ICRS-13 & RPSD-2016

13th *International Conference on Radiation Shielding*
&
19th Topical Meeting of the *Radiation Protection & Shielding Division*
of the American Nuclear Society -2016

Closing session
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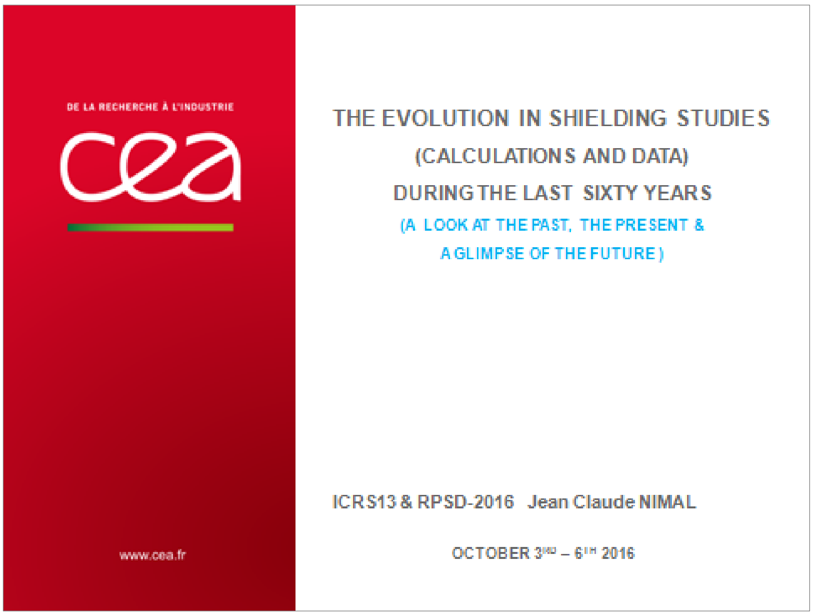
I will talk about the evolution of radiation shielding studies over the last sixty years mainly from my French point of view. I will also offer some indications for future developments.



As a preliminary remark, please note that the guiding thread of my talk stems from two observations:

The first observation concerns the three following improvements made during this period:

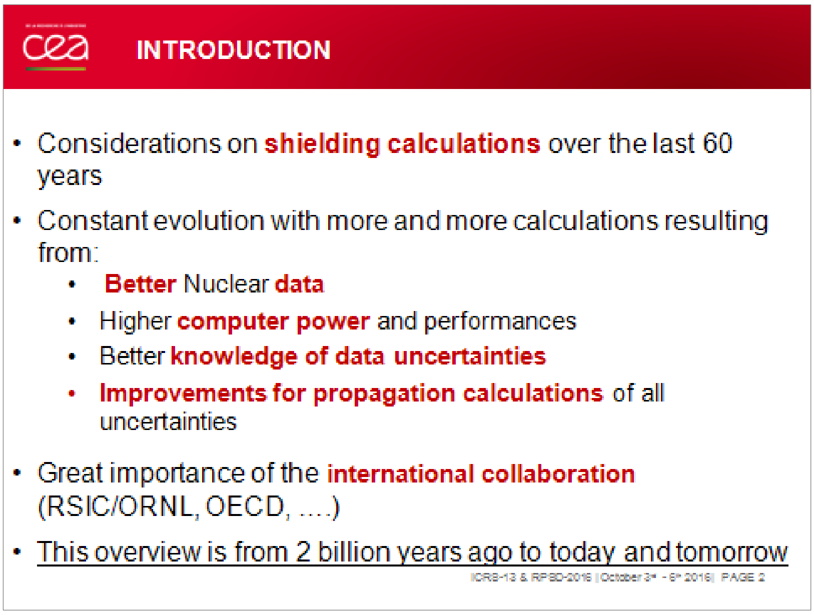
- The first one is better nuclear data knowledge: accurate values and their uncertainties.
- The second one is the exponential explosion of computer power with the capability of treating huge amounts of data and with increased calculation speed thus allowing precise and complex calculations using realistic physical models.

- The third one is to note the evolution in the field of radiation shielding studies which now involve the high energy range and many types of particles. There are medical and spatial applications, accelerator shielding studies, etc. A number of papers presented during this conference have been devoted to these new fields of application.

The second observation concerns the interdisciplinary approach bringing together different disciplines: computer sciences and data processing, fundamental physics and theoretical mathematics. We can observe that codes are put together in "calculation systems". Concerning the oral presentations let me cite two examples presented at this conference: TRIPOLI 4 with GEANT4 and FIFRELIN-TRIPOLI 4 coupling. Many presentations in the poster sessions have also shown the associating of several disciplines like the one which received an award today.

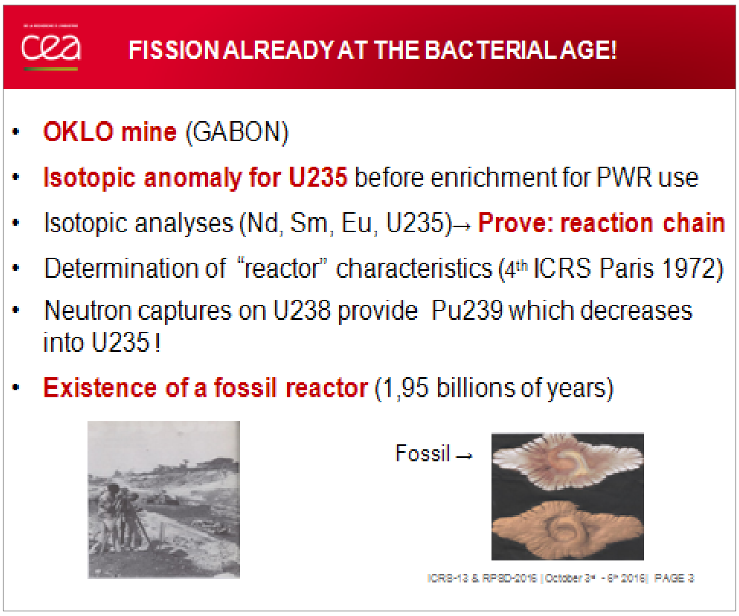
It must also be noted that great "international collaboration" exists within the "shielding community" and this is true since the beginning of radiation shielding studies. From the sixties many exchanges occurred with the USA essentially with RSIC (radiation shielding information center) and with several centers (ORNL, Los Alamos national laboratory) or Universities. The OEDC's Nuclear Energy Agency played and still plays a very important part in the shielding community. Also, many European shielding engineers meet annually in Zurich, as they have for many years, to exchange their points of view concerning software improvements, design studies, etc.

I will now distinguish four sections in my talk going from the bacterial era to the future.



I. The bacterial age.

You were not born or even me when the first reactor we know of diverged about 2 billion years ago in Gabon, Africa. It was located in the uranium mine, called "Oklo mine". This reactor operated for only several centuries. It is now a fossil reactor. Isotopic analyses were performed in 1972 by the French Atomic Energy Commission. These isotopic measurements involved stable fission products such as Nd, Sm, Eu and essentially U235. It was possible to prove the existence first of the chain fission reactions and secondly the conversion from U238 to Pu239. OKLO was thus the first thermal nuclear reactor using fuel recycling. The features of this reactor were fully presented at the fourth ICRS in Paris in October 1972. This reactor did not need sophisticated calculations or nuclear data like cross sections which we need today. OKLO is now the subject of many discussions and many hazardous assumptions since its discovery by Professor El Albany (Poitiers University, CNRS). In 2010, he and his collaborators extracted close to 250 fossils from the Oklo site. The dating of sediments allows asserting that these fossils are 2,1 billion years old. This means that they date back to 1,5 billion years before the oldest previously known trace of evolved life on Earth. The most interesting fact of the Oklo site is the simultaneous spatial and temporal presence of bacteria, oxygen, radioactivity and high grade uranium metal ore.

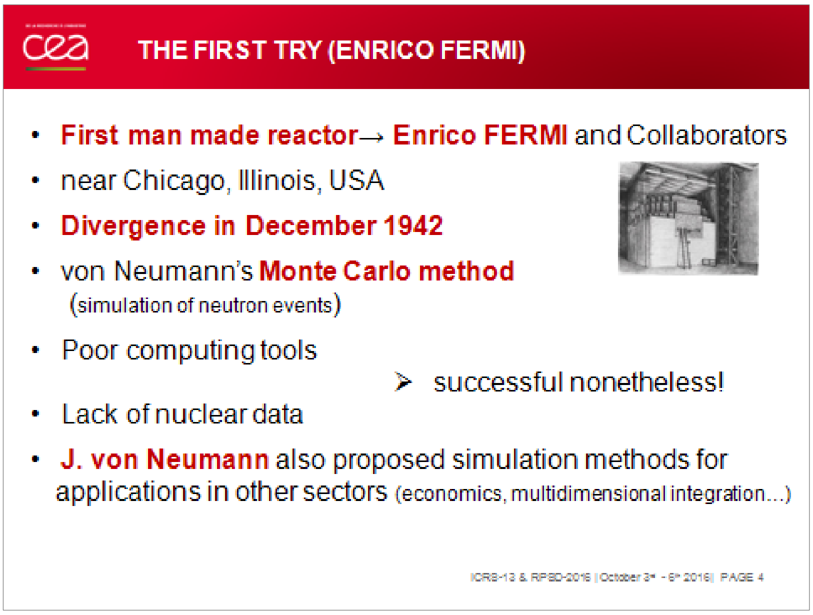


II. "The first try"

We will now take a giant step in time, leaving the prehistoric era to reach the Enrico Fermi reactor located near Chicago, USA at its first occurrence of divergence initiated by physicists in December 1942. It was also at this time that John von Neumann was a precursor in the development and the use of the simulation method for solving complex physical problems. His first applications were devoted to calculations in neutronics with the criticality approach and the explosion height determination. A name was attributed to the corresponding classified document: "Monte Carlo". As a reminder, the essential notion of this method is the game theory. But before going forward, let us take a small step backwards to the naturalist Buffon (1707-1788). This scientist presented a game (1833) for a literary salon which permitted to simply calculate the value of "π". The experiment consisted in dropping needles on a floor made of parallel and equidistant strips to estimate the π value. John von Neumann, along with others, developed theoretical studies in physics and on mathematics. This Monte Carlo method is now applied in other fields like economics, theoretical physics for multi-dimensional integral calculations and other numerical applications. For physics applications, two conditions must exist simultaneously:

- First an exact knowledge of all physical laws for the studied phenomena.
- And second good computing capacity coupled eventually with variance reduction techniques to obtain sufficient statistical accuracy.

The two preceding requirements dictated the orientation of work related to the nuclear field. The execution of radiation transport calculations (shielding and core studies) precise and representative is at the same time a consequence and a motivation of the joint evolution of nuclear data improvements and of the exponential growth of computing powers. If the numerical methods greatly rose during this half-century, the use, a priori not very realistic, of the Monte Carlo methods became common. The Monte Carlo method, based on simulation, has indeed two particular inherent characteristics: the slowness of statistical convergence according to calculation time but also the great consistency in the description of physical phenomena. The increasing interest of the Monte Carlo method is due to these last two features and to the nuclear data accuracy combined with the computing power improvement.



The following slides show the evolution of radiation shielding studies over time.

III. The age of modeling using mock ups for radiation shielding calculations

For this third section, we make a second jump in time to reach the 1950s and 60s. At this time, French shielding engineers employed formulas and abacuses from handbooks like the "Handbook Shielding Design Manual" by Theodor Rockwell III published in the USA (1956) and the "Handbook for the Calculations of Reactor Protections published in France in 1963 (CEA report prepared by C. Devillers).

Some years later, shielding calculations were performed using specific codes written by the CEA. These simplified codes were based on diffusion or removal approximations and on the point attenuation kernel method. The NARMER software and MERCURE 6 code belong to these series of codes using synthetic models. The still used MERCURE 6 code is still also distributed in several countries. For calculations involving particle spectrum use, numerical codes like NIOBE, ANISN and DOT were imported from the United States and used in France since the sixties. This is an important example of the RSIC's international dissemination. At the same time, the diffusion/removal software SABINE from Italy's ISPRA center was used as well.

The simplified codes using removal cross sections or the diffusion theory with few energy groups needed synthetic data. These data were absorption, transfer cross sections, diffusion coefficients. In France, these data were determined by attenuation measurements in bulk shields placed in the NAÏADE facility. It was during this same period that a number of nuclear shielding facilities were developed in other countries (USA, UK, Italy …). I will only mention here the British facility located in WINFRITH coupled to the NESTOR reactor core.

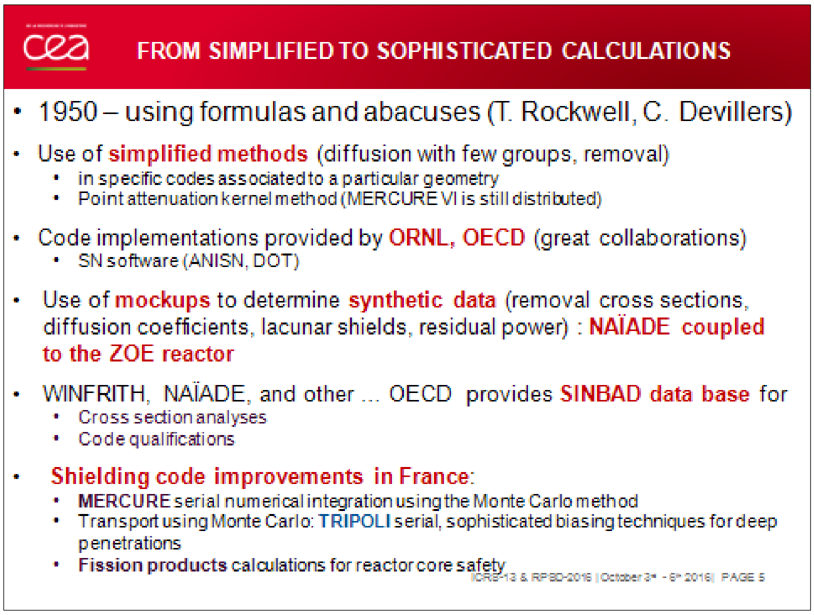
The first version of the French facility, NAÏADE 1, was coupled to the ZOE reactor core (first occurrence of divergence in December 1948). The NAÏADE 1 and the WINFRITH facilities both have a large experimental area containing various mock ups. This area was located behind a converter plate irradiated by the thermalization of fission neutrons issued from a reactor core. For the British facility, the converter plate was very thin and consisted of enriched Uranium. In the French case, the converter plate was composed of natural Uranium and thus had to be 2 centimeters thick meaning more complicated power plate calculations. Political reasons were at the origin of these constraints.

In the ZOE environment, calorimeters were used to measure the residual heat for spent fissile isotopes like U235 and Pu239, both thermal neutrons, and fast neutrons like U238. These measurements result in heat decay curves after "the elementary fission" on several fissile isotopes. These synthetic data were used by convolution software to calculate the residual core power after shutdown.

A second version of the French facility, NAÏADE 2, was constructed with a subcritical fuel assembly located behind the swimming pool reactor core (TRITON). The neutron emission power of this second facility was greatly increased when compared to NAÏADE 1's fission neutron emission power.
The French facility was used in the sixties and seventies to carry out three types of applications:

- Multilayer bulk shields for synthetic data determination.
- Lacunar mock ups with annular spaces, gaps or pipes, were implanted essentially for shielding studies involving graphite gas cooled reactors used in France at that time.
- Fission product decay analyses using calorimetric methods.

The measurements from WINFRITH and FONTENAY are still used today to create shielding benchmarks. These benchmarks and those provided by other countries have been put together by the OECD/AEN in the SINBAD data base for cross section analysis and code qualification. Papers on these benchmarks have been presented during this conference.



We leave this period with simplified codes to move to the period of sophisticated software improvements and uses.

IV. From simplified to high computer calculations with uncertainty analysis.

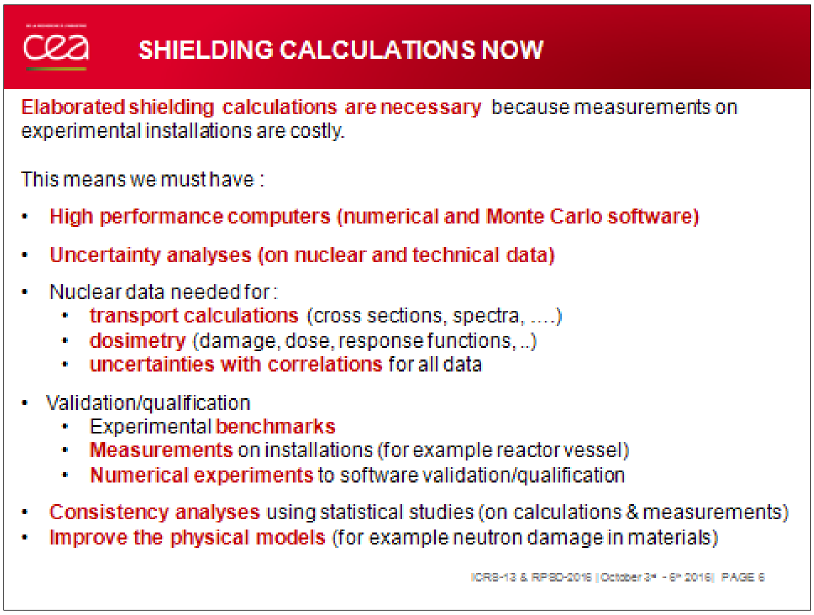
To show the evolution of high computer use, I will present two typical aspects of the TRIPOLI software creation. These aspects were the outcome of many deep reflections since 1965!

The first aspect concerns biasing techniques. It was a successful idea developed during the sixties. Particular attention was provided by the decision-makers (P. Lafore and J. Rastoin) concerning the choice of the forward-looking software features: "a 3D polycinetic Monte Carlo neutron transport code for deep penetration calculations". Thus the non-analog game was studied and implemented using the exponential transform on the neutron path simulation according to a given importance distribution. Associated collision biasing completed the successful spatial biasing. Two types of collision biasing were implemented: the first one devoted to the "normal" bulk shields and the second one for the pipes and experimental reactor channels. The primary importance definition was performed using hand-made drawings. To make TRIPOLI easier to use, the first improvement we made was to automatically determine the spatial importance variations. Based on the initial manual graphic method, we developed the INIPOND module using the Dijkstra algorithm. This algorithm allows calculating the spatial importance by minimizing for each spatial point the shortest optical pathway to reach the result area. The Monte Carlo biasing techniques offered the opportunity for many theoretical discussions on "the zero variance game" and its associated "figure of merit". The INIPOND formulation is in accordance with a quote from Seneca:

"The wind is only favorable for he who knows where he is going".

(SENECA, Sénèque in French, was born ~4 years before Christ). This sentence appears on the first page of the TRIPOLI 3 report. It seems to me to be excellent advice not only valuable for neutron propagation!

The aim of the second aspect was to "simulate the neutron thermalization in some moderators, like light or heavy water, directly from the frequency spectra of the molecules without using the well-known S (α, β) functions." It was overambitious at the time and was a complete failure. But could it be possible in the future with the improvement of computer capabilities? It is nonetheless possible to directly simulate thermalization with the free gas model.

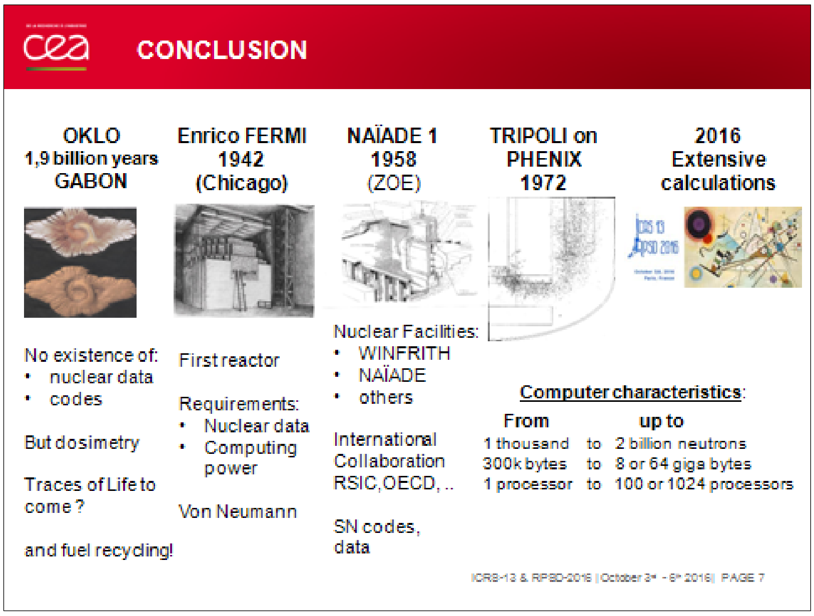


The following slide 7, presents the four stages we have seen and I will briefly make two remarks:

Remark 1: in 1968, the number of simulated particles in some Monte Carlo calculations was a few thousand for a benchmark calculation in the sodium tank placed in the Harmonie reactor. In the 1980s, 2 calculations using 30,000 neutrons were necessary to predict the control rod efficiency. The difference between these two calculations allows to appreciate the control rod efficiency to avoid criticality experiments. Such sophisticated calculations using a simulation technique can reduced the utilization of the experimental way if and only if first the nuclear data are accurate and reliable and secondly if there are sufficiently accurate uncertainty calculations. Now with TRIPOLI 4 we simulate 1 to 3 billion particles to calculate the damage rate for the pressure vessel in a PWR!

Remark 2: in 1968 the memory size of 300 kilo bytes available for the sodium activation calculation (PHENIX reactor) obliged us to represent the double differential cross sections with "half words" (2 octets). The memory size can now reach eight giga bytes or more and some hundreds of processors can easily be used with Monte Carlo software. Monte Carlo methods are naturally well adapted to a parallel treatment. The memory capacities now allow the fine treatment of a large amount of physical data.

The uncertainty calculations on calculated values are now reliable. Initially for the uncertainty calculations they were limited to linear evaluations using sensitivities and partial derivatives. Several software were then improved like SWANLAKE, DUCKPOND and SUSD3D. The nonlinear approaches have been improved with the “correlated sampling method” in the Monte Carlo software. For these approaches, geometrical perturbations can’t be treated. More general methods now exist: codes using probability tables or determination from simulations using a lot of random values of data. The aim of these methods is to calculate the probability density of all results from which we can deduce the interval of confidence. These general methods allow the treatment any perturbations without approximation but require important calculation power.

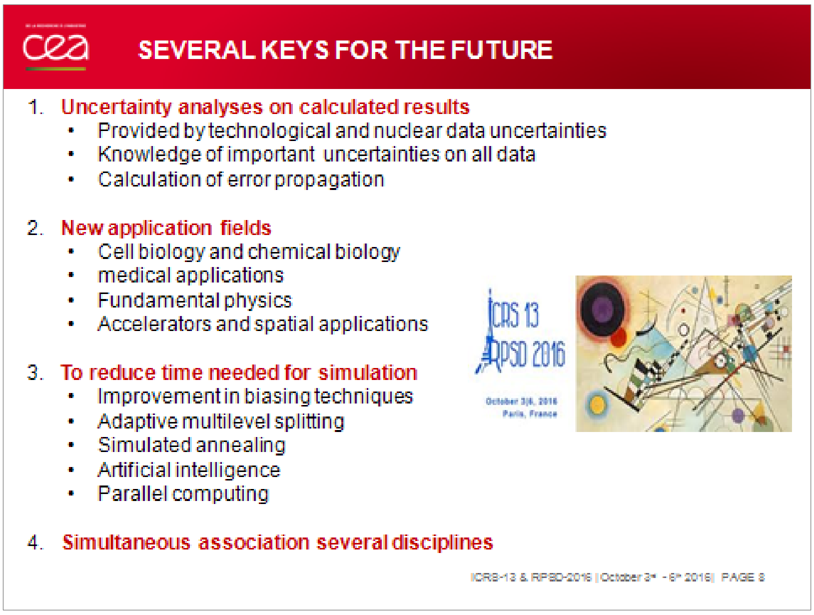


What could be for the future?

For me, the following two remarks are important:

- Improvements in new application fields. At the beginning, the Monte Carlo method was only applied to neutron transport calculations like criticality conditions or sky shine effects. Later it was extended to reliability studies in many fields such as nuclear reactor safety. It could be useful in cell biology, medicine, fundamental research in physics, physical-chemistry and so on. These applications will require more and more calculation power.

- Some applications involve very rare events such as particle transmissions through deep shields or accidents in a nuclear plant (reliability). To reduce computing time used for simulations we will need more powerful biasing techniques. The biasing techniques were already used for deep penetration of neutrons. Always for rare event estimations, despite the high performances of the computer, it will be essential to develop new techniques such as Adaptive Multilevel Splitting, or to improve biasing parameter values using simulated annealing or artificial intelligence. It would be useful to take into account new knowledge as it is acquired along the way during the simulation.



I wish to thank the organizers for the excellent quality of this 5-day conference and also to extend my thanks to Elizabeth COUVERT (*Cedc Consultancy*, devlin.couvert@gmail.com) for our various discussions on these subjects and for helping me to prepare this presentation in English.