AN ABSTRACT OF THE THESIS OF

Edward K. Kropp for the degree of Master of Science in Radiation Health Physics presented on August 12, 1998.

Title: Design and Simulation of a Self-Powered Neutron Spectrometer.

Abstract approved: _______________ Stephen E. Binney _______________

A self-powered neutron detector (SPND) is a device that, coupled with a current meter, provides a readout proportional to neutron population. This thesis discusses the design parameters of an array of such devices, their characteristics, and the use of these devices as a self-powered neutron spectrometer (SPNS) to provide information about the energy distribution in a neutron radiation field.

Neutron absorption in an appropriate material produces subsequent beta emissions. In a SPND, some of these beta particles will cross a non-conducting region and stop in a collector material. A net exchange of charge between these regions can be read as a current flowing between the emission region and the collector region.

One potential SPNS design was modeled using a Monte Carlo simulation of the device's interaction with a radiation field. The Monte Carlo program used predicts the beta flux which is proportional to the current that would be produced by an actual device. Various beta emitting materials were considered for this device, and a sensitivity study of each was included.

The design considered is comprised of a concentric set of these cylindrical SPND detector elements which, in themselves, are currently available technology.

Design and Simulation of a Self-Powered Neutron Spectrometer

by

Edward K. Kropp

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 12, 1998
Commencement June 1999

Master of Science thesis of Edward K. Kropp presented on August 12, 1998

APPROVED:

Major Professor, representing Radiation Health Physics

Head of Department of Nuclear Engineering

Redacted for privacy

Dean of Graduate School

I understand the my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for privacy

Edward K. Kropp, Author

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

Design and Simulation of a Self-Powered Neutron Spectrometer

Chapter 1. INTRODUCTION

Neutrons are particulate radiation released in nuclear reactions under certain conditions such as a fission reaction. They may have various energies which are defined loosely as fast, epithermal, and thermal. A fast neutron has an energy on the order of the mass-defect of a nuclear reaction, from approximately 10 keV to 15 MeV. An epithermal neutron has a much lower energy and may react with various atomic nuclides in a non-linear fashion, with high interaction probability or cross section at specific energies, but a low interaction cross section at slightly above or below these resonance energies. Thermal neutrons, defined as below 0.5 eV, typically have average energies of about 1/40 eV [1], act much more like a gas, and follow a Maxwellian energy distribution. An application such as verification of a nuclear core model, evaluating a neutron beam port, or prediction of a dose in a neutron field may potentially require simultaneous measurement of neutrons in these three regions.

Figure 1 is plotted from theoretical distribution formulas and shows the three distinct neutron spectral regions. The thermal region follows a Maxwell-Boltzmann distribution which is dependent on the temperature of the surrounding media. The center region is called epithermal and follows an inverse kinetic energy (1/E) profile. Fast neutrons are distributed according to a Watt spectrum. Each distribution has a significantly different shape.

A self-powered neutron detector (SPND) can be used to measure the flux of an intense neutron field. This device utilizes beta emissions from materials, which absorb some fraction of the neutrons and provide a current that can be measured on a sensitive picoammeter. A series of these detector elements, nested within each other, could (in theory) provide readings of thermal, epithermal, and fast energy neutron fluxes.

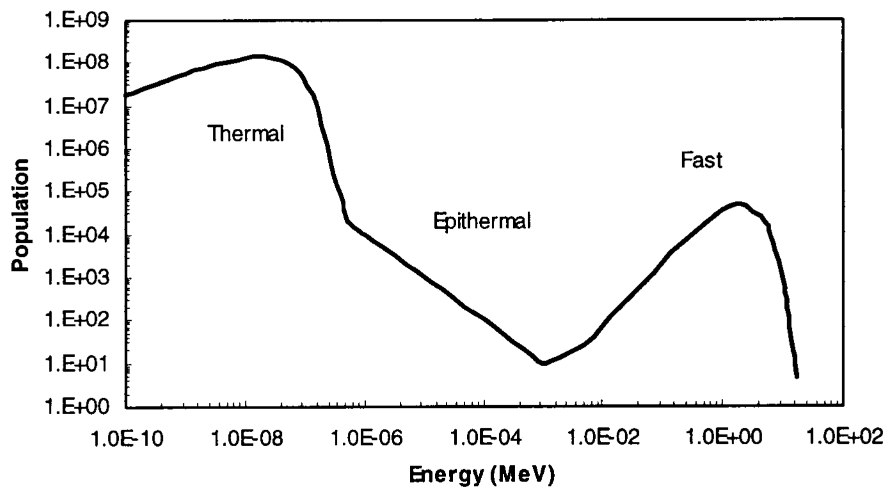

Figure 1. Neutron Spectrum

1.1 Problem Definition

Determine a suitable design for a SPND-based Self- Powered Neutron Spectrometer (SPNS) and use computer modeling to predict operating performance.

1.2 Statement of Purpose

Using established SPND technology, determine materials required for a SPNS. Use MCNP4B to determine the thicknesses of emitter and insulator regions in each detector element. Simulate actual operation of a complete SPNS using MCNP4B.

Chapter 2. LITERATURE REVIEW

A search of current literature shows many different types of neutron spectrometers, some with fine resolution or a very wide range. The actual list is quite long and includes devices that are based on neutron moderation, fast-neutron scattering, and fast neutron-induced reactions. Due to the large number of actual neutron spectrometers, only a select few will be mentioned here.

2.1 Bonner Spheres

Bonner spheres are a series of neutron detector elements, spherical in shape with radii varying from about 6 to 20 cm. An array of detectors, each with a distinct energy response, can be used to measure neutrons of various energies. Three detectors, for thermal, epithermal, and fast neutrons, are needed to characterize a three energy group neutron spectrum. More typically a much larger array of spheres is required to determine the shape of a spectrum.

Bonner spheres detect neutrons by first moderating the neutrons to thermal energies with various thicknesses of hydrocarbon shells [2] and then detecting some of these thermalized neutrons with a central LiI scintillation counter. A boron containing detector chamber or ^{3}He gas proportional counter may also be used. The spherical symmetry of this device eliminates any angular dependence. A drawback of this approach is that a set of these spheres can take up considerable volume, which means that they are hard to place in a reactor or other confined space and would certainly effect the criticality of any fissionable assembly. Hence they are more useful for external beams.

2.2 Semiconductors

Silicon semiconductor devices rely on electron-hole pair production to produce a signal to indicate the presence of neutrons. However, under a high flux field, severe lattice damage may occur, limiting sensitivity and energy resolution, which results in a very short useful device life-span [3]. With various degrees of shielding, energy discrimination can be improved.

2.3 Self-Powered Neutron Detectors

A self-powered neutron detector, Figure 2 [4], uses an (n, γ) reaction with a delayed β which is read directly, without amplification, by a picoammeter. It involves three materials. The first is the beta source material which absorbs neutrons and emits beta particles (high energy electrons). This region may or may not need a conductive backing. The second is an insulator material, which is designed to electrically isolate the beta source material from the collector material. The most important consideration for this material it that it does not significantly attenuate the beta emissions. This is best done with a material composed of low atomic number atoms, and on the order of a millimeter thick, depending on the emitted beta energy. The last material is a conducting material that absorbs the emitted beta particles. Movement of charge, proportional to the neutron flux, can be read by connecting the source material to the collector material with a very sensitive current sensing instrument, a picoammeter.

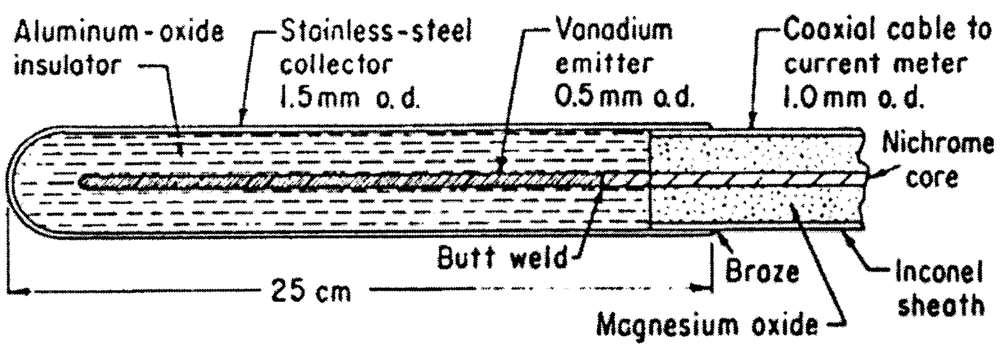

Figure 2. A Typical SPND

Several SPNDs can be nested inside each other provided they do not interfere with each other. These can be nested cylinders, such as shown in Figure 3. The dark lines show boundaries of detector units, and the light lines within signify surfaces between materials.

The sensitivity of a single SPND is dependent on several factors, including beta energy and geometry. An analytical formula for the sensitivity can be expressed as:

$$\text{Electrical Current} = \phi * \sigma * N * \%\beta * G * C/\beta$$

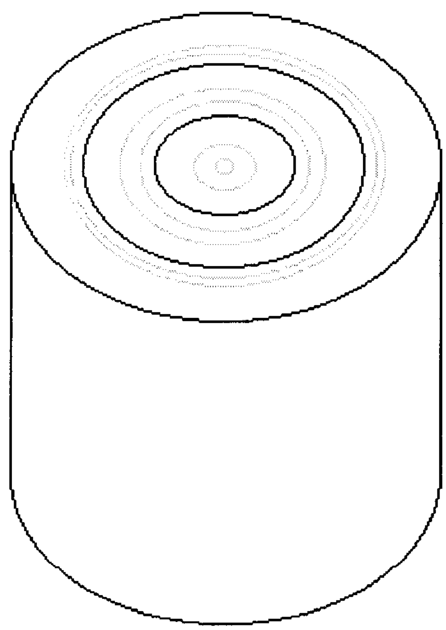

Figure 3. Concentric detector elements in a SPNS

The term ϕ, in units of neutrons $cm^{-2}\ s^{-1}$, is the neutron flux in the emitter material of the detector. The cross section σ represents the apparent size of one atom, or probability of interaction with a nearby free neutron, and has units of $cm^2\ atom^{-1}$. N is merely the total number of atoms in the emitter region. The term $\%\beta$ refers to the fraction of neutron captures that result in a beta decay and is 1.0 for most materials under consideration. The geometrical factor G is the most complicated term, as it depends on the combination of beta energy and material densities and arrangement. The last factor, C/β, is the charge of one electron, which causes the final result to have units of current (A).

Chapter 3. SPECTROMETER DESIGN

3.1 Details of Self-Powered Neutron Detector Array

The array of SPNDs, which is called a SPNS here, consists of three individual SPNDs which each have three regions, the neutron absorber/beta emitter region, the insulator, and the collector/shield. Wires attached to the absorber/emitter and collector regions deliver current to a remote meter. A typical SPND is cylindrical in design, so the spectrometer is also cylindrical, with concentric SPND units as shown in Figure 3.

3.2 Emitter Materials

The materials for the neutron absorbing, beta emitting region are subject to a few constraints, the first of which is that it be a metal or be present in some other solid, manufacturable form. A second consideration is half life, which should be reasonable as compared to measurement time requirements, with several minutes as an upper boundary. To approach steady state currents, the spectrometer would have to be exposed to the flux for at least four half lives of the longest half life beta emitter, and a half hour may be considered a very long time to wait for a reading. A third consideration is that the parent nuclide have a significant neutron cross section to aid in sensitivity of the device. A fourth concern is the beta spectrum emitted by the emitter material after neutron capture. The beta energies should be high enough so that a significant fraction will cross the insulator region, but not so high as to require heavy shielding. Table 1 shows a selection of nuclides that were considered as emitters [5].

Table 1. Potential Nuclides for SPNS Emitters

Parent Nuclide	Parent Abundance (%)	Parent Thermal Cross Section	Parent Epithermal Cross Section	Daughter Nuclide	Daughter Half life	Daughter beta-Max (MeV)
^{103}Rh	100	11 b	13 b	^{104}Rh	42.3 s	2.442
^{27}Al	100	0.233 b	0.17 b	^{28}Al	2.25 m	2.863
^{51}V	99.750	4.9 b	2.7 b	^{52}V	3.76 m	2.47
^{55}Mn	100	13.3 b	14.0 b	^{56}Mn	2.578 h	2.84

Table 2 shows the relative strength of emitted betas within several energy groups for the materials in Table 1. Each isotope has a finite upper limit to the beta energy. These are the beta energy spectra used as input in the MCNP4B model.

Table 2. Normalized Beta Spectra of Emitter Progeny

Energy Bin (MeV)	^{104}Rh	^{52}V	^{56}Mn	^{28}Al
0 - 0.01	0.00241	0.00156	0.0069	0.00080
0.01 - 0.02	0.00247	0.00162	0.0070	0.00087
0.02 - 0.04	0.0051	0.00344	0.0143	0.00197
0.04 - 0.1	0.0170	0.0122	0.0466	0.0077
0.1 - 0.3	0.075	0.061	0.174	0.0425
0.3 - 0.6	0.159	0.141	0.230	0.108
0.6 - 1.3	0.446	0.434	0.270	0.380
1.3 - 2.5		0.345	0.245	0.448
1.3 - 2.442	0.289			
2.5 - 2.542		0.0000259		
2.5 - 2.849			0.0055	
2.5 - 2.863				0.0112

Figure 4 shows the same information graphically.

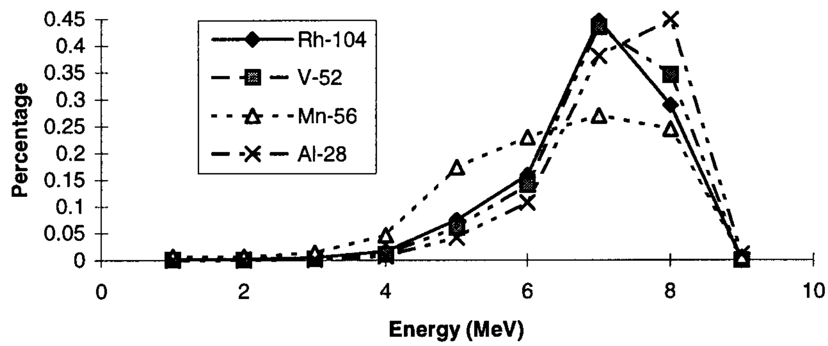

Figure 4. Beta Spectrum

3.3 Insulators

Many materials can be used to insulate the beta-emitting/neutron absorber material from the collector/conductor region. Ceramics make good insulators and are relatively stable under high temperatures. Physical shock or transients of various kinds can shatter them, however. Epoxy, however, can easily be applied in the form of coating, glue, or paint. Power coatings are formed with very low solvent fractions, are therefore harder than paints and epoxies, and have a minimum amount of void space. Hydrocarbon polymers make fair insulators, are very inexpensive, but are less stable than other alternatives. To chose between any of these options, principles of economy and manufacturability should be applied, but these are beyond the scope of this thesis. The exact formulation of any insulator compound, however, should be evaluated for long-term neutron activation products. Actual evaluation may require testing of different materials from different sources with their many impurities, and is beyond the scope of this paper.

3.4 Conductors

Lead is a fair conductor, and is suitable for the low currents in the SPNS. It is especially resistant to neutron bombardment, is ductile and corrosion resistant. Lead can anneal at fairly low temperatures, and has alloys with a broad range of melting points over the temperature expected in a reactor core. The closer a metal is to its melting temperature, the faster it will anneal. Copper is a very good conductor, second only to silver. It is ductile, a good plating agent, and can also anneal at relatively low temperatures.

Most other common metals are not good choices due to cost, difficulty in fabrication, or por neutronic behavior. An isotope such as ^{59}Co can absorb a neutron and become ^{60}Co. ^{60}Co beta decays with a half life of 5.3 years but emits two penetrating gamma rays. These gammas can penetrate any light shielding, and the long half life means that they will be produced for some time after neutron bombardment ceases. This would make for a detector that is hazardous to service and inconvenient to dispose of. However, cobalt may be well suited for measuring higher energy neutrons due to the emission of prompt gammas during neutron capture. These gammas will produce Compton electrons which can be read as a signal in a SPND. Many materials must be avoided that could possibly contain this isotope or any similarly hazardously activating isotopes. Aluminum produces unreliable electric connections and therefore may not be favorable choice.

Iron makes a fair conductor and can be used in this application, as signal strength losses would be minimal with the minute current expected. Iron and its alloys have been used in commercial SPNDs [4], can have low activation cross sections, and are therefore used in these simulations.

3.5 A Complete Unit

A complete unit consists of three (or more) SPNDs. Each beta emission region should have a different response to the neutron flux. This may be accomplished by requiring neutron absorbing/beta emitting materials to have different neutron cross sections at the neutron energies of interest. An alternative is to shape the neutron flux between each region. Of key importance is a significant contrast in neutron response in each SPND element.

3.6 Decoupling Signals For Different Energy Neutrons

The neutrons of the three energy ranges will produce emitted betas, to some extent, in all the detector elements. This is an unavoidable aspect of the energy dependent cross section. As much as these elements will be cross-coupled to each other, the signals derived may still be used to properly register the different energies.

Signal data were generated, from known energy distributions, one energy or distribution region at a time. The responses from each energy region can be combined into a vector, and these vector responses used to form a response matrix. The inversion of this matrix can then be used to deconvolute signal data into an energy-dependent spectrum.

Chapter 4: EXPERIMENTAL DESIGN

4.1 Description Of Monte Carlo Technique

Monte Carlo simulations are a class of non-deterministic or stochastic computer programs. It is used here to emulate interaction of radiation fields with matter by tracking individual particles. This method is generally attributed to Fermi, von Neumann, and others and emerged from work done at Los Alamos during World War II [6]. Particles emanate from a source region, travel a distance randomly determined by their interaction cross sections, are eventually captured, and may also cause the creation of other particles which are then tracked later. The simulation requires the tracking of neutrons (the field particles of interest), and electrons (which will provide a current reading for a meter), and photons which can create additional electrons to be tracked.

4.2 Advantages Of Monte Carlo Over Rules-Of-Thumb

The Monte Carlo technique has several advantages over deterministic or rule-of-thumb procedures used for calculating interactions of radiation with matter. Particles follow the rules of the known experimental data through complicated geometries. In general, a large population for neutrons is tracked to estimate the effects of an extremely large neutron flux. Rare but important events can be tracked as well by biasing the input data to favor their occurrence. This bias can then be removed by a simple calculation at the end. Rule-of-thumb calculations usually involve very simple geometries and provide only an estimated result.

4.3 MCNP4B Program

The particular program used is called Monte Carlo, N-Particle, version 4B (MCNP4B) and is currently supported by the X-CI Code Integration Group at the Los

Alamos National Laboratory. MCNP4B is able to track particle histories for neutrons, photons, and electrons.

4.4 Neutron Source

Initial simulated particles can be placed in a source region or, as in these simulations, on a source surface with specified energy and direction distributions. They then proceed through the model, interact with the various materials until they are absorbed or leave the system. Particles other than neutrons may be eliminated if they fall below some kinetic energy cutoff, but neutrons are tracked down into thermal energies.

The neutrons in this experiment originate outside the detector and interact with materials to produce unstable nuclei. These nuclei are the source of beta particles which will eventually be read as a current with a picoammeter.

4.5 Beta Dose/Counts For Current

MCNP predicts current tallies on a surface that divides the insulator region in half. The reason for choosing this seemingly arbitrary surface is that many electrons will not penetrate the insulator region. They may later drift to one conductor or the other. However, there still will be an immediate effect on current as their presence will induce charge displacement in one region or the other.

The emitter region can attenuate some of its emitted betas in a process called self-shielding. Figure 5 shows the effect of increasing the beta emitting region's thickness while maintaining a constant specific activity which would be consistent with a fixed neutron flux. The yield scale on this chart indicates beta tallies (electrons that, for these purposes, have crossed the insulator junction) produced per source neutron. Aluminum has a slightly higher beta energy, but more significantly, a lower density, which greatly reduces the effect of this self-shielding. However, most of these materials produce little effective sensitivity increase beyond 0.1 cm thickness.

The effect of varying thickness of the insulator region is shown in Figure 6. The beta yield drops significantly with even a small increase in this thickness.

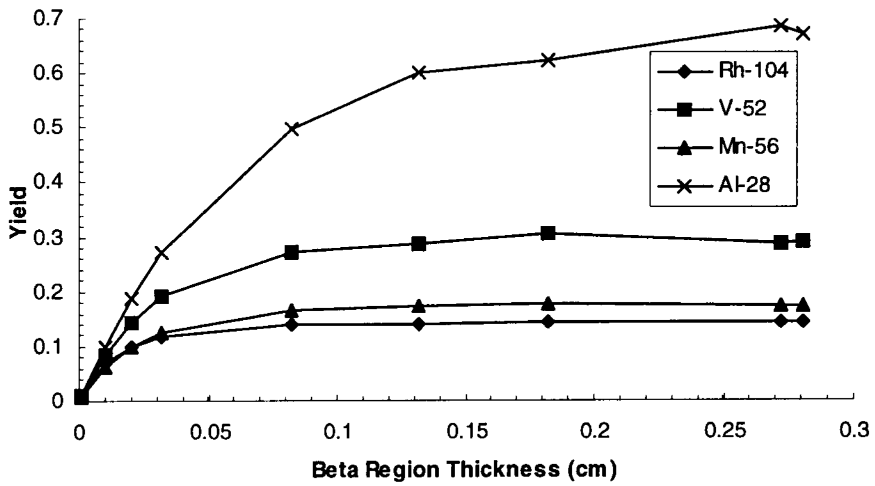

Figure 5. Effect of Beta Source Thickness on Relative Yield

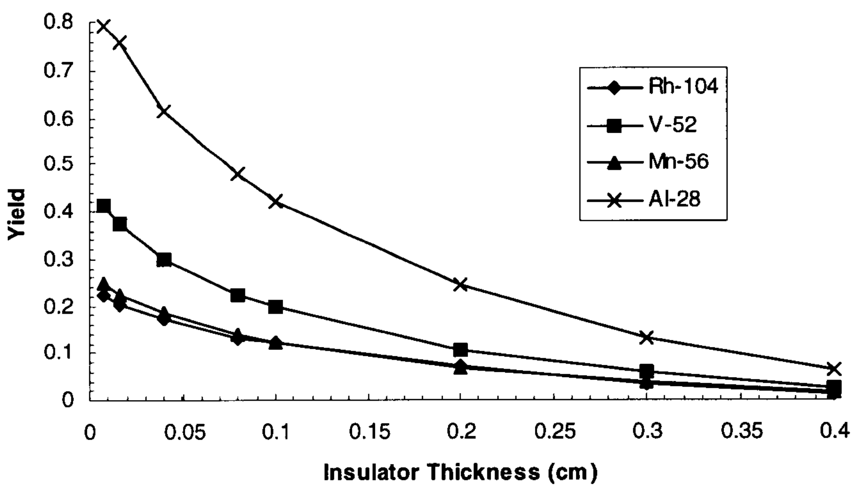

Figure 6. Effect of Insulator Thickness on Relative Yield

For arbitrary reasons, the insulator thickness used in the simulations was 0.008 cm, as this may be a reasonably manufacturable insulator thickness and has the lowest attenuation of the beta current.

Appendix A shows the MCNP4B input and output for one typical run which was used to generate data for the above figures. Not all runs are shown separately as each data point constitutes one MCNP4B run. Various beta spectra or variation of cell thickness were used to generate these graphs, but only one of the several dozen simulations is included for brevity.

Several factors have an effect on the beta yield and therefore the sensitivity of a detector element. Electrons produced by beta decay following (n, γ) reactions must first be able to leave the source material, and only half of these will be heading in the right direction, toward the collector. Some of these will be attenuated by the insulator material. As electrons are charged particles and have a finite range, this attenuation will be minimal if the insulator is thin (Figure 5). Betas can be detected farther away due to Compton production from gammas which are not as easily shielded. The probability of a given particle crossing the insulator region is dependent on the thickness of the region, the direction it is traveling, and its energy. Figure 3 shows the beta spectrum for the materials used in the beta-emitting regions. The remaining beta particles are then absorbed into the collector plate, producing a net exchange of charge. The ratio of the beta tally relative to incident neutrons determines the response of the device.

4.6 Neutron, Gamma, and Beta Source Simulations.

MCNP4B is capable of modeling multiple sources; however they must be of the same particle type. Also, all the cross section tables used in MCNP do not produce the delayed betas. This is a time dependent problem, as some betas may not be emitted for a significant time after absorption of the neutron. So the input deck should be run three times. The first run has a source that is an isotropic neutron flux originating on the inside of a spherical surface. Some small fraction of these neutrons are absorbed in various cells to produce tallies. This was a neutron-only problem.

The results of the neutron absorption simulation could have been used as the source strength for the beta emission simulation, but this was not required as the results scale linearly, and only one beta simulation is needed for each combination of material type and thickness. The beta simulation tracks both betas and photons, but only betas were used as the source term.

A third simulation could have been run with photons as the source. This would have been a sum of the capture gammas, transition gammas and gammas associated with beta decay. This would also have been a photon/electron problem. Electrical current produced would be the product of the sum of the second two runs with appropriate conversion factors. A gamma production cross section is required for this type of calculation but was not available for rhodium, so this contribution was neglected.

Admittedly, this method leaves something to be desired as neutron capture in other regions, as well as other neutron-gamma production modes is ignored. This is unavoidable as a ^{103}Rh cross section table with gamma production is not available.

4.7 Decoupling Matrix Derived From Model Response

Since every detector element will be at least somewhat responsive to all the neutron energies, the signals derived from them will be coupled. By noting the response of each detector segment as it is irradiated with neutrons of known energies, a response matrix can be developed as a model for the spectrometer response. The successive measurements can be multiplied by the inverse of this response matrix, and the thermal, epithermal, and fast neutron spectrum components can be determined.

4.8 Time Dependence

There are two time-dependent considerations associated with SPNSs. The first is that there is a time delay between neutron absorption and beta emission. This can easily be dealt with by waiting ten half lives of the daughter nuclide, so the device reaches approximate steady-state operation. In this case, there is no time dependence built into the MCNP model so all betas were be assumed to be emitted at the same time as neutron capture.

The second time-dependent factor involves burning of the emitter atoms. Exposure of the SPNS while in operation will result in burnup or loss of the beta-emitting atoms as they are converted to another isotope with the capture of a neutron, and then to another element with the subsequent beta decay. The response of the detector will decrease with the loss of available material. Burnup is also a time-dependent problem beyond the scope of this thesis, but would have to be considered in an operational spectrometer.

4.9 Final design

The final form of the SPNS looks much like the form shown in Figure 3. The exact dimensions are shown in Table 3. The dimensions given produce a total

Table 3. SPNS Dimensions.

	Material	Density ($g\ cm^{-3}$)	Outer radius (cm)	Thickness (cm)
Inner beta region	Rh	12.4	0.1	0.2
Inner insulator	MgO	3.97	0.108	0.008
Inner conductor	Fe	7.86	0.15	0.042
Middle beta region	V	6.1	0.25	0.1
Middle insulator	MgO	3.97	0.258	0.008
Middle conductor	Fe	7.86	0.3	0.042
Outer beta region	Mn	7.43	0.4	0.1
Outer insulator	MgO	3.97	0.408	0.008
Outer conductor	Fe	7.86	0.5	0.092

diameter of 1 cm. This device can be any length, but an arbitrary length of 6 cm was used for the model.

These dimensions were constrained by a 1 cm diameter. Actual thicknesses of the regions were compromises between size and device sensitivity as determined in Tables 4 and 5

Chapter 5. RESULTS

The spectrometer absorption response can be expressed as a vector, with each component corresponding to the neutron absorption per unit flux in each of the three detector regions. Normalizing (making unit length) is one way of comparing these vectors. The response vectors for the three energy regions (thermal, epithermal, fast) together become a response matrix which, when multiplied by a vector representing an incident flux, gives an approximate prediction of the system response.

The initial MCNP4B runs with different emitter materials in the spectrometer are shown in Table 4. The numbers in parentheses represent the relative (or fractional) error, instead of the absolute error, in the MCNP4B results.

Table 4. Response of Three Material SPNS

Raw Data	**Inner SPND (Rh)**	**Middle SPNS (V)**	**Outer SPNS (Mn)**
Thermal	0.087599 (0.04249)	0.024207 (0.0419)	0.13449 (0.0341)
Epithermal	0.18993 (0.0374)	0.051765 (0.0299)	0.28388 (0.0259)
Fast	0.51722 (0.0205)	0.131867 (0.0168)	0.729653 (0.0149)

These data show an almost complete indifference in the response ratios to the three neutron energy regions (see Appendix C).

Table 5 shows the response of the spectrometer with cadmium shielding added (in place of some of the conductor regions) to shape the neutron flux.

Table 5. Response of Cadmium Shielded Rhodium SPNS

Raw Data	Inner SPND	Middle SPNS	Outer SPNS
Thermal	5.12035E-5 (0.1698)	2.97292E-2 (0.0178)	1.60490E-1 (0.0107)
Epithermal	3.89807E-3 (0.0881)	8.85402E-2 (0.0148)	4.30689E-1 (0.0086)
Fast	1.00719E-2 (0.0205)	3.16939E-1 (0.0086)	1.62252E0 (0.0057)

While these vectors are not collinear (not in the same direction), taken together they still form a nearly singular matrix (one with a determinant of nearly zero, that does not span any significant volume.)

Chapter 6. DISCUSSION

Like the first spectrometer type using various neutron absorbers, the second spectrometer design has a nearly singular response with its associated non-invertable matrix. Unlike the first case which has collinear response vectors, the second arrangement is merely coplanar. This means that any pair of response vectors are linearly independent, but the system as a whole would not make a working three-region spectrometer. Two of the regions, thermal and epithermal, could be used for a two element, two-region spectrometer which could distinguish between thermal and higher energy neutrons. This is due to the fact that the fast and epithermal responses are in the same plane as the thermal response, but each has a different angle from the thermal response vector. Any linear combination of the vectors is in this same plane, which means a lack of linear independence among the response vectors. This means that the system cannot be inverted, so the incident neutron spectrum cannot be determined from the response of this SPNS.

Chapter 7. SUMMARY AND CONCLUSIONS

The self-powered neutron detector has many advantages. It can be formed using simple conduction and insulation materials, can withstand intense neutron bombardment, and can be made relatively small as compared to a series of Bonner spheres. In addition, it can be made in a cylindrical shape allowing easy insertion into small apertures, as may be required in a reactor or other heavily shielded structure.

The SPNS readout is simple and requires minimal instrumentation. A remote picoammeter is all that is needed as a display. A small number of parts, coupled with remote control electronics (away from any neutron flux) may provide high system reliability.

By reading several coaxial SPNDs with associated computer-interfaced meters, a neutron spectrum can be obtained with separate flux readings for thermal, epithermal, and fast neutron energies, if these responses are linearly independent.

Using various neutron absorbers/beta emitters in this design does not produce a workable spectrometer. Any emitter material seems to have much the same neutron absorption response to the various energy regions.

Modifying the neutron flux with cadmium shielding does produce a spectrometer that distinguishes between energies. This can be useful for a two-region spectrometer, but the response vectors for thermal, epithermal, and fast neutron fluxes are coplanar so this version of a SPNS also cannot be used to distinguish three regions.

Further work can be carried out by building a detector and operating it in a reactor to verify its operation against reactor models. Another idea for further work is to add more elements and make a spectrometer that acts more like a large number of Bonner spheres. One more important area to research is the time dependence of this spectrometer with varying flux and with "burnup" instead of assuming a steady-state calibrated system.

BIBLIOGRAPHY

1. Segre`, E. 1977. *Nuclei and Particles.* Second Edition, Reading, Massachusetts: The Benjamin/Cummings Publishing Company, Inc.

2. Bramblett, R. L., Ewing, R. I. and Bonner, T. W. 1960. *A new type of Neutron Spectrometer*, Nuclear Instrumentation and Methods.

3. Knoll, G. F. 1989. *Radiation Detection and Measurement*, Second Edition, Ann Arbor, Michigan, John Wiley & Sons.

4. Hilborn, J. W. 1964. Self-Powered Neutron Detectors for Reactor Flux Monitoring. In *Nucleonics*, Volume 22, Number 2, p 69.

5. Joslin, C. W. 1972. Self-powered neutron detectors. In *Nuclear Engineering International*, Volume 17, Number 192, p 399.

6. Briesmeister, J. F, Editor. 1997. *MCNP™- A General Monte Carlo N-Particle Transport Code.* Los Alamos National Laboratory report LA-12625-M, p iii.

APPENDICES

Appendix A: Beta Emitter MCNP4B Output

```
1mcnp     version 4b   ld=02/04/97                      03/29/98 07:26:01
 **************************************************************************          probid =   03/29/98 07:26:01

      Sphere  $ V sphere    Unit area detector region, vary insulator
      10  5 -6.1      -200       IMP:N,P,E= 1.  $ core (V)
      20  5 -6.1  200 -201       IMP:N,P,E= 1.  $ beta emitter/neutron abs (V)
      C 20  6 -7.43 200 -201       IMP:N,P,E= 1.  $ beta emitter/neutron abs (Mn)
      30  3 -3.58 201 -202       IMP:N,P,E= 1.  $ insulator (source side) (MnO)
      35  3 -3.58 202 -203       IMP:N,P,E= 1.  $ insulator (collector side)
      40  2 -7.86 203 -204       IMP:N,P,E= 1.  $ conductor (Fe)
      98  1 -1.00 204 -207       IMP:N,P,E= 1.  $ water
      99  0       207            IMP:N,P,E= 0.  $ outside universe (Void)

      C length units are in cm, mass densities in g/cu cm, cross sections in barns
      C radius of sphere with surface area of 1 cu cm: 0.2820947917739  cm
      C 0.02 cm thick beta region
      200 SO 0.2620947917739              $ vary 200 for plot (and source term below)
      201 SO 0.2820947917739
      202 SO 0.2860947917739              $ half way point in insulator
      203 SO 0.2900947917739              $ fixed insulator region (0.008 cm)
      204 SO 0.3020947917739
      207 SO 0.32

      M1  001001    2 008016 1 $ water                                   {d=1.00}
      M2  026000    1          $ iron (conductors/beta shield)           {d=7.86}
      M3  012000    1 008016 1 $ MnO magnesium oxide (insulator)         {d=3.58}
      C M4  45103.01e 1        $ rhodium (rh, 100 barn, 42s)(.50c -> n) {Rh d=12.4}
      M5  23000.01e 1        $ vanadium (5.0, 2.8)                     {V d=6.1}
      C M6  025000.01e 1         $ Manganese                                {Mn d=7.43}
      C neutron section *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
      C MODE N $ implied if missing
      C SDEF SUR=207 NRM=-1 ERG=14 WGT=1 PAR=1
      C PHYS:N 15 0
      C F1:N 201
      C F4:N 10 20 30
      C associated beta emission *-*-*-*-*-*-*-*-*-*-*-*-*-*-*
      C sdef: sphere defined by using pos and rad (not axs or ext -> cylinder)
      MODE P E
      SDEF POS=0 0 0 ERG=D1 RAD=D2 WGT=1 PAR=3
      C beta spectra from Table of Radioactive Isotopes
      C Edgardo Browne and Richard B. Firestone
      C New York, John Wiley & Sons, 1986
      C =-=-= Rh-104 beta spectrum (p104-3): SpA: 2.544E9 Ci/g
      C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.442
      C SP1 0 0.00241 0.00247 0.0051 0.0170 0.075 0.159 0.446 0.289
      C =-=-= V-52 beta spectrum(p52-1): 9.63E8 Ci/g
      SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.5 2.542
```

```
SP1  0 0.00156 0.00162 0.00344 0.0122 0.061 0.141 0.434 0.345 0.0000259
C =-=-= Mn-56 beta spectrum(p56-2): SpA: 2.1702E7 Ci/g
C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.5 2.849
C SP1  0 0.0069 0.0070 0.0143 0.0466 0.174 0.230 0.270 0.245 0.0055
SI2 0.2620947917739 0.2820947917739 $ <<--==-==-- variable source thickness
SP2 -21 2   $ -21 = sphere , 2 ==> r^2 source probability function/(default)
C Tally type 1: Current integrated over a surface (particles * weight / nps)
FC1 Tally comment =-= this should be a current, not flux, directional =-=
F1:E 201 202 203 $ current over these spherical surfaces (particles)
FT1 ELC 2 $ special tally modifier, positron, electron, sum, separated
C common section *-*-*-*-*-*-*-*-*-*-*-*-*-*
NPS  20000 $ history limit
CTME  30 $ processor time (not absolute) limit

warning.    2 materials had unnormalized fractions. print table 40.
1cells                                                                                                    print table 60

                    atom        gram                                                neutron    photon     electron
      cell  mat    density     density      volume       mass       pieces importance importance importance

    1   10    5  7.21111E-02 6.10000E+00 7.54161E-02 4.60038E-01       1  1.0000E+00 1.0000E+00 1.0000E+00
    2   20    5  7.21111E-02 6.10000E+00 1.86155E-02 1.13555E-01       1  1.0000E+00 1.0000E+00 1.0000E+00
    3   30    3  1.06992E-01 3.58000E+00 4.05699E-03 1.45240E-02       1  1.0000E+00 1.0000E+00 1.0000E+00
    4   35    3  1.06992E-01 3.58000E+00 4.17203E-03 1.49359E-02       1  1.0000E+00 1.0000E+00 1.0000E+00
    5   40    2  8.47576E-02 7.86000E+00 1.32225E-02 1.03928E-01       1  1.0000E+00 1.0000E+00 1.0000E+00
    6   98    1  1.00309E-01 1.00000E+00 2.17752E-02 2.17752E-02       1  1.0000E+00 1.0000E+00 1.0000E+00
    7   99    0   .00000E+00  .00000E+00  .00000E+00  .00000E+00       0   .0000E+00  .0000E+00  .0000E+00

 total                                    1.37258E-01 7.28756E-01

   minimum source weight = 9.9984E-01    maximum source weight = 1.0000E+00

         1 warning message so far.
1cross-section tables                                                                                     print table 100

     table    length

                         tables from file mcplib02

   1000.02p     623                                                                                             01/15/93
   8000.02p     623                                                                                             01/15/93
  12000.02p     643                                                                                             01/15/93
  23000.02p     651                                                                                             01/15/93
  26000.02p     651                                                                                             01/15/93

  total        3191

 maximum photon energy set to  100.0 mev (maximum electron energy)

                         tables from file el1
```

```
  1000.01e     478                                                                                    11/16/88
  8000.01e     478                                                                                    11/16/88
 12000.01e     478                                                                                    11/16/88
 23000.01e     478                                                                                    11/16/88
 26000.01e     478                                                                                    11/16/88



 decimal words of dynamically allocated storage

     general             230520
     tallies               6608
     bank                  6803
     cross sections        3191

     total               243258     =      973032 bytes

 ***********************************************************************************************************************
 dump no.    1 on file runtpe       nps =         0     coll =              0     ctm =     .00     nrn =              0


          1 warning message so far.
 bank is full.  bank backup file is being created.  nps =       18

 ***********************************************************************************************************************
 dump no.    2 on file runtpe       nps =      8198     coll =       56255636     ctm =   15.01     nrn =      347604307

1problem summary

      run terminated when it had used   30 minutes of computer time.
+                                                                                                     03/29/98 07:56:51
      Sphere  $ V sphere   Unit area detector region, vary insulator                       probid =   03/29/98 07:26:01
0
 photon creation     tracks      weight        energy            photon loss         tracks      weight        energy
                                 (per source particle)                                           (per source particle)

 source                   0    0.            0.                  escape                1261    7.7321E-02    1.4938E-02
                                                                 energy cutoff            0    0.            0.
                                                                 time cutoff              0    0.            0.
 weight window            0    0.            0.                  weight window            0    0.            0.
 cell importance          0    0.            0.                  cell importance          0    0.            0.
 weight cutoff            0    0.            0.                  weight cutoff            0    0.            0.
 energy importance        0    0.            0.                  energy importance        0    0.            0.
 dxtran                   0    0.            0.                  dxtran                   0    0.            0.
 forced collisions        0    0.            0.                  forced collisions        0    0.            0.
 exp. transform           0    0.            0.                  exp. transform           0    0.            0.
 from neutrons            0    0.            0.                  compton scatter          0    0.            4.2913E-04
 bremsstrahlung        6533    4.0059E-01    1.9328E-02          capture              13193    8.0896E-01    6.4447E-03
```

```
 p-annihilation          0    0.           0.                 pair production          0    0.            0.
 electron x-rays      7796    4.7803E-01   2.4419E-03
 1st fluorescence      125    7.6647E-03   4.2196E-05
 2nd fluorescence        0    0.           0.
     total           14454    8.8628E-01   2.1812E-02               total          14454    8.8628E-01    2.1812E-02

   number of photons banked                  14329          average time of (shakes)              cutoffs
   photon tracks per source particle    8.8642E-01            escape              8.9241E-04        tco    1.0000E+34
   photon collisions per source particle 8.3773E-01           capture             3.0680E-04        eco    1.0000E-03
   total photon collisions                   13660            capture or escape 3.5789E-04          wc1   -5.0000E-01
                                                              any termination   3.5789E-04          wc2   -2.5000E-01
0
 electron creation    tracks      weight        energy           electron loss       tracks      weight        energy
                                  (per source particle)                                          (per source particle)

 source               16306    9.9984E-01    1.1486E+00          escape               4601    2.8212E-01    2.8618E-01
                                                                 energy cutoff     1391595    8.5329E+01    8.4105E-02
                                                                 time cutoff             0    0.            0.
 weight window            0    0.            0.                  weight window           0    0.            0.
 cell importance          0    0.            0.                  cell importance         0    0.            0.
 weight cutoff            0    0.            0.                  weight cutoff           0    0.            0.
 energy importance        0    0.            0.                  energy importance       0    0.            0.
 pair production          0    0.            0.                  scattering              0    0.            1.1390E+00
 compton recoil         189    1.1589E-02    4.2858E-04          bremsstrahlung          0    0.            1.9435E-02
 photo-electric       13153    8.0651E-01    6.2555E-03
 photon auger           403    2.4711E-02    1.2990E-04
 electron auger       47860    2.9347E+00    1.0618E-02
 knock-on           1318285    8.0834E+01    3.6262E-01
     total          1396196    8.5611E+01    1.5287E+00              total         1396196    8.5611E+01    1.5287E+00

   number of electrons banked                1379890                                              cutoffs
   electron tracks per source particle    8.5625E+01                                                tco    1.0000E+34
   electron sub-steps per source particle 6.8982E+03                                                eco    1.0000E-03
   total electron sub-steps                112482652                                                wc1     .0000E+00
                                                                                                    wc2     .0000E+00

 computer time so far in this run    30.12 minutes            maximum number ever in bank       200
 computer time in mcrun              30.01 minutes            bank overflows to backup file    2693
 source particles per minute          5.4343E+02              dynamic storage     243262 words,       973048 bytes.
 random numbers generated              694958440              most random numbers used was    195362 in history      8342

 warning.   random number stride    152917 exceeded       34 times.

 range of sampled source weights = 9.9984E-01 to 9.9984E-01
1photon    activity in each cell                                                                          print table 126

                 tracks      population    collisions    collisions      number        flux         average       average
        cell    entering                                  * weight      weighted      weighted    track weight   track mfp
                                                        (per history)    energy        energy      (relative)      (cm)

    1    10        382          6453          5976     3.6643E-01    1.8211E-01    1.8211E-01    9.9984E-01    8.6588E-01
```

2	20	862	6078	4929	3.0223E-01	1.5851E-01	1.5851E-01	9.9984E-01	7.3425E-01
3	30	1237	1445	266	1.6310E-02	1.6834E-01	1.6834E-01	9.9984E-01	1.7186E+00
4	35	1265	1450	239	1.4655E-02	1.6611E-01	1.6611E-01	9.9984E-01	1.6796E+00
5	40	1165	3435	2223	1.3631E-01	1.7248E-01	1.7248E-01	9.9984E-01	5.5480E-01
6	98	1257	1283	27	1.6556E-03	1.9055E-01	1.9055E-01	9.9984E-01	6.5025E+00
total		6168	20144	13660	8.3760E-01				

1electron activity in each cell print table 126

	cell	tracks entering	population	substeps	substeps * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	10	8453	555282	46734118	2.8656E+03	6.3605E-01	7.8123E-01	9.9984E-01	1.3256E-03
2	20	22585	514501	42433033	2.6019E+03	7.2212E-01	8.8685E-01	9.9984E-01	1.5067E-03
3	30	12337	64693	2646375	1.6227E+02	7.3125E-01	8.7549E-01	9.9984E-01	3.3505E-03
4	35	11975	63093	2586491	1.5860E+02	7.0545E-01	8.4995E-01	9.9984E-01	3.2483E-03
5	40	9090	212743	17383664	1.0659E+03	6.9208E-01	8.5015E-01	9.9984E-01	1.1031E-03
6	98	4878	23380	698971	4.2859E+01	8.4447E-01	9.5955E-01	9.9984E-01	1.4613E-02
total		69318	1433692	112482652	6.8972E+03				

1tally 1 nps = 16306

+ Talley comment =-= this should be a current, not flux, directional =-=

tally type 1 number of particles crossing a surface.
tally for electrons
this tally is modified by ft elc

surface 201
.00000E+00 .0000

surface 201
7.57517E-01 .0106

surface 201
7.57517E-01 .0106

surface 202
.00000E+00 .0000

surface 202
7.25509E-01 .0109

surface 202
7.25509E-01 .0109

surface 203
.00000E+00 .0000

surface 203
7.12326E-01 .0116

```
 surface  203
                 7.12326E-01  .0116
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   1 with nps =     16306    print table 160


 normed average tally per history  = 7.57517E-01          unnormed average tally per history  = 7.57517E-01
 estimated tally relative error    =  .0106               estimated variance of the variance  =  .0007
 relative error from zero tallies  =  .0076               relative error from nonzero scores  =  .0074

 number of nonzero history tallies =        8361          efficiency for the nonzero tallies  =  .5128
 history number of largest  tally  =       10496          largest  unnormalized history tally = 1.19981E+01
 (largest  tally)/(average tally)  = 1.58388E+01          (largest  tally)/(avg nonzero tally)= 8.12142E+00

 (confidence interval shift)/mean  =  .0001               shifted confidence interval center  = 7.57594E-01


 if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

      estimated quantities           value at nps           value at nps+1          value(nps+1)/value(nps)-1.

      mean                            7.57517E-01             7.58206E-01                      .000910
      relative error                  1.06375E-02             1.06660E-02                      .002678
      variance of the variance        7.25050E-04             7.66049E-04                      .056545
      shifted center                  7.57594E-01             7.57595E-01                      .000002
      figure of merit                 2.94519E+02             2.92947E+02                     -.005335

 the estimated slope of the  84 largest  tallies starting at  5.49914E+00 appears to be decreasing at least exponentially.
 the history score probability density function appears to have an unsampled region at the largest  history scores: please examine.

 ===================================================================================================================================

           results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally   1

 tfc bin     --mean--      ---------relative error---------      ----variance of the variance----      --figure of merit--     -pdf-
 behavior    behavior      value   decrease   decrease rate      value   decrease   decrease rate       value     behavior      slope

 desired      random       < .10      yes      1/sqrt(nps)       <0.10      yes         1/nps          constant    random       >3.00
 observed     random         .01      yes          yes             .00      yes          yes           constant    random       10.00
 passed?       yes           yes      yes          yes             yes      yes          yes              yes        yes          yes

 ===================================================================================================================================


 this tally meets the statistical criteria used to form confidence intervals: check the tally fluctuation chart to verify.
 the results in other bins associated with this tally may not meet these statistical criteria.

 estimated asymmetric confidence interval(1,2,3 sigma): 7.4953E-01 to 7.6565E-01; 7.4148E-01 to 7.7371E-01; 7.3342E-01 to 7.8177E-01
 estimated  symmetric confidence interval(1,2,3 sigma): 7.4946E-01 to 7.6558E-01; 7.4140E-01 to 7.7363E-01; 7.3334E-01 to 7.8169E-01
```

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (5.434E+02)*(7.362E-01)**2 = (5.434E+02)*(5.420E-01) = 2.945E+02

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

1   passed the 10 statistical checks for the tally fluctuation chart bin result
passed all bin error check: 9 tally bins had   3 bins with zeros and   0 bins with relative errors exceeding .10

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

the tally bins with zeros may or may not be correct: compare the source, cutoffs, multipliers, et cetera with the tally bins.

1tally fluctuation charts

		tally 1			
nps	mean	error	vov	slope	fom
1000	7.4488E-01	.0412	.0086	10.0	337
2000	7.6638E-01	.0295	.0051	10.0	316
3000	7.6621E-01	.0239	.0031	10.0	320
4000	7.5763E-01	.0208	.0023	10.0	319
5000	7.4848E-01	.0186	.0018	10.0	317
6000	7.5588E-01	.0171	.0015	10.0	311
7000	7.5888E-01	.0158	.0013	10.0	313
8000	7.5976E-01	.0148	.0011	10.0	311
9000	7.5755E-01	.0140	.0011	10.0	308
10000	7.5988E-01	.0134	.0011	10.0	303
11000	7.6143E-01	.0129	.0011	10.0	298
12000	7.6130E-01	.0123	.0010	10.0	299
13000	7.5796E-01	.0119	.0009	10.0	297
14000	7.5924E-01	.0114	.0008	10.0	297
15000	7.5602E-01	.0110	.0008	10.0	297
16000	7.5782E-01	.0107	.0007	10.0	295
16306	7.5752E-01	.0106	.0007	10.0	295

****

dump no.   3 on file runtpe   nps =   16306   coll =   112496312   ctm =   30.01   nrn =   694958440

2 warning messages so far.

run terminated when it had used   30 minutes of computer time.

computer time =   30.13 minutes

mcnp   version 4b   02/04/97   03/29/98 07:56:52   probid =   03/29/98 07:26:01

Appendix B: Beta Emission MCNP4B Output

```
1mcnp     version 4b    ld=02/04/97                    04/29/98 23:27:00
*************************************************************************          probid =    04/29/98 23:27:00

Self-Powered Neutron Spectrometer *Cd Shield*   $Title card
C Edward K. Kropp, Oregon State University
C to execute this file (named inp), type: mcnp4b
C three detector spnd:
C Thermal E(n) < 0.5 eV
C Epithermal 0.5 eV < E(n) < 10 keV
C Fast 10 keV < E(n)  (fission: 100 keV - 15 MeV)
C
C Cell Material Density Surfaces    Particle importance
C      V--- density: -value = g/cm^3
C INNER DETECTOR ELEMENT (Rh):
C inner core conductor/beta emitter material
11  4  -12.4      -211 -250  260     $ Rh
C inner insulator material A
12  3  -3.97  211 -212 -250  260     $ MgO
C inner insulator material B
13  3  -3.97  212 -213 -250  260     $ MgO
C collector/conductor/beta shield
14  2  -7.86  213 -214 -250  260     $ Fe
15  30 -8.65  214 -215 -250  260     $ Cd
C
C MIDDLE DETECTOR ELEMENT (Rh):
C middle neutron absorber/beta emitter material
21  4  -12.4  215 -221 -250  260     $ Rh
C 21  5  -6.1   215 -221 -250  260     $ V
C middle insulator material
22  3  -3.97  221 -222 -250  260     $ MgO
C middle insulator material
23  3  -3.97  222 -223 -250  260     $ MgO
C middle collector/conductor/beta shield
24  2  -7.86  223 -224 -250  260     $ Fe
25  2  -7.86  224 -225 -250  260     $ Fe (Rh is enough shield)
C 25  30 -8.65  224 -225 -250  260     $ Cd
C
C OUTER DETECTOR ELEMENT (Rh):
C middle neutron absorber/beta emitter material
31  4  -12.4  225 -231 -250  260     $ Rh
C 31  6  -7.43  225 -231 -250  260     $ Mn
C outer insulator material A
32  3  -3.97  231 -232 -250  260     $ MgO
C outer insulator material B
33  3  -3.97  232 -233 -250  260     $ MgO
C outer detector collector material
34  2  -7.86  233 -234 -250  260     $ Fe
C
```

```
C OTHER SPECTROMETER PARTS:
C endcaps (make material = water for no endcap) M30 = Cd
40  30 -8.65 -225  250 -251 $ top
41  30 -8.65 -234  250 -259 #40 $ endcaps split for IMP matching
50  30 -8.65 -225  261 -260 $ bottom
51  30 -8.65 -234  269 -260 #50
C
C OUTSIDE REGIONS:
80  1  1.0 #(-234 -259 269) -299 -280  $ water (presume LLR coolant)
81  1  1.0 280 -281 -299 $ water (presume LLR coolant)
82  1  1.0 281 -282 -299 $ "
83  1  1.0 282 -283 -299 $ "
84  1  1.0 283 -299      $ "
99  0       299                    $ Void outside universe

C Surface Geometry Dimension (radius, cm)
C cylindrical boundaries
211 CX  0.1   $ boundary inner beta emitter & insulator (arbitrary) Rh
212 CX  0.104 $ halfway point in insulator
213 CX  0.108 $ boundary inner insulator & collector/conductor/shield
214 CX  0.12  $ Cd shield
215 CX  0.15  $ boundary inner and middle detectors (arbitrary)
221 CX  0.25  $ outer surface of 2nd beta region V
222 CX  0.254 $ halfway point in insulator
223 CX  0.258 $ boundary middle beta insulator & collector/conductor/shield
224 CX  0.29  $ Cd shield
225 CX  0.3   $ boundary middle and outer detectors (arbitrary)
231 CX  0.4   $ boundary outer beta emitter & insulator Mn
232 CX  0.404 $ halfway point in insulator
233 CX  0.408 $ boundary outer insulator $ collector/conductor/shield
234 CX  0.5   $ outer radius of spectrometer outer boundaries
250 PX  3.0   $ detector top
251 PX  3.1   $ endcap mid
259 PX  3.2   $ endcap top
260 PX -3.0   $ detector bottom
261 PX -3.1   $ endcap mid
269 PX -3.2   $ endcap bottom
280 CX  1.0   $ surfaces for neutron importances...
281 CX  1.5   $ "
282 CX  2.0   $ "
283 CX  2.5   $ "
299 SO  3.5   $ spherical system limit (and isotropic neutron flux source)

C Instructions Section
C neutron cross sections in .50c and .60c
C common materials (Appendix G mcnp4a manual)
M1  001001      2 008016 1 $ water                                  {d=1.00}
M2  026000      1          $ Fe (conductors/beta shield)            {d=7.86}
M3  012000      1 008016 1 $ MgO magnesium oxide (insulator)        {d=3.58}
M4  45103       1          $ rhodium (nb, 100 barn, 42s)(.50c -> n)   {d=12.4}
C   45103 defaults to .50c, 45103.50c & 50d  both lack gamma ray production
```

```
C M5  23000.60c   1         $ vanadium (5.0, 2.8)                        {d=6.1}
C M6  25055.60c   1         $ manganese                                  {d=7.43}
C M4  45103.01e 1         $ rhodium (nb, 100 barn, 42s)(.50c -> n)   {d=12.4}
C M5  23000.01e 1         $ vanadium (5.0, 2.8)                        {d=6.1}
C M6  25000.01e 1         $ manganese                                  {d=7.43}
C M7  13027.01e 1         $ aluminum                                   {d=2.70}
C additional materials
M30 048000      1         $ cadmium (thermal neutron shield)           {d=8.65}
C M40 027059    1         $ cobalt (nge, 35 barn, prompt)              {d=8.90}
C M41 078000    1         $ platinum (nge+ge, <10 barn, prompt)        {d=21.4}
C M50 82000     1         $ lead                                       {d=11.4}
C . . . . . . . . . . . . . . . . . . . .
C . step 1, neutron absorption problem  . (with combinations)
C . . . . . . . . . . . . . . . . . . . .
MODE N
C ....... Neutron source term
C TRIGA (@ Lazy Susan) t%:3E12 e%:1E11 f%:6E11 (@ Rabbit) t%:9E12 e%:4E11 f%:3E1
C SDEF POS=0 5 0 CEL=98 ERG=14 WGT=1 $ neutron point source N:PAR=1
SDEF SUR=299 NRM=-1 ERG=D1 WGT=154 PAR=1 $ inward/isotropic n
C source on spherical surface, flux: 1 n cm^-2 s^-1 (area = 154 cm^2)
SI1 S 2 3 4
SP1 0 0 6  $ epithermal only!
C SP1 30 1 6  $ Lazy Susan ratios
C thermal: 0 - 0.5ev
C ERG -2 a $ p(E)=C E^.5 exp(-E/a) a: temperature in MeV
SP2 -2 2.53E-8 $ thermal/Maxwellian distribution
C epithermal: 0.5 - 10 keV
C  $ epithermal/ 1/E distribution histogram
SI3 H 0 5E-7 1E-6 2E-6 5E-6 1E-5 2E-5 5E-5 1E-4 2E-4 5E-4 1E-3 3E-3 5E-3 1E-2
SP3 0 0.69 0.69 0.91 0.69 0.69 0.91 0.69 0.69 0.91 0.69 0.69 0.91 0.69 0.69
C ERG -3 a b $ p(E) = C exp(-E/a) sinh(bE)^.5 a: width b: ave energy (p3-50)
C defaults a = 0.965 MeV b =2.29 MeV^-1
C fast:  > ??????????? MeV
SP4 -3     $ fast/Watt spectrum
PHYS:N 15 0               $ default p3-103
C tallies................
C F4 flux averaged over a cell
F4:N 11         $ straight tally (track length estimate??)
FC4: Number of Rh-104 atoms created in cell 11
C FM# C M# Xsect-type FMx: p3-75, ex p 4-34
C where C = conversion Av*10^-24 * (mass of cell)/AW
C AW = Rh:102.90660 V:50.9415 Mn:54.93805 Al:26.981539
FM4  0.013678 4 102  $ Rh
C 0.04786:conversion, atom/barn*cm)  4:material 4 (Rh) 102:radiative capture
F14:N 21        $ straight tally
FC14: Number of V-52 atoms created in cell 21
FM14 0.054712 4 102  $ Rh
C FM14 0.05437  5 102 $ V
F24:N 31        $ straight tally
FC24: Number of Mn-56 atoms created in cell 31
FM24 0.095752 4 102  $ Rh
```

```
C FM24 0.107462 6 102 $Mn
C . . . . . . . . . . . . . . . . . . . . . . . . .
C . . step 2, beta emission/absorption problem  . .
C . . . . . . . . . . . . . . . . . . . . . . . . .
C CUT:E 0.0001                        $ MCNP4A low energy cutoff (100 Volts)
C SDEF CEL=D1 POS=0 0 0 AXS=0 0 1 EXT=D2 RAD=FCEL D3 ERG FCEL=D7 WGT=100 PAR=3
C SC1 beta sources (part II/after neutron section is run)
C SI1 L 11 21 31              $ beta source cells
C SP1 d 0.2 0.7 0.1           $ probability (strength) of each cell
C SB1 d 0.33 0.33 0.34        $ source bias (set equal for now)
C SI2  3.                     $ half height for each beta soruce cell
C DS3  s 4 5 6                $ set of set of cell radii
C SI4  0 0.3
C SI5  0.5 0.6
C SI6  0.8 0.9
C =-=-= Al-28 beta spectrum
C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.5 2.863
C SP1 0 0.00080 0.00087 0.00197 0.0077 0.0425 0.108 0.380 0.448 0.0112
C =-=-= Rh-104 beta spectrum (p104-3): SpA: 2.544E9 Ci/g
C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.442
C SP1 0 0.00241 0.00247 0.0051 0.0170 0.075 0.159 0.446 0.289
C =-=-= V-52 beta spectrum (p52-1): 9.63E8 Ci/g
C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.5 2.542
C SP1  0 0.00156 0.00162 0.00344 0.0122 0.061 0.141 0.434 0.345 0.0000259
C =-=-= Mn-56 beta spectrum (p56-2): SpA: 2.1702E7 Ci/g
C SI1 H 0 0.01 0.02 0.04 0.1 0.3 0.6 1.3 2.5 2.849
C SP1  0 0.0069 0.0070 0.0143 0.0466 0.174 0.230 0.270 0.245 0.0055
C tallies...............
C . . . . . . . . . . . . . . . . . . . . .
C . step 3, associated photon emission  .
C . . . . . . . . . . . . . . . . . . . . .
C need to look this up!!! Monday!!!
C . . . . . . . . . . . . . . . . . . . . .
C . . . . . . . . . . . . . . . . . . . . .
C beta current (directional) tallies
C F1: current integrated over a surface (unit: particles)
C F1:E 212 222 232 $ beta tallies for surfaces pg. 3-60
C FT1 ELC 2 $ special tally modifier, positron, electron, sum, seperated
C FC1 electron tallies 212:inner  222:middle  232:outer
C . . . . . . . . . . . . . . . . . . . . .
C . common commands for n, p and e runs:  .
C . . . . . . . . . . . . . . . . . . . . .
IMP:N 64 64 64 64 64 32 32 32 32 16 16 16 16 16 32 16 32 16 8 4 2 1 1 0
IMP:P,E 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0
C Print $ print tables....
NPS   3000000                         $ run 50000 origin particles
CTME  180

warning.    2 materials had unnormalized fractions. print table 40.
1cells                                                               print table 60
```

	cell	mat	atom density	gram density	volume	mass	pieces	neutron importance	photon importance	electron importance
1	11	4	7.25650E-02	1.24000E+01	1.88496E-01	2.33734E+00	1	6.4000E+01	1.0000E+00	1.0000E+00
2	12	3	1.18648E-01	3.97000E+00	1.53812E-02	6.10635E-02	1	6.4000E+01	1.0000E+00	1.0000E+00
3	13	3	1.18648E-01	3.97000E+00	1.59844E-02	6.34582E-02	1	6.4000E+01	1.0000E+00	1.0000E+00
4	14	2	8.47576E-02	7.86000E+00	5.15724E-02	4.05359E-01	1	6.4000E+01	1.0000E+00	1.0000E+00
5	15	30	4.63393E-02	8.65000E+00	1.52681E-01	1.32069E+00	1	6.4000E+01	1.0000E+00	1.0000E+00
6	21	4	7.25650E-02	1.24000E+01	7.53982E-01	9.34938E+00	1	3.2000E+01	1.0000E+00	1.0000E+00
7	22	3	1.18648E-01	3.97000E+00	3.80007E-02	1.50863E-01	1	3.2000E+01	1.0000E+00	1.0000E+00
8	23	3	1.18648E-01	3.97000E+00	3.86039E-02	1.53257E-01	1	3.2000E+01	1.0000E+00	1.0000E+00
9	24	2	8.47576E-02	7.86000E+00	3.30546E-01	2.59809E+00	1	3.2000E+01	1.0000E+00	1.0000E+00
10	25	2	8.47576E-02	7.86000E+00	1.11212E-01	8.74129E-01	1	1.6000E+01	1.0000E+00	1.0000E+00
11	31	4	7.25650E-02	1.24000E+01	1.31947E+00	1.63614E+01	1	1.6000E+01	1.0000E+00	1.0000E+00
12	32	3	1.18648E-01	3.97000E+00	6.06202E-02	2.40662E-01	1	1.6000E+01	1.0000E+00	1.0000E+00
13	33	3	1.18648E-01	3.97000E+00	6.12234E-02	2.43057E-01	1	1.6000E+01	1.0000E+00	1.0000E+00
14	34	2	8.47576E-02	7.86000E+00	1.57462E+00	1.23765E+01	1	1.6000E+01	1.0000E+00	1.0000E+00
15	40	30	4.63393E-02	8.65000E+00	2.82743E-02	2.44573E-01	1	3.2000E+01	1.0000E+00	1.0000E+00
16	41	30	4.63393E-02	8.65000E+00	1.28805E-01	1.11417E+00	1	1.6000E+01	1.0000E+00	1.0000E+00
17	50	30	4.63393E-02	8.65000E+00	2.82743E-02	2.44573E-01	1	3.2000E+01	1.0000E+00	1.0000E+00
18	51	30	4.63393E-02	8.65000E+00	1.28805E-01	1.11417E+00	1	1.6000E+01	1.0000E+00	1.0000E+00
19	80	1	1.00000E+00	9.96924E+00	1.65095E+01	1.64587E+02	1	8.0000E+00	1.0000E+00	1.0000E+00
20	81	1	1.00000E+00	9.96924E+00	2.55972E+01	2.55184E+02	1	4.0000E+00	1.0000E+00	1.0000E+00
21	82	1	1.00000E+00	9.96924E+00	3.32023E+01	3.31001E+02	1	2.0000E+00	1.0000E+00	1.0000E+00
22	83	1	1.00000E+00	9.96924E+00	3.76965E+01	3.75806E+02	1	1.0000E+00	1.0000E+00	1.0000E+00
23	84	1	1.00000E+00	9.96924E+00	6.15624E+01	6.13730E+02	1	1.0000E+00	1.0000E+00	1.0000E+00
24	99	0	.00000E+00	.00000E+00	.00000E+00	.00000E+00	0	.0000E+00	.0000E+00	.0000E+00
total					1.79594E+02	1.78956E+03				

minimum source weight = 1.5400E+02   maximum source weight = 1.5400E+02

1 warning message so far.

1cross-section tables   print table 100

table	length			
		tables from file endf601		
1001.60c	1402	1-h-1 from endf-vi.1	mat 125	11/25/93
8016.60c	38367	8-o-16 from endf/b-vi	mat 8 25	11/25/93
12000.60c	39099	12-mg-nat from endf/b-vi	mat1200	11/25/93
		tables from file rmccs1		
26000.55c	76892	njoy	(260)	10/21/82
48000.51c	4762	njoy	(1281)	03/10/80
		tables from file rmccsa1		

```
 45103.50c   16241  njoy                                                                        ( 1310)     11/01/85

 total      176763

any neutrons with energy greater than emax = 1.50000E+01 from the source or from a collision will be resampled.

neutron cross sections outside the range from  .0000E+00 to 1.5000E+01 mev are expunged.



decimal words of dynamically allocated storage

    general               9854
    tallies              19536
    bank                  6803
    cross sections      176763

    total               201364     =      805456 bytes

***********************************************************************************************************************
dump no.    1 on file runtpe       nps =         0     coll =              0     ctm =     .00     nrn =              0


         1 warning message so far.

***********************************************************************************************************************
dump no.    2 on file runtpe       nps =    110603     coll =       15032720     ctm =   15.01     nrn =      256851376

warning.  source energy > emax.
nps =    202651     ijk = 253436993943137     erg = 1.5013E+01

***********************************************************************************************************************
dump no.    3 on file runtpe       nps =    221298     coll =       30072519     ctm =   30.01     nrn =      513881005


***********************************************************************************************************************
dump no.    4 on file runtpe       nps =    330248     coll =       45116067     ctm =   45.02     nrn =      770934437


***********************************************************************************************************************
dump no.    5 on file runtpe       nps =    439752     coll =       60164968     ctm =   60.03     nrn =     1028060158


***********************************************************************************************************************
dump no.    6 on file runtpe       nps =    549490     coll =       75208187     ctm =   75.04     nrn =     1285052609


***********************************************************************************************************************
dump no.    7 on file runtpe       nps =    659154     coll =       90252217     ctm =   90.04     nrn =     1542100155
```

```
 ****************************************************************************************************************
 dump no.    8 on file runtpe       nps =    768242     coll =       105288532     ctm =  105.04     nrn =      1799034046

 ****************************************************************************************************************
 dump no.    9 on file runtpe       nps =    878101     coll =       120342437     ctm =  120.05     nrn =      2056221286

 ****************************************************************************************************************
 dump no.   10 on file runtpe       nps =    988314     coll =       135386330     ctm =  135.06     nrn =      2313273594

 ****************************************************************************************************************
 dump no.   11 on file runtpe       nps =   1098406     coll =       150430175     ctm =  150.07     nrn =      2570270320

 ****************************************************************************************************************
 dump no.   12 on file runtpe       nps =   1208920     coll =       165472694     ctm =  165.07     nrn =      2827276837
1problem summary

      run terminated when it had used  180 minutes of computer time.
+                                                                                                         04/30/98 02:29:30
      Self-Powered Neutron Spectrometer *Cd Shield*   $Title card                              probid =   04/29/98 23:27:00
0
 neutron creation    tracks      weight        energy            neutron loss        tracks      weight        energy
                                 (per source particle)                                           (per source particle)

 source              1318186    1.5400E+02    1.9819E+00         escape               991653    9.2417E+01    2.5376E-01
                                                                 energy cutoff             0    0.            0.
                                                                 time cutoff               0    0.            0.
 weight window             0    0.            0.                 weight window             0    0.            0.
 cell importance     2997625    5.4635E+01    1.0488E-01         cell importance     2315232    5.4668E+01    1.0513E-01
 weight cutoff             0    1.0092E+01    5.2979E-09         weight cutoff       1008937    1.0121E+01    5.5384E-09
 energy importance         0    0.            0.                 energy importance         0    0.            0.
 dxtran                    0    0.            0.                 dxtran                    0    0.            0.
 forced collisions         0    0.            0.                 forced collisions         0    0.            0.
 exp. transform            0    0.            0.                 exp. transform            0    0.            0.
 upscattering              0    0.            4.7957E-07         downscattering            0    0.            1.7076E+00
                                                                 capture                   0    6.1521E+01    2.0274E-02
 (n,xn)                   22    2.0954E-04    2.2688E-06         loss to (n,xn)           11    1.0477E-04    8.5299E-06
 fission                   0    0.            0.                 loss to fission           0    0.            0.
     total           4315833    2.1873E+02    2.0868E+00             total           4315833    2.1873E+02    2.0868E+00

   number of neutrons banked                     2997636        average time of (shakes)              cutoffs
   neutron tracks per source particle     3.2741E+00              escape            2.9575E+02          tco   1.0000E+34
   neutron collisions per source particle 1.3689E+02              capture           1.4977E+03          eco    .0000E+00
   total neutron collisions                    180449845          capture or escape 7.7611E+02          wc1  -5.0000E-01
   net multiplication              1.0000E+00  .0000              any termination   9.9499E+02          wc2  -2.5000E-01
```

computer time so far in this run 180.34 minutes
computer time in mcrun 180.01 minutes
source particles per minute 7.3227E+03
random numbers generated 3083182460

maximum number ever in bank 21
bank overflows to backup file 0
dynamic storage 201368 words, 805472 bytes.
most random numbers used was 91692 in history 46183

range of sampled source weights = 1.5400E+02 to 1.5400E+02

20 source particles had energies > emax.

1neutron activity in each cell print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	11	141053	138508	14929	7.3912E-02	1.8049E-02	1.2432E+00	4.2448E+02	2.1698E+00
2	12	279665	144004	936	4.5489E-03	1.7880E-02	1.2485E+00	4.2212E+02	2.9015E+00
3	13	290731	149719	968	4.9208E-03	1.7899E-02	1.2482E+00	4.2148E+02	2.9047E+00
4	14	313434	167036	3632	1.7802E-02	1.7791E-02	1.2238E+00	4.2244E+02	3.7392E+00
5	15	425610	262594	60582	1.2758E-01	1.1547E-02	1.2105E+00	4.1924E+02	3.6982E+00
6	21	394205	336060	114365	5.8103E-01	2.5249E-03	1.1285E+00	3.7651E+02	2.0331E+00
7	22	463160	337187	1439	1.2355E-02	1.5311E-03	1.0642E+00	3.4991E+02	2.8063E+00
8	23	471057	341093	1567	1.3588E-02	1.5289E-03	1.0690E+00	3.5043E+02	2.8095E+00
9	24	510843	376254	20389	1.4108E-01	1.4882E-03	1.0729E+00	3.4944E+02	3.3690E+00
10	25	275093	225551	3262	4.4550E-02	1.5092E-03	1.0695E+00	3.5045E+02	3.3862E+00
11	31	544389	473194	259155	2.1067E+00	8.4309E-04	9.8079E-01	3.1755E+02	1.8128E+00
12	32	573132	469213	1983	2.5221E-02	3.8312E-04	8.0748E-01	2.7084E+02	2.6666E+00
13	33	581692	472352	2101	2.7098E-02	3.7536E-04	8.1556E-01	2.6935E+02	2.6757E+00
14	34	707740	556767	114700	1.1039E+00	3.0803E-04	7.5081E-01	2.5642E+02	2.6910E+00
15	40	22909	22467	1988	2.2536E-02	1.6545E-02	1.2462E+00	6.9933E+02	3.7025E+00
16	41	52407	47578	19371	3.3284E-01	8.7679E-03	1.1565E+00	7.1753E+02	3.6255E+00
17	50	22800	22313	2089	2.3466E-02	1.6366E-02	1.1905E+00	7.0537E+02	3.6915E+00
18	51	53027	48084	20030	3.4157E-01	8.1409E-03	1.1185E+00	7.1463E+02	3.6107E+00
19	80	1752324	1252212	28675198	4.5275E+02	1.1896E-04	5.0755E-01	2.0361E+02	1.3352E-01
20	81	2425602	1622766	41164056	9.5332E+02	7.5736E-05	3.8905E-01	1.4027E+02	1.1402E-01
21	82	2299975	1536000	38487087	1.4591E+03	7.4693E-05	3.8371E-01	1.1233E+02	1.1330E-01
22	83	1731916	888946	28064727	1.9747E+03	8.2130E-05	4.0461E-01	1.0281E+02	1.1701E-01
23	84	1723074	1032139	43415291	3.2975E+03	1.6137E-04	6.0197E-01	1.1356E+02	1.4922E-01
total		16055838	10922037	180449845	8.1424E+03				

1tally 4 nps = 1318186
\+ Number of Rh-104 atoms created in cell 11
tally type 4 track length estimate of particle flux.
tally for neutrons

volumes
cell: 11
1.88496E-01

cell 11
multiplier bin: 1.36780E-02 4 102

```
              1.00719E-02  .0418
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   4 with nps =   1318186    print table 160


 normed average tally per history  = 1.00719E-02          unnormed average tally per history  = 1.89851E-03
 estimated tally relative error    =  .0418               estimated variance of the variance  =  .0478
 relative error from zero tallies  =  .0070               relative error from nonzero scores  =  .0412

 number of nonzero history tallies =       20237          efficiency for the nonzero tallies  =  .0154
 history number of largest  tally  =      419680          largest  unnormalized history tally = 4.11275E+01
 (largest  tally)/(average tally)  = 2.16630E+04          (largest  tally)/(avg nonzero tally)= 3.32573E+02

 (confidence interval shift)/mean  =  .0037               shifted confidence interval center  = 1.01093E-02


 if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

      estimated quantities          value at nps          value at nps+1          value(nps+1)/value(nps)-1.

      mean                           1.00719E-02            1.02374E-02                      .016433
      relative error                 4.18113E-02            4.41984E-02                      .057092
      variance of the variance       4.77748E-02            5.37485E-02                      .125038
      shifted center                 1.01093E-02            1.01154E-02                      .000601
      figure of merit                3.17767E+00            2.84369E+00                     -.105101

 the estimated inverse power slope of the 198 largest  tallies starting at 1.86724E+00 is 2.9784
 the history score probability density function appears to have an unsampled region at the largest  history scores: please examine.


 ===================================================================================================================================

          results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally   4

 tfc bin     --mean--      ---------relative error---------      ----variance of the variance----      --figure of merit--     -pdf-
 behavior    behavior      value   decrease   decrease rate      value   decrease   decrease rate       value     behavior     slope

 desired      random      < .10       yes       1/sqrt(nps)      <0.10      yes         1/nps          constant    random      >3.00
 observed     random        .04       yes           yes            .05      yes          yes           constant    random       2.98
 passed?       yes          yes       yes           yes            yes      yes          yes             yes         yes          no

 ===================================================================================================================================


 warning.  the tally in the tally fluctuation chart bin did not pass  1 of the 10 statistical checks.

 fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (7.323E+03)*( 2.083E-02)**2 = (7.323E+03)*(4.339E-04) = 3.178E+00
1unnormed tally density for tally   4          nonzero tally mean(m) = 1.237E-01   nps =   1318186    print table 161

 abscissa              ordinate   log plot of tally probability density function in tally fluctuation chart bin(d=decade,slope= 3.0)
  tally  number num den log den:d-----------d------------d------------d------------d------------d------------d------------d---------
 7.94-06      3 7.76-01   -.110 ***********|************|************|************|************|************|************|*****
```

```
1.26-05      2 3.27-01   -.486 ************|************|************|************|************|************|************|
2.00-05      4 4.12-01   -.385 ************|************|************|************|************|************|************|*
3.16-05     10 6.50-01   -.187 ************|************|************|************|************|************|************|****
5.01-05     28 1.15+00    .060 ************|************|************|************|************|************|************|*******
7.94-05     35 9.06-01   -.043 ************|************|************|************|************|************|************|******
1.26-04     68 1.11+00    .045 ************|************|************|************|************|************|************|*******
2.00-04    136 1.40+00    .146 ************|************|************|************|************|************|************|********
3.16-04    217 1.41+00    .149 ************|************|************|************|************|************|************|********
5.01-04    404 1.66+00    .219 ************|************|************|************|************|************|************|*********
7.94-04    642 1.66+00    .220 ************|************|************|************|************|************|************|*********
1.26-03    906 1.48+00    .170 ************|************|************|************|************|************|************|********
2.00-03   1200 1.24+00    .092 ************|************|************|************|************|************|************|*******
3.16-03   1524 9.91-01   -.004 ************|************|************|************|************|************|************|******
5.01-03   1645 6.75-01   -.171 ************|************|************|************|************|************|************|****
7.94-03   1767 4.57-01   -.340 ************|************|************|************|************|************|************|**
1.26-02   1729 2.82-01   -.549 ************|************|************|************|************|************|************|
2.00-02   1639 1.69-01   -.772 ************|************|************|************|************|************|*********   |
3.16-02   1566 1.02-01   -.992 ************|************|************|************|************|************|******      |
5.01-02   1395 5.72-02  -1.242 ************|************|************|************|************|************|***         |
7.94-02   1264 3.27-02  -1.485 ************|************|************|************|************|************|            |
1.26-01   1075 1.76-02  -1.756 mmmmmmmmmmmm|mmmmmmmmmmmm|mmmmmmmmmmmm|mmmmmmmmmmmm|mmmmmmmmmmmm|mmmmmmmmm   |            |
2.00-01    879 9.06-03  -2.043 ************|************|************|************|************|******      |            |
3.16-01    675 4.39-03  -2.358 ************|************|************|************|************|*           |            |
5.01-01    484 1.99-03  -2.702 ************|************|************|************|**********  |            |            |
7.94-01    378 9.78-04  -3.010 ************|************|************|************|******      |            |            |
1.26+00    243 3.97-04  -3.401 ************|************|************|************|*           |            |            |
2.00+00    135 1.39-04  -3.857 ************|************|************|********    |    s       |            |            |
3.16+00     83 5.40-05  -4.268 ************|************|************|***         | s          |            |            |
5.01+00     53 2.17-05  -4.663 ************|************|**********  |          s |            |            |            |
7.94+00     18 4.66-06  -5.332 ************|************|**          |      s     |            |            |            |
1.26+01     19 3.10-06  -5.508 ************|************|            | s          |            |            |            |
2.00+01      6 6.18-07  -6.209 ************|***         |       s    |            |            |            |            |
3.16+01      4 2.60-07  -6.585 *********** |            | s          |            |            |            |            |
5.01+01      1 4.10-08  -7.387 *           |       s    |            |            |            |            |            |
  total  20237 1.54-02         d-----------d-----------d-----------d-----------d-----------d-----------d-----------d---------
1tally  14        nps =  1318186
+                                   Number of V-52 atoms created in cell 21
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           volumes
                   cell:      21
                         7.53982E-01

 cell  21
 multiplier bin:   5.47120E-02    4        102
                 3.16939E-01  .0086
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  14 with nps =   1318186    print table 160


 normed average tally per history  = 3.16939E-01         unnormed average tally per history  = 2.38967E-01
```

```
estimated tally relative error    =  .0086              estimated variance of the variance  =  .0008
relative error from zero tallies  =  .0037              relative error from nonzero scores  =  .0078

number of nonzero history tallies =      67830          efficiency for the nonzero tallies  =  .0515
history number of largest  tally  =     982434          largest  unnormalized history tally = 2.57884E+02
(largest  tally)/(average tally)  = 1.07916E+03         (largest  tally)/(avg nonzero tally)= 5.55305E+01

(confidence interval shift)/mean  =  .0001              shifted confidence interval center  = 3.16969E-01


if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

     estimated quantities           value at nps           value at nps+1          value(nps+1)/value(nps)-1.

     mean                            3.16939E-01             3.17199E-01                       .000818
     relative error                  8.64218E-03             8.67369E-03                       .003647
     variance of the variance        7.60800E-04             8.26143E-04                       .085888
     shifted center                  3.16969E-01             3.16970E-01                       .000003
     figure of merit                 7.43789E+01             7.38393E+01                      -.007254

the estimated slope of the 200 largest  tallies starting at  7.56632E+01 appears to be decreasing at least exponentially.
the large score tail of the empirical history score probability density function appears to have no unsampled regions.

===================================================================================================================================

          results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally  14

tfc bin     --mean--      ---------relative error---------      ----variance of the variance----      --figure of merit--     -pdf-
behavior    behavior      value   decrease   decrease rate      value   decrease   decrease rate       value     behavior     slope

desired      random       < .10      yes      1/sqrt(nps)       <0.10      yes         1/nps          constant    random      >3.00
observed     random         .01      yes          yes             .00      yes          yes           constant    random      10.00
passed?        yes          yes      yes          yes             yes      yes          yes              yes         yes        yes

===================================================================================================================================


this tally meets the statistical criteria used to form confidence intervals: check the tally fluctuation chart to verify.
the results in other bins associated with this tally may not meet these statistical criteria.

estimated asymmetric confidence interval(1,2,3 sigma): 3.1423E-01 to 3.1971E-01; 3.1149E-01 to 3.2245E-01; 3.0875E-01 to 3.2519E-01
estimated  symmetric confidence interval(1,2,3 sigma): 3.1420E-01 to 3.1968E-01; 3.1146E-01 to 3.2242E-01; 3.0872E-01 to 3.2516E-01

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (7.323E+03)*( 1.008E-01)**2 = (7.323E+03)*(1.016E-02) = 7.438E+01
1tally  24        nps =  1318186
+                                    Number of Mn-56 atoms created in cell 31
          tally type 4    track length estimate of particle flux.
          tally for  neutrons
```

```
          volumes
                 cell:       31
                      1.31947E+00

 cell  31
 multiplier bin:   9.57520E-02    4        102
                 1.62252E+00  .0057
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  24 with nps =   1318186    print table 160


 normed average tally per history  = 1.62252E+00          unnormed average tally per history  = 2.14087E+00
 estimated tally relative error    =  .0057               estimated variance of the variance  =  .0003
 relative error from zero tallies  =  .0028               relative error from nonzero scores  =  .0049

 number of nonzero history tallies =      118275          efficiency for the nonzero tallies  =  .0897
 history number of largest  tally  =      177710          largest  unnormalized history tally = 1.02632E+03
 (largest  tally)/(average tally)  = 4.79396E+02          (largest  tally)/(avg nonzero tally)= 4.30141E+01

 (confidence interval shift)/mean  =  .0000               shifted confidence interval center  = 1.62258E+00


 if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

      estimated quantities           value at nps           value at nps+1          value(nps+1)/value(nps)-1.

      mean                            1.62252E+00             1.62311E+00                       .000363
      relative error                  5.65047E-03             5.66005E-03                       .001696
      variance of the variance        2.93010E-04             3.07477E-04                       .049373
      shifted center                  1.62258E+00             1.62258E+00                       .000001
      figure of merit                 1.73991E+02             1.73402E+02                      -.003384

 the estimated slope of the 200 largest  tallies starting at  3.56847E+02 appears to be decreasing at least exponentially.
 the large score tail of the empirical history score probability density function appears to have no unsampled regions.

 ===================================================================================================================================

           results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally  24
```

tfc bin behavior	--mean-- behavior	---------relative error--------- value	decrease	decrease rate	----variance of the variance---- value	decrease	decrease rate	--figure of merit-- value	behavior	-pdf- slope
desired	random	< .10	yes	1/sqrt(nps)	<0.10	yes	1/nps	constant	random	>3.00
observed	random	.01	yes	yes	.00	yes	yes	constant	random	10.00
passed?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

```
 ===================================================================================================================================
```

this tally meets the statistical criteria used to form confidence intervals: check the tally fluctuation chart to verify.
the results in other bins associated with this tally may not meet these statistical criteria.

estimated asymmetric confidence interval(1,2,3 sigma): 1.6134E+00 to 1.6318E+00; 1.6042E+00 to 1.6409E+00; 1.5951E+00 to 1.6501E+00
estimated symmetric confidence interval(1,2,3 sigma): 1.6134E+00 to 1.6317E+00; 1.6042E+00 to 1.6409E+00; 1.5950E+00 to 1.6500E+00

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (7.323E+03)*(1.541E-01)**2 = (7.323E+03)*(2.376E-02) = 1.740E+02
1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4   missed 1 of 10 tfc bin checks: the slope of decrease of largest tallies is less than the minimum acceptable value of 3.0
passed all bin error check: 1 tally bins all have relative errors less than .10 with no zero bins

14   passed the 10 statistical checks for the tally fluctuation chart bin result
passed all bin error check: 1 tally bins all have relative errors less than .10 with no zero bins

24   passed the 10 statistical checks for the tally fluctuation chart bin result
passed all bin error check: 1 tally bins all have relative errors less than .10 with no zero bins

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

warning. 1 of the 3 tally fluctuation chart bins did not pass all 10 statistical checks.
1tally fluctuation charts

	tally 4					tally 14					tally 24				
nps	mean	error	vov	slope	fom	mean	error	vov	slope	fom	mean	error	vov	slope	fom
128000	9.3742E-03	.1029	.1178	2.7	5.4E+00	3.1126E-01	.0271	.0059	7.5	78	1.6316E+00	.0182	.0029	8.6	174
256000	9.3517E-03	.0707	.0491	2.9	5.8E+00	3.1276E-01	.0198	.0047	9.1	74	1.6308E+00	.0129	.0018	10.0	172
384000	9.3582E-03	.0577	.0316	3.0	5.7E+00	3.1644E-01	.0160	.0028	10.0	75	1.6458E+00	.0105	.0010	10.0	174
512000	1.0401E-02	.0674	.1525	2.6	3.1E+00	3.1979E-01	.0139	.0021	10.0	74	1.6366E+00	.0091	.0008	10.0	173
640000	1.0198E-02	.0621	.1104	2.6	3.0E+00	3.2158E-01	.0125	.0016	10.0	73	1.6276E+00	.0081	.0006	8.8	173
768000	9.9297E-03	.0547	.0988	2.7	3.2E+00	3.1999E-01	.0114	.0013	10.0	73	1.6244E+00	.0074	.0005	9.0	173
896000	9.9117E-03	.0513	.0860	2.8	3.1E+00	3.1848E-01	.0105	.0011	10.0	75	1.6226E+00	.0068	.0004	7.2	175
1024000	9.7946E-03	.0467	.0770	2.9	3.3E+00	3.1743E-01	.0098	.0010	10.0	74	1.6215E+00	.0064	.0004	9.9	175
1152000	9.9681E-03	.0451	.0605	2.9	3.1E+00	3.1676E-01	.0093	.0009	10.0	74	1.6239E+00	.0060	.0003	9.6	174
1280000	1.0088E-02	.0424	.0500	3.0	3.2E+00	3.1655E-01	.0088	.0008	10.0	75	1.6211E+00	.0057	.0003	8.3	175
1318186	1.0072E-02	.0418	.0478	3.0	3.2E+00	3.1694E-01	.0086	.0008	10.0	74	1.6225E+00	.0057	.0003	10.0	174

****
dump no. 13 on file runtpe nps = 1318186 coll = 180449845 ctm = 180.01 nrn = 3083182460

4 warning messages so far.

run terminated when it had used 180 minutes of computer time.

computer time = 180.35 minutes

mcnp   version 4b   02/04/97   04/30/98 02:29:30   probid =   04/29/98 23:27:00

Appendix C: Three-Emitter SPNS Spreadsheet

	Cell 11	Cell 21	Cell 31		A A^-1	(Check)	
	Thermal run:				1	-7.1E-15	8.882E-16
response	8.76E-02	0.024207	0.13449		0	1	0
error	0.0449	0.0419	0.0341		0	0	1
	Epithermal run:						
response	1.90E-01	5.18E-02	0.28388				
error	0.0374	0.0299	0.0259				
	Fast run:						
response	5.17E-01	1.32E-01	7.30E-01				
error	0.0205	0.0168	0.0149	<--(relative or fractional error)			
Response Matrix (A)				Normalized Response matrix:			
8.76E-02	2.42E-02	1.34E-01		0.539675	0.149133	0.828559	
1.90E-01	5.18E-02	2.84E-01		0.549793	0.149845	0.821751	
5.17E-01	1.32E-01	7.30E-01		0.572117	0.145863	0.807097	
Error Matrix (dA)				Determinant of Normalized			
0.003933	0.001014	0.004586		Response Matrix:			
0.007103	0.001548	0.007352		-6.7E-05			
0.010603	0.002215	0.010872					
Calibration Matrix (A^-1)							
-98.4354	-21.1123	26.35762					
-2415	1653.082	-198.017					
506.2285	-283.789	18.4735					
Intermediate Calculation (dA A^-1)							
-0.51501	0.292152	-0.01245					
-0.71505	0.322074	0.016569					
-0.89018	0.353025	0.04163					
Intermediate Calculation (A^-1 dA A^-1)							
42.32878	-26.2529	1.973232					
237.989	-243.038	49.21848					
-74.2358	63.01654	-10.2367					
Associated Errors for Inverted Matrix (dA^-1)							
-42.3288	26.25292	-1.97323					
-237.989	243.0377	-49.2185					
74.23579	-63.0165	10.23673					

Appendix D: Cadmium Shielded SPNS Spreadsheet

	Cell 11	Cell 21	Cell 31		A A^-1	(Check)	
	Thermal run:				1	0	0
response	2.30E-01	1.71646	6.44764		8.88E-16	1	1.137E-13
error	0.0051	0.0028	0.0021		1.39E-17	1.11E-16	1
	Epithermal run:						
response	1.30E-01	6.71E-01	1.75473				
error	0.0089	0.0054	0.0048				
	Fast run:						
response	5.00E-03	1.99E-02	3.45E-02				
error	0.0073	0.005	0.0045				
Response Matrix (A)				Normalized Response matrix:			
2.30E-01	1.72E+00	6.45E+00		0.034411	0.257103	0.965771	
1.30E-01	6.71E-01	1.75E+00		0.069262	0.35647	0.931736	
5.00E-03	1.99E-02	3.45E-02		0.124608	0.496295	0.859165	
Error Matrix (dA)				Determinant of Normalized			
0.001172	0.004806	0.01354		Response Matrix:			
0.001161	0.003625	0.008423		-0.00052			
3.65E-05	9.96E-05	0.000155					
				Typical combined response vector			
Calibration Matrix (A^-1)				(Lazy Susan ratios:)			
44.67875	-262.111	4985.044		0.191593	1.41382	5.28205	
-16.1932	92.07714	-1658.06		Associated errors (%):			
2.874042	-15.1731	263.7803		0.002	0.0011	0.0009	
				Experimental Error:			
Intermediate Calculation (dA A^-1)				0.000383	0.001555	0.004754	
0.013436	-0.07001	1.443506					
0.017372	-0.09829	1.998171		Calculated incidence flux			
0.000464	-0.00275	0.057782		0.84667	-0.18339	4.201185	
Intermediate Calculation (A^-1 dA A^-1)				Associated derived errors:			
-1.63862	8.911983	-171.201		0.094497	-0.019	0.432891	
0.612182	-3.35222	64.80419					
-0.1025	0.564012	-10.928					
Associated Errors for Inverted Matrix (dA^-1)							
1.63862	-8.91198	171.2012					
-0.61218	3.352215	-64.8042					
0.102503	-0.56401	10.92796					