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Contents

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Preface

The RACC-Pulse radioactivity code is based on the RACC code originally developed by Dr. Jungchung Jung of Argonne National Laboratory in the late 70's (1978,1979). A pulsed/intermittent history modeling capability was implemented within the original version to enhance the code's utility for fusion reactor induced radioactivity calculations. The RACC-Pulse code should not be confused with the RACC-P code developed by Dr. Hosny Attaya of Argonne National Laboratory. Both newer versions of the RACC code were developed independently of each other, have different features and capabilities and utilize different data libraries.

The RACC-Pulse code has been compiled and executed on the following Unix based computer workstations and mainframes: HP735, DEC5000/200, and Cray-2. The code is written in standard FORTRAN and hence portability to most computer systems should not pose a problem.

1 Introduction

This document provides a brief description of the input to the RACC-Pulse code, the pulsed/intermittent history version of the RACC radioactivity code. The original version of the RACC program employed the GEAR [1-3] method to solve the system of stiff first order differential equations obtained from the formulation of the coupled system of transmutation and decay rate equations. The code was originally developed for steady state activation analysis and hence lacked the capability to perform pulsed/intermittent calculations. With the implementation of the pulsed capability the RACC-Pulse code is able to model irradiation histories of varying flux levels having varying pulse widths and dwell periods and varying maintenance periods. This flexibility provides the user with the capability of modeling a diverse array of pulse histories which could be encountered in the design or operation of experimental reactor facilities. The GEAR package is not supported in this version of the RACC code as the new solution package has proven itself to be less computationally intensive. The solution method implemented within the code is a matrix based method which relies on the evaluation of the matrix exponential and is discussed in the following section.

2 Method of Solution

2.1 The Pulsed/Intermittent Activation Problem

It is well known that the mathematical description of the neutron transmutation and decay processes leads to a system of coupled first order differential equations which can be written in general matrix form:

$$\frac{d\overline{N}}{dt} = \mathbf{A}\,\overline{N}(t)\,. \tag{1}$$

The formal mathematical solution of the above matrix equation is

$$\overline{N}(t) = e^{\mathbf{A}t} \times \overline{N}(0) \tag{2}$$

where $e^{\mathbf{A}t}$ is called the matrix exponential. The matrix $\mathbf{A}$ contains both the total destruction rates $(\lambda + \sigma_t \phi)$ which are the diagonal elements a_{ii} and the production rates $(\sigma_i \phi$ or $\lambda)$ which are the off diagonal elements (a_{ij}). $\overline{N}(0)$ is the initial number density vector.

The above general solution describes the concentration of the affected nuclides as a function of time and has been utilized to obtain results for a continuous operation period. In order to treat problems having a pulsed structure the above description requires some modification.

The following derivation of the pulsed/intermittent matrix solution methodology is presented in its entirety in reference [4]. The essential features of the derivation are reproduced here for completeness.

Consider a uniform series of pulses having a pulse width of Δt_1 and a dwell time of Δt_2. Using Eq. 2 the solution after the first pulse is

$$\overline{N}(\Delta t_1) = e^{\mathbf{A}\Delta t_1} \times \overline{N}(0) \tag{3}$$

where $\mathbf{A}$ is a matrix containing the transmutation and decay rates for the pulse period. The solution after the first decay period is

$$\begin{aligned} \overline{N}(\Delta t_1 + \Delta t_2) &= e^{\mathbf{B}\Delta t_2} \times \overline{N}(\Delta t_1) \\ &= e^{\mathbf{B}\Delta t_2} \times e^{\mathbf{A}\Delta t_1} \times \overline{N}(0) \end{aligned} \tag{4}$$

where $\mathbf{B}$ is the decay matrix for the dwell period.
It can be easily shown [4] that after the n'th pulse period the solution is given by

$$\overline{N}\big((n\Delta t_1 + (n-1)\Delta t_2\big) = e^{\mathbf{A}\Delta t_1} \times \left(e^{\mathbf{B}\Delta t_2} \times e^{\mathbf{A}\Delta t_1}\right)^{(n-1)} \times \overline{N}(0). \tag{5}$$

The above represents an accurate description of the pulsed activation process which accounts for continuous burnup (transmutation) during the pulse on periods and decay during the dwell periods. For the case of a series of uniform pulses discussed above, the solution involves raising a matrix to a power and one matrix and two vector multiplications. The above result is easily extended to more complex histories. In general the number of matrix and vector multiplications depends on the complexity of the pulsed operation history. Increased nonuniformity of the pulsing structure results in an increased number of matrix and vector multiplications which increases the computational time.

Once the solution to the operation period is obtained the calculation proceeds to the after shutdown time. The only nuclear processes occurring after shutdown are decay processes and the general solution at a time t after shutdown is

$$\overline{N}(t) = e^{\mathbf{B}t} \times \overline{N}(n\Delta t_1 + (n-1)\Delta t_2) \tag{6}$$

where $\mathbf{B}$ is the decay matrix for the dwell period.
The formal solution to the pulsed/intermittent activation problem involves evaluations of the matrix exponential for the pulse period, dwell period and post shutdown periods. For complex pulse histories additional matrix exponential evaluations are performed for each series of different pulse groupings and flux levels. In addition the solution involves raising a matrix to a power.

2.2   Matrix Solution Method

Equation 5, the solution for the nuclide transmutation-activation problem during operation, is solved using matrix based solution methods which rely on the evaluation of the

matrix exponential. The evaluation of the matrix exponential for a given general matrix $\mathbf{C}$ is unfortunately not a trivial task. Fortunately, the numerical evaluation of the matrix exponential has, for the general case, been investigated in some detail in a review paper by Moler and Van Loan [5]. This paper discusses 19 methods which have been employed to evaluate the matrix exponential, all termed "dubious". Recommended methods for the evaluation of the matrix exponential are the Páde approximation, Schür matrix decomposition and the scaling and squaring technique. The latter two options have been implemented in the code.

Due to the occurrence of (n, xn) and $(n, charged\,particle)$ neutron transmutation reactions during the pulse on periods, neutron reaction/decay chain loops occur in the transmutation/decay scheme of a stable input isotope. Loops occur when an isotope is transmuted or decays to a preceding nuclide in its reaction-decay pathway. If the nuclide entries in matrix $\mathbf{A}$ are stored in increasing Z (atomic number) and A (atomic mass) order, the occurrences of loops complicate the structure of the matrix $\mathbf{A}$ by introducing entries in the upper triangular half of the matrix. When this is the case, the evaluation of the matrix exponential proceeds using the Schür decomposition or the scaling and squaring technique general matrix exponential solvers.

During the dwell periods, the only nuclear process occurring for transmutation induced nuclides of interest in fusion calculations is nuclear decay by $\beta^-, \beta^+, \epsilon$ (electron capture), and α-decay. If the nuclide entries in matrix $\mathbf{B}$ are stored in a similar fashion as matrix $\mathbf{A}$, then matrix $\mathbf{B}$, the matrix for the dwell period, is nearly lower triangular with a few entries in the upper-triangular part due to β^+, ϵ and α decays. The evaluation of the matrix exponential of $\mathbf{B}$ proceeds using the same routines as for the evaluation of matrix $\mathbf{A}$.

For the post shutdown period, the evaluation of matrix B proceeds in a different manner than for the dwell periods, since for the post shutdown period, one is interested in the nuclide concentrations at various time intervals after shutdown. A computationally efficient routine was sought to evaluate Eq. 6 for various times t after shutdown. Three methods were examined: (1) if no coupling between the lower- and upper-triangular parts (which is usually the case) of matrix $\mathbf{B}$ exists, both triangular parts of the matrix are evaluated using Parlett's algorithm [7,8]; (2) matrix $\mathbf{B}$ is decomposed into linear chains, and (3) matrix $\mathbf{B}$ is decomposed by using a balanced binary tree for linear chain construction. Since matrix $\mathbf{B}$ is quite sparse, Parlett's algorithm, which utilizes all the matrix elements in its evaluation process, is computationally the most intensive. The balance binary tree decomposition was the most efficient.

2.2.1 Scaling and Squaring Technique

This technique uses a Taylor series expansion of matrix $\mathbf{A}$ combined with scaling and squaring to compute $e^{\mathbf{A}t}$ as follows:

$$ B = (e^{\frac{t*\mathbf{A}}{2^n}})^{2^n} = (e^{\mathbf{C}})^{2^n} $$

$$e^{\mathbf{C}} = \mathbf{I} + \mathbf{C} + \frac{\mathbf{C}^2}{2!} + ... + \frac{\mathbf{C}^k}{k!} + ...$$

The truncation criteria for the Taylor series is:

$$||\mathbf{C}^k/k!|| < eps * max(abs(c_{ij}))$$

$$||\mathbf{C}^k/k!|| := \sum(abs(c_{ij}))\,.$$

This technique, with proper diagnostics can be quite efficient.

2.2.2 Schür Decomposition

The Schür decomposition of a matrix is the following:

$$\mathbf{A} = \mathbf{Q}\mathbf{T}\mathbf{Q}^T$$

where $\mathbf{T}$ is an upper-triangular matrix. Details on the decomposition can be found in most linear algebra texts. Once matrix $\mathbf{A}$ has been decomposed, the matrix exponential is evaluated from the expression:

$$e^{\mathbf{A}t} = \mathbf{Q}e^{\mathbf{T}t}\mathbf{Q}^T\,.$$

LAPACK routines [6] are used to perform the Schür decomposition. The evaluation of the matrix exponential of a upper-triangular matrix is performed using an algorithm developed by Parlett [7,8].

2.2.3 Matrix Raised to a Power

The formal solution of the pulsed/intermittent irradiation history problem during the operation time involves raising a matrix to a power (note Eq. 5). There are several methods that can be employed to raise a matrix to a power of which a subset are: (1) the direct multiplication of the matrix with itself repeated n times, (2) the eigenvalue decomposition method details of which can be found in most linear algebra texts and (3) a $\log_2$ based algorithm which utilizes repeated squaring and multiplication of the matrix. Of the three methods indicated above method 3 is computationally the most efficient and the method implemented in the RACC-Pulse code.

2.3 Pulsing Scheme

The unique characteristic of RACC-Pulse is that it can model a wide variety of pulsed/-intermittent operation histories including the steady state case. The steady state operation scheme and homogeneous pulsed operation schemes are typical single period operation

schemes. Multi-period operation schemes are a bit more difficult to set up. A set of examples is provided in Figs. A1-A4 to illustrate the flexibilty in pulsing scenario and their input parameters.

RACC-Pulse subdivides the whole operation history into different "periods". Each period has the same flux level (power level) and can have many pulse levels. Each level is a grouping of pulses having the same pulse width and dwell times. Pulses in different periods can have different pulse structures and power levels. This scheme allows the user considerable flexibility in modeling regular and irregular irradiation histories. Varying pulse width, dwell times, maintenance periods and power levels can all be modeled. This flexibility has its costs, as increasing complexity in the irradiation structure results in an increase in the run time. A detailed explanation of the pulsing options and the input is provided in Appendix A.

3   Transmutation and Decay Data Libraries

The transmutation library (raccxlib) utilized in the current version of the code has been processed from the USACT93 [9] neutron transmutation library. The library is in a 46 neutron group format with the group structure given in Table 1. The radionuclide decay data library (raccdlib) has been processed from ENDF/B-VI data files. The libraries contain 2323 isotopes of which 625 of them have transmutation data.

The user of the code is encouraged to update the transmutation library as this library contains only a subset of the reactions from the USACT93 library. In addition, gamma source data must still be incorporated into the library.

Table 1. Neutron 46 Multigroup Structure in eV Group Limits

Group	E(Top)	E(Low)	E(Midpoint)
1	1.4918 (+7)	1.3499 (+7)	1.4208 (+7)
2	1.3499 (+7)	1.2214 (+7)	1.2856 (+7)
3	1.2214 (+7)	1.1052 (+7)	1.1633 (+7)
4	1.1052 (+7)	1.0000 (+7)	1.0526 (+7)
5	1.0000 (+7)	9.0484 (+6)	9.5242 (+6)
6	9.0484 (+6)	8.1873 (+6)	8.6187 (+6)
7	8.1873 (+6)	7.4082 (+6)	7.7977 (+6)
8	7.4082 (+6)	6.7032 (+6)	7.0557 (+6)
9	6.7032 (+6)	6.0653 (+6)	6.3843 (+6)
10	6.0653 (+6)	5.4881 (+6)	5.7767 (+6)
11	5.4881 (+6)	4.9659 (+6)	5.2270 (+6)
12	4.9659 (+6)	4.4933 (+6)	4.7296 (+6)
13	4.4933 (+6)	4.0657 (+6)	4.2795 (+6)
14	4.0657 (+6)	3.6788 (+6)	3.8722 (+6)
15	3.6788 (+6)	3.3287 (+6)	3.5038 (+6)
16	3.3287 (+6)	3.0119 (+6)	3.1703 (+6)
17	3.0119 (+6)	2.7253 (+6)	2.8686 (+6)
18	2.7253 (+6)	2.4660 (+6)	2.5956 (+6)
19	2.4660 (+6)	1.8268 (+6)	2.1464 (+6)
20	1.8268 (+6)	1.3534 (+6)	1.5901 (+6)
21	1.3534 (+6)	1.0026 (+6)	1.1700 (+6)
22	1.0026 (+6)	7.4274 (+5)	8.7260 (+5)
23	7.4274 (+5)	5.5023 (+5)	6.4848 (+5)
24	5.5023 (+5)	4.0762 (+5)	4.7892 (+5)
25	4.0762 (+5)	3.0197 (+5)	3.5480 (+5)
26	3.0197 (+5)	2.2371 (+5)	2.6284 (+5)
27	2.2371 (+5)	1.6573 (+5)	1.9472 (+5)
28	1.6573 (+5)	1.2277 (+5)	1.4425 (+5)
29	1.2277 (+5)	6.7379 (+4)	9.5080 (+4)
30	6.7379 (+4)	3.1828 (+4)	4.9604 (+4)
31	3.1828 (+4)	1.5034 (+4)	2.3431 (+4)
32	1.5034 (+4)	7.1017 (+3)	1.1068 (+4)
33	7.1017 (+3)	3.3546 (+3)	5.2281 (+3)
34	3.3546 (+3)	1.5846 (+3)	2.4696 (+3)
35	1.5846 (+3)	7.4852 (+2)	1.1666 (+3)
36	7.4852 (+2)	3.5358 (+2)	5.5105 (+2)
37	3.5358 (+2)	1.6702 (+2)	2.6030 (+2)
38	1.6702 (+2)	7.8893 (+1)	1.2296 (+2)
39	7.8893 (+1)	3.7267 (+1)	5.8080 (+1)
40	3.7267 (+1)	1.7603 (+1)	2.7435 (+1)
41	1.7603 (+1)	8.3152 (+0)	1.2959 (+1)
42	8.3152 (+0)	3.9279 (+0)	6.1216 (+0)
43	3.9279 (+0)	1.8554 (+0)	2.8917 (+0)
44	1.8554 (+0)	8.7643 (-1)	1.3659 (+0)
45	8.7643 (-1)	4.1399 (-1)	6.4521 (-1)
46	4.1399 (-1)	2.2000 (-2)	2.1800 (-1)

4 Input

The following is the input for the RACC-Pulse code. Most of the input instructions are the same as for the original RACC code. Additional lines of input occur at the end of the standard input file and are the parameters for the pulsing routine. For a more detailed explanation of the standard input section, the user is referred to the original RACC manual, "Theory and Use of the Radioactivity Code RACC" by Jungchung Jung.

All of the data arrays in RACC-Pulse are read by using the standard/format free FIDO input system. Each FIDO array in RACC-Pulse must be followed by the terminator symbol, t. Certain arrays are conditional in RACC-Pulse. Those conditions are indicated in brackets []. Quantities in parentheses () stand for array dimensions and numbers following the symbol † show reference numbers for the detailed data notes in Chapter IV of the original RACC manual.

Input Data
(1) Title FORMAT (18A4) Problem Title
(2) Arrays

   1$$ Control Integer Parameters (50)

1.	ID	Problem ID number
2.	IDIM	problem dimension (†1)
		1 - one dimension
		2 - two dimensions
		3 - three dimensions
3.	IGE	Geometry of system (†1)
		0 - any
		1 - slab
		2 - sphere
		3 - cylinder
		4 - torus
4.	IGM	No. of total energy groups of input flux
5.	IGN	No. of neutron energy groups of input flux
6.	IGG	No. of gamma energy groups of input flux
7.	IM	No. of fine intervals in x (r) direction (†1)
8.	JM	No. of fine intervals in y (θ/z) direction (†1)
9.	KM	No. of fine intervals in z (ϕ) direction (†1)
10.	IZM	No. of zones in x (r) direction (†1)
11.	JZM	No. of zones in y (θ/z) direction (†1)
12.	KZM	No. of zones in z (ϕ) direction (†1)

13.	NPP	No. of radioactivity calculation problem zones
14.	MS1	Mixing table length for basic material makeup (†2,3)
15.	MS3	Mixing table length for composite material makeup (†4)
16.	MS2	Mixing table length for problem zone makeup
17.	IVOL	Problem zone volumes (†1)
		0 - input
		1 - calculate
18.	ISD	System shutdown calculation
		0 - no - only pre-shutdown calculation
		1 - yes - both pre and post-shutdown calculation
19.	NT1	No. of time steps before shutdown - 2 (always)
20.	NT2	No. of time steps after shutdown
21.	IFXA	input of group flux (†7)
		0 - card
		1 - ANISN file (not active)
		2 - DOT file (not active)
		3 - TWODANT file (not active)
		4 - MORSE file (not active)
		5 - VIM file (not active)
		6 - ONEDANT file (not active)
		7 - Special formatted file (file name: fluxin)
		8 - any FIDO formatted file (not active)
		if IFXA is negative, the flux is double precision (does not apply to option 7)
22.	IXSA	Input of group cross section (†7)
		0 - card
		1 - disk/tape
23.	IDLA	Input of decay data (†7)
		0 - card
		1 - disk/tape
24.	IFXB	Storage of group flux (†8)
		0 - card
		1 - disk
25.	IXSB	Storage of cross section (†8)
		0 - card
		1 - disk
26.	IDLB	Storage of decay data (†8)
		0 - card
		1 - disk

27.	IPRFX	Print group flux (†9)
		0 - no
		1 - only interval group flux
		2 - only zone group flux
		3 - both
28.	IPRXS	Print group cross section (†9)
		0 - no
		1 - yes
29.	IPRDA1	Print decay data for chain construction (†9)
		0 - no
		1 - yes
30.	IPRDA2	Print decay chain table (†9)
		0 - no
		1 - yes
31.	IPRDA3	Print isotopes involved in the problem (MDX table) (†9)
		0 - no
		1 - yes
32.	IPRDB1	Print decay constants/branching ratios (†9)
		0 - no
		1 - yes
33.	IPRDC1	Print radioactivity-related data for edit (†9)
		0 - no
		1 - yes
34.	ISTART	Problem restart (†10)
		0 - no
		N - yes from level N
35.	IDUMP	Core dump (†10)
		0 - no
		N - yes if time left is less than N seconds
36.	IEDT1	BHP (air) edit (†11)
		0 - no
		1/-1 - specific edit/and save
		2/-2 - total edit/and save
		3/-3 - both/and save
37.	IEDT2	BHP (water) edit (†11)
		0 - no
		1/-1 - specific edit/and save
		2/-2 - total edit/and save
		3/-3 - both/and save

38.	IEDT3	Decay heat edit (†11)
		0 - no
		1/-1 - specific edit/and save
		2/-2 - total edit/and save
		3/-3 - both/and save
39.	IEDT4	Radioactivity edit (†11)
		0 - no
		1/-1 - specific edit/and save
		2/-2 - total edit/and save
		3/-3 - both/and save
40.	IEDT5	Decay gamma spectrum edit (†11)
		0 - no
		1/-1 - specific edit/and save
		2/-2 - total edit/and save
		3/-3 - both/and save
41.	IEDT6	Print system matrix/solution of equations (†12)
		0 - no
		1 - system matrix
		2 - solution of ODE (atomic transmutation rates)
		3 - both
42.	IEDT7	For future use
43.	IGGEDT	No. of output gamma-source energy group (†11) [IEDT5$\geq$0]
44.	NULL6	For future use
45.	NULL5	For future use
46.	NULL4	For future use
47.	NULL3	For future use
48.	NULL2	For future use
49.	NULL1	For future use
50.	MF	For future use

2**   Control Floating Parameters (10)

1.	EPS	Precision required for solution (†14)
2.	FACFLX	Input flux normalization constant (cm^2-s) (†15) no effect if FACFLX is 0.0
3.	FACVLM	System volume normalization constant (cm^3) (†15) no effect if FACVLM is 0.0
4.	FACPWR	System power normalization constant (MWth) (†15)
5.	RMAJOR	Major radius of torus (cm) [IGE = 4] (†1)

      6.   RNULL5   For future use
      7.   RNULL4   For future use
      8.   RNULL3   For future use
      9.   RNULL2   For future use
   10.   RNULL1   For future use

3$$ Basic Material Numbers for Basic Material Makeup (MS1) (†3)

4$$ Constituent Isotope JZA ID Numbers for Basic Material Makeup (MS1) (†2,3)

5**   Constituent Isotope Number Densities (atom/barn-cm) for Basic Material Makeup (MS1) (*3)

6**   Constituent Isotope Source Densities (atom/barn-cm-s) for Basic Material Makeup (MS1).
      For RACC_Pulse all data of this array are 0.0

7$$ Composite Material Numbers for Composite Material Makeup (MS3) (†4)

8$$ Constituent Basic Material Numbers for Composite Material Makeup (MS3) (†4)

9**   Constituent Basic Material Fractions for Composite Material Makeup (MS3) (†4)

10** Constituent Basic Material Source Fractions for Composite Material Makeup (MS3) (†4)
      For RACC_Pulse all data of this array are 0.0

11$$ No. of I-Fine Intervals in Each I-Zone (IZM) (†1)

12$$ No. of J-Fine Intervals in Each J-Zone (JZM) [IDIM≥2] (†1)

13$$ No. of K-Fine Intervals in Each K-Zone (KZM) [IDIM≥3] (†1)

14$$ Problem Zone Numbers for Problem Zone Makeup (MS2) (†1,5)

15$$ I-Zone Numbers for Problem Zone Makeup (MS2) (†1,5)

16$$ J-Zone Numbers for Problem Zone Makeup (MS2) [IDIM≥2] (†1,5)

17$$ K-Zone Numbers for Problem Zone Makeup (MS2) [IDIM≥3] (†1,5)

18** I-Dimensional Volume Elements (IMM) [IVOL = 0] (†1)
      IMM = IM if IDIM = 1 or IGE ≠ 4
      IMM = 2*JM otherwise

19** J-Dimensional Volume Elements (JMM) [IVOL = 0 and IDIM≥2] (†1)
      JMM = JM if IGE ≠ 4
      JMM = 2*JM if IGE = 4

20** K-Dimensional Volume Elements (KM) [IVOL = 0 and IDIM = 3] (†1)

21** I-Fine Interval Boundaries (IM + 1) [IVOL = 1] (†1)

22** J-Fine Interval Boundaries (JM + 1) [IVOL = 1 and IDIM≥2] (†1)

23** K-Fine Interval Boundaries (KM + 1) [IVOL = 1 and IDIM =3] (†1)

24$$ Composite Material Numbers for Problem Zones (NPP)
25$$ No. of Neutron Reaction Generations to be Followed for Problem Zones (NPP) (†6)
26** Time Step Boundaries for Pre-Shutdown Calculation (2)
  0.0 and total operation time
27** Time Step Boundaries for Post-Shutdown Calculation (NT2) [ISD = 1]
28** Output Decay Gamma Source Energy Group Boundaries (IGGEDT +1)
29** Group Flux (IM*JM*KM*IGN) [IFXA = 0] (†7)

Pulsed History Parameters (not FIDO Formatted Input Data)

LINE 1   **Free Format Integers (3)**
                    1. lsolution - solution option
                              0 - squaring and scaling
                              1 - Schür decomposition
                    2. nlevel - number of levels in any periods
                    3. nperiod - number of periods in whole operating time

LINE 2   **Free Format Integers (nlevel * nperiod)**
                    (npulses(j, i), j = 1, nlevel)
                    [repeat this input card for each period]
                    npulses(j, i) - number of pulses of level j in period i

LINE 3   **Free Format Real Numbers (nlevel * nperiod)**
                    ton(i) (toff(j, i), j = 1, nlevel)
                    [repeat this input card for each period]
                    ton(i) - pulse width in period i. [s]
                    toff(j, i) - dwell time of level j in period i [s]

LINE 4   **Free Format Real Numbers (nperiod-1)**
                    (tdwell(i), i = 1, nperiod-1)
                    tdwell(i) - dwell time between period i and i+1 [s]

LINE 5   **Free Format Real Numbers (nperiod)**
                    (fpower(i), i = 1, nperiod)
                    fpower(i) - normalization factor of power level in period i

Acknowledgement

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Appendix

A. Pulsed History Operation

As mentioned in Section 2.3, the RACC-Pulse code can model a wide variety of pulsed/-intermittent operation histories inclusive the steady state case. RACC-Pulse subdivides the operation history into "periods," within each period the power level is constant as well as the pulse width. Hence different periods can have different pulse widths and power levels. Each period can have a different number of pulse levels, e.g. the operation scheme can be steady state in the first period and homogeneous pulsed scheme in the second period, multi-period with multilevel scheme in the third period, etc. Each level is a grouping of pulses having the same pulse widths and dwell times. Four different types of pulse histories are described below as examples of pulsing schemes which can be modeled by the RACC-Pulse code. The pulse history input is given to the left of the figure.

```
0 1 1
1
1000.0 0.0
1.0
```
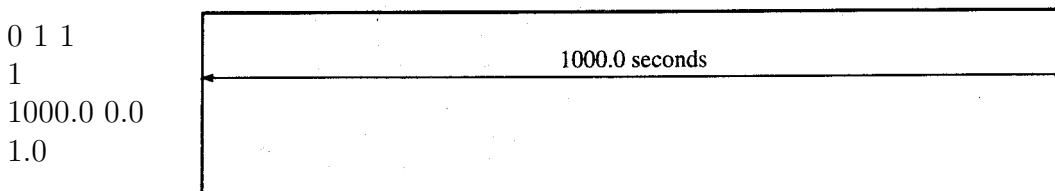

Example 1 — Steady state scheme Fig. A1

Figure A1 depicts the simplest of the operation histories, the 1 pulse or steady state operation scenario. The scaling and squaring option has been chosen, the number of levels is 1 and the number of periods is 1. The operation time is 1000.0 seconds and the flux normalization factor for that period is 1.

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1000.0 s

0 1 1
20
1000.0 2000.0
1.0

2000.0 s
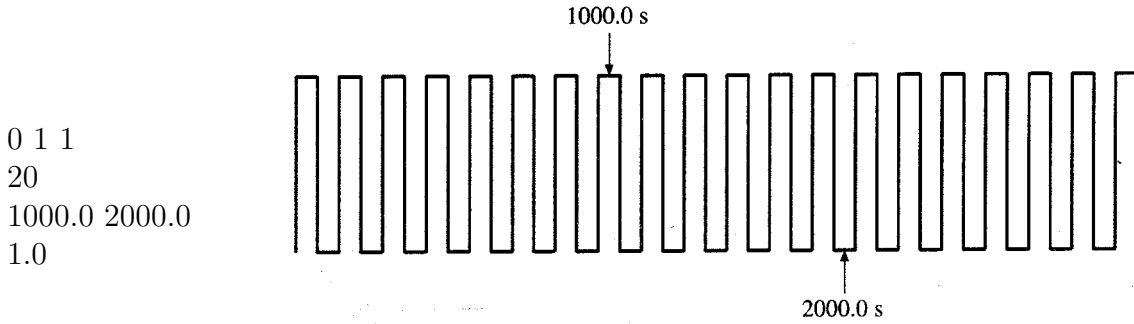
Example 2 — Homogeneous pulsed scheme Fig. A2

The simplest of the pulsed operation scenarios is a series of homogeneous pulses and is depicted in Fig. A2. The scaling and squaring option has been chosen and the number of levels and periods is 1. The number of pulses considered is 20. The pulse width (on time) is 1000.0 seconds and the dwell period (off time) is 2000.0 seconds. The flux normalization factor is 1 (same flux level) for all pulses.

1000.0 s

0 2 1
10 2
1000.0 2000.0 3000.0
1.0

3000.0 s

2000.0 s
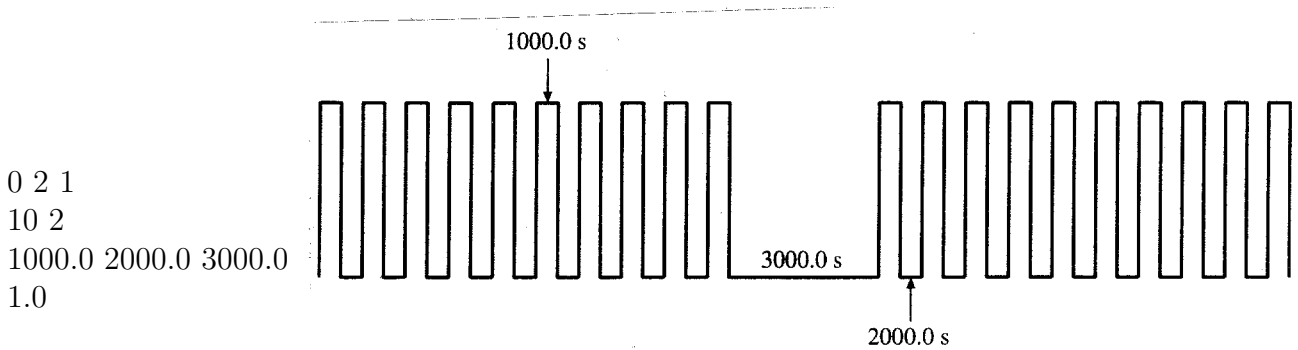
Example 3 — Single period with 2 levels Scheme Fig. A3

Figure A3 depicts a 1 period (same flux level), 2 level (two different dwell periods) operation history. It consists of two groupings of 10 pulses (both groups have the same dwell length) separated by a longer dwell period. The pulse width is 1000.0 seconds, the first dwell period between the pulses is 2000.0 seconds and the dwell period between the groupings of 10 pulses is 3000.0 seconds. The flux normalization factor is 1.

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```
1 4 3
8 1 1 1
1 1 1 1
2 3 2 3
100.0 200.0 0.0 0.0 0.0
5000.0 0.0 0.0 0.0 0.0
20.0 30.0 40.0 50.0 60.0
1000.0 2000.0
0.5 1.0 1.5
```

Multi-period with Multilevel Scheme with Inhomogeneous Power Level

Period 1: Homogeneous Pulsing Scheme at Power Level of 0.5*P(flux)
Period 2: Steady State Scheme at Power Level of 1.0*P(flux)
Period 3: Multilevel Pulsing Scheme at Power Level of 1.5*P(flux)
   P(flux) is the power corresponding to the input flux specified in
   the general input data.

Example 4 — Multi-period with multilevel scheme with inhomogeneous power level Fig. A4a

A multi-period operation scenario is depicted in Fig. A4. It is a 4 level 3 period scheme. The first period consists of 8 pulses with the same flux level (50% of the nominal flux level) and dwell widths. A steady state operation interval makes up the second period. The pulsing structure for the third period is depicted in Fig. A5. Note the complexity of the pulsing scheme which can be modeled. The dwell time between each period is 1000.0 and 2000.0 seconds. The flux normalization factor for each of the periods are 0.5, 1.0 and 1.5.
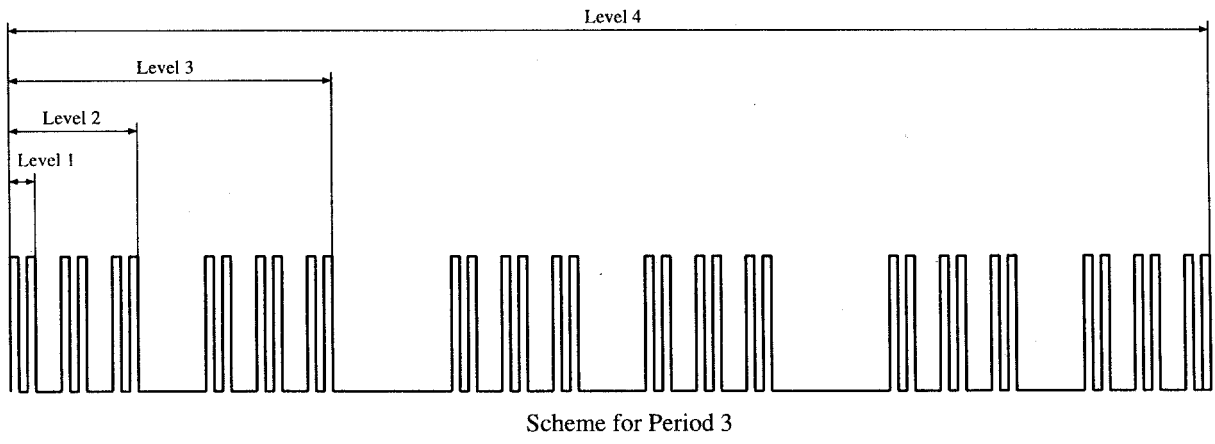
Scheme for Period 3

Fig. A4b — Multilevel pulsing scheme for period 3 of the inhomogeneous power level pulsing scenario of Fig. A4a

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B. Sample Problem Input for the RACC-Pulse Code

The example problem provided with the manual is the water cooled SS316 nonbreeding blanket/shield design of the ITER fusion facility considered during the ITER (EDA) blanket option trade-off study (BOTS) [10]. The calculation is performed for a nominal fusion power of 3.0 GW and an average wall loading of 2.0 MW/m^2. The radial build and the material composition of the various zones for this blanket design can be gleaned from the schematic shown in Fig. A5. There are a total of 15 zones in this calculation. One transmutation generation is considered for this problem. The maximum number of isotopes considered in an individual zone is approximately 350 nuclides (stable + radioactive). The temporal history consists of 359 pulses having a pulse width of 1000 seconds with a dwell time of 4000 seconds. The previous pulse grouping is repeated 10 more times with a 9 day dwell period between the pulse groupings. A long maintenance period of 39 days follows and the whole sequence is repeated 11 more times. This is considered a 1 period 3 level pulsing scheme.
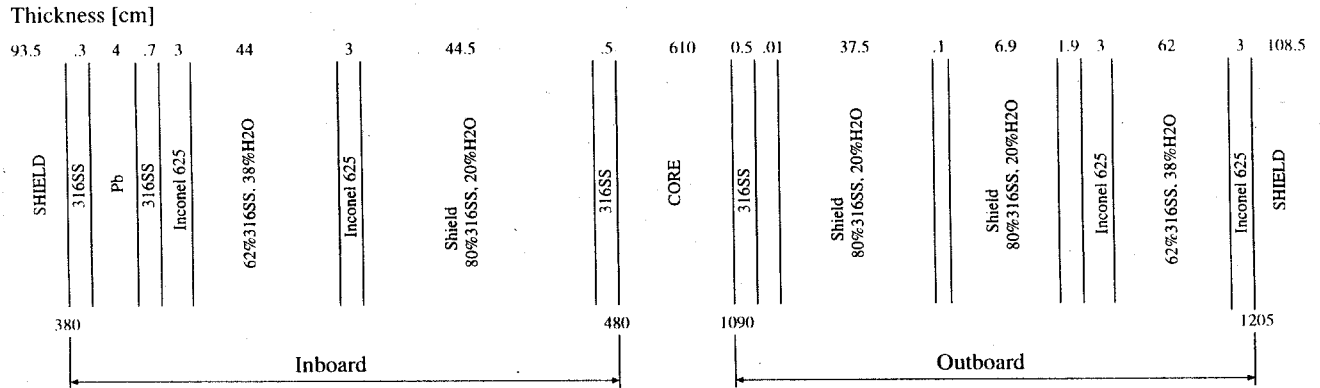
Fig. A5 — Radial build of the first wall, blanket, shield, and bacuum vessel for the nonbreeding SS/H$_2$O BOTS design option

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Input for Sample Problem

```
       374    1    1     27      1     1 /IM   JM   KM   IZM   JZM   KZM
        14   71   84     14      1     1 /NPP  MS1  MS3  MS2   IVOL  ISD
/__18
         2   10    7      1      1     1 /NT1  NT2  IFXA IXSA  IDLA  IFXB
         1    1    0      0      0     0 /IXSB IDLB IPRFX IPRXS IPRDA1 IPRDA2
         0    0    0      0      0     0 /IPRDA3 IPRDB1 IPRDC1 ISTART IDUMP IEDT1
/__36
         0    2    2      0      0     0 /IEDT2 IEDT3 IEDT4 IEDT5 IEDT6 IEDT7
/__42
         0    0    0      0      0     0
         0   21                          /NULL1 MF
  t
2**   1.0-5  1.0-24  0.0  1.0 /EPS FACFLX FACVLM FACPWR
       0.0    0.0    0.0   0.0  0.0  0.0
  t
3$$   2r1
      2r2
       3
       4
       5
      3r6
      2r7
      5r8
       9
     4r10
      11
     3r12
      13
     5r14
     2r15
     5r16
      17
     7r18
     5r19
    10r20
      21
     4r22
     4r23
  t
4$$  50100    50110                                                    /b
     60120    60130                                                    /c
     70140                                                             /n
     80160                                                             /o
    130270                                                             /al
    140280   140290   140300                                           /si
    190390   190410                                                    /k
    220460   220470   220480   220490   220500                         /ti
    230510                                                             /v
    240500   240520   240530   240540                                  /cr
    250550                                                             /mn
    260540   260560   260570                                           /fe
    270590                                                             /co
    280580   280600   280610   280620   280640                         /ni
    290630   290650                                                    /cu
    400900   400910   400920   400940   400960                         /zr
    410930                                                             /nb
    420920   420940   420950   420960   420970   420980   421000       /mo
    481080   481100   481120   481140   481160                         /cd
    501120   501140   501150   501160   501170   501180   501190       /sn
    501200   501220   501240
    731810                                                             /ta
    741820   741830   741840   741860                                  /w
    822040   822060   822070   822080                                  /pb
  t
5**
    0.871-6   0.350-5
    0.701-4   0.785-6
    0.236-3                            18
    0.590-5
    0.526-3
```

```
        0.715-3  0.362-4  0.240-4
        0.564-6  0.408-7
        0.316-5  0.288-5  0.292-4  0.217-5  0.213-5
        0.370-5
        0.676-3  0.130-1  0.148-2  0.368-3
        0.146-2
        0.322-2  0.501-1  0.115-2
        0.241-4
        0.726-2  0.278-2  0.120-3  0.382-3  0.968-4
        0.515-4  0.229-4
        0.535-6  0.117-6  0.178-6  0.181-6  0.291-7
        0.102-5
        0.183-3  0.114-3  0.196-3  0.206-3  0.118-3  0.298-3
        0.119-3
        0.684-7  0.260-6  0.369-7  0.461-7
        0.131-6
        0.309-9  0.677-7  0.367-7  0.790-7
        0.256-8  0.440-7  0.404-7  0.957-7
  t
6**  f0.0  t
7$$  23r1                                          / 100% 316SS
     23r2                                          /  80% 316SS
     23r3                                          /  62% 316SS
     13r4                                          / inconel 625
      2r5                                          / pb
  t
8$$  1   2   3   4   5   6   7   8   9 10 11 12 13 14 15 16
     17 18 19 20 21 22 23
      1   2   3   4   5   6   7   8   9 10 11 12 13 14 15 16
     17 18 19 20 21 22 23
      1   2   3   4   5   6   7   8   9 10 11 12 13 14 15 16
     17 18 19 20 21 22 23
      2   5   6       8  10 11 12 13 14 15 17 18 21
     15          23
  t
9**  23r1.0
     23r0.8
     23r0.62
     2.38  0.482  0.442  5.096  1.390  0.025
     0.0426  1.786  4.984  0.321  1638.6  3.974  1649.6
     0.00289   180650.0
  t
10** f0.0  t
11$$     50      49      1       3       1
          2      21      2      34       1
         91       1      1      29       1
          5       1      3      25       2
          1       5      1       1       1
          1      41
  t
14$$  1   2   3   4   5   6   7   8   9  10  11  12
      13  14
  t
15$$ 3   4   5   6   7   8   9  10  12  14  16  18  19  20
  t
21**     49i0.0     48i286.5    380.0   2i380.3  384.3
         1i385.0    20i388.0    1i432.0 33i435.0 479.5
         90i480.0    1090.0     1090.5  28i1090.51
         1128.0    4i1128.1     1135.0  2i1136.9
         24i1140.0   1i1202.0
         1205.0     4i1205.1
         1230.0      1230.1      1231.2    1231.3  40i1231.4
         1313.5
  t
24$$ 1  5  1  4  3  4  2  1  1  2  2  4  3  4
  t
25$$  f1   t
26**
      0.0   4.7304+7  t
27**
        0.0     1.0+2     1.0+3     1.0+4     1.0+5
        1.0+6     1.0+7     1.0+8     1.0+9     1.0+10
  t
  0  3  1
  359  11  12
  1000.0  4000.0  7.776e+5  3.3696e+6
  1.0
```