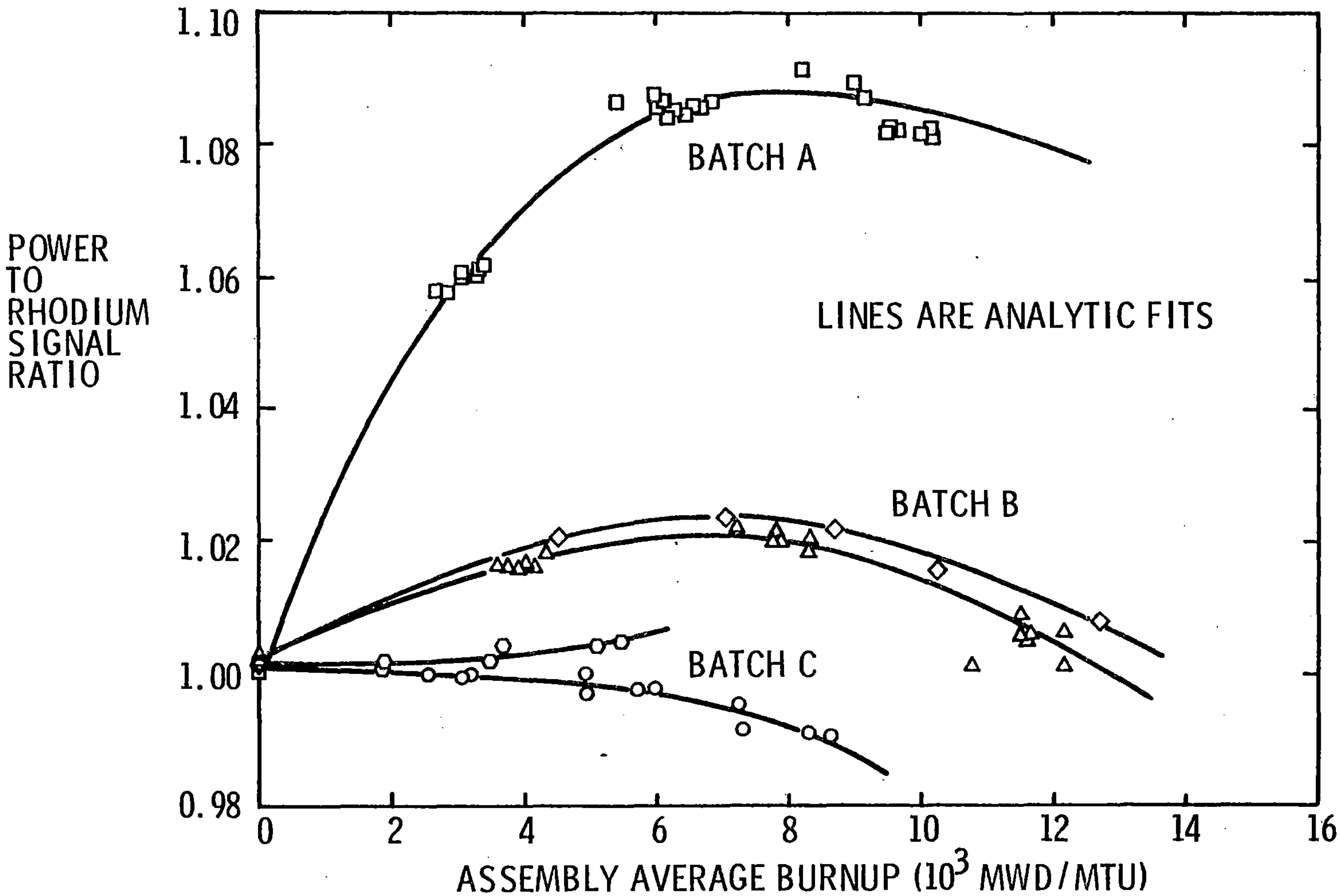
$BORON_{em}$ = expression for the dependence of W_{emn} on the boron concentration.

The behaviour of the WPRIMES is indicated in Fig. III-4, where they have all been normalized to unity at beginning-of-life. Note that the abscissa is the assembly average burnup, not the core average burnup. For all but Batch A, the burnup effect is quite small, perhaps a 2% variation over first cycle. Batch A, however, exhibits a rather large 9% variation over first core life. The necessary simplifying trends are quite apparent. Once could easily infer an average shape for each batch with only a small spread about the curve, but, in order to reduce the RMS error involved with the fit to .2%, and the maximum deviation to less than .5%, five shapes were derived from the data on Fig. III.4. Polynomials of degree three were chosen as the fitting equations, the coefficients of which were derived via least squares procedures. Within each batch, the initial (50 hour) values of WPRIME for all assemblies was essentially constant. The ratio between batches was approximately: A:B:C - 10:13:15.

The burnup dependence of the spectral and spatial conversion coefficients was fit by cubic expressions in assembly burnup, with a different initial value for each assembly, i.e.,

Figure III.4

POWER TO RHODIUM SIGNAL CONVERSION FACTORS vs ASSEMBLY AVERAGE BURNUP



$$WPRIME_{emn} = \left[(AO_{emn}) + (Al_{emn} \cdot BU_{emn}) + (A2_{emn} \cdot BU^2_{emn}) + (A3_{emn} \cdot BU^3_{emn}) \right]$$

The dependence of W_{emn} on both boron concentration and power level are also included through the use of simple fits. Because of the small variation with power and boron levels, simple linear expressions were used. Note that the boron variation considered is that deviating from the calculated critical concentration at a specific time in life, not the difference from some burnup independent value. Therefore, the boron swing should be small and linear expressions will be adequate. The expressions utilized in INCA are:

$$BORON_{em} = BO_{em} + Bl_{em} * PPM$$

$$MWTH_{em} = CO_{em} + Cl_{em} * KORPOWR$$

where

$$PPM = \left[DO + D1*TOTEP + D2*TOTEP^2 \right] - SOLBOR$$

KORPOWR = CAL-2200.

with

TOTEP = average core exposure, MWD/teU

SOLBOR = measured boron concentration, ppmb

CAL = calorimetric power, MWth.

Note that the expression in brackets for the PPM expression is simply a fit of the calculated critical concentration versus core average exposure.

The spectral and spatial vanadium conversion coefficients are treated identically to the rhodium coefficients. The following expressions are programmed into INCA:

$$WV_{emn} = \left[WVPRIME*WINITL \right]_{emn} * BORON*MWTH$$

$$WPRIME_{emn} = \left[AVO_{emn} + AV1_{emn}*FUEXP_{emn} + AV2_{emn}*FUEXP^2_{emn} + AV3_{emn}*FUEXP^3_{emn} \right]$$

$$BORONV_{em} = BVO_{em} + BV1_{em} * PPM$$

$$MWTHV_{em} = CVO_{em} + CV1_{em} * KORPOWR$$

2. Single Pin Power Peaking Factors - The one pin peaking factor, R, is defined as the ratio of the maximum pin power in an assembly to the average pin power in that assembly, and depends on assembly, fuel burnup, and control rod configuration. The range of peaks is quite large, from 1.1 to greater than 2.3. In addition, the burnup variation is quite large, the shapes differing greatly among assemblies (see Fig. III.5). It is found that assemblies cannot be grouped together as easily as were the W_{emn}'s, but that the shapes can be easily duplicated through the use of quadratic expressions. Such fits have been included for each octant assembly for each rod bank region possible, i.e., for each assembly,

$$R(J,M) = RR(J,M) \cdot \left[(RO(J,M)) + (R1(J,M) \cdot BU(J)) + (R2(J,M) \cdot BU(J)^2) \right]$$

RR = initial value (50 hours)
J = assembly
M = control rod configuration
BU = assembly burnup

3. Four Pin Peaking Factors - The four pin (or channel) peaking factor, T, is defined as the ratio of the maximum of the average power of four adjacent pins to that of the average pin power in that assembly. The range of values is not as large as that of the R's, but their burnup and spatial behavior is as erratic. Therefore, the same fitting procedure as developed for the R's was used for the T's, i.e.,

$$T(J,M) = TT(J,M) \cdot \left[(TO(J,M)) + (T1(J,M) \cdot BU(J)) + (T2(J,M) \cdot BU(J)^2) \right]$$

TT = initial value (50 hours)
J = assembly
M = control rod configuration
BU = assembly burnup

4. Coupling Coefficients - In the event of inoperable detectors, one has the option of employing the failed detector routine, described in Section III.B.2, which makes use of the coupling coefficients, A, B, C, and D (UCA, UCB, UCC, and UCD in the algorithms). These coefficients are spatially dependent and vary with fuel burnup and rod bank insertion. The initial values have a spread like that of the T's, and the variation with burnup (indicated for a few assemblies in

Figure III.5

SINGLE PIN PEAKING FACTOR VARIATION WITH BURNUP

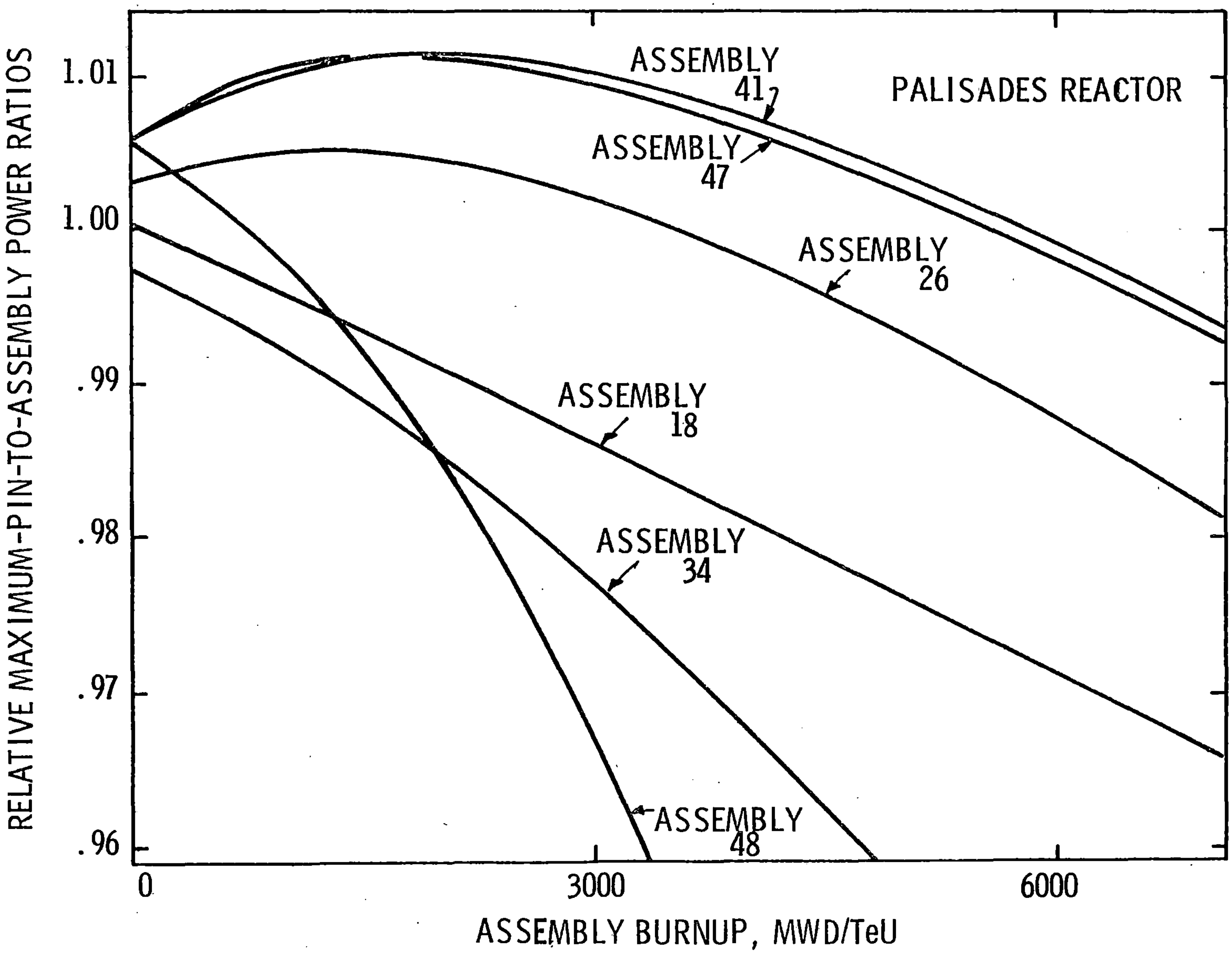


Fig. III.6) is indeed erratic and significant (some coefficients experience a 20% variation with life). Quadratic expressions in assembly burnup for each coefficient for each assembly and rod configuration have been included in the algorithms, i.e.,

$$UCi(J,M) = Ui(J,M) \cdot \left[(UiO(J,M)) + (Ui1(J,M) \cdot BU(J)) + (Ui2(J,M) \cdot BU(J)^2) \right]$$

i = A, B, C, or D
Ui = initial value (at 50 hours)
J = assembly
M = control rod configuration
BU = assembly burnup

5. Control Rod Perturbation Coefficient - The conversion of rhodium activation to assembly power integrals was effected in the following manner:

$$P_{emn} = E_{emn} \cdot \left[W_{emn} + \sum_i A^i_{emn} \cdot w_{emn} \right]$$

E_{emn} = detector signal
w_{emn} = fractional insertion of neighboring control rods
A^i_{emn} = control rod perturbation coefficients

As initially formulated, four values of A^i_{emn} were needed, one for each of the four nearest control rods. Upon analysis, however, it was found that only two such coefficients were needed - one for rod patterns with the nearest rod inserted, and one for rod patterns without the nearest rod inserted. This was found also to be fairly independent of the time in life. For a nearest rod fully shadowing the nth detector in assembly em, i.e., w_{emn} = 1.0, the value of A was found to be .088 W, or 8.8% of the conversion coefficient, W_{emn}. For any but the nearest rod completely shadowing the detector, the corresponding value of A was found to be .0075·W.

6. Summary - A complete list of the methods used in INCA to include burnup variations in the library coefficients is given in Table III-2 for completeness.

Figure III.6

UNINSTRUMENTED ASSEMBLY COUPLING COEFFICIENTS AS A FUNCTION OF CORE BURNUP (PALISADES) UNRODDED BURN

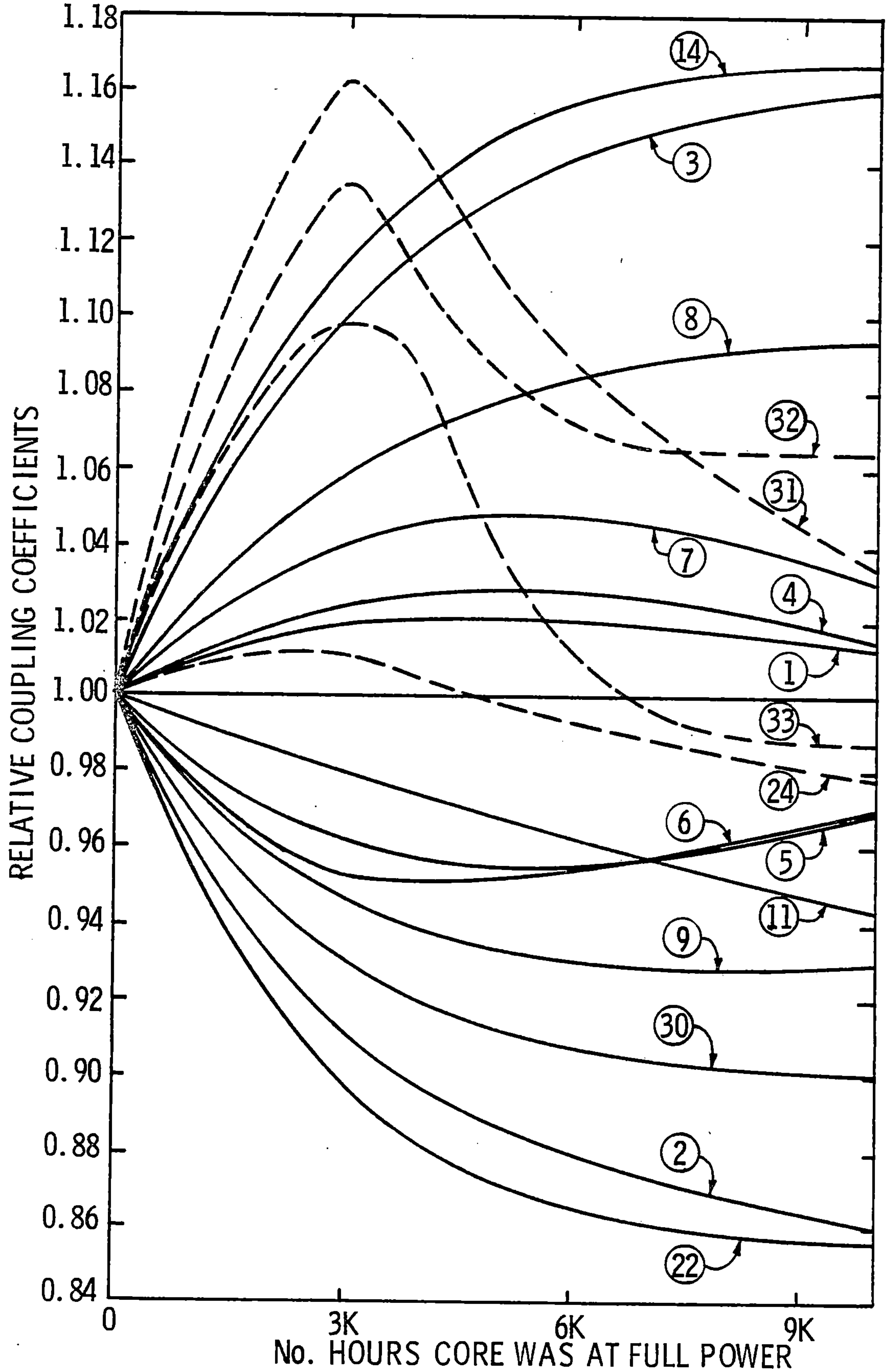


Table III-2

METHODS USED IN INCA TO INCLUDE BURNUP VARIATIONS IN THE LIBRARY COEFFICIENTS

COEFFICIENT	TREATMENT
SPECTRAL AND SPATIAL CONVERSION COEFFICIENTS	-- CUBIC FIT TO ASSEMBLY BURNUP, LINEAR IN BORON CONCENTRATION AND POWER LEVEL -- ASSEMBLIES TEND TO FALL IN GROUPS, THUS A SMALL NUMBER OF SUCH EXPRESSIONS ARE REQUIRED
ONE- AND FOUR-PIN PEAKING FACTORS	-- POLYNOMIAL IN BURNUP FOR EACH OCTANT ASSEMBLY
UNINSTRUMENTED COUPLING COEFFICIENTS	-- POLYNOMIAL IN BURNUP FOR EACH OCTANT ASSEMBLY

ATTACHMENT C

PALISADES CYCLE 2 RADIAL POWER DISTRIBUTION
AT 10,500 MWd/Mt AVERAGE BURNUP

1.058 1.018 -3.7	1.322 1.306 -1.2	1.299 1.323 +1.8	1.009 .997 -1.2	1.175 1.252 +6.6	.947 .904 -4.5	1.045 1.099 +5.2	.767 .741 -3.4
	1.083 1.065 -1.7	1.270 1.329 +4.6	1.006 1.028 +2.2	.980 .959 -2.1	1.205 1.178 -2.2	.859 .816 -5.0	.704 .699 -0.7
		1.039 1.029 -1.0	1.226 1.259 +2.7	1.181 1.237 +4.7	.930 .896 -3.7	1.008 .987 -2.1	.586 .570 -2.7
			1.210 1.247 +3.1	.956 .939 -1.8	1.046 1.081 +3.3	.821 .818 -0.4	
				1.098 1.097 -0.1	.855 .844 -1.3	.530 .509 -5.5	
				xxxx yyyy z.z	Exxon PDQ7 INCA % Difference		