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ABSTRACT.

Since the last ICRS in 1988, the advent of affordable and powerful workstations has released the full potential of the Monte Carlo method to the shield designer.

Approximations of method and data inherent in the less accurate workhorse codes of the 70's and 80's are no longer necessary as most Monte Carlo methods permit the analyst to routinely define his problem with confidence in all aspects of the physical model. There is no longer the need for shield designers/analysts to compromise on the quality of their calculational tools.

However, although continuous development has led to the basic Monte Carlo algorithms being fully developed, the age of a lot of the coding calls into question its applicability in today's - and tomorrow's - environment of increasing demands regarding Quality Assurance, user-friendliness and evidence of validation.

This paper identifies the general problems the codes will have in facing an increase in the use of Monte Carlo and the associated demands from regulators and users, and describes the current status of the general purpose code MCBEND and the way it is being managed and developed to ensure its future into the 21st century.

I. INTRODUCTION.

The Monte Carlo method has been developed in the UK as a corner stone to the calculational procedures for shielding design and assessment. It has been used both as a reference to validate simpler design procedures or approximate data sets and as a design method in its own right. Increasingly it has become the first choice method for the many design assessment studies. This has been brought about mainly as a result of two separate factors. Firstly the development of improved, automated, acceleration techniques now greatly simplifies the preparation of the case data and removes much of the mysticism previously associated with the method. Within a few days the newcomer to Monte Carlo can, with confidence, set up a practical case and, owing to the technique of automatic acceleration, obtain a reliable design estimate. Secondly the advent of the modern workstation has provided the user with a massive, yet inexpensive, computer resource for individual use. With Monte Carlo the shield designer now has a method capable of solving most practical problems associated with radiation transport. Furthermore the method is rigorous and, within constraints imposed by material tolerances and subjective modelling approximations, its accuracy is limited only by the knowledge of the basic cross-section data.

This paper identifies the general problems nuclear codes have in facing the future with the increasing demands from regulators and users. It describes the current status of the general purpose code MCBEND and the way it is being managed and developed to ensure its future into the 21st century. The new features of the latest version of MCBEND along with examples of recent applications and new validation data are described.

II. FUTURE REQUIREMENTS FACING NUCLEAR CODES.

Underpinning any software product for the future is quality. One of the key problems facing a large proportion of the nuclear software for radiation transport in use today is that it was developed without the benefits of contemporary QA practice. The total redevelopment of these codes is unrealistic and unnecessary in the short term. If a code is to survive into the future a basic requirement is that its life cycle must be controlled within an quality management system. Retrospective work can be completed to satisfy the basic QA requirements such as documentation. This may be easier said than done as the 'greying' of expertise may mean that the original authors have moved on.

An emphasis on validation can be used in the short term to effectively compensate for the lack of formal QA practices during the development of existing code. But again much of the validation work was completed without the benefits of contemporary QA practice and therefore needs regular reviewing. Centralised and maintained general validation libraries are a requirement for the future.

Fortunately validation has traditionally been a strong point of nuclear codes but the closure of many benchmarking facilities has reduced the supply of new benchmarks. Industry support for future benchmarking exercises for application into new areas is required.

Validation of methods is a practical and pragmatic way of demonstrating that the code works, provided appropriate benchmark experiments exist. For the future the importance of clear evidence of verification (or testing) that the code computes the expected result will rise. The verification of Monte Carlo methods which stochastically calculate the distribution of particles in three dimensional space as a function of energy and time presents a challenging problem that will require innovative solutions.

Software suppliers can no longer treat quality assurance as an add-on. It is now effectively a compulsory requirement. Quality extends further than just documentation and procedures. For example the ISO 9001 quality standard embraces the entire quality of a product and includes user support as an important requirement. For the future, user care and support services will be as important a part of the code package as say the latest nuclear data. User support begins with training and subsequently users must be able to turn to a resourced help-line for application support. It also extends to incorporating customers needs by involving them in the code development program and provision of QA'd code load modules on different computers. Increased usage will put a strain on current support mechanisms with the consequence that unless the support function is adequately resourced the productivity of the user will suffer. To some users this isn't important at the moment and the trials of running codes are viewed by some as necessary 'training' - it is nothing of the sort. The model of the resident full time guru or expert in running a particular code will be replaced. Modern working practices which are aimed at securing capabilities for the future call for a more flexible work force able to retain their productivity even though they might not have used the code for a period of some time. User emphasis will be placed on code application rather than code maintenance. Increased ease of use and reuse is an essential feature for the future.

To maintain the codes and support them into the future as outlined above requires secure funding. Ultimately it will be the user who decides which codes are required and survive and inevitably it will be the user who pays for this choice. Fortunately those codes which cannot face this future can be secured in the international data banks.

III BASIC FUNCTIONALITY OF MCBEND.

The functionalities of the current generation of major Monte Carlo codes used in the analysis of radiation transport are very similar. A basic description of MCBEND is provided for completeness and by way of introduction to the following sections.

MCBEND is a general geometry Monte Carlo code for shielding calculations, and is one of the ANSWERS suite of codes for Reactor Physics, Shielding and Criticality. It may be used for neutron, gamma-ray, electron/positron and coupled calculations. The neutron data are presented in 8200 groups and are derived from the UK Nuclear Data Library, JEF and ENDF/B-VI compilations. This fine group treatment has explicit representation of the energy/angle laws. The gamma-ray data are described in a continuous energy scheme and based upon the UKNDL compilations, which are derived from the work of Hubbel[1]. Coupled (n,γ) calculations are performed by running the neutron calculation and writing details of the neutron collisions to a dump file[2]. This is then combined with a gamma-ray production library to produce the source for the gamma-ray calculation. Multi-group data are also available for neutron, gamma-ray or coupled calculations.

The material regions in the system are described using Combinatorial Geometry (CG) techniques, which construct the material zones by the combination or subtraction of simple geometric bodies. This allows a very accurate model of the system to be created.

The method of accelerating MCBEND is based on splitting and Russian roulette, with the geometry model being overlaid by an orthogonal splitting mesh and energy dependent importances being specified for each spatial interval. The values of importance are usually generated by a diffusion calculation run in adjoint mode which is performed as an integral part of the MCBEND run[3].

The source regions are defined with respect to either an orthogonal geometry mesh or by a CG representation. The former allows sophisticated weighting algorithms to be applied; e.g. angular weighting and the direct use of space/energy importances for source weighting. Built-in fission spectra are available. The latter source type has more geometric flexibility, being based on the same body types as used in CG.

Several quantities may be scored in a MCBEND calculation. The basic tally is of volume-averaged flux or response, but facilities exist to score sensitivity, angular fluxes and currents, heat or charge deposition and pulse height distribution. A simple point estimator is also available.

In many instances the efficient utilisation of the Monte Carlo method for reactor shield design in the UK has been achieved by linking MCBEND with other codes to form calculational sequences. Modules have been developed to interface between MCBEND and other ANSWERS Shielding codes, e.g. the point kernel code RANKERN[4], the kernel-albedo code MULTISORD, the SN codes DOT and BISTRO[5].

Clear and informative input data and documentation is an integral part of the MCBEND package. For the user guide a simple input syntax, based upon a flow diagram format, has been in successful use for some years. The guide permits a quick and easy assimilation of the input requirements and gives detailed notes to clarify specific items. The user guide is supported by an expanding range of introductory texts and applications guides.

IV PREPARING MCBEND FOR THE FUTURE.

A. Resourcing and Management.

Recognising the Monte Carlo method's emergence as a routine design tool, AEA Technology realised that to assure MCBEND's future the issues of quality, software life cycle management, ease of use, code support services and funding, were all of key importance. The AEA ANSWERS Software Service was set up in 1985 to address these issues for MCBEND and other AEA codes. MCBEND is now resourced by income from the ANSWERS service and by partnerships with industry.

For the past 3 years the development of MCBEND has been the responsibility of NCD, a joint collaboration between AEA Technology and BNFL.

The collaboration pools the expertise available in both companies and provides a stable framework, with the necessary financial backing and long term commitment, for the on-going support of the Monte Carlo expertise associated with MCBEND and also its sister criticality code, MONK[6]

B. Development Environment.

Both MCBEND and MONK have been developed and used for over twenty-five years in support of the design and operation of a wide range of nuclear plant. In order to prepare the foundations for future large-scale developments, a new modular code scheme called MCANO has been created from which new versions of both codes have emerged. In setting up MCANO the principal aims and objectives have included: creation of an effective common software development environment for the two main codes; optimisation of the use of the available mathematical modelling and software development expertise by removing unnecessary duplication, e.g. collision processing and tracking are now served by modules common to both codes; judicious rationalisation to produce a common user environment that has significant efficiency benefits for users of both codes. A full description of the MCANO system and its resulting benefits to maintenance and development costs are given in reference 7.

C. Code Rejuvenation.

In addition to the implementation of new features into MCBEND a programme of code rejuvenation is underway with the objective of replacing existing functionality with modern code. The neutron collision package used by MCBEND was built around the use of UKNDL data and has given sterling service for many years. To take advantage of data presented in modern formats, it is now time to produce a new collision package, to be known as BINGO. Instead of holding cross-section data in effectively a histogram of 8200 energy groups as DICE does at present, BINGO will use as many energy points as are required to reproduce precisely the basic data, with interpolation between points and a sub-group treatment of the resonance region adding to the accuracy of the package. Furthermore, the package is being designed to be able to handle doubly differential energy/angle distributions and have a treatment for coherent elastic scattering of thermal neutrons (which is needed for crystalline materials such as graphite). BINGO will serve for neutrons, gamma-rays and eventually electrons, so that one collision package will replace the three used at present for the different particle types.

D. Quality Assurance.

Quality has always been of prime importance to the AEA, BNFL and ANSWERS[8]. The first ANSWERS reference set of codes was set up in 1982. The ANSWERS Quality Standards for code development were developed in 1985. In 1992 ANSWERS and the associated software development departments were amongst the first technical suppliers of software to obtain QA certification under the TickIT Scheme now operated by the British Standards Institute. This confirmed full compliance with the ISO 9001 (BS5750) software quality standards. BNFL also holds ISO 9001 certification.

E. User Support.

An integral part of the MCBEND code package is the support available to the user. The ANSWERS Software Service provides a high level of user support by way of customised training, user group seminars, comprehensive documentation and a "hot-line" support service. Emphasis on dialogue between the users and MCBEND developers is facilitated through these formal arrangements.

F. Verification.

In order to verify a computer program it is necessary to have some expected values to compare to computed values. Analytical results for the verification of Monte Carlo are difficult to produce due to the complexity of the nuclear data. This was seen to be a weakness in the testing of the MCBEND and the desire to move to a structured method of unit testing was sought. In a companion paper at this conference[9] a novel verification technique is described which produces analytical results which will test virtually any section of the code. The technique uses a fictitious set of nuclides each having simple properties for which analytical solutions can be determined.

G. Validation.

The validation base for MCBEND is extensive and covers all the areas in which it has been used. The most fundamental form of validation is the analysis of highly specified experimental benchmarks, often performed at Winfrith[10]. The tri-partite facilities and expertise of code developers, experimentalists and analysts under one roof has given the code an unprecedented degree of co-ordinated development, use and validation. The validation base also includes the comparison of MCBEND calculations against measurement on operating plant, whether this be commercial power plant, reprocessing plant or waste storage facilities, and in such applications as the shielding of fuel transport flasks[11]. There are also many examples of the successful application of the code over the years which give confidence in its use.

Historically the documentary evidence for MCBEND's validation was not centralised, but existed as numerous reports to technical committees, conferences or funding agencies. A database has been set up to rationalise the situation. Details of all past and present exercises pertinent to the validation of the code are indexed via a PC database with the usual search features. At present, the database is mainly concerned with work performed within AEA Technology, but it is expanding to include work performed by other organisations as appropriate. Centralising the validation base will ensure that knowledge of the code's validation and range of application will be available to future users of the code.

MCBEND has substantial validation for traditional nuclear applications. For the analysis of nuclear logging tools the situation was poor. To overcome this the AEA have developed a club funding model for supporting research projects. A series of such projects, using new experimental facilities, has yielded substantial new validation data in this area. This work is discussed later in the paper in section VI.C.

V THE NEW FEATURES OF MCBEND 9.

MCBEND9, the first version of MCBEND to be created from MCANO, is due for release in the Spring of 94. At present it is undergoing in-house and external beta testing. This section summarises its new features.

A. Fractal Geometry.

A rational rethink of the geometry modelling of the material space for Monte Carlo calculations has been carried out resulting in a new modelling package known as 'Fractal' Geometry (FG).

Geometry modelling techniques need to be user-friendly and numerically robust whilst having an efficient method of tracking the particles. The former requirements suggested that the construction of the model should be based upon a set of body primitives; the latter favoured the definition by mathematical surfaces. An alternative option attractive for regions with detailed fine structure or high order surfaces is the hole tracking technique due to Woodcock which eliminates the need to compute boundary crossings. A discussion of the merits of the individual techniques and the development of the best features of the various techniques into the Fractal Geometry (FG) method is described in a companion paper[12].

FG allows for the separate specification of individual components of the geometry model(known as parts). The parts are defined with respect to their own co-ordinate system and can be included as a single item within other parts to form new parts. This process can be repeated over and over. Thus the user can build a MCBEND geometry model as it is done in real life by assembling individual components to form larger components etc. etc. which eventually form the completed system. A benefit of the method is that the user can construct unique libraries of tested parts, i.e. models of fuel elements, instruments, logging tools, etc., for inclusion in larger geometric models.

B. Secure Geometry.

An extension of FG is the Secure Geometry option. This provides a facility whereby a model of a commercially sensitive item, such as a neutron spectrometer or oil well logging tool, can be made available to the user, in an encrypted form, as a fractal part for incorporation within the overall calculational model without its structure being revealed. In addition to the geometry model SG can contain all other information relating to the component. For the case of the logging tool this would be source description material description, splitting information, detector description, and scoring requirements.

C. Acceleration.

The adjoint diffusion method for importance generation works very well for calculations which involve penetration through bulk material or which include a moderate degree of radiation streaming; but for problems in which streaming is the dominant mode of penetration this approach can be inadequate and two new capabilities have been introduced into MCBEND.

The first method is designed to improve the efficiency of the analysis of collimated systems, and involves the addition to the normal Monte Carlo tracking of a deterministic - or "forced" - flight from collision sites to the collimator. When applied to the analysis of collimated gamma-density tools used in oil well logging increases in efficiency by a factor of 30 have been obtained.

The second capability caters for the more general streaming calculation and involves biasing the angle of scatter at a collision so that particles will preferentially scatter into important directions along the streaming path. Increase in efficiency are very problem dependent but improvements between 2 and 70 have been realised.

These new acceleration capabilities are fully described in a companion paper at this conference[13].

The MCBEND sensitivity option has been extended to function with the forced - flight option.

D. Pulse Height Scoring.

MCBEND has the capability to directly score a pulse height distribution (PHD) response in gamma-ray detector systems such as NaI scintillators as used in Nuclear logging tools. The technique has recently been developed so that it can be requested in a calculation in which splitting/roulette is used for variance reduction. Up to this point, PHD scoring and splitting/roulette were incompatible because the contributions from each split particle could not be determined individually. The problem was overcome by switching splitting/roulette off near the detector. The particle then undergoes analogue transport until its death, when splitting/roulette is switched back on. In this way, particles can be accelerated efficiently towards a detector, using the forced-flight technique as appropriate, and the correct PHD score can be obtained. A more sophisticated option is also available in which the history of a particular particle is retained as it is tracked, so that the correlation between particles from, say a pair production event may be treated correctly.

E. Source.

The source in MCBEND may be defined either with respect to an XYZ or RθZ orthogonal mesh or using a general source module. The latter is based upon CG techniques. Sources, defined relative to the CG body primitives, are superimposed to create the desired spatial distribution. Additional flexibility in the definition of complicated sources is provided by a new option allowing linear variation of source over a body. The variation is defined with respect to the body axes and can apply along more than one axis.

For an efficient calculation it is necessary to adjust the source sampling according to the energy and spatial variations of the importance function. Using the XYZ and RθZ mesh options this can be carried out automatically. The source routines have also been extended for the specification of an angular variation, both polar and azimuthal, of source strength. This option was provided for use as part of a linked calculational sequence as discussed below but can be used independently.

F. New Data Libraries.

The original cross-section libraries used by MCBEND were based upon the UK Nuclear Data Library. The UK has participated in the setting up of the European JEF Library and MCBEND has been used extensively for benchmarking this library. The new JEF 2.2 Library has been processed for use with MCBEND and benchmarking for a range of typical LWR applications has been carried out[14]. Similar studies have been performed for the ENDF/B-VI Library[15]. New releases of MCBEND will allow users the choice of either JEF 2.2 or ENDF/B-VI Libraries.

Now that statistical uncertainties in calculation can be removed it has become appropriate to consider more fully the uncertainties due to the nuclear data. A new $S(\alpha,\beta)$ treatment for the scattering of thermal neutrons by light nuclei has been developed which employs a continuous sampling algorithm, and an improved free gas model for heavier nuclei and higher energies has also been included in the code.

G. New code links.

By linking MCBEND with other codes calculational sequences can be efficiently performed to solve particular shield assessment problems.. The determination of the containment dose-rates on a PWR[16] - see Figure 1 - serves to illustrate the procedure.

The penetration from the reactor source, through the radial shield, to the reactor pressure vessel (RPV) cavity is determined by MCBEND using an exact geometry model. The dispersion of the radiation within the cavity is estimated using MULTISORD, which generates a wall leakage source term for the RANKERN code. Streaming currents at the nozzle and flange regions, predicted by RANKERN, are input to MCBEND, which predicts the dispersion over these complicated geometry regions. The migration within the containment is also determined using MCBEND.

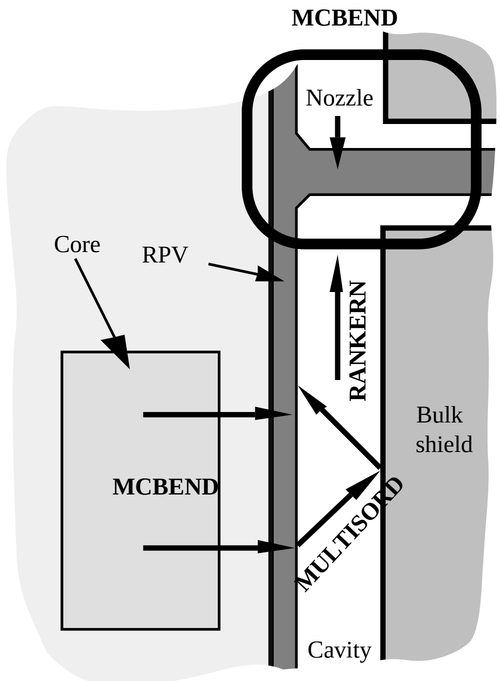

Figure 1 - Calculational route for LWR cavity streaming

Accurate pressure vessel fluence modelling in LWRs requires detailed neutron source information within the LWR core. This is normally obtained from reactor physics core performance calculations. A new module has been written to interface MCBEND with the whole core code PANTHER[17] to integrate the acquisition of core source data in the form required by MCBEND for all periods of reactor operation. PANTHER was developed by Nuclear Electric and employs nodal diffusion methods for steady state performance, fuel management, safety transient analysis and on-line operational support.

Modifications have also been made to the source and scoring routines of MCBEND to allow for the linking of separate MCBEND runs. The code will now output a file containing the angular current at a surface which can be accessed by the source routines for use in a subsequent calculation. This technique is very powerful and allows the entire analysis of the LWR cavity streaming example shown in Figure 1 to be completed entirely with MCBEND. Three examples are given to illustrate the advantages of using this method;

a) for a complicated calculation it may be beneficial to use different importances for the different penetration stages. For an LWR RPV calculation a switch can be made from the use of XYZ splitting geometry in the core to RθZ splitting geometry for the radial shield penetration.

b) for calculation of the reaction rates within small samples the penetration calculation can be carried out in the conventional forward mode and linked to an adjoint calculation for the detector position.

c) for a gas cooled reactor charge face the leakage from an individual channel can be obtained and used to construct the total leakage over the entire charge face for the subsequent penetration calculation. This process, referred to as the "black albedo technique", is described more fully in Section VI.B.

H. Geometry Preparation Macros.

Data preparation macros have been written to simplify the preparation of the input data for selected standard problems. An example is PUFFIN, which takes the user, step by step, through the preparation of the input data for the analysis of a steady state neutron porosity tool as used for bore hole logging in oil exploration. PUFFIN is primarily intended to help the new user to get started and has been simplified by restricting the available options. Nevertheless, mud lining of the bore holes and stratified rock beds, with intrusions, can be analysed. The simple PUFFIN models can also form the basis of more specific cases by using an editor to modify the general model.

J. Geometry Visualisation.

A suite of user-friendly, mouse-driven, visualisation packages, has been developed for geometry display and error diagnosis. VISAGE[12] overlays the geometry with a fine orthogonal mesh and employs the tracking routines of MCBEND to output an identifier (representing the material or geometry zone) for each mesh. A resolution of up to 5000 meshes across the display can be employed. The display is a two-dimensional cross-section of the model in either colour or monochrome. The user can interactively confirm the location of the geometry bodies, change the colour of individual regions, zoom in on regions of particular interest and output the display to a printer. The high resolution provides for accurate checking of geometry models.

For three-dimensional displays, VISTA-WIRE[12] creates wire frame displays of the geometry models using PHIGS and allows user manipulation of the display through a Motif based interface. Its companion code, VISTA-RAY[12], outputs a rendering of the three-dimensional geometry model using simulated optical ray tracing techniques. The image is produced by analysing the propagation of rays through transparent or semi-transparent media and interacting with opaque surfaces. The contrast of the picture is enhanced through the simulation of the diffuse reflection resulting from a single light source. To make the production of ray trace pictures efficient the user can use the fast VISTA-WIRE package to set up the required view, with cutaways etc. and the then invoke the VISTA ray to produce the solid body representation.

VISAGE will shortly be incorporated into the VISTA suite as VISTA-SLICE.

VI. EXAMPLES OF RECENT APPLICATIONS AND NEW VALIDATION.

The shield design of all the major UK nuclear facilities, including the THORP plant of BNFL at Sellafield and the Sizewell B PWR have been substantiated using MCBEND. It has been used within the European fast reactor collaboration for the design of the EFR[10] and in the fusion field for the analysis of the experiments at JET. Outside the reactor field it has been widely used in the analysis of nuclear techniques used in process control and in borehole logging. A few examples from recent studies are presented to illustrate the range of problems which are routinely examined using MCBEND.

A. RPV Dosimetry

The determination of the neutron fluence on a reactor pressure vessel for damage predictions is one of the most demanding of radiation transport problems. It is necessary to model in detail the outer core, shield and structural regions between the core and RPV in order to satisfy the accuracy requirements. Multi-group methods impose an unacceptable bias unless compensated using correction factors derived from an extensive range of validation studies. It is the AEA view that the only method capable of handling the geometry and material data with sufficient precision to meet the target accuracies is the 'point-energy' Monte Carlo method. Studies have recently been carried out for both Magnox[18] and LWRs[15,19].

B Pipeline assay

As well as simplifying the analysis of a complicated system by splitting the calculation into several stages, as described in Section IV.C.4, linked calculation methods also provide an efficient route for the analysis of design variations or to determine sensitivity of results to parametric changes.

It is sometimes required to determine the effects of changing the material compositions of parts of a system. A particular case is that of nuclear logging devices which are passed through sea floor pipelines to detect whether they are supported by sediment or whether the sediment has been eroded leaving the pipeline unsupported and possibly stressed. In such cases it is laborious to perform complete calculations for each tool/pipeline/sediment configuration, especially as only small changes in response might be expected. The so-called "black albedo" technique is therefore used.

Firstly, an interface is specified at the outer surface of the pipe. The interface is specified as an albedo material with a very low probability of reflection - hence the name of the technique. The particles hitting the interface effectively form a first crossing current and are used as the source terms for a series of second-stage calculations which model the external systems and, in this example, the subsequent transport of radiation back to the tool detector. This method isolates those particles which will be affected by changes in the material surrounding the pipe. The particles which reach the detector without passing through the pipe wall are not modelled so the method is also free from any uncertainties in the background signal. Because the tracking of particles to the interface is performed only once, the overall efficiency of the calculations is increased. Furthermore, as the first stage of each calculation is common, the statistical uncertainties in the interface source for the second stages are fully correlated and can be cancelled from the analysis. Thus the differences in the results of the second stage may be directly related to differences in the configurations.

C. Bore hole logging.

Gamma-Ray Density Sondes are commonly used in petrophysical logging for the in-situ measurement of the bulk density of the formation immediately surrounding the borehole. The formation is irradiated with gamma-rays which interact with the atomic electrons of the formation. If the gamma-rays arriving back at the NaI detectors in the density tool are counted above an energy threshold (~200keV), then the gamma-rays detected will have undergone only Compton scattering interactions in the formation. Hence irrespective of the number of collisions the gamma-rays have undergone the detector response is determined almost entirely by the electron density which is directly related to the bulk density.

MCBEND's ability to model gamma-ray transport can be applied to the interpretation of the performance of such density tools[18,20]. It has major advantages over other calculational methods in that it can accurately model the complex geometry of the tool and formation; it can calculate the measured quantity (the pulse height distribution from gamma-ray interactions in the sodium iodide detector) directly; it can automatically generate a comprehensive, energy dependent importance map to accelerate the calculation; and it incorporates the forced flight method, described in Section V.C, to improve the efficiency of Monte Carlo calculations for configurations with detector collimators. Use of MCBEND in new situations such as borehole logging has led to developments in the code which are tailored to a specific application but also have more general application, the two techniques of forced flight and PHD scoring being cases in point. Furthermore, the high absolute accuracy and very low statistical accuracies required by such analyses - around 1% - have also led to approximations in the code's algorithms being investigated and more detailed algorithms being developed. Such feedback can only improve the health of the code in general. The development of club funded R&D projects by the AEA into the calibration of nuclear logging tools has yielded new validation data for MCBEND. This is discussed below.

As part of an AEA research club sponsored by 18 Oil and Gas companies, logging companies and the CEC a systematic range of studies has been carried out to validate MCBEND for use with gamma-ray density tools by comparisons with a series of experimental benchmarks. The validation programme started with a simple bare NaI detector and mono-energetic gamma-ray source in air and ranged progressively through more complicated configurations. Simple transmission benchmark studies were followed by backscatter studies with a simplified slab geometry mock up of a density tool. The final studies were against measurements using a complete, well-characterised, reference gamma-ray density tool in a series of calibrated test formations. Perturbations in response of the reference tool caused by a variety of mudcakes on the borehole wall completed the programme.

For the bare detector benchmark studies and the simple transmission benchmark studies the calculated absolute detector responses - integrated count-rates above an energy threshold - were in good agreement with the corresponding measured values, with typical calculated/measured ratios of between 0.96 to 1.05. For the backscatter benchmark studies in the gamma density rig the calculated absolute detector responses were also generally in good agreement with the corresponding measured values - with typical C/M ratios of between 0.91 and 1.01 for both clean hole and mudcake conditions.

The final benchmark studies included the treatment of complicated borehole and tool geometries through a series of realistic measurements in full size test formations in the SPARTAN facility at Winfrith, using a reference tool which closely resembled the geometry and characteristics of a commercial tool. MCBEND gave C/M ratios of between 0.94 and 0.99 for clean hole conditions, but investigations showed that the detector responses are very sensitive to small changes (of the order of fractions of mm) in key tool parameters, e.g. source and detector location. The exercise demonstrated conclusively the ability of MCBEND to calculate accurately the sensitivity of the tool response to small changes of tool design, thus confirming MCBEND's use as a valuable diagnostic tool. The code is now being used to analyse the response of more complex commercial tools used by the oil industry, with changes in detector count-rate due to changes in formation density being routinely predicted to within 5%.

Similar exercises have been performed for dual detector thermal neutron porosity tools as part of a separate AEA research club using the new AEA EUROPA well logging calibration facility near Aberdeen in Scotland[20]. Again a reference logging tool, that closely resembled the characteristics of a commercial tool, was constructed and logged in the reference borehole formations. The tool contained an Am/Be neutron source configured in line with near and far He3 detectors. The agreement between the measurements and calculated detector count-rates for the ten EUROPA freshwater filled, 216mm diameter boreholes is given in Table 1. The absolute response of the detectors are accurately predicted to within the 2% measurement and 2% calculation uncertainties.

The AEA have now launched a "Pulsed Neutron Logging tool" research club for time-dependent coupled (n,γ) tools. The completion of this club will complete MCBEND's validation for gamma, neutron and pulsed neutron logging tools.

VII. SUMMARY.

The Monte Carlo method as embodied in the MCBEND code is firmly established as the preferred method of calculation in the UK for most radiation physics and shielding studies. The applications extend from reactor design, through radiation transport and the fuel cycle, to process industries and oil exploration studies. Secure arrangements within ANSWERS and the NCD collaboration for maintenance, development and exploitation of the code within an approved Quality Management System and development of centralised suport services ensure that MCBEND is able to meet users' future requirements in terms of functionality, accuracy, efficiency and image. MCBEND can face the 21st century with confidence.

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Formation	Porosity (%)	Grain Density	Near Detector Response (cps)			Far Detector Response (cps)			Apparent Limestone Porosity (pu)		
			MCBEND	Meas	C/E	MCBEND	Meas	C/E	MCBEND	Meas	C-E
Salterwath	0.38	2.685	4963	4710	1.05	389.7	404.3	0.96	4.22	3.35	0.9
Derbyshire	8.26	2.695	4251	4004	1.06	208.6	204.2	1.02	10.30	9.69	0.6
Portland	18.49	2.700	3493	3369	1.04	104.10	100.2	1.04	20.90	20.94	0.0
French	24.1	2.696	3196	3062	1.04	80.05	75.75	1.06	26.63	27.12	-0.5
Jasper	0.3	2.648	5417	5458	0.99	707.3	748.6	0.94	0.13	-0.16	0.3
Plumpton	12.41	2.631	3866	3801	1.02	162.0	165.4	0.98	13.05	12.35	0.7
Clashach	17.33	2.638	3622	3517	1.03	123.1	123.4	1.00	17.48	16.73	0.7
Lee	0.81	2.860	5543	5446	1.02	463.8	480.5	0.97	3.59	3.09	0.5
Whitwell	13.1	2.830	3618	3541	1.02	102.4	101.8	1.01	22.41	21.93	0.5
Tadcaster	21.93	2.878	3156	3134	1.01	71.29	73.7	0.97	31.13	29.25	1.9

Table 1 MCBEND Predictions and Measured Reference Tool Response in the EUROPA Formations

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