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A TIME-DEPENDENT MODEL FOR GLOVEBOX PROCESSING OF FISSILE MATERIAL

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ABSTRACT

A new modeling system for high-intensity neutral-particle radiation fields is presented. The code PANDEMONIUM calculates external effective dose rates from neutrons and photons produced at specific locations within an industrial-size plutonium processing facility. The new version of PANDEMONIUM introduces time-dependent neutronics for source multiplication coupled with transient source and detector positions. The code is designed to provide quick and efficient total effective dose estimates for scenarios and facilities for which conventional methods prove impractical and costly to model. The next version of the code will also include more rigorous calculations of layered and oblique-angle buildup factors for photons. The energy range of the code will also be extended to include prompt-fission photons.

INTRODUCTION

The computer code PANDEMONIUM[1] was designed several years ago to quickly model the radiation dose field in a room containing high intensity sources of neutral particles located within gloveboxes. Although a variety of radiation transport modeling tools exists [2, 3, 4, 5] (using, for example, Monte Carlo and discrete-ordinates methods), the user is required to possess extensive knowledge of transport phenomena and detailed training in the use of such tools. Additionally, lengthy input files and long run times characterize available computer codes, and not all codes are capable of modeling photons and neutrons, both of which are of primary interest in this work.

PANDEMONIUM's original version offers the ability to determine the effective dose rate (henceforth abbreviated "dose") for a static arrangement of gloveboxes, sources, detectors, and shielding in a fraction of the time typically required to yield similar results using Monte Carlo. The calculational engine for radiation transport consists of diffusion theory for neutrons and point-kernel methods for photons.

For neutrons, diffusion theory is used to determine the flux inside the source. With the flux, the current density on the edge of the source is calculated and radially attenuated to the detector position. Fission neutrons are assumed to exists at 2 MeV, consistent with the fission neutron energy spectrum, and with the exception of hydrogenous materials, shielding materials (lead, steel) are transparent. The neutron source strength is a function of neutrons from (α,n) reactions with low-Z material within the source, spontaneous fission, and subsequent neutron-induced fission.

Photon source strength is found by calculating the mass-normalized source strength for the source materials in discrete energy bins ranging from 10 keV to 1 MeV. The photons in each energy bin are exponentially attenuated through shielding materials to the detector locations. Used in the attenuation calculations are the maximum energies of the bin (e.g., photons with energies between 10 keV and 15 keV are assumed to all have an energy equal to 15 keV). Both neutron and photon sources are assumed to be isotropic.

Although applicable for static situations, PANDEMONIUM would be even more useful if it were to model the transient nature of such a facility. As sources are transferred to different gloveboxes and as workers move around the room, shielding characteristics at each point in the room and therefore dose rates vary with time. Furthermore, if two or more sources containing sufficient fissile material become close enough that source interaction increases neutron multiplication, an accidental excursion could result. To address these and other technical issues inherent in the code, the new version of PANDEMONIUM is under development. Presented in this paper are the implemented improvements for the new version and results to date.

REALISTIC GEOMETRY

PANDEMONIUM models a fissile material production facility in two dimensions. At the height of the typical worker's dosimeter, the room is modeled in plan view as shown in Figure 1. Microsoft Visio® [6] provides the method by which one designs the facility layout. Gloveboxes, sources (with user-defined isotopic and elemental compositions), and detectors are placed in desired locations. When the physical layout is complete, a Microsoft Visual Basic macro translates the design into an input file for PANDEMONIUM.

The glovebox geometry within the code's original version consists of all enclosing regions of lead and steel. This contradicts reality in that at the dosimeter level, gloveboxes include gloveports and windows that constitute material inhomogeneities. The assumption that gloveboxes contain no other materials potentially leads to a consistent overestimation of shielding materials and a resultant underestimation of dose.

To address this concern, PANDEMONIUM has been modified to include several types of gloveboxes (including gloveports and windows) whose dimensions are based upon blueprints describing the facility. Shown also in Figure 1 is an example of glovebox geometry improvements; note that the glovebox with windows and gloveports better represents a two-dimensional glovebox design.

TIME-DEPENDENCE

The transient nature of fissile material processing is well understood. At the macroscopic level, sources of various sizes, shapes, and elemental composition move around the facility. Workers spend time on the materials in their specific glovebox prior to moving across the room to work on another. Such large-scale movement can directly affect the more subtle properties of a neutron source. For example, were a neutron source of sufficient fissile material to be placed near a low-Z medium providing neutron reflection, that source could conceivably cause a nuclear excursion. An-order-of-magnitude jump in neutron population within the source results in a corresponding increased flux throughout the room. The neutron and photon dose received by a worker in the facility would therefore also increase. It should be noted that in reality, extensive administrative controls are in place that greatly reduce the likelihood of such an excursion. They are modeled in PANDEMONIUM solely for training exercises.

PANDEMONIUM now allows the user to identify velocities of sources and detectors, total simulation time, and time-step width for each scenario. At each time step, source/detector positions are updated and slant-path shielding thicknesses are calculated, and these results are used to determine neutron fluxes at detector locations.

Neutron and photon fluxes are calculated at each time-step. To determine the effects of source multiplication from source location, a series of Monte Carlo calculations of k_{eff} will be used to provide neutron multiplication as a function of distance for common geometries and quantities of material. Between two time-steps the reactivity associated with the movement of material can be determined, and as criticality is approached this quantity is used to numerically solve the point reactor kinetic equations as shown in Equations 1 and 2,

$$\Delta\rho_t = \frac{k_{eff,t} - k_{eff,t-1}}{k_{eff,t} \cdot k_{eff,t-1}} \qquad (1)$$

where:

$\Delta\rho_t$ = change in reactivity between successive time steps [unitless]
$k_{eff,t}$ = effective multiplication at time step t [unitless], and

$$\frac{dn}{dt} = \left[\frac{\rho(t)-\beta}{\Lambda}\right]n(t) + \sum_{i=1}^{6}\lambda_i C_i(t) \qquad (2a)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda}n(t) - \lambda_i C_i(t), \qquad i = 1,\ldots,6 \qquad (2b)$$

where:

$n(t)$ = neutron population in source [neutrons/cm^3]
$\rho(t)$ = time-dependent reactivity [unitless]
β = total yield for delayed neutrons [unitless]
Λ = prompt-neutron lifetime [s]
λ_i = decay constant for delayed neutron group i [s^{-1}]
β_i = yield for delayed neutron group i [unitless]
$C_i(t)$ = precursor concentration for delayed neutron group i [atoms/cm^3].

The primary purpose of introducing excursion analysis is its usefulness from a training perspective. It is beyond the scope of this work to implement calculation of k_{eff} for each scenario. However, given predetermined k_{eff} calculations for specific instances (e.g., identical solid spheres, spherical shells, and cylinders of plutonium solutions, or PuO_2), important properties of excursions may be extracted and conveyed to the worker.

Introducing the time variable into PANDEMONIUM allows for the determination of a total dose per scenario. As the user defines the length of time, velocities of sources and detectors, and time-step width, dose rates are calculated at each time-step. Trapezoidal numerical integration is used to calculate a total effective dose.

IMPROVED PHOTON TREATMENT

The code's photon treatment is currently being improved via a number of ways. First, the energy range of photon analysis (150 keV through 1 MeV) neglects prompt fission and neutron capture photons, whose energies can extend to 7 MeV[(7)]. Although the yields of higher energy photons rapidly decrease, the photons produced at these energies will have higher probabilities of traversing the shielding present between a source-to-detector pair and thus influencing dose. The code's photon energy range will be increased to 7 MeV to include higher energy photons.

Secondly, the method by which PANDEMONIUM treats the shielding material is basic in that total shielding thicknesses are determined, but the order in which the shielding is encountered by photons is ignored. A generalized buildup factor is then used, which multiplies buildup factors for each of the materials encountered.

A more sophisticated method will be introduced into the new version. The shielding calculation portion of the code will maintain shielding order. And with this information, layered buildup factor techniques will be implemented according to the methods described by Assad et al[(8)]. Energy-dependent, infinite-media buildup factors described in the 1991 ANSI [(9)] report for photons can be used if they are modified for the finite shielding encountered in PANDEMONIUM. Also, angular dependence can have a significant effect on buildup factors at any given energy [(10)]. Finite media correction factors and angular dependence on photon buildup have been analyzed for a narrow set of energies and angles. A more extensive set of correction factors will be determined by using discrete-ordinates methods. Discrete ordinates will also be used to observe the effect of incident angle on photon buildup through several materials.

Dose conversion coefficients currently used in PANDEMONIUM originate from another aforementioned ANSI report[11]. However it has been suggested that fluence-to-ambient dose equivalent factors may be more appropriate, and this will be investigated.

VALIDATION AND VERIFICATION

Throughout the development of PANDEMONIUM, measures are taken to ensure reasonably accurate results when compared to more rigorous modeling tools. Results from MCNP[(2)] serve as the primary validation as this is the method of choice for modeling at Los Alamos and many other institutions. Administrative and cost limitations preclude additional benchmarks of PANDEMONIUM with physical measurements beyond those described in Ref. 1.

OPERATION OF PANDEMONIUM

As previously mentioned, PANDEMONIUM offers a user-friendly alternative to conventional methods for modeling large processing facilities. The ease-of-use aspect of PANDEMONIUM lies within its user interface, designed in Microsoft Visio®. Figure 2 displays a typical 2-dimensional facility model. The user is free to choose the type of glovebox, source, or detector from a template. The user can then redefine specific properties of that template. For example, glovebox outer dimensions and positions can be altered (however, gloveport and window sizes remain unchanged). The user must input the number densities of fissile and other materials, in addition to positions and sizes of spherical (solid or shell) or cylindrical sources. Detectors may be placed in the model one at a time, or by defining a detector grid, sized appropriately, with user-defined numbers of detectors in each of the two dimensions.

The user may also indicate time variables such as total simulation time and velocity vectors of individual sources and detectors. The time to develop a typical model can range from 1 to a maximum of 10 minutes, depending on model complexity. Note that this time is still significantly less than that required to create an input deck of such a facility using traditional methods.

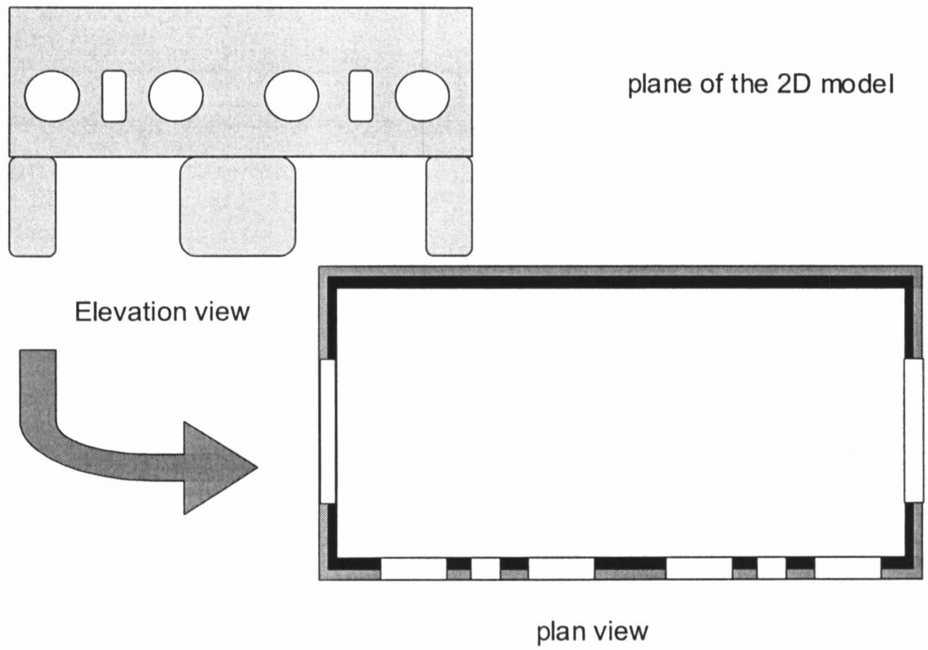
A macro written in Visual Basic exports the graphical data into an input file for PANDEMONIUM, which is then executed in the normal fashion. Output appears as a series of text files indicating dose rates and integrated doses from photons and neutrons as a function of source and detector number. Total doses are also provided, along with slant-path shielding thicknesses for each source-to-detector pair, source strengths, and source/detector positions for verification.

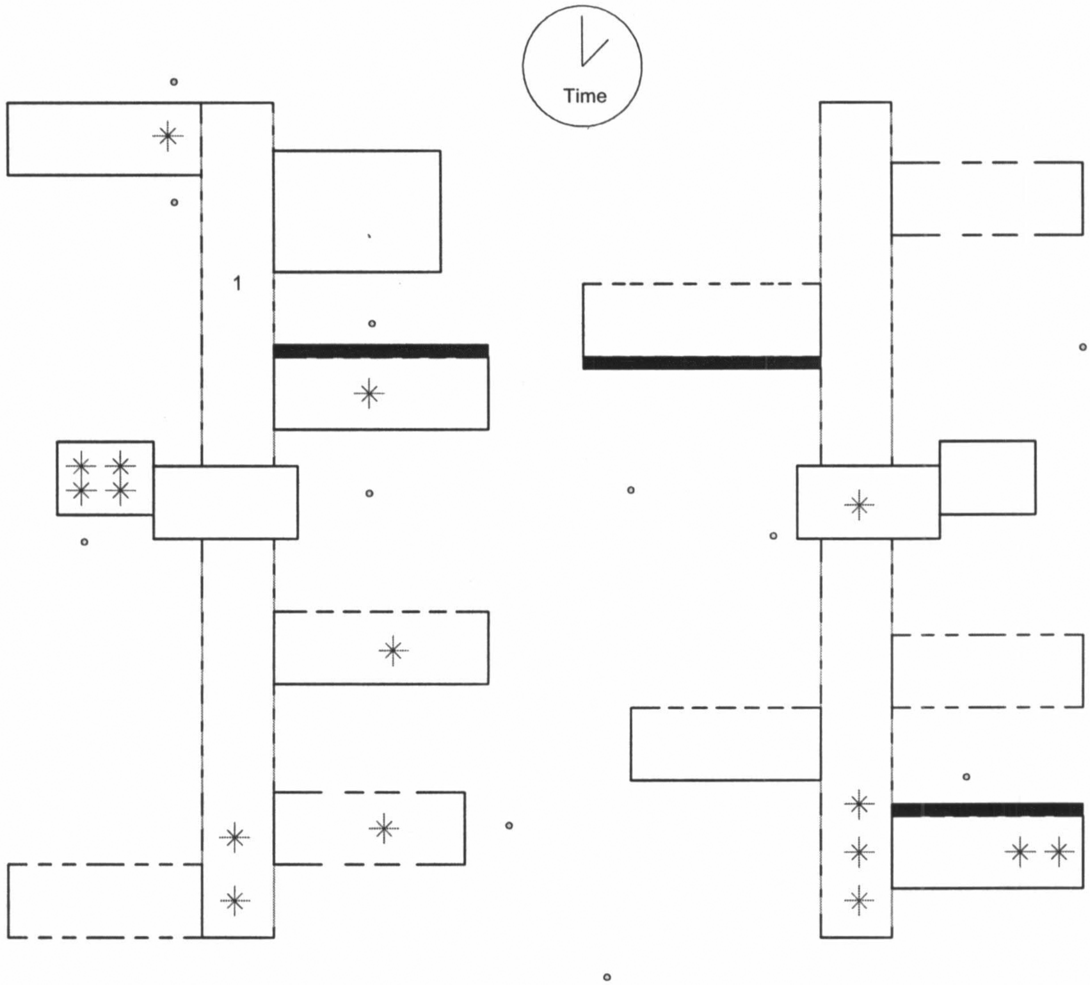
The use of the detector grid allows for sufficient resolution to create a dose profile of the facility, although this calculation takes much longer than with fewer detector points. Figure 3 presents a sample dose-rate profile using the code's first version. Once the described improvements in the model are complete, a time-dependent dose profile will be possible. It is anticipated that the new version of PANDEMONIUM will assist facility managers in training workers in nuclear materials safety, and by providing a simple and fast approach to planning work without the detail and expertise required by currently available methods.

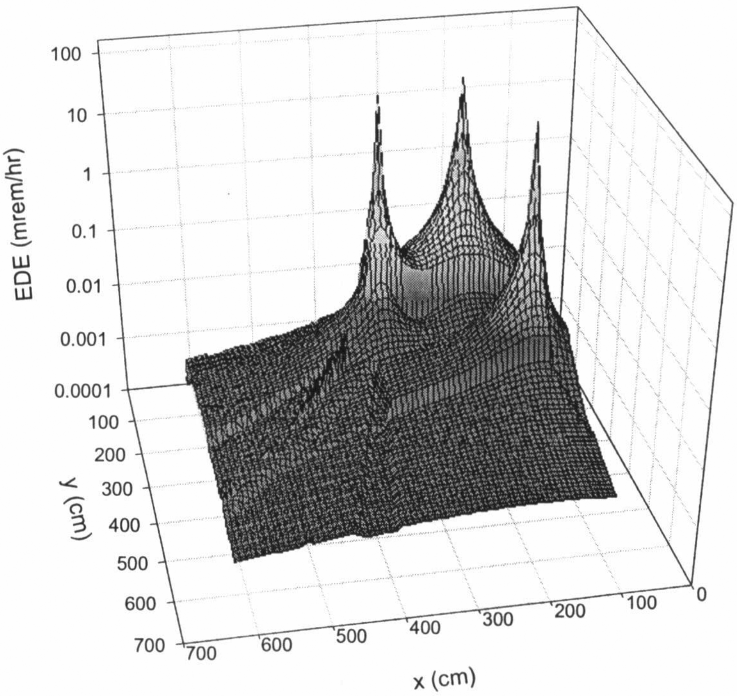
Figure 1. Improved glovebox geometries in PANDEMONIUM. At the plane of the worker's dosimeter, glovebox inhomogeneities (gloveports and windows) have been added.

Figure 2. An example 2-dimensional representation of room containing gloveboxes, sources (stars), and detectors (circles). Microsoft Visio® with a special template is used to define geometric properties and source number densities. Some gloveboxes are shown with hydrogenous shielding. The clock icon indicates a time dependent scenario in which sources/detector positions are updated with each time step.

Figure 3. Example PANDEMONIUM output. Shown is the static dose rate vs. x- and y-position in and surrounding a glovebox containing three sources. The new time-dependent version of the code will provide time-dependent effective dose rate profiles.


plane of the 2D model
Elevation view
plan view


Time
1



100
10
1
0.1
0.01
0.001
0.0001
EDE (mrem/hr)
100
200
300
400
500
600
700
y (cm)
700
600
500
400
300
200
100
0
x (cm)

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