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CALCULATED REACTIVITY OF VINS

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Idaho Falls, Idaho — 83401

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CALCULATED REACTIVITY OF VINS

by

R. M. Brugger and F. J. Wheeler

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ABSTRACT

The Very Intense Neutron Source (VINS) is one proposal for an oscillated reactivity neutron booster to provide intense thermal neutron bursts for use in neutron beam research. Three-dimensional steady state neutron transport calculations have been performed for a module of the system using the Monte Carlo codes RAFFLE and KENO. These calculations have aided in the design of the system by: 1) providing an estimate of the critical mass of a module loaded with one of three fuels, ie, ^{233}U , ^{235}U , and ^{239}Pu ; 2) determining the reactivity response of the module as it passes under a fixed beryllium reflector and thus allowing a design of the reflector geometry such that a near optimum shape of reactivity oscillation is obtained; and 3) yielding an estimate of life time, component reactivity worths, leakage currents and other parameters required in the design of the system.

Verification of the cross sections and codes used in the study was obtained by comparison of results from the two independent Monte Carlo codes and comparison with two critical experiments in the literature.

Although these calculations are preliminary in nature they have further demonstrated the feasibility of the system and laid the groundwork for further design refinements and critical experiments necessary for further development of the system.

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CALCULATED REACTIVITY OF VINS

I. INTRODUCTION

The proposed Very Intense Neutron Source VINS^[1] is a pulsed thermal neutron source that could be used for neutron beam research. Future developments of this concept should be initiated by analysis and critical experiments to optimize the design. The calculations reported here are a step in that direction and can form the base for a critical mockup.

Thermal neutrons have become a powerful tool with which to study the microscopic physical properties of solids, liquids and molecules.^[2] Several high flux steady state reactors are available in the U.S. (HFBR^[3] at 1.6×10^{15} thermal n/cm²sec and HFIR^[4] at $1.5-5 \times 10^{15}$ thermal n/cm²sec) and several steady state reactors are being built (Grenoble^[3] at $\sim 2 \times 10^{15}$ thermal n/cm²sec) or planned (British^[5], $\sim 3 \times 10^{15}$ thermal n/cm²sec) in Europe. Unfortunately these steady state reactors have reached the practical limit of flux as indicated by the nominal increase estimated for the newest reactors. A break through this practical barrier is needed and is provided by pulsed reactors coupled with time-of-flight techniques. The power of pulsed reactors has been demonstrated by the Russians with their 30 KW pulsed reactor at Dubna^[6] which for many experiments has the experimental capability of a megawatt steady state reactor. The Russians are now building a 1 MW pulsed reactor IBR-II^[6] and the nations of the JRC Ispra group are in the final design stage on the MW pulsed reactor SORA.^[7] The U.S. has no such pulsed reactor even though several have been proposed. VINS is one of these proposals.

VINS is a device having several (as originally conceived, there would be 60) fast reactor assemblies called modules on the periphery of a slowly rotating wheel. As each module passes the target area, it is driven near to delayed critical by passing near a reflector. Since there are few delayed neutrons present as each module returns to the target area, the device does not produce many neutrons until a source of neutrons is injected from an accelerator. The electrons which are injected by the accelerator directly into the near critical module are converted to gamma rays and then to neutrons. These bursts of neutrons are multiplied by the near critical module to give intense but short bursts of fast neutrons. Moderators near the target area moderate the fast neutrons and direct them toward the beam holes. These bursts of near thermal neutrons would then be used for time-of-flight experiments.

When the original calculations were made on VINS only a spherical geometry S_n transport code SCAMP was used. This demonstrated the feasibility of VINS but approximated the critical mass, reflector worth, decoupling, etc. Recently a Monte Carlo code, RAFFLE^[8] has become operational which allows a more precise description of the proposed geometry of VINS. This code and another Monte Carlo code, KENO,^[9] have been used to analyze some of the characteristics of VINS. Details of the Monte Carlo studies are given in Appendix I. These calculations can form the base for the next step, the critical experiments, in the development of VINS.

II. CODES

The RAFFLE code is a general-purpose Monte Carlo neutron transport code which solves iteration type problems to obtain the multiplication factor K_{eff} and normal mode fluxes, or it can solve external source problems. For any type of problem, the neutron slowing down treatment is detailed including inelastic discrete levels and evaporation model scattering, $n-2n$ scattering, and elastic scattering with any degree of anisotropic angular scattering. In the resolved resonance range, absorption, fission and scatter are computed pointwise assuming a single-level formalism. A multithermal P_1 treatment in the lab system, with full upscattering, is allowed. The output of RAFFLE can be quite detailed including the multiplication factor, lifetime, generation time, groupwise fluxes, currents, absorption rates and fission rates. The RAFFLE library was recently upgraded to include the ENDF/B-II cross sections needed in this calculation except for ^{233}U . The KENO code which is a more restricted Monte Carlo code was used to determine the relative K_{eff} of $^{235}\text{U}/^{233}\text{U}/^{239}\text{Pu}$ since its library (Hansen & Roach) included a ^{233}U cross section.

The rectangular parallelepiped geometry of RAFFLE was used to describe one module of VINS. Figure 1 shows the regions. The central fuel region in the VINS concept was selected to be a cube 16.5 cm on a side assembled from fourteen clad fuel plates 16.5 cm $\times$ 16.5 cm $\times$ 0.9 cm with 0.25 cm cooling gaps between each plate. In the RAFFLE calculation, this area was represented by homogeneous 93% ^{235}U and 7% ^{238}U at a variable density. The top reflector piece was divided into several regions so that different combinations of regions with variable densities could be selected to represent different shapes and positions of the movable reflector. The moderators were represented by a Nelkin Kernel for hydrogen in water and a free gas kernel for the oxygen. This gives a reasonable hydrogen concentration for the calculations but may misrepresent the moderation at thermal. However, this thermal moderation was not important to these calculations at this time. One moderator is divided into two regions of 16.5 $\times$ 8.25 $\times$ 4 cm so that the current of neutrons emitted by a near and far section of moderator can be calculated.

III. K_{eff} VS. DENSITY OF FUEL

The K_{eff} of the reflected module was calculated as a function of density of the fuel in the module. These calculations were made with the 3-cm thick $\times$ 20.5-cm long Be reflector slab centered on the module. Figure 2 shows this K_{eff} vs. density of fuel. The points define a straight line dependence which can be used to normalize later calculations having different reflector shapes to give the desired K_{eff} for the desired multiplication.

Figure 3 shows the multiplication M expected from each module determined from the equation $M = 1/(1 - K')$ where K' is the reactivity of the fast neutrons since the delayed neutron source is supposed to be minimal. Thus $K' = K_{eff} - 0.007$.

Figure 1 Orthogonal planes through the center of the movable VINS module and stationary beryllium top reflector.

Figure 2 The reactivity of the VINS module vs. the density of fuel in the central $(16.5 \text{ cm})^3$ fuel area.

Figure 3 The prompt neutron multiplication of the VINS module vs. the reactivity.

The Monte Carlo code KENO was used to calculate the relative reactivity of ^{235}U , ^{233}U and ^{239}Pu . In this case the top reflector was a shortened dog-boned reflector but the shape was the same for all three calculations. Table I gives the atom density of each isotope in the fuel region and the calculated reactivity. The U atom density is 17% of the theoretical metal density.

TABLE I

RELATIVE REACTIVITY OF A MODULE FOR THREE FUELS

<u>Fuel</u>	<u>Atom Density</u> (atoms/cc $\times 10^{-24}$)	<u>K_{eff}</u>
²³⁵ U	0.034	1.0232 $\pm$ 0.0037
²³⁸ U	0.00256	
²³³ U	0.034	1.318 $\pm$ 0.005
²³⁸ U	0.00256	
²³⁹ Pu	0.034	1.463 $\pm$ 0.005
²³⁸ U	0.00256	
²³³ U	0.0173	1.0 $\pm$ 0.02
²³⁸ U	0.00256	
²³⁹ Pu	0.0146	0.989 $\pm$ 0.014
²³⁸ U	0.00256	

Since scaling these numbers indicated that a ²³⁹Pu core would be critical at 43% density and ²³³U core at 51% density, a rerun of KENO for these densities was made to obtain a better estimate of the critical mass of a module with these two fuels. Table I also gives these K_{eff}'s.

IV. K_{eff} VS. MOVEMENT OF A MODULE PAST THE REFLECTOR

RAFFLE calculations were made to determine the worth of the movement of the reflector as a function of its position above the module. While the 3-cm thick by 20.5-cm long reflector gave reasonable results it was realized that a shaped reflector should give a better square topped reactivity curve. Figure 4 shows the curves as a function of distance as the reflectors move over the core.

The ideal reflector response was judged to be a square wave with a width equal to the core (16.5 cm) and a height of ~ 5 . The 3-cm thick by 20.5-cm long reflector has a flat top but extends well past the ± 8.25 -cm distance and does not drop as low as desired at the repeat distance of ± 16.5 cm. The thin solid block has too sharp a peak and drops too soon. The "dog-bone" shape does hold the flat top but drops earlier than the flat slab. However it shows that a reasonable reflector response can be approached. For the dog bone the K_{eff} has dropped to $\Delta K = 4$ by the repeat distance. Both the shape and the magnitude can probably be improved by adjustment of the dog-bone design and thickness.

Figure 4 The reactivity of the VINS module vs. the position of the module under the stationary beryllium top reflector as calculated by RAFFLE. Reactivities for three shapes of the reflector are shown.

V. K_{eff} OF MODULE PARTS

As a guide for critical measurements, K_{eff} was calculated for the module as each set of parts was added to the assembly. Table II gives the results.

TABLE II

REACTIVITY ADDITION OF SETS OF PARTS OF MODULE OF VINS

Part	K_{eff}	ΔK	Generation Time (nsec)	Lifetime (nsec)
Core (76% U)	0.8631±0.0011		5.83	11.9
Add Be Reflector	0.9684±0.0015	0.1053±0.0019	8.34	15.5
Add ^{10}B Decouplers	1.0050±0.0015	0.0366±0.0021	9.51	15.6
Add $\text{H}_2\text{O} + ^{10}\text{B}$ Decouplers	1.0174±0.0016	0.0124±0.0022	9.77	23.1
Add H_2O Moderators	1.0153±0.0018	-0.0021±0.0023	9.77	262.1

Each new addition has a positive ΔK_{eff} . Even though some materials are strong absorbers, each new piece does cause some reflection which increases K_{eff} . The essentially zero ΔK_{eff} of the moderators is desirable. But the magnitude of the positive ΔK_{eff} of the ^{10}B loaded H_2O decouplers is a little surprising since the decouplers are further removed from the core than are the moderators. This result may be fallacious because of statistical errors even though the estimated errors are smaller than the difference. The critical measurements are needed to verify this.

In the original report of VINS it was estimated that the fast neutron lifetime should be less than 20 nsec to prevent smearing of the burst in the moderators. The lifetimes calculated with RAFFLE indicate that the fast neutron lifetime in the core is small (~ 10 nsec). The large value of the lifetime calculated for the module plus the moderator does not represent the neutron lifetime in the core but averages in the longer lifetimes of the neutrons in the moderators. The more representative lifetimes are those calculated without the moderators.

VI. BEAM CURRENTS

One can ask RAFFLE to determine the current of neutrons from one region to another and as a distribution of energy. Thus the current from one face of the moderator was obtained. This current was divided into two parts; that current from the first 8.25 cm of moderator nearer the core and second from the outer 8.25 cm of moderator (see Figure 1). For an input source term of one neutron and no multiplication the total flux from the inner face was 1.19×10^{-2} neutrons and that from the outer face was 2.27×10^{-3} . These give the calculated relation between the leakage current from the beams and the input source. One notes that the outer moderator piece gives 1/5 the current as the inner which indicates that the outer section is not very effective and a redesign of the moderator is needed.

The flux profile for 10 groups is given in Figure 5. The lack of a strong thermal peak indicates that the moderators are relatively thin and upscattering and burst spreading in time has probably not become important. Thicker moderators could probably be used with an increase of beam current but minor adverse effect on burst time. The uncertainty in these results remains relatively large because Monte Carlo is sampling from a region of low flux and only one thermal group was used in the calculations. More analytical and experimental work is needed in this area.

VII. CONCLUSIONS

The RAFFLE calculations have improved the analytical analysis of VINS and have produced no embarrassing surprises. The worth of components can be used to estimate the experimental mockup. The relative worth of K_{eff} for ^{235}U , ^{233}U , and ^{239}Pu indicate that the total fuel inventory of VINS could be reduced to <2000 Kgms by using the latter two fuels. It is predicted that additional dynamic calculations will show that VINS can run effectively on <30 modules thus cutting the inventory again in half. These reductions would produce a major savings in fuel inventory.

The RAFFLE calculations indicate that one moving reflector will be adequate to get at least \$4 reactivity change. This reflector can be shaped to give a better reactivity signal as the module passes the target area.

Figure 5 A ten group current being emitted by one side of the inner $8.25 \times 16.5 \text{ cm}^2$ area of one moderator.

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APPENDIX I

The Monte Carlo calculations relating to the VINS system consisted of three parts, these being 1) comparison with experimental results for two fast critical assemblies to validate the codes and cross section libraries; 2) calculations with the RAFFLE Monte Carlo code on one module of VINS; and 3) calculations with the KENO Monte Carlo code on one module of VINS to provide a comparison of two independent codes and an estimate of the savings in fuel mass that could be obtained through the use of ^{239}Pu or of ^{233}U as the fissile material.

I. THE RAFFLE MONTE CARLO CODE

Monte Carlo studies of a VINS module were performed with RAFFLE, a general-purpose Monte Carlo code developed by Aerojet Nuclear personnel. RAFFLE is written in FORTRAN IV for the IBM 360/75 computer. The code can be used to solve iteration type problems to obtain the multiplication factor (k) and normal mode fluxes and reaction rates, or it can be used to solve external source problems. The external sources may be distributed volume sources of any shape or may be incoming current sources specified on particular surfaces; the current sources may have any energy and angular distributions. For external source problems, subsequent generated fission daughters can be followed. The geometrical capability of the RAFFLE code is restricted to decrease computer time, but retains enough flexibility so that all practical geometrical models can be handled.

Along with the neutron's pointwise spatial coordinates, a pointwise energy, direction, and time variable are associated with the neutron. Because of this pointwise characterization, the RAFFLE code can use as data, cross sections which are entirely specified pointwise in energy, or it can use a combination of a pointwise and multigroup cross section representation. For a particular isotope, the pointwise representation may extend over certain energy ranges, and over the remaining energy ranges a multigroup representation can be specified. In one particular option of the combined pointwise-multigroup cross section representation, multigroup cross sections are used for the spatial transport of the neutron and pointwise cross sections are used for the determination of the mode of scattering.

In addition to this pointwise-multigroup flexibility, the resolved resonance contributions can be represented as multigroup or can be treated by the single-level Breit-Wigner formulation. For the pointwise treatment, the resonance cross sections are Doppler broadened using a Maxwellian distribution for the velocity of the target nucleus. The temperatures for the Doppler broadening can be specified by isotope or can be spatially dependent. At present, the unresolved resonance range is treated by a single-level formalism or by a pointwise representation.

With regard to neutron scatterings, discrete level inelastic scattering can be pointwise represented with linear interpolation used during execution. Evaporation model inelastic scattering, with an allowable arbitrary energy-dependent temperature, can be likewise represented. The (n,2n) type interactions can be handled, with an evaporation model type spectrum being used for the energy of the emitted neutrons. For elastic scattering, any degree of anisotropic scattering can be pointwise represented. Since the neutron energy variable is pointwise, the scattered energy is exactly determined once the scattering cosine is determined.

The RAFFLE code has its own cross section library which at present is taken from the ENDF/B-II data files; an ENDF/B-III library is being prepared as time allows. Auxiliary programs exist which automatically convert the ENDF/B data to the formats used in RAFFLE's library. In addition to its own library, any other data sources can be used for the RAFFLE code. The standard RAFFLE library contains 68 quarter-lethargy groups below 10 MeV and one thermal group below 0.414 eV. At the user's option, however, a multi-thermal (up to 100 groups) library may be used. In this case the full P_0 and P_1 scatter matrix is read either by material or by isotope with the P_n components assumed to be for the laboratory coordinate system.

The results of the RAFFLE calculations for a VINS module will not be repeated here since they are reported in the body of the report.

II. THE KENO MONTE CARLO CODE

Calculations were also performed using the KENO Monte Carlo code. KENO is a special purpose code developed at Oak Ridge for use with fast reactor systems. The geometry is restricted for ease of input and efficiency in the calculation. The code is easily used in simple geometry and is especially advantageous if the problem contains a repeating-call type of geometry. The version of KENO used in these calculations has a transport corrected 16 group Hansen and Roach library with 6 downscatter groups.

The KENO code was selected because its library contained data for ^{233}U and was used to obtain a comparison of ^{233}U , ^{235}U , and ^{239}Pu used as the fissile material in VINS. An additional benefit obtained from using the code was its value as an independent check of the results obtained from RAFFLE and several additional calculations were made for this purpose.

Because of the geometry restrictions in KENO, the regions containing hydrogen were not represented in any of the runs. Also, the ^{10}B was replaced by natural boron in the decouplers since ^{10}B was not available in the library. One run on VINS was made using the same model as RAFFLE for the core surrounded on 5 sides by the boron decouplers and topped by the 3-cm Be reflector. For this case RAFFLE gives $K_{\text{eff}} = 0.9684 \pm 0.0015$. A KENO run for this same case yields $K_{\text{eff}} = 0.9698 \pm 0.0034$.

Figure A-1 The reactivity of the VINS module vs. the position of the module under the beryllium top reflector (as calculated by KENO).

KENO problems were also run for a shaped reflector to obtain the reactivity response as the module passes under the reflector; the dimensions of the reflector and the resulting reactivity curve are shown in Figure A-1. In the RAFFLE calculations the geometric shape of the dog-bone reflector was not represented exactly but the height was approximated by varying the Be density in the various reflector regions. It is felt that this would not introduce much error in the result. In the KENO runs the regions were set up so that the geometry of the reflector was represented exactly as the module passed beneath.

III. CRITICAL STUDIES

To substantiate the RAFFLE code and the cross section set used for these calculations, K_{eff} calculations were performed for two fast critical assemblies. The first assembly was a bare 93.9% enriched ^{235}U sphere (Godiva), and the second was a 93.5 enriched ^{235}U sphere with a one-inch beryllium reflector. These assemblies were chosen because they were composed of the two main materials chosen for this design of VINS and also because of the ease with which the input can be prepared and the fact that only a small amount of computer time is required to obtain good statistics. Both RAFFLE and KENO were used to compute K_{eff} for the two systems, the results are presented in Table A-I.

TABLE A-I

MONTE CARLO COMPARISON FOR TWO HIGHLY ENRICHED U METAL CRITICAL SPHERES

Reflector	Exp. Crit. Mass and Radius	Method	K_{eff}	Generation Time (nsec)	Lifetime (nsec)
None	52.02 kg r = 8.717 cm	Experiment*	1.0		6.0
		KENO	0.9973±0.0023		
		RAFFLE	0.9981±0.0024	5.1±0.02	5.7±0.02
		Experiment**	1.0		
1" Beryllium	29.2 kg r = 7.184 cm	KENO	0.9992±0.0021		
		RAFFLE II	0.9932±0.0036	8.1±0.012	10.6±0.008
		RAFFLE III	0.9860±0.0036	7.8±0.006	10.7±0.008

*R. E. Peterson and G. A. Newby, "An Unreflected U-235 Critical Assembly", NS&E, 1, 112 (1956).

**"Reactor Physics Constants", ANL-5800, 2nd ed., Argonne National Laboratory (1963).

For the beryllium reflected sphere, two RAFFLE cases are given. Since the value of K_{eff} obtained using ENDF/B-II was 0.7% low, a second case was run using ENDF/B-III data for beryllium. As shown, the results were worse using the ENDF/B-III and for this reason version II data was selected for use in the VINS calculations. In future calculations the reasons for the underestimation of the beryllium reactivity worth should be investigated. Three possibilities exist; 1) the basic data in the ENDF/B files is in error, 2) the representation of the basic data in the library is inadequate, or 3) the treatment of the $n,2n$ reaction in the RAFFLE algorithms is inadequate for beryllium. RAFFLE allows the secondary neutrons from an $n,2n$ reaction to be distributed

isotropically in angular space when in actuality the emitted neutrons are anisotropic, also the energy distribution of the secondary neutrons is not quite right. There RAFFLE assumes the same as for inelastic evaporation scatter, ie, a Maxwellian distribution with a nuclear temperature equal to $3.23 \times 10^3 \sqrt{E/A}$ where E is in eV and A is in amu units. The magnitude of the errors introduced by these approximations is not known at the present time but they should be small. The variation in K_{eff} observed when going from version II data to version III data tends to point to either the basic data or its representation being in error.

The conclusion from these criticality calculations is that although RAFFLE may underestimate the beryllium reflector worth slightly, either code should be adequate for studies of the VINS system. From the standpoint of cost, the RAFFLE code should be selected over KENO since in all cases run during this study RAFFLE required substantially less computer time.