Nuclear Mathematical and Computational Sciences: A Century in Review, A Century Anew
Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2003)

Modification of MCNP code for Neutron Gas Pressure Simulation

E.A. Ivanov, S.V. Chernov
State scientific center of Russian Federation -
Institute of physics and power engineering
named after A.I. Leypunskiy,
Bondarenko sq.1, 249020, Obninsk, Russia
ivanoff@ippe.obninsk.ru

ABSTRACT

Well known code MCNP-4A [1] was modified for numerical modeling of pulse transferring from neutron field to solid body. Phenomenon of neutron "pressure" on solid body was detected and measured experimentally [2] in 70's. It's genuine observable function of neutron current. Modifications of MCNP code were made by documented opportunity of user's "detector" functions making.

Key words: method Monte-Carlo, neutron field current, MCNP code.

1. INTRODUCTION

As a background of the present work we should reference the article [2], which describes actual experimental data and evaluation results of neutron gas pressure on beryllium reflector of a space nuclear reactor. The present paper concerns only mathematical modeling of this phenomenon by means of up-to-date computation tools.

There are a large number of scientific explorations and practical applications dealing with interactions between neutrons and matter. However, the phenomenon of neutron gas pressure falls out of this huge list despite it was observed experimentally in 1970's. Nevertheless the considered object has several interesting for investigation and useful features.

It is well known that neutron gas in a nuclear reactor behaves as a statistical ensemble of huge number of particles and can be described by 1-particle distribution function. As a result, every element of nuclear reactor should undergo neutron gas pressure alike ordinary gas pressure. In other words, we should see some mechanical effect on a solid body under neutron flux.

However, a distinction of the given phenomenon is as follows. Unlike ordinary gas pressure or pressure of light ("soft" radiation) which effects on the surface of a solid body, neutrons and high-energy photons act in the volume. So the quantity of neutron gas pressure should be a functional of the particle field distribution in a body.

Neutrons and photons from fission source transfer mechanical impulse. It is easy to evaluate the value of impulse depending on the energy of a particle:

$$p_n(E_n) = \sqrt{2m_n E_n}\,, \tag{1}$$

$$p_g(E_g) = \frac{E_g}{c}\,, \tag{2}$$

where p – impulse, E – energy, m – particle's mass (in case of neutron), c – velocity of light. We can evaluate the value of total disposable impulse of the flux using the energy distribution for fission neutrons and photons. The numerical value appreciated is *about 0.5 milli-Neutons per 1 kW* of thermal power released in U^{235}.

It is clear that the total disposable impulse is partly transferred to the reactor structural elements and partly leaked out. However, as we noted above, the macroscopic effect depends significantly on the form of particle field.

In any case, the effect is so small against the background of other interactions that it is inappreciable in a land nuclear reactor. The situation changes radically on the orbit of Earth satellite, away of gravity and planet atmosphere. The phenomenon of neutron gas pressure during operation of space nuclear reactor was actually observed, and initial experimental data are available.

The offered work concerns the development of computation technique to describe numerically the given phenomenon by means of the Monte-Carlo code MCNP [1].

We could utilize the phenomenon of neutron gas pressure only if the following things are available:

1. Identification of the phenomenon and possibility to find relation between macroscopic parameters of neutron source and neutron pressure value.
2. Possibility to justify the required precision of particle fields modeling.

As to the second thing, the main problems of precision substantiation are as follows. First of all, there is an opinion that neutrons responsible for mechanical effect do not take active part in reaching the criticality, so the modeling precision of these neutrons may occur substantially less than one for neutrons with other energies. To clear up this question we compared importance of neutrons in regard to criticality and pressure effect. The second problem is presence of other nuclear effects (gamma-particles). In this case the direct coupled modeling of particles transfer can be the only criterion to justify the fact that neutron pressure is dominant.

The code for modeling the mechanical effects of neutron and photon fields is developed as a functional extension of the Monte-Carlo code MCNP. Our code allows evaluating the impulse transfer to a confined region of a reactor. As follows are the description of the computation routine and results for model task that corresponds to reactor BOUK/RORSAT. The model is developed based on available materials.

2. BACKGROUND AND EXPERIMENTAL DATA

The mechanical effect of neutron field was detected during operation of satellites powered by space nuclear reactors BOUK/RORSAT [2]. At the on-orbit test series the significant distinction was observed between operation control processes on Earth and on the orbit. The control system of reactor BOUK is composed of 6 beryllium cylinders in side reflector moving reciprocally along the axis of the reactor. Each rod is confined in special case filled with argon. To prevent jamming there are radial gaps of about 1 millimeter between control rod and his case. The existence of these gaps makes available the radial shifting of control rods in regard to their cases under any mechanical forces. At once the effectiveness of control rods in the given reactor is so large that even small shift in relation to the core influences the reactivity significantly. At the on-earth conditions, under gravitation, the gaps in the control system are taken up completely. On the other hand, the micro gravity conditions allow the control rods to “float” within the gaps.

It was discovered that during the operation of the reactor the control rods are undergone the action of unknown radial forces so that they are shifting to the maximal distance from the reactor axis. At any mechanical perturbation such as jet engine activation, control rods are moving in the direction of the core and after transient process they return to the initial point. As a result telemetry shows pulses of reactivity and power. Theoretical analysis of the experimental data [1] showed that the effect is caused by neutron gas pressure on the “floating” control rods.

Despite there is no doubt about conclusions of the article [2], some additional exploration seems to be useful. In particular, in present work we offer a numerical evaluation of the mechanical effect. In addition, we should define practical applications of the effect, for example, in the field of diagnostics and physical experiments. In the current paper we propose several possible applications.

Starting our analysis, first of all we should define mathematical model connecting the considered phenomenon and experimental data (device readings). In [2] the value of pressure is considered to depend linearly on the control rod shifting which determines behavior of reactivity, power and response of measuring system.

Generally the mechanical influence of neutron field on any body under micro gravity conditions is described by the following differential equation in approach of slow motion:

$$\frac{d^2(m\cdot y)}{dt^2} = m\cdot\frac{d^2 y}{dt^2} + \frac{dm}{dt}\cdot\frac{dy}{dt} = F_r\,, \tag{3}$$

where m_r – mass of the rod (moving body), $y = y(t)$ – radial coordinate of the rod's center, F_r – radial force, $\frac{dm}{dt}$ – attached mass increment velocity.

In case of our control rod we can rewrite the above equation in the following form:

$$m\cdot\frac{d^2 y}{dt^2} + K_r\cdot\frac{dy}{dt} = F_r\,, \tag{4}$$

where K_r=*const* is medium resistance coefficient (the rod is moving in argon). Supposing zero initial conditions and constant external force we can get the following decision:

$$y(t) = \int_0^t \exp\left(-\int_0^t \frac{K_r}{m}\cdot dJ\right)\cdot\left[C + \int_0^t \exp\left(\int_0^q \frac{K_r}{m}\cdot dJ\right)\cdot\frac{F_r}{m}\cdot dq\right]\cdot dt\,, \tag{5}$$

$$y(t) = \left(\frac{F_r}{K_r} - C\right)\cdot\frac{m}{K_r}\cdot\left(\exp\left(-\frac{K_r}{m}\cdot t\right) - 1\right) + \frac{F_r}{K_r}\cdot t\,. \tag{6}$$

Asymptotic decision for $t >> \frac{m}{K_r}$ looks as follows:

$$y(t) = \frac{F_r}{K_r}\cdot t\,, \tag{7}$$

$$\frac{dy}{dt} = \frac{F_r}{K_r}\,. \tag{8}$$

So the velocity of control rod is constant. The reactivity change speed is also constant [1]:

$$\frac{dr}{dt} = \frac{F_r}{K_r}\cdot\frac{\partial r}{\partial y(t)}\,. \tag{9}$$

The offered equations allow us to make numerical evaluations and comparisons. Coefficient K_r for the control rod in BOUK is *about 0.2 kg/sec* [2]. The value of external force (neutron gas pressure), as we will see later, is *about 5.22* 10^{-5} *Newton*. So the time interval required for the control rod to cover the gap is *about 13.5 sec*. This result is in good agreement with experimental data.

Thereby to evaluate the value of neutron pressure we should determine the coefficient of relation between reactivity and control rod's position and the medium resistance coefficient. Both can always be measured independently with precision required. To measure the neutron gas pressure we have to consider any reactor's element influencing on reactivity and moving with constant velocity. Measurements of reactivity and neutron power pulses caused by the element's periodical movement would give us all the necessary data for evaluation.

3. DETAILS OF TECHNIQUE AND COMPUTER CODE FOR NEUTRON GAS PRESSURE EVALUATION

Up-to-date software tools for neutron physics research, and first of all Monte-Carlo method realizations which are conventionally used to research and develop small-size nuclear reactor cores, allow user to receive wide variety of particle field functionals. The problem we consider is not typical for neutron physics analysis however it can be solved very easily and delicately within the framework of Monte-Carlo code. The way of solution is as follows.

Within the Monte-Carlo simulation we have in our hands microscopic parameters of current particle such as velocity, flight direction etc. The process of impulse transmission from particle flux to solid body can be presented as the balance of contributions from incoming and outgoing particles (see Fig. 1).

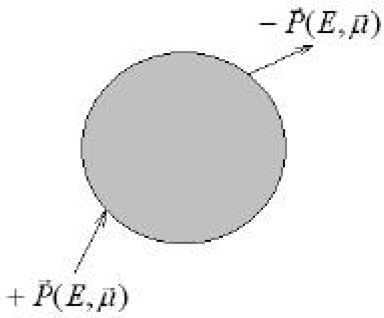

Fig. 1

So the simulation routine of impulse transfer seems to be quite simple: we should register incoming and outgoing particles on the border of a given region and score up the value of vector *P* (particle's impulse) with appropriate sign. As a result for plenty of neutron histories we should get the normal value of mechanical impulse:

$$P_{xk}^{n} = w_k \sqrt{2mE_k}\, m_{xk} \tag{10}$$

$$P_{xk}^{g} = w_k \frac{E_k}{c} m_{xk} \tag{11}$$

$$P_x = MP_{xk} \tag{12}$$

Here P_{xk} – a contribution to x-component of vector P, w_k – particle's weight within numerical simulation, m – mass of neutron, E_k – particle's energy, m_{xk} – flight direction cosine, c – velocity of light; $P_x = MP_{xk}$ means that the total result is mathematical expectation for Monte-Carlo simulation series.

The code MCNP [1] gives surpassing capabilities for solving the considered problem. MCNP user can modify simulation results (tallies) using any internal code variable relating to the whole problem or current neutron history. In our investigation we have taken advantage of the MCNP user's interface and developed our own tally modification routine (subroutine TALLYX modification) that allows calculating the vector of mechanical impulse transferred to a reactor component from neutron or photon flux.

The routine developed is distributed as a patch to the standard MCNP source. It is applied to any version of MCNP since, at least, MCNP4a by means of standard MCNP preprocessor.

To activate the user-supplied routine of impulse transmission modeling you should add the appropriate tally cards in your task description file as it is defined in [1]. The mask of these cards looks as follows:

`F1` (<*assign surfaces - borders of given region*>)
`FS1` <*assign exact bounds of the region as segments of the border surfaces*>
`FU1` <*3 numbers – number(s) of cells comprising the region*> `NT`

The first two cards define modified integrated current over the border of a target region: the routine is activated when particle passes through assigned surfaces. Cell numbers specified in the third card are used to define the sign of particle's contribution in tally. So, if the given region consists of several cells, you should assign only border cells of the given region.

For example, suppose that the target region is a cylinder cell *101* confined by two planes (*1* and *2*) and cylindrical surface *3*. Suppose that the cylinder is inscribed in sphere surface *4*. Then the tally cards required are as follows:

```
F1   (1 2 3)
FS1  -4
FU1  101 2R NT
```

The last card `FUx` should allocate 3 tally bins for 3 components of the impulse vector (P_x, P_y and P_z in basic Cartesian co-ordinate). So, the given region can be composed of up to 3 border cells (and ad lib internal cells).

The output values of 3 vector components are presented in 10^{-24} *kg×m/sec per 1 source particle*. If you have to receive the value of force (in *Newton*) acting on the given region, you should multiply the output values by the magnitude of source intensity (in *particles per second*).

4. TEST SAMPLE FOR NEUTRON GAS PRESSURE SIMULATION: REACTOR BOUK/RORSAT

Using the developed routine we appreciated by Monte-Carlo simulation the value of neutron and photon flux pressure on the control rods of reactor BOUK/RORSAT (see the background of the question earlier in this paper).

The results are presented in Table 1. As we see, the pressure of neutrons is higher than one of photons in two orders of magnitude. The *x*-component of vector *P* is dominant as the geometry of the model supposes.

Table 1

Component of vector	*Impulse of photons per 1 source neutron, 10^{-24} kg m/sec*	*Impulse of neutrons per 1 source neutron, 10^{-24} kg m/sec*	*Force acting on the control rod at the reactor's nominal power 100 kW*
X	96,0 (±0.5%)	12000 (±0.14%)	$5.22\ 10^{-5}$
Y	0	0	0
Z	23,9 (±1.5%)	960,0 (±1.3%)	$4.27\ 10^{-6}$

The geometry of the MCNP model (sector of symmetry) is shown on Fig. 2. Shaded part corresponds to the target region (beryllium control rod).

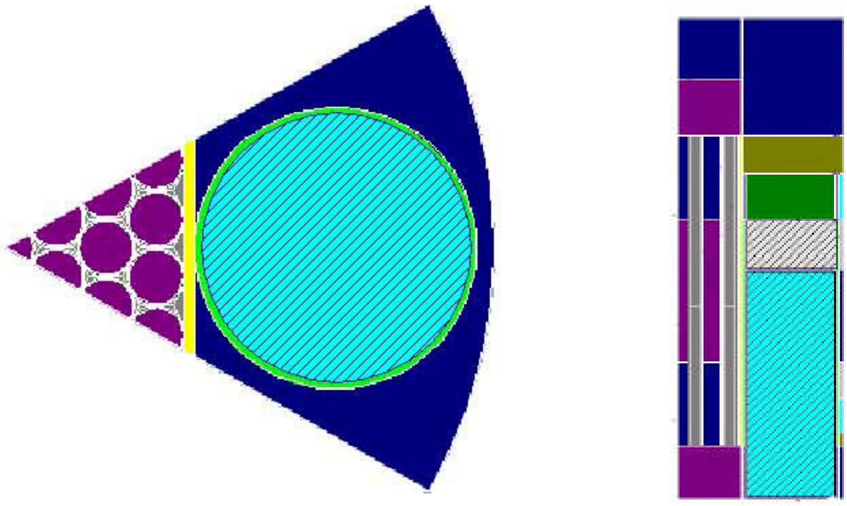

Fig. 2

Fig. 3 shows distributions of neutron importance functions in relation to mechanical effect and criticality for ABBN group partitioning [3]. It should characterize the precision of the mechanical effect simulation using nuclear reactor engineering tools.

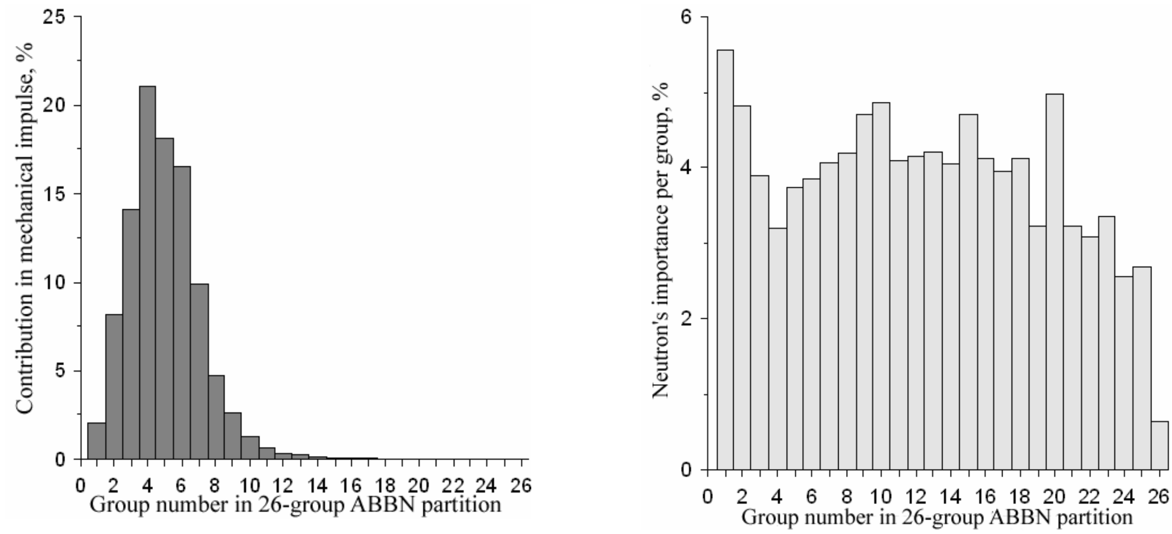

Fig. 3

Like other reactor parameters the quantity of neutron pressure depends on geometry, materials used etc. To illustrate this feature we carried out additional calculations. We replaced beryllium in control rod with zirconium hydride ZrH_2. The results are shown in Table 2.

Table 2

Component of vector	*Impulse of photons per 1 source neutron, 10^{-24} kg m/sec*		*Impulse of neutrons per 1 source neutron, 10^{-24} kg m/sec*	
	Be	ZrH_2	Be	ZrH_2
X	96,0 (±0.5%)	165,4 (±0.4%)	12000 (±0.14%)	9400 (±0.15%)
Z	23,9 (±1.5%)	7,1 (±8%)	960 (±1.3%)	340 (±3%)

5. CONCLUSIONS

As we can see [2], an operating space nuclear reactor may be used as a device for measurements and for receiving new scientific information. This fact makes possible using the value of neutron gas pressure for verification of techniques and computer codes.

We present a new technique and computer code for evaluation of mechanical effect of particle flux on a solid body. The code is developed as extension of the well-known Monte-Carlo code MCNP [1].

The essential feature of the considered quantity is that it is the only currant characteristic of neutron and photon fields that can be measured experimentally. So it can be used as additional independent verification criterion for new computer codes.

The mechanical effect can be applied on practice as a measurer base (for example, to measure absolute level of reactor’s power). We cannot give ultimate recommendations about utilization of the given phenomenon, however the above consideration should prove possibility and perspectives of actual research investigations in this field of neutron physics.

REFERENCES

1. J.Briesmeister, Ed. MCNP-4A – A General Monte-Carlo N-Particle Transport Code // Los Alamos National Laboratory report, LA-12625-M (1993).
2. A.V.Zrodnikov, V.Ya.Poupko, G.M.Gryaznov. Experimental detection of neutron gas pressure on the control rods of a nuclear reactor under the microgravity conditions // Proceedings of the 11th Symposium on Space Nuclear Power and Propulsion, USA, New Mexico, Albuquerque, 9–13 January, 1994, pp. 625–629.
3. G.N.Manturov, M.N.Nikolaev, A.M.Tsiboulya. ABBN-93 Group Data Set. Part I: Nuclear Data for Calculation on Neutron and Photon Radiation Fields (Rus. Systema Gruppovich Konstant BNAB-93. Chast I: Yadernye Konstanty dlya Rascheta Neitronnich i Fotonnich Polei Izlucheniya). Jornal VANT, Ser. Nuclear Data (1996), v.1, p.59-98.