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The Experimental Determination of the Relative Abundances and Decay Constants of Delayed Neutrons of the IPEN/MB-01 Reactor

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An in-pile experiment for the determination of the relative abundances and decay constants of delayed neutrons has been successfully performed at the IPEN/MB-01 research reactor facility. The experimental data are of good quality and can be used to validate theoretical predictions of the delayed neutron group constants based on the current knowledge of the fission products yields and emission probabilities for known precursors. The theory/experiment comparison shows that the current of ENDF/B-VI, namely release 8, shows severe discrepancies in both relative abundances and in the first decay constant. The revised version performed at LANL shows very good progress in both aspects. The best performance is obtained from JENDL3.3. One of the main achievements of the experiment was the consistency of the measured first decay constant to that of ^{87}Br. This consistency has never been proved in an in-pile experiment. Furthermore, for the first time it is shown experimental results from an in-pile experiment for an eight-group model.

KEYWORDS: delayed neutrons, reactor kinetics, nuclear data, experiments, ENDF/B-VI, JENDL3.3, IPEN/MB-01, benchmark

1. Introduction

Delayed neutrons play an important role on the reactor physics field. Even though comprising less than 1 % of the total neutrons from fission, they are very crucial in the safety area such as in the accident analysis and in the conversion of period into reactivity. In the event of the fission reaction chain there are many fission products (approximately 250) which can be considered potential delayed neutron emitters. However, an experimental characterization of all these emitters is very difficult due to their very low yield and/or low half-lives and also due to their very complex transmutation chain. However, it is possible to determine experimentally the aggregate behavior and generate a few group model where the decay constants and abundances are mean values of various emitters with similar decay constant.

There are several experimental procedures to determine the delayed neutron parameters [1] and they are generally classified as "in-pile" and "out-of-pile" experiments. The so called "in-pile" experiments are performed in the multiplying system where there is no separation of the prompt and delayed neutrons. For the point reactor model this category of experiments are very important because they can provide valuable experimental information related to the effective delayed neutron parameters used in the model. Such

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effective delayed neutron parameters are system-dependent.

The available experimental support applied to the effective parameters of delayed neutrons to be used in the point reactor model is scarce and in many cases its utilization is not so straightforward and very well established. The main purpose of this work is an attempt to fulfill this need for a thermal reactor application. For such a purpose the in-pile experiment performed at the IPEN/MB-01 reactor for the determination of its relative abundances and decay constants of delayed neutrons will be presented. The experimental procedure employs the multiple transient technique developed by Spriggs [1]. The IPEN/MB-01 research reactor facility consists of a 28x26 array of UO_2 fuel rods, 4.3% enriched and clad by stainless steel (type 304) inside of a light water tank. A complete description of the IPEN/MB-01 reactor can be found in Ref. 2. The theoretical analyses will consider the verification of the adequacy of the nuclear data of several libraries such as: ENDF/B-VI.8 [3], ENDF/B-VI (LANL revision) [4], and JENDL3.3 [5].

2. The Spriggs' Method

The multiple transient technique developed by Spriggs is based on a least-squares-fitting algorithm that simultaneously fits a series of transients produced by small reactivity perturbations of arbitrary size. The function that is least-squares fit is the analytic solution for a step change in reactivity as given by the point reactor model for an arbitrary number of delayed neutron groups. The Spriggs' method is based solely on the measurable quantities of relative power, time, and one of the roots of the Inhour equation. The number of delayed neutron groups that can be resolved is constrained only by the quality and range of the transient data used in the fit.

2.1 Theoretical Background of the Spriggs' Method

The main assumption of the Spriggs' method is the validity of the point reactor model. In the special case of no reactivity feedback, initially critical system, the solution of the point kinetics model, following a step change of reactivity at t=0, can be written as:

$$\frac{n-n_b}{n_0-n_b}=\sum_j \frac{\omega_\alpha \Lambda+\sum_i \frac{\omega_\alpha \beta_i}{\omega_\alpha+\lambda_i}}{\omega_j\left[\Lambda+\sum_i \frac{\beta_i \lambda_i}{(\omega_j+\lambda_i)^2}\right]} e^{\omega_j t}, \qquad (1)$$

where n is the power level at time t; n_0 is the initial power level; n_b is the background power level associated with intrinsic/external neutron sources; ω_j is the j' root of the Inhour equation; Λ is the prompt neutron generation time; λ_i is the decay constant of the i'th precursor group; β_i is the effective delayed fraction of the i'th precursor group; and ω_α is either the asymptotic inverse period or the prompt neutron-decay-period, a measured quantity in the experiment.

Equation (1) states that the relative power is a function of two independent variables (time and one of measurable roots of the Inhour equation) and 2m+1 parameters: β_1, β_2, β_3, ...,β_m, λ_1, λ_2, λ_3,.....λ_m, and Λ. Given a set of the delayed neutron parameters, a neutron lifetime and one root of the Inhour Equation, one can readily obtain the remaining roots (ω_j). Equation (1) is the fundamental equation for the Spriggs' method. Given a specific number of transients produced by step changes in reactivity, the 2m+1 parameters, interpreted as unknown parameters, can be found by simultaneously fitting the relative power as function of time into Equation (1) for all transients.

Basically, the least-squares-fitting scheme starts with the input data: the relative power versus time and its corresponding measured root of the Inhour equation for each transient and an initial estimate of the delayed neutron parameters. The next steps are iterative. For each iteration the remaining roots of the Inhour equation are calculated and a basic non-linear least squares approach is employed. New estimates of the delayed neutron parameters are determined as well as the sum of squares of the step-response function for the whole set of the transients. The process is continued until the sum of squares of the deviations of the step response function is minimized.

3. The Experiment Performed at the IPEN/MB-01 Reactor

The standard configuration of the IPEN/MB-01 reactor core was employed for all the experimental work performed in this work. The perturbations to produce the transients were induced at the central position of the reactor core. An empty tube of SS-304 of the same diameter and thickness of the fuel rods but very high was employed for this purpose. Inside of this tube, it was placed a stopper to accommodate a small sample of Ag-In-Cd (80% Ag, 15% In, and 5% Cd). The stopper was designed such that it could have its height adjusted in order to change the sample reactivity. The sample was placed very close to the central position of the active core in order to optimize its reactivity. The transients were produced by removing rapidly the sample from the active core.

According to Spriggs, there are four key experimental conditions for the successful execution of the experiment: a) a very fast sample removal system (removal time less than 20 ms); b) a very fast acquisition system; c) accurate determination of the initial point, i.e., the time from where the solution of the relative power is a sum of exponential functions; and d) accurate measurement of one root of the Inhour equation. The IPEN/MB-01 removal system consists of a high speed electric motor coupled with a beam catcher. The measured removal time is of the order of 6 ms (10^{-3} seconds) which is more than adequate for the experimental purposes of this work. Therefore, condition (a) is satisfactorily attended.

The experiment has several features that must be contemplated by the acquisition system. Initially, when the sample is removed from the core there is a very fast change in the relative power due to the rapid decay of the largest (negative) root of the Inhour equation. After that the relative power change is less pronounced by still very important for the determination of the relative abundance and decay constants of delayed neutrons. Therefore, the experimental acquisition system has to be fast enough to describe all the physics details of the transient (condition (b) and (c)). The experimental set up for the data collection of this work is composed of two compensated ionization chambers working in a current mode strategically located in the reactor core. The signals from these chambers are fed into the electrometers where there is a conversion from current to voltage (0-2 V). After that, the data are input into a Daq Card 16XE-50 which was set to 1kHz which guarantees a very high acquisition rate. At every 1 ms one experimental data is collected. This last aspect is very important to describe the initial points of the transient mainly for the determination of the starting point (t=0) of the transient. The initial point is a kind of artificial because the transient is not truly a step. The fourth point is the measurement of one root of the Inhour equation. Also, here the experiment performed at the IPEN/MB-01 reactor addressed this aspect adequately by collecting the data in a long run to let the terms of all negative roots do decay to nearly zero.

The experiment basically can be described as follow. Initially the reactor is criticalized at 1 W with the sample inside of the core. The automatic control system is turned off and the reactor is run in the manual mode. The IPEN/MB-01 reactor possesses a very accurate mechanism for the relative control rod positioning [2]. Hence, an experienced operator positions the control rod such that the reactivity is a few cents from the true critical condition. This aspect is very important for the experiment and will guarantee that in the initial condition the reactor is really pretty close to the criticality. The whole system is stabilized. The data collection system is activated and the detector currents which are proportional to the reactor power are writing in a computer file for the subsequent power normalization. These data are collected for at least 5 minutes before the removal of the sample from the core. This aspect will guarantee a proper power normalization before the transient starts. The sample is then removed from the reactor core and the transient starts. The data are acquired in a length of time large enough that all the events necessary for the analyses are contemplated. Later on, the experimental data are normalized taking into consideration the power before the transient and the final result is kept in a computer file. Figure 1 shows an example of the experimental data collected in this work.

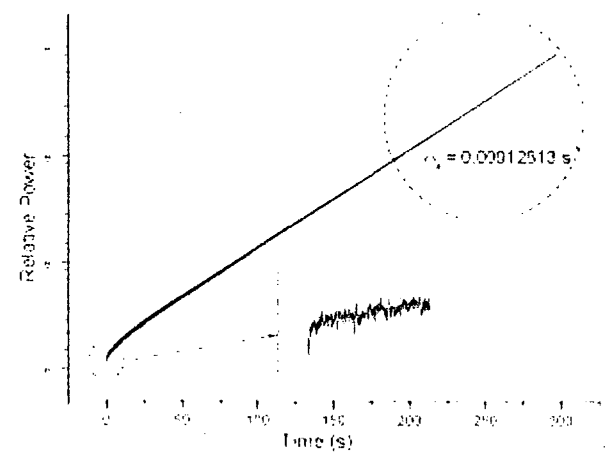

Fig. 1 The Relative Power as a Function of Time

Figure 1 shows clearly the fast change of the relative power density at the beginning of the transient as well as the region where the behavior becomes asymptotic which allows the determination of the first root of the Inhour equation (ω_α). A total of 52 transients ranging from approximately 40 to 110 pcm was produced in this work. They constitute the experimental data basis for the effective delayed neutron parameter determinations.

3.1 The Experimental Results

The least-squares-fitting approach considered in this work assumes six and eight groups of delayed neutrons. In all cases, the neutron generation time was fixed to 32 μs. This value was obtained experimentally in a previous work [6]. Due to the complexity of the comparison between theory and experiment, this work will consider a simplified approach in the least-square-fitting process. Each nuclear data library has its own set of decay constants which depends on the fissionable nuclide. The exception here is the LANL revised version of ENDFB-VI which has the same decay constant set for ^{235}U and ^{238}U. The procedure adopted here to make feasible the comparison theory and experiment will be to fix the decay constants of the major fissionable nuclide from the library under consideration and to fit the relative abundances. By major is meant the nuclide that most contribute to the total fission rate. For the specific case of the IPEN/MB-01 reactor ^{235}U is by far the most important fissile nuclide since it contributes to about 97% of the total fission density. Therefore, the choice of the decay constants of ^{235}U will not impose a very heavy restriction to the analyses of the problem and will allow the comparison theory and experiment feasible. The fitting of the decay constants was also performed in a six group model but in this case it was considered an iterative approach. First, the relative abundances are fixed and the decay constants are fitted. Then, taking into account the new estimates of the decay constants, the process is inverted and the relative abundances are fitted. The process is repeated until convergence is achieved. In all cases all the group relative abundances were set free to vary.

Initially, Table 1 shows the decay constants arising from the iterative approach, the relative abundances for the decay constants of the ENDF/B.8 (LANL Revision), both in a six group model, and the measured relative abundances for a eight group model. In this last case, it was considered the decay constants from Ref. [8]. The 52 transients were simultaneously analyzed using the least-squares-fitting scheme previously described. The intention here is to show the degree of accuracy of the measured parameters as well as to show that for the first time the determination of the first decay constant in an in-pile experiment is consistent to that of ^{87}Br. This aspect has never been proved in an in-pile experiment. Generally speaking the uncertainties increases as the decay constants of the delayed neutron group increases. This aspect is very predictable since the sensitivity of the relative power to the delayed neutron parameters decreases as the group half-live decreases. Also, Table 1 shows that the uncertainties for the six group model is quite adequate to verify the applicability of any nuclear data library. In the eight-group model the uncertainty increases drastically due to the higher number of parameters to be resolved.

Table 1 Effective Delayed Neutron Parameters of the IPEN/MB-01 Reactor

Group	Decay Constant (s^{-1})	β_i/β_{eff}	β_i/β_{eff}
1	1.2456E-02 (0.25%)	0.0510 (1.18%)	0.0462 (2.49%)
2	3.2738E-02 (0.34%)	0.1908 (1.21%)	0.0940 (3.00%)
3	1.2084E-01 (0.58%)	0.2061 (1.21%)	0.1307 (2.84%)
4	3.2814E-01 (0.61%)	0.3305(1.27%)	0.1642 (2.85%)
5	1.7971E+00 (4.45%)	0.1537 (1.69%)	0.3430 (2.60%)
6	3.87 (fixed)	0.0679 (4.03%)	0.092 (9.00%)
7			0.1030 (10.57%)
8			0.0275 (31.10%)

4. The Theory/Experiment Comparison

Following a standard approach , it can be shown [7] that the effective delayed neutron fraction for the delayed neutron group j (β_{effj}) can be found as:

$$\beta_{eff_j} = \frac{1}{F}\int...\int \chi_{d_j}(E)\beta_j \nu\Sigma_f(r,E')\phi(r,\Omega',E')\phi^+(r,\Omega,E)drd\Omega'dE'd\Omega dE \quad (2)$$

where the symbols follows the same meaning as in Ref.[7].

The relative effective abundances of delayed neutrons in group j is obtained as $\beta_{effj} / \beta_{eff}$, where β_{eff} is the sum of β_{effj} for all groups j. This is the quantity to be compared to the experimental values. Compared to another reactor physics responses such as k_{eff} and reaction rates that can employ a very powerful and nearly exact capability of MCNP-4C

[9], the effective delayed neutron parameters does not have a calculational methodology that can reduce the uncertainty in the reactor modeling and in the solution of the neutron transport equation to a value smaller than that inherent in the nuclear data libraries used in the analyses. Consequently, in the theory/experiment comparison the discrepancies of the calculational quantities will not be due solely to the nuclear data library used in the process but it will carry also the part due to the methodology itself. The approach used here will be twofold. Initially, the commonly methodology used at IPEN for the reactor analysis in general based in the coupled systems HAMMER-TECHNION [10] for the cross section generation and weighting and CITATION [11] for neutron diffusion in the reactor will be employed. In an attempt to make a methodology based on transport theory, this work will employ also the coupled NJOY/AMPX-II/TORT [12] systems. The advantage of TORT [13] as already said is the solution of the neutron transport equation (forward and adjoint) as well as the flexibility to use several neutron groups. A specific computer program was written to perform the integrals shown in equation (2).

Initially, Table 2 compares the relative the effective relative delayed neutron abundances by both methodologies for the ENDF/B-VI.8 case. As shown in Table 2 , the effect of the number of groups and the S_N order in the relative abundances is quite small. There is an important effect on β_{eff} as the number of groups increases. Comparing the CITATION and TORT values, there is only a significant difference in the delayed neutron group 1. The another delayed neutron groups shows only a slight difference.

Table 2 Calculated Effective Delayed Neutron Parameters

Effective Parameters	CITATION	TORT		
	4 groups	4 groups – S_2	4 groups – S_{16}	16 groups – S_{16}
β_{eff}	7.79853 x 10^{-3}	7.79991 x 10^{-3}	7.73787 x 10^{-3}	7.92414 x 10^{-3}
β_1/β_{eff}	3.80750 x 10^{-2}	3.35050 x 10^{-2}	3.34634 x 10^{-2}	3.35906 x 10^{-2}
β_2/β_{eff}	1.74487 x 10^{-1}	1.75575 x 10^{-1}	1.75474 x 10^{-1}	1.75635 x 10^{-1}
β_3/β_{eff}	1.69713 x 10^{-1}	1.70861 x 10^{-1}	1.70655 x 10^{-1}	1.69774 x 10^{-1}
β_4/β_{eff}	3.82917 x 10^{-1}	3.84401 x 10^{-1}	3.84616 x 10^{-1}	3.84893 x 10^{-1}
β_5/β_{eff}	1.65752 x 10^{-1}	1.66374 x 10^{-1}	1.66462 x 10^{-1}	1.66661 x 10^{-1}
β_6/β_{eff}	6.90574 x 10^{-2}	6.92835 x 10^{-2}	6.93306 x 10^{-2}	6.94471 x 10^{-2}

The comparison theory/experiment is shown in Figure 2. The calculated values are from CITASTION. In general there is a good qualitative agreement between theory and experiment for the several nuclear data libraries used in this work. Figure 2 shows that there is a systematic underprediction of the calculated relative abundance for the first group of the delayed neutron precursor. The current release of ENDF/B-VI, namely release 8, shows the worst performance with deviations as high as 26 %. However, the LANL revision of ENDF/B-VI shows an excellent progress and the agreement to the experimental values can be considered very good. The best performance is due to JENDL3.3 which shows a really remarkable comparison. Figure 2 also shows the measured eight-group model for the IPEN/MB-01 reactor with the eight-group decay constants from Ref.8. This comparison has been included to demonstrate that the in-pile measurement technique can provide valuable integral data even for the eight-group model. The comparison shows that very good similarity can be obtained between theory and the experiment.

The first decay constant is the only one that has a physical meaning. It is practically equal to that of ^{87}Br. The importance of the first decay constant can be seen in the determination of the reactivity. It has been determined in a previous work [14] that the ENDFB-VI.8 underpredict reactivity by as much as 47% and the main reason is its first decay constant whose value is 0.01334 s^{-1}. The experimental data of this work can definitively give a direct check on the value of ENDFB-VI.8. The measured value of 0.012456 s^{-1} demonstrate that the ENDFB-VI.8 does not have the appropriate value of the first decay constant and the conclusions reached in Ref. 14 is completely correct. The LANL revision of ENDFB-VI possesses a value of 0.012498 which is in a better agreement. The best value according to this work is the one from JENDL3.3. (0.01244 s^{-1}).

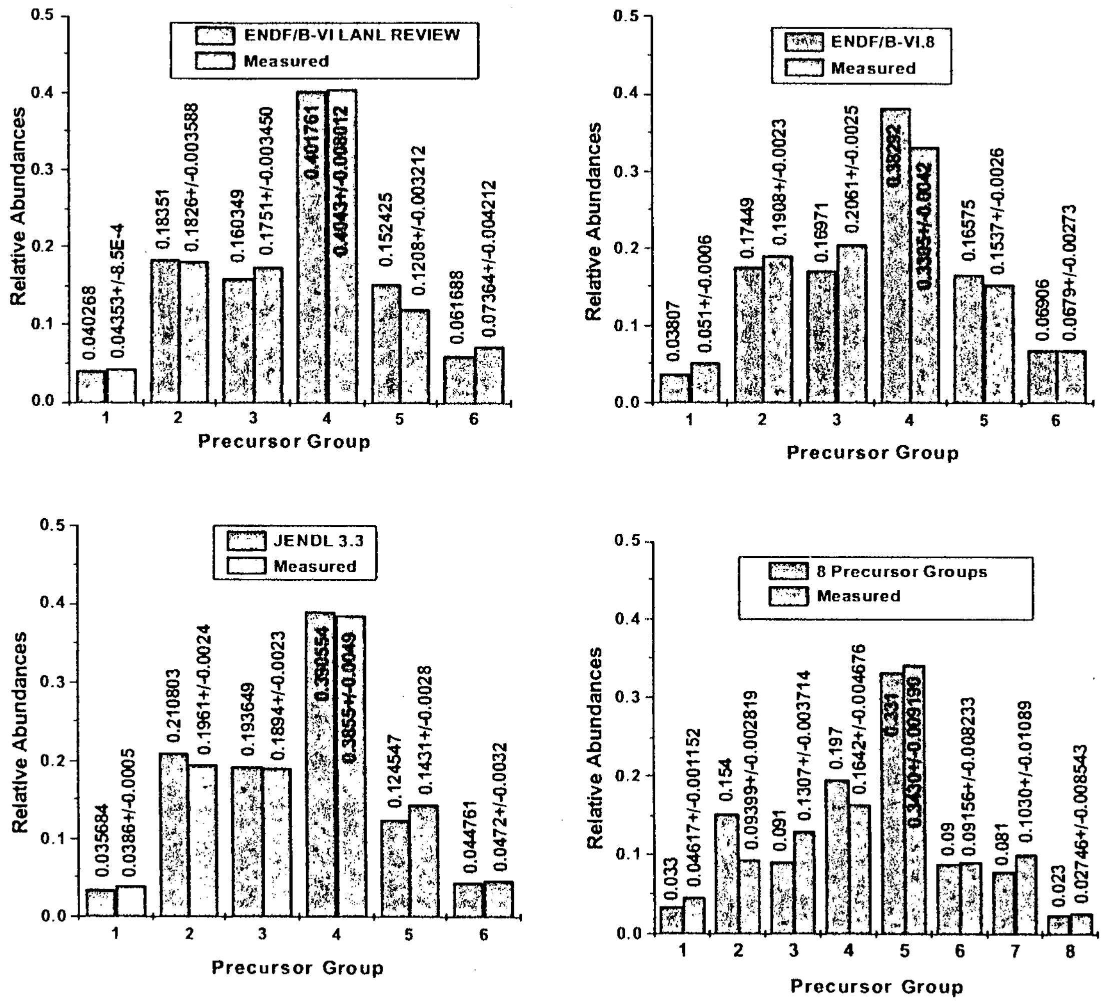

Fig. 2 Comparison Theory/Experiment

5. Conclusions

The experiment for the determination of the relative abundances and decay constants of delayed neutrons of the IPEN/MB-01 reactor has been successfully performed. The sample removal system was designed and tested satisfactorily and the measured removal time was around 6 ms which is more than adequate for the purposes of the experiment. The experimental data basis consisted of 52 transients which were simultaneously fitted to extract the relative abundances and decay constants. The final fitted results are of good quality and can be very helpful to validate theoretical predictions of the delayed neutron constants based on the current knowledge of fission yields and emission probabilities for known precursors. Furthermore, the decay constants in a six group model were also determined and for the first time the first decay constant it has been proven experimentally in an in-pile that this decay constant is consistent to that of ^{87}Br. The comparison between theory and experiment performed in this work shows that the current release of ENDF/B-VI, namely release 8, has the worst performance. Not only its delayed neutron relative abundances of delayed neutron shows severe discrepancies but also its first decay constant is overpredicted which imposes severe restriction on the determination of the reactivity. The revised version of ENDF/B-VI performed at LANL shows very good progress and also its first decay constant is very close to the one determined in this work. The best performance is obtained by JENDL3.3 which shows excellent agreement in all types of comparison performed in this work.

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PALAVRAS CHAVES PARA IDENTIFICAR O TRABALHO: delayed neutrons, reactor kinetics, nuclear data experiments, ENDF/B-VI, Jendl 3.3, IPEN/MB-01, benchmark.

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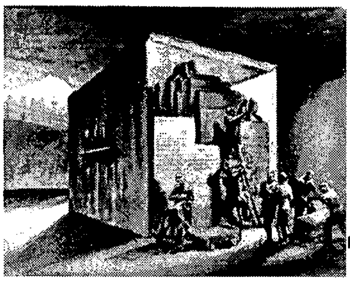
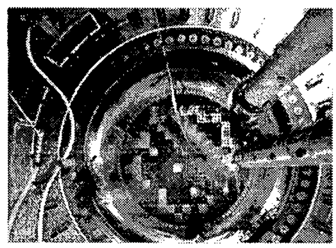
Welcome from the General Chairs



This meeting on the Physics of Reactors is one of a series of meetings sponsored by the Reactor Physics Division (RPD) of the American Nuclear Society (ANS). The purpose of the meeting is to provide a forum for reviewing recent developments in reactor physics and related computational methods and applications for nuclear power and associated technologies, identifying research and development needs, and setting the stage for future advances.

We welcome your participation at the PHYSOR-2004 Topical Meeting. Over 60 years ago, Chicago served as the birthplace of nuclear reactor technology. Today, the city provides a fitting location for the presentation of global developments in reactor and fuel cycle physics for mature technologies, and for a new generation of nuclear systems.



Best Regards,

Massimo Salvatores　　Yoon Chang
General Chairs, PHYSOR-2004

Over sixty years ago, on December 2, 1942, the world's first self-sustaining nuclear chain reaction took place on a squash court beneath Stagg Field on the University of Chicago campus. Right after Enrico Fermi ordered the reaction stopped, the Hungarian born theoretical physicist Eugene Wigner presented him with a bottle of Chianti wine. Fermi uncorked the wine bottle and sent out for paper cups. He poured a little wine in each cup, and silently, solemnly, without toasts, the scientists raised the cups to their lips -- the Canadian Zinn, Compton, Anderson, Hilberry, and a score of others. They drank to success -- and to hope they were the first to succeed.

As the group filed from the West Stands, one of the guards asked Zinn: "What's going on, Doctor, something happen in there?" The guard did not hear the message which Arthur Compton was giving James B. Conant at Harvard, by long distance telephone. Their code was not prearranged.

"The Italian navigator has landed in the New World," said Compton.

"How were the natives?" asked Conant.

"Very friendly," was the reply.

U.S. Atomic Energy Commission, Washington, D.C., November 1949