Review of Monte Carlo Modelling Codes

The Panel on Gamma & Electron Irradiation Modelling Working Group

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PANEL ON GAMMA & ELECTRON IRRADIATION

CONTENTS

1 Scope

The Irradiation Panel's Modelling Working Group has reviewed a range of Monte Carlo modelling codes, from the perspective of the industrial irradiation business. This document is primarily intended for potential modellers of industrial irradiation processes, whether they are gamma, e-beam or X-ray. It strives to inform the potential user of some of the strengths and weaknesses of a range of Monte Carlo codes in order to try and simplify the process of selecting an appropriate code.

A selection of six codes has been included: EGSnrc, egspp, Geant4, MCBEND, MCFANG & MCNP. Consideration has been given to a range of features such as ease of geometry input, visualisation capabilities and cost. This report aims to arm the potential user with some basic information on each code, to facilitate an initial choice of the code most suited to their requirements.

Note that whilst every effort has been taken to check the information given in this review, accuracy cannot be assured. For convenience, a number of web links direct to web site pages have been included. These were live at the time of publication however given the nature of the internet the sites listed may well change over time.

2 Introduction to the Monte Carlo Method

The Monte Carlo method is one of the most powerful modelling techniques currently available for dose rate/shielding calculations. At its most basic level, the concept is simple even though the software codes used to run the calculations are very complex.

The capability to calculate absorbed doses with the Monte Carlo method offers plant operators a tool that may assist in:

- Prediction of doses that will be received by products, in order to assist with product scheduling or the assessing of new products.
- Assessment of the impact of packaging changes or a revised product packing pattern.
- Reviewing the effects of a new cobalt loading in a gamma plant, before Operational Qualification is run.
- Assessment of the impact of an unplanned change to the irradiation process, e.g. multiple stoppages during a gamma plant irradiation resulting in multiple transit doses as the source rack returns to the safe position each time.
- Designing an irradiation plant, aiming for optimal efficiency and dose uniformity.

2.1 Monte Carlo in Principle

Monte Carlo simulations are calculations involving realistic simulations of modelled physical systems and are used in many areas of physics and chemistry but are of particular importance in the modelling of radiation transport. Particles are created according to rules which determine their type, energy and initial direction. Their interactions with electrons and nuclei within the material of interest are followed according to probabilistic functions using random numbers, which allow the complete history of a particle to be followed as it loses energy within a simulated medium, perhaps generates other particles, and ultimately is 'killed' as it either escapes from the geometry of interest or its energy falls below a given threshold. It is this use of probability functions and random numbers which gives the Monte Carlo method its name.

Repeated many times, this allows quantities of interest such as the absorbed dose within a medium to be calculated. The precision with which the absorbed dose is calculated increases approximately as $N^{1/2}$, where N is the number of histories calculated within the model. The time required for a particular calculation to be performed then depends upon the model complexity, the detail or resolution used to model the particle tracks, the required precision of the final result, and the speed with which the computer used can perform complex floating-point operations. Laptop computers available now are significantly faster than even supercomputers were in the 1980s and early 1990s, so calculations giving useful results can be obtained in only a few hours (or even minutes, if using a Grid-based system).

Assuming accurate geometry and material compositions have been entered into the model then, when run for millions or billions of particle histories, the simulation closely represents what actually occurs during an irradiation process.

Shultis and Faw[1] contains a very detailed description of the Monte Carlo method as applied to radiation transport.

3 Other Modelling Techniques

Whilst this report focuses on the Monte Carlo technique, it is by no means the only approach available or appropriate for this industry. Point Kernel modelling, for calculations involving photons, has been widely and successfully used within the industry for gamma shielding and dose rate calculations. Whilst Point Kernel still has an advantage over Monte Carlo in terms of speed of computation, it does not offer the same degree of accuracy in predicting absolute dose rates, nor can it be used for e-beam.

Note that normalisation to obtain an absolute dose rate may be required, although when correctly applied, Monte Carlo calculations are capable of predicting actual absorbed doses with an accuracy limited only by the physics built in to the particular model.

ISO 11137[2] has a basic explanation of the two principal types of model and discusses some uses of modelling within the industry. ASTM E2232[3] offers an excellent overview of the range of modelling techniques available.

4 Introduction to the Codes

The paragraphs and then tables below give outline descriptions of several of the available and more commonly-used Monte Carlo codes. For more information, readers are referred to the websites and other documentation available.

All of these codes are widely used within their principal markets. Given the relatively small number of codes reviewed, the differences in price and usability of the codes is considerable. Some codes require significant programming knowledge, some do not. Some codes require a knowledge of the physics involved, while with others the physics is already incorporated.

If the codes are suitable for running simulations of the irradiation technology of interest (see section 5.3) then in principle they should also be suitable for modelling both Operational Qualification (OQ) and Performance Qualification (PQ). In practice, the relative ease of coding complex geometries differs between the codes. This might make some of them more suited to PQ, for example, where actual product would need to be modelled. Geometry input has not been investigated at that level of detail for this review, although the Irradiation Panel is undertaking a separate exercise to more fully compare ease of geometry input. When using the method in plant design calculations, of course, the fine detail of particular products is not usually a consideration.

4.1 EGSnrc

EGSnrc is a version of EGS (Electron Gamma Shower) that has been developed by the National Research Council of Canada. It is free for non-commercial use (currently NRC is not charging users at all, but NRC should be consulted if significant commercial use is made either of the code itself or the results of calculations) and there is some support available through the website and user community. EGSnrc is limited to photons and electrons, but it aims to model the physics of these particles very accurately. In fact, the strength of EGSnrc lies in its physics capabilities for high precision modelling, particularly of electrons. However, the geometry input and error checking for EGSnrc is extremely challenging and there are limited visualisation tools available.

Pros: Excellent physics for photons and electrons.

Cons: Difficulty of geometry input.

Web Site: http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html

4.2 egspp

This is a relatively new development from the National Research Council of Canada which was released with EGSnrc in October 2005. Egspp is not a standalone package, but a library of C++ routines that sit on top of the existing EGSnrc code. They greatly simplify the setting up of the model, especially the geometry which can be created using an intuitive text based approach. The geometry files can be read by a visualisation package which works ‘offline’ so that geometries can be modified and viewed without running any simulations. The code is still new, though, so support from the user base is expected to be limited and some of the documentation is not yet complete.

Pros: Excellent physics for photons and electrons (uses EGSnrc) and ease of geometry input/viewing.

Cons: Relatively new and untested, contains some bugs.

Web Site: http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html

4.3 Geant4

Geant4 has been developed through an international collaboration of the high energy physics community. It is open source software, with multiple groups working to develop different parts of the code. Described as a ‘a toolkit for the simulation of the passage of particles through matter’, this highlights two key features:

1. This is an extensive 'toolkit' rather than a single program. The use of Geant4 requires some C++ skills to bring the various parts of the toolkit together in a program that will run the simulation.
2. Flexibility and breadth of the physics. Geant4 covers an extensive range of particles and interactions.

The scale of the Geant4 collaboration means that there are several options available for tasks such as geometry visualisation/checking. It is a very powerful package that can be programmed to run interactively, either through a graphical interface or the command line, with changes being made to the model parameters. Macros are also available to allow parameters to be changed recursively e.g. to simulate moving objects. The power and scale of Geant4 is, however, both its strength and its weakness:

Pros: A powerful package with the scope to run moving, interactive, graphical simulations of industrial irradiators.

Cons: The initial learning curve for Geant4 is steeper and higher than any other code reviewed here. Some knowledge of C++ is essential as everything must be programmed and there are few shortcuts readily available. A fairly detailed knowledge of the physics being modelled is also required.

Web Site: http://geant4.web.cern.ch/geant4/

4.4 MCBEND

Both MCBEND and MCFANG differ quite significantly from the other codes reviewed here in that they are fully commercial packages. These packages have been developed to meet the needs of the nuclear industry and are maintained and distributed by Serco Assurance. Serco Assurance also provide a contract modelling service.

Serco offer a comprehensive package encompassing the software license, phone line technical support and extensive documentation. Data input for MCBEND is relatively simple, with all data contained in one single input file. This is a similar approach to MCNP (see section below) but it also supports the use of names for labelling geometry objects, making it more intuitive. These install as standard software packages and no programming knowledge is required. Comprehensive geometry visualisation and error checking packages are also available.

Pros: MCBEND offers a complete package including geometry visualisation and error checking. It requires no programming knowledge and the physics options are built-in.

Cons: The support and development overheads are higher for fully commercial software and this is reflected in the cost.

Web Site:
http://www.sercoassurance.com/ANSWERS/resource/areas/shield/mcbend.htm

4.5 MCFANG

MCFANG has not been tested for this review, however most of the features are common with MCBEND. The key difference of relevance to the irradiation industry is that MCFANG does not model electrons, either as sources or those arising from ionisation events. Instead, the energy is deposited at the point of the interaction.

Pros: A slightly cheaper option than MCBEND.

Cons: Photons only: no electron physics.

Web Site: http://www.sercoassurance.com/ANSWERS/

4.6 MCNP

MCNP is a well established code that has been developed by Los Alamos National Laboratory in the USA. The development of this code split at version 4, branching into MCNP5 and MCNPX. MCNPX has, essentially, been redeveloped to model a wider range of particles and energies. MCNPX has not been included in this review although many of the features are common to both codes.

At the time of testing, MCNP5 was not available for distribution through the European NEA data bank and version 4C2 has been tested.

Like MCBEND, all MCNP data input is in a single file and no programming skills are required. MCNP4 includes a 2D geometry viewer that can also check for geometry errors; MCNP5 also includes the 3D Visual Editor suite of tools. Geometry objects are defined by intersecting surfaces which offers flexibility, however objects are referred to by numbers not names. Physics options can be modified but the defaults will suffice for most applications. The single data output file includes a range of statistical checks, with pass/fail criteria, to help judge the validity of the calculations.

Pros: MCNP is well established and requires no programming knowledge. Automatic statistical checks on the results will benefit users who are new to the Monte Carlo technique.

Cons: Geometry input is made more difficult by the requirement to refer to objects by number.

Web Site: http://mcnp-green.lanl.gov/index.html

5 Code Comparison Tables

5.1 Basic Code Details

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
Available from	National Research Council Canada	National Research Council Canada	CERN	Serco Assurance ANSWERS Software Service	Serco Assurance ANSWERS Software Service	USA - Radiation Safety Information Computational Center (RSICC): http://www-rsicc.ornl.gov/ Outside USA – NEA Data bank: http://www.nea.fr/
Version Tested	v4.2.2	(included with EGSnrc)	v7.1	10A	Not tested	4C2
Web site	http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html	http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html	http://geant4.web.cern.ch/geant4/	http://www.sercoassurance.com/ANSWERS/resource/areas/shield/mcbend.htm	http://www.sercoassurance.com/ANSWERS/	http://mcnp-green.lanl.gov/index.html
Brief License Details	Free of charge only for non-commercial research or educational purposes. Written consent is required if the code is to be used for a commercial product or service. In practice at the time of writing, NRC is not charging.	Open source software (GNU GPL), however egspp requires EGSnrc.	Open source software. Geant4 from version 8.1 onwards is covered by the following license agreement: http://geant4.web.cern.ch/geant4/support/license	Annual, single processor license fee of the order of £20k; 2D & 3D visualisation packages available at approx £3k each.	Annual, single processor license fee of the order of £16.5k. 2D & 3D visual packages available at approx £3k each.	The NEA data bank imposes restrictions on the use of the software: http://www.nea.fr/html/dbprog/restrictions.htm RSICC single user license details can be found at: http://www-rsicc.ornl.gov/rsiccnew/license.pdf The cost of obtaining a copy of MCNP differs significantly depending on the user's country: • USA through RSICC - single user license $800. • France via NEA data bank – free • In the UK a full annual access fee to the NEA data bank, administered through NPL, is required. Costs are

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
						currently: £5k for companies with an annual turnover less than £50M £10k for companies with an annual turnover greater than £50M. Users from other countries should contact NEA for the costs of accessing the databank.
Level & Type of Technical Support Offered	Some support is offered through contact details on the web site. Users can subscribe to the EGS listserver, a low volume discussion group (mailing list), for update/patch announcements, and to ask questions which may be answered by other users or by the writers.	See EGSnrc	Support section of the web site contains training materials & FAQs. A user forum provides access to developers & users.	Comprehensive technical support is available by phone/email. There is an annual seminar where updates are reviewed.	As for MCBEND.	Los Alamos National Laboratory offers limited, free, technical support. The MCNP web site hosts a listserver forum with a searchable archive.
Documentation	An extensive series of manuals are installed along with the program and are also available from the web site. http://www.irs.inms.nrc.ca/EGSnrc/documentation.html	Limited documentation is currently available as a user manual. A developers manual is promised but has not yet been released. http://www.irs.inms.nrc.ca/EGSnrc/documentation.html	Extensive documentation is available on the web site. http://geant4.web.cern.ch/geant4/support/userdocuments.shtml	Comprehensive user manual, available as pdf or hard copy.	As for MCBEND.	Comprehensive manuals. The MCNP5 manual is now in three volumes: Overview, User's Guide & Developer's Guide. The overview (Volume 1) is available on the web site: http://mcnp-green.lanl.gov/manual.html
Examples[1]	Yes	Yes	Yes	Yes	As for MCBEND.	No
Training	NRC hold courses on EGS approximately every 1-2 years.	As for EGSnrc	Regular training courses (approx 1-2 per year) are held in global locations. Many of these are free to attend. There is an annual conference plus Geant4 workshops relating to specific topics (http://geant4.web.cern.ch/ge	Both introductory & advanced courses are offered. Courses may also be tailored to a particular application. NB - Serco Assurance are offering free training places (for a maximum of 3 people) on the standard Introduction to MCBEND Course, with	As for MCBEND.	Regular introductory & advanced courses are held globally, although mainly at Los Alamos National Laboratory. Courses now use MCNP5.

[1] Some codes include example problems that can be modified and run. This can be an effective way of learning how to use software features.

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
			ant4/pastevents.shtml)	each MCBEND Licence leased by a member of the Irradiation Industry.		
User community	There is an active user community, mainly academia based. Much use of EGSnrc is also made within the medical physics community for radiotherapy and diagnostics calculations.	Limited at present.	Extensive, worldwide, mainly academia based. Much use of Geant4 is also made within the medical physics community for radiotherapy and diagnostics calculations.	Users are predominantly based in the UK/European nuclear industry. Networking with other users is possible at the annual seminar.	As for MCBEND.	Extensive, worldwide. MCNP is already used within the irradiation industry.

5.2 Prerequisites

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
Hardware requirements (PC only listed)	No specific requirements	No specific requirements	No specific requirements	Pentium III, 128 MB RAM (256 recommended)	As for MCBEND.	Pentium II, 128 MB RAM. Minimum 70 MB hard disk space; complete installation requires 2.3 GB.
Operating System	Linux / UNIX / Windows	Linux / UNIX / Windows	Linux recommended but can be run under Windows via cygwin. *NB: Most tools/graphics tend to work best under Linux UNIX although a number of tools (e.g. JAS3) are written in platform independent languages (e.g. Java).*	Linux / UNIX / Windows	Linux / UNIX / Windows	Linux / UNIX / Windows
Programming languages	Knowledge of Mortran is required. Knowledge of FORTRAN helpful.	Whilst no specific programming skills are required, some knowledge of C++/Mortran/Fortran or even a basic scripting language would assist in setting up complicated plant geometries.	Knowledge of C++ essential.	No programming required.	No programming required.	No programming required.
Essential Additional Software Required	None	None	Windows implementation requires C++ compiler e.g. Microsoft Visual C++ Express version (free) plus windows platform software development kit (free) *NB: You can run under*	2D (VISAGE) and/or 3D (VISTA-RAY) visualisation/geometry checking packages highly recommended.	2D (VISAGE) and/or 3D (VISTA-RAY) visualisation/geometry checking packages highly recommended.	None

			windows using cygwin/g77 (i.e. without Visual C++) but this is not the 'official' way to do it.			

5.3 Applications

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
e-beam	Yes	Yes	Yes	Yes	No	Yes
gamma	Yes	Yes	Yes	Yes	Yes; photons only, no electron transport	Yes
X-ray	Yes (No photoneutrons)	Yes (No photoneutrons)	Yes	Yes	Yes; by defining x-ray source directly rather than using electron interactions. (No photoneutrons)	Yes
shielding	Yes (but no neutrons)	Yes (but no neutrons)	Yes	Yes	Yes (but no neutrons)	Yes
photoneutron / product activation	No	No	Yes (photonuclear physics starts at 10 MeV)	No	No	Yes

5.4 Code Technical Details

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
Underlying programming language	Written in FORTRAN, with a Mortran front end.	C++ running on top of the EGSnrc FORTRAN/Mortran. NB: Further development is expected to move egspp entirely into C++.	C++ The development of the Geant4 code follows rigorous software engineering practices (http://geant4.web.cern.ch/geant4/OOAandD/index.html)	FORTRAN	FORTRAN	FORTRAN.
Physics	**electrons/photons** • Extremely good physics for electrons/photons. Generally, calculations can be run with all of the physics options active by default so, whilst some parameters can be adjusted, it is not normally necessary to do so. • Cannot handle neutrons e.g. photoneutrons	Same as EGSnrc	**All relevant particles** • Need to build in user's choice of physics, however the standard electromagnetic physics package would suite most applications. • Extensions available to low energies (i.e. MeV region downwards) which are becoming more accurate as users add	**electrons/photons/neutrons** • Physics is built-in for electrons, photons and neutrons. • Variance reduction/acceleration is accommodated. • Neutron data available from most of the standard evaluated nuclear data files.	**photons/neutrons** • NB – MCFANG does not have electron tracking. If an ionisation event occurs, the energy is dumped at the photon interaction point. • MCFANG is 'multigroup'. Whilst MCBEND calculates or looks up cross-sections explicitly for energy, the multigroup	**electrons/photons/neutrons** • Physics is built-in for electrons, photons and neutrons. • Can adjust parameters (such as cut-offs) as required. • Can be used for calculations where photoneutrons are generated for example in high-energy X-ray

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
	generated in high-energy X-ray facilities.		improvements. • Individual physics objects are under complete user control and new ones are being developed continually by the user community. • Can be used for calculations where photoneutrons are generated. The necessary photonuclear physics only starts at 10 MeV, though, so it is not suitable for photoneutrons from X-ray facilities where the energies are below 7 MeV.		approach uses a series of average values over ranges of energies.	facilities.
Radiation Source Definition	Source geometries and spectra need to be explicitly defined, independently of the materials geometry.	Same as EGSnrc	Sources and spectra need to be explicitly defined, independently of the geometry.	Sources in MCBEND can be defined in several ways: • as previously defined geometry objects • as sources independent of geometry • by material.	As for MCBEND.	Sources and spectra need to be explicitly defined, independently of the geometry.
Energy Range	1keV – 10 GeV	Same as EGSnrc	~250eV – 100 TeV (for electromagnetic processes of interest in this work). Photonuclear physics starts at 10 MeV.	10 keV – 14 MeV	10 keV – 14 MeV	1 keV – 100 GeV (photons) 1 keV – 1 GeV (electrons)
Validation / Benchmarking	The EGSnrc distribution includes the NRCC Report PIRS-703 describing QA tests. Many other references exist describing benchmarking tests including for the critical radiotherapy applications.	As for EGSnrc at least as regards physics; egspp is too new to have significant industry benchmarking as yet for other applications.	Significant documentation exists and is being added to by the Geant4 collaboration including for the critical radiotherapy applications. http://geant4.web.cern.ch/geant4/results/results.shtml	MCBEND is validated for an extensive range of applications. The validation database covers many of the materials and geometries that are encountered in the nuclear industry. Gamma-ray benchmarks cover scatter and reflection of gamma-rays as well as penetration through shield materials. http://www.sercoassurance.com/ANSWERS/resource/area	No benchmarking validation to date.	Significant documentation exists including for the critical radiotherapy applications. http://mcnp-green.lanl.gov/publication/mcnp_publications.html

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
				s/shield/mcbdval.htm		

5.5 Data Input

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
GUIs	Some configuration and the setup of a run can be done using a GUI.	Same GUI used as for EGSnrc.	The MOMO GUI combines facilities for geometry viewing and running. There are many tools available for Geant, however the primary method of working is by programming code. GUIs can be created for each application.	A GUI called Launchpad offers some functionality to load files, launch text editors and run simulations.	As for MCBEND.	Visual Editor is included with MCNP5. This has not been reviewed, however the web site describes it as a GUI including the following capabilities: • creation & display of geometries • 3D visualisation • Plotting of particle tracks http://mcnpvised.com
Geometry Input	Inputting complex geometries is challenging. All geometries must be defined by explicitly stating the distances between objects and boundaries (HOWFAR and HOWNEAR routines). This is not intuitive.	Geometries and sources defined in text files; complex geometries relatively easy to enter.	• Geometry usually entered directly using C++, however geometry design tools (e.g. GGE, part of MOMO) are under development or available. • GDML can be used to describe geometries in a more 'readable', portable fashion using an XML type language.	• Text-based input for geometry, materials & sources. • All data input is held in one file. *NB: Objects and materials can be defined by name, not just a number. This makes the file easier to read and interpret than MCNP.*	As for MCBEND.	• Text-based input for geometry, materials & sources. • All data input is held in one file. *NB: See note under MCBEND.*
Geometry Replication	Each object must be specifically defined; objects cannot be defined once and then replicated.	Geometries can be readily translated/repeated or exported to other models.	Geometries can be readily repeated or exported to other models; the object oriented approach of Geant4 naturally lends itself to geometry replication.	Replication of parts within a geometry is supported. It is simple to transfer geometries between different MCBEND models.	As for MCBEND.	Geometries can be replicated and exported, with care.
Geometry Visualisation /Checking	Debugging geometry is difficult; there is no universal geometry viewer. Under Linux, the egs_windows geometry viewer can be used.	• 3D Geometry can be easily viewed offline using egs_view under Linux or Windows. Objects/regions can be very simply faded or coloured by choice. • Basic geometry checking	• Inbuilt geometry checking commands and external tools such as DAVID are available. • Runtime geometry viewing and verification options.	• 2D (VISAGE) & 3D (VISTA-RAY) visualisation / geometry checking packages can be run from the GUI. • VISAGE displays 2D slices calculated using ray-	As for MCBEND.	• A 2D viewer is included with MCNP. This offers geometry checking by visually highlighting multiply defined regions within a 2D section; the checking is limited to the

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
		available. • Some bugs exist but may be worked around. (Cannot place objects inside a prism geometry; some difficulties with replicated coaxial cylinders inside a geometry.)	• Geometries can be exported to standard formats such as OpenGL or VRML. Standard software is readily available for viewing these file types.	tracing. It can also measure geometry coordinates. • VISTA-RAY displays 3D images, also ray-traced. • Both packages display region identification information. • Both packages offer geometry checking by searching for multiply defined regions. This can be output to a file or displayed visually. • Both packages can display the radiation source on the geometry model display.		section on view. • The 2D viewer will also display particle tracks during a simulation run. • A 3D visualisation package/visual editor (Visual Editor) is included with MCNP5 http://mcnpvised.com; Sabrina is an alternative third party package.
Moving Product Simulation	Not possible directly, would have to run successive static simulations with changed geometries. Difficulties with geometry setup/checking would make this difficult.	Not possible directly, would have to run successive static simulations with changed geometries. This is relatively easy using the EGS_Transformation macro to move objects.	Simulation of moving product possible directly through macros. This could also be done interactively during a run.	Can handle movements within a simulation using some parameterisation / looping.	As for MCBEND.	Not possible directly, would have to run successive static simulations with changed geometries.

5.6 Data Output

	EGSnrc	egspp	Geant4	MCBEND	MCFANG	MCNP
Data Analysis	None - basic text output.	None - basic text output.	• Geant4 provides some analysis options including statistical analysis (e.g. JAS3). • Supports AIDA interfaces which enables other AIDA-compliant analysis tools to be used e.g. OpenScientist.	None, but you have control over the output format so it can be tailored for your choice of analysis package. *NB - Currently it does not provide absorbed dose as an output parameter.*	As for MCBEND.	• Basic text output. • By default, it performs ten statistical checks on the results indicating pass/fail based on given criteria.

6 Further Information

As well as the web sites for each of the individual codes, there are several publications which are of interest to the potential modeller. ISO 11137 discusses the application of modelling within the irradiation industry. ASTM E2232 is a more extensive guide to the use of modelling techniques, including Monte Carlo, to calculate absorbed dose. In addition, there is an EC document published by NPL that reviews a range of Monte Carlo codes[4]. Whilst some of the codes have now been upgraded, much of the information is still relevant. Copies of the review are available through the working group or directly from NPL.

The Modelling Working Group meets several times a year to discuss and resolve issues relating to modelling within the irradiation industry. New members are welcome and further information can be found at http://www.irradiationpanel.org.

RPSMUG (Radiation Process Simulation and Modeling Users Group http://www.rpsmug.org) is a worldwide organisation advancing the use of mathematical modelling within the irradiation industry. RPSMUG offers training courses and meetings are held at least annually. The web site is a valuable resource for members including an online library, industry news and member contact details.

7 Glossary

GNU General Public License agreement - This is a general open source license agreement that allows the program to be used for any purpose. The program may be freely copied, distributed or modified and the modified version released to the public so long as access to the source code is always given. Programs derived from a GPL licensed program are also encompassed by the GPL license agreement and cannot be distributed as proprietary software.

Listservers - These are open discussion groups. Users can register and then send or receive e-mails to/from all members of the discussion group.

Mortran - an extension of FORTRAN. It introduces syntax changes, including the use of semicolons to end statements, in order to improve readability and flexibility.

Open Source Software - Open source generally refers to software for which the programming code is available and open for inspection, modification and redistribution by anyone. Any code derived from it must also be open source. Whilst open source software is often free, it does not necessarily have to be.

8 Contributors

This document has been prepared by the Modelling Working Group of the Irradiation Panel. Many group members have contributed to the development of this document, particular thanks are extended to:

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9 References

[1] 'Radiation Shielding', J. K. Shultis and R. E. Faw, Prentice Hall, 1996.
[2] ISO 11137-3:2006, 'Sterilization of health care products -- Radiation -- Part 3: Guidance on dosimetric aspects', Annex A.
[3] ASTM E2232-02, 'Standard Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications'
[4] 'Review of Monte Carlo and Deterministic Codes in Radiation Protection and Dosimetry', H. Tagziria, published by National Physical Laboratory (2000). ISBN 0946754322.