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A Sample Problem for Variance Reduction in MCNP

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by

Thomas E. Booth

ABSTRACT

The Los Alamos computer code Monte Carlo Neutron Photon (MCNP) has many useful variance reduction techniques to aid the Monte Carlo user. This report applies many of these techniques to a conceptually simple but computationally demanding neutron transport problem.

I. INTRODUCTION

This report is based on a series of four 50-min variance reduction talks ("MCNP Variance Reduction Techniques," video reels #12-15) given at the Magnetic Fusion Energy Conference on MCNP,* Los Alamos National Laboratory, October 1983. It is an overview of all variance reduction techniques in MCNP and not an in-depth consideration of any. In fact, the techniques are described only in the context of a single conceptually simple, but demanding, neutron transport problem, with only enough theory presented to describe the general flavor of the techniques. Detailed descriptions are in the MCNP manual.[1]

This report assumes a general familiarity with Monte Carlo transport vocabulary such as weight, roulette, score, bias, etc.

II. VARIANCE REDUCTION

Variance-reducing techniques in Monte Carlo calculations can often reduce the computer time required to obtain results of sufficient *precision.* Note that precision is only one requirement for a good Monte Carlo calculation. Even a zero variance Monte Carlo calculation cannot accurately predict natural behavior if other sources of error are not minimized. Factors affecting accuracy were outlined by Art Forster, Los Alamos (Fig. 1).**

This paper demonstrates how variance reduction techniques can increase the efficiency of a Monte Carlo calculation. Two user choices affect that efficiency, the choice of tally and of random walk sampling. The tally choice (of for example, collision vs track length estimators) amounts to trying to obtain the best results from the random walks sampled. The chosen random walk sampling amounts to preferentially sampling "important" particles at the expense of "unimportant" particles.

A. Figure of Merit

The measure of efficiency for MCNP calculations is the figure of merit (FOM) defined as

$$\mathrm{FOM} = \frac{1}{\sigma_{mr}^2\,T} ,$$

*Videotapes of the entire conference are available from Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, TN 37830. The reader wishing to run the sample problem here should refer to the appendix beginning on page 67 for input file details modified since the conference and after the writing of this report.

**Video reel #11, "Relative Errors, Figure of Merit" from MCNP Workshop, Los Alamos National Laboratory, October 4-7, 1983. Available from Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

1. CODE FACTORS

- PHYSICS AND MODELS
- DATA UNCERTAINTIES
- CROSS-SECTION REPRESENTATION
- ERRORS IN THE CODING

2. PROBLEM-MODELING FACTORS

- SOURCE MODEL AND DATA
- GEOMETRICAL CONFIGURATION
- MATERIAL COMPOSITION

3. USER FACTORS

- USER-SUPPLIED SUBROUTINE ERRORS
- INPUT ERRORS
- VARIANCE REDUCTION ABUSE
- CHECKING THE OUTPUT
- UNDERSTANDING THE PHYSICAL MEASUREMENT

Fig. 1. Factors affecting accuracy.

where σ_{mr} = relative standard deviation of the mean and T = computer time for the calculation (in minutes). The FOM should be roughly constant for a well-sampled problem because σ^2_{mr} is (on average) proportional to N^{-1} (N = number of histories) and T is (on average) proportional to N; therefore, the product remains approximately constant.

B. General Comments

Although all variance reduction schemes have some unique features, a few general comments are worthwhile. Consider the problem of decreasing

$$\sigma_{mr} = \frac{\sigma}{\sqrt{N}}/\mu \ ,$$

(where σ^2 = history variance, N = number of particles, and μ = mean) for fixed computer time T. To decrease σ_{mr}, we can try to decrease σ or increase N—that is, decrease the time per particle history—or both. Unfortunately, these two goals usually conflict because decreasing σ normally requires more time per history because better information is required and increasing N normally increases σ because there is less time per history to obtain information. However, the situation is not hopeless. It is often possible to decrease σ substantially without decreasing N too much or increase N substantially without increasing σ too much so that

$$\sigma_{mr} = \frac{\sigma}{\mu\sqrt{N}}$$

decreases.

Many techniques described here attempt to decrease σ_{mr} by either producing or destroying particles. Some techniques do both. In general, (1) techniques that produce tracks work by decreasing σ (we hope much faster than N decreases), and (2) techniques that destroy tracks work by increasing N (we hope much faster than σ increases).

III. THE PROBLEM

The problem is illustrated in Fig. 3, but before discussing its Monte Carlo aspects, I must point out that the problem is atypical and not real. I invented the sample problem so most of the MCNP variance reduction techniques could be applied. Usually, a real problem will not need so many techniques. Futhermore, without understanding and caution, "variance-reducing" techniques often increase the variance.

Figure 2 is the input file for an analog MCNP calculation and Fig. 3 is a slice through the geometry at z = 0.

```
SAMPLE PROBLEM FOR MFE TALKS
C       TALLIES FOR PARTICLES WITH E>.01MEV
    1 0  (1 -21):-2
 2      1 -2.03E0  -1  -3   2
 3      1 -2.03E0  -1  -4   3
 4      1 -2.03E0  -1  -5   4
 5      1 -2.03E0  -1  -6   5
 6      1 -2.03E0  -1  -7   6
 7      1 -2.03E0  -1  -8   7
 8      1 -2.03E0  -1  -9   8
 9      1 -2.03E0  -1  -10  9
10      1 -2.03E0  -1  -11  10
11      1 -2.03E0  -1  -12  11
12      1 -2.03E0  -1  -13  12
13      1 -2.03E0  -1  -14  13
14      1 -2.03E0  -1  -15  14
15      1 -2.03E0  -1  -16  15
16      1 -2.03E0  -1  -17  16
17      1 -2.03E0  -1  -18  17
18      1 -2.03E0  -1  -19  18
19      1 -2.03E0  -1  -20  19
20      0  -1  -21  20
21      1 -2.03E-2  -1   -22  21
   22 0 1 21 -22
   23 0 22

 1      CY   100
 2      PY   0
 3      PY   10
 4      PY   20
 5      PY   30
 6      PY   40
 7      PY   50
 8      PY   60
 9      PY   70
10      PY   80
11      PY   90
12      PY   100
13      PY   110
14      PY   120
15      PY   130
16      PY   140
17      PY   150
18      PY   160
19      PY   170
20      PY   180
21      PY   2000
22      PY   2010

MODE    0
C         THE FOLLOWING IS SCHAEFFER PORTLAND CONCRETE
M1      1001   -.010
        8016   -.529
        11023 -.016
        12000 -.002
        13027 -.034
        14000 -.337
        19000 -.013
        20000 -.044
        26000 -.014
        6012   -.001
SRC1   0 1.E-6 0 2 1.0
SI     2 2  14 14
SP     0 .5 .5 1
NPS    100000
IN     0 1 3R 15R 2R 0
F1     20
F4     21
F5     200 2005 0 0
PDO    0 19R 1 0 0<-------ONLY CELL 21 CONTRIBUTES TO POINT DETECTOR TALLY
EO     .01 100
TO     100 1000  10000
CUTN   1.0E123 0.0  0 0
CTME   45
PRDMP  -5 -5
PRINT
```

Fig. 2. Input file for an analog MCNP calculation.

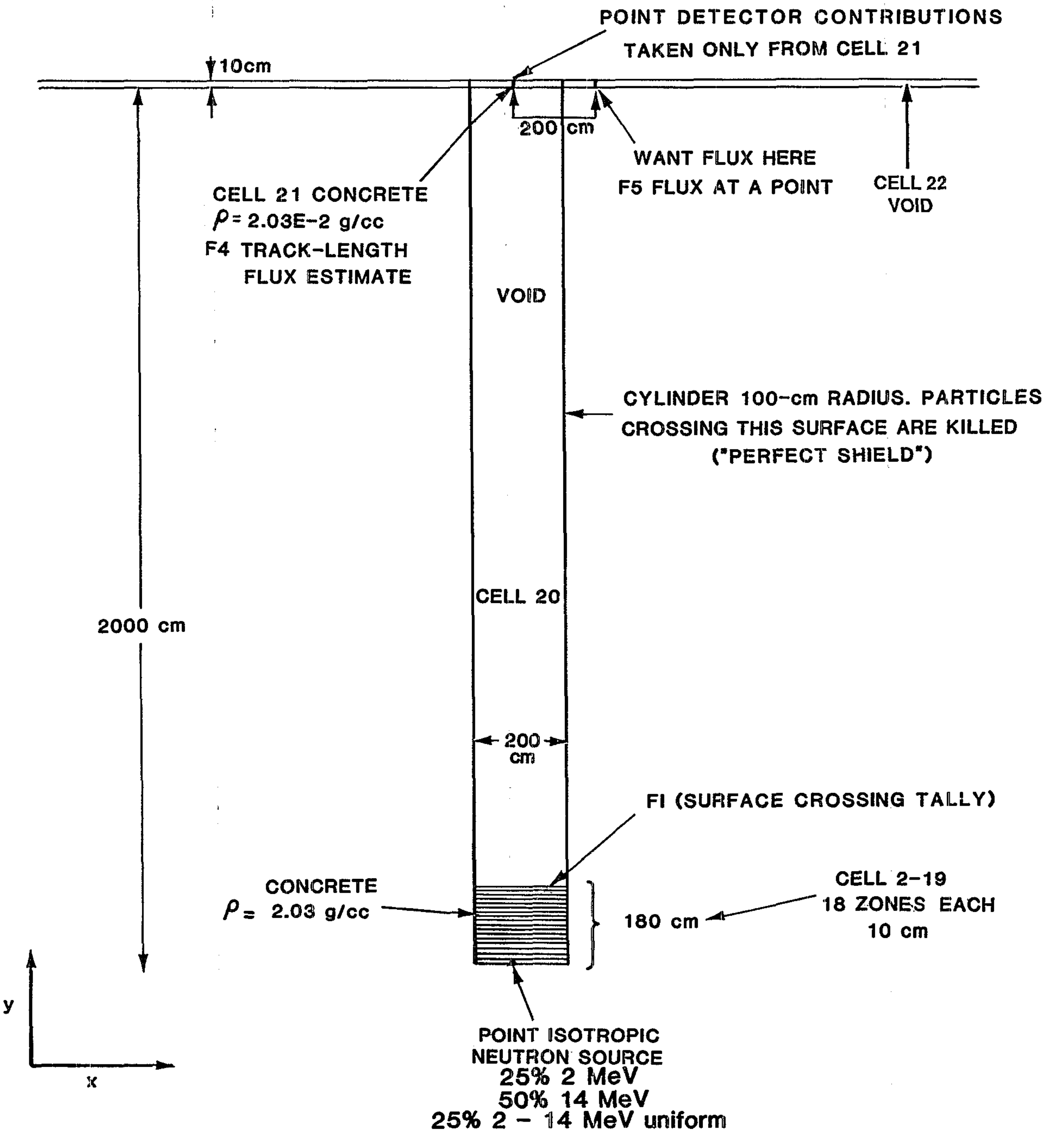


Fig. 3. The problem.

The primary tally is the point detector tally (F5) at the top of Fig. 3, 200 cm from the axis of the cylinder (y-axis). A point isotropic neutron source is just barely inside the first cell (cell 2) at the bottom of Fig. 3. The source energy distribution is 25% at 2 MeV, 50% at 14 MeV, and 25% uniformly distributed between 2 and 14 MeV. For this problem, the detectors will respond only to neutrons above 0.01 MeV.

A "perfect shield" immediately kills any neutrons leaving the cylinder (except from cell 21 to cell 22). Thus, to tally (F5), a neutron must

1. penetrate 180 cm of concrete (cells 2-19),
2. leave the concrete (cell 19) with a direction close enough to the cylinder axis that the neutron goes from the bottom of cell 20 (the cylindrical void) to the top and crosses into cell 21,
3. collide in cell 21 (because point detector contributions are made only from collision/source points), and
4. have energy above 0.01 MeV.

These events are unlikely because

1. 180 cm of 2.03-g/cm^3 concrete is difficult to penetrate,
2. there is only a small solid angle up the "pipe" (cell 20),
3. not many collisions will occur in 10 cm of 0.0203-g/cm^3 concrete, and
4. particles lose energy penetrating the concrete.

Before approaching these four problems, knowledge about the the point detector technique can be applied to keep from wasting time; only collisions in cell 21 can contribute to the point detector. Collisions in cells 2-19 cannot contribute through the perfect shield, that is, zero importance region. Thus, the MCNP input is set (PD0 card, Fig. 2) so that the point detector ignores collisions not in cell 21. If the point detector did not ignore collisions in cells 2-19, the following would happen at each collision.

1. The probablity density for scattering toward the point detector would be calculated.
2. A point detector pseudoparticle would be created and pointed toward the point detector.
3. The pseudoparticle would be tracked and exponentially attenuated through the concrete.
4. The pseudoparticle would eventually enter the perfect shield (cell 1) and be killed because a straight line from any point in cells 2-19 to the point detector would enter the perfect shield.

There is no point proceeding with these steps because the pseudoparticles from cells 2-19 are always killed; time is saved by ignoring point detector contributions from cells 2-19.

IV. ANALOG CALCULATION

Inspection of Fig. 4, which is derived from MCNP summary tables, shows that the analog calculation fails. Note that the tracks entering dwindle to zero as they try to penetrate the concrete (cells 2-19). This problem will be addressed in more detail later, but first note that the number weighted energy (NWE) is very low, especially in cells 12, 13, and 14. The NWE is simply the average energy, that is

$$\mathrm{NWE} = \frac{\int N(E)E\ dE}{\int N(E)\ dE},$$

where E = energy and N(E) = number density at energy E. This indicates that there are many neutrons below 0.01 MeV that the point detector will not respond to. There is no sense following particles too low in energy to contribute; therefore, MCNP kills neutrons when they fall below a user-supplied energy cutoff.

V. ENERGY AND TIME CUTOFFS

A. Energy Cutoff

The energy cutoff in MCNP is a single user-supplied problem-wide energy level. Particles are terminated when their energy falls below the energy cutoff. The energy cutoff terminates tracks and thus decreases the time per history. The energy cutoff should be used only when it is *known* that low-energy particles are either of zero importance or almost zero importance. A number of pitfalls exist.

1. Remember that low-energy particles can often produce high-energy particles (for example, fission or low-energy neutrons inducing high-energy photons). Thus, even if a detector is not sensitive to low-energy particles, the low-energy particles may be important to the tally.
2. The energy cutoff is the same throughout the entire problem. Often low-energy particles have zero importance in some regions and high importance in others.
3. The answer will be biased (low) if the energy cutoff is killing particles that might otherwise have contributed. Furthermore, as N→∞ the apparent error will go to zero and therefore mislead the unwary. Serious consideration should be given to two techniques (discussed later), energy roulette and space-energy weight window, that are always unbiased.

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	4783	3931	13949	3.5593E+00	2.4144E-03	4.7075E+00	1.0000E+00	5.8207E+00
3	3	2176	931	15057	3.8421E+00	4.5943E-04	1.9643E+00	1.0000E+00	3.9404E+00
4	4	1563	593	12510	3.1921E+00	2.0566E-04	1.2067E+00	1.0000E+00	3.3058E+00
5	5	939	362	7390	1.8857E+00	1.4450E-04	8.4454E-01	1.0000E+00	3.0062E+00
6	6	511	205	4213	1.0750E+00	9.3995E-05	5.6654E-01	1.0000E+00	2.7411E+00
7	7	287	115	2219	5.6622E-01	1.0022E-04	5.8205E-01	1.0000E+00	2.7733E+00
8	8	170	63	1587	4.0495E-01	6.4696E-05	4.4866E-01	1.0000E+00	2.5496E+00
9	9	87	40	961	2.4522E-01	6.2827E-05	4.6476E-01	1.0000E+00	2.6046E+00
10	10	44	16	304	7.7571E-02	1.0691E-04	5.1448E-01	1.0000E+00	3.0390E+00
11	11	31	10	230	5.8688E-02	6.2272E-05	2.4500E-01	1.0000E+00	2.4143E+00
12	12	31	7	330	8.4205E-02	2.2207E-05	1.1767E-01	1.0000E+00	2.1161E+00
13	13	18	6	218	5.5626E-02	1.9931E-06	6.6168E-04	1.0000E+00	1.9191E+00
14	14	4	2	17	4.3378E-03	3.7686E-06	7.9961E-04	1.0000E+00	2.0823E+00
15	15	0	0	0	0.	0.	0.	0.	0.
16	16	0	0	0	0.	0.	0.	0.	0.
17	17	0	0	0	0.	0.	0.	0.	0.
18	18	0	0	0	0.	0.	0.	0.	0.
19	19	0	0	0	0.	0.	0.	0.	0.
20	20	0	0	0	0.	0.	0.	0.	0.
21	21	0	0	0	0.	0.	0.	0.	0.
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		10644	6281	58985	1.5051E+01				

ANALOG CALCULATION – NO VARIANCE REDUCTION TECHNIQUES

	TALLY 1			TALLY 4			TALLY 5		
NPS	MEAN	ERROR	FOM	MEAN	ERROR	FOM	MEAN	ERROR	FOM
1000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
2000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
3000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
3919	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0

```
**************************************************************************
DUMP NO.   2 ON FILE RUNTPE            NPS =     3919          CTM =     .61
```

Fig. 4. Analog calculation.

B. Time Cutoff

The time cutoff in MCNP is a single user-supplied, problem-wide time value. Particles are terminated when their time exceeds the time cutoff. The time cutoff terminates tracks and thus decreases the computer time per history. The time cutoff should only be used in time-dependent problems where the last time bin will be earlier than the cutoff.

The sample problem in this report is time-independent, so the time cutoff is not demonstrated here.

C. The Sample Problem with Energy Cutoff

Figure 5 gives the results of an MCNP calculation with a 0.01-MeV energy cutoff. Note that the number weighted energy is about 1000 times higher, so the energy cutoff has changed the energy spectrum as expected. Furthermore, note that about four times as many histories were run in the same time although the total number of collisions is approximately constant.

Despite more histories, fewer tracks enter deep into the concrete cylinder. This may seem a little counter-intuitive until one remembers that the energy cutoff kills the typical particle that has had many collisions and is below the energy cutoff, that is, the typical particle deep in the concrete. This decrease in the tracks entering is not alarming because we know that only tracks with energy less than 0.01 MeV were killed and they cannot tally.

The trouble with the calculation is that the large amount of concrete is preventing neutron travel from the source to the tally region. The solution is to preferentially push particles up the cylinder. Four techniques in MCNP can be used for penetration,

1. geometry splitting/Russian roulette,
2. exponential transorm,
3. forced collisions,* and
4. weight window.

VI. GEOMETRY SPLITTING AND RUSSIAN ROULETTE

Geometry splitting/Russian roulette is one of the oldest, most widely used variance reduction techniques. As with most biasing techniques, the objective is to spend more time sampling important (spatial) cells and less time sampling unimportant cells. The technique (Fig. 6) is to

1. divide the geometry into cells;
2. assign importances (I_n) to these cells; and
3. when crossing from cell m to cell n, compute $\nu = I_n/I_m$. If
   a. $\nu = 1$, continue transport;
   b. $\nu < 1$, play Russian roulette,
   c. $\nu > 1$, split the particle into $\nu = I_n/I_m$ tracks.

*There will not be an example using forced collisions for penetration problems because it is awkward to do in MCNP. In fact, an alteration to the weight cutoff game is often necessary.

A. Russian Roulette ($\nu < 1$)

If $\nu < 1$, the particle is entering a cell that we wish to sample less frequently, so the particle plays Russian roulette. That is,

1. with probability ν, the particle survives and its weight is multiplied by ν^{-1}, or
2. with probability $1 - \nu$ the particle is killed.

In general, Russian roulette increases the history variance but decreases the time per history, allowing more histories to be run.

B. Splitting ($\nu > 1$)

If $\nu > 1$, the particle is entering a more important region and is split into "ν" subparticles. If ν is an integer, this is easy to do; otherwise ν must be sampled. Consider $n < \nu < n + 1$, then

Probability	Split Weight	
$p(n) = n + 1 - \nu$	$wt_s = wt/n$	sampled
$p(n+1) = \nu - n$	$wt_s = wt/(n + 1)$	splitting

The sampled splitting scheme above conserves the total weight crossing the splitting surface, but the split weight varies, depending on whether n or n + 1 particles are selected.

Actually, MCNP does not use the sampled splitting scheme. MCNP uses an expected value scheme:

Probability	Split Weight	
$p(n) = n + 1 - \nu$	$wt_s = wt/\nu$	expected value
$p(n + 1) = \nu - n$	$wt_s = wt/\nu$	splitting

The MCNP scheme does not conserve weight crossing a splitting surface at each occurrence. That is, if n particles are sampled, the total weight entering is

$$n \cdot \frac{wt}{\nu} = \frac{n}{\nu} \cdot wt < wt ,$$

but if n + 1 particles are sampled, the total weight entering is

$$(n + 1) \frac{wt}{\nu} = \frac{n + 1}{\nu} wt > wt .$$

However, the *expected* weight crossing the surface is wt:

$$p(n) \cdot n \cdot \frac{wt}{\nu} + p(n + 1) \cdot (n + 1) \cdot \frac{wt}{\nu} = wt .$$

CELL PROGR	PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	15416	14004	27380	1.9602E+00	2.2661E+00	6.0830E+00	1.0000E+00	6.9686E+00
3	3	4445	3098	15611	1.1176E+00	1.0718E+00	3.9688E+00	1.0000E+00	5.9464E+00
4	4	2197	1580	7830	5.6057E-01	8.8425E-01	3.4412E+00	1.0000E+00	5.6866E+00
5	5	973	716	3661	2.6210E-01	7.9762E-01	2.9569E+00	1.0000E+00	5.5260E+00
6	6	467	331	1726	1.2357E-01	7.2799E-01	2.6838E+00	1.0000E+00	5.4005E+00
7	7	233	171	765	5.4768E-02	8.0105E-01	2.6783E+00	1.0000E+00	5.5811E+00
8	8	110	85	420	3.0069E-02	7.4818E-01	2.4966E+00	1.0000E+00	5.5021E+00
9	9	56	43	186	1.3316E-02	9.0855E-01	2.6749E+00	1.0000E+00	5.6290E+00
10	10	40	24	155	1.1097E-02	5.8161E-01	1.7610E+00	1.0000E+00	4.9657E+00
11	11	20	15	78	5.5842E-03	5.3100E-01	1.6936E+00	1.0000E+00	4.4423E+00
12	12	8	7	42	3.0069E-03	4.0663E-01	1.5199E+00	1.0000E+00	4.6999E+00
13	13	3	2	8	5.7274E-04	4.8527E-02	3.3019E-01	1.0000E+00	3.1147E+00
14	14	0	0	0	0.	0.	0.	0.	0.
15	15	0	0	0	0.	0.	0.	0.	0.
16	16	0	0	0	0.	0.	0.	0.	0.
17	17	0	0	0	0.	0.	0.	0.	0.
18	18	0	0	0	0.	0.	0.	0.	0.
19	19	0	0	0	0.	0.	0.	0.	0.
20	20	0	0	0	0.	0.	0.	0.	0.
21	21	0	0	0	0.	0.	0.	0.	0.
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		23968	20076	57862	4.1425E+00				

HAS INCREASED

COLLISIONS PER HISTORY HAS DECREASED

AVERAGE ENERGY HAS INCREASED

TOTAL NUMBER OF COLLISIONS PROCESSED ABOUT THE SAME

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
2000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
3000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
4000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
5000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
6000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
7000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
8000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
9000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
10000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
11000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
12000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
13000	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0
13968	0.	0.0000	0	0.	0.0000	0	0.	0.0000	0

```
***************************************************************************
DUMP NO.  2 ON FILE RUNTPF           NPS =    13968        CTM =     .60
```

NOTES:

ENERGY CUTOFF–0.01 MeV

1) N INCREASED FROM 3919 TO 13968
2) TRACKS STOP SOONER BECAUSE OF ENERGY CUTOFF
3) PARTICLES NOT GETTING TO TALLY REGIONS

Fig. 5. Energy cutoff of 0.01 MeV.

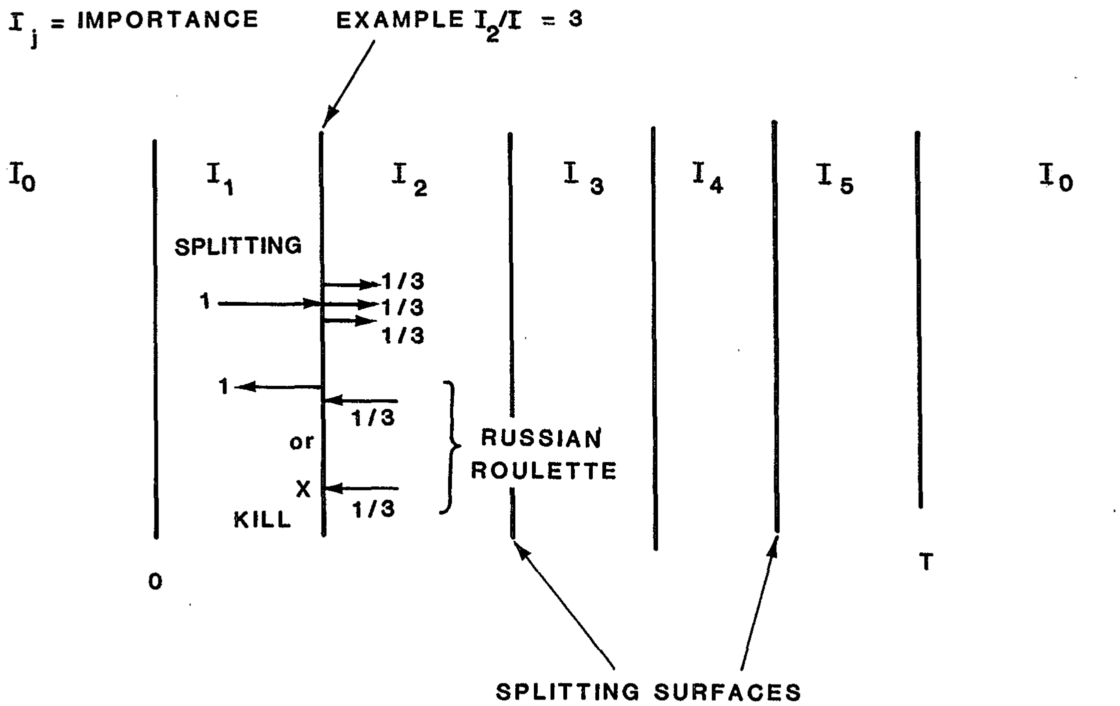


Fig. 6. Geometry splitting/Russian roulette technique.

The MCNP scheme has the advantage that all particles crossing the surface will have weight wt/v. Furthermore, if

1. geometry splitting/Russian roulette is the only nonanalog technique used and
2. all source particles start in a cell of importance I_s with weight w_s, then all particles in cell j will have weight

$$w_s \cdot \frac{I_s}{I_j}$$

regardless of the random walk taken to cell j.

MCNP's geometry splitting/Russian roulette introduces no variance in particle weight within a cell. The variation in the *number* of tracks scoring rather than a variation in particle weight determines the history variance. Empirically, it has been shown that large variations in particle weights affect tallies deleteriously. Booth[2] has shown theoretically that expected value splitting is superior to sampled splitting in high-variance situations.

C. Comments on Geometry Splitting/Russian Roulette

One other small facet deserves mention. MCNP never splits into a void although Russian roulette may be played entering a void. Splitting into a void accomplishes nothing except extra tracking because all the split particles must be tracked across the void and they all make it to the next surface. The split should be done according to the importance ratio of the last nonvoid cell departed and the first nonvoid cell entered (integer splitting into a void wastes time, but it does not increase the history variance). In contrast, noninteger splitting into a void may increase the history variance and waste time.

Finally, splitting generally decreases the history variance but increases the time per history.

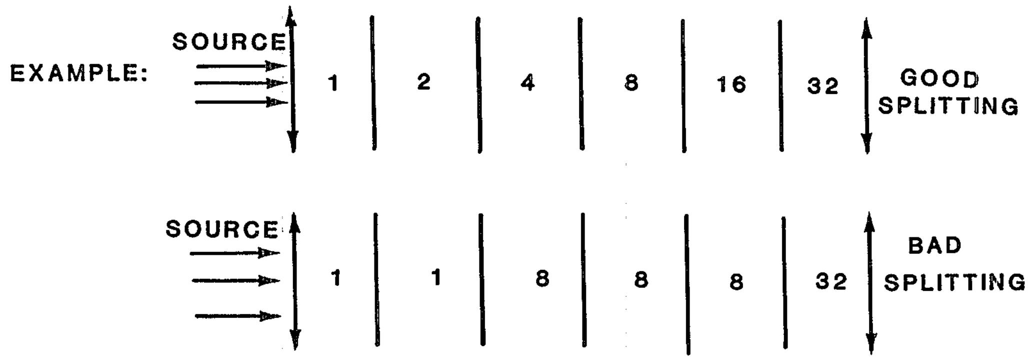
Note three more items:

1. Geometry splitting/Russian roulette works well only in problems without extreme angular dependence. In the extreme case, splitting/Russian roulette can be useless if no particles ever enter an important cell where the particles can be split.
2. Geometry splitting/Russian roulette will preserve weight variations. The technique is "dumb" in the sense that it never looks at the particle weight before deciding appropriate action. An example is geometry splitting/Russian roulette used with source biasing.
3. Geometry splitting/Russian roulette are turned on or off *together.*

D. Cautions

Although splitting/Russian roulette is among the oldest, easiest to use, and most effective techniques in MCNP, it can be abused. Two common abuses are:

1. compensating for previous poor sampling by a very large importance ratio and doing the splitting "all at once."



2. using splitting/Russian roulette with other techniques (for example, exponential transform) without forethought to possible interference effects.

E. The Sample Problem with Geometry Splitting/Russian Roulette

Returning to the problem, recall

	Cell		Tracks
	Progr	Probl	Entering
Source Cell	2	2	15416
	3	3	4445
	4	4	2197
	5	5	973
	6	6	467
	7	7	233
	8	8	110
	9	9	56
	10	10	40
	11	11	20
	12	12	8
	13	13	3
	14	14	0
	15	15	0
	16	16	0
	17	17	0
	18	18	0
	19	19	0
	20	20	0
	21	21	0
	22	22	0

Note that except for the source cell, the tracks entering are decreasing by about a factor of 2 in each subsequent cell. Furthermore, because half the particles from cell 2 (the source cell) immediately exit the geometry from the isotropic source, the rough factor of 2 even holds for the source cell. Thus as a first rough guess, try importance ratios of 2:1 through the concrete; that is, factor of 2 splitting.

Figure 7 indicates that this splitting is much better than no splitting. Not only did particles finally penetrate the concrete (see Tally 1) but the "tracks entering" column is roughly constant within a factor of 2. Slightly more splitting in cells 9-19 might improve the "tracks entering" just a little bit more. The splitting ratios were refined to be 2 in cells 2-8 and 2.15 in cells 9-19 in the next calculation.

Figure 8 summarizes the refined splitting. Immediately evident is that the FOM (Tally 1) unexpectedly decreased from 27 (Fig. 7) to 23, so at first glance, the refined splitting appears worse. However, note that the refined splitting had the desired effect; the "tracks entering" numbers are flatter. Thus I think the refined splitting is better despite the lower FOM.

What justifies being so cavalier about FOMs? Remember that the FOM is only an estimate of the calculational efficiency. At relative-error estimates near 25%, these FOMs are not meaningful enough to take the 27-to-23 FOM difference seriously. Furthermore, the FOM is only one of the *many* available pieces of summary information. At 25% error levels, it is much more important that the refined splitting appears to be sampling the geometry better.

F. Discussion of Results

The effect of refined splitting in this sample problem illustrates an important point about most variance reduction techniques; most of the improvement can usually be gained on the first try. Either one of these splitting/Russian roulette runs is several orders of magnitude better than the run without splitting. In fact, this

NOTE: MUCH BETTER

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	2329	2229	4011	1.8938E+00	2.2793E+00	6.0872E+00	1.0000E+00	7.0075E+00
3	3	1279	1119	4424	1.0444E+00	1.1595E+00	4.2228E+00	1.0000E+00	6.0880E+00
4	4	1323	1140	4803	5.6693E-01	9.6248E-01	3.5562E+00	1.0000E+00	5.8928E+00
5	5	1321	1131	4719	2.7851E-01	8.8914E-01	3.1819E+00	1.0000E+00	5.7399E+00
6	6	1326	1156	4687	1.3831E-01	8.3666E-01	2.9173E+00	1.0000E+00	5.6134E+00
7	7	1353	1154	5038	7.4333E-02	7.1902E-01	2.5852E+00	1.0000E+00	5.3490E+00
8	8	1358	1177	4881	3.6008E-02	7.5760E-01	2.6075E+00	1.0000E+00	5.4513E+00
9	9	1261	1081	4777	1.7621E-02	6.7145E-01	2.2906E+00	1.0000E+00	5.2870E+00
10	10	1182	1013	4632	8.5428E-03	6.2347E-01	2.1041E+00	1.0000E+00	5.2385E+00
11	11	1089	931	4118	3.7974E-03	5.7569E-01	1.9068E+00	1.0000E+00	5.1391E+00
12	12	998	853	3755	1.7313E-03	5.5764E-01	1.7904E+00	1.0000E+00	5.0335E+00
13	13	823	697	3127	7.2089E-04	5.8678E-01	1.8015E+00	1.0000E+00	5.1663E+00
14	14	792	678	3220	3.7117E-04	5.5526E-01	1.7102E+00	1.0000E+00	5.0461E+00
15	15	734	623	2798	1.6126E-04	5.5983E-01	1.7822E+00	1.0000E+00	5.1226E+00
16	16	664	568	2489	7.1726E-05	5.6580E-01	1.8696E+00	1.0000E+00	5.1708E+00
17	17	525	453	1807	2.6036E-05	6.1889E-01	1.9954E+00	1.0000E+00	5.2508E+00
18	18	514	441	1826	1.3155E-05	5.7871E-01	1.8610E+00	1.0000E+00	5.1414E+00
19	19	406	375	1323	4.7657E-06	7.4292E-01	2.1918E+00	1.0000E+00	5.5246E+00
20	20	163	163	0	0.	1.5219E+00	3.3568E+00	1.0000E+00	1.0000+123
21	21	0	0	0	0.	0.	0.	0.	0.
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		19440	16982	66435	4.0653E+00				

LOW BECAUSE NEXT TO A VOID

VOID CELL

F4 TALLY IN THIS TOP CELL IS ZERO BECAUSE NO PARTICLES EVER ENTERED THE CELL

NEXT RUN : INCREASE SPLITTING AT CELL 9 TO 2.15 UNTIL CELL 19

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	8.08716E-07	.3220	31	0.	0.0000	0	0.	0.0000	0
2000	5.95093E-07	.2532	27	0.	0.0000	0	0.	0.0000	0
2118	5.87154E-07	.2445	27	0.	0.0000	0	0.	0.0000	0

WE GOT A TALLY!

```
**********************************************************************************
DUMP NO.   2 ON FILE RUNTPG          NPS =     2118          CTM =     .60
```

PARTICLES STARTED HAVE DECREASED FROM 13968

Fig. 7. Factor of 2 splitting from cells 2 to 19.

FACTOR OF 2 SPLITTING CELLS 2 – 8 FACTOR OF 2.15 SPLITTING 9 –19

FACTOR OF 2

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	1673	1598	2818	1.8539E+00	2.3501E+00	6.2140E+00	1.0000E+00	7.0985E+00
3	3	936	816	3320	1.0921E+00	1.1862E+00	4.1852E+00	1.0000E+00	6.1472E+00
4	4	1017	867	3605	5.9293E-01	9.2757E-01	3.4306E+00	1.0000E+00	5.8783E+00
5	5	1024	869	3705	3.0469E-01	8.2254E-01	2.9743E+00	1.0000E+00	5.6386E+00
6	6	1000	882	3818	1.5699E-01	7.7874E-01	2.7444E+00	1.0000E+00	5.4952E+00
7	7	971	845	3588	7.3766E-02	6.6696E-01	2.4201E+00	1.0000E+00	5.3016E+00
8	8	910	797	3115	3.2021E-02	6.7071E-01	2.3358E+00	1.0000E+00	5.3777E+00
9	9	959	838	3462	1.6553E-02	6.2399E-01	2.2691E+00	1.0000E+00	5.3498E+00
10	10	1021	881	3615	8.0391E-03	7.2649E-01	2.2829E+00	1.0000E+00	5.4503E+00
11	11	1110	954	3948	4.0836E-03	6.8330E-01	2.1960E+00	1.0000E+00	5.3577E+00
12	12	1182	1034	4499	2.1644E-03	6.5035E-01	2.0670E+00	1.0000E+00	5.2891E+00
13	13	1147	1006	4278	9.5725E-04	6.0991E-01	2.0765E+00	1.0000E+00	5.2858E+00
14	14	1066	957	3955	4.1162E-04	6.2387E-01	2.0088E+00	1.0000E+00	5.1735E+00
15	15	1026	914	3870	1.8733E-04	6.1733E-01	2.0714E+00	1.0000E+00	5.2052E+00
16	16	1011	893	3704	8.3395E-05	6.1399E-01	1.9799E+00	1.0000E+00	5.1022E+00
17	17	886	772	3409	3.5699E-05	5.5395E-01	1.8365E+00	1.0000E+00	4.9429E+00
18	18	801	710	3099	1.5094E-05	4.8961E-01	1.6415E+00	1.0000E+00	4.8516E+00
19	19	666	617	2448	5.5458E-06	5.4063E-01	1.7694E+00	1.0000E+00	5.0166E+00
20	20	222	222	0	0.	1.0130E+00	2.5229E+00	1.0000E+00	1.0000+123
21	21	1	1	0	0.	9.5608E-02	9.5608E-02	1.0000E+00	2.9257E+02
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		18629	16473	64256	4.1390E+00				

FACTOR 2.15

SLIGHTLY FLATTER

TALLY FLUCTUATION CHARTS

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	5.37182E-07	.3002	26	0.	0.0000	0	0.	0.0000	0
1520	5.02929E-07	.2693	23	7.21401E-14	.9997	1	0.	0.0000	0

```
***************************************************************************
DUMP NO.  2 ON FILE RUNTPE          NPS =    1520          CTM =     .58
```

1 HISTORY SCORED

THESE FOM NOT TERRIBLY MEANINGFUL
AT THESE ERROR LEVELS.
CONCLUSION: LIKE THESE SPLITTING FACTORS
BETTER BECAUSE OF TRACKS ENTERING
COLUMN, DESPITE "LOWER" FOM

DECREASED FROM 2118
BECAUSE OF HIGHER SPLITTING

Fig. 8. Refined splitting.

problem is so bad without splitting that it is hard to guess how much splitting/Russian roulette has improved the efficiency. Contrast this improvement to the (questionable) FOM difference of 27 (Fig. 7) to 23 (Fig. 8) between the factor of 2 splitting and the refined splitting. Usually one can do better with a variance reduction technique on the second try than on the first, but usually by not more than a factor of 2.

Quickly reaching diminishing returns is characteristic of a competent user and a good variance reduction technique. Competent users can quickly learn good importances because there is a very broad near-optimal range. Because the optimum is broad, the statistics often mask which importance set is best when they are all in the vicinity of the optimum.

Now that a reasonably flat track distribution has been obtained, perhaps it is time to explain why one expects this to be near optimal. There are some plausible arguments, but the real reason is empirical; it has been observed in many similar problems (that is, essentially one-dimensional bulk penetration problems) that a flat track distribution is near optimal. The radius of the concrete cylinder is large enough (100 cm) that the cylinder appears much like a slab; very few particles cross its cylindrical surface at a given depth (y-coordinate) compared to the particle population at that depth. Indeed, if the radius were infinite, the cylinder would be a slab and no particles would cross its cylindrical surface.

A plausible argument for flat track distribution can be made by considering an extremely thick slab and possible track distributions for two cases. For too little splitting, the track population will decrease roughly exponentially with increasing depth and no particles will ever penetrate the slab. For too much splitting, the importance ratios are too large; the track population will increase roughly exponentially and a particle history will never terminate. In both cases, albeit for different reasons, there are never any tallies. If neither an exponentially decreasing population nor an exponentially increasing population is advisable, the only choice is a flat distribution.

Of course, there are really many more choices than exponentially decreasing, flat, or exponentially increasing populations, but track populations usually behave in one of these ways because the importance ratios from one cell to the next are normally chosen (at least for a first guess) equal. The reason is that one cell in the interior is essentially equivalent to the next cell, so there is little basis to choose a different importance ratio from one cell to the next. However, the cells are not quite equivalent because they are different depths from the source, so the average energy (and mean free path) decreases with increasing depth. This is probably why it was necessary to increase the importance ratio from 2 to 2.15 in the deep parts of the sample problem. Note, however, that this is a small correction.

Returning to Fig. 8, note that the energy and mean free path decrease with increasing depth, as expected. Not also that the higher splitting has decreased the particles per minute.

VII. ENERGY SPLITTING/ROULETTE

Energy splitting/Russian roulette is very similar to geometry splitting/Russian roulette except energy splitting/roulette is done in the energy domain rather than in the spatial domain. Note two differences.

1. Unlike geometry splitting/roulette, the energy splitting/roulette uses actual splitting ratios as supplied in the input file rather than obtaining the ratios from importances.
2. It is possible to play energy splitting/roulette only on energy decreases if desired.

There are two cautions.

1. The weight cutoff game takes no account of what has occurred with energy splitting/roulette.
2. Energy splitting/roulette is played throughout the entire problem. Consider using a space-energy weight window if there is a substantial space variation in what energies are important.

One can expect an improvement in speed using energy roulette by recalling that the problem ran a factor of 4 faster with an energy cutoff of 0.01 MeV than without an energy cutoff. Low-energy particles get progressively less important as their energy drops, so it might help to play Russian roulette at several different energies as the energy drops. In the following run, a 50% survival game was played at 5 MeV, 1 MeV, 0.3 MeV, 0.1 MeV, and 0.03 MeV. The energies and the 50% survival probability were only guesses.

The energy roulette (splitting does not happen here because there is no upscatter) results are shown in Fig. 9. Note that there were substantially ($\sim$50%) more tracks entering, approximately the same number of collisions, and three times as many particles run. The FOM looks better, but the mean (Tally 1) has increased from 5.0E-7 (Fig. 8) to 8.4E-7. This deserves note and caution, but not panic, because the error is 18%, so poor estimates in both tally and error can be expected. Despite the previous statement, the energy roulette looks successful in improving tallies 1 and 4.

VIII. IMPLICIT CAPTURE AND WEIGHT CUTOFF

A. Implicit Capture

Implicit capture, survival biasing, and absorption by weight reduction are synonymous. Implicit capture is a

AT 5 1 0.3 0.1 0.03MeV

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	4925	4840	5669	1.9902E+00	2.3276E+00	6.1205E+00	1.2907E+00	7.0018E+00
3	3	2071	1921	4678	1.1643E+00	1.0958E+00	3.9717E+00	1.6928E+00	5.9897E+00
4	4	1837	1698	4111	5.8076E-01	8.0935E-01	3.3359E+00	1.9502E+00	5.6657E+00
5	5	1567	1438	3601	2.5505E-01	9.3732E-01	3.1243E+00	1.9957E+00	5.6926E+00
6	6	1362	1270	3176	1.3056E-01	7.8732E-01	2.8812E+00	2.1442E+00	5.5827E+00
7	7	1260	1166	2822	5.3775E-02	8.7579E-01	2.8324E+00	2.1363E+00	5.7139E+00
8	8	1179	1099	2638	2.5744E-02	7.9706E-01	2.6317E+00	2.2040E+00	5.6698E+00
9	9	1208	1134	2558	1.2297E-02	8.3991E-01	2.7341E+00	2.1718E+00	5.7046E+00
10	10	1290	1183	2941	7.3733E-03	6.7628E-01	2.3517E+00	2.4449E+00	5.3481E+00
11	11	1391	1276	3403	4.2709E-03	6.2320E-01	2.1638E+00	2.6094E+00	5.1918E+00
12	12	1327	1225	2960	1.6659E-03	6.6384E-01	2.1940E+00	2.5545E+00	5.3025E+00
13	13	1309	1200	3201	8.0190E-04	7.1465E-01	2.2723E+00	2.4564E+00	5.4214E+00
14	14	1295	1192	2862	3.0306E-04	9.3180E-01	2.4979E+00	2.2807E+00	5.7146E+00
15	15	1321	1218	3155	1.7364E-04	6.2616E-01	2.0338E+00	2.6129E+00	5.2835E+00
16	16	1372	1265	3097	8.2605E-05	5.4080E-01	1.9274E+00	2.7255E+00	5.1923E+00
17	17	1353	1268	2968	3.6516E-05	5.8219E-01	2.0133E+00	2.6598E+00	5.2528E+00
18	18	1361	1282	3143	1.7358E-05	5.5134E-01	1.9932E+00	2.6756E+00	5.2760E+00
19	19	1283	1240	2708	6.5219E-06	6.4948E-01	2.0873E+00	2.5420E+00	5.5096E+00
20	20	570	570	0	0.	1.0062E+00	2.6046E+00	4.3766E+00	1.0000+123
21	21	6	6	0	0.	7.2412E-01	1.1786E+00	3.0008E+00	4.2805E+02
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		29287	27491	59691	4.2274E+00				

SUBSTANTIALLY MORE TRACKS

SLIGHTLY FEWER COLLISIONS

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	7.09853E-07	.3305	66	0.	0.0000	0	0.	0.0000	0
2000	8.88887E-07	.2890	42	2.00483E-13	.9997	3	0.	0.0000	0
3000	9.61129E-07	.2133	52	3.00442E-13	.6381	5	0.	0.0000	0
4000	9.46209E-07	.1857	53	2.25331E-13	.6381	4	0.	0.0000	0
4699	8.37540E-07	.1796	50	1.91812E-13	.6382	4	0.	0.0000	0

```
*****************************************************************************
DUMP NO.  2 ON FILE RUNTPF            NPS =   4699         CTM =    .61
```

FOM LOOKS BETTER, BUT INCREASE IN MEAN FROM 5.0 TO 8.4 DESERVES NOTE AND CAUTION. ERROR IS 18%, SO EXPECT POOR ESTIMATES BOTH IN TALLY AND IN ERROR.

INCREASED FROM 1520 WITH THE INTRODUCTION OF ENERGY ROULETTE

Fig. 9. Using energy roulette
(50% survival at 5 1 0.3 0.1 0.03 MeV)

variance reduction technique applied in MCNP *after* the collision nuclide has been selected. Let

σ_{ti} = total microscopic cross section for nuclide i and
σ_{ai} = microscopic absorption cross section for nuclide i.

When implicit capture is used rather than sampling for absorption with probability σ_{ai}/σ_{ti}, the particle always survives the collision and is followed with new weight

$$wt \cdot \left(1 - \frac{\sigma_{ai}}{\sigma_{ti}}\right).$$

Two advantages of implicit capture are

1. a particle that has finally, against considerable odds, reached the tally region is not absorbed just before a tally is made, and
2. the history variance, in general, decreases when the surviving weight (that is, 0 or wt) is not sampled, but an expected surviving weight is used instead (but see weight cutoff discussion, Sec. VIII.B).

Two disadvantages are

1. implicit capture introduces fluctuation in particle weight and
2. increases the time per history (but see weight cutoff discussion, Sec. VIII.B).

Note that

1. Implicit capture is the default in MCNP (except for note 4).
2. Implicit capture is always turned on for neutrons unless the weight cutoff game is turned off.
3. Explicit (analog) capture is not allowed for the photon simple physics treatment (high energy).
4. Analog capture is allowed only in detailed photon physics.

B. Weight Cutoff

In weight cutoff, Russian roulette is played if a particle's weight drops below a user-specified weight cutoff. The particle is either killed or its weight is increased to a user-specified level. The weight cutoff was originally envisioned for use with geometry splitting/Russian roulette and implicit capture. Because of this,

1. the weight cutoffs in cell j depend not only on WC1 and WC2 (see Fig. 2) on the CUTN and CUTP cards, but also on the cell importances. This dependence is intended to adjust the weight cutoff values to make sense with geometry splitting/Russian roulette.
2. Implicit capture is always turned on (except in detailed photon physics) whenever a nonzero WC1 is specified.

The weight cutoffs WC1 and WC2 are illustrated in Fig. 10. If a particle's weight falls below $R_j \cdot WC2$, a weight cutoff game is played; with probability $wt/(WC1 \cdot R_j)$ the particle survives with new weight $WC1 \cdot R_j$; otherwise the particle is killed.

As mentioned earlier, the weight cutoff game was originally envisioned for use with geometry splitting and implicit capture. Consider what can happen without a weight cutoff. Suppose a particle is in the interior of a very large medium and there are no time nor energy cutoffs. The particle will go from collision to collision, losing a fraction of its weight at each collision. Without a weight cutoff, the particle's weight would eventually be too small to be representable in the computer, at which time an error would occur. If there are other loss mechanisms (for example, escape, time cutoff, or energy cutoff), the particle's weight will not decrease indefinitely, but the particle may take an unduly long time to terminate.

Weight cutoff's dependence on the importance ratio can be easily understood if one remembers that the weight cutoff game was originally designed to solve the low-weight problem sometimes produced by implicit capture. In a high-importance region, the weights are low *by design*, so it makes no sense to play the same weight cutoff game in high- and low-importance regions. In fact, as mentioned in a previous section, if splitting is the only nonanalog technique used, all particles in a given cell have the same weight, so no weight cutoff game would make sense. That is, if the particle weight is too small in a cell, the cell importance simply needs to be decreased. The weight cutoff is meant to indicate when a particle's weight is too low to be worth transporting.

In addition to the weight cutoff's dependence on cell importance, the weight cutoffs are automatically made relative to the minimum source weight if the source is a standard MCNP source and the weight cutoffs (WC1, WC2) are prefixed by a negative sign.

1. Cautions

a. Many techniques in MCNP cause weight change; the weight cutoff was really designed with geometry splitting and implicit capture in mind. Care should be taken in the use of other techniques.
b. In most cases, if you specify a weight cutoff, you automatically get implicit capture.

2. Notes

a. Weight cutoff games are unlike time and energy cutoffs. In time and energy cutoffs, the random walk is *always* terminated when the threshold is crossed. Potential bias may result if the particle's importance was not zero. A weight cutoff (weight roulette would be a better name) does *not* bias the game because the weight is increased for those particles that survive.

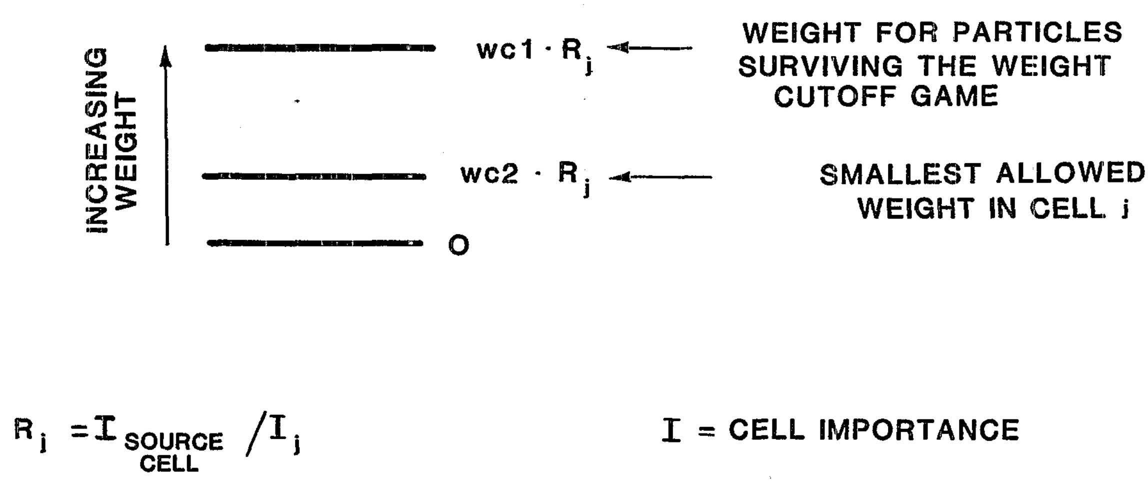


Fig. 10. Weight cutoff mechanics.

b. By default, the weight cutoff game is turned off in a weight window cell.

C. Weight Cutoff and Implicit Capture Applied to the Sample Problem

Figure 11 shows the result of adding weight cutoff and implicit capture techniques in addition to the

1. energy cutoff,
2. refined geometry splitting/Russian roulette, and
3. energy roulette techniques.

Comparing Fig. 11 to Fig. 9, one can see that implicit capture and weight cutoff did apparently reduce the tally 1 error for the same number of particles. However, the number of particles run was down by a factor of 2, resulting in a net decrease in the FOM. In general, if a nonanalog technique does not show a clear improvement, do not use it; thus for the next run, the implicit capture and weight cutoff will be turned off.

Tally 1 seems reasonably well optimized by

1. geometry splitting and roulette,
2. energy cutoff,
3. energy roulette (and splitting), and
4. analog capture.

Tally 4 is bad because very few tracks exit the concrete cylinder (cell 19) in the small solid angle subtended by cell 21. Tally 5 is even worse, in fact nonexistent, because of the few particles that do reach cell 21, none collide, so there are no point detector contributions.

Consider improving the worst tally (tally 5) first. Note from the summary charts that the free path in cell 21 is ~1000 cm and the cell is 10 cm thick. Only a tiny fraction of the particles entering cell 21 will collide in an analog fashion. The forced collision technique in MCNP solves this problem by *requiring* each track entering a cell to collide.

IX. FORCED COLLISIONS

Forced collision is normally used to sample collisions in optically thin (fractional mean free path) cells where not enough collisions are being sampled. A track entering a forced collision cell is split into two tracks: uncollided and collided. That is, MCNP calculates the expected weight traversing the cell and assigns that weight to the uncollided track, and MCNP calculates the expected weight colliding in the cell and assigns that weight to the collided track (Fig. 12). The uncollided track is put on the cell boundary (the point intersected by the cell boundary and the track direction), and the collided track's collision site is sampled in the usual way except that the collision site must now be sampled from a conditional probability, the condition being that a collision occurs at a distance $0 < x < \ell$.

A. Comments

1. Although the forced collision technique is normally used to obtain collisions in optically thin cells, it can also be used in optically thick cells to get the uncollided transmission.
2. The weight cutoff game is normally turned off in a forced collision cell (see MCNP Manual for exceptional cases[1]).
3. The forced collision technique decreases the history variance, but the time per history increases.
4. More than one collision can be forced in a cell.
5. ℓ of Fig. 12 is always the distance from the point at which the track is split into its collided and uncollided parts to the boundary. In Fig. 12, the split is done upon entrance to the cell, but the split can occur at an interior point as well (splits at interior

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	2237	2189	2898	2.1476E+00	1.8374E+00	5.6742E+00	1.2206E+00	6.7028E+00
3	3	1186	1097	2897	1.1189E+00	1.2427E+00	4.0314E+00	1.3540E+00	5.8642E+00
4	4	1325	1208	3166	6.4234E-01	8.5774E-01	3.1891E+00	1.4630E+00	5.5270E+00
5	5	1491	1358	3368	3.0964E-01	9.1416E-01	3.1710E+00	1.3746E+00	5.7341E+00
6	6	1415	1310	3201	1.3708E-01	7.9773E-01	2.9849E+00	1.3433E+00	5.6437E+00
7	7	1398	1295	3302	7.8890E-02	5.9432E-01	2.5009E+00	1.4377E+00	5.2856E+00
8	8	1418	1313	3188	3.1016E-02	7.7036E-01	2.7295E+00	1.2648E+00	5.5940E+00
9	9	1445	1320	3317	1.6468E-02	6.4889E-01	2.4403E+00	1.2894E+00	5.3027E+00
10	10	1464	1356	3522	7.0522E-03	8.0370E-01	2.5044E+00	1.1811E+00	5.4445E+00
11	11	1405	1305	3208	2.9794E-03	6.6734E-01	2.4093E+00	1.1671E+00	5.3589E+00
12	12	1450	1344	3129	1.4564E-03	5.5143E-01	2.1809E+00	1.2476E+00	5.1541E+00
13	13	1492	1366	3362	6.9754E-04	7.1905E-01	2.2514E+00	1.1605E+00	5.3834E+00
14	14	1565	1453	3683	3.3628E-04	6.4563E-01	2.1268E+00	1.1339E+00	5.1845E+00
15	15	1577	1465	3625	1.5533E-04	5.9601E-01	2.0087E+00	1.1594E+00	5.1098E+00
16	16	1611	1484	3696	7.1971E-05	5.9638E-01	2.0357E+00	1.1115E+00	5.1709E+00
17	17	1632	1514	3831	3.2251E-05	6.1970E-01	2.0445E+00	1.0851E+00	5.3119E+00
18	18	1601	1489	3358	1.1371E-05	7.3876E-01	2.2109E+00	9.9903E-01	5.5864E+00
19	19	1484	1438	3236	5.0066E-06	7.1488E-01	2.3301E+00	9.6091E-01	5.6517E+00
20	20	652	652	0	0.	1.7044E+00	3.4031E+00	1.4500E+00	1.0000+123
21	21	4	4	0	0.	1.7145E+00	1.7156E+00	7.7972E-01	5.8049E+02
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		27852	25960	59987	4.4947E+00				

NUMBER OF COLLISIONS PROCESSED THE SAME, BUT ABOUT HALF THE NUMBER OF PARTICLES RUN

APPARENTLY THE WEIGHT CUTOFF AND IMPLICIT CAPTURE DID REDUCE THE HISTORY VARIANCE, BUT LOST SINCE THE TIME PER HISTORY INCREASED TOO MUCH

REDUCED RELATIVE ERROR FOR SAME PARTICLES

TALLY FLUCTUATION CHARTS

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	4.45147E-07	.2634	49	7.21958E-14	.9995	3	0.	0.0000	0
2000	5.47418E-07	.2031	42	5.86343E-14	.7254	3	0.	0.0000	0
2099	5.61666E-07	.1933	37	5.58688E-14	.7254	2	0.	0.0000	0

****

DUMP NO. 2 ON FILE RUNTPG NPS = 2099 CTM = .61

APPEARS WORSE THAN FOM = 50 LAST TIME; STATISTICS STILL NOT VERY RELIABLE

NEXT TIME REMOVE WEIGHT CUTOFF AND IMPLICIT CAPTURE

Fig. 11. Weight cutoff (.5 .25) and implicit capture.

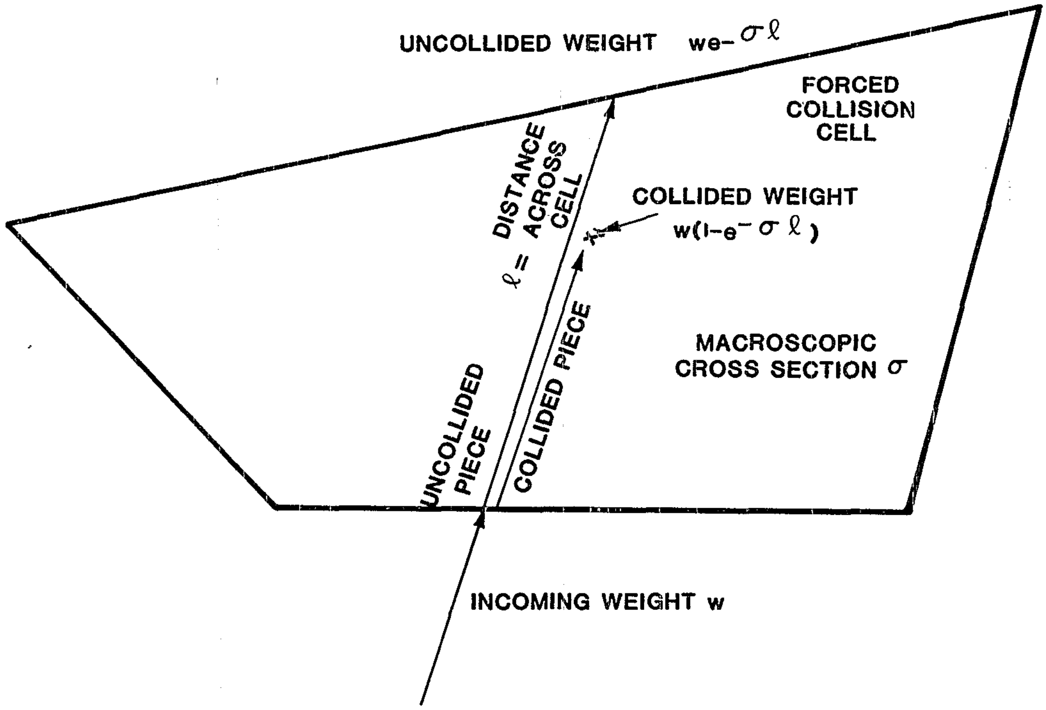


Fig. 12. Forced collision procedure.

points normally occur when more than one collision per entering track is forced).

B. Caution

Because weight cutoffs are turned off in forced collision cells, the number of tracks can get exceedingly large if there are several adjacent forced collision cells.

C. Forced Collisions Applied to the Sample Problem

Recall that the point detector tally (tally 5) was nonexistent because there were no collisions in cell 21. Figure 13 shows the effects of forcing one collision in cell 21 in addition to energy cutoff, refined geometry splitting/Russian roulette, and energy roulette. Note that 44 tracks entered cell 21 and there were 44 collisions in cell 21. Also note that the point detector tally is now obtaining contributions. Thus, the forced collision has really helped the point detector tally. The trouble now is not the lack of collisions from tracks that enter cell 21, but rather the small number of particles that enter cell 21. Angle biasing in some form is required to preferentially scatter particles into cell 21.

X. DXTRAN

The DXTRAN technique and source angle biasing are currently the only angle-biasing techniques in MCNP. Unlike source angle biasing, DXTRAN biases the scattering directions as well as the source direction.

Before explaining the DXTRAN theory, I will first loosely describe what occurs. A typical problem in which DXTRAN might be employed is much like the sample problem; a small region (for example, cell 21) is being inadequately sampled because particles almost never scatter toward the small region. To ameliorate this situation, the user can specify a DXTRAN sphere (in the input file) that encloses the small region. Upon particle collision (or exiting the source) outside the sphere, the DXTRAN technique creates a special "DXTRAN particle" and deterministically scatters it toward the DXTRAN sphere and deterministically transports it, without collision, to the surface of the DXTRAN sphere (Fig. 14). The collision itself is otherwise treated normally, producing a non-DXTRAN particle that is sampled in the normal way, with no reduction in weight. However, the non-DXTRAN particle is killed if it tries to enter the DXTRAN sphere.

The subtlety about DXTRAN is how the extra weight created for the DXTRAN particles is balanced by the

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	33158	32585	38721	1.9463E+00	2.2794E+00	6.0714E+00	1.2965E+00	6.9546E+00
3	3	14914	13932	34186	1.1305E+00	1.0507E+00	3.8230E+00	1.7265E+00	5.8555E+00
4	4	13784	12817	31887	5.7432E-01	8.8826E-01	3.2690E+00	1.9341E+00	5.6357E+00
5	5	13485	12457	30177	2.7660E-01	7.7716E-01	2.9746E+00	2.0974E+00	5.5166E+00
6	6	12627	11649	28028	1.3317E-01	7.8522E-01	2.8797E+00	2.1597E+00	5.5396E+00
7	7	11729	10786	26188	6.3336E-02	7.8444E-01	2.7773E+00	2.2148E+00	5.5669E+00
8	8	10735	9904	24261	3.0388E-02	7.5598E-01	2.6051E+00	2.2929E+00	5.5113E+00
9	9	10630	9847	24056	1.4810E-02	6.7951E-01	2.4260E+00	2.3985E+00	5.4027E+00
10	10	10475	9692	24365	7.0740E-03	6.7178E-01	2.3186E+00	2.4523E+00	5.3440E+00
11	11	10265	9545	23448	3.1479E-03	6.7630E-01	2.3071E+00	2.4446E+00	5.3741E+00
12	12	10218	9461	23357	1.4920E-03	6.6839E-01	2.2525E+00	2.4837E+00	5.3770E+00
13	13	10203	9435	23575	7.0432E-04	6.6659E-01	2.2037E+00	2.4998E+00	5.3401E+00
14	14	10157	9377	23262	3.3582E-04	6.2614E-01	2.1241E+00	2.5585E+00	5.2455E+00
15	15	10134	9398	24042	1.5945E-04	6.1916E-01	2.0813E+00	2.5892E+00	5.1981E+00
16	16	10070	9313	23380	7.1203E-05	6.0021E-01	2.0213E+00	2.6266E+00	5.1843E+00
17	17	9993	9291	23245	3.2652E-05	5.9809E-01	2.0129E+00	2.6205E+00	5.1975E+00
18	18	9661	8978	22146	1.3640E-05	6.3806E-01	2.0663E+00	2.5577E+00	5.2681E+00
19	19	8727	8431	19918	5.3706E-06	6.9204E-01	2.1459E+00	2.4912E+00	5.4016E+00
20	20	3669	3665	0	0.	1.5197E+00	3.4888E+00	3.6344E+00	1.0000+123
21	21	44	88	44	2.8836E-11	5.3640E+00	6.1170E+00	5.8094E-01	8.4249E+02
22	22	7	7	0	0.	4.8993E+00	5.0533E+00	2.1420E-02	1.0000+123
TOTAL		224685	210658	468286	4.1825E+00				

ONE COLLISION PER TRACK

NOW GET DETECTOR TALLY FROM COLLISIONS

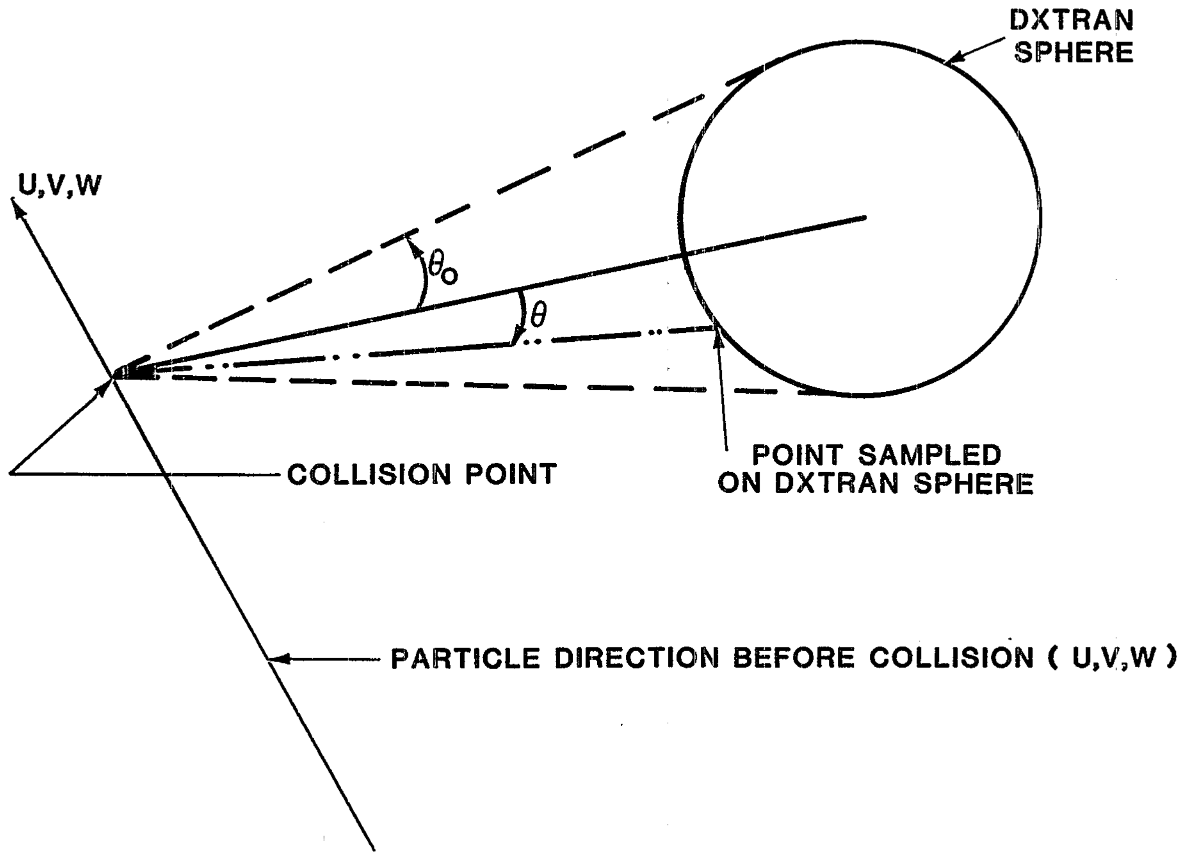
	TALLY 1			TALLY 4			TALLY 5		
NPS	MEAN	ERROR	FOM	MEAN	ERROR	FOM	MEAN	ERROR	FOM
2000	4.43762E-07	.2926	38	3.93854E-14	.9997	3	1.09306E-17	.9997	3
4000	5.00005E-07	.2048	39	1.96927E-14	.9999	1	5.46528E-18	.9999	1
6000	4.89498E-07	.1735	38	1.31285E-14	.9999	1	3.64352E-18	.9999	1
8000	5.45431E-07	.1560	35	2.95408E-14	.7453	1	2.73264E-18	.9999	0
10000	5.75778E-07	.1318	38	2.36326E-14	.7453	1	2.18611E-18	.9999	0
12000	5.76643E-07	.1146	42	2.64523E-14	.6109	1	5.74344E-18	.7528	0
14000	5.67196E-07	.1050	43	3.40704E-14	.4703	2	9.73618E-18	.5345	1
16000	5.64437E-07	.0982	43	5.44775E-14	.3741	3	1.63891E-17	.4208	2
18000	5.44298E-07	.0930	44	4.84244E-14	.3741	2	1.45681E-17	.4208	2
20000	5.34245E-07	.0895	43	4.35820E-14	.3741	2	1.31113E-17	.4208	1
22000	5.45122E-07	.0845	44	5.04040E-14	.3346	2	1.61184E-17	.3816	2
24000	5.78085E-07	.0791	45	6.92172E-14	.3261	2	2.47790E-17	.3653	2
26000	5.59956E-07	.0770	44	7.60020E-14	.2963	3	2.66047E-17	.3296	2
28000	5.51656E-07	.0739	44	7.05733E-14	.2963	2	2.47043E-17	.3296	2
30000	5.52045E-07	.0706	46	7.11231E-14	.2842	2	2.42602E-17	.3172	2
31617	5.58607E-07	.0682	45	7.52914E-14	.2664	2	2.61322E-17	.2919	2

****

DUMP NO. 2 ON FILE RUNTPF NPS = 31617 CTM = 4.61

PART / MIN = 6858

Fig. 13. Weight cutoff and implicit capture removed; forced collision used in cell 21.



1. A point on the DXTRAN sphere is sampled.
2. A particle is scattered towards the selected point.
3. The particle's weight is exponentially decreased by the optical path and adjusted for bias in the scattering angle.
4. The original particle is sampled in the normal way (with no reduction in weight).
5. If the original particle tries to enter the DXTRAN sphere, it is terminated.

Fig. 14. DXTRAN concept.

weight killed as non-DXTRAN particles cross the DXTRAN sphere. The non-DXTRAN particle is followed without any weight correction, so if the DXTRAN technique is to be unbiased, the extra weight put on the DXTRAN sphere by DXTRAN particles must somehow (on average) balance the weight of non-DXTRAN particles killed on the sphere.

A. DXTRAN Viewpoint #1

One can view DXTRAN as a splitting process (much like the forced collision technique) wherein each particle is split upon departing a collision (or source point) into two distinct pieces:

1. the weight that does not enter the DXTRAN sphere on the next flight either because the particle is not pointed toward the DXTRAN sphere or because the particle collides before reaching the DXTRAN sphere, and
2. the weight that enters the DXTRAN sphere on the next flight.

Let w_o be the weight of the particle before exiting the collision, let p_1 be the analog probability that the particle does not enter the DXTRAN sphere on its next flight, and let p_2 be the analog probability that the particle does enter the DXTRAN sphere on its next flight. The particle must undergo one of these mutually exclusive events, thus $p_1 + p_2 = 1$. The expected weight not entering the DXTRAN sphere is $w_1 = w_o\, p_1$, and the expected weight entering the DXTRAN sphere is $w_2 = w_o\, p_2$. Think of DXTRAN as deterministically splitting the original particle with weight w_o into two particles, a non-DXTRAN (particle 1) particle of weight w_1 and a DXTRAN (particle 2) particle of weight w_2. Unfortunately, things are not quite that simple.

Recall that the non-DXTRAN particle is follwed with unreduced weight w_o rather than weight $w_1 = w_o\, p_1$. The reason for this apparent discrepancy is that the non-DXTRAN particle (#1) plays a Russian roulette game. Particle 1's weight is increased from w_1 to w_o by playing a Russian roulette game with survival probability $p_1 = w_1/w_o$. The reason for playing this Russian roulette game is simply that p_1 is not known, so assigning weight $w_1 = p_1\, w_o$ to particle 1 is impossible. However, it is possible to play the Russian roulette game without explicitly knowing p_1. It is not magic, just slightly subtle.

The Russian roulette game is played by sampling particle 1 normally and keeping it only if it does not enter (on its next flight) the DXTRAN sphere; that is, particle 1 survives (by definition of p_1) with probability p_1. Similarly, the Russian roulette game is lost if particle 1 enters (on its next flight) the DXTRAN sphere; that is, particle 1 loses the roulette with probability p_2. Now I restate this idea. With probability p_1, particle 1 has weight w_o and does not enter the DXTRAN sphere and with probability p_2, the particle enters the DXTRAN sphere and is killed. Thus, the expected weight not entering the DXTRAN sphere is $w_o\, p_1 + 0 \cdot p_2 = w_1$, as desired.

So far, this discussion has concentrated on the non-DXTRAN particle and ignored exactly what happens to the DXTRAN particle. The sampling of the DXTRAN particle will be discussed after a second viewpoint on the non-DXTRAN particle.

B. DXTRAN Viewpoint #2

If you have understood the first viewpoint, you need not read this viewpoint. On the other hand, if the first viewpoint was not clear, perhaps this second one will be.

This second way of viewing DXTRAN does not see it as a splitting process but as an accounting process where weight is both created and destroyed on the surface of the DXTRAN sphere. In this view, DXTRAN estimates the weight that should go to the DXTRAN sphere upon collision and creates this weight on the sphere as DXTRAN particles. If the non-DXTRAN particle does not enter the sphere, its next flight will proceed exactly as it would have without DXTRAN, producing the same tally contributions and so forth. However, if the non-DXTRAN particle's next flight attempts to enter the sphere, the particle must be killed or there would be (on average) twice as much weight crossing the DXTRAN sphere as there should be, the weight crossing the sphere having already been accounted for by the DXTRAN particle.

C. The DXTRAN Particle

Although the DXTRAN particle does not confuse people nearly as much as the non-DXTRAN particle, the DXTRAN particle is nonetheless subtle.

The problem is how to sample the DXTRAN particle's location on the DXTRAN sphere. One cannot afford to calculate a cumulative distribition function to select the scattering direction θ indicated in Fig. 14. [The azimuthal angle is sampled uniformly in $(0,2\pi)$]. This would essentially involve integrating the scattering probability density at each collision. Instead of sampling the true probability density, one samples an arbitrary density and adjusts the weight appropriately.

As indicated above, a point on the DXTRAN sphere can be selected from any density function because the weight of the DXTRAN particle is modified by

$$\frac{\text{true density to select point } p_s}{\text{density sampled to select } p_s}$$

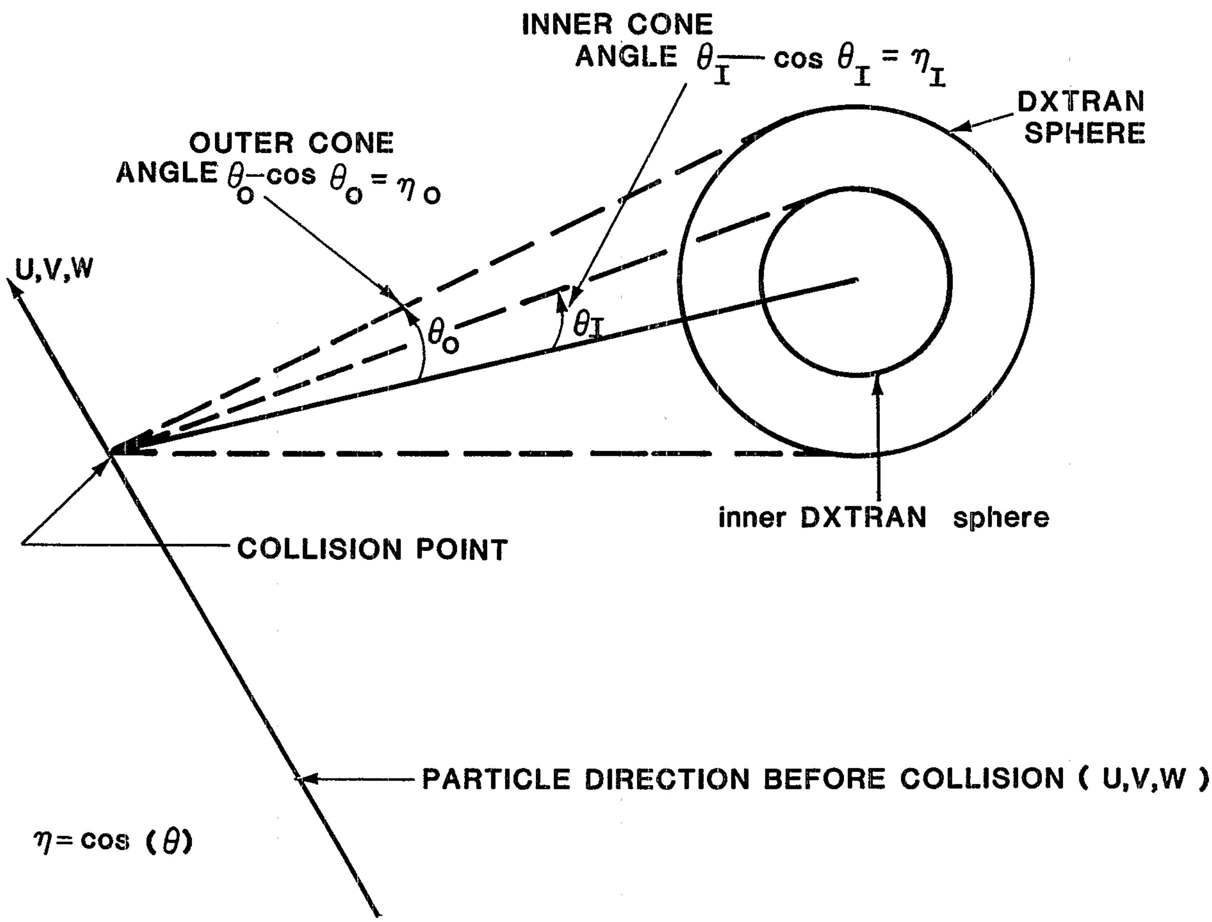


Fig. 15. Sampling the DXTRAN particle.

This is easy to do because the true scattering density function is immediately available even if its integral is not. MCNP arbitrarily uses the two-step density described below. In fact, the inner DXTRAN sphere has *only* to do with this arbitrary density and is not essential to the DXTRAN concept.

MCNP samples the inner cone uniformly in $(\eta_I, 1)$, and the outer cone uniformly in (η_o, η_I) (Fig. 15). However, the inner cone is sampled with five times the probability density that the outer is sampled. That is to say the inner cone is taken to be five times as important as the outer cone. Further mathematical details are given in the MCNP manual[1] and will not be discussed here.

After the scattering angle has been chosen, the DXTRAN particle is deterministically transported to the DXTRAN sphere without collision and with weight attenuated by the exponential of the optical path.

D. Inside the DXTRAN Sphere

So far, only collisions outside the DXTRAN sphere have been discussed. At collisions inside the DXTRAN sphere, the DXTRAN game is not played* because first, the particle is already in the desired region and second, it is impossible to define the angular cone of Fig. 14.

E. Terminology - Real Particle, Pseudoparticle

In X-6 documentation, at least through the April 1981 MCNP Manual,[1] the DXTRAN particle is called a

*If there are several DXTRAN spheres and the collision occurs in sphere i, then DXTRAN will be played for all spheres except sphere i.

pseudoparticle and the non-DXTRAN particle is called the original or real particle. The terms "real particle" and "pseudoparticle" are potentially misleading. Both particles are equally real; both execute random walks, both carry nonzero weight, and both contribute to tallies. The only stage at which the DXTRAN particle should be considered "psuedo" or "not real" is during creation. A DXTRAN particle is created on the DXTRAN sphere, but creation involves determining what weight the DXTRAN particle should have upon creation. Part of this weight determination requires calculating the optical path between the collision site and the DXTRAN sphere. MCNP determines the optical path by tracking a pseudoparticle from the collision site to the DXTRAN sphere. This pseudoparticle is deterministically tracked to the DXTRAN sphere simply to determine the optical path; no distance to collision is sampled, no tallies are made, and no records of the pseudoparticle's passage are kept (for example, tracks entering). In contrast, once the DXTRAN particle is created at the sphere's surface, the particle is no longer a pseudoparticle; the particle has real weight, executes random walks, and contributes to tallies.

F. Comments

1. DXTRAN spheres have their own weight cutoffs.
2. The DD card (by default) stops extremely low-weighted tracks by roulette. See the manual[1] for how this is accomplished.
3. Strongly consider producing DXTRAN particles only on some fraction of the number of collisions, as allowed by the DXCPN card.

G. CAVEATS

1. DXTRAN should be used carefully in optically thick problems. Do not rely on DXTRAN to do penetration.
2. If the source is user-supplied, some provision (SRCDX, page 263 of the MCNP manual[1]) must be made for obtaining the source contribution to particles on the DXTRAN sphere.
3. Extreme care must be taken when more than one DXTRAN sphere is in a problem. Cross-talk between spheres can result in extremely low weights and an explosion in particle tracks.
4. A different set of weight cutoffs is used inside the DXTRAN sphere.

H. DXTRAN Applied to the Sample Problem

Recall that there was a problem getting enough particles to scatter in the direction of cell 21. To solve this problem, a DXTRAN sphere was specified just large enough to surround cell 21 (Fig. 16). If a larger DXTRAN sphere were used, some DXTRAN particles would miss cell 21 and this would be less efficient. If a smaller DXTRAN sphere were used, it would be possible for a non-DXTRAN particle to enter cell 21, resulting in an undesirable large weight fluctuation in cell 21. Note also that the inner and outer DXTRAN spheres are coincident. This choice was made because specifying different spheres would introduce a five-to-one weight variation even though all particles entering cell 21 are about equally important.

I. Discussion

Note from Fig. 17 that DXTRAN did have the desired effect; the tracks entering cell 21 have increased dramatically and the FOMs for tallies 4 and 5 have increased by a factor of 7. However, note that the particles-per-minute number has decreased by a factor of 4; this is reflected in a factor of 4 decrease in tally 1's FOM. It would be wonderful if DXTRAN did not slow the problem down so much. Fortunately in some cases, a little thinking and judicious use (described below) of the DXCPN card can alleviate this speed problem.

Recall the caveat about using DXTRAN carefully in optically thick problems, in particular, not to rely on DXTRAN to do the penetration. Geometry splitting has done well at penetration, so DXTRAN is needed mostly for the angle bias, as is desirable. However, at every collision, regardless of how many mean free paths the

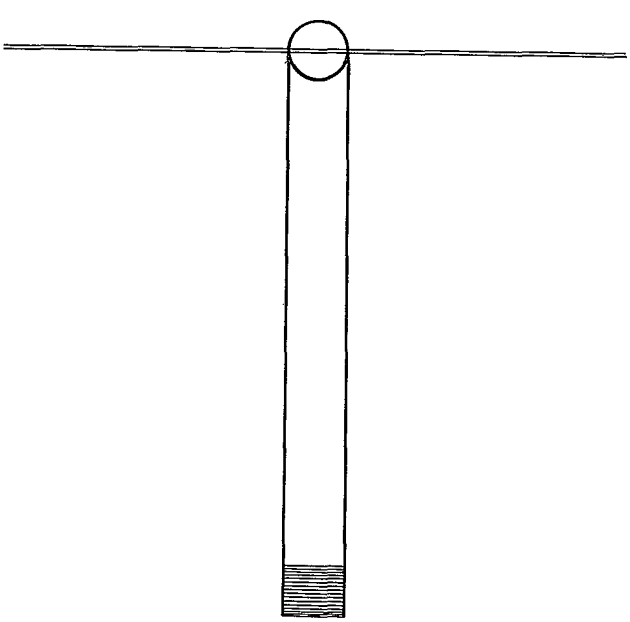


Fig. 16. DXTRAN sphere. The inner and outer spheres are identical because specifying different spheres would just create weight fluctuation.

collision is from cell 21, a DXTRAN particle is produced. DXTRAN particles that are many free paths from the DXTRAN sphere will have their weights exponentially decreased by the optical path so that their weights are negligible by the time they are put on the DXTRAN sphere. MCNP automatically (unless turned off on the DD card) plays Russian roulette on the DXTRAN particles as their weight falls exponentially, because of transport, below some fraction of the average weight (on the DXTRAN sphere). This provides the user some protection against spending a lot of time following DXTRAN particles of inconsequential weight. However, there is a better solution for the sample problem.

Although the DD card will play roulette on DXTRAN particles as they are transported through media to the DXTRAN sphere, it still takes time to produce and follow the DXTRAN particles until they can be rouletted. It is much better not to produce so many DXTRAN particles in the first place. MCNP allows the user (on the DXCPN card) to specify, by cell, what fraction of the collisions will result in DXTRAN particles. Everything is treated the same except that if p is the probability of creating a DXTRAN particle, then when a DXTRAN particle is created, its weight is multiplied by p^{-1}, thus making the game unbiased. The destruction game is unaffected; regardless of whether the sampling produced a DXTRAN particle, the non-DXTRAN particle is killed if it tries to enter the DXTRAN sphere.

As usual, this new capability requires even more input parameters; that is, the entries on the DXCPN card. Before despairing unduly, note that the entries on the DXCPN card are not highly critical, and the user has already gained a lot of useful information in the geometry-splitting optimization.

Table I shows the DXCPN probabilities that I chose for the sample problem. Note three things from this table.

1. Near the top of the concrete cylinder (cells 18 and 19) every collision creates a DXTRAN particle ($p = 1$).
2. As the cells get progressively farther (cells 12-17) from the DXTRAN sphere, p gets progressively smaller by roughly a factor of 2, chosen because the importance from cell to cell decreases by factors of about 2.
3. Not much thought was spent selecting p's for cells 2-11 because these cells contribute almost no weight to the DXTRAN sphere. Thus within reason, almost any values can be selected if they are small enough that not much time is spent following DXTRAN particles in cells 2-11. Note that even $p = 0.001$ will not totally preclude creating DXTRAN particles because there are 2000-3000 collisions in each of cells 2-5, where $p = 0.001$.

Before examining what happened when the DXCPN card was used, I would like to digress and use item 3 above as a specific example of a general principle. When biasing against random walks of presumed low importance, always make sure that at least a few of these random walks are followed so that if the presumption is wrong, the statistics will so indicate by bouncing around. As an example, I fully believe that $p = 10^{-6}$ would be appropriate in cell 2, but I chose $p = 10^{-3}$. Had I chosen $p = 10^{-6}$, probably no DXTRAN particles would be produced from collisions in cell 2. Thus if these DXTRAN particles turn out to be a lot more important than anticipated, the tally may be missing a substantial contribution with no statistical indication that something is amiss. By choosing $p = 0.001$ in cells 2-5, I cause the MCNP to produce approximately ten DXTRAN particles by the 10,000 or so collisions in cells 2-5 (see Fig. 17). Following 10 DXTRAN particles is a very small time price to pay to be sure that they are not important. If the problem were to be run long enough that there would be 10^7 collisions in cell 2, then I would not hesitate to use $p = 10^{-6}$ because *some* DXTRAN particles would be produced.

J. Results of Using DXTRAN with the DXCPN card

The result of adding the DXCPN card is shown in Fig. 18. Note that all FOMs improved by better than a factor of 2. The histories per minute increased from 1560 to 4395 when the DXCPN card was added, but 4395 is still slower than the 6858 without DXTRAN. The FOM for tally 1, although almost three times as good as that without the DXCPN card, is nonetheless still less than the no DXTRAN FOM of 45. This is an example of the general rule:

Increasing sampling in one region in general is at the expense of another region.

In the sample problem, we have decided to increase the sampling of cell 21 at the expense of cells 2-19. Overall, however, DXTRAN has clearly improved the calculation.

XI. TALLY CHOICE, POINT DETECTOR VERSUS RING DETECTOR

Recall from the introductory section on variance reduction that the FOM is affected by the tally choice as well as by the random walk sampling. So far, I have tinkered only with the random walk sampling; now, suppose I tinker with the tally.

Consider tally 5, the point detector tally. Note that the sample problem is symmetric about the y-axis, so a ring

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	2357	2301	2909	2.0318E+00	2.3810E+00	5.9965E+00	1.2916E+00	6.9395E+00
3	3	1159	1075	2685	1.2673E+00	8.7258E-01	3.6570E+00	1.7528E+00	5.6912E+00
4	4	1005	944	2340	6.0928E-01	8.1250E-01	3.2031E+00	2.0094E+00	5.4488E+00
5	5	957	901	2247	2.5856E-01	1.1096E+00	3.2913E+00	1.9192E+00	5.7046E+00
6	6	872	808	1912	1.0868E-01	1.3123E+00	3.3536E+00	1.8915E+00	6.0199E+00
7	7	793	742	1718	5.3250E-02	9.6440E-01	2.8593E+00	2.1229E+00	5.5466E+00
8	8	846	783	1899	3.3400E-02	6.8582E-01	2.5136E+00	2.3368E+00	5.3099E+00
9	9	857	796	2073	1.7817E-02	6.3392E-01	2.3447E+00	2.4164E+00	5.2447E+00
10	10	896	828	2026	7.9255E-03	7.0803E-01	2.3925E+00	2.3320E+00	5.4905E+00
11	11	941	858	2122	3.9925E-03	6.9361E-01	2.1789E+00	2.3943E+00	5.3566E+00
12	12	980	894	2287	1.9016E-03	7.1915E-01	2.1137E+00	2.4458E+00	5.2989E+00
13	13	983	895	2319	1.0406E-03	5.0262E-01	1.7716E+00	2.7835E+00	4.9197E+00
14	14	974	907	2445	5.6999E-04	4.7699E-01	1.5858E+00	2.9712E+00	4.7692E+00
15	15	906	844	2156	1.9251E-04	7.1176E-01	1.8944E+00	2.5154E+00	5.3166E+00
16	16	892	826	2223	8.8589E-05	7.2278E-01	1.8604E+00	2.5116E+00	5.1586E+00
17	17	914	840	2202	4.1190E-05	6.0178E-01	1.8622E+00	2.5492E+00	5.1533E+00
18	18	897	828	2091	1.7260E-05	6.4129E-01	1.8927E+00	2.5250E+00	5.2535E+00
19	19	755	731	1823	6.8759E-06	5.8583E-01	1.8406E+00	2.5705E+00	5.2381E+00
20	20	2172	9716	0	0.	7.6847E-01	2.5674E+00	3.0960E-01	1.0000+123
21	21	8813	17634	9015	6.7811E-11	1.7049E+00	3.6797E+00	3.1082E-04	7.3565E+02
22	22	703	703	0	0.	9.0071E-01	2.6050E+00	1.5934E-05	1.0000+123
TOTAL		29672	44854	48492	4.3959E+00				

INCREASED FROM 44 WITHOUT DXTRAN

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	7.31774E-07	.3642	10	1.11808E-13	.3077	14	6.89810E-17	.3427	11
2000	7.18177E-07	.2485	12	1.14993E-13	.2149	17	7.12499E-17	.2307	14
2231	7.34682E-07	.2293	12	1.23719E-13	.2053	15	7.62305E-17	.2177	14

```
***************************************************************************
DUMP NO.  2 ON FILE RUNTPG          NPS =   2231          CTM =   1.43
```

DECREASED BY FACTOR OF 4

INCREASED BY FACTOR OF 7

PART / MIN = 1560
WITHOUT DXTRAN = 6858

CONCLUSION: DXTRAN TECHNIQUE SUCCESSFUL FOR TALLY 4 AND TALLY 5 BUT TOO SLOW.

Fig. 17. DXTRAN sphere at about cell 21.

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	11938	11744	13796	1.9875E+00	1.9553E+00	5.8909E+00	1.3213E+00	6.8365E+00
3	3	5292	4918	11952	1.0727E+00	1.1897E+00	4.0414E+00	1.6629E+00	5.9855E+00
4	4	5010	4651	11384	5.7591E-01	8.6965E-01	3.3229E+00	1.9476E+00	5.6454E+00
5	5	4827	4469	10847	2.7700E-01	7.9325E-01	3.0387E+00	2.0971E+00	5.5575E+00
6	6	4414	4073	9805	1.2674E-01	7.8981E-01	2.9908E+00	2.1426E+00	5.6477E+00
7	7	4177	3816	9507	6.2377E-02	7.9364E-01	2.8062E+00	2.2181E+00	5.5340E+00
8	8	4114	3780	9500	3.2883E-02	7.5226E-01	2.5813E+00	2.3164E+00	5.4448E+00
9	9	4114	3803	9158	1.5241E-02	7.2149E-01	2.5273E+00	2.3520E+00	5.4441E+00
10	10	4105	3833	9297	7.4165E-03	7.0749E-01	2.4918E+00	2.3750E+00	5.4572E+00
11	11	4112	3803	9202	3.2429E-03	7.5649E-01	2.4433E+00	2.3664E+00	5.4819E+00
12	12	4293	3948	9827	1.7202E-03	6.9620E-01	2.3424E+00	2.4325E+00	5.3524E+00
13	13	4384	4040	9759	8.0545E-04	6.5721E-01	2.2911E+00	2.4785E+00	5.3043E+00
14	14	4337	4017	9621	3.6893E-04	6.6088E-01	2.2587E+00	2.4924E+00	5.3570E+00
15	15	4312	3977	9935	1.7810E-04	6.6189E-01	2.1957E+00	2.5004E+00	5.3071E+00
16	16	4365	4059	10039	7.9894E-05	7.0947E-01	2.1324E+00	2.5102E+00	5.3140E+00
17	17	4274	3982	9862	3.6959E-05	6.3603E-01	2.0865E+00	2.5629E+00	5.2996E+00
18	18	4248	3935	9946	1.6748E-05	6.6484E-01	2.0783E+00	2.5527E+00	5.3146E+00
19	19	3867	3749	8538	6.2137E-06	7.0403E-01	2.2236E+00	2.4620E+00	5.4511E+00
20	20	4927	18224	0	0.	1.2396E+00	3.2943E+00	7.9810E-01	1.0000+123
21	21	15223	30451	15598	6.5663E-11	1.7785E+00	4.1554E+00	9.1074E-04	7.3805E+02
22	22	1283	1283	0	0.	7.0419E-01	2.7866E+00	3.6840E-05	1.0000+123
TOTAL		107616	130555	197573	4.1643E+00				

SUBSTANTIALLY IMPROVED

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	9.91356E-07	.3667	27	1.50695E-13	.3251	34	1.06148E-16	.3673	27
2000	6.41539E-07	.2949	26	1.06818E-13	.2461	38	6.85473E-17	.2928	27
3000	5.70257E-07	.2393	27	1.02834E-13	.1982	40	6.49562E-17	.2387	27
4000	6.76150E-07	.1863	32	1.11525E-13	.1622	43	6.79132E-17	.1910	31
5000	6.76891E-07	.1679	32	1.13338E-13	.1465	42	6.89970E-17	.1686	31
6000	6.73265E-07	.1516	32	1.14934E-13	.1312	43	6.74936E-17	.1510	33
7000	6.89040E-07	.1378	34	1.14298E-13	.1198	45	6.74760E-17	.1359	34
8000	6.86656E-07	.1262	35	1.17711E-13	.1095	46	6.87251E-17	.1245	36
9000	7.04305E-07	.1167	36	1.18117E-13	.1023	47	6.97952E-17	.1161	36
10000	7.25099E-07	.1093	36	1.22116E-13	.0990	44	7.09365E-17	.1114	35
11000	7.00085E-07	.1046	36	1.18453E-13	.0948	45	6.88873E-17	.1060	36
11427	7.32339E-07	.1049	34	1.22412E-13	.0946	42	7.21438E-17	.1049	34

15 LAST TIME

14 LAST TIME

```
************************************************************************************
DUMP NO.  2 ON FILE RUNTPH          NPS =    11427        CTM =    2.60
```

PART/MIN = 4395
NO DXTRAN = 6858
DXTRAN w/o DXCPN = 1560

IMPROVED OVER DXTRAN w/o DXCPN = 12
LESS THAN NO DXTRAN = 45
"INCREASING SAMPLING IN ONE REGION GENERALLY
IS AT THE EXPENSE OF ANOTHER REGION"

Fig. 18. DXTRAN with DXCPN card.

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	12267	12069	14170	1.9999E+00	1.9012E+00	5.8573E+00	1.3269E+00	6.8191E+00
3	3	5437	5058	12296	1.0869E+00	1.1533E+00	4.0162E+00	1.6748E+00	5.9734E+00
4	4	5161	4795	11784	5.8976E-01	8.2627E-01	3.2750E+00	1.9771E+00	5.6004E+00
5	5	4995	4650	11188	2.7224E-01	8.2094E-01	3.0841E+00	2.0808E+00	5.6112E+00
6	6	4531	4188	9948	1.2760E-01	7.8146E-01	2.9328E+00	2.1763E+00	5.5937E+00
7	7	4356	3990	9656	6.1955E-02	7.7673E-01	2.8035E+00	2.2300E+00	5.5322E+00
8	8	4249	3911	9806	3.3255E-02	7.2755E-01	2.5684E+00	2.3299E+00	5.4246E+00
9	9	4262	3953	9630	1.5418E-02	7.5269E-01	2.4927E+00	2.3562E+00	5.4483E+00
10	10	4227	3940	9239	7.1770E-03	7.1804E-01	2.4483E+00	2.3960E+00	5.4227E+00
11	11	4360	4043	9877	3.5594E-03	6.9409E-01	2.4199E+00	2.4038E+00	5.4096E+00
12	12	4523	4166	10278	1.7099E-03	7.1522E-01	2.3994E+00	2.3964E+00	5.4387E+00
13	13	4502	4173	10136	7.7209E-04	7.3122E-01	2.3975E+00	2.3815E+00	5.4710E+00
14	14	4367	4043	10118	3.6972E-04	7.0748E-01	2.2789E+00	2.4366E+00	5.4459E+00
15	15	4254	3951	9909	1.7815E-04	6.2624E-01	2.1304E+00	2.5420E+00	5.3036E+00
16	16	4238	3935	9817	8.2112E-05	5.6490E-01	2.0276E+00	2.6416E+00	5.1548E+00
17	17	4138	3844	9647	3.5603E-05	6.3267E-01	2.0781E+00	2.5646E+00	5.2647E+00
18	18	4038	3769	8985	1.4550E-05	6.8669E-01	2.1483E+00	2.5146E+00	5.3785E+00
19	19	3752	3656	8076	5.7453E-06	7.1626E-01	2.2956E+00	2.4092E+00	5.5517E+00
20	20	4746	17086	0	0.	1.3419E+00	3.3144E+00	7.3638E-01	1.0000+123
21	21	14236	28475	14579	6.1953E-11	1.6976E+00	4.1392E+00	9.5542E-04	7.5010E+02
22	22	1203	1203	0	0.	5.2820E-01	2.0685E+00	5.5808E-05	1.0000+123
TOTAL		107842	128898	199139	4.2009E+00				

≈ SAME AS BEFORE

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	8.28190E-07	.3164	37	1.46477E-13	.3050	40	7.26710E-17	.2824	46
2000	7.03344E-07	.2359	38	1.29340E-13	.2278	40	6.75743E-17	.2308	39
3000	6.14756E-07	.2082	34	1.10453E-13	.1961	39	5.88587E-17	.1959	39
4000	6.85420E-07	.1707	37	1.18986E-13	.1612	42	6.70328E-17	.1642	40
5000	6.68980E-07	.1523	39	1.12148E-13	.1417	45	6.32091E-17	.1454	42
6000	6.26705E-07	.1427	38	1.08285E-13	.1321	44	6.11213E-17	.1363	41
7000	6.31120E-07	.1302	38	1.10299E-13	.1217	44	6.27649E-17	.1267	41
8000	6.48337E-07	.1196	39	1.13456E-13	.1108	46	6.52710E-17	.1185	40
9000	6.79583E-07	.1123	39	1.17471E-13	.1045	45	6.79360E-17	.1102	40
10000	6.78869E-07	.1045	40	1.18658E-13	.0984	45	6.86693E-17	.1028	41
11000	6.65474E-07	.1032	38	1.17063E-13	.0965	43	6.74821E-17	.1001	40
11755	6.53648E-07	.1000	38	1.16162E-13	.0930	44	6.77615E-17	.0964	41

INCREASED FROM 34 WITH POINT DETECTOR
(MORE DIFFERENCE WOULD BE SEEN IN A SCATTERING MEDIUM)

```
****************************************************************************
DUMP NO.  2 ON FILE RUNTPE            NPS =   11755          CTM =    2.60
```

≈ SAME

Fig. 19. Ring detector.

TABLE I. DXCPN Card Entries

Cell	Probability
2	0.001
3	0.001
4	0.001
5	0.001
6	0.01
7	0.01
8	0.01
9	0.01
10	0.01
11	0.01
12	0.015
13	0.02
14	0.04
15	0.08
16	0.2
17	0.4
18	1
19	1
20	VOID, no collisions
21	INSIDE SPHERE, no DXTRAN game played
22	VOID, no collisions

detector can be used instead of a point detector. The ring detector estimates the average flux on a ring rather than the flux at a point, but because the sample problem is symmetric, these tallies (on average) will be the same. The ring detector gives lower variance estimates than the point detector, especially if, unlike the sample problem, the detectors are embedded in a scattering medium. On average, collisions are closer to a ring detector than to a point detector, so the ring detector better samples the close collisions that tend to trounce the point detector statistics. Particularly important in some problems, but not this sample problem, is that the ring detector has finite variance even in a scattering medium. The point detector does not.

For the sample problem, I chose a ring of radius 200 cm about the y-axis such that the ring detector went through the point where the point detector had been. The results are shown in Fig. 19. Note that everything is about the same as with the point detector, except that the ring detector's FOM has increased from 34 (Fig. 18) to 41. More difference would be seen if the detector were in, or close to, cell 21.

XII. BIASING THE SOURCE

No attempt has been made to bias the source although

1. source particles moving downward ($-\hat{y}$) are unimportant because they immediately escape, and
2. high-energy source particles (14 MeV) penetrate better than low-energy source particles (2 MeV) so are more important.

MCNP has two types of source direction bias that will be employed, followed by source energy bias.

A. Cone Bias

Cone biasing, a type of angular biasing, is illustrated in Fig. 20. A cone is specified that divides the angular domain into two pieces, one inside and one outside the cone. The user then specifies the fraction of particles to be started inside the cone and outside the cone. All particles started inside are of one weight; all particles started outside are of another (in the absence of other source biasing, for example, source energy biasing). One consequence of all particles inside the cone having one weight and all particles outside the cone having a different one is that there is weight discontinuity at the cone surface. This weight discontinuity should be considered before using heavy cone biasing. Exponential source biasing, discussed in Sec. XII-B, should be considered if the cone bias weight discontinuity is too large.

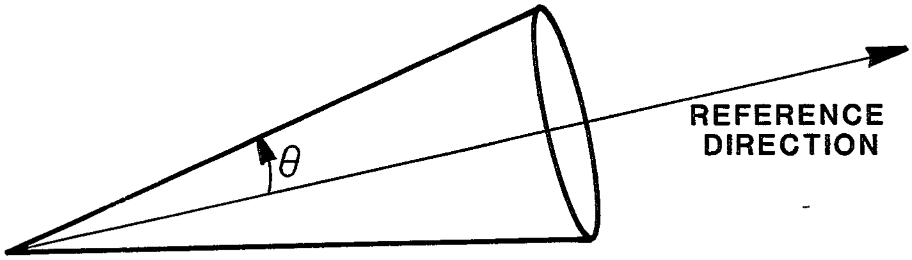
Figure 21 shows the effects of using cone biasing to send 99% of the particles in the $+\hat{y}$ half-space. Note that the FOMs are roughly the same as before cone biasing. Indeed, the only major difference is that the number of particles started has dropped by a factor of 2, as might be expected because almost all of the time is spent following particles moving in the $+\hat{y}$ direction. No improvement occurred because the source sampling is very fast and it does not take long for source particles going in $-\hat{y}$ direction to die. Stated another way, both runs had about 6000 particles sampled in the $+\hat{y}$ direction, so both runs gave roughly the same results. The cone bias saved only a small amount of time *not* sampling the 6000 particles that would have gone in the $-\hat{y}$ direction.

B. Exponential Source Biasing

In addition to the cone bias just discussed, MCNP has a continuous angle bias called exponential source biasing because the sampled density is an exponential in the cosine of the angle with respect to a specified reference direction. That is, the probability density function for exponential source biasing is

$$p(\mu) = Ce^{k\mu} \quad (\mu = \cos\theta),$$

where k = user-selected biasing parameter $0.01 \leq k \leq 3.5$ and C = normalization constant $C = k/(e^{k}-e^{-k})$. Table II shows how the particle weight at some angles varies with k. Note that although the exponential angle biasing has no weight discontinuities, large weight fluctuations can be introduced by setting k too large. For



SPECIFY:

1. $\nu = \cos(\theta)$ FOR FAVORED CONE

2. FRACTION OF PARTICLES STARTED INSIDE CONE

COMMENTS:

1. ALL PARTICLES INSIDE CONE HAVE IDENTICAL WEIGHTS

2. ALL PARTICLES OUTSIDE CONE HAVE IDENTICAL WEIGHTS

Fig. 20. Cone Bias.

example, with $k = 3.5$, the weight ratio between $\theta = 0°$ and $\theta = 180°$ is 1094.

I chose the exponential biasing parameter $k = 2$ on the basis of Table II. Recall that any particle departing the source in the $-\hat{y}$ direction ($\theta > 90°$) will be killed immediately. Thus I confined my attention to the weight variation between $\theta = 0°$ and $\theta = 90°$. For $k = 2$, there is a factor of about 8 fluctuation in weight between $\theta = 0°$ and 90°. Experience indicated that a source particle at $\theta = 0°$ might be eight times as imortant as a source particle at 90°. Maybe 8 was not a particularly good guess, but I would be highly surprised if the "right" ratio were not within a factor of 3.

Figure 22 shows the effects of exponential source biasing. The FOM columns indicate no drastic change and probably a small degradation in calculational efficiency. Thus source angle biasing did not appear effective for the sample problem. However, a conference participant (John Hendricks) suggested that source angle biasing might have worked better with the weight window technique (Sec. XIII) than with the geometry splitting/Russian roulette technique used here. I shall have more to say about Hendricks' suggestion in Sec. XIV.

C. Source Alteration in the Sample Problem

The runs so far have been with an isotropic source with the following energy distribution:

1. 25% of the particles started at 2 MeV.
2. 25% of the particles uniformly distributed between 2 MeV and 14 MeV.
3. 50% of the particles at 14 MeV.

In preparing this report I had intended to use 50% at 2 MeV and 50% at 14 MeV, so source energy biasing could be tried on a simple case. After discovering the input error that arose from using the first energy distribution above rather than the second, I decided that if the source was going to change anyway, a more interesting source could be used instead of the second distribution. All subsequent runs have 95% at 2 MeV and 5% at 14 MeV, making it easy to demonstrate biasing in energy. Note that this spectrum is much softer than the one used before, so tallies will drop and the calculation will therefore be more difficult than before.

The first run with the new source uses all the successful variance reduction techniques (with identical parameters) used for the sample problem with the old source except energy roulette. Specifically, the first run with the new source uses

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	6605	6406	14695	1.9658E+00	2.0739E+00	6.0195E+00	6.6003E-01	6.8857E+00
3	3	5640	5220	12812	1.1148E+00	1.1286E+00	3.9936E+00	8.5805E-01	5.9323E+00
4	4	5330	4934	12290	6.0646E-01	8.2161E-01	3.2831E+00	1.0041E+00	5.5831E+00
5	5	5074	4718	11282	2.6844E-01	7.9748E-01	3.1278E+00	1.0501E+00	5.6114E+00
6	6	4681	4306	10143	1.2446E-01	8.0250E-01	2.9926E+00	1.0843E+00	5.6203E+00
7	7	4464	4090	10110	6.6575E-02	7.3839E-01	2.7183E+00	1.1594E+00	5.4194E+00
8	8	4115	3799	9267	3.0420E-02	7.6131E-01	2.6942E+00	1.1432E+00	5.5398E+00
9	9	4161	3858	9322	1.4746E-02	7.1952E-01	2.5393E+00	1.1895E+00	5.4467E+00
10	10	4302	3985	9585	7.4080E-03	7.0524E-01	2.4389E+00	1.2186E+00	5.4138E+00
11	11	4424	4105	10231	3.5739E-03	6.7007E-01	2.3164E+00	1.2352E+00	5.3339E+00
12	12	4498	4157	10257	1.7292E-03	6.8539E-01	2.2800E+00	1.2411E+00	5.3575E+00
13	13	4683	4329	10229	8.0300E-04	6.7528E-01	2.2984E+00	1.2314E+00	5.4287E+00
14	14	4671	4340	10751	3.8336E-04	6.9439E-01	2.2499E+00	1.2361E+00	5.4183E+00
15	15	4614	4271	10494	1.7918E-04	6.6366E-01	2.1724E+00	1.2611E+00	5.3735E+00
16	16	4721	4384	10802	8.6520E-05	6.0949E-01	2.0604E+00	1.3078E+00	5.2351E+00
17	17	4653	4309	11002	3.9905E-05	6.1264E-01	1.9942E+00	1.3234E+00	5.2048E+00
18	18	4359	4060	9952	1.6436E-05	6.4482E-01	2.0619E+00	1.2907E+00	5.3094E+00
19	19	3916	3823	8868	6.4892E-06	6.8815E-01	2.1795E+00	1.2469E+00	5.4875E+00
20	20	4486	16134	0	0.	1.4905E+00	3.5288E+00	3.9695E-01	1.0000+123
21	21	13367	26736	13672	6.7894E-11	1.5740E+00	3.9432E+00	5.5103E-04	7.2941E+02
22	22	1063	1063	0	0.	7.2051E-01	1.9923E+00	1.8421E-05	1.0000+123
TOTAL		103827	123027	205764	4.2059E+00				

ROUGHLY THE SAME

NPS	TALLY 1 MEAN	TALLY 1 ERROR	TALLY 1 FOM	TALLY 4 MEAN	TALLY 4 ERROR	TALLY 4 FOM	TALLY 5 MEAN	TALLY 5 ERROR	TALLY 5 FOM
1000	9.62664E-07	.2587	28	1.52991E-13	.2256	37	8.70445E-17	.2290	36
2000	8.86500E-07	.1777	33	1.39145E-13	.1591	41	8.47413E-17	.1652	38
3000	7.21686E-07	.1543	32	1.18189E-13	.1358	41	7.33522E-17	.1420	38
4000	6.89222E-07	.1295	34	1.19786E-13	.1124	45	7.30212E-17	.1185	41
5000	6.49018E-07	.1225	31	1.15679E-13	.1031	44	7.00919E-17	.1077	40
6000	6.87974E-07	.1084	32	1.23255E-13	.0924	45	7.42021E-17	.0972	40
6049	6.82401E-07	.1084	32	1.22481E-13	.0922	45	7.37452E-17	.0970	40

```
**************************************************************************
DUMP NO.  2 ON FILE RUNTPF            NPS =   6049          CTM =    2.60
```

AS EXPECTED, ABOUT HALF

CONCLUSION: NO IMROVEMENT BECAUSE DID NOT TAKE LONG FOR SOURCE PARTICLES GOING IN $-\hat{y}$ DIRECTION TO DIE.

Fig. 21. Cone biasing—99% in $+\hat{y}$ half-space.

1. energy cutoff,
2. geometry splitting/Russian roulette (refined parameters),
3. forced collision in cell 21,
4. DXTRAN with DXCPN probabilities, and
5. ring detector.

Figure 23 shows the results of the first run. Note that, as expected, the tallies and FOMs have decreased substantially. The geometry splitting could probably be improved somewhat to keep the "tracks entering" roughly constant.

TABLE II. Exponential Biasing Parameter

k	Cumulative Probability	Theta	Weight
.01	0	0	0.990
	0.25	60	0.995
	0.50	90	1.000
	0.75	120	1.005
	1.00	180	1.010
1	0	0	0.432
	0.25	42	0.552
	0.50	64	0.762
	0.75	93	1.230
	1.00	180	3.195
2	0	0	0.245[a]
	0.25	31	0.325
	0.50	48	0.482
	0.75	70	0.931
	1.00	180	13.40
3.5	0	0	0.143
	0.25	23	0.190
	0.50	37	0.285
	0.75	53	0.569
	1.00	180	156.5

[a]k = 2 was chosen because the weight is approximately 2 at 90°, which is eight times the weight at 0°; this does not seem unreasonable.

Before worrying about optimizing the geometry splitting, I shall discuss the effect of source energy biasing because first, geometry splitting optimization has already been illustrated, and second, the source energy biasing will increase the energy spectrum of the tracks, making the average track penetrate better. Tracks with longer free paths will need less splitting to keep the tracks entering approximately constant. In short, the "tracks entering" column in Fig. 23 can be expected to improve because of source energy biasing.

D. Source Energy Bias

MCNP allows biasing the source in the energy domain as well as in the angular domain. In biasing, the SB card is used with the SI and SP cards. The SI card supplies energy ranges, the SP card supplies analog probabilities, and the SB card supplies the actual probabilities used to sample the energy ranges. Before attempting a long run, look at the source bias information in the MCNP output and check that the weight multiplier is not unreasonable. Figure 24 is an example of the source bias information from the run described next.

Recall that the natural source is 95% at 2 MeV and 5% at 14 MeV. It is a good guess (based on experience) that the 14-MeV source neutrons are much more important than the 2-MeV source neutrons; therefore, I biased the source to get 10% at 2 MeV and 90% at 14 MeV. The "weight multiplier" column in Fig. 24 shows that the ratio of weights is 171; that is, the source energy biasing assumes that 14-MeV neutrons are 171 times as important as 2-MeV neutrons. This seems too high until one considers that 180 cm of concrete must be penetrated. The 14-MeV neutrons can probably penetrate 171 times better. In any case, thousands of neutrons are run, which means that there will be hundreds of 2-MeV source neutrons. Thus the statistics can indicate whether 171 is much too large because 2-MeV source neutrons are not precluded by the source biasing.

Figure 25 shows the results of the source energy biasing. All FOMs increased by a factor of 4 and, as predicted, the "tracks entering" column has improved substantially. Source energy biasing has definitely improved things, but could the same improvement be obtained using the energy splitting and roulette scheme that was successful earlier?

E. Energy Roulette (Without Source Energy Bias) Applied to the Sample Problem

Figure 26 shows the results of removing the source energy bias and inserting the energy roulette game:

> 50% survival crossing 5-MeV, 1-MeV, 0.3-MeV, 0.1-MeV and 0.03-MeV energy bounds.

The FOMs are a factor of 2 better than the reference case (Fig. 23) that had no biasing in the energy domain, but a factor of 2 worse than the source energy biasing. The "tracks entering" column is flat deep into the concrete cylinder but decreasing very fast at the source end. This decrease is probably because the 2-MeV particles fail to survive the energy roulette game. Indeed, a look at the creation and loss ledger (Fig. 27) tends to confirm that energy roulette is killing a lot of tracks. The energy splitting and Russian roulette are the "ENERGY IMPORT" entries.

CELL PROGR	PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	5914	5720	11445	1.9890E+00	2.2985E+00	6.1297E+00	7.7324E-01	6.9710E+00
3	3	5307	4923	11491	1.0608E+00	1.0972E+00	3.9329E+00	8.1038E-01	5.8903E+00
4	4	5111	4763	11787	5.9832E-01	8.5958E-01	3.2519E+00	8.8653E-01	5.5618E+00
5	5	5180	4810	11538	2.7965E-01	7.2047E-01	2.9029E+00	9.1888E-01	5.4167E+00
6	6	5015	4616	11211	1.3685E-01	7.0215E-01	2.7985E+00	9.3529E-01	5.3996E+00
7	7	4695	4312	10524	6.2767E-02	7.2576E-01	2.7575E+00	9.1509E-01	5.4285E+00
8	8	4242	3945	9629	2.9178E-02	7.1694E-01	2.6206E+00	9.2397E-01	5.3921E+00
9	9	4161	3854	9329	1.4144E-02	6.1629E-01	2.4115E+00	9.8567E-01	5.2563E+00
10	10	4285	3955	9734	6.4125E-03	6.9663E-01	2.4682E+00	9.3585E-01	5.3448E+00
11	11	4384	4053	9845	3.0105E-03	6.9835E-01	2.3887E+00	9.2738E-01	5.3195E+00
12	12	4273	3992	9556	1.3470E-03	6.7214E-01	2.3123E+00	9.2956E-01	5.2919E+00
13	13	4117	3814	8807	5.9640E-04	6.1880E-01	2.3277E+00	9.3717E-01	5.2995E+00
14	14	4147	3828	9325	2.7289E-04	7.4179E-01	2.4115E+00	8.9202E-01	5.4420E+00
15	15	4261	3980	9609	1.3223E-04	7.3805E-01	2.3203E+00	8.9575E-01	5.3573E+00
16	16	4505	4207	9857	5.8674E-05	7.5736E-01	2.4096E+00	8.7379E-01	5.5164E+00
17	17	4715	4376	10409	2.7660E-05	7.9721E-01	2.4079E+00	8.5441E-01	5.5688E+00
18	18	4973	4612	11199	1.4528E-05	7.1284E-01	2.2599E+00	9.0298E-01	5.4450E+00
19	19	4813	4667	10456	5.8531E-06	7.3157E-01	2.3271E+00	8.8620E-01	5.5518E+00
20	20	5247	17752	0	0.	1.6527E+00	3.7587E+00	3.1599E-01	1.0000+123
21	21	14447	28900	14780	5.7952E-11	1.7306E+00	4.2168E+00	3.9238E-04	7.2168E+02
22	22	1218	1218	0	0.	2.9313E-01	1.3919E+00	2.3560E-05	1.0000+123
TOTAL		105010	126297	200531	4.1826E+00				

NOTE: HAS DECREASED

IF ANYTHING, THE RESULTS ARE WORSE

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	6.76998E-07	.2279	35	1.08405E-13	.2017	45	6.41533E-17	.2303	34
2000	7.76445E-07	.1899	26	1.17538E-13	.1684	33	7.32270E-17	.1813	29
3000	6.57440E-07	.1608	27	1.01848E-13	.1424	34	6.21477E-17	.1533	29
4000	6.44592E-07	.1331	30	9.99931E-14	.1212	36	6.17369E-17	.1294	31
5000	6.53824E-07	.1144	32	1.02744E-13	.1045	38	6.25061E-17	.1115	33
5404	6.78768E-07	.1073	33	1.05245E-13	.0984	39	6.43094E-17	.1042	35
			38 = NO BIAS			44 = NO BIAS			41 = NO BIAS

```
*************************************************************************************
DUMP NO.   2 ON FILE RUNTPG            NPS =     5404          CTM =     2.59
```

Fig. 22. Exponential source biasing, K = 2.0.

95% AT 2 MeV 5% AT 14 MeV

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	36626	35147	84028	2.5392E+00	8.1404E-01	1.6748E+00	1.0000E+00	5.0804E+00
3	3	20612	17717	89215	1.2254E+00	4.1376E-01	1.0791E+00	1.0000E+00	4.1250E+00
4	4	16863	14731	71948	4.7060E-01	3.3049E-01	9.6776E-01	1.0000E+00	3.8814E+00
5	5	12689	11113	52606	1.5640E-01	3.1602E-01	1.0160E+00	1.0000E+00	3.8749E+00
6	6	8232	7213	33982	5.0516E-02	3.1378E-01	1.1137E+00	1.0000E+00	3.9250E+00
7	7	5345	4665	22071	1.6405E-02	3.3660E-01	1.2637E+00	1.0000E+00	4.0813E+00
8	8	3499	3078	13604	5.0558E-03	3.8861E-01	1.5567E+00	1.0000E+00	4.3308E+00
9	9	2704	2388	10299	1.7802E-03	4.6442E-01	1.8798E+00	1.0000E+00	4.6472E+00
10	10	2126	1870	7936	6.3804E-04	5.6864E-01	2.1439E+00	1.0000E+00	5.0175E+00
11	11	1940	1687	7020	2.6251E-04	6.4275E-01	2.3902E+00	1.0000E+00	5.3084E+00
12	12	1847	1603	6787	1.1804E-04	6.8158E-01	2.4418E+00	1.0000E+00	5.4103E+00
13	13	1935	1649	6835	5.5293E-05	6.8520E-01	2.4479E+00	1.0000E+00	5.4328E+00
14	14	1921	1651	6909	2.5996E-05	6.7867E-01	2.3340E+00	1.0000E+00	5.3967E+00
15	15	1864	1622	6958	1.2177E-05	6.7540E-01	2.3111E+00	1.0000E+00	5.3200E+00
16	16	1827	1610	6515	5.1826E-06	6.8789E-01	2.3831E+00	1.0000E+00	5.4192E+00
17	17	1752	1542	6225	2.2509E-06	6.9864E-01	2.3035E+00	1.0000E+00	5.3890E+00
18	18	1719	1508	6112	1.0044E-06	6.4792E-01	2.2378E+00	9.9959E-01	5.3291E+00
19	19	1460	1379	5244	3.9020E-07	7.2496E-01	2.3171E+00	9.9710E-01	5.5252E+00
20	20	2987	10250	0	0.	1.5228E+00	3.7671E+00	2.1540E-01	1.0000+123
21	21	9646	19293	9982	4.0126E-12	1.9111E+00	4.6916E+00	2.4317E-04	7.4538E+02
22	22	962	962	0	0.	4.8276E-01	1.7833E+00	7.7522E-06	1.0000+123
TOTAL		138556	142678	454276	4.4665E+00				

MIGHT HELP TO INCREASE SPLITTING

INFLUENCE OF FORCED COLLISION

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
2000	4.20276E-08	.7812	5	6.75611E-15	.8612	4	3.79689E-18	.8929	4
4000	3.33748E-08	.6050	4	5.80450E-15	.6311	4	3.40807E-18	.6406	4
6000	2.47221E-08	.5491	4	4.27827E-15	.5756	3	2.58330E-18	.5725	3
8000	2.00867E-08	.5094	3	3.69877E-15	.5063	3	2.36517E-18	.4839	4
10000	2.07666E-08	.4301	4	4.19567E-15	.4050	4	2.51507E-18	.4027	4
12000	3.52290E-08	.3672	4	6.77026E-15	.3363	5	4.08518E-18	.3521	4
14000	4.67954E-08	.3164	4	8.74776E-15	.3154	4	5.06476E-18	.3118	5
16000	4.68175E-08	.2868	5	8.55125E-15	.2883	5	4.90277E-18	.2871	5
18000	4.54612E-08	.2694	5	8.38284E-15	.2704	5	4.81680E-18	.2686	5
20000	4.25220E-08	.2607	5	7.73913E-15	.2640	4	4.46717E-18	.2614	5
22000	4.95566E-08	.2771	4	8.53243E-15	.2606	4	4.88221E-18	.2581	4
24000	4.84141E-08	.2672	4	8.39374E-15	.2522	4	4.76392E-18	.2499	4
26000	4.54506E-08	.2633	3	7.89398E-15	.2483	4	4.49672E-18	.2454	4
28000	4.49413E-08	.2505	4	7.80158E-15	.2366	4	4.45104E-18	.2334	4
30000	4.68896E-08	.2341	4	8.07256E-15	.2230	4	4.62160E-18	.2201	4
32000	4.39590E-08	.2342	4	7.56834E-15	.2230	4	4.33278E-18	.2201	4
33092	4.43014E-08	.2265	4	7.57040E-15	.2166	4	4.34913E-18	.2134	4

****
DUMP NO. 2 ON FILE RUNTPE NPS = 33092 CTM = 4.60

Fig. 23. New source (angle bias and energy roulette removed).

```
SOURCE = 1

SOURCE COEFFICIENTS

        1      0.
        2      1.0000E-06
        3      0.
        4      2.0000E+00
        5      1.0000E+00
```

SI card SP card SB card

BIASED SOURCE DISTRIBUTION 0

SOURCE ENTRY	SOURCE VALUE	CUMULATIVE PROBABILITY	BIASED CUMULATIVE	PROBABILITY DENSITY	BIASED PROBABILITY	WEIGHT MULTIPLIER
1	2.00000E+00	9.500000E-01	1.000000E-01	9.500000E-01	1.000000E-01	9.500000E+00
2	1.40000E+01	1.000000E+00	1.000000E+00	5.000000E-02	9.000000E-01	5.555556E-02

AVERAGE VALUE USING BIN MIDPOINTS = 2.6000E+00

Fig. 24. SI, SP, and SB cards in source energy bias.

NATURAL 95% 2MeV / 5% 14MeV —BIASED→ 10% 2MeV / 90% 14 MeV

IMPROVED TRACKS ENTERING

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	6972	6719	11236	2.4159E+00	8.4842E-01	1.7006E+00	9.9753E-01	5.1519E+00
3	3	4563	3961	15126	1.1709E+00	4.3988E-01	1.1247E+00	7.8609E-01	4.1335E+00
4	4	5203	4515	18181	4.4346E-01	3.5671E-01	1.0511E+00	5.3181E-01	3.9318E+00
5	5	5812	5042	20223	1.4352E-01	3.7649E-01	1.1059E+00	3.5288E-01	3.9570E+00
6	6	5698	4915	20329	4.1596E-02	3.5477E-01	1.2067E+00	2.1776E-01	4.0420E+00
7	7	5384	4627	19703	1.3995E-02	4.1701E-01	1.4003E+00	1.5920E-01	4.2950E+00
8	8	5329	4595	18889	6.3198E-03	3.6196E-01	1.3787E+00	1.3716E-01	4.1704E+00
9	9	5420	4702	19148	1.8645E-03	4.0415E-01	1.7327E+00	9.2617E-02	4.5694E+00
10	10	5645	4879	20119	7.4253E-04	4.6754E-01	1.9855E+00	7.6064E-02	4.8298E+00
11	11	5920	5134	21337	3.0860E-04	5.6113E-01	2.1422E+00	6.7175E-02	4.9740E+00
12	12	6078	5264	21968	1.1915E-04	6.4761E-01	2.3362E+00	5.7361E-02	5.3143E+00
13	13	6288	5463	22861	5.3917E-05	6.6897E-01	2.3569E+00	5.5556E-02	5.3960E+00
14	14	6174	5435	22266	2.4425E-05	6.8243E-01	2.3400E+00	5.5556E-02	5.4191E+00
15	15	6340	5532	23227	1.1851E-05	6.8723E-01	2.2842E+00	5.5556E-02	5.4051E+00
16	16	6683	5821	24654	5.7176E-06	6.6909E-01	2.2022E+00	5.5556E-02	5.3389E+00
17	17	6938	6049	25412	2.6788E-06	6.4062E-01	2.1177E+00	5.5556E-02	5.2728E+00
18	18	6635	5848	24702	1.1836E-06	6.4581E-01	2.0951E+00	5.5556E-02	5.3000E+00
19	19	5798	5450	20798	4.5270E-07	6.9464E-01	2.2024E+00	5.5530E-02	5.4584E+00
20	20	7473	22973	0	0.	1.2085E+00	3.2355E+00	2.0560E-02	1.0000+123
21	21	20687	41375	21355	4.6036E-12	1.7734E+00	4.2512E+00	2.4781E-05	7.5623E+02
22	22	1928	1928	0	0.	6.3728E-01	2.0664E+00	9.6952E-07	1.0000+123
TOTAL		136968	160227	391534	4.2388E+00				

	TALLY 1			TALLY 4			TALLY 5		
NPS	MEAN	ERROR	FOM	MEAN	ERROR	FOM	MEAN	ERROR	FOM
1000	3.85940E-08	.2906	17	6.20273E-15	.2767	19	3.79043E-18	.2697	20
2000	4.75214E-08	.2030	17	8.09356E-15	.2009	17	4.94164E-18	.1957	18
3000	4.14782E-08	.1799	15	8.04785E-15	.1792	15	4.51650E-18	.1745	16
4000	4.48775E-08	.1479	16	8.08531E-15	.1480	16	4.74614E-18	.1428	17
5000	4.48569E-08	.1303	16	8.12581E-15	.1303	17	4.74559E-18	.1258	18
6000	4.81852E-08	.1195	16	8.53562E-15	.1169	16	5.06492E-18	.1139	17
6306	4.90487E-08	.1149	16	8.60624E-15	.1126	17	5.10226E-18	.1099	17
			4 NO E BIAS			4 NO ENERGY BIAS			4 NO E BIAS

****

DUMP NO. 2 ON FILE RUNTPF NPS = 6306 CTM = 4.63

CONCLUSION: SOURCE ENERGY BIAS HERE QUITE USEFUL

WEIGHT (2MeV) = 9.5

WEIGHT (14 MeV) = 5.556E − 2

COMPARE TO ENERGY ROULETTE ON NEXT RUN

Fig. 25. Energy bias on source.

50% SURVIVAL AS CROSS ENERGY BOUNDS 5 1 0.3 0.1 0.03

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	70107	68555	111894	2.6091E+00	7.8547E-01	1.6404E+00	1.3098E+00	5.0400E+00
3	3	28187	25777	86177	1.2351E+00	4.2534E-01	1.0934E+00	1.7163E+00	4.1322E+00
4	4	19828	18176	60187	4.6799E-01	3.3841E-01	9.9897E-01	1.9583E+00	3.9106E+00
5	5	13820	12737	41740	1.6086E-01	3.1246E-01	1.0617E+00	2.1207E+00	3.9001E+00
6	6	8586	7917	25110	5.0656E-02	3.4457E-01	1.2451E+00	2.1743E+00	4.0577E+00
7	7	5552	5098	15603	1.6388E-02	3.9613E-01	1.4552E+00	2.2459E+00	4.2423E+00
8	8	3870	3551	10631	5.4346E-03	4.8289E-01	1.7392E+00	2.2241E+00	4.5756E+00
9	9	3051	2810	7946	2.3048E-03	4.1794E-01	1.7727E+00	2.5434E+00	4.5869E+00
10	10	2479	2288	6335	8.1435E-04	5.6787E-01	2.1160E+00	2.3964E+00	5.0126E+00
11	11	2262	2091	5371	3.4185E-04	5.9145E-01	2.2002E+00	2.4426E+00	5.1905E+00
12	12	2137	1991	4679	1.3379E-04	7.2614E-01	2.3382E+00	2.3497E+00	5.4811E+00
13	13	2065	1909	4585	5.8148E-05	7.7816E-01	2.3630E+00	2.3155E+00	5.5358E+00
14	14	1941	1806	4342	2.8205E-05	6.1960E-01	2.1829E+00	2.5192E+00	5.2813E+00
15	15	1864	1729	4389	1.3275E-05	6.9134E-01	2.0983E+00	2.5261E+00	5.3021E+00
16	16	1879	1746	4490	6.8583E-06	6.1553E-01	1.9085E+00	2.7108E+00	5.1032E+00
17	17	1844	1702	4486	2.8800E-06	6.6752E-01	1.9462E+00	2.6280E+00	5.2474E+00
18	18	1870	1706	4409	1.4005E-06	6.0413E-01	1.9480E+00	2.7121E+00	5.1846E+00
19	19	1736	1690	3923	5.0556E-07	7.2824E-01	2.1497E+00	2.5339E+00	5.4375E+00
20	20	2709	10111	0	0.	9.3521E-01	2.7747E+00	7.2627E-01	1.0000+123
21	21	8535	17070	8755	5.4317E-12	1.7017E+00	4.0791E+00	7.6034E-04	7.3132E+02
22	22	747	747	0	0.	1.2796E+00	2.0507E+00	2.5020E-05	1.0000+123
TOTAL		185069	191207	415052	4.5493E+00				

LOST TO E ROULETTE PROBABLY

CHECK CREATION AND LOSS PAGE

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
4000	5.62428E-08	.5925	9	1.10868E-14	.5061	12	6.85957E-18	.5109	12
8000	6.21143E-08	.4683	7	1.39254E-14	.3725	12	8.49671E-18	.3930	10
12000	6.83978E-08	.3618	8	1.28214E-14	.3109	11	7.50953E-18	.3265	10
16000	5.96421E-08	.3216	8	1.14008E-14	.2748	11	6.49283E-18	.2912	10
20000	6.51427E-08	.2646	9	1.22680E-14	.2305	13	7.27391E-18	.2412	11
24000	6.64407E-08	.2498	9	1.21877E-14	.2257	11	7.24270E-18	.2323	10
28000	6.93985E-08	.2315	9	1.17701E-14	.2106	11	6.89511E-18	.2172	10
32000	6.48955E-08	.2195	9	1.08231E-14	.2021	10	6.29969E-18	.2092	10
36000	6.16679E-08	.2091	9	1.04173E-14	.1921	10	5.95547E-18	.1998	9
40000	6.56990E-08	.1862	10	1.07598E-14	.1740	11	6.19549E-18	.1798	10
44000	6.09625E-08	.1830	9	1.00179E-14	.1705	11	5.75220E-18	.1764	10
48000	6.10327E-08	.1752	9	9.84176E-15	.1628	11	5.63330E-18	.1686	10
52000	6.00462E-08	.1675	9	9.56935E-15	.1566	11	5.51862E-18	.1624	10
56000	6.18936E-08	.1604	10	9.46712E-15	.1501	11	5.42811E-18	.1558	10
60000	6.67085E-08	.1566	9	1.02460E-14	.1452	11	6.18120E-18	.1536	10
64000	6.34663E-08	.1550	9	9.75654E-15	.1435	10	5.89703E-18	.1517	9
66475	6.21818E-08	.1529	9	9.79947E-15	.1405	10	5.93803E-18	.1482	9

16 ← ENERGY SOURCE BIAS **17 ← ENERGY BIAS** **ENERGY BIAS → 17**

```
*****************************************************************************************
DUMP NO.  2 ON FILE RUNTPG          NPS =   66475          CTM =   4.61
```

10 TIMES AS MANY PARTICLES STARTED AS WITH ENERGY SOURCE BIASING

Fig. 26. No energy source bias; energy roulette used.

RUN TERMINATED 19 SECONDS BEFORE JOB TIME LIMIT.

SAMPLE PROBLEM FOR MFE TALKS S 09/19/83 11:13:02

NO PARTICLES UPSCATTERED LEDGER OF NET NEUTRON CREATION AND LOSS (FOR ACCOUNTING ONLY)

LARGE NUMBER LOST TO ENERGY ROULETTE

	TRACKS	WEIGHT (PER SOURCE	ENERGY PARTICLE)
SOURCE	66475	1.0000E+00	2.5991E+00
SCATTERING	0	0.	0.
FISSION	0	0.	0.
(N,XN)	67	3.6737E-04	9.1998E-04
FORCED COLLISION	8535	0.	0.
WEIGHT CUTOFF	0	0.	0.
WEIGHT WINDOW	0	0.	0.
CELL IMPORTANCE	49918	1.1656E-01	1.0066E-01
ENERGY IMPORT.	0	4.6479E-01	1.5012E-01
DXTRAN	9343	3.0923E-10	1.2561E-09
EXP. TRANSFORM	0	0.	0.
TOTAL	134338	1.5817E+00	2.8508E+00

	TRACKS	WEIGHT (PER SOURCE	ENERGY PARTICLE)
ESCAPE	62929	7.6327E-01	1.6367E+00
SCATTERING	0	0.	8.6664E-01
CAPTURE	2514	8.6574E-03	9.5842E-02
ENERGY CUTOFF	5590	2.3566E-01	1.2582E-03
TIME CUTOFF	0	0.	0.
WEIGHT CUTOFF	0	0.	0.
WEIGHT WINDOW	0	0.	0.
CELL IMPORTANCE	14468	1.1712E-01	1.0112E-01
ENERGY IMPORT.	48832	4.5701E-01	1.4924E-01
DXTRAN	5	7.8099E-10	8.0133E-10
EXP. TRANSFORM	0	0.	0.
DEAD FISSION	0	0.	0.
TOTAL	134338	1.5817E+00	2.8508E+00

PREDICTED AVG OF SRC FUNCTION ZERO		2.6000E+00
TRACKS PER NEUTRON STARTED		2.0209E+00
COLLISIONS PER NEUTRON STARTED		6.2437E+00
TOTAL COLLISIONS		415052
NET MULTIPLICATION	1.0004E+00	.0001

AVERAGE LIFETIME, SHAKES	
ESCAPE	5.2613E-01
CAPTURE	6.7963E-01
CAPTURE OR ESCAPE	5.2785E-01
ANY TERMINATION	2.5120E+00

CUTOFFS	
TCO	1.0000+123
ECO	1.0000E-02
WC1	0.
WC2	0.

COMPUTER TIME SO FAR IN THIS RUN	4.66 MINUTES
COMPUTER TIME IN MCRUN (4CO)	4.61 MINUTES
SOURCE PARTICLES PER MINUTE	1.4420E+04
FIELD LENGTH	371584 = 1325600B
RANDOM NUMBERS GENERATED	4653934
LAST STARTING RANDOM NUMBER	33054041550251218
NEXT STARTING RANDOM NUMBER	7246405510430155B

TOTAL NEUTRONS BANKED	61820
PER SOURCE PARTICLE	9.2997E-01
TOTAL PHOTONS BANKED	0
PER SOURCE PARTICLE	0.
MAXIMUM NUMBER EVER IN BANK	44
BANK OVERFLOWS TO DISK	0

Fig. 27. Creation and loss ledger—energy roulette, no source biasing.

F. Source Energy Biasing and Energy Roulette Applied to the Sample Problem

Both source energy biasing and energy roulette individually improved the FOMs. The natural temptation at this point is to try both techniques and hope for improvement. Before trying both techniques, a suspicious person might wonder whether *two* energy biasing techniques would be too much of a good thing. Would the calculation be overbiased? Fortunately, for reasons explained below, the techniques work well together.

Figure 28 gives the results of using both source energy biasing and energy roulette. First, note that the "tracks entering" column looks very nice. Second, note that the FOMs are

1. a factor of 4 better than energy roulette alone,
2. a factor of 2 better than source energy bias alone, and
3. a factor of 8 better than with neither energy roulette nor source energy bias.

Hindsight, aided by elementary arithmetic ($4 \cdot 2 = 8$) indicates that the two techniques operate essentially independently. Although both are energy biasing, they are biasing different things. Source energy biasing is applied only at the source and supplies the right initial spectrum; thereafter it does nothing to keep the right spectrum after collisions. In contrast, the energy roulette technique does nothing to alter the effects of the initial spectrum. That is, if N_1 14-MeV source tracks produce a track distribution $n_1(\vec{r}, \vec{v}, t)$, biasing the source to instead produce N_2 14-MeV source tracks will produce a track distribution $n_2(\vec{r}, \vec{v}, t) = (N_2/N_1)n_1(\vec{r}, \vec{v}, t)$. The energy roulette game takes no account of the source energy biasing. Synergism can be viewed as follows: the source energy bias produces good initial track distribution on which the energy roulette works to produce a good subsequent track distribution. However, if the initial track distribution is not good, the subsequent track distribution cannot be good because the energy roulette game is independent of the initial track distribution and therefore cannot "correct" it. Energy splitting/Russian roulette thus contrasts with the next energy-biasing technique considered, the space-energy-dependent weight window. The weight window, if set properly, will correct poor track distributions and if set poorly, will destroy good track distributions.

XIII. THE WEIGHT WINDOW TECHNIQUE

The weight window (Fig. 29) is a space-energy-dependent splitting and Russian roulette technique. For each space-energy phase-space cell, the user supplies a lower weight bound and an upper weight bound. These weight bounds define a window of acceptable weights. If a particle is below the lower weight bound, Russian roulette is played and the particle's weight is either increased to be within the window, or the particle is terminated. If a particle is above the upper weight bound, the particle is split so that all the split particles are within the window. No action is taken for particles within the window.

Figure 30 is a more detailed picture of the weight window. Three important weights define the weight window in a space-energy cell,

1. W_L, the lower weight bound,
2. W_S, the survival weight for particles playing roulette, and
3. W_U, the upper weight bound.

The user specifies (WFN cards) W_L for each space-energy cell, and W_S and W_U are calculated using two problem-wide constants, C_S and C_U (WDWN card), as $W_S = C_S W_L$ and $W_U = C_U W_L$. Thus all cells have an upper weight bound C_U times the lower weight bound and a survival weight C_S times the lower weight bound.

A. Weight Window Compared to Geometry Splitting

Although both weight window and geometry splitting employ splitting and Russian roulette, there are some important differences:

1. the weight window is space-energy dependent, whereas geometry splitting is only space dependent;
2. the weight window discriminates on particle weight before deciding appropriate action, whereas geometry splitting is done regardless of particle weight;
3. the weight window works with absolute weight bounds, whereas geometry splitting is done on the *ratio* of the importances across a surface;
4. the weight window can be applied at surfaces, collision sites, or both, whereas geometry splitting is applied only at surfaces; and
5. the weight window can control weight fluctuations introduced by other biasing techniques by requiring all particles in a cell to have weight $W_L < W < W_U$, whereas the geometry splitting will preserve any weight fluctuations because it is weight independent.

B. Special Weight Window Features Described in MCNP Manual[1]

1. There is a maximum split/roulette feature that limits the amount of splitting/rouletting that can occur at any particular weight window game.
2. The window is always adjusted to be at least a factor of 2 wide, that is $W_U/W_L \geq 2$.
3. A spatial weight window (only one energy range) may be specified inversely proportional to

CELL PROGR	PROBL		TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2		17683	17421	18401	2.9228E+00	6.5198E-01	1.5652E+00	1.4126E+00	4.9220E+00
3	3		8189	7706	16529	1.2165E+00	4.0135E-01	1.1114E+00	1.3999E+00	4.1031E+00
4	4		8169	7614	16990	4.9640E-01	3.0337E-01	9.8723E-01	1.1273E+00	3.8762E+00
5	5		8536	7961	18531	1.4888E-01	3.0433E-01	1.1073E+00	7.2806E-01	3.9825E+00
6	6		7933	7319	16656	3.6534E-02	4.6654E-01	1.3970E+00	4.2323E-01	4.2507E+00
7	7		7628	7053	16376	1.3413E-02	3.0623E-01	1.4438E+00	3.3037E-01	4.2524E+00
8	8		7469	6918	16581	5.5635E-03	2.5863E-01	1.5428E+00	2.7380E-01	4.3058E+00
9	9		7545	7028	16253	1.2710E-03	7.7427E-01	2.3836E+00	1.6293E-01	5.2930E+00
10	10		7743	7203	16785	5.7509E-04	7.5529E-01	2.5027E+00	1.4951E-01	5.4140E+00
11	11	**NICE**	8053	7458	17529	2.8978E-04	7.9740E-01	2.3184E+00	1.5977E-01	5.3391E+00
12	12		8444	7789	18993	1.5350E-04	6.1156E-01	2.0427E+00	1.7034E-01	5.0493E+00
13	13		8326	7719	19073	9.0588E-05	3.9260E-01	1.6872E+00	2.0404E-01	4.6376E+00
14	14		8054	7500	18292	4.1931E-05	3.6699E-01	1.7155E+00	1.8709E-01	4.6382E+00
15	15		7951	7353	18213	1.2188E-05	6.9409E-01	2.2246E+00	1.4018E-01	5.3930E+00
16	16		7914	7356	18333	5.5212E-06	6.9344E-01	2.1793E+00	1.4163E-01	5.3620E+00
17	17		8124	7558	18452	2.7658E-06	6.3633E-01	2.0456E+00	1.5086E-01	5.2695E+00
18	18		7959	7429	18246	1.1762E-06	6.6921E-01	2.0945E+00	1.4122E-01	5.3503E+00
19	19		7487	7257	16836	4.7207E-07	6.8370E-01	2.1757E+00	1.3770E-01	5.4548E+00
20	20		9186	33133	0	0.	1.1969E+00	3.2996E+00	4.3458E-02	1.0000+123
21	21		27603	55209	28270	4.7499E-12	1.7495E+00	4.1883E+00	5.3933E-05	7.4440E+02
22	22		2344	2344	0	0.	8.8156E-01	2.4404E+00	2.0311E-06	1.0000+123
TOTAL			192340	234328	345339	4.8425E+00				

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
1000	6.75738E-08	.3135	33	1.02821E-14	.2841	40	6.11613E-18	.2781	42
2000	5.30839E-08	.2317	35	8.19119E-15	.2050	45	4.78299E-18	.2057	44
3000	4.74756E-08	.1977	33	7.70589E-15	.1733	43	4.64642E-18	.1780	41
4000	4.16499E-08	.1768	32	7.08741E-15	.1546	42	4.18273E-18	.1585	40
5000	4.18353E-08	.1530	35	7.13209E-15	.1344	45	4.18036E-18	.1392	42
6000	4.47058E-08	.1361	35	7.84299E-15	.1191	46	4.48464E-18	.1231	43
7000	4.90518E-08	.1218	36	8.58856E-15	.1082	46	4.92879E-18	.1119	43
8000	5.06288E-08	.1114	36	8.89479E-15	.0982	47	5.13099E-18	.1017	44
9000	5.26031E-08	.1032	37	9.16675E-15	.0917	47	5.26253E-18	.0950	43
10000	5.16829E-08	.0979	37	9.00032E-15	.0867	47	5.15435E-18	.0898	44
11000	5.17916E-08	.0947	36	8.90241E-15	.0834	46	5.13525E-18	.0867	43
12000	5.27634E-08	.0917	35	9.07606E-15	.0810	45	5.35139E-18	.0850	40
13000	5.40505E-08	.0874	35	9.17604E-15	.0774	45	5.40450E-18	.0809	41
14000	5.17889E-08	.0861	35	8.78389E-15	.0762	44	5.17840E-18	.0799	40
15000	5.19164E-08	.0831	34	8.94873E-15	.0739	44	5.28099E-18	.0779	39
16000	5.12984E-08	.0805	35	8.78145E-15	.0721	43	5.20501E-18	.0758	39
16957	5.04281E-08	.0803	33	8.81392E-15	.0759	37	5.14446E-18	.0755	38
			16	**SOURCE ENERGY BIASING WITH**		**17**	**NO ENERGY ROULETTE**		**17**

****

DUMP NO. 2 ON FILE RUNTPH NPS = 16957 CTM = 4.61

COMPARE WITH 6306 FOR SOURCE BIASING IN ENERGY WITHOUT ENERGY ROULETTE

CONCLUSION – GOOD IDEA TO USE BOTH

Fig. 28. Source biasing and energy roulette.

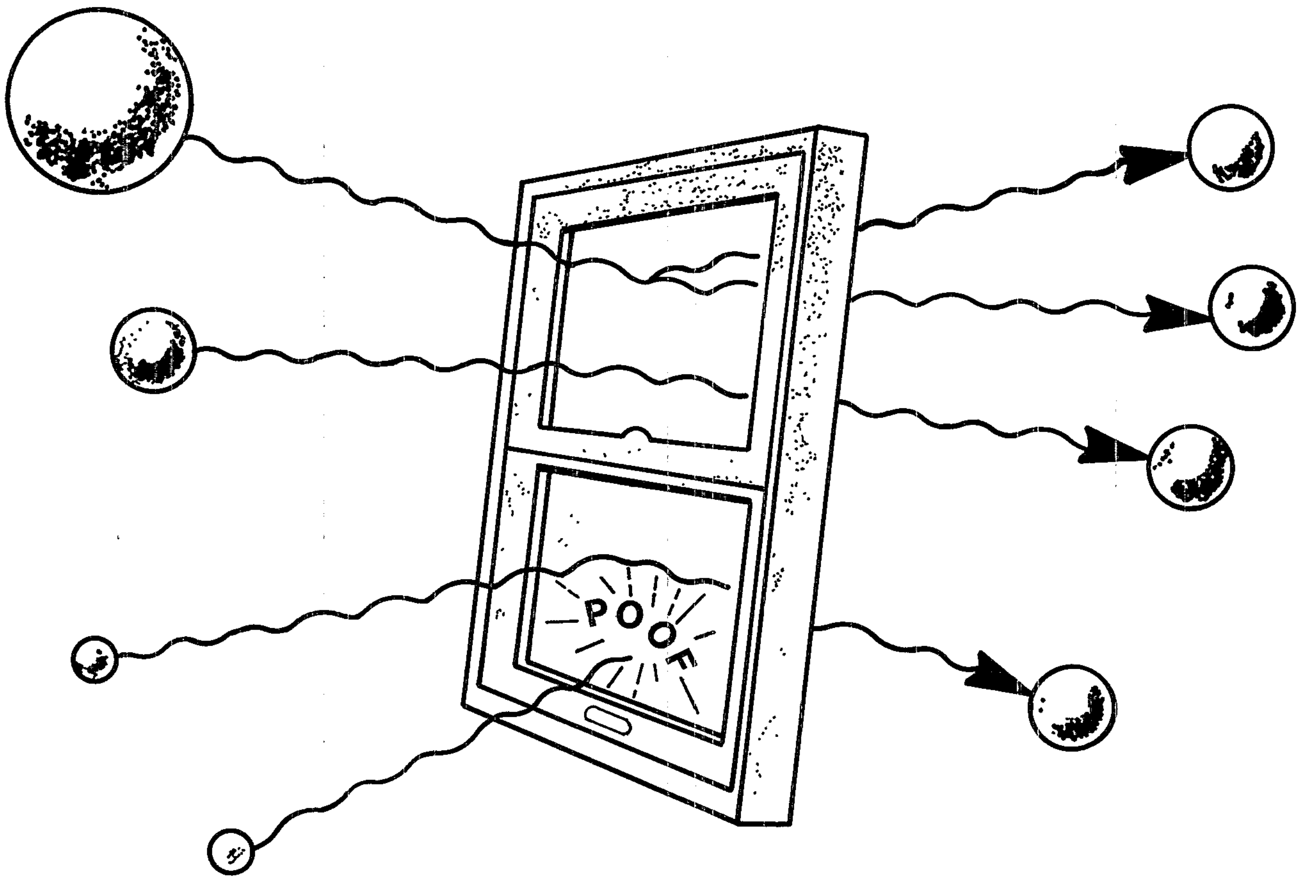


Fig. 29. The weight window. Tracks entering a phase-space cell with weight above the window's upper bound are split into several tracks within the window. Those with weights below the window play Russian Roulette. Therefore, particles passing through the window have weights within the window bounds.

previously optimized cell importances from the geometry-splitting technique.

C. Specifying the Weight Windows for the Sample Problem

The weight window parameters should be such that the weight windows are inversely proportional to the space-energy importance. Thus one must either guess what the importance function looks like or use information from experience. The geometry-splitting optimization has already provided a spatial importance function that can be used (see item 3 in Sec. XIII.B) to obtain a space-only weight window. If the cell importances were not available, one could either pick window parameters that flattened the track distribution (in the same iterative procedure used for geometry splitting) or one could use the weight window generator described later.

The weight windows are chosen according to available cell importances (except for cells 20-22).

$W_L = 0.5/\text{cell importances}$	lower weight bound
$W_S = 3.0 \cdot W_L$	survival weight
$W_U = 5.0 \cdot W_L$	upper weight bound

Furthermore (see item 1 in Sec. XIII.B), no particle (in any given game) will be split more than five for one, nor rouletted harsher than one in five. The weight window game was turned off in cells 20-22 because that part of the problem is too angle dependent for the weight window to be effective. The weight window was applied both at collisions and surface crossings.

D. Spatial Weight Window Results

The source energy bias and energy roulette were removed for this run. The following techniques were used:

1. energy cutoff,
2. forced collision in cell 21,
3. DXTRAN with DXCPN probabilities,

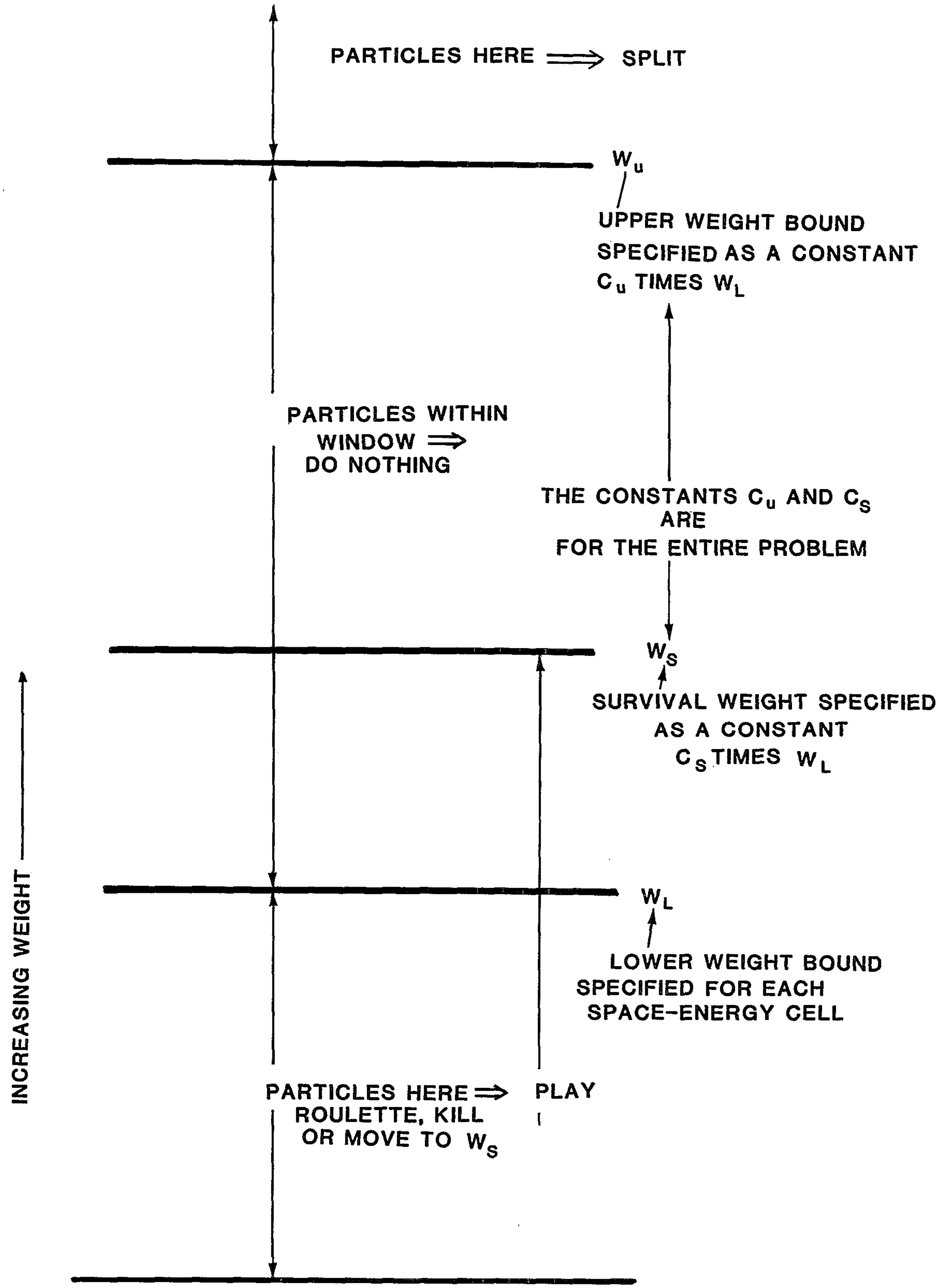


Fig. 30. Detail of the weight window.

LOWER BOUND = 0.5 / CELL IMPORTANCE WDWN 5 3 5

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	52284	47147	122223	2.5784E+00	8.0176E-01	1.6607E+00	9.9061E-01	5.0620E+00
3	3	15527	10937	65628	1.2195E+00	4.1592E-01	1.0881E+00	8.8647E-01	4.1249E+00
4	4	9275	9759	55801	4.8096E-01	3.3695E-01	9.6786E-01	4.1114E-01	3.9027E+00
5	5	6744	9174	50117	1.6131E-01	3.1896E-01	1.0225E+00	1.5173E-01	3.9083E+00
6	6	5230	5994	32120	5.1613E-02	3.2700E-01	1.1480E+00	7.5598E-02	4.0113E+00
7	7	3561	4108	21736	1.7265E-02	3.4312E-01	1.2971E+00	3.7451E-02	4.1350E+00
8	8	2478	2807	14601	5.7387E-03	4.1889E-01	1.5625E+00	1.8594E-02	4.4885E+00
9	9	1833	2096	10746	2.1335E-03	4.7275E-01	1.7415E+00	9.3591E-03	4.6580E+00
10	10	1441	1596	8478	8.1523E-04	5.4895E-01	2.0562E+00	4.5771E-03	5.0049E+00
11	11	1362	1446	7522	3.4185E-04	5.6917E-01	2.0650E+00	2.1716E-03	5.1335E+00
12	12	1233	1258	6771	1.5712E-04	6.1261E-01	2.1111E+00	1.1042E-03	5.2412E+00
13	13	1183	1250	6324	6.8100E-05	6.2743E-01	2.0964E+00	5.2149E-04	5.2389E+00
14	14	1033	1347	6934	2.8037E-05	5.8460E-01	2.0346E+00	1.9258E-04	5.1695E+00
15	15	1095	1218	5960	1.1938E-05	6.4650E-01	2.1922E+00	9.5655E-05	5.3455E+00
16	16	1046	1161	5564	5.3848E-06	6.7465E-01	2.1985E+00	4.6191E-05	5.3729E+00
17	17	1005	1060	5159	2.4907E-06	6.9146E-01	2.2742E+00	2.3142E-05	5.4961E+00
18	18	1174	1204	6139	1.3226E-06	7.2900E-01	2.2244E+00	1.0671E-05	5.4990E+00
19	19	681	1330	5902	5.7313E-07	7.2447E-01	2.2032E+00	4.5460E-06	5.5027E+00
20	20	3186	10629	0	0.	1.2647E+00	3.3709E+00	4.8959E-07	1.0000+123
21	21	10006	20013	10379	5.6930E-12	1.6975E+00	4.0827E+00	5.6635E-10	7.4286E+02
22	22	946	946	0	0.	4.4692E-01	6.1713E-01	1.0980E-10	1.0000+123
TOTAL		122323	136480	448104	4.5183E+00				

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
4000	7.03977E-08	.5470	7	1.60055E-14	.6033	6	8.83721E-18	.5702	7
8000	1.14310E-07	.6041	3	1.81517E-14	.5325	4	1.03267E-17	.5099	4
12000	7.62067E-08	.6041	2	1.21175E-14	.5319	2	6.89378E-18	.5092	3
16000	6.33715E-08	.5484	2	1.00078E-14	.4860	2	5.60263E-18	.4725	2
20000	6.31303E-08	.4782	2	1.06621E-14	.4331	2	5.70488E-18	.4198	2
24000	6.30845E-08	.4196	2	1.06500E-14	.3781	3	5.98017E-18	.3629	3
28000	6.22926E-08	.3761	2	1.01164E-14	.3480	3	5.75692E-18	.3320	3
32000	6.28397E-08	.3361	2	1.05989E-14	.3154	3	5.79892E-18	.3019	3
36000	6.30160E-08	.3143	2	1.06457E-14	.2958	3	5.88347E-18	.2840	3
40000	5.93140E-08	.3018	2	1.01066E-14	.2819	3	5.59554E-18	.2706	3
44000	5.59769E-08	.2928	2	9.92630E-15	.2661	3	5.43684E-18	.2589	3
46770	5.86550E-08	.2681	3	1.04766E-14	.2435	3	5.82362E-18	.2347	3

```
**********************************************************************
DUMP NO.   2 ON FILE RUNTPE             NPS =    46770          CTM =    4.60
```

FOM 3 HERE AND 4 FOR SPLITTING DIRECTLY, BUT STATISTICS ARE BAD

Fig. 31. Window (space only) from importances.

4. ring detector, and
5. spatial weight window from refined cell importances.

Figure 31 shows the spatial weight window results. Comparison with Fig. 23 shows that the FOM (tally 1) is 3 for the weight window versus 4 for geometry splitting, but the statistics are bad on both runs. The main point is that a spatial weight window and geometry splitting give comparable results. In fact, in most cases where the statistics are good enough to judge, a spatial window is marginally superior to geometry splitting.

XIV. THE WEIGHT WINDOW GENERATOR

The weight window generator semiautomatically obtains optimized weight windows. The generator can be very useful for experienced Monte Carlo users; it is not recommended for novices. Weight window generator details are described in the September 16, 1982, X-6 memo, titled "Use of the Weight Window Generator."

A. Comments

1. The generator requires considerable user understanding and and *intervention* to work effectively.
2. The generator is scheduled to become a standard MCNP feature, but is currently only a standard (maintained) patch to MCNP.
3. Running MCNP with the generator typically costs an extra 20-50% of the required time for running MCNP without the generator.
4. Tracking is not affected by the generator; that is, every particle executes a random walk identical to its random walk when the generator is not used.

B. Importance Generator Theory

The importance of a particle at a point P in phase-space is equal to the expected score a unit weight particle will generate. Imagine dividing the phase-space into a number of phase-space "cells" or regions. The importance of a cell can then be defined as the expected score generated by a unit weight particle after entering the cell. Thus with a little bookkeeping, the cell's importance can be estimated as

$$\begin{array}{c}\text{Importance}\\ \text{(expected}\\ \text{score)}\end{array} = \frac{\text{total score because of particles (and their progeny) entering the cell}}{\text{total weight entering the cell}} .$$

Consider the example of Fig. 32, which represents a generic phase-space geometry of four cells. In this example, the capture probability at each collision is 0.5, and capture is treated implicitly by weight reduction in conjunction with a weight cutoff. Particles are born in cell 1 and are scored as they leave the slab from cell 4. The S values are used to determine the splitting and Russian roulette games played at boundary crossings between the four phase-space cells. In practice, these S values are usually the user's best initial guess at an importance function. Each particle trajectory is consecutively numbered. Table III shows the importance estimation process for the three particle histories of Fig. 32. Note also that this importance estimation works regardless of the variance reduction techniques used during the calculation (tracks that reenter the same phase-space cell should not be counted twice as weight entering).

C. Setting the Weight Window from the Estimated Importances

Although the generator and weight window concepts are independent, they are complementary. One cannot

TABLE III. Importance Estimation Process for Particle Histories in Fig. 32.

Row	Description	Cell 1	Cell 2	Cell 3	Cell 4
	Weight				
1	Trajectories entering	1, 8, 13	3, 4, 9, 10	14, 15	6, 17
2	Weight entering associated with above trajectories	1, 1, 1	0.25, 0.25, 0.5, 0.5	0.5, 0.5	0.5, 0.5
3	Total weight entering	3	1.5	1	1
	Score				
4	Trajectories entering that resulted in score	7, 17	7	17	7, 17
5	Scores associated with above trajectories	0.25, 0.5	0.25	0.5	0.25, 0.5
6	Total score	0.75	0.25	0.5	0.75
	Estimate				
7	Estimated importance Row 6/Row 3	0.25	0.167	0.5	0.75

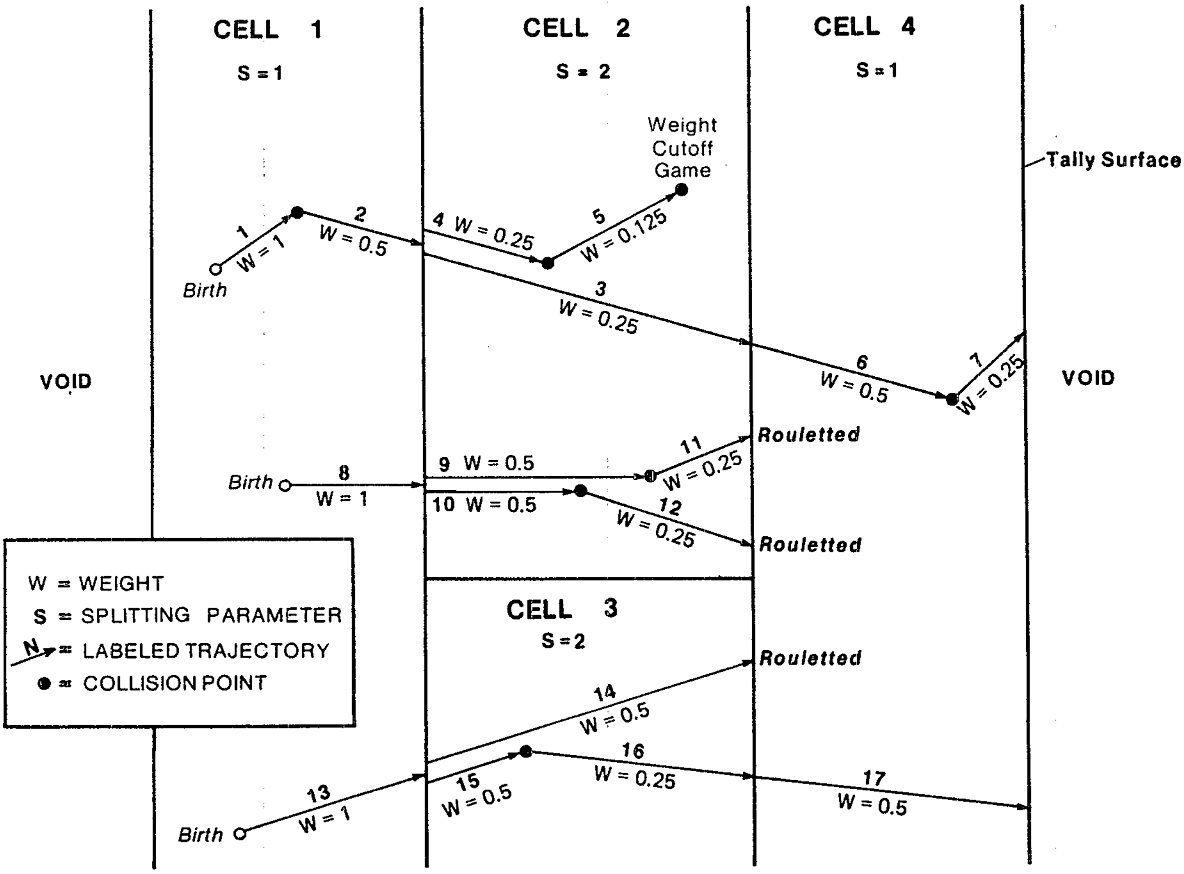


Fig. 32. Generic Monte Carlo problem of four cells with three particle histories, illustrating how importances can be estimated.

insist that every history contribute the same score (a zero variance solution), but by using a window inversely proportional to the importance, one can insist that the mean score from any track in the problem be roughly constant. In other words, the window is chosen so that the track weight times the mean score (for unit track weight) is approximately constant. Under these conditions, the variance is caused mostly by the variation in the number of contributing tracks rather than by the variation in track score.

Thus far, two weight window properties remain unspecified, the constant of inverse proportionality and the width of the window. Empirically, it has been observed that an upper weight bound five times the lower weight bound works well, but the results are reasonably insensitive to this choice anyway. The constant of inverse proportionality is chosen so that the lower weight bound in some reference cell is chosen appropriately. For example, in the problem described here, the constant was chosen so that the lower weight bound in the source cell was 0.5. The source particles were of unit weight, so they all started within the (0.5-2.5) window. In most instances the constant should be chosen this way so the source particles start within the window.

D. Spatial Generator Results

Figure 33 is the same run as Fig. 31 except that the generator is turned on. Note that the runs track perfectly and the generator has slowed the calculation by 4%. Typically, the generator will slow the calculation by 20-50%, but of course the generator can be turned off when a good weight window has been generated. Thus no time penalty need be paid for the final run to grind the statistics down.

Figure 34 shows the generated spatial weight window inserted in the input file for the next run. Many windows will be displayed, so I will explain how to interpret the WFN card entries, lines 67-72. Line 67 indicates that the first (and here the only) neutron weight window has an upper energy range of 100 MeV. If there were more

CELL PROGR	PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	52284	47147	122223	2.5784E+00	8.0176E-01	1.6607E+00	9.9061E-01	5.0620E+00
3	3	15527	10937	65628	1.2195E+00	4.1592E-01	1.0881E+00	8.8647E-01	4.1249E+00
4	4	9275	9759	55801	4.8096E-01	3.3695E-01	9.6786E-01	4.1114E-01	3.9027E+00
5	5	6744	9174	50117	1.6131E-01	3.1896E-01	1.0225E+00	1.5173E-01	3.9083E+00
6	6	5230	5994	32120	5.1613E-02	3.2700E-01	1.1480E+00	7.5598E-02	4.0113E+00
7	7	3561	4108	21736	1.7265E-02	3.4312E-01	1.2971E+00	3.7451E-02	4.1350E+00
8	8	2478	2807	14601	5.7387E-03	4.1889E-01	1.5625E+00	1.8594E-02	4.4885E+00
9	9	1833	2096	10746	2.1335E-03	4.7275E-01	1.7415E+00	9.3591E-03	4.6580E+00
10	10	1441	1596	8478	8.1523E-04	5.4895E-01	2.0562E+00	4.5771E-03	5.0049E+00
11	11	1362	1446	7522	3.4185E-04	5.6917E-01	2.0650E+00	2.1716E-03	5.1335E+00
12	12	1233	1258	6771	1.5712E-04	6.1261E-01	2.1111E+00	1.1042E-03	5.2412E+00
13	13	1183	1250	6324	6.8100E-05	6.2743E-01	2.0964E+00	5.2149E-04	5.2389E+00
14	14	1033	1347	6934	2.8037E-05	5.8460E-01	2.0346E+00	1.9258E-04	5.1695E+00
15	15	1095	1218	5960	1.1938E-05	6.4650E-01	2.1922E+00	9.5655E-05	5.3455E+00
16	16	1046	1161	5564	5.3848E-06	6.7465E-01	2.1985E+00	4.6191E-05	5.3729E+00
17	17	1005	1060	5159	2.4907E-06	6.9146E-01	2.2742E+00	2.3142E-05	5.4961E+00
18	18	1174	1204	6139	1.3226E-06	7.2900E-01	2.2244E+00	1.0671E-05	5.4990E+00
19	19	681	1330	5902	5.7313E-07	7.2447E-01	2.2032E+00	4.5460E-06	5.5027E+00
20	20	3186	10629	0	0.	1.2647E+00	3.3709E+00	4.8959E-07	1.0000+123
21	21	10006	20013	10379	5.6930E-12	1.6975E+00	4.0827E+00	5.6635E-10	7.4286E+02
22	22	946	946	0	0.	4.4692E-01	6.1713E-01	1.0980E-10	1.0000+123
TOTAL		122323	136480	448104	4.5183E+00				

	TALLY 1			TALLY 4			TALLY 5		
NPS	MEAN	ERROR	FOM	MEAN	ERROR	FOM	MEAN	ERROR	FOM
4000	7.03977E-08	.5470	7	1.60055E-14	.6033	6	8.83721E-18	.5702	6
8000	1.14310E-07	.6041	3	1.81517E-14	.5325	3	1.03267E-17	.5099	4
12000	7.62067E-08	.6041	2	1.21175E-14	.5319	2	6.89378E-18	.5092	3
16000	6.33715E-08	.5484	2	1.00078E-14	.4860	2	5.60263E-18	.4725	2
20000	6.31303E-08	.4782	2	1.06621E-14	.4331	2	5.70488E-18	.4198	2
24000	6.30845E-08	.4196	2	1.06500E-14	.3781	2	5.98017E-18	.3629	3
28000	6.22926E-08	.3761	2	1.01164E-14	.3480	2	5.75692E-18	.3320	3
32000	6.28397E-08	.3361	2	1.05989E-14	.3154	3	5.79892E-18	.3019	3
36000	6.30160E-08	.3143	2	1.06457E-14	.2958	3	5.88347E-18	.2840	3
40000	5.93140E-08	.3018	2	1.01066E-14	.2819	3	5.59554E-18	.2706	3
44000	5.59769E-08	.2928	2	9.92630E-15	.2661	3	5.43684E-18	.2589	3
46770	5.86550E-08	.2681	2	1.04766E-14	.2435	3	5.82362E-18	.2347	3

```
************************************************************************
DUMP NO.  2 ON FILE RUNTPI            NPS =    46770          CTM =    4.79
```

NOTE THAT RUNS TRACK BUT THAT GENERATOR RUN SLOWER BY 4.79/4.60 = 1.04 ie 4% SLOWER. USUALLY ~ 20%–50% SLOWER

Fig. 33. Window (space only) from importances; generator turned on. Compare with Fig. 31.

```
                    6012   -.001
          SRC1  0 1.E-6 0 2 1.0
          SI      L 2 14
          SP     95 .05
          NPS   46770
          WDWN  5 3 5 0
          WFN 1      1.0000E+02
                -1.0000E+00  5.0000E-01  2.8397E-01  1.1260E-01  4.2877E-02
                 1.4097E-02  4.3848E-03  1.5307E-03  5.4155E-04  2.1984E-04
                 8.6148E-05  3.9955E-05  1.7132E-05  7.5150E-06  3.5905E-06
                 1.6974E-06  8.4587E-07  4.0167E-07  1.9687E-07  0.0000E-05
                 0.0000E-02  0.                     -1.0000E+00
          WWG   1 2 .05  0 1.E8 0
          WGEN    1 2.01 4 7 10 100
          F1    20
          F4    21
          F5Y   2005 200 0
          PDO   0 19R 1 0 0
          C     DXN    0 2005 0   100.2 100.2
          DXCPN 0 .001 3R   .01 4R   .01 .015 .02 .04 .08
WARNING.  VALUES OTHER THAN 0. OR 1. CAN CAUSE TROUBLE.
                .2 .4 1 1 0    0 0 0
          FCN   0 19R 1 0 0
          EO    .01 100
          TO    100 1000   10000
          CUTN  1.0E123 .01   0 0
          EXTYN  0 0.0 17R 0 0 0 0
          CTME   45
          PRDMP  -5 -5
          PRINT
```

100 MeV UPPER ENERGY RANGE

SMOOTH BEHAVIOR FOR WINDOW

NEUTRON WEIGHT WINDOW

ENERGY RANGE 1

SPATIAL WEIGHT WINDOW GENERATED FROM PREVIOUS RUN

TURN OFF DXTRAN WHILE OPTIMIZING WINDOW

WEIGHT WINDOW TURNED OFF IF ENTRY = 0

-1 INDICATES ZERO IMPORTANCE REGION

THIS RUN WILL GENERATE A SPACE-ENERGY WINDOW WITH ENERGY RANGES

0 - 1 MeV	4 - 7 MeV
1 - 2.01 MeV	7 - 10 MeV
2.01 - 4 MeV	10 - 100 MeV

Fig. 34. Input for generating space-energy window.

energy ranges, the upper energy bound for the i^{th} window would be the lower energy bound for the $i + 1^{st}$ window. The lower energy bound for the first window is always zero. Lines 68 to 72 are the lower weight bounds for cells 1 to 23 and read, in order, from left to right and top to bottom. For example, the lower weight bound in cell 15 is 3.5905E-06. A zero lower weight bound turns off the weight window and a −1 indicates a zero importance region where the particle is terminated upon entering.

Earlier, I cautioned that user intervention is required. This intervention can be seen in the WFN1 entries (Fig. 34) for cells 20-22 where I turned off the weight window game by entering zeros because I did not want to use the window in this highly angle-dependent part of the problem. The window behaved smoothly, falling off roughly by factors of 2; thus the weight window needed no further intervention.

E. Generating a Space-Energy Weight Window

As mentioned earlier, the spatial weight window of Fig. 34 looks reasonable and is probably about as good as it will get. Furthermore, experience has proved biasing in the energy domain to be quite important. Therefore, the generator was employed, using the input shown in Fig. 34, to generate a space-energy window. The energy ranges chosen were

0	–	1	MeV
1	–	2.01	MeV
2.01	–	4	MeV
4	–	7	MeV
7	–	10	MeV
10	–	100	MeV

The choices were based mostly on experience and not on detailed analysis nor on inspiration. In particular, note that factors of 2 pervade the Monte Carlo choices. Note (line 79) that DXTRAN has been turned off while a space-energy window is generated (C indicates a comment card). This is perfectly reasonable because the space-energy window will be used to penetrate the concrete and will therefore be optimized for tally 1; DXTRAN is used to improve tallies 4 and 5 but not tally 1.

Figure 35 summarizes the run that used the spatial window of Fig. 34 to produce a space-energy window (Fig. 36). Note that removing DXTRAN allowed many more particles to be run.

F. Discussion of the Generated Space-Energy Window

The space-energy window produced is shown in Fig. 36. Wherever a zero entry appears, it means that the generator was unable to estimate importance for that space-energy cell because no particle ever left these space-energy cells and contributed to tally 1. Note that the zero entries are usually far from the tally surface and low in energy, indicating that low-energy particles far from the tally surface have a hard time tallying, as expected. If a zero is left as an entry, then no weight window game will be played, an undesirable situation; thus the user must supply nonzero weight windows.

Figure 37 shows how I adjusted the weight windows. An adjusted window entry is indicated by three trailing zeros in the entry. The window was adjusted according to two general patterns observed from Fig. 36. If W_{ij} is the lower weight bound in energy region i and spatial cell j, then these two general patterns can be expressed as $W_{ij} < W_{i-m,j}$ and $W_{ij} < W_{i,j-n}$, where m and n are positive integers. Thus Fig. 37 was obtained by interpolation and extrapolation from Fig. 36.

G. Results Using the Space-Energy Weight Window

The space-energy window of Fig. 37 was inserted in the input file; Fig. 38 shows the results. Tally 1 has improved nicely from an FOM of 6 to 43. However, note in the middle of Fig. 38 that the source particles are not starting within the window, indicating that the source should be biased so that the source particles start in the weight window.

The window (in source cell 2) for 2-MeV particles is 9 to 45, (recall that the upper bound is 5 times the lower bound) (Fig. 37), whereas the window for 14-MeV particles is .05 to .25. Recall (Fig. 36) that previous source energy biasing gave source weights of 9.5 and 0.055 at 2 MeV and 14 MeV, respectively. From this lucky coincidence we already know the proper source biasing. Without this coincidence, one could experiment with different source energy biasing until the last column of Fig. 36 indicated source weights within the window.

H. Results Using Space-Energy Window and Source Energy Bias

Figure 39 shows the effect of starting the source particles within the window; the FOM for tally 1 improves from 43 (Fig. 38) to 75. The only peculiar thing in Fig. 39 is the sudden rise and fall in the "tracks entering" and "population" columns around cells 6 and 7. A reexamination (see Fig. 37) of the adjusted space-energy window reveals that the window for cell 6 in the sixth energy range looks wrong; it does not fit the general pattern. This entry was altered from 3.4489E-04 to 2.2000E-3. Also, the window for cell 16 in the second energy range was altered from 4.5208E-6 to 1.0000E-5. Although cell 16's window was not responsible for the

THIS RUN GENERATED A SPACE-ENERGY WEIGHT WINDOW

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	31563	28369	73109	2.5609E+00	8.0044E-01	1.6463E+00	9.9001E-01	5.0488E+00
3	3	9235	6559	39580	1.2364E+00	4.0437E-01	1.0730E+00	8.9203E-01	4.0870E+00
4	4	5318	5726	31791	4.5867E-01	3.3009E-01	9.7941E-01	4.1401E-01	3.8937E+00
5	5	4689	5964	32365	1.5856E-01	3.1409E-01	1.0067E+00	1.3957E-01	3.8815E+00
6	6	4428	5792	31037	5.1074E-02	3.1464E-01	1.1052E+00	4.6976E-02	3.9459E+00
7	7	4198	5609	29062	1.5737E-02	3.3910E-01	1.2547E+00	1.5437E-02	4.1301E+00
8	8	4292	5635	28558	5.0913E-03	3.8529E-01	1.4915E+00	5.0716E-03	4.3485E+00
9	9	4005	5375	27348	1.7710E-03	4.5086E-01	1.7681E+00	1.8445E-03	4.6537E+00
10	10	4335	4679	23179	6.5910E-04	5.3091E-01	1.9515E+00	8.2099E-04	4.9305E+00
11	11	4010	5243	26509	2.8124E-04	5.4582E-01	1.9532E+00	3.0345E-04	4.9764E+00
12	12	4571	4918	24772	1.1931E-04	5.7551E-01	2.0257E+00	1.3936E-04	5.1013E+00
13	13	4215	5480	27612	4.8943E-05	5.9478E-01	2.0723E+00	5.0869E-05	5.1656E+00
14	14	4451	4942	24393	2.1525E-05	6.0769E-01	2.0888E+00	2.5386E-05	5.2023E+00
15	15	3971	4415	22316	9.8004E-06	5.9963E-01	2.0263E+00	1.2641E-05	5.1988E+00
16	16	3851	4140	20789	4.3415E-06	6.1546E-01	2.0906E+00	6.0496E-06	5.2793E+00
17	17	3582	3808	19422	2.0380E-06	6.2432E-01	2.0620E+00	3.0269E-06	5.2785E+00
18	18	3023	3244	16161	8.7591E-07	6.5356E-01	2.0774E+00	1.5639E-06	5.3515E+00
19	19	1772	2568	10985	3.4732E-07	6.7128E-01	2.1300E+00	8.9100E-07	5.4105E+00
20	20	1155	1154	0	0.	1.4029E+00	3.3493E+00	8.9086E-07	1.0000+123
21	21	5	10	5	1.8217E-12	6.5340E+00	8.3827E+00	3.7267E-07	8.6976E+02
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		106669	113630	508993	4.4893E+00				

NPS	TALLY 1 MEAN	TALLY 1 ERROR	TALLY 1 FOM	TALLY 4 MEAN	TALLY 4 ERROR	TALLY 4 FOM	TALLY 5 MEAN	TALLY 5 ERROR	TALLY 5 FOM
2000	4.42065E-08	.7235	5	0.	0.0000	0	0.	0.0000	0
4000	3.48294E-08	.5557	4	0.	0.0000	0	0.	0.0000	0
6000	2.63453E-08	.5039	4	0.	0.0000	0	0.	0.0000	0
8000	2.71267E-08	.4092	4	0.	0.0000	0	0.	0.0000	0
10000	2.20586E-08	.4029	4	0.	0.0000	0	0.	0.0000	0
12000	2.65686E-08	.3186	5	0.	0.0000	0	0.	0.0000	0
14000	3.06192E-08	.2893	5	0.	0.0000	0	0.	0.0000	0
16000	2.77965E-08	.2812	5	1.78371E-15	1.0000	0	0.	0.0000	0
18000	3.04967E-08	.2519	5	1.58552E-15	1.0000	0	0.	0.0000	0
20000	3.35645E-08	.2332	5	5.72437E-15	.7910	0	1.89637E-18	1.0000	0
22000	3.12439E-08	.2286	5	5.20397E-15	.7910	0	1.72397E-18	1.0000	0
24000	3.07538E-08	.2168	5	4.77030E-15	.7910	0	1.58031E-18	1.0000	0
26000	3.13077E-08	.2077	5	4.40336E-15	.7910	0	1.45875E-18	1.0000	0
28000	3.61601E-08	.1885	6	5.10598E-15	.6640	0	1.96601E-18	.7559	0
28144	3.65780E-08	.1861	6	5.07986E-15	.6640	0	1.95595E-18	.7559	0

MEAN LOW AND NO DXTRAN WORK

NOTE INCREASE FROM 2 WITH IMPORTANCES USED.

TIME = 4.63 MINUTES

Fig. 35. Spatial window with no DXTRAN.

```
WFN 1      1.0000E+00
        -1.0000E+00  0.           0.           0.           0.
         0.          0.           0.           0.           0.
         0.          0.           0.           0.           1.4100E-04
         8.1682E-05  7.4357E-06   1.6792E-06   6.8234E-07   0.
         0.          0.          -1.0000E+00
WFN 2      2.0100E+00
        -1.0000E+00  0.           0.           0.           0.
         0.          0.           0.           0.           0.
         1.2125E-02  5.0272E-03   7.6270E-04   1.0793E-04   3.9958E-05
         4.5208E-06  2.5657E-06   7.6579E-07   2.7840E-07   0.
         0.          0.          -1.0000E+00
WFN 3      4.0000E+00
        -1.0000E+00  0.           1.1223E-01   4.8144E-02   2.4881E-02
         8.1246E-03  4.7221E-03   2.0442E-03   7.1146E-04   3.9582E-04
         1.5468E-04  6.2149E-05   2.1354E-05   9.6969E-06   4.0856E-06
         1.8644E-06  8.4843E-07   3.9794E-07   2.0447E-07   0.
         0.          0.          -1.0000E+00
WFN 4      7.0000E+00
        -1.0000E+00  0.           1.6534E-02   1.1285E-02   5.3483E-03
         2.9056E-03  9.7180E-04   2.1018E-04   2.5524E-04   1.3185E-04
         5.1451E-05  9.6495E-06   1.1916E-05   3.8168E-06   2.4425E-06
         1.1805E-06  6.2537E-07   3.7240E-07   1.9655E-07   0.
         0.          0.          -1.0000E+00
WFN 5      1.0000E+01
        -1.0000E+00  0.           1.1635E-02   4.1318E-03   3.4173E-03
         2.3599E-03  1.0721E-03   1.5395E-04   1.4119E-04   7.6465E-05
         3.8697E-05  2.1199E-05   1.0413E-05   5.3956E-07   2.6293E-06
         1.5106E-06  2.6978E-07   1.3489E-07   1.8884E-07   0.
         0.          0.          -1.0000E+00
WFN 6      1.0000E+02
        -1.0000E+00  5.0000E-02   1.3488E-02   1.0148E-02   4.7609E-03
         3.4489E-04  1.1949E-03   6.2029E-05   2.1723E-04   8.2253E-05
         5.7428E-05  2.8461E-06   1.0432E-05   4.6621E-06   2.2761E-06
         1.2537E-06  7.1526E-07   2.6978E-07   2.1982E-07   0.
         0.          0.          -1.0000E+00
```

Fig. 36. Space-energy weight window produced.

```
WFN 1      1.0000E+00
        -1.0000E+00  2.6000E+01   2.6000E+01   8.6000E+00   2.9000E+00
         9.6000E-01  3.2000E-01   1.1000E-01   3.5000E-02   1.2000E-02
         3.9000E-03  1.3000E-03   4.4000E-04   1.5000E-04   4.9000E-05
         1.6000E-05  5.4000E-06   1.8000E-06   6.0000E-07   0.
         0.          0.          -1.0000E+00
WFN 2      2.0100E+00
        -1.0000E+00  9.0000E+00   4.5000E+00   2.3000E+00   1.1000E+00
         5.6000E-01  2.8000E-01   1.4000E-01   7.0000E-02   3.5000E-02
         1.2125E-02  5.0272E-03   7.6270E-04   1.6000E-04   3.9958E-05
         4.5208E-06  2.5657E-06   7.6579E-07   2.7840E-07   0.
         0.          0.          -1.0000E+00
WFN 3      4.0000E+00
        -1.0000E+00  3.0000E-01   1.1223E-01   4.8144E-02   2.4881E-02
         8.1246E-03  4.7221E-03   2.0442E-03   7.1146E-04   3.9582E-04
         1.5468E-04  6.2149E-05   2.1354E-05   9.6969E-06   4.0856E-06
         1.8644E-06  8.4843E-07   3.9794E-07   2.0447E-07   0.
         0.          0.          -1.0000E+00
WFN 4      7.0000E+00
        -1.0000E+00  5.0000E-02   1.6534E-02   1.1285E-02   5.3483E-03
         2.9056E-03  9.7180E-04   5.0000E-04   2.5524E-04   1.3185E-04
         5.1451E-05  2.5000E-05   1.1916E-05   5.0000E-06   2.4425E-06
         1.1805E-06  6.2537E-07   3.7240E-07   1.9655E-07   0.
         0.          0.          -1.0000E+00
WFN 5      1.0000E+01
        -1.0000E+00  5.0000E-02   1.1635E-02   4.1318E-03   3.4173E-03
         2.3599E-03  1.0721E-03   4.0000E-04   1.4119E-04   7.6465E-05
         3.8697E-05  2.1199E-05   1.0413E-05   5.0000E-06   2.6293E-06
         1.5106E-06  5.0000E-07   2.0000E-07   1.0000E-07   0.
         0.          0.          -1.0000E+00
WFN 6      1.0000E+02
        -1.0000E+00  5.0000E-02   1.3488E-02   1.0148E-02   4.7609E-03
         3.4489E-04  1.1949E-03   5.0000E-04   2.1723E-04   8.2253E-05
         5.7428E-05  2.0000E-05   1.0432E-05   4.6621E-06   2.2761E-06
         1.2537E-06  7.1526E-07   2.6978E-07   1.0000E-07   0.
         0.          0.          -1.0000E+00
```

Fig. 37. Adjusted (by hand) space-energy weight window. Look for three zeros as indication of hand adjustment.

LEDGER OF NET NEUTRON CREATION AND LOSS (FOR ACCOUNTING ONLY)

	TRACKS	WEIGHT (PER SOURCE PARTICLE)	ENERGY (PER SOURCE PARTICLE)
SOURCE	79266	1.0000E+00	2.6006E+00
SCATTERING	0	0.	0.
FISSION	0	0.	0.
(N,XN)	428	3.4146E-04	7.8500E-04
FORCED COLLISION	30	0.	0.
WEIGHT CUTOFF	0	0.	0.
WEIGHT WINDOW	95295	9.4426E-01	1.1818E+00
CELL IMPORTANCE	0	0.	0.
ENERGY IMPORT.	0	0.	0.
DXTRAN	0	0.	0.
EXP. TRANSFORM	0	0.	0.
TOTAL	175019	1.9446E+00	3.7831E+00

	TRACKS	WEIGHT (PER SOURCE PARTICLE)	ENERGY (PER SOURCE PARTICLE)
ESCAPE	50305	7.6849E-01	1.6402E+00
SCATTERING	0	0.	8.7143E-01
CAPTURE	18796	9.1107E-03	9.5665E-02
ENERGY CUTOFF	6783	2.2893E-01	1.2512E-03
TIME CUTOFF	0	0.	0.
WEIGHT CUTOFF	0	0.	0.
WEIGHT WINDOW	99135	9.3807E-01	1.1746E+00
CELL IMPORTANCE	0	0.	0.
ENERGY IMPORT.	0	0.	0.
DXTRAN	0	0.	0.
EXP. TRANSFORM	0	0.	0.
DEAD FISSION	0	0.	0.
TOTAL	175019	1.9446E+00	3.7831E+00

PREDICTED AVG OF SRC FUNCTION ZERO	2.6000E+00
TRACKS PER NEUTRON STARTED	2.2080E+00
COLLISIONS PER NEUTRON STARTED	5.4481E+00
TOTAL COLLISIONS	431852
NET MULTIPLICATION	1.0003E+00 .0001

AVERAGE LIFETIME, SHAKES	
ESCAPE	5.1106E-01
CAPTURE	9.3320E-01
CAPTURE OR ESCAPE	5.1601E-01
ANY TERMINATION	1.5297E+00

CUTOFFS	
TCO	1.0000+123
ECO	1.0000E-02
WC1	0.
WC2	0.

COMPUTER TIME SO FAR IN THIS RUN	4.67 MINUTES
COMPUTER TIME IN MCRUN (4CO)	4.61 MINUTES
SOURCE PARTICLES PER MINUTE	1.7198E+04
FIELD LENGTH	376688 = 1337560B
RANDOM NUMBERS GENERATED	4305494
LAST STARTING RANDOM NUMBER	052752771503 1145B
NEXT STARTING RANDOM NUMBER	603270047163 1661B

TOTAL NEUTRONS BANKED	72558
PER SOURCE PARTICLE	9.1537E-01
TOTAL PHOTONS BANKED	0
PER SOURCE PARTICLE	0.
MAXIMUM NUMBER EVER IN BANK	16
BANK OVERFLOWS TO DISK	0

3967 SOURCE PARTICLES HAD WEIGHT ABOVE WINDOW.
BY INCREASING WW ENERGY INTERVAL: 0 0 0 0 0 3967

WINDOW DOING WHAT SOURCE BIASING OUGHT TO BE DOING

75299 SOURCE PARTICLES HAD WEIGHT BELOW WINDOW.
BY INCREASING WW ENERGY INTERVAL: 0 75299 0 0 0 0

NOTE IMPROVEMENT FROM FOM = 6 AND LOW MEAN

TIME = 4.61 MIN

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
4000	4.26255E-08	.3126	40	0.	0.0000	0	0.	0.0000	0
8000	3.93201E-08	.2170	44	1.80090E-15	.9999	2	1.25350E-18	.9999	2
12000	3.62294E-08	.1831	45	3.75877E-15	.7518	2	8.35669E-19	1.0000	1
16000	3.78523E-08	.1531	48	2.81908E-15	.7518	2	6.26752E-19	1.0000	1
20000	3.84399E-08	.1436	43	2.25526E-15	.7518	1	5.01402E-19	1.0000	0
24000	3.69001E-08	.1348	42	1.87939E-15	.7518	1	4.17835E-19	1.0000	0
28000	3.74802E-08	.1250	42	1.61090E-15	.7518	1	3.58144E-19	1.0000	0
32000	3.96024E-08	.1155	42	2.62570E-15	.5210	2	1.65752E-18	.6340	1
36000	3.95712E-08	.1078	43	3.35794E-15	.4230	2	1.73638E-18	.5536	1
40000	3.96848E-08	.1022	43	3.02214E-15	.4230	2	1.56274E-18	.5536	1
44000	4.01664E-08	.0973	43	3.62170E-15	.4015	2	1.80785E-18	.4849	1
48000	4.08935E-08	.0922	43	3.31989E-15	.4015	2	1.65720E-18	.4849	1
52000	4.31095E-08	.0878	43	3.66148E-15	.3735	2	1.93062E-18	.4367	1
56000	4.41742E-08	.0837	43	4.82611E-15	.3394	2	2.66350E-18	.3921	1
60000	4.45244E-08	.0808	43	4.50437E-15	.3394	2	2.48593E-18	.3921	1
64000	4.44663E-08	.0790	43	5.16357E-15	.3074	2	2.84505E-18	.3458	2
68000	4.42586E-08	.0764	43	6.64840E-15	.2779	3	3.37077E-18	.3108	2
72000	4.50210E-08	.0742	43	8.14304E-15	.2465	3	4.31000E-18	.2738	3
76000	4.46087E-08	.0720	43	8.58957E-15	.2296	4	4.42186E-18	.2586	3
79266	4.48032E-08	.0704	43	8.23565E-15	.2296	4	4.23966E-18	.2586	3

TIME = 4.61 MIN

Fig. 38. Space-energy window.

BIASED SOURCE
10% AT 2 MeV
90% AT 14 MeV

WHAT HAPPENED ?

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	72900	71569	64844	2.5985E+00	7.9765E-01	1.6550E+00	1.4970E+00	5.0683E+00
3	3	13967	13065	22767	1.3658E+00	3.8362E-01	1.0424E+00	1.8665E+00	4.0300E+00
4	4	6869	11224	18913	4.4432E-01	3.2624E-01	1.0203E+00	6.7267E-01	3.9124E+00
5	5	6189	10196	16387	1.6382E-01	2.9485E-01	9.9241E-01	2.8660E-01	3.8271E+00
6	6	5776	20034	26603	5.2169E-02	3.0415E-01	1.1445E+00	5.2098E-02	3.9416E+00
7	7	10695	11731	18387	1.3503E-02	3.2685E-01	1.4222E+00	2.2751E-02	4.1834E+00
8	8	6713	9403	15363	5.0785E-03	3.4114E-01	1.6170E+00	1.0314E-02	4.3812E+00
9	9	5685	9455	15729	1.6771E-03	5.5594E-01	2.0278E+00	3.7507E-03	4.8771E+00
10	10	5692	9068	15237	7.4597E-04	5.8661E-01	2.1211E+00	1.6788E-03	4.9174E+00
11	11	5420	9177	16089	2.3916E-04	7.5402E-01	2.5748E+00	5.7359E-04	5.4790E+00
12	12	5645	8902	16326	1.1446E-04	7.1401E-01	2.5327E+00	2.6741E-04	5.4651E+00
13	13	5922	9225	18071	5.4526E-05	7.8201E-01	2.4512E+00	1.1940E-04	5.4770E+00
14	14	6118	8851	18914	2.7250E-05	6.7606E-01	2.2546E+00	5.9161E-05	5.2972E+00
15	15	5950	9320	20500	1.1794E-05	6.4999E-01	2.2862E+00	2.4826E-05	5.3760E+00
16	16	6488	9782	25896	5.2562E-06	6.6610E-01	2.3080E+00	9.7062E-06	5.4234E+00
17	17	7228	10092	28621	2.5251E-06	6.5633E-01	2.2104E+00	4.4270E-06	5.3554E+00
18	18	7192	10409	31844	1.1580E-06	6.3917E-01	2.1387E+00	1.9383E-06	5.3137E+00
19	19	5451	9074	29875	4.5332E-07	7.1276E-01	2.2535E+00	8.8928E-07	5.4711E+00
20	20	4670	4665	0	0.	1.2199E+00	3.3018E+00	7.5707E-07	1.0000+123
21	21	21	42	22	6.7924E-12	1.2606E+00	3.1874E+00	2.7759E-07	6.0228E+02
22	22	4	4	0	0.	6.7857E-02	2.1071E-01	4.5584E-08	1.0000+123
TOTAL		194595	255288	420388	4.6460E+00				

NATURAL SOURCE
95% AT 2 MeV
5 % AT 14 MeV

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
4000	5.57495E-08	.2280	68	6.34674E-15	.7133	6	4.22938E-18	.7305	6
8000	4.56612E-08	.1668	69	2.30878E-14	.6567	4	3.30529E-17	.6802	4
12000	4.36483E-08	.1478	61	1.72329E-14	.5962	3	2.34337E-17	.6424	3
16000	4.67028E-08	.1221	66	1.44250E-14	.5443	3	1.75753E-17	.6424	2
20000	4.79930E-08	.1048	71	1.37601E-14	.4705	3	1.48115E-17	.6120	2
24000	5.24382E-08	.0916	76	1.48934E-14	.4291	3	2.37583E-17	.5761	1
28000	5.18837E-08	.0848	77	1.27658E-14	.4291	3	2.03643E-17	.5761	1
32000	4.95469E-08	.0794	77	1.16204E-14	.4143	2	1.79888E-17	.5708	1
36000	5.12823E-08	.0741	76	1.12201E-14	.3896	2	1.63018E-17	.5602	1
40000	5.27996E-08	.0691	78	1.06390E-14	.3733	2	1.46716E-17	.5602	1
44000	5.06052E-08	.0667	77	1.01628E-14	.3585	2	1.33378E-17	.5602	1
48000	4.92408E-08	.0640	78	9.92531E-15	.3420	2	1.27618E-17	.5383	1
52000	4.87547E-08	.0623	76	9.43925E-15	.3333	2	1.18694E-17	.5343	1
56000	5.06014E-08	.0599	76	8.76501E-15	.3333	2	1.10216E-17	.5343	0
60000	4.98803E-08	.0581	76	8.18068E-15	.3333	2	1.02868E-17	.5343	0
64000	4.98051E-08	.0565	75	8.55026E-15	.3084	2	1.01502E-17	.5090	0
68000	4.94767E-08	.0548	75	8.04731E-15	.3084	2	9.55314E-18	.5090	0
71167	4.91626E-08	.0536	75	8.47612E-15	.2875	2	9.19833E-18	.5052	0

NOTE IMPROVEMENT

TIME = 4.61 MIN

Fig. 39. Space-energy window and source energy bias.

peculiarity, 10^{-5} just looked more reasonable because in energy range 2, the windows were decreasing by factors of 4. Figure 40 shows the corrected window.

Figure 41 shows the results of correcting the bad window. The "tracks entering" and "population" columns look much better. Perversely, the FOM decreases, but the decrease is not statistically significant and the corrected window was used for subsequent runs.

I. Exponential Source Angle Biasing and the Weight Window

Recall that exponential source angle biasing did not improve the FOMs for the problem. As with most biasing techniques, competing factors affect calculation. Exponential source angle biasing preferentially samples source neutrons moving close to the $+\hat{y}$ direction. Thus source neutrons that are more likely to score are sampled more often. However, the biasing also introduces a weight fluctuation that the geometry splitting/Russian roulette technique preserves. Probably the negative effects of this weight fluctuation cancelled the benefit of sampling more important source neutrons more often.

A conference participant (John Hendricks, Los Alamos) suggested that the exponential source angle biasing might have worked if it had been tried with the weight window technique rather than with geometry splitting/Russian roulette. He said that the weight window would probably alleviate the weight fluctuation problem; thus the exponential source angle biasing, in conjunction with the weight window, probably would improve the FOMs.

I agree with his assessment and include it here, without proof, as a good example of analyzing the interaction of different variance reduction techniques. However, the source angle biasing should not be expected to yield the same dramatic improvement in FOM as the source energy bias because the particles that tally will typically have many collisions and will quickly forget their source angle. In other words, after a few collisions, a preferred source particle will be essentially identical (except possibly its weight) to an unpreferred

```
                                  WFN 1      1.0000E+00
                                          -1.0000E+00  2.6000E+01  2.6000E+01  8.6000E+00  2.9000E+00
                                           9.6000E-01  3.2000E-01  1.1000E-01  3.5000E-02  1.2000E-02
                                           3.9000E-03  1.3000E-03  4.4000E-04  1.5000E-04  4.9000E-05
                                           1.6000E-05  5.4000E-06  1.8000E-06  6.0000E-07  0.
                                           0.          0.         -1.0000E+00
                                  WFN 2      2.0100E+00
                                          -1.0000E+00  9.0000E+00  4.5000E+00  2.3000E+00  1.1000E+00
                                           5.6000E-01  2.8000E-01  1.4000E-01  7.0000E-02  3.5000E-02
                                           1.2125E-02  5.0272E-03  7.6270E-04  1.6000E-04  3.9958E-05
ALTERED FROM 4.5208E-06 ------------->     1.0000E-05  2.5657E-06  7.6579E-07  2.7840E-07  0.
                                           0.          0.         -1.0000E+00
                                  WFN 3      4.0000E+00
                                          -1.0000E+00  3.0000E-01  1.1223E-01  4.8144E-02  2.4881E-02
                                           8.1246E-03  4.7221E-03  2.0442E-03  7.1146E-04  3.9582E-04
                                           1.5468E-04  6.2149E-05  2.1354E-05  9.6969E-06  4.0856E-06
                                           1.8644E-06  8.4843E-07  3.9794E-07  2.0447E-07  0.
                                           0.          0.         -1.0000E+00
                                  WFN 4      7.0000E+00
                                          -1.0000E+00  5.0000E-02  1.6534E-02  1.1285E-02  5.3483E-03
                                           2.9056E-03  9.7180E-04  5.0000E-04  2.5524E-04  1.3185E-04
                                           5.1451E-05  2.5000E-05  1.1916E-05  5.0000E-06  2.4425E-06
                                           1.1805E-06  6.2537E-07  3.7240E-07  1.9655E-07  0.
                                           0.          0.         -1.0000E+00
                                  WFN 5      1.0000E+01
                                          -1.0000E+00  5.0000E-02  1.1635E-02  4.1318E-03  3.4173E-03
                                           2.3599E-03  1.0721E-03  4.0000E-04  1.4119E-04  7.6465E-05
                                           3.8697E-05  2.1199E-05  1.0413E-05  5.0000E-06  2.6293E-06
                                           1.5106E-06  5.0000E-07  2.0000E-07  1.0000E-07  0.
                                           0.          0.         -1.0000E+00
                                  WFN 6      1.0000E+02
                                          -1.0000E+00  5.0000E-02  1.3488E-02  1.0148E-02  4.7609E-03
ALTERED FROM 3.4489E-04 ------------->     2.2000E-03  1.1949E-03  5.0000E-04  2.1723E-04  8.2253E-05
                                           5.7428E-05  2.0000E-05  1.0432E-05  4.6621E-06  2.2761E-06
                                           1.2537E-06  7.1526E-07  2.6978E-07  1.0000E-07  0.
                                           0.          0.         -1.0000E+00

                                         THIS IS EXPLANATION FOR STRANGE BEHAVIOR IN TRACKS ENTERING
```

Fig. 40. Adjusted (by hand) space-energy weight window.

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	75839	74458	67419	2.5887E+00	7.9638E-01	1.6533E+00	1.4940E+00	5.0648E+00
3	3	14452	13526	23624	1.3723E+00	3.8601E-01	1.0408E+00	1.8806E+00	4.0246E+00
4	4	7094	11621	19613	4.4147E-01	3.2964E-01	1.0203E+00	6.7903E-01	3.9177E+00
5	5	6463	10463	17155	1.7049E-01	2.9225E-01	9.7468E-01	2.9678E-01	3.8096E+00
6	6	6025	8987	15519	5.3747E-02	2.9966E-01	1.1276E+00	1.0221E-01	3.9156E+00
7	7	5431	8875	14304	1.3574E-02	3.2879E-01	1.4363E+00	3.0759E-02	4.1831E+00
8	8	5290	8625	14496	5.0786E-03	3.4398E-01	1.6151E+00	1.1507E-02	4.3780E+00
9	9	5284	9240	16077	1.7477E-03	5.4043E-01	1.9626E+00	3.9657E-03	4.8172E+00
10	10	5604	9935	16767	7.2720E-04	5.4411E-01	2.0717E+00	1.5457E-03	4.8804E+00
11	11	5837	9861	16517	2.7529E-04	5.8899E-01	2.2996E+00	6.2135E-04	5.1875E+00
12	12	5865	9534	17366	1.1332E-04	6.4903E-01	2.4117E+00	2.5637E-04	5.3153E+00
13	13	6120	9832	18524	5.2946E-05	6.7115E-01	2.3792E+00	1.1583E-04	5.3554E+00
14	14	6243	9828	19735	2.4367E-05	6.7946E-01	2.3729E+00	5.1952E-05	5.3850E+00
15	15	6496	9846	20748	1.1101E-05	6.7425E-01	2.3827E+00	2.3384E-05	5.4389E+00
16	16	6904	10237	23801	5.0579E-06	7.1928E-01	2.3795E+00	1.0239E-05	5.5013E+00
17	17	7323	10736	29314	2.5555E-06	6.7818E-01	2.2056E+00	4.4929E-06	5.3450E+00
18	18	7585	11349	34042	1.1560E-06	6.5039E-01	2.1465E+00	1.8680E-06	5.3270E+00
19	19	5876	10556	30980	4.6402E-07	6.9589E-01	2.2556E+00	8.5181E-07	5.4331E+00
20	20	5424	5422	0	0.	1.2470E+00	3.5400E+00	6.8250E-07	1.0000+123
21	21	29	58	29	5.1765E-12	8.5566E-01	2.9814E+00	2.6879E-07	6.9683E+02
22	22	4	4	0	0.	2.6789E+00	2.8768E+00	1.3916E-08	1.0000+123
TOTAL		195188	252993	416030	4.6483E+00				

PROBLEM FIXED

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
4000	4.63475E-08	.2790	47	2.53090E-14	.8405	5	2.68446E-18	.9999	3
8000	4.37917E-08	.1876	56	1.26545E-14	.8406	2	1.34223E-18	.9999	1
12000	4.58544E-08	.1421	66	1.25263E-14	.6535	3	2.92610E-18	.7585	2
16000	4.32273E-08	.1230	67	1.08950E-14	.5801	3	2.19458E-18	.7585	1
20000	4.53445E-08	.1118	65	1.10367E-14	.4817	3	2.99296E-18	.6073	2
24000	4.80343E-08	.1006	66	1.07584E-14	.4246	3	3.64405E-18	.4737	3
28000	5.00952E-08	.0927	67	9.65057E-15	.4082	3	3.12347E-18	.4737	2
32000	4.87681E-08	.0870	67	8.44425E-15	.4082	3	2.73304E-18	.4737	2
36000	5.17198E-08	.0786	71	7.50600E-15	.4082	2	2.42937E-18	.4737	1
40000	5.43840E-08	.0729	73	9.64150E-15	.4140	2	2.60061E-18	.4289	2
44000	5.35161E-08	.0695	73	9.03835E-15	.4026	2	2.47533E-18	.4121	2
48000	5.22673E-08	.0669	74	8.28516E-15	.4026	2	2.26905E-18	.4121	1
52000	5.16625E-08	.0649	73	8.06101E-15	.3854	2	2.09451E-18	.4121	1
56000	5.20026E-08	.0627	73	7.90250E-15	.3689	2	1.94490E-18	.4121	1
60000	5.13074E-08	.0606	73	7.77769E-15	.3536	2	2.01116E-18	.3845	1
64000	5.05774E-08	.0589	72	7.88994E-15	.3312	2	2.03202E-18	.3640	1
68000	5.05022E-08	.0570	73	7.85279E-15	.3179	2	1.91249E-18	.3640	1
72000	5.10846E-08	.0552	73	8.63009E-15	.2822	2	2.20504E-18	.3182	2
74051	5.08709E-08	.0547	72	8.60730E-15	.2762	2	2.20049E-18	.3111	2

TIME = 4.60 MINUTES

PERVERSELY THE FOM DECREASES, BUT NOT STATISTICALLY SIGNIFICANT

Fig. 41. Bad window corrected.

source particle. In contrast, a 14-MeV source particle will typically have higher energy in every part of the problem than a 2-MeV source particle would have. Thus the benefit of source energy biasing is felt throughout the entire problem, but the source angle biasing will be felt only within a few free paths of the source. Most of the sample problem is more than a few free paths from the source, so I would be surprised to see more than a 10% FOM improvement with *any* type of source angle bias.

XV. THE EXPONENTIAL TRANSFORM

The exponential transform in MCNP stretches distances between collisions in the forward direction and shrinks them in the backward direction by modifying the total macroscopic cross section by

$$\sigma_{\text{modified}} = \sigma_{\text{true}}\,(1 - p\mu)$$
$$\mu = 1 \rightarrow \text{forward direction,}$$

where μ is the cosine of the angle with respect to a reference direction (currently only $+\hat{y}$ in MCNP) and p is the user input exponential transform parameter ($0 \leq p \leq 1$) with

p = 0	no bias
p = 1	complete bias.

Many claims for the exponential transform exist in the Monte Carlo literature, but they are usually based on analysis of one-dimensional problems and often on one-dimensional monoenergetic problems. In practice at Los Alamos, the exponential transform is considered a dangerous biasing technique unless accompanied by weight control (for example, the weight window in MCNP), In fact, so many MCNP users had problems obtaining reliable mean and variance estimates with the exponential transform (when used without the weight window) that the technique was sometimes referred to as the "dial an answer technique."

Los Alamos experience indicates that the weight window eliminates the "dial an answer" phenomenon and that the exponential transform can be effective when used with a weight window. The exponential transform both with and without a weight window will be demonstrated on the sample problem.

A. Comments

1. MCNP gives a warning message if the exponential transform is used and a weight window is not.
2. The exponential transform is not recommended for novices.
3. The exponential transfrom works best in highly absorbing media and very poorly in highly scattering media.
4. Empirically, p = 0.7 seems to work well for shielding calculations on fission or fusion spectrums with shielding materials like concrete or earth.
5. There is a standard (maintained) patch to allow the reference direction to be arbitrary, not just $+\hat{y}$ as currently implemented.

B. The Sample Problem with the Exponential Transform

An exponential transform (with p = 0.7) was added to the input file that produced Fig. 42. That is, the following techniques were used in the next run:

1. energy cutoff,
2. forced collision in cell 21,
3. ring detector,
4. space-energy weight window,
5. source energy biasing, and
6. exponential transform (p = 0.7)

Figure 42 shows the results of using the exponential transform with a space-energy window; the FOM improved from 72 to 126. Results from running the same problem without the space-energy window are shown in Fig. 43. Note that the errors are much worse, and moreover, are not decreasing monotonically with increasing histories. Admittedly, the error levels are too high to make them reliable; however, one can certainly except less jumpy statistics. For instance, compare tally 1 with tally 4 of the previous table. Note that even though the initial errors are high for tally 4, they are decreasing monotonically. Jumps in the relative errors indicate a few large weight particles trouncing the tally and thus indicate poor sampling. I have seen such relative error jumps frequently at the 10% level and occasionally at the 5% level. The higher the transform parameter is and the more collisions that are undergone per particle, the worse these jumps become. The weight window splits particles before their weights can become excessive enough to trounce the tallies.

Concerning tally 1 of Fig. 43, note that at 80,000 histories, the stated results are 2.75E-8 ± 30.6%, yet Fig. 42 indicates that the true mean is close to 4.85E-8. A quick calculation gives

standard deviation = .306 · 2.75E-8	= 8.41 E-9
"true" - estimate = 4.85E-8 - 2.75E-8	= 2.1E-8
standard deviations from the true mean	$= \dfrac{2.1\text{E-}8}{8.41\text{E-}9} = 2.5$
ratio true/estimate	= 1.76 ,

which indicates just how unreliable error estimates can be when the sampling is poor.

CELL PROGR	PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	82381	82065	53810	2.6281E+00	8.2171E-01	1.7031E+00	1.6858E+00	7.9556E+00
3	3	19981	23648	25074	1.1835E+00	4.3859E-01	1.1523E+00	1.3032E+00	7.2574E+00
4	4	16444	18607	18914	5.0508E-01	3.0316E-01	9.4543E-01	6.6849E-01	6.6648E+00
5	5	13541	15386	15706	1.4711E-01	3.1359E-01	1.0435E+00	2.5234E-01	6.8687E+00
6	6	11461	13496	14039	4.0306E-02	3.3080E-01	1.2151E+00	8.5035E-02	7.2066E+00
7	7	10417	13454	13729	1.6137E-02	3.3603E-01	1.3958E+00	3.1007E-02	7.5390E+00
8	8	10189	13378	13591	4.8696E-03	3.9568E-01	1.6342E+00	1.0773E-02	8.1615E+00
9	9	10250	14088	14822	1.6739E-03	5.2252E-01	1.9818E+00	3.5829E-03	8.7372E+00
10	10	10659	13949	14231	5.8934E-04	6.1559E-01	2.3504E+00	1.3240E-03	9.4099E+00
11	11	10642	13602	14796	2.1034E-04	7.5516E-01	2.6706E+00	5.2503E-04	1.0151E+01
12	12	10527	14024	15551	9.9072E-05	8.1054E-01	2.6844E+00	2.3439E-04	1.0440E+01
13	13	10986	14644	17538	5.0323E-05	7.6932E-01	2.4881E+00	1.0879E-04	1.0112E+01
14	14	11539	15409	19466	2.5835E-05	6.5316E-01	2.2961E+00	5.0285E-05	9.7571E+00
15	15	12046	15625	21329	1.2003E-05	6.4574E-01	2.2270E+00	2.3125E-05	9.6251E+00
16	16	12356	15632	23077	5.2759E-06	6.8950E-01	2.3015E+00	1.0010E-05	9.9596E+00
17	17	12553	16094	28198	2.6284E-06	6.7305E-01	2.1726E+00	4.5005E-06	9.6617E+00
18	18	13192	16913	32669	1.1979E-06	6.2959E-01	2.1103E+00	1.9486E-06	9.6765E+00
19	19	11444	16369	31267	4.7481E-07	6.5745E-01	2.1606E+00	8.5094E-07	1.0147E+01
20	20	11122	11101	0	0.	1.2966E+00	3.4708E+00	3.2605E-07	1.0000+123
21	21	97	194	100	5.4336E-12	2.1163E+00	4.2544E+00	9.7467E-08	7.7796E+02
22	22	11	11	0	0.	3.8622E+00	4.0376E+00	3.1275E-09	1.0000+123
TOTAL		301838	357689	387907	4.5278E+00				

NOTE IMPROVEMENT

	TALLY 1			TALLY 4			TALLY 5		
NPS	MEAN	ERROR	FOM	MEAN	ERROR	FOM	MEAN	ERROR	FOM
4000	4.47297E-08	.1825	119	1.18956E-14	.6162	10	1.03622E-17	.5654	12
8000	4.70824E-08	.1307	121	1.11439E-14	.4389	10	6.52695E-18	.4726	9
12000	5.14633E-08	.0996	138	8.94383E-15	.3784	9	5.17462E-18	.4082	8
16000	4.66144E-08	.0894	139	8.73207E-15	.3215	10	5.38702E-18	.3371	9
20000	4.82730E-08	.0813	133	1.02135E-14	.3102	9	5.76006E-18	.2992	9
24000	5.00965E-08	.0731	134	1.14411E-14	.2876	8	5.41260E-18	.2795	9
28000	4.84900E-08	.0680	135	1.10845E-14	.2689	8	4.77614E-18	.2723	8
32000	4.81146E-08	.0643	133	1.06399E-14	.2541	8	4.29410E-18	.2657	7
36000	4.89508E-08	.0597	135	1.15818E-14	.2237	9	4.82404E-18	.2366	8
40000	4.85085E-08	.0575	132	1.20101E-14	.2095	10	4.92557E-18	.2259	8
44000	4.74248E-08	.0550	134	1.10572E-14	.2073	9	4.55676E-18	.2226	8
48000	4.90814E-08	.0529	131	1.11509E-14	.1962	9	4.62668E-18	.2103	8
52000	4.94231E-08	.0512	129	1.10281E-14	.1888	9	4.73347E-18	.1993	8
56000	4.84339E-08	.0497	127	1.13865E-14	.1802	9	4.91778E-18	.1882	8
60000	4.78067E-08	.0481	128	1.07393E-14	.1786	9	4.61025E-18	.1875	8
64000	4.79871E-08	.0463	129	1.03275E-14	.1752	9	4.55199E-18	.1830	8
68000	4.85386E-08	.0447	129	1.03254E-14	.1725	8	4.42669E-18	.1787	8
72000	4.80605E-08	.0440	127	9.75179E-15	.1725	8	4.18076E-18	.1787	7
76000	4.77400E-08	.0427	128	1.06664E-14	.1581	9	4.48125E-18	.1689	8
80000	4.85226E-08	.0417	126	1.06919E-14	.1512	9	4.68326E-18	.1623	8
81021	4.85159E-08	.0413	126	1.05571E-14	.1512	9	4.62424E-18	.1623	8

```
************************************************************************
DUMP NO.  2 ON FILE RUNTPF           NPS =    81021          CTM =    4.60
```

Fig. 42. Exponential transform added to window and source energy biasing.

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	96181	91238	111089	2.5198E+00	8.6550E-01	1.7329E+00	1.2491E+00	8.0095E+00
3	3	35093	28206	76403	1.2822E+00	3.8936E-01	1.1036E+00	8.8494E-01	7.0651E+00
4	4	27485	22117	59796	4.4946E-01	3.4393E-01	1.0430E+00	4.1483E-01	6.9745E+00
5	5	21461	17290	48555	1.2996E-01	4.0420E-01	1.1680E+00	1.7108E-01	7.2457E+00
6	6	16611	13419	37059	4.1437E-02	3.6572E-01	1.2887E+00	7.1158E-02	7.4306E+00
7	7	12568	10230	28225	1.5941E-02	3.6370E-01	1.3805E+00	3.3393E-02	7.4765E+00
8	8	9535	7784	21493	5.4137E-03	3.4697E-01	1.5524E+00	1.5208E-02	7.9025E+00
9	9	7244	5916	16548	1.5428E-03	5.4647E-01	2.1499E+00	5.9476E-03	9.0756E+00
10	10	5456	4481	12119	4.9606E-04	6.4096E-01	2.4462E+00	3.4040E-03	9.6654E+00
11	11	4147	3392	9405	2.5471E-04	7.0352E-01	2.3951E+00	2.1180E-03	1.0100E+01
12	12	3099	2532	6734	9.4154E-05	7.6177E-01	2.5143E+00	1.2221E-03	1.0660E+01
13	13	2339	1943	5296	4.4372E-05	9.3756E-01	2.7578E+00	6.6207E-04	1.1573E+01
14	14	1728	1441	3690	2.2395E-05	8.6658E-01	2.4142E+00	4.7175E-04	1.2577E+01
15	15	1351	1108	2858	1.4547E-05	7.4977E-01	2.3739E+00	3.3141E-04	1.1595E+01
16	16	1042	852	2393	8.5873E-06	7.8925E-01	2.0621E+00	2.5560E-04	1.0105E+01
17	17	758	627	1786	2.5484E-06	8.4360E-01	2.1049E+00	1.2964E-04	1.0738E+01
18	18	565	460	1178	7.7701E-07	9.8625E-01	2.6221E+00	6.1559E-05	1.4056E+01
19	19	366	338	713	2.1124E-06	2.5649E-01	9.8710E-01	1.0306E-04	7.1472E+00
20	20	254	254	0	0.	2.8549E+00	4.1084E+00	1.0913E-05	1.0000+123
21	21	1	2	1	6.4189E-14	1.2361E+01	1.2361E+01	2.6632E-07	9.2473E+02
22	22	0	0	0	0.	0.	0.	0.	0.
TOTAL		247284	213630	445341	4.4467E+00				

NPS	TALLY 1 MEAN	ERROR	FOM	TALLY 4 MEAN	ERROR	FOM	TALLY 5 MEAN	ERROR	FOM
8000	6.06622E-09	.5761	7	0.	0.0000	0	0.	0.0000	0
16000	7.24200E-09	.3988	7	0.	0.0000	0	0.	0.0000	0
24000	2.26703E-08	.6227	2	0.	0.0000	0	0.	0.0000	0
32000	2.86467E-08	.4303	3	0.	0.0000	0	0.	0.0000	0
40000	2.57597E-08	.3908	3	0.	0.0000	0	0.	0.0000	0
48000	3.68352E-08	.3766	2	0.	0.0000	0	0.	0.0000	0
56000	3.44787E-08	.3468	2	0.	0.0000	0	0.	0.0000	0
64000	3.17947E-08	.3298	2	0.	0.0000	0	0.	0.0000	0
72000	2.98460E-08	.3136	2	0.	0.0000	0	0.	0.0000	0
80000	2.75398E-08	.3060	2	2.15935E-16	1.0000	0	9.76105E-20	1.0000	0
88000	4.06829E-08	.3541	1	1.96305E-16	1.0000	0	8.87368E-20	1.0000	0
90897	4.04549E-08	.3452	1	1.90048E-16	1.0000	0	8.59086E-20	1.0000	0

```
*************************************************************************************
DUMP NO.   2 ON FILE RUNTPE           NPS =    90897          CTM =    4.60
```

HAVE OFTEN SEEN JUMPS AT 10% ERROR LEVEL

Fig. 43. Same as previous run, but with weight window removed.

XVI. THE GRAND FINALE—TURNING DXTRAN BACK ON

Recall that DXTRAN was turned off while the space-energy window and the exponential transform optimized the penetration. Figure 44 shows the results of turning DXTRAN back on. This "best" run uses

1. energy cutoff,
2. forced collision in cell 21,
3. ring detector,
4. space-energy weight window,
5. source energy biasing,
6. exponential transform (p = 0.7), and
7. DXTRAN with DXCPN card.

As observed previously, DXTRAN vastly improves tallies 4 and 5 at some expense to tally 1.

XVII. CORRELATED SAMPLING AND PERTURBATION CAPABILITY

A standard MCNP perturbation patch allows up to three slightly different Monte Carlo problems to be run simultaneously. The perturbation calculation estimates the difference in tallies between similar Monte Carlo problems and it estimates the standard tallies.*

Another way of estimating perturbations is correlated sampling in MCNP that allows tally differences to be estimated between two different runs by correlating their random number sequences. The i^{th} particle in run #2 is started with the same random number that starts the i^{th} particle in run #1. Because the i^{th} particle in run #1 might use k_1 random numbers, and the i^{th} particle in run #2 might use $k_2 \neq k_1$, random numbers, the $i + 1^{st}$ particle does not start with the next random number in the sequence after the i^{th} particle terminates. Instead, the $i + 1^{st}$ particle starts with the J^{th} random number beyond the starting random number for the i^{th} random number. In other words, there is a random number jump of J random numbers between the start of particle i and the start of particle i + 1. Thus the i^{th} particle in runs #1 and #2 will both be starting at the $(i - 1) \cdot J$ position in the random number sequence. J, of course, should be large enough so that both k_1 and k_2 are less than J for all particle histories. This correlation of random number sequences is depicted in Table IV.

*For further information, refer to video reel #24, "Various MCNP Patches, Column Input, Exponential Transform, Importance Generator, Perturbation," by Robert G. Schrandt, from MCNP Workshop, Los Alamos National Laboratory, October 4-7, 1983. Available from Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

The correlated sampling problem is identical to the sample problem except that the density in cell 21 (Fig. 3) has been changed. The two correlated problems have

1. density in cell 21 = 2.03E-4 and
2. density in cell 21 increased by 1% to 2.0503E-4.

Figure 45 summarizes the two problems, each run for 20,000 histories. Everything is identical between the two summary charts up to cell 21 because all particles have exactly the same random walk until they enter that cell. Furthermore, a particle entering cell 21, where the random walks diverge, will probably never scatter back toward cell 19. Presumably, if enough particles were run, backscatter from cell 21 would cause very small differences in cells 1-19.

Figure 46 shows FOM tables for the two problems. Note that the means differ by about 1% and that this difference appears to be statistically insignificant because of the 9% errors in the means. However, these charts can be used to obtain batch statistics on 20 batches of 1000. That is to say, the numbers can be postprocessed to figure out the tally for each batch of 1000 particles and then the difference in tally for each batch of 1000 particles can be computed. Error estimates in the tally difference can then be made on the basis of the 20 tally differences. Figure 47 shows the 20 means for each problem and the mean and relative error of the difference. Note that with correlated sampling, a 1% difference has been found to within 8% despite a 9% error in each of the problems.

XVIII. PHOTONS

The sample problem described here is a neutron-only problem. Regarding the variance reduction techniques in MCNP, whatever can be done for neutrons can be done for photons. Only the neutron-induced gamma problem needs special consideration. The difficulty arises in setting reasonable parameters (PWT card) to decide when a photon should be produced at a neutron collision. These parameters specify, on a cell-by-cell basis, the minimum weight for producing a photon. This weight should be inversely proportional to the cells' photon importance. One either has to make a guess or obtain an adjoint solution, such as provided by the weight window generator. In fact, if a photon weight window is used, these (PWT) parameters should be chosen as the lower weight bounds for the most important particles (typically the highest-energy window).

XIX. FUTURE PLANS

Goals for the future are

1. more automatic biasing (learning techniques),

TABLE IV. Random Number Usage in Correlated Runs

Random Numbers for Run #1 (* indicates the random number was actually used)		Random Numbers for Run #2 (* indicates the random number was actually used)
0.14784 *	first particle starts here	0.14784 *
0.29376 *		0.29376 *
0.21632 *		0.21632 *
0.78048		0.78048 *
0.14336		0.14336 *
0.10304		0.10304
0.66592		0.66592
0.38144 *	second particle starts here	0.38144 *
0.52416 *		0.52416 *
0.22912 *		0.22912 *
0.03968		0.03968
0.15776		0.15776
0.14464		0.14464
0.25248		0.25248
0.46272 *	third particle starts here	0.46272 *
0.75904 *		0.75904

2. weight window and generator in more arbitrary phase space,
3. several random number generators (tallies should not affect random walks, and mode 1 neutrons should track mode 0 neutrons), and
4. more perturbation capability.

XX. CONCLUSION

The Los Alamos Monte Carlo neutron/photon particle transport code, MCNP, contains many effective variance reduction capabilities. However, these techniques must be used judiciously and their effects must be monitored using the summary information provided by a Monte Carlo run. This paper has illustrated most of the MCNP variance reduction techniques on a conceptually simple, yet computationally demanding, neutron transport problem. These illustrations should help novice users better understand the capabilities of MCNP techniques more concretely than presented in the MCNP manual, which I hope this report will complement. Whereas the MCNP manual must be complete and general, this report makes no attempt to be either. Use this report to get a flavor for MCNP and the manual to set up problems.

SPACE-ENERGY WEIGHT WINDOW
SOURCE-ENERGY BIAS
FORCED COLLISION
EXPONENTIAL TRANSFORM

ENERGY CUTOFF
RING DETECTOR

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	52768	52592	34328	2.5399E+00	9.2311E-01	1.7392E+00	1.7168E+00	7.9987E+00
3	3	12705	15099	15942	1.1702E+00	3.9682E-01	1.1223E+00	1.2707E+00	7.1343E+00
4	4	10501	11828	11591	3.3196E-01	4.0449E-01	1.2012E+00	4.9750E-01	7.5345E+00
5	5	8667	9811	9421	1.0961E-01	3.1777E-01	1.2243E+00	1.9474E-01	7.4841E+00
6	6	7385	8763	8766	3.2022E-02	3.2130E-01	1.3933E+00	6.9772E-02	7.9168E+00
7	7	6831	8683	8967	1.5076E-02	4.1320E-01	1.4311E+00	2.9334E-02	7.7015E+00
8	8	6485	8498	8718	4.2997E-03	5.1356E-01	1.7967E+00	9.9026E-03	8.4482E+00
9	9	6420	8784	9177	1.4895E-03	6.0602E-01	2.2127E+00	3.2265E-03	9.4105E+00
10	10	6727	8803	8978	7.2261E-04	5.9781E-01	2.0800E+00	1.6019E-03	8.9933E+00
11	11	6846	8863	10033	3.8955E-04	5.7577E-01	1.9760E+00	7.7078E-04	8.8303E+00
12	12	6767	9051	10555	1.7687E-04	4.8943E-01	1.8211E+00	3.5954E-04	8.4750E+00
13	13	7160	9531	11788	6.8770E-05	5.5921E-01	2.0523E+00	1.3282E-04	9.1027E+00
14	14	7378	9933	13009	2.9408E-05	6.0583E-01	2.1495E+00	5.4545E-05	9.3185E+00
15	15	7530	9831	13627	1.2217E-05	6.1099E-01	2.2692E+00	2.2980E-05	9.5956E+00
16	16	7724	9675	14451	5.1402E-06	6.9159E-01	2.3093E+00	1.0162E-05	9.7832E+00
17	17	7814	9889	16742	2.3384E-06	6.9604E-01	2.3162E+00	4.3319E-06	9.8582E+00
18	18	7999	10371	19925	1.1333E-06	6.9670E-01	2.2434E+00	1.9051E-06	9.7979E+00
19	19	7083	10072	18907	4.4401E-07	6.9389E-01	2.2434E+00	8.4349E-07	1.0230E+01
20	20	15368	41010	0	0.	1.2146E+00	3.2985E+00	1.0146E-07	1.0000+123
21	21	34103	68211	35140	4.5204E-12	1.8146E+00	4.3974E+00	1.4958E-10	7.5167E+02
22	22	3133	3133	0	0.	9.8733E-01	2.6367E+00	7.9758E-12	1.0000+123
TOTAL		237394	332431	280065	4.2060E+00				

NPS	TALLY 1 MEAN	TALLY 1 ERROR	TALLY 1 FOM	TALLY 4 MEAN	TALLY 4 ERROR	TALLY 4 FOM	TALLY 5 MEAN	TALLY 5 ERROR	TALLY 5 FOM
4000	4.84254E-08	.1712	77	1.01029E-14	.1610	87	5.54516E-18	.1694	79
8000	5.09067E-08	.1317	70	9.44709E-15	.1240	79	5.62934E-18	.1371	65
12000	5.48174E-08	.1067	71	1.03463E-14	.1023	77	5.80554E-18	.1064	71
16000	5.15928E-08	.0941	73	9.69119E-15	.0905	79	5.41515E-18	.0943	72
20000	5.15698E-08	.0856	72	9.36512E-15	.0826	77	5.34619E-18	.0858	71
24000	4.99339E-08	.0787	73	8.87587E-15	.0768	77	5.14850E-18	.0802	70
28000	4.83468E-08	.0728	74	8.40354E-15	.0716	77	4.90214E-18	.0747	70
32000	4.72914E-08	.0677	76	8.29573E-15	.0673	77	4.79002E-18	.0698	71
36000	4.72683E-08	.0633	77	8.47937E-15	.0655	72	4.85927E-18	.0651	73
40000	4.68660E-08	.0603	77	8.29090E-15	.0620	73	4.79463E-18	.0621	73
44000	4.66976E-08	.0582	76	8.27052E-15	.0597	72	4.77221E-18	.0596	72
48000	4.74397E-08	.0549	77	8.45769E-15	.0573	71	4.85959E-18	.0566	73
51909	4.74217E-08	.0529	77	8.46207E-15	.0551	71	4.86481E-18	.0542	73

****
DUMP NO. 2 ON FILE RUNTPG NPS = 51909 CTM = 4.60

DECREASED FROM 126 WITHOUT DXTRAN

INCREASED FROM 9

INCREASED FROM 8

Fig. 44. DXTRAN turned on.

ρ =2.03E-4

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	20310	20245	13230	2.9038E+00	7.8576E-01	1.6392E+00	1.8336E+00	7.7302E+00
3	3	4854	5773	6121	1.2068E+00	3.2962E-01	1.1022E+00	1.2787E+00	7.1288E+00
4	4	3983	4493	4395	2.0630E-01	5.6021E-01	1.4968E+00	3.9232E-01	8.9520E+00
5	5	3241	3709	3566	9.5539E-02	3.8258E-01	1.3786E+00	1.7657E-01	7.9343E+00
6	6	2762	3309	3316	2.8814E-02	4.3184E-01	1.5712E+00	6.4595E-02	8.1847E+00
7	7	2532	3204	3194	1.3999E-02	5.5666E-01	1.5506E+00	2.7739E-02	8.0382E+00
8	8	2463	3233	3286	5.1721E-03	3.6626E-01	1.5002E+00	1.2042E-02	8.0029E+00
9	9	2447	3364	3416	1.1440E-03	7.7182E-01	2.3990E+00	2.9081E-03	9.9393E+00
10	10	2596	3356	3506	8.1792E-04	5.8220E-01	1.9761E+00	1.7170E-03	8.7167E+00
11	11	2628	3430	3916	5.1950E-04	4.6087E-01	1.6235E+00	1.0072E-03	8.1114E+00
12	12	2668	3595	4368	2.4198E-04	4.1003E-01	1.4915E+00	4.6929E-04	7.7865E+00
13	13	2789	3740	4692	7.7618E-05	4.8312E-01	1.8747E+00	1.4560E-04	8.9391E+00
14	14	2911	3895	5208	3.2070E-05	5.3047E-01	2.0756E+00	5.6759E-05	9.1714E+00
15	15	3017	4004	5647	1.2871E-05	5.9777E-01	2.2049E+00	2.3315E-05	9.5372E+00
16	16	3154	4178	6746	5.7756E-06	6.8805E-01	2.3307E+00	9.4765E-06	9.8171E+00
17	17	3339	4116	6794	2.4249E-06	6.7461E-01	2.2597E+00	4.3407E-06	9.8965E+00
18	18	3318	4277	8139	1.1850E-06	6.7566E-01	2.1622E+00	1.9121E-06	9.6692E+00
19	19	2847	4074	7528	4.5173E-07	6.7608E-01	2.2620E+00	8.3146E-07	1.0292E+01
20	20	6112	16583	0	0.	1.2958E+00	3.4588E+00	1.0138E-07	1.0000+123
21	21	13803	27610	13805	4.7205E-14	1.8236E+00	4.4833E+00	1.5149E-10	7.6105E+04
22	22	1348	1348	0	0.	3.4188E+00	7.1054E+00	2.4142E-12	1.0000+123
TOTAL		93122	131536	110873	4.4633E+00				

DID THE SAME THINGS UNTIL ENTERING THE PERTURBED REGION BECAUSE THE RANDOM NUMBERS WERE THE SAME

ρ =2.0503E-4

CELL PROGR	CELL PROBL	TRACKS ENTERING	POPULATION	COLLISIONS	COLLISIONS * WEIGHT (PER HISTORY)	NUMBER WEIGHTED ENERGY	FLUX WEIGHTED ENERGY	AVERAGE TRACK WEIGHT (RELATIVE)	AVERAGE TRACK MFP (CM)
2	2	20310	20245	13230	2.9038E+00	7.8576E-01	1.6392E+00	1.8336E+00	7.7302E+00
3	3	4854	5773	6121	1.2068E+00	3.2962E-01	1.1022E+00	1.2787E+00	7.1288E+00
4	4	3983	4493	4395	2.0630E-01	5.6021E-01	1.4968E+00	3.9232E-01	8.9520E+00
5	5	3241	3709	3566	9.5539E-02	3.8258E-01	1.3786E+00	1.7657E-01	7.9343E+00
6	6	2762	3309	3316	2.8814E-02	4.3184E-01	1.5712E+00	6.4595E-02	8.1847E+00
7	7	2532	3204	3194	1.3999E-02	5.5666E-01	1.5506E+00	2.7739E-02	8.0382E+00
8	8	2463	3233	3286	5.1721E-03	3.6626E-01	1.5002E+00	1.2042E-02	8.0029E+00
9	9	2447	3364	3416	1.1440E-03	7.7182E-01	2.3990E+00	2.9081E-03	9.9393E+00
10	10	2596	3356	3506	8.1792E-04	5.8220E-01	1.9761E+00	1.7170E-03	8.7167E+00
11	11	2628	3430	3916	5.1950E-04	4.6087E-01	1.6235E+00	1.0072E-03	8.1114E+00
12	12	2668	3595	4368	2.4198E-04	4.1003E-01	1.4915E+00	4.6929E-04	7.7865E+00
13	13	2789	3740	4692	7.7618E-05	4.8312E-01	1.8747E+00	1.4560E-04	8.9391E+00
14	14	2911	3895	5208	3.2070E-05	5.3047E-01	2.0756E+00	5.6759E-05	9.1714E+00
15	15	3017	4004	5647	1.2871E-05	5.9777E-01	2.2049E+00	2.3315E-05	9.5372E+00
16	16	3154	4178	6746	5.7756E-06	6.8805E-01	2.3307E+00	9.4765E-06	9.8171E+00
17	17	3339	4116	6794	2.4249E-06	6.7461E-01	2.2597E+00	4.3407E-06	9.8965E+00
18	18	3318	4277	8139	1.1850E-06	6.7566E-01	2.1622E+00	1.9121E-06	9.6692E+00
19	19	2847	4074	7528	4.5173E-07	6.7608E-01	2.2620E+00	8.3146E-07	1.0292E+01
20	20	6112	16583	0	0.	1.2958E+00	3.4588E+00	1.0138E-07	1.0000+123
21	21	13803	27610	13805	4.7677E-14	1.8236E+00	4.4832E+00	1.5149E-10	7.5351E+04
22	22	1348	1348	0	0.	3.4173E+00	7.1042E+00	2.4147E-12	1.0000+123
TOTAL		93122	131536	110873	4.4633E+00				

Fig. 45. Correlated sampling example.

ρ =2.03E-4

TALLY 5

NPS	MEAN	ERROR	FOM
1000	9.39391E-20	.3471	69
2000	8.55653E-20	.2516	72
3000	6.67066E-20	.2251	68
4000	7.04297E-20	.1841	74
5000	6.79854E-20	.1649	76
6000	6.40329E-20	.1498	79
7000	6.30279E-20	.1355	85
8000	6.18213E-20	.1272	84
9000	6.37404E-20	.1198	81
10000	6.19940E-20	.1148	82
11000	6.41550E-20	.1081	82
12000	6.66364E-20	.1112	71
13000	6.40622E-20	.1077	71
14000	6.24940E-20	.1041	72
15000	6.14167E-20	.1012	72
16000	6.18275E-20	.0971	73
17000	5.98841E-20	.0953	73
18000	6.01460E-20	.0915	74
19000	5.96264E-20	.0894	73
20000	5.90955E-20	.0894	70

****

DUMP NO. 2 ON FILE RUNTPF NPS = 20000 CTM = 1.77

ρ =2.0503E-4

TALLY 5

NPS	MEAN	ERROR	FOM
1000	9.30107E-20	.3471	70
2000	8.47200E-20	.2516	72
3000	6.60475E-20	.2251	68
4000	6.97337E-20	.1841	74
5000	6.73137E-20	.1649	76
6000	6.34001E-20	.1498	79
7000	6.24051E-20	.1355	85
8000	6.12105E-20	.1272	84
9000	6.31105E-20	.1198	81
10000	6.13814E-20	.1148	82
11000	6.35210E-20	.1081	82
12000	6.59779E-20	.1112	71
13000	6.34292E-20	.1077	71
14000	6.18765E-20	.1041	72
15000	6.08098E-20	.1012	72
16000	6.12165E-20	.0971	73
17000	5.92923E-20	.0953	73
18000	5.95516E-20	.0915	74
19000	5.90371E-20	.0894	73
20000	5.85115E-20	.0894	70

THE DIFFERENCE BETWEEN THESE TWO IS PROBABLY STATISTICALLY SIGNIFICANT, BUT MCNP DOES NOT DIRECTLY GIVE THE ERROR IN THE DIFFERENCE. HOWEVER, THIS CAN BE FIGURED OUT FROM THE FOM CHARTS BECAUSE WE CAN DO BATCH STATISTICS, HERE 20 BATCHES OF 1000.

AVERAGE SCORE DUE TO PARTICLES 9001–10,000 IS

$$\frac{10{,}000 * 6.13814\text{E}{-20} - 9000 * 6.31105\text{E}{-20}}{1000}$$

****

DUMP NO. 2 ON FILE RUNTPE NPS = 20000 CTM = 1.77

FIG. 46. PROCESS FOR OBTAINING BATCH STATISTICS.

Fig. 46. Process for obtaining batch statistics.

CELL 21 DENSITIES 1% DIFFERENT
(CELL 21 IS THIN FORCED COLLISION
CELL NEAR RING DETECTOR)

ρ = 2.03E-4	ρ = 2.0503E-4
9.301070E-20	9.393910E-20
7.642930E-20	7.719150E-20
2.870250E-20	2.898920E-20
8.079230E-20	8.159900E-20
5.763370E-20	5.820820E-20
4.383210E-20	4.427040E-20
5.643510E-20	5.699790E-20
5.284830E-20	5.337510E-20
7.831050E-20	7.909320E-20
4.581950E-20	4.627640E-20
8.491700E-20	8.576500E-20
9.300380E-20	9.393180E-20
3.284480E-20	3.317180E-20
4.169140E-20	4.210740E-20
4.587600E-20	4.633450E-20
6.731700E-20	6.798950E-20
2.850510E-20	2.878970E-20
6.395970E-20	6.459830E-20
4.977610E-20	5.027360E-20
4.852510E-20	4.900840E-20

20 MEANS FOR BATCHES OF 1000 HISTORIES FROM FOM TABLES

MEAN OF DIFFERENCES → MEAN - 5.840000E-22 REL ERROR = 7.783477E-02 ← HIGHER DENSTIY IS CONTRIBUTING ABOUT 1% MORE THAN LOWER DENSITY

MEAN FOR ρ=2.03E-4		MEAN FOR ρ = 2.0503E-4	
5.85115E-20	0.0894	5.90955E-20	0.0894

CONCLUSION:

USING CORRELATED SAMPLING, HAVE FOUND A 1% DIFFERENCE TO WITHIN 8% DESPITE THE 9% ERROR IN BOTH CALCULATIONS

Fig. 47. Means for standard density and perturbed density problems.

XXI. SUMMARY

SUMMARY PROBLEM #1

Page This Report	Techniques	Particles Time Part/Min	F1 σ_{mr} FOM	F4 σ_{mr} FOM	F5 σ_{mr} FOM	Comments
6	Analog	3919 0.61 min 6425	0	0	0	No particles get past cell 14 (Point detector contributions only from cell 21).
8	Energy Cutoff .01 MeV	13968 0.60 min 23280	0	0	0	*Assumes* particles below .01 MeV do not contribute; No particles beyond cell 13.
11	Geometry Splitting (factor of 2, cells 2-19) Energy Cutoff	2118 0.60 min 3530	5.87E-7 0.24 27	0	0	Particles now penetrating concrete; use "tracks entering" to refine importances.
12	Refined Splitting Energy Cutoff	1520 0.58 min 2620	5.03E-7 0.27 23	7.21E-14 1.00 1	0	Keep refined splitting on "tracks entering" information.
14	Energy Roulette Refined Splitting Energy Cutoff	4699 0.61 min 7703	8.38E-7 0.18 50	1.92E-13 0.64 4	0	Factor of 2 gained by energy roulette.
17	Weight Cutoff/ Implicit Capture Energy Roulette Refined Splitting Energy Cutoff	2099 0.61 min 3441	5.62E-7 0.19 37	5.59E-14 0.73 2	0 0	Implicit capture and weight cutoff did reduce the history variance, but time per history increased too much. Thus analog capture better.
19	Forced Collision Energy Roulette Refined Splitting Energy Cutoff	31617 4.61 min 6858	5.59E-7 0.068 45	7.53E-14 0.27 2	2.61E-17 0.29 2	Forced collision allows the point detector (F5) to get tallies. Material too thin.
25	DXTRAN Forced Collision Energy Roulette Refined Splitting Energy Cutoff	2231 1.43 min 1560	7.35E-7 0.23 12	1.24E-13 0.21 15	7.62E-17 0.22 14	DXTRAN successful for tallies 4 and 5, but too slow; angle biasing definitely helps, work on speed.
26	DXCPN and DXTRAN Forced Collision Energy roulette Refined Splitting Energy Cutoff	11427 2.60 min 4395	7.32E-7 0.10 34	1.22E-13 0.095 42	7.21E-17 0.10 34	DXCPN solves speed problem. Note F1 tally 4395/1560≃34/12=FOM ratio.

PROBLEM #1 (continued)

Page This Report	Techniques	Particles Time Part/Min	F1 σ_{mr} FOM	F4 σ_{mr} FOM	F5 σ_{mr} FOM	Comments
27	Ring Detector Energy Roulette DXTRAN/DXCPN Forced Collision Refined Splitting Energy Cutoff	11755 2.60 min 4521	6.54E-7 0.10 38	1.16E-13 0.093 44	6.78E-17 0.096 41	Ring detector looks marginally better.
30	Cone Biasing Ring Detector DXTRAN/DXCPN Forced Collision Refined Splitting Energy Cutoff Energy Roulette	6049 2.60 min 2327	6.82E-7 0.11 32	1.22E-13 0.092 45	7.37E-17 0.097 40	Cone bias has little effect because $-\hat{y}$ source particles die quickly. Remove cone bias below.
32	Exponential Bias Ring Detector DXTRAN/DXCPN Forced Collision Refined Splitting Energy Roulette Energy Cutoff	5404 2.59 min 2086	6.79E-7 0.11 33	1.05E-13 0.098 39	6.43E-17 0.10 35	Exponential source bias looks marginally detrimental.

SUMMARY PROBLEM #2
New Source 95% at 2 MeV and 5% at 14 MeV

Page This Report	Techniques	Particles Time Part/Min	F1 σ_{mr} FOM	F4 σ_{mr} FOM	F5 σ_{mr} FOM	Comments
33	Splitting (same) Energy Cutoff, Ring Detector/Forced Collision/DXTRAN/ DXCPN (subsequent runs use above techniques unless specified otherwise)	33092 4.60 min 7194	4.43E-8 0.23 4	7.57E-15 0.22 4	4.35E-18 0.21 4	Problem much harder because source spectrum much softer. Factor 15 less transmission.
35	Source Energy Bias	6306 4.63 min 1362	4.90E-8 0.11 16	8.61E-15 0.11 17	5.10E-18 0.11 17	Factor of four improvement by E bias.
36	*No* source energy bias, energy roulette	66475 4.61 min 14420	6.22E-8 0.15 9	9.80E-15 0.14 10	5.94E-18 0.15 9	Worse than source energy bias, better than *no* energy discrimination.
39	Source Energy Bias Energy Roulette	16957 4.61 min 3678	5.04E-8 0.080 33	8.81E-15 0.76 37	5.14E-18 0.076 38	Good idea to use both in this problem.
42	Turn off splitting and use importances as weight window	46770 4.60 min 10167	5.87E-8 0.27 3	1.05E-14 0.24 3	5.82E-18 0.23 3	Within statistics, about the same as splitting.

Subsequent Runs Use Weight Window Unless Otherwise Specified						
Page This Report	**Techniques**	**Particles Time Part/Min**	**F1 σ_{mr} FOM**	**F4 σ_{mr} FOM**	**F5 σ_{mr} FOM**	**Comments**
45	Window from importance generator on (spatial)	46770 4.79 min 9764	5.87E-8 0.27 2	1.05E-8 0.24 3	5.82E-18 0.23 3	Note this run and previous run tracked; only difference is a 4% reduction in speed.
48	Use generated space window, turn DXTRAN off, space-energy generator on	28144 4.63 6079	3.66E-8 0.19 6	5.08E-15 0.66 0	1.96E-18 0.76 0	DXTRAN turned off while window is being optimized for penetration.
50	Space-energy window generated above; DXTRAN off	79266 4.61 min 17194	4.48E-8 0.070 43	8.24E-15 0.23 4	4.24E-18 0.26 4	Space-energy window gives dramatic improvement.
51	Source energy bias so that particles start within space-energy window	71167 4.61 min 15438	4.92E-8 0.054 75	8.48E-15 0.29 2	9.20E-18 0.51 0	Note good improvement with source energy bias.
53	Same as above, except correct bad window	74051 4.60 min 16098	5.09E-8 0.55 72	8.61E-15 0.28 2	2.20E-18 0.31 2	Murphy's Law.
55	Exponential transform, space-energy window, source-energy bias	81021 4.60 min 17613	4.85E-8 0.041 126	1.06E-14 0.15 9	4.62E-18 0.16 8	Exponential transform works well with weight window.
56	Same as above, except remove window	90897 4.60 min 19760	4.05E-8 0.35 1	1.90E-16 1 0	8.59E-20 1 0	Exponential transform *requires* window.
59	GRAND FINALE Turn DXTRAN back on	51909 4.60 min 11285	4.74E-8 0.053 77	8.46E-15 0.055 71	4.86E-18 0.054 73	

REFERENCES

1. Los Alamos Monte Carlo Group, "MCNP—A General Monte Carlo Code for Neutron and Photon Transport," Los Alamos National Laboratory report LA-7396-M (Rev.) (April 1981).

2. Thomas E. Booth, "Monte Carlo Variance Comparison for Expected Value Versus Sampled Splitting," *Nuclear Science and Engineering* **89**, 305-309 (1985).

APPENDIX

Input File Differences for MCNP Version 3A

The calculations described in this report were done with MCNP version 2D, and some of the input file specifications have been changed in version 3A. This appendix was added to aid the reader who wants to run the sample problem on MCNP3A.

The source specification (cards SRC1, SI, and SP of Fig. 2) will have to be altered substantially. In addition, the reader should be aware of the following changes:

1. Particle Types:

MCNP3A will recognize two particle types with the following mnemonics:

N = neutron
P = photon

2. Data Cards:

The particle type of each data card will be the first data entry and no longer appear as part of the data card name. This means that the following data cards are renamed:

New Name	Old Name(s)	Description
IMP	IN,IP	importance
CUT	CUTN,CUTP	time, energy, weight cutoffs
PHYS	ERGN,ERGP	energy physics cutoffs
WWN	WFN,WFP	weight window bounds
WWE	WFN,WFP	weight window energies
WWGE	WGEN,WGEP	weight window generator energies
WWP	WDWN,WDWP	weight window game parameters
ESPLT	NSPLT,PSPLT	energy splitting/roulette
EXT	EXTYN,EXTYP	exponential transform
DXT	DXN,DXP	DXTRAN sphere specification
FCL	FCN,FCP	forced collisions
DXC	DXCPN,DXCPP	DXTRAN cell contributions

The new root entry will appear in columns 1-5; the N or P data type will be the first entry beyond column 5. If the first data entry is not an N or P, there will be a fatal error. Note that only one particle type may be specified. If the particle type is inconsistent with the problem mode, there will be a warning error. A warning rather than a fatal error will be issued so that a coupled neutron/photon run may be switched to a neutron-only run without removing all the photon data cards. In MCNP3A the old data cards will be accepted with a warning that they will be obsolete in MCNP3B.

3. MODE Card:

The MODE card will specify the problem particle types. Examples:

MODE N	(old mode 0)
MODE N P	(old mode 1)
MODE P N	(old mode 1)
MODE P	(old mode 2)

If both N and P are specified, the order does not matter for MCNP3A and the two entries must be separated by at least one space. The space is required so that future versions of the code can have particle types with more than one character mnemonics.

The old MODE card will be accepted with a warning that it will have different entries in MCNP3B.

4. Tally Particle Types:

Whether a tally is a neutron or photon tally is specified by an N or P as the first entry on the tally Fn card regardless of the tally number. For MCNP3A, if the N or P is missing then a warning will be issued and the particle type will be assumed from the tally number as in previous versions. Examples:

F4	P c1 c2 c3	photon flux tally
F15	N x y z ro	neutron detector tally
F7	c1 c2 c3	neutron heating tally: warning issued.

The neutron and photon heating tallies may be added together by having both an N and a P as the first and second data entries. The N and P may be in any order, i.e., P and N, and they must be separated by a space. The F6 and F16 tally types are the only tally types that may be added in this way. A corresponding FMn card for the combined tally causes a fatal error if it contains anything more than constants. Examples of proper usage:

```
F6      P N c1 c2 c3
FM6      C1

F36     N P c1 c2 c3 c4
FM36     (C1) (C2) (C3) (C4) (C5)
```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