Los Alamos NATIONAL LABORATORY

EST. 1943

Delivering science and technology
to protect our nation
and promote world stability

Fission, Monte Carlo Method, and MCNP, and Nuclear Safeguards

A Brief Review of Our 70 Year History

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XCP-3 Group Leader

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Outline

- **A little info about Los Alamos and the laboratory**
- **State of the world in 1930 – 1940**
- **Origins of the Monte Carlo method**
  - Development of electronic computers and Monte Carlo method occur simultaneously
  - Ulam, Von Neumann, Richtmeyer, Metropolis, Fermi
- **Growth and usage of Monte Carlo codes**
  - 1950's, 1960's, and 1970's
    - Monte Carlo becomes mainstream; nuclear criticality and reactor
- **Emergence of MCNP**
- **MCNP's history and upcoming future**
- **Nuclear Arms Race**
- **Relevant Treaties**
- **Nuclear Safeguards,**

***nearly all MC references can be found at: https://laws.lanl.gov/vhosts/mcnp.lanl.gov/references.shtml**

***other references are cited in the presentation**

Abstract

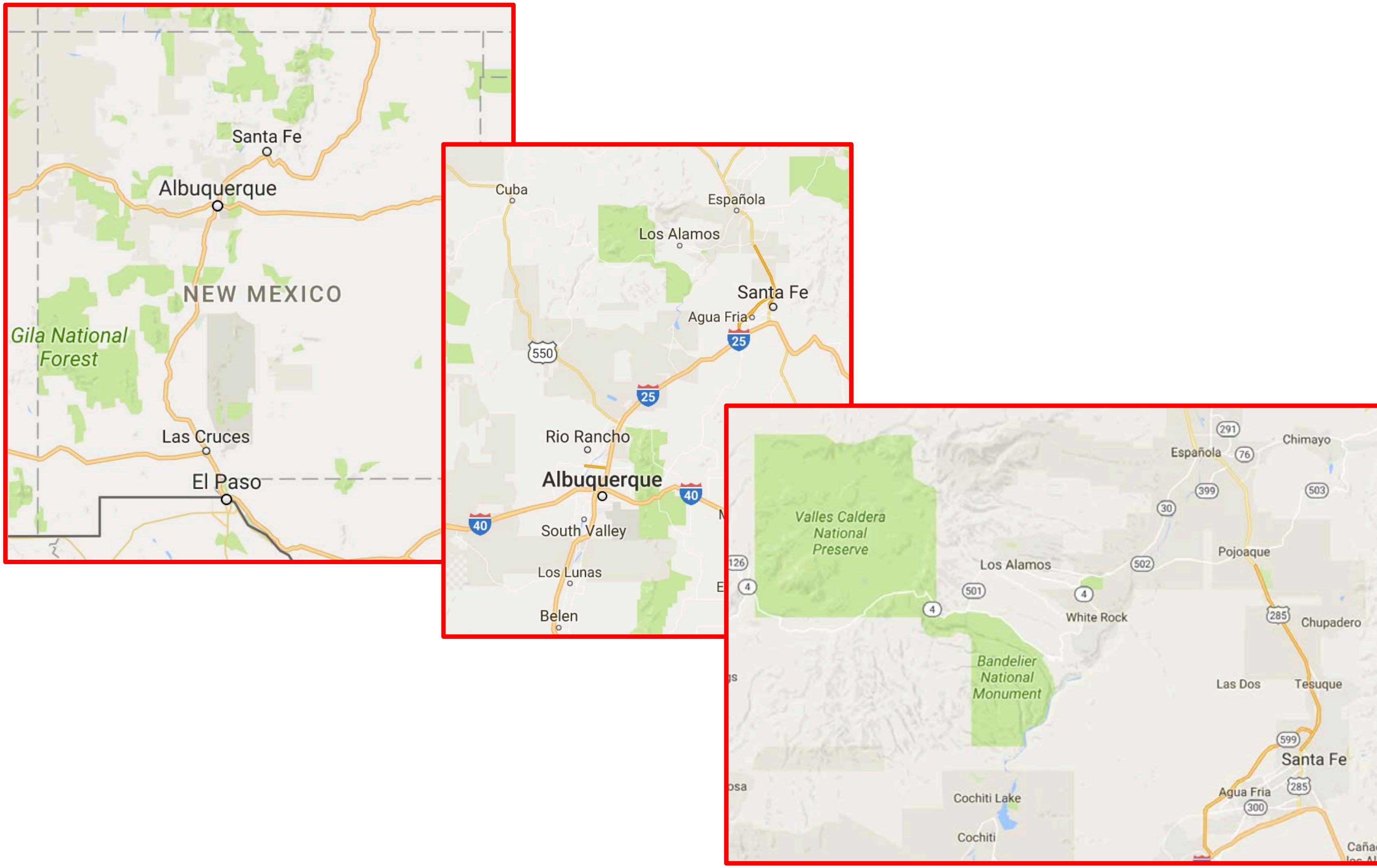
A single point in time, the successful test of Trinity at 0530 on 16 July 1945 near Alamorgordo, NM, brought about significant developments in "everything nuclear" - from technical developments like the first super computers and radiation transport, but also in the responsibilities associated with it. This talk will cover two aspects relevant to nuclear engineers that developed from this historic moment: (1) the development of super-computing and the Monte Carlo method, and (2) a brief history of nuclear safeguards and non proliferation.

The Monte Carlo method for radiation particle transport has its origins at LANL dating back to the 1940’s. The creators of these methods were Drs. Stanislaw Ulam, John von Neumann, Robert Richtmyer, and Nicholas Metropolis. Monte Carlo methods for particle transport have been driving computational developments since the beginning of modern computers; this continues today. In the 1950’s and 1960’s, these new methods were organized into a series of special-purpose Monte Carlo codes, including MCS, MCN, MCP, and MCG. These codes were able to transport neutrons and photons for specialized LANL applications. In 1977, these separate codes were combined to create the first generalized Monte Carlo radiation particle transport code, MCNP. In 1983, MCNP3 was released for public distribution to the Radiation Safety Information Computational Center (RSICC). The upcoming release of MCNP (version 6.2) is expected in June 2017. Approximately 20,000 copies of MCNP have been distributed to users in government institutions, academia, and private industries worldwide.

Nuclear nonproliferation and safeguards started during the arms race with the Soviet Union with Eisenhower's "Atoms for Peace" speech to the UN General Assembly in 1953. The formation of the IAEA followed in 29 July 1957 with the goal of facilitating peaceful uses of nuclear energy. A number of agreements facilitating the non-proliferation of materials, information and weapons have followed. We will discuss a few of these cases with a review of some safeguard techniques used in these fields.

Los Alamos and the Laboratory: An overview

Where are Los Alamos, NM and LANL?



Life in Los Alamos

- **Extensive outdoor recreational opportunities**
  - Bandelier National Monument
  - Valle Caldera National Monument
  - Los Alamos County Trails
  - Pajarito Ski Hill
  - Hours from CO border
- **~45 minutes from Santa Fe**
- **~1.5 hours from Albuquerque**

Los Alamos National Laboratory: solve national security challenges through scientific excellence.

- **Missions:**
  - Nuclear Deterrence/Stockpile Stewardship,
  - Global Nuclear Security,
  - Basic Science
- **Mission-Oriented Science and Engineering**
  - **Charlie McMillan, Director: "For the last 70 years there has not been a world war, and I have to think that our strong deterrent has something to do with that fact.“**
    - as security hedge in very uncertain world
    - to reassure allies that U.S. security guarantee remains unquestioned
    - as a disincentive to adversaries from taking hostile and aggressive actions against the U.S. and its allies
  - **Stockpile Stewardship program**
    - In 1989, the United States halted the design and manufacture of new nuclear weapons
    - In 1992, the United States conducted its last full-scale, underground nuclear weapons test.
    - In 1994, Congress established the science-based Stockpile Stewardship program, which combines advanced scientific and experimental capabilities with high-performance supercomputing to help scientists and engineers understand and resolve issues in the nation’s nuclear deterrent
    - Congress directed directors of the nuclear weapons laboratories (Los Alamos, Lawrence Livermore, and Sandia) annually report on the state and health of the stockpile to the President of the United States, through the Secretaries of Energy and Defense.

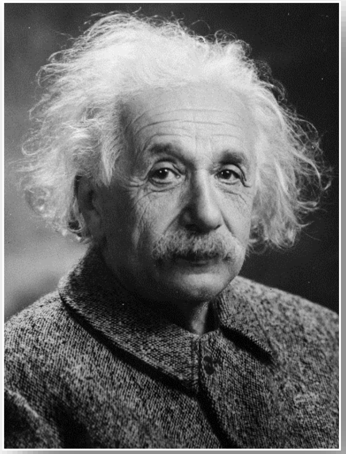
A Little Bit of History…

State of the World in 1930's and 1940's

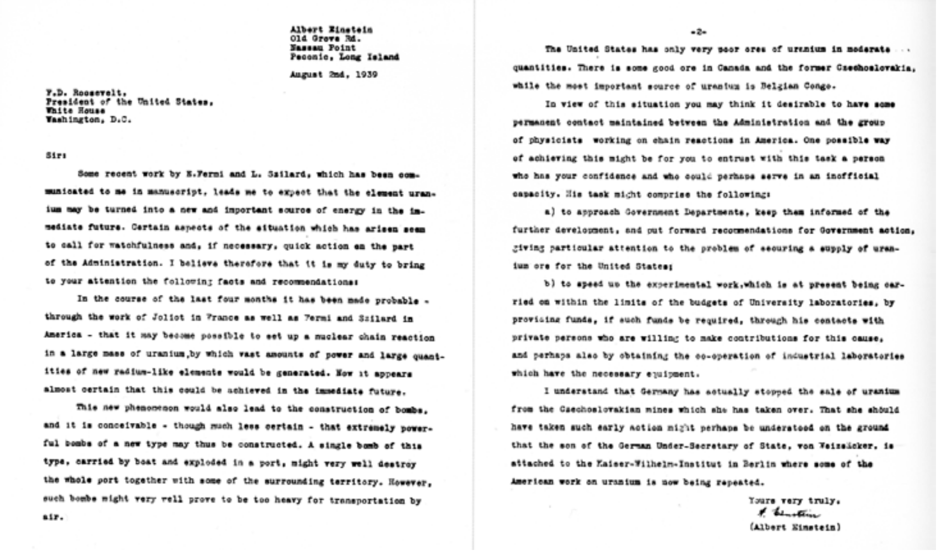
- **Fission discovered in Germany in 1938**

- **In 1939, during WWII, Albert Einstein wrote a letter warning then President Franklin D. Roosevelt about an "extremely powerful" uranium based bomb**
- **Einstein believed Nazi Germany was also pursuing such a device**
- **FDR set up a committee to investigate this capability**

- **The US accelerated its efforts for fear of falling behind the Nazi Program**
- **Early research was conducted at the University of Chicago and Berkeley**
- **Two paths to the bomb were illustrated: Uranium and Plutonium**



Einstein's Letter to Roosevelt



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

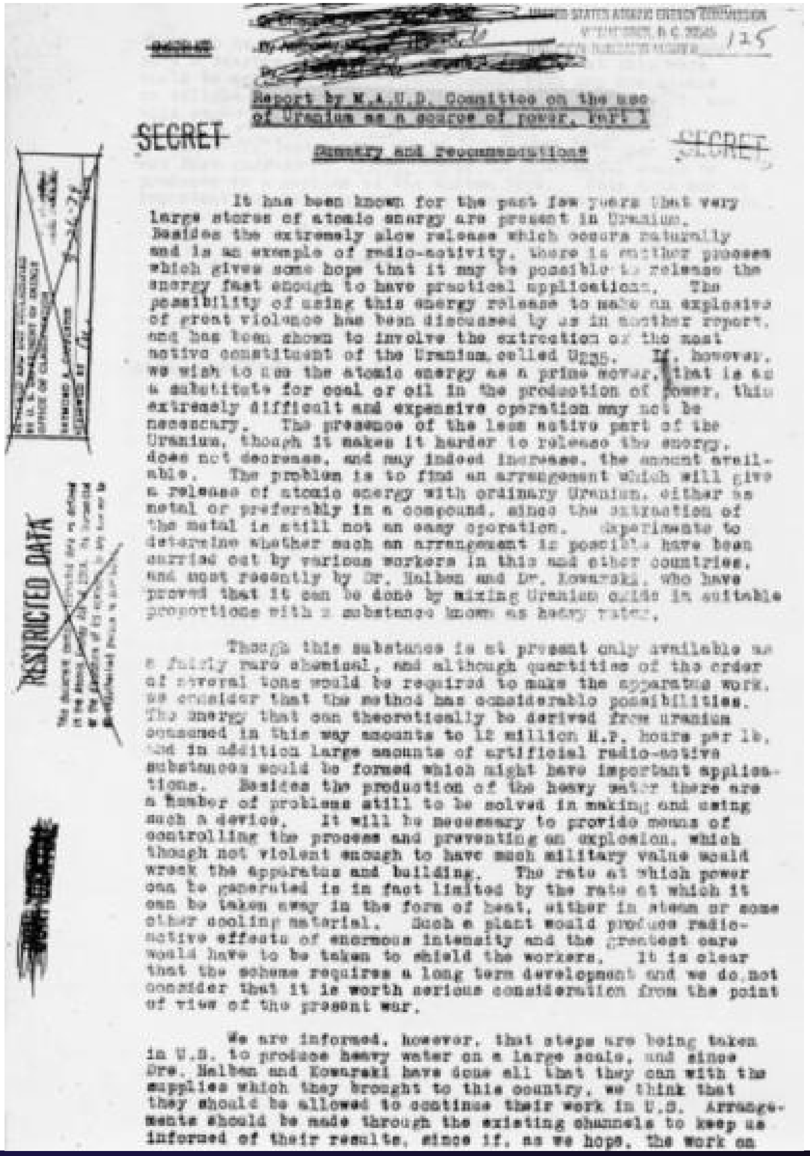
Yours very truly,

(Albert Einstein)

The beginnings of the Manhattan Project

- In July 1941, the MAUD Report was published
- Committee set up by the British to study the feasibility of developing nuclear weapon
- Established that a "significantly purified critical mass of U-235 could fission even with fast neutrons"
- Estimated a critical mass to be 10kg, small enough to load onto existing aircraft
- Provided an estimated time frame for creating such a bomb of 2 years
- The US accelerated its efforts for fear of falling behind the Nazi Program

Source:
https://www.osti.gov/opennet/manhattan-project-history/Events/1939-1942/maud.htm



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Report by M.A.U.D. Committee on the use of Uranium as a source of power, Part I

SECRET

Summary and recommendations

RESTRICTED DATA

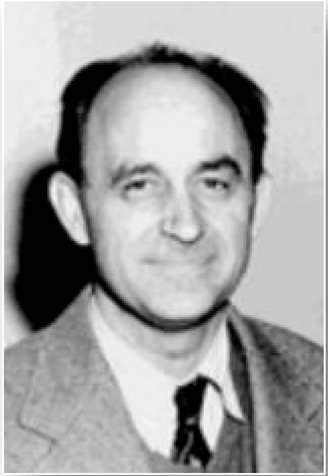
It has been known for the past few years that very large stores of atomic energy are present in Uranium. Besides the extremely slow release which occurs naturally and is an example of radio-activity, there is another process which gives some hope that it may be possible to release the energy fast enough to have practical applications. The possibility of using this energy release to make an explosive of great violence has been discussed by us in another report, and has been shown to involve the extraction of the most active constituent of the Uranium called U_{235}. If, however, we wish to use the atomic energy as a prime mover, that is as a substitute for coal or oil in the production of power, this extremely difficult and expensive operation may not be necessary. The presence of the less active part of the Uranium, though it makes it harder to release the energy, does not decrease, and may indeed increase, the amount available. The problem is to find an arrangement which will give a release of atomic energy with ordinary Uranium, either as metal or preferably in a compound, since the extraction of the metal is still not an easy operation. Experiments to determine whether such an arrangement is possible have been carried out by various workers in this and other countries, and most recently by Dr. Halban and Dr. Kowarski, who have proved that it can be done by mixing Uranium oxide in suitable proportions with a substance known as heavy water.

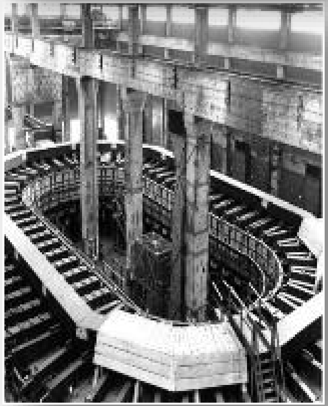
Though this substance is at present only available as a fairly rare chemical, and although quantities of the order of several tons would be required to make the apparatus work, we consider that the method has considerable possibilities. The energy that can theoretically be derived from uranium consumed in this way amounts to 12 million H.P. hours per lb. and in addition large amounts of artificial radio-active substances would be formed which might have important applications. Besides the production of the heavy water there are a number of problems still to be solved in making and using such a device. It will be necessary to provide means of controlling the process and preventing an explosion, which though not violent enough to have much military value would wreck the apparatus and building. The rate at which power can be generated is in fact limited by the rate at which it can be taken away in the form of heat, either in steam or some other cooling material. Such a plant would produce radio-active effects of enormous intensity and the greatest care would have to be taken to shield the workers. It is clear that the scheme requires a long term development and we do not consider that it is worth serious consideration from the point of view of the present war.

We are informed, however, that steps are being taken in U.S. to produce heavy water on a large scale, and since Dre. Halban and Kowarski have done all that they can with the supplies which they brought to this country, we think that they should be allowed to continue their work in U.S. Arrangements should be made through the existing channels to keep us informed of their results, since if, as we hope, the work on

The Manhattan Project is born!

- **Inspired by the MAUD report, US Efforts escalated**
  - Estimated Total Cost: $20,000,000,000 (1996 dollars)
- **Initial Plutonium research took place at the University of Chicago under Enrico Fermi**
  - The first sustained reaction on December 2, 1942
-
- **Plutonium was produced at the X-10 Graphite Reactor at ORNL and Hanford**
- **ORNL was chosen for U production**
  - Y-12 Electromagnetic Plant
  - K-25 Gaseous Diffusion Plant
- **LANL was selected for as the central facility for U bomb research and design**



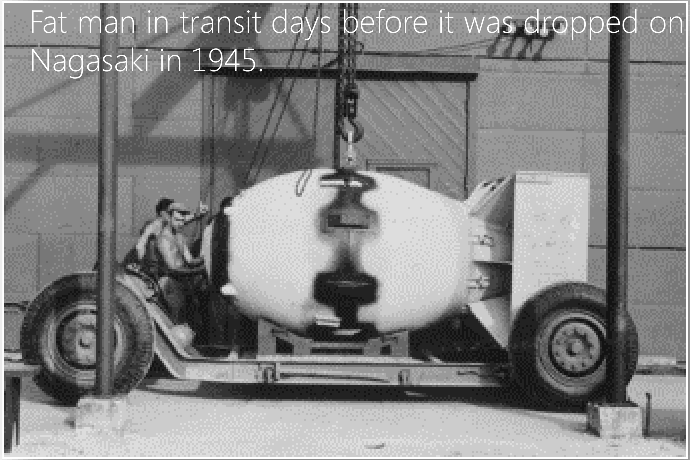


Source(s):
https://www.osti.gov/opennet/manhattan-project-history/Events/1942-1944_ur/1942-1944_uranium.htm
https://www.osti.gov/opennet/manhattan-project-history/Events/1942-1944_pu/1942-1944_plutonium.htm

A defining point in time…

- **The first test took place at 5:30am on July 16, 1945 at the Trinity Test Site**
- **The success of the Trinity Test presented a way to end the war against Japan without an invasion or help from the Soviets**
- **The final decision to drop the bomb was made on July 25 1945**
- **“Little Boy” an HEU-based assembly was dropped on Hiroshima August 6, 1945**
- **“Fat Man” – a plutonium implosion assembly was dropped on Nagasaki August 9, 1945**
- **Japan surrendered on August 10, 1945**
- **Tens of thousands of warheads of over 60 variations were built from 1945-1990**

A fireball begins to rise, and the world's first atomic mushroom cloud begins to form, nine seconds after Trinity detonated on July 16, 1945.



Fat man in transit days before it was dropped on Nagasaki in 1945.

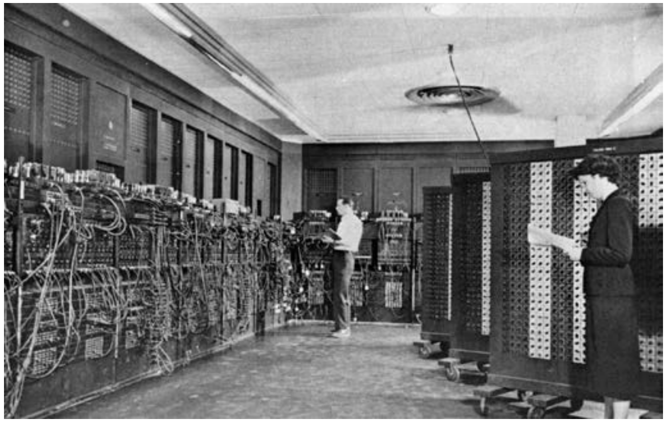
Source(s):
https://www.osti.gov/opennet/manhattan-project-history/Events/1942/1942.htm
https://www.TheAtlantic.com

Out of WW II comes computing and the Monte Carlo Method

The Origins of Monte Carlo – 1946 Stanislaw Ulam

- **“***The year was 1945. Two earthshaking events took place: the successful test at Alamogordo and the building of the first electronic computer***”** – N. Metropolis
- **The method was invented by Stanislaw Ulam in 1946 playing Solitaire while recovering from an illness.**
- **“***After spending a lot of time trying to estimate success by combinatorial calculations, I wondered whether a more practical method…might be to lay it out say one hundred times and simply observe and count the number of successful plays***”** – S. Ulam

Stanislaw Ulam



ENIAC– the first electronic computer, University of Pennsylvania. Solved ballistic trajectory problems for Army Ballistics Research Lab. Used electron tubes instead of mechanical counters. Minutes instead of days. Declassified in 1946.

Trinity – code name for first nuclear detonation

“Stan Ulam, John von Neumann, and the Monte Carlo Method,” R. Eckhardt, Los Alamos Science Special Issue 1987.

The Origins of the Monte Carlo Method

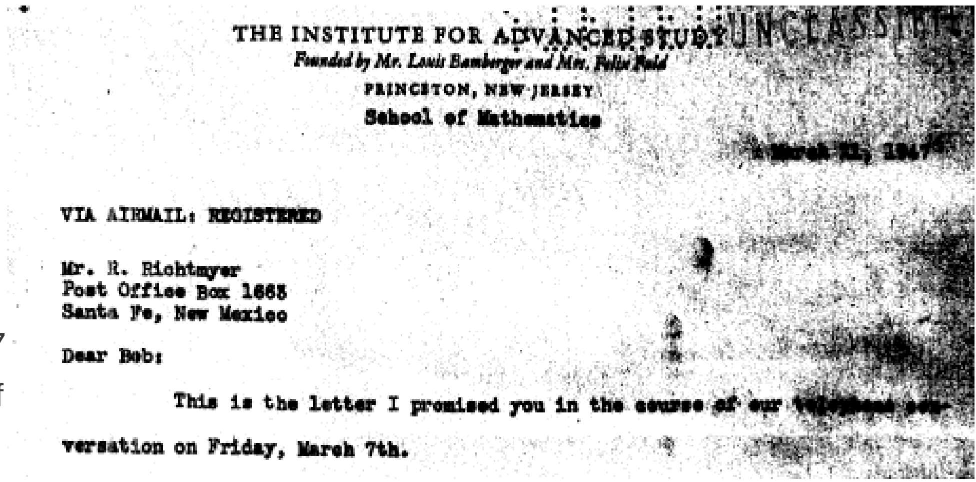
- **Ulam describes this idea to John von Neumann in a conversation in 1946**

- **Von Neumann is intrigued**
  - 1943: Electro-Mechanical computers solved non-linear diff. eq. via production line. Punch card used for every point in space/time
  - New computers could count/arithmetic and hence solve difference equations (BRL at Aberdeen, MD)
  - Statistical sampling on electronic computers
  - Especially suitable for exploring neutron chain reactions in fission – neutron multiplication rates
- **R.D Richtmyer and J. von Neumann "Statistical Methods in Neutron Diffusion", Los Alamos (LAMS-557) April 9, 1947.**
  - Detailed letter from John von Neumann to Robert Richtmyer describing a conversation in March 1947
    - "I have been thinking a good deal about the possibility of using statistical methods to solve neutron diffusion and multiplication problems in accordance with the principle suggested by Stan Ulam"
    - Letter contained 81-step pseudo code for using MC for particle transport

John von Neumann

Consultant to Aberdeen and Los Alamos

J. Von Neumann invented scientific computing in the 1940's
- Stored programs now called software
- Algorithms/Flowcharts
- Hardware design



THE INSTITUTE FOR ADVANCED STUDY
Founded by Mr. Louis Bamberger and Mrs. Felix Fuld
PRINCETON, NEW JERSEY
School of Mathematics

March 11, 1947

VIA AIRMAIL: REGISTERED

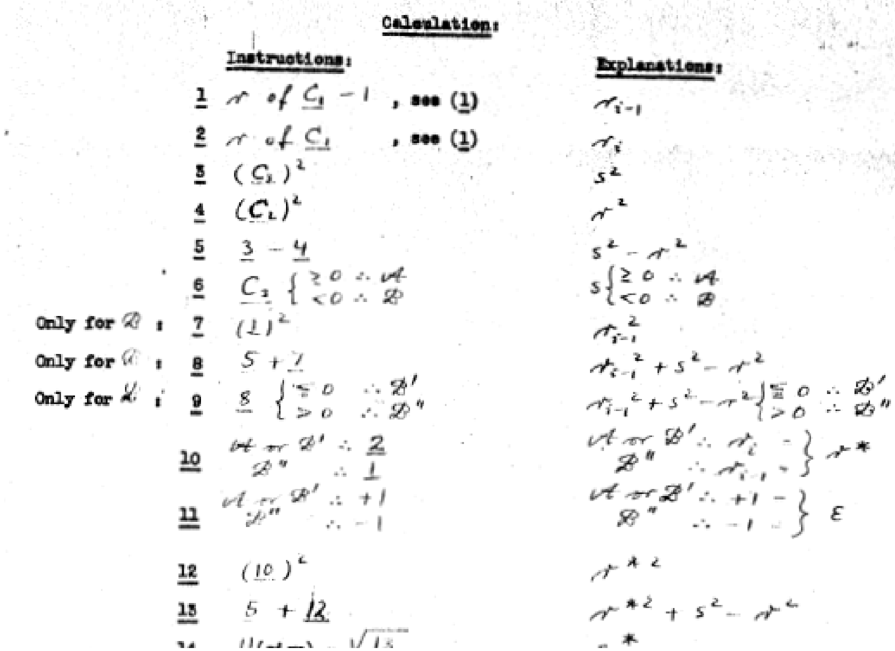
Mr. R. Richtmyer
Post Office Box 1663
Santa Fe, New Mexico

Dear Bob:

This is the letter I promised you in the course of our [illegible] conversation on Friday, March 7th.

The first Monte Carlo (pseudo) Code - 1947

- **Von Neumann's Assumptions:**
  - Time-dependent, continuous energy, spherical but radially-varying, 1 fissionable material, isotropic scattering and fission production, fission multiplicities of 2,3, or 4
- **Suggested 100 neutrons each to be run for 100 collisions**
  - Thought these were too much
- **Estimated time: 5 hrs on ENIAC**
- **Richtmyer's response:**
  - Very interested in idea and proposed suggestions
    - Allow for multiple fissionable materials, no fission spectrum energy dependence, single neutron multiplicity, run for computer time not collisions
- **ENIAC: first calculations run April/May 1948**
  - Code finalized in **December 1947**;
  - Continuous energy neutrons, fission spectra and XS tabulated at interval mid-points, histogram energy-dependence of XS, pseudo-RN.



R.D Richtmyer and J. von Neumann "Statistical Methods in Neutron Diffusion", Los Alamos (LAMS-557) April 9, 1947.

April 2, 1947

Professor John vonNeumann,
The Institute for Advanced Study,
School of Mathematics
Princeton, New Jersey

Dear Johnny:

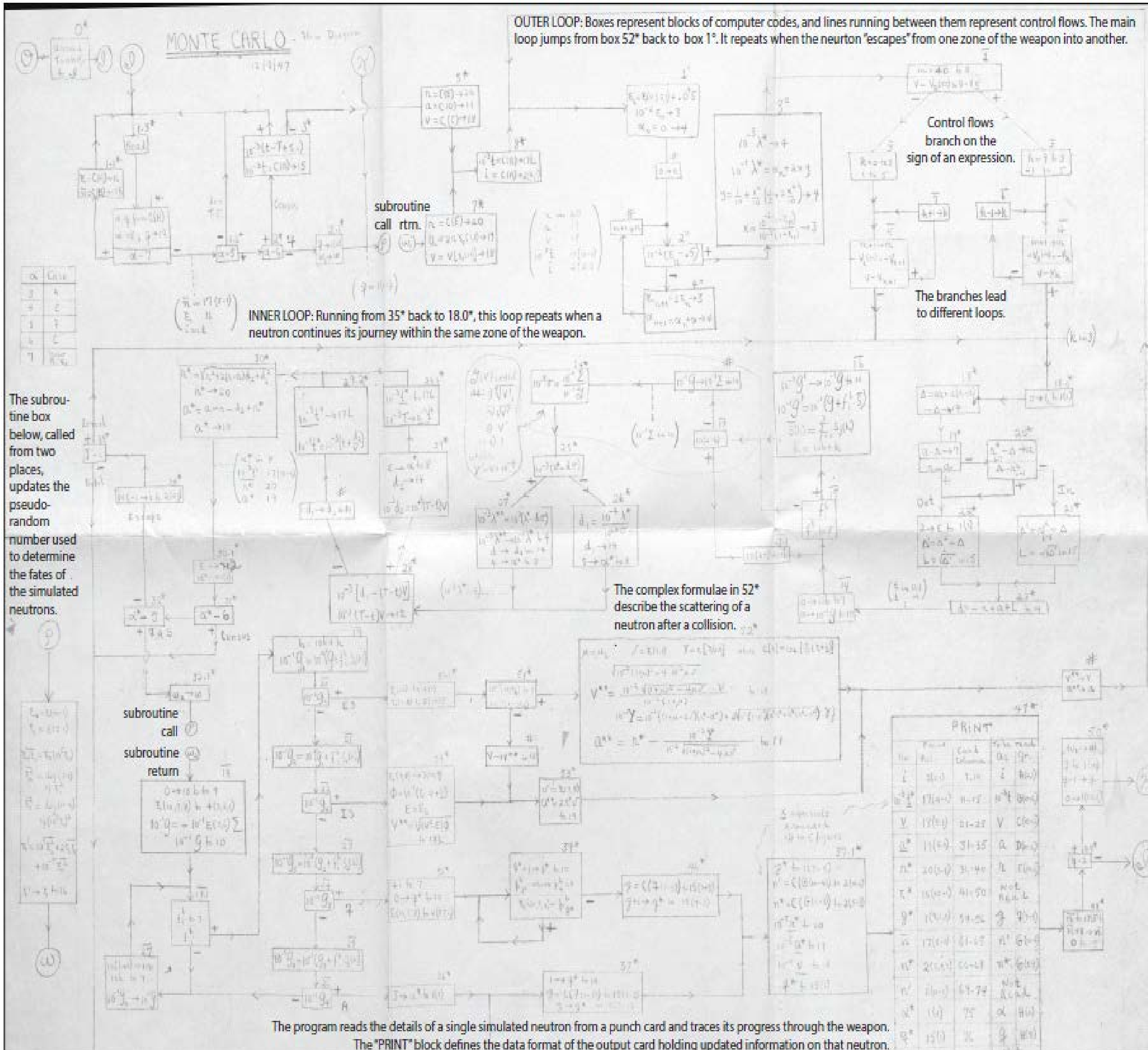
As Stan told you, your letter has aroused a great deal of interest here. We have had a number of discussions of your method and Bengt Carlson has even set to work to test it out by hand calculation in a simple case.

Thomas Haight, et al., "Los Alamos Bets on ENIAC: Nuclear Monte Carlo Simulations, 1947-1948, IEEE Ann. Of History of Comp July-Sept 2014

ENIAC in Action: MC Program / flowchart

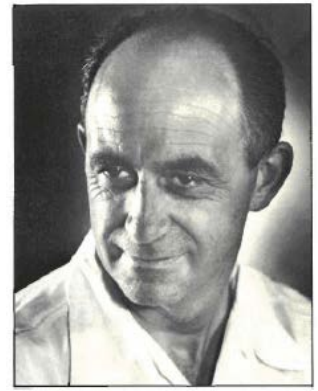
Boxes	Function
1* – 8*	Read a card and store neutron characteristics
1° – 4°	Calculate random parameter λ*
$\overline{1}$ – $\overline{7}$	Find neutron's velocity interval
18* – 23*	Calculate distance to zone boundary
$\overline{14}$ – $\overline{17.1}$, 24*	Calculate cross-section of material in zone
25* – 27*	Determine if terminal event is collision or escape
28* – 30*	Determine if a census comes first
31* – 35*	Discriminate between terminal events
Subroutine ρ/ω	Refresh random number
$\overline{18}$ – $\overline{27}$	Determine collision type
51* – 52*	Elastic scattering
53* – 54*	Inelastic scattering
36* – 39*, 46*	Absorption/fission
37.1*, 47* – 50*	Print card and restart main loop

Thomas Haight, Mark Priestley, and Crispin Rope, "ENIAC in Action: Making and Remaking the Modern Computer," MIT Press 2016

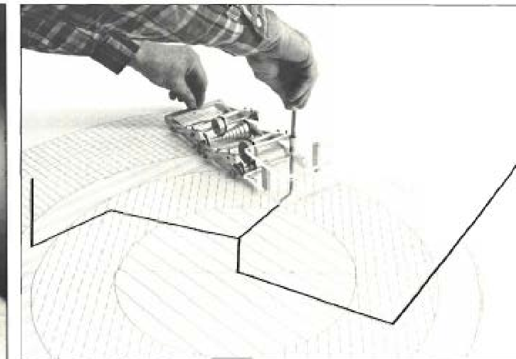


Enrico Fermi: Independently developed Monte Carlo!

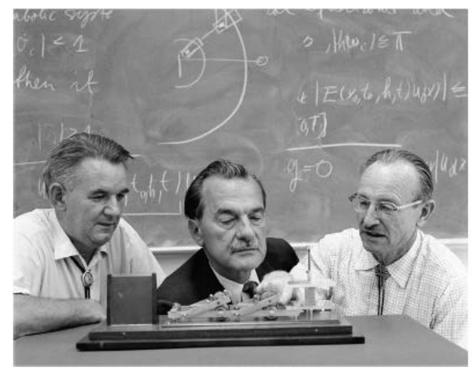
- **Emilio Segre, Fermi's student and collaborator:**
  - "*Fermi had invented, but of course not named, the present Monte Carlo method when he was studying the moderation of neutrons in Rome. He did not publish anything on the subject, but he used the method to solve many problems with whatever calculating facilities he had, chiefly a small mechanical adding machine*"
- **Astonished Roman colleagues when he would predict experimental results remarkably accurately. He revealed that he used statistical sampling techniques whenever insomnia struck.**
  - 15 years prior to Ulam
- **While in Los Alamos and awaiting ENIAC's move, he created an analog device to study neutron transport.**
  - Called FERMIAC
  - Generated the site of next collision based upon characteristics of material; Another choice was made at boundary crossing; "slow" and "fast" neutron energies

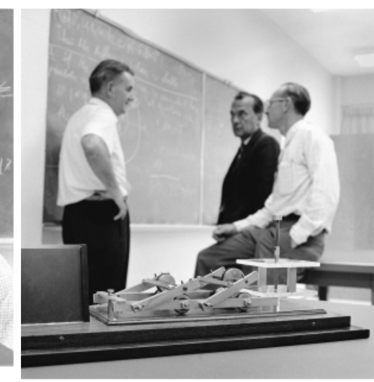


Enrico Fermi



FERMIAC

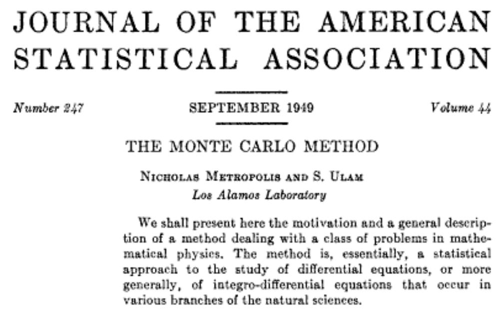




Los Alamos Scientists: Bengt Carlson, Nicholas Metropolis, LDP King with Fermiac (1966)

MANIAC – Nicholas Metropolis

- **Post-war ENIAC started a revolution that continues today**
- **MANIAC – Mathematical and Numerical Integrator and Computer**
  – Was a product of Nicholas Metropolis at LANL; borrowed concepts from von Neumann's IAS, operational in 1952;
  – MADCAP – high-level language and compiler
  – Rapid growth of computing: AVIDAC (Argonne) ORACLE (Oak Ridge), ILLIAC (U of I)
  – Special effort that helped bind Von Neumann, Fermi, Beta, Teller, Ulam, Feynman, etc in post-war efforts. MANIAC was a fascination.
  – First time "Monte Carlo" appears in publication:
    - Nicholas Metropolis and S. Ulam , "The Monte Carlo Method," *Journal of the American Statistical Association* Vol. 44, No. 247 (Sep., 1949)
  – MC on MANIAC used for multiple problems other than radiation transport:



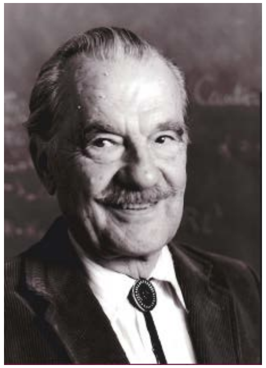
JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION

Number 247 SEPTEMBER 1949 *Volume 44*

THE MONTE CARLO METHOD

NICHOLAS METROPOLIS AND S. ULAM
Los Alamos Laboratory

We shall present here the motivation and a general description of a method dealing with a class of problems in mathematical physics. The method is, essentially, a statistical approach to the study of differential equations, or more generally, of integro-differential equations that occur in various branches of the natural sciences.



Pion-proton phase-shift analysis (Fermi, Metropolis; 1952)
Phase-shift analysis (Bethe, deHoffman, Metropolis; 1954)
Nonlinear coupled oscillators (Fermi, Pasta, Ulam; 1953)
Genetic code (Gamow, Metropolis; 1954)
Equation of state: Importance sampling (Metropolis, Teller; 1953)
Two-dimensional hydrodynamics (Metropolis, von Neumann; 1954)
Universalities of iterative functions (Metropolis, Stein, Stein; 1973)
Nuclear cascades using Monte Carlo (Metropolis, Turkevich; 1954)
Anti-clerical chess (Wells; 1956)
The lucky numbers (Metropolis, Ulam; 1956)

1950's: Monte Carlo is becoming mainstream!

- **Herman Kahn, "Applications of Monte Carlo," AECU-3259 (April 19, 1954).**
  - General and not specific to radiation particle transport
  - Direct sampling for common distributions
  - Rejection sampling – if direct sampling does not work
    - Use a simple, easy to sample distribution, to get an estimate and correct later.
  - Russian Roulette
  - Stratified sampling, importance sampling, splitting
- **E.D. Cashwell and C.J. Everett, "A Practical Manual on the Monte Carlo Method for Random Walk Problems," LA-2120 (December 18, 1957)**
  - Well-described report specific to particle transport
  - Detailed diagrams and flowcharts
    - Neutron collisions – (in)elastic scattering, fission, etc
    - Photon collisions – Compton scattering, photoelectric, pair prouction
    - Particle direction after collision – direction cosines
  - Did not deal with thermal neutron collisions nor pseudo-random number generation

Thomas Sutton and David Griesheimer, "The Monte Carlo Method: The Past 70 Years, Current State and Future Prospects," ANS Math and Computational Division Topical (Jeju, South Korea, April 2017)

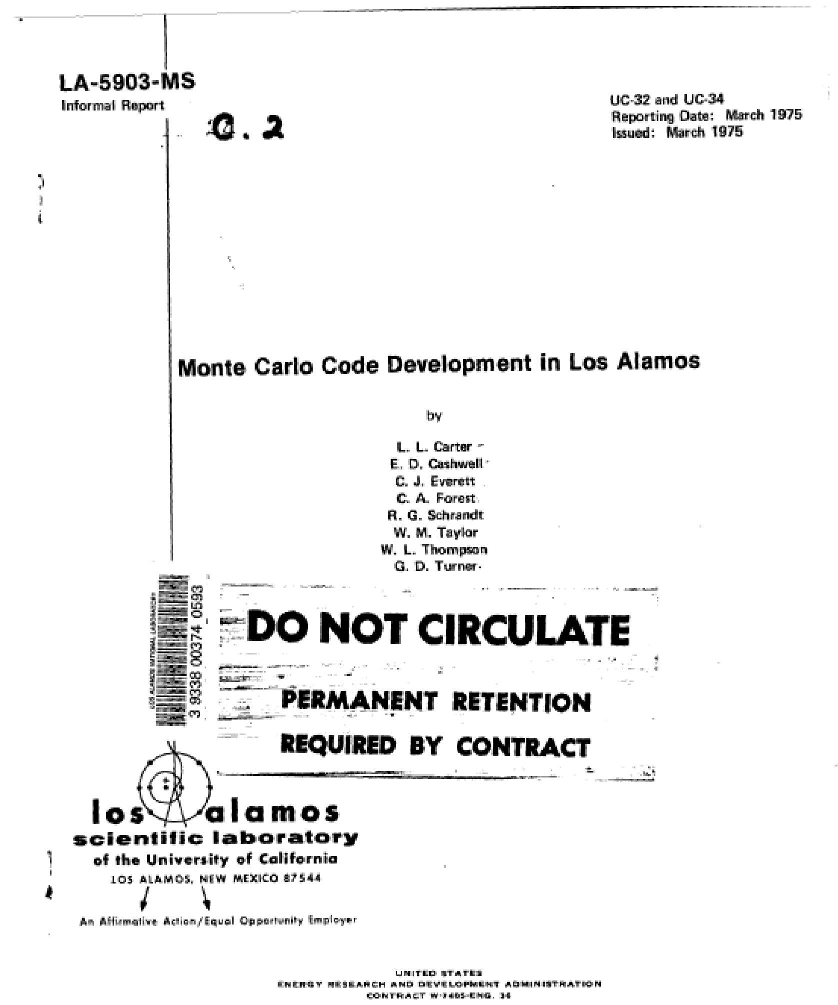
1960's: Initial work on Criticality and Reactor Calculations

- **JJ.B. Parker, and E.R. Woodcock, "Monte Carlo Criticality Calculations," Prog. In Nucl. Ener, 4 (1961).**
  - Introduced concept of neutron generations or batches of particles as histories
- **E.R. Woodcock, T. Murphy, P.J. Hemmings, and T.C. Longworth, "Techniques Used in the GEM Code for Monte Carlo Neutronics Calculations in Reactors and Other Systems of Complex Geometry," ANL-1050 (1965).**
  - Describes "Woodcock tracking" (aka delta-tracking)
    - Regular tracking on geometries with many surfaces is expensive; esp for 2nd order surfaces
    - Avoids multiple distance-to-boundary calculations by using fictitious XS and adjusting
- **J. Lieberoth, "A Monte Carlo Technique to Solve the Static Eigenvalue Problem of the Boltzmann Transport Equation," Nukleonik 11, 213-219 (1968)**
- **M.R. Mendelson, "Monte Carlo Criticality Calculations for Thermal Reactors," Nucl. Sci. Eng 32, 319-331 (1968).**

Thomas Sutton and David Griesheimer, "The Monte Carlo Method: The Past 70 Years, Current State and Future Prospects," ANS Math and Computational Division Topical (Jeju, South Korea, April 2017)

1970: MCNP first emerges

- **1974 – NEA Committee on Reactor Physics (NEACRP)**
  - E.D. Cashwell presented a paper on Monte Carlo development at Los Alamos
    - MCN – neutrons
    - MCNA – neutron adjoint
    - MCG – gamma rays
    - MCP – general photons
    - MCNG – coupled neutron-gamma ray
    - MCMG – multi-group coupled neutron-gamma ray
    - MCGE – coupled electron-photon
    - MCGB – gamma rays with Bremsstrahlung
- **1977: MCNG was merged with MCP to form MCNP**
  - 2017 is the 40th Anniversary of MCNP
  - 2017 is also the 70th Anniversary of the Monte Carlo method


LA-5903-MS
Informal Report

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UC-32 and UC-34
Reporting Date: March 1975
Issued: March 1975

Monte Carlo Code Development in Los Alamos

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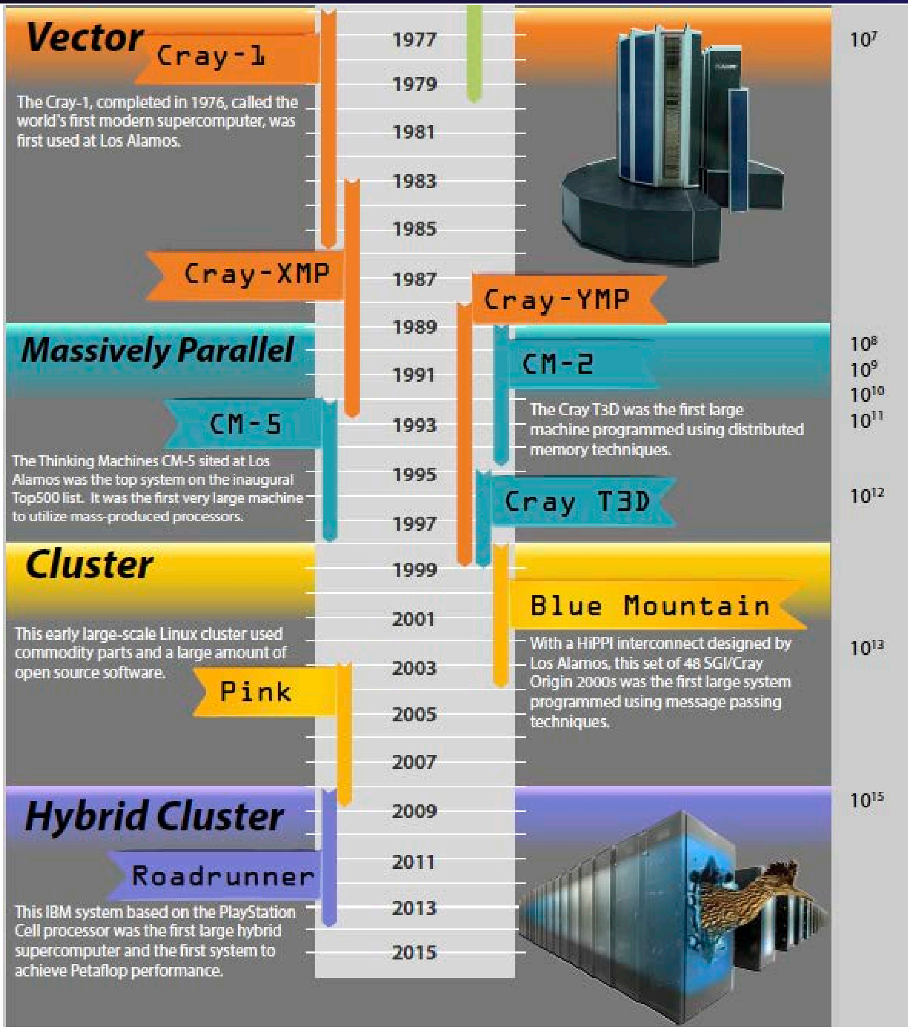
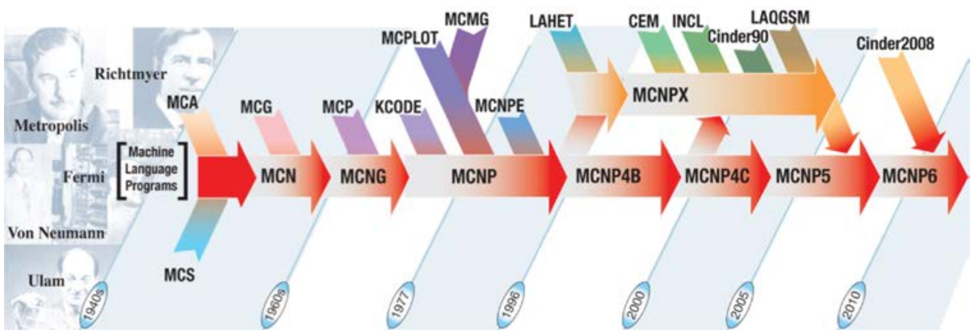
Monte Carlo & MCNP History

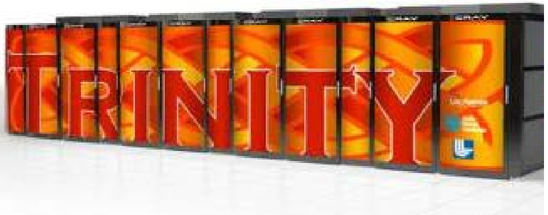




70 years of Monte Carlo methods development


Cielo: 2 PFLOPs

Trinity: 40 PFLOPs



Crossroads is coming in FY20

MCNP or its predecessors have been run on *every* high-performance computer architecture since ENIAC

1980 – 1999: MCNP Becomes the Gold Standard

MCNP Version	Release Month/Year	Some Significant New Features (For a more detailed description, see each version's release notes).
MCNP3	1983	First release through RSICC. Written in Fortran 77
MCNP3A	1986	
MCNP3B	1988	Plotting graphics, generalized source, surface sources, repeated structures/lattice geometries
MCNP4	1990	Parallel multitasking, electron transport
MCNP4A	10/1993	Enhanced statistical analysis, new photon libraries, ENDF-6, color X-Windows graphics, dynamic memory allocation
MCNP4B	4/1997	Operator perturbations, enhanced photon physics, PVM load balancing, cross-section plotting, 64-bit executables, lattice universe mapping, enhanced lifetimes
MCNPX 2.1.5	11/1999	First public release of MCNPX, based on MCNP4B with CEM INC, HTAPE3X, mesh and radiography tallies, and an improved collisional energy loss model.

T. Goorley, et al. "Initial MCNP6 Release Overview," LA-UR-13-22934 (2013)

- **Key Value: MCNP provides a predictive capability that can replace expensive or impossible-to-perform experiments**
- **Used to design large-scale measurements providing significant time/cost savings**
- **MCNP represents a synergistic capabilities developed at LANL**
  - Evaluated nuclear data (ENDF) and data processing code NJOY
  - MCNP could not exist without this!
- **International user community's high confidence in MCNP's predictive capabilities are based upon its performance with verification and validation test suites.**

2000 – 2011: MCNP undergoes exponential growth

MCNP4C	4/2000	Unresolved resonance treatments, macrobodies, superimposed importance mesh, perturbation, electron transport, plotter and tally enhancements
MCNP4C2	1/2001	Photonuclear physics, interactive plotting, plot superimposed weight-window mesh, weight-window improvements
MCNPX 2.3.0	4/ 2002	LAHET 2.8 and some 3.0 extensions.
MCNPX 2.4.0	8/2002	Update to MCNP4C, build system for Windows OS, support for Fortran 90.
MCNP5 1.14	11/2002	Fortran 90, photonuclear collisions, geometry superimposed mesh tallies, time splitting, shared memory threading with OpenMP. Mac OSX support
MCNP5 1.20	10/2003	Increased number of detectors to 100 and number of tallies to 1000. Mostly a code defect fix release.
MCNP5 1.30	8/2004	Explicit 8-byte integers for nps > 2.1 billion, Lattice and fmesh tally enchantments. Support for MPI on Mac OSX.
MCNPX 2.5.0	4/2005	34 particle types, four light ions, mix and match nuclear data tables and model physics, CEM2k, INCL4/ABLA physics models, fission multiplicity, spontaneous fission sources, pulse height tallies with variance reduction, pulse height light tally, coincident capture tallies, variance reduction with model
MCNP5 1.40	11/2005	Lethargy plots, logarithmic data interpolation, neutron multiplicity distributions, stochastic geometry, source entropy, mesh tally plots, new electron energy loss straggling
MCNPX 2.6.0	4/ 2008	Depletion/Burnup, heavy ion transport, LAQGSM physics, CEM03 physics, delayed gamma emission, energy-time weight windows, charged ions from neutron capture, spherical mesh weight windows, spontaneous photons
MCNP5 1.51	1/2009	Photon Doppler broadening, variance reduction with pulse height tallies, annihilation gamma tracking, Doppler broadening in makxsf, large lattice enhancements
MCNP5 1.60	8/2010	Adjoint weighted tallies for point kinetics parameters, mesh tallies for isotopic reaction rates, up to 100 million cells & surfaces, up to 10 thousand tallies
MCNPX 2.7.0	4/2011	Tally Tagging, embedded sources, cyclic time bins, focused beam sources, PTRAC coincidence, LLNL fission multiplicity, Receiver-operator characterization (ROC) tally, NRF data in ACE libraries, triple & quadruple coincidence, LAQGSM 3.03 and CEM 3.03 physics.

2011 – today: MCNP5 & MCNPX to MCNP6

mcnp5
neutrons, photons, electrons
cross-section library physics
criticality features
shielding, dose
"low energy" physics
V&V history
documentation

New Criticality Features
Sensitivity/Uncertainty Analysis
Fission Matrix
OTF Doppler Broadening

Fission
MCNP5/X multiplicity
LLNL fission package
CGM/LLNLGAM,   CGMF (soon)

mcnp6

mcnp6.1   – 2013
mcnp6.1.1 – 2014
mcnp 6.2 – Sept. 2017

mcnp6
protons, proton radiography
high energy physics models
magnetic fields

Partisn mesh geometry
Abaqus unstructured mesh

mcnpx
33 other particle types
heavy ions
CINDER depletion/burnup
delayed particles

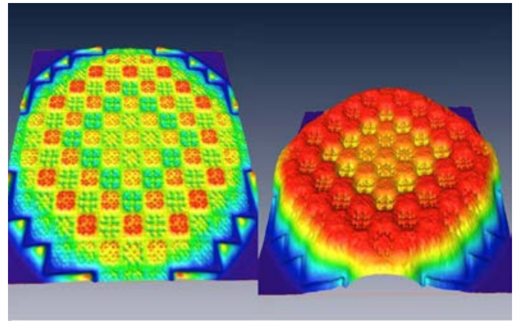
High energy physics models
CEM, LAQGSM, LAHET,
MARS, HETC

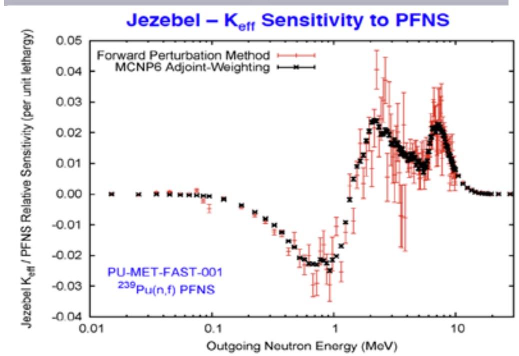
Continuous Testing System
~10,000 test problems / day

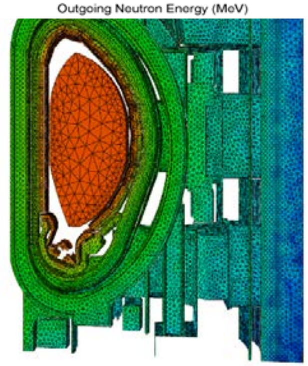
MCNP® Capabilities

- **Physics:**
  - Continuous energy particle transport
  - Neutron, photon, electron, and many more particle types
- **Algorithms:**
  - k-eigenvalue calculations
  - Fixed source calculations
- **Recently Implemented Features:**
  - Unstructured mesh transport
  - Electric and magnetic field transport
  - High-energy physics models
  - 33 additional particle types
  - Reactor fuel depletion and burnup
  - Radiation source and detection capabilities
  - Sensitivity and uncertainty analysis for nuclear criticality safety
- **Extensive Variance Reduction**
  - Weight Windows
  - DXTRAN

Whole-core Thermal & Total Flux



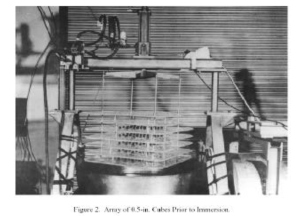




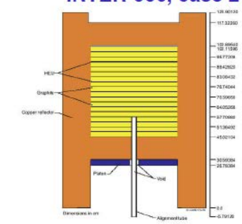
ITER Neutron Flux Calculations

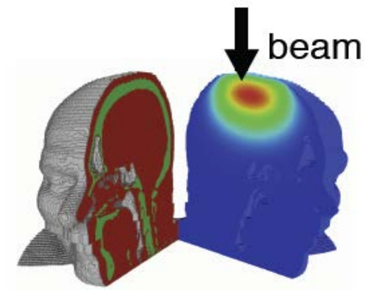
Experimental Benchmarks with Critical Assemblies

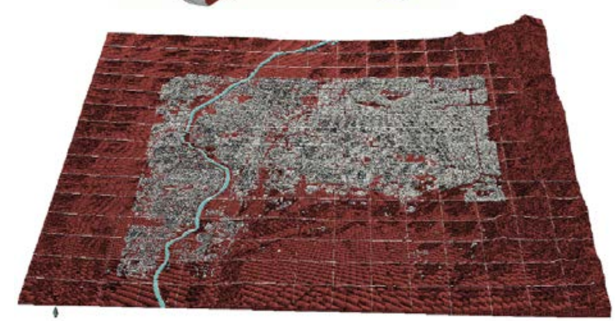
HEU-MET-THERM-003



Zeus-2, HEU-MET-INTER-006, case 2







City model used to study nuclear weapon effects

Monte Carlo Codes from across the globe

- **Monte Carlo Codes Session at SNA+MC 2013**
  – Annals of Nuclear Energy, 82 (2015)

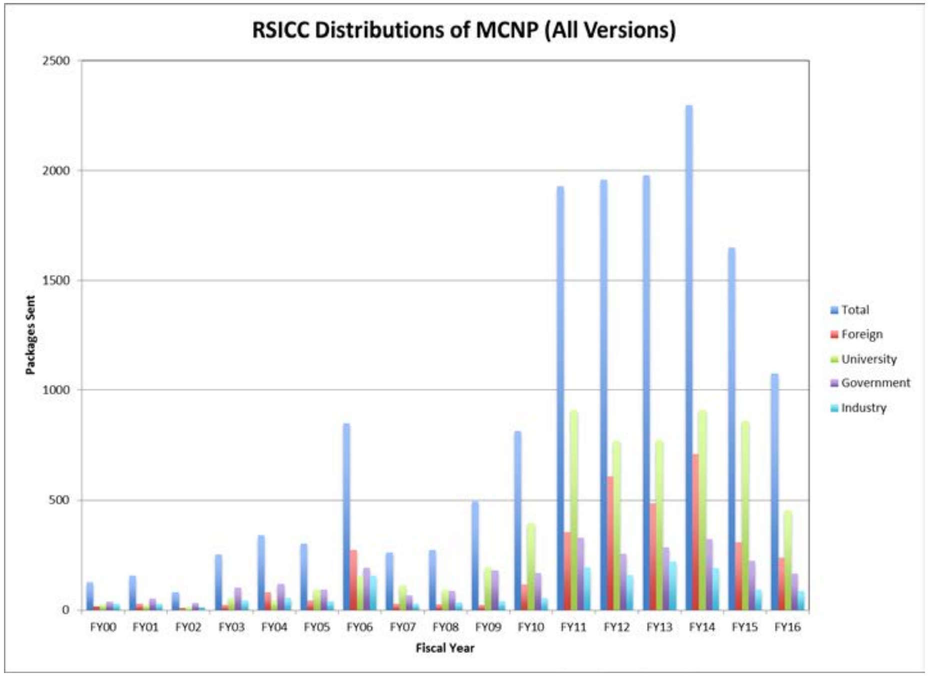
code	institution	
ARCHER	RPI	USA
COG11	LLNL	USA
DIANE	CEA	France
FLUKA	INFN & CERN	Italy & CERN
GEANT4	GEANT4	International
KENO and MONACO	ORNL	USA
MC21	Naval Nucl. Lab.	USA
MCATK	LANL	USA
MCCARD	Seoul Natl. Univ.	ROK
MCNP6	LANL	USA
MCU	Kurchatov Inst.	Russia

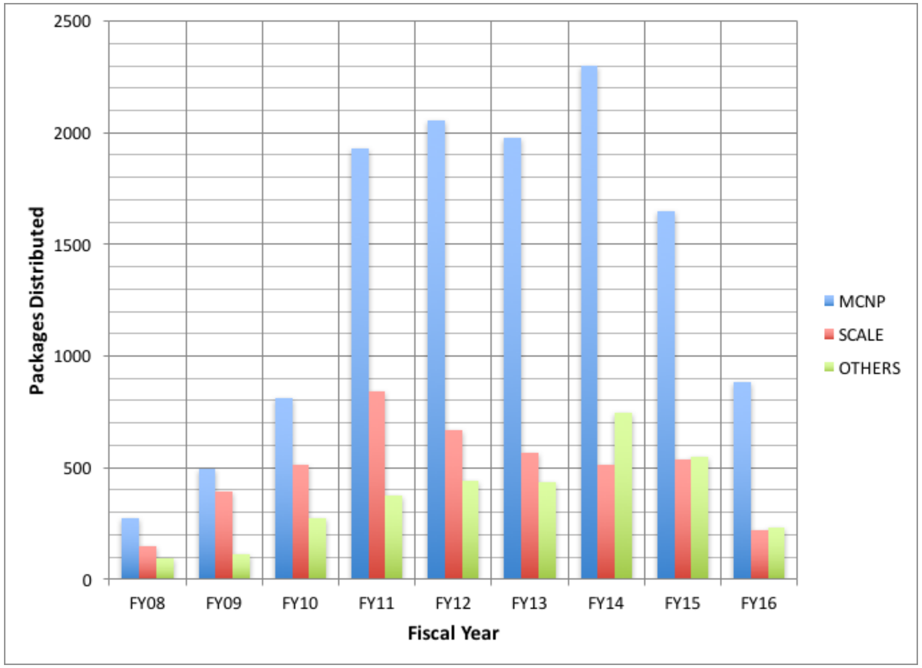
code	institution	
MONK & MCBEND	AMEC Foster Wheeler	UK
MORET5	IRSN	France
MVP2	JAEA	Japan
OPENMC	MIT	USA
PENELOPE	Barcelona Univ.	Spain
PHITS	JAEA	Japan
PRIZMA	VNIITF	Russia
RMC	Tsinghua Univ.	China
SERPENT	VTT	Finland
SUPERMC	CAS INEST FDS	China
TRIPOLI-4	CEA	France

MCNP Distribution: RSICC

- **MCNP is export controlled and is distributed:**
  - USA: RSICC – Oak Ridge National Laboratory, LANL
  - Europe: NEA Databank; Japan, Korea: KAIST – coordinated through RSICC
- **Approximately 20,000 copies of MCNP licenses have been distributed.**
  - 8000 copies of MCNP 6 since 2011 (Data provided by T. Valentine, RSICC)

Today: All requests eventually are through RSICC or LANL with appropriate DOE / export control reviews





MCNP in the near future

- **Motivation: LANL, DOE/NNSA, DHS-DNDO, and DTRA sponsors need a predictive capability**
- **Biggest needs are:**
  - Validated models of geometry and materials; complex radiation sources; direct comparison with radiation detection instruments
- **MCNP 2020 vision:**
  - Library-based Monte Carlo framework
  - Software quality improvements
- **Applications:**
  - Next-generation high performance computers
  - Multi-physics: MCNP often needed within other scientific software
  - Tools to assist users
    - Geometry: Collaborations with industry
      - Allow users to take CAD/CAE, modify and develop mesh-based models; Variance reduction with Sn
    - Radiation Source: ISC – generalized intrinsic source (aged) from any decay library
    - Transport physics: Correlated source/collision physics
    - Tallies: MCNP tools – a package to facilitate user access to MCNP output
      - Users can produce tools to make plots, analyze data, etc without headache of having to parse data
      - One application: radiation detector response

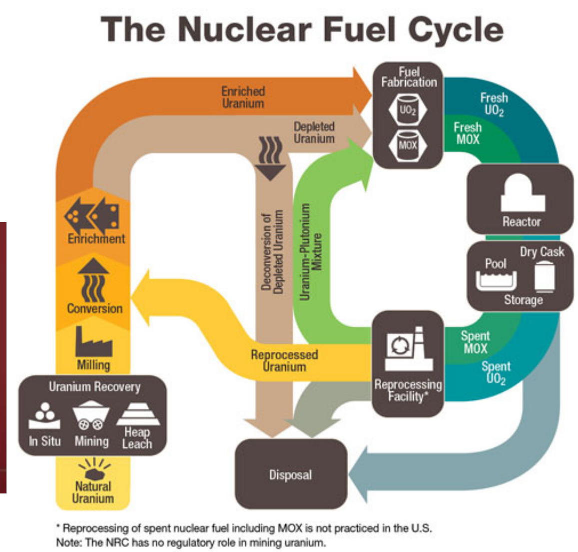
Nuclear Nonproliferation

Derived from LA-UR-17-21214: INITIAL Module

Goals for Nuclear Nonproliferation and Safeguards

- **Nuclear Nonproliferation - what is our goal?**
  - Avoid detonation of a weapon
  - Reduce the total number of weapons
  - Reduce attempts to obtain or construct nuclear weapons
- **What can we do?**
  - Encourage/ensure peaceful nuclear uses
  - Secure, safeguard, and/or dispose of dangerous nuclear and radiological material
  - Detect and control the proliferation of related WMD technology and expertise
- **How can we do it?**
  - Nuclear Nonproliferation Treaty:
    - Bans acquisition of nuclear weapons by non-weapon states
  - Comprehensive Test Ban Treaty:
    - Bans nuclear explosions
  - Fissile Material (Cutoff) Treaty:
    - Would ban fissile material production
- **Verification is the key element**
- **Science and technology play a vital role**

- **Safeguards - what is our goal?**
  - The objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons
  - Inspect nuclear facilities worldwide, monitor amounts of nuclear materials to ensure that it isn't going to illicit uses
- **Science and technology play a vital role**



Atoms for Peace and the IAEA

- **The end of WWII left Europe greatly weakened and susceptible to the spread of Communism**
- **An arms race emerged as the first Soviet reactor went critical on December 25, 1946**
  - 500 tests between 1945-1967
- **Nonproliferation efforts that had begun in 1943 gained strength**
- **Eisenhower delivered his "Atoms for Peace" speech to the UN General Assembly on December 8, 1953**
  - Warned of the dangers of global proliferation and called for the establishment of an international atomic energy agency to control nuclear stockpiles

- **The IAEA Statute came into force on July 29, 1957 with the goal to facilitate peaceful uses of nuclear energy**
  - 56 States signed the treaty in 1957, including 4 of the 5 weapon States (US, UK, USSR, France)
  - China joined in 1984
- **The first safeguards system (INFCIRC/26) was established on March 30, 1961**
- **In August 1965, the first treaty to prevent the spread of nuclear weapons was drafted**

Source(s):
https://www.iaea.org/about/history
https://www.TheAtlantic.com

Nuclear Detonations from 1945 to present – plotted on a world map

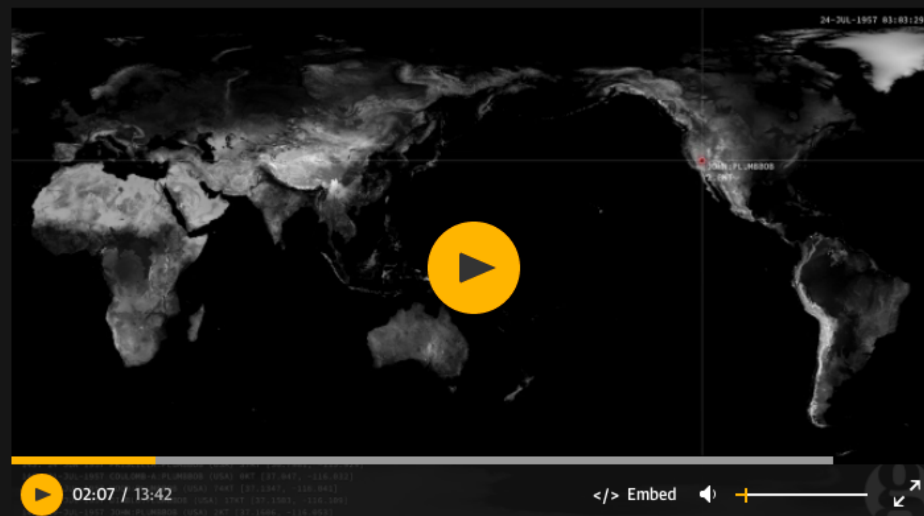
Nuclear weapons

Nuclear detonations from 1945 to present plotted on a world map - video

1,799 74

Source: Orbital Mechanics

Thursday 13 August 2015 21.38 EDT



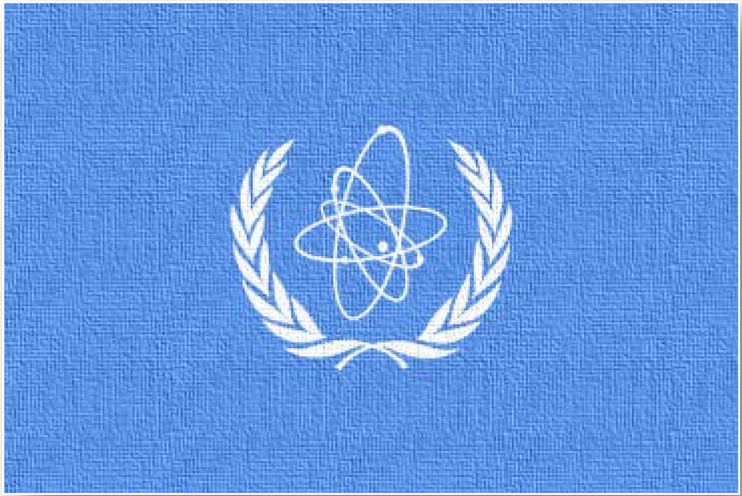
This eerie visualisation was created by Ortibal Mechanics, an audiovisual collective based in Montreal. It begins in 1945, before picking up speed with thousands of detonations over the following decades. Each one is colour-coded: red for atmospheric, yellow for underground, and blue for underwater.

Coder Ehsan Rezaie included every detonation he could cross-reference in both the Australian government's geoscience database and this archive. The only specific omission is the 2013 North Korean test, which has only been verified by detection of seismic activity

https://www.theguardian.com/world/video/2015/aug/14/nuclear-weapon-detonation-hiroshima-nagasaki-trinity-1945-world-map-video

Nuclear Nonproliferation Treaty – July 1968

- **The NPT has Three Pillars:**
  - Stop the further spread of nuclear weapons
  - Provide a sound basis for international cooperation in peaceful uses of nuclear energy
  - Commit all parties to undertake negotiations in good faith on disarmament
- **Intended to provide stability and country behavior predictability**
- **62 States signed the Nuclear Non-Proliferation Treaty (NPT) on July 1, 1968**
- **Review Conferences are held every 5 years since to ensure that the provisions of the treaty are being properly realized**
- **The DPRK is the only nation to have exercised the right to withdraw provided in Article X**



Source(s):
http://fas.org/nuke/control/npt/

Comprehensive Safeguards

- **In the 1990s, clandestine programs were discovered in Iraq and DPRK**
  – It became apparent that the IAEA was inefficient in discovering clandestine programs because it only had access to inspect declared sites

- **The Additional Protocol (INFCIRC/540) was approved in 1997 to strengthen safeguards**

- **The AP is an addition to full-scope safeguards, providing a broader mandate to cover most aspects of the nuclear fuel-cycle**
  – Expanded State Declarations, complementary access, and added mining, milling and disposal to safeguards

Source(s):
https://www.iaea.org/safeguards/index.html
http://www.iaea.org/safeguards/documents/safeg_system.pdf
https://www.iaea.org/publications/documents/infcircs/model-protocol-additional-agreements-between-states-and

Case Study: Iraq & the State Level Concept

- **Iraq's clandestine nuclear program was discovered in 1991**
  - Until that point, the IAEA only inspected declared facilities and implemented safeguards on a facility-by-facility basis
- **In 1993, the IAEA began working on 2 new safeguards measures:**
  - IAEA would look at a state's nuclear program as a whole, rather than separately assessing verification results from each individual facility
  - Additional Protocol
- **This framework, called integrated safeguards, was implemented in 2002; the term "state-level concept" was introduced in a 2005 IAEA report**

It was discovered that Iraq had been developing (EMIS devices), a destroyed device is shown in the image in the bottom right. The EMIS facility is shown in the top right.

Safeguards-by-Design (SBD)

- **Historically, IAEA safeguards were applied mainly to existing or already designed plants**
  - Safeguards techniques and methods used were adapted to take this into account
- **SBD is an approach in which "international safeguards are fully integrated into the design process of a new nuclear facility from the initial planning through design, construction, operation, and decommissioning"**
- **Two main objectives:**
  - (1) avoid costly and time-consuming redesign work or retrofits of new nuclear fuel cycle facilities
  - (2) make the implementation of international safeguards more effective and efficient at facilities

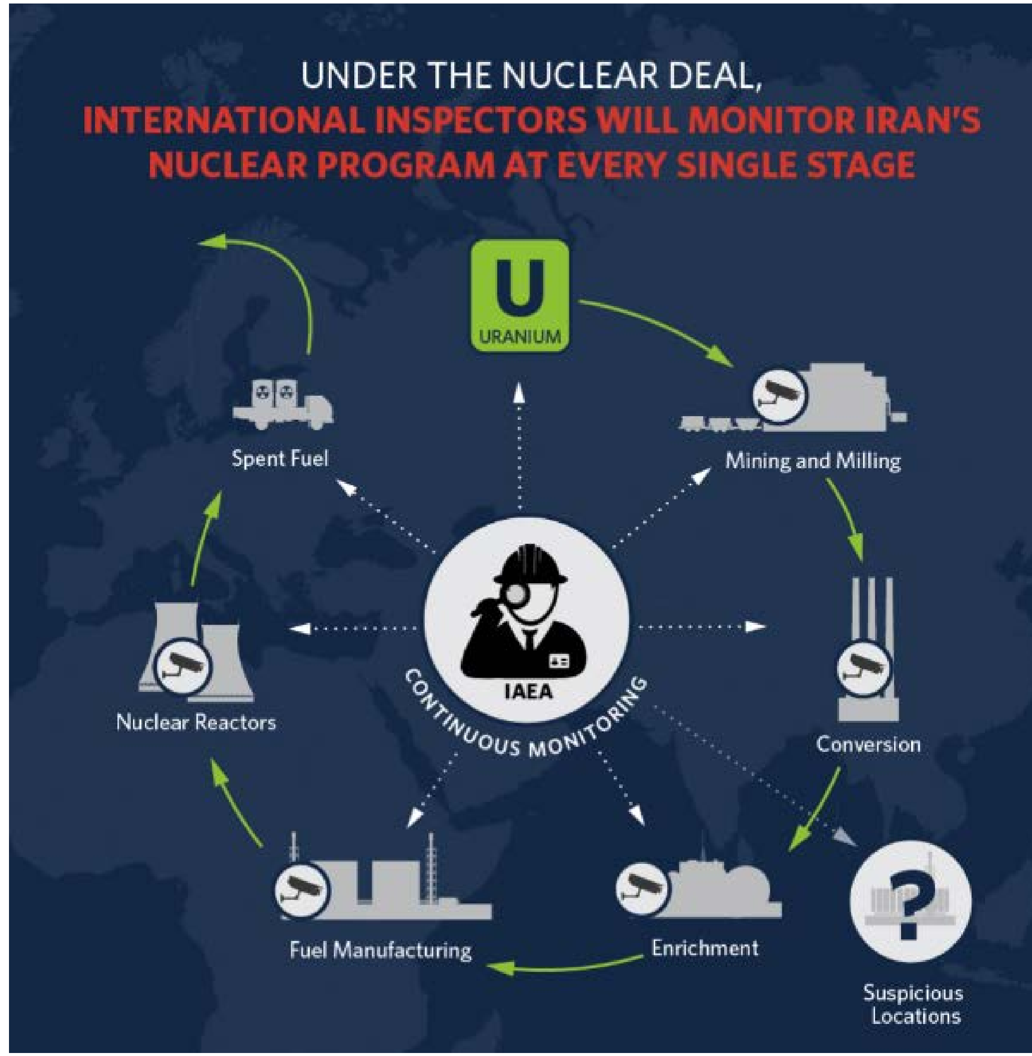
Source(s):
https://www.iaea.org/safeguards/symposium/2010/Documents/PapersRepository/024.pdf
https://nnsa.energy.gov/aboutus/ourprograms/dnn/nis/safeguards/sbd

Case Study: Iran Deal History

- **1970s**
  - Iran ratifies Nonproliferation Treaty, plans for construction of 23 nuclear plants
  - Seizure of US Embassy during Iranian Revolution damages relationship between Iran and the West
- **1980s**
  - US Department of State adds Iran to list of state sponsors of terrorism, imposes sweeping sanctions in 90s
- **1990s**
  - Additional Protocol signed and implemented voluntarily
- **2000s**
  - IAEA reports on Iran's failure to report nuclear material and activities
  - Iran backs out of AP and continues enrichment activities
  - Sanctions broaden
- **2010**
  - Further sanctions and asset freeze, extended to 2016
- **2011**
  - Agreement attempted and failed

Case Study: Iran Deal Provisions

- **Relations between Iran and the west were damaged repeatedly**
- **Iran undertook enrichment activities that led to sweeping sanctions, but the damage was done**
- **Several agreements were attempted between 2011-2015**
- **Iran Deal agreed to in 2015, many sanctions lifted in exchange for unprecedented access**



Case Study: Iran Deal Provisions (Continued)

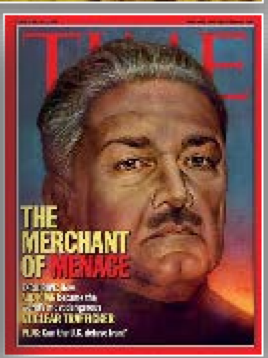
- **Iran can only produce LEU for 15 years**
- **Inspectors can visit suspected sites if they present evidence**
- **Caps on nuclear R&D end in 10 years**
- **The UN arms embargo against Iran will last 5 yrs**

July	Likely September	Likely late October	December 15	Likely early 2016	Five years after adoption	Eight years after adoption	Ten years after adoption	Fifteen years later
Resolution endorsing the deal goes to U.N. Security Council for quick adoption.	Congress's deadline to vote on the deal. President Obama has vowed to veto any rejection.	90 days after U.N. Security Council resolution, the agreement comes into effect.	Deadline for IAEA chief to report on Iran compliance with its efforts to investigate Tehran's past nuclear activities.	The IAEA reports Iran has carried out all first-stage actions. Europe and U.S. suspend most nuclear-related sanctions.	Arms ban expires.	EU and U.S. will terminate sanctions—subject to congressional approval in U.S. The U.N.'s ballistic missile ban ends.	Special U.N. channel for Iran to buy nuclear-related goods ends.	Iran can start to significantly increase its nuclear program and start enriching uranium above the 3.67% level.

Wall Street Journal

Case Study: Libya

- **Early 1970s: initial interest in a nuclear program**
  - Gadhafi believed weapons would bring international prestige, and took pride in the idea of an “Arab Bomb”
- **1975 agreement:**
  - USSR provides a research reactor to Libya (10MW light-water reactor)
  - In exchange Libya ratifies the NPT and concludes a safeguards agreement with the IAEA
- **1978-1981: Libya imports more than 1,200 tons of yellowcake uranium ore**
- **1980s: begin U enrichment and PU separation efforts**
  - Purchased enrichment equipment including a modular Uranium conversion facility and specialized furnace from Japan and vacuum pumps from Europe
  - UF6 and UF4 from a nuclear weapons state (likely USSR)
- **1997: establish contact with A.Q. Khan**
  - Use his network to acquire centrifuge components, UF6 gas, technical training, partial weapons design
- **By 2002: complete 9 centrifuge cascade; working on 19 and 64 centrifuge cascades**



Source(s):
http://www.nti.org/country-profiles/libya/nuclear/
https://www.armscontrol.org/factsheets/LibyaChronology

Nonproliferation Tools in Libya

- **Economic and diplomatic sanctions**
  - The US, the EU, and the UN all imposed sanctions at various points during Libya's nuclear program
- **Proliferation Security Initiative**
  - Member states commit to strengthen and enforce their own nonproliferation laws, notify other nations of suspicious shipments, and participate in interdiction training and operations
  - Facilitated the interdiction of the BBC China, destined for Libya (October 2003)
  - US and British intelligence notified German and Italian authorities that they believed the ship was carrying illegal cargo
  - The ship was diverted to an Italian port, where inspectors discovered Malaysian origin centrifuge components procured through the A.Q. Khan network
- **This discovery:**
  - Pressured the Libyan government to allow US and UK technical experts into the country, where they were able to gather further information on the extent of the program
  - Helped unravel the A.Q. Khan network

Source(s):
http://www.cfr.org/border-and-port-security/proliferation-security-initiative/p11057

Is Libya a Success Story?

- **Motivated by international pressure and information gathered through interdiction and technical experts on the ground, the Libyan government publicly renounced nuclear weapons on December 19, 2003**
  - Agreed to weapons programs, with assistance and verification by US, UK, and IAEA experts
  - Agreed to sign an IAEA Additional Protocol
  - Agreed to adhere to commitments under the NPT, Biological Weapons Convention, Chemical Weapons Convention, and Missile Technology Control Regime
- **Libya was allowed to keep operating the research reactor, and to retain stockpiles of uranium ore.**
  - Security of these materials became an IAEA concern when conflict erupted in Libya in 2011
- **In 2008, the IAEA declared that Libya was in compliance with its commitments and required only routine inspections**

Source(s):
http://fas.org/nuke/guide/libya/iaea0804.pdf
http://carnegieendowment.org/2009/08/28/libya-iaea-reports
http://www.nti.org/analysis/articles/was-libyan-wmd-disarmament-success/

Nondestructive Analysis for Nuclear Safeguards

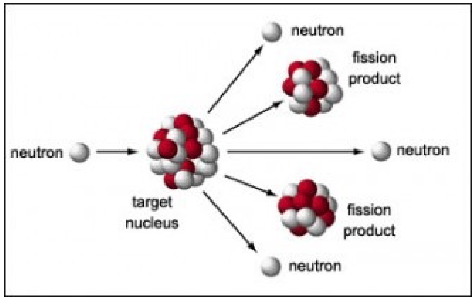
Derived from LA-UR-17-21214: INITIAL Module

Nondestructive Analysis for Nuclear Safeguards

- **Objective: Determine if special nuclear material is where it should be and in the proper amounts.**
- **Nuclear materials that can be used to make a weapon are considered SNM**
  - Highly Enriched Uranium (HEU)
  - Weapons Grade Plutonium (Pu)
- **Certain isotopes of Pu undergo fission spontaneously, without any prompting**
- **Certain isotopes of U undergo fission primarily when induced with a neutron source**
- **Diversion path for HEU: enrichment facilities**
  - Weapons program can be disguised as a peaceful power program, which is protected under the NPT
- **Diversion path for Pu: spent fuel (repositories, interim storage, reprocessing facilities)**

Sources of radiation used in nuclear safeguards

Neutrons



Origins

- Spontaneous / induced fission
- (α,n)
- Cosmic rays
- (p,n)
- (n,2n)
- (γ,n)

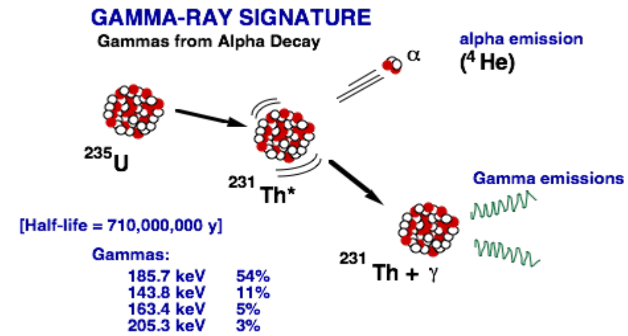
Less common

Signal: Time and correlations

Shielding: Low Z material

Detectors: ^{3}He, Scintillators, fission chambers

Photons



Nucleus (gamma-ray)
Nuclear collision (gamma-ray)
Electron cloud (x-ray)

Weapons Grade Pu clad in Stainless Steel and surrounded by a Tungsten Reflector

Energy

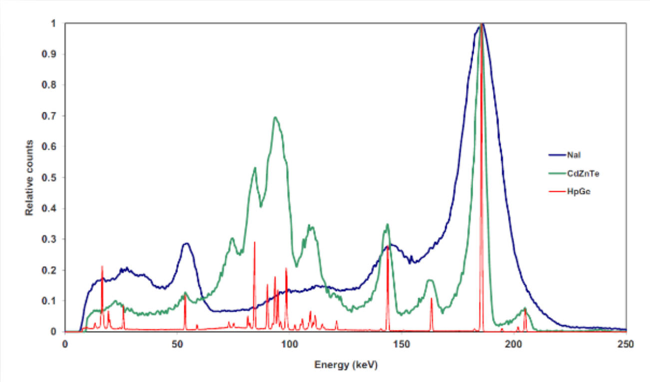
High Z material

HPGe, Scintillators, NaI

NonDestructive Analysis: Passive/Active Neutron, Photon detection

- **What do we want to learn from NDA?**
  - Multiplication (how many neutrons created per source neutron)
  - Initial enrichment, burnup, cooling time (spent fuel)
  - Plutonium mass
- **Passive: no external source**
- **Active: neutrons or gammas irradiate source to magnify signal**
- **Materials such as Pu have a strong passive neutron signal already. Materials such as HEU have a weak passive neutron signal and can be easily shielded**
  - Based on material type, may choose active or passive technique for identification
- **What if we don't know what material we're looking for?**


Rail radiation portal monitor (RPM) at the Port of Antwerp, Belgium



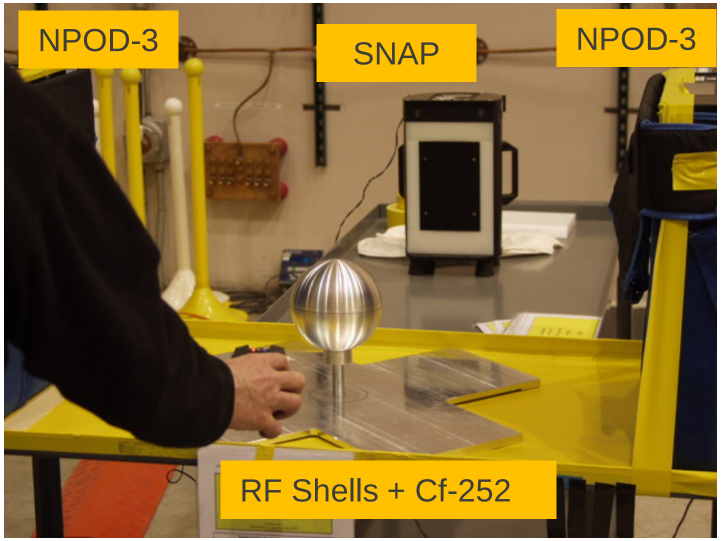
- 235U spectrum, characteristic peak at 186 keV
- SNM emits gamma rays in addition to neutrons which can be used to identify the material
- Determination of gamma ray energies along with absolute intensities can provide quantitative information about the amount of SNM present

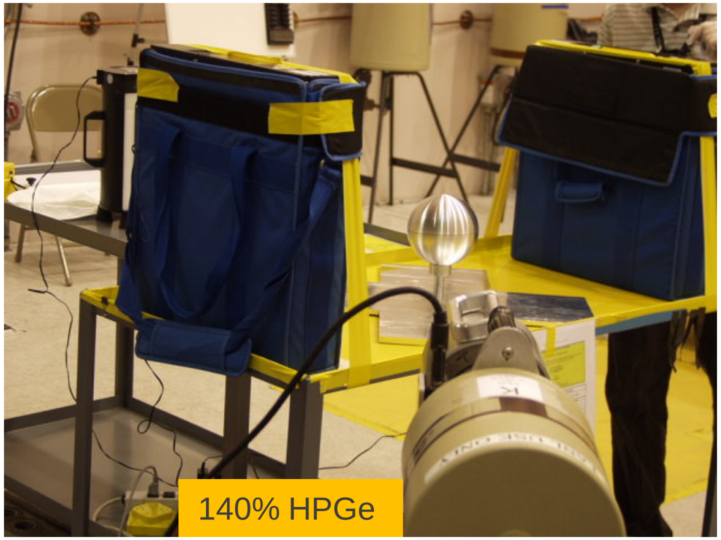
Case Study: Finding SNM in Cargo

- Limited amount of time in which to scan, abundant shielding is a strong possibility
- Because we don't know what we're looking for, active interrogation is the option most likely to succeed
- Irradiate cargo container with gammas and/or neutrons, measure signal coming out. If there are coincident neutrons and gamma rays, SNM is likely present

Types of Neutron Counting

- **Total Neutron Counting**
  - Record the total number of neutrons detected in a certain amount of time
  - Accurate assays can be obtained only for very few types of SNM
- **Coincidence Counting**
  - Record the number of times two neutrons arrive within a set time window (gate)
  - Wide application for international safeguards
  - focused on verifying declared materials
- **Neutron Multiplicity Counting**
  - Extension of neutron coincidence counting
  - Record the number of times we detect 2, 3, 4, etc. neutrons within a gate
  - It improves neutron assay accuracy dramatically by adding more measured information





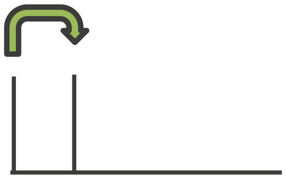
Sub-critical Measurements-Radiation Detection – Total (Gross) Counting -

- **Things we can learn from gross neutron counting:**
  - The location of sources of neutrons/confirmatory measurements.
  - If the efficiency of the detector system is well known, one can estimate the neutron emission rate of a system.
  - If multiple measurements are performed it might be possible to learn the following (note that here the efficiency does not need to be known):
    - Relative multiplication of a system (comparison of the multiplication of two similar systems).
    - Multiplication of a system (if the multiplication from one of the measurements is known from other means or if replacement measurements are performed).
    - Absorption properties of materials.
    - Room return information.

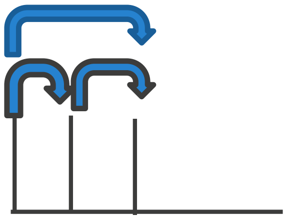
Coincidence Counting

- **Now looking for doubles only, incidences of two neutrons arriving within a designated time window**
- **Shift register is most common coincidence counting technique**
- **Same gate setup as with multiplicity counting, but instead of counting the number of neutrons in the gate, count the number of times two neutrons are detected in coincidence**

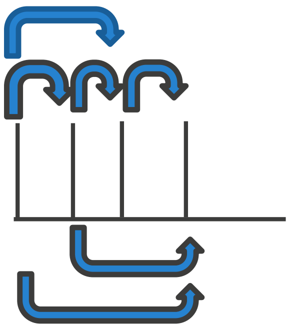
1 pulse,
0 Coincidences



2 pulses,
1 Coincidence



3 pulses,
3 Coincidences



4 pulses,
6 Coincidence

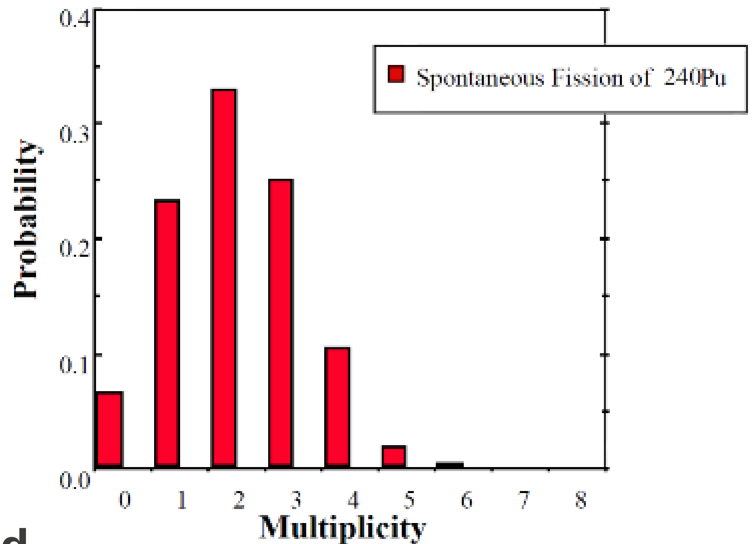
Sub-critical Measurements-Radiation Detection – Correlated Neutron Analysis-

- **Many methods exist. Most take advantage of the physics properties shown in the previous slides (particularly the fact that multiple prompt neutrons are emitted "instantly" after fission).**
- **Most methods were developed for zero power reactors and later applied to subcritical systems or power reactors.**
  – Most of the work took place from 1940s-1960s.
- **Differ in energy response, timing required, detection system required, multiplication over which the method is valid, etc…**
- **Time-Correlation Analysis**
  - Rossi-Alpha, Interval distribution (Babala), Correlation analysis
- **Moments Analysis**
  - Feynman variance (Hansen-Dowdy or Hage-Cifarelli), Bennett Variance
- **Probability of Neutron Detection**
  - Zero-Count probability (Mogilner)

Multiplicity Counting

- **Stable, reliable, and accurate method for finding SNM or determining 235U and Pu content**
- **The probability of any given number of neutrons being emitted in a fission event can be found in the multiplicity distribution**
  - Neutrons are highly penetrating and do not have a large background signal
- **To construct a multiplicity distribution, the number of neutrons falling within a coincidence resolving time window is counted**
  - Because neutrons are emitted simultaneously from fission, neutrons from the same fission event will arrive close together in time
  - Neutrons from different events will also arrive in the same time window, by chance. These are called accidentals. The rate of detection of accidentals is constant (because they are random) and can be subtracted

Example: 240Pu

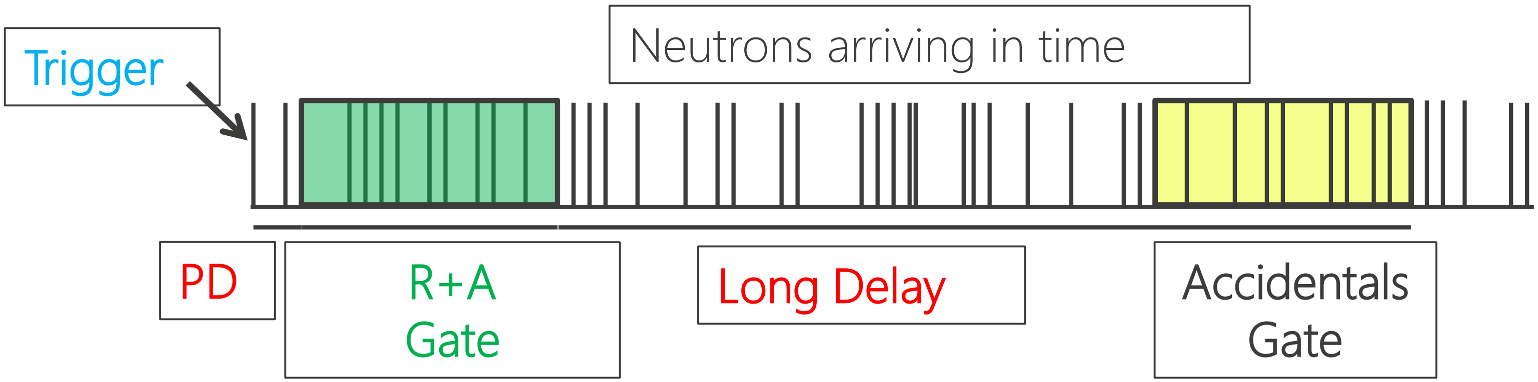


Most probable number of neutrons released by 240Pu is 2

Distribution is unique to each isotope, can be used to find plutonium mass in a sample

Multiplicity Counting

- Multiplicity electronics use R+A and A gates to build multiplicity distribution
- Neutron detection called a “trigger”, initiates a pre-delay (PD ~ 3-4.5μs) followed by an R+A gate (~ 64μs)



- Count number of neutrons in R+A gate, add to multiplicity distribution
- Long delay is opened next to ensure that no coincident neutrons could still be thermalizing (slowing down through scattering) before detection
- Accidentals gate is opened to count neutrons that are random and uncorrelated to trigger neutron

Relevant Physics for Sub-Critical Multiplication

- **(Source) Passive neutrons from fissionable material emitted from:**
  - Spontaneous fission neutron sources:
    - Correlated in time and location of fission
    - Examples: Cf-252, Pu-240
  - (α ,n) reactions:
    - Produced when α particle is absorbed and neutron is emitted
    - Not correlated in time and location
    - Examples: Am-Be
- **(Induced) Neutron multiplication dominated by two physical processes:**
  - (n,2n)
    - Occurs mostly above 7 MeV
    - Does not contribute significantly to most scenarios
  - Neutron-induced Fission

Simulations need to be "microscopically" correct for comparisons with measured data.

Relevant Physics for Sub-Critical Multiplication

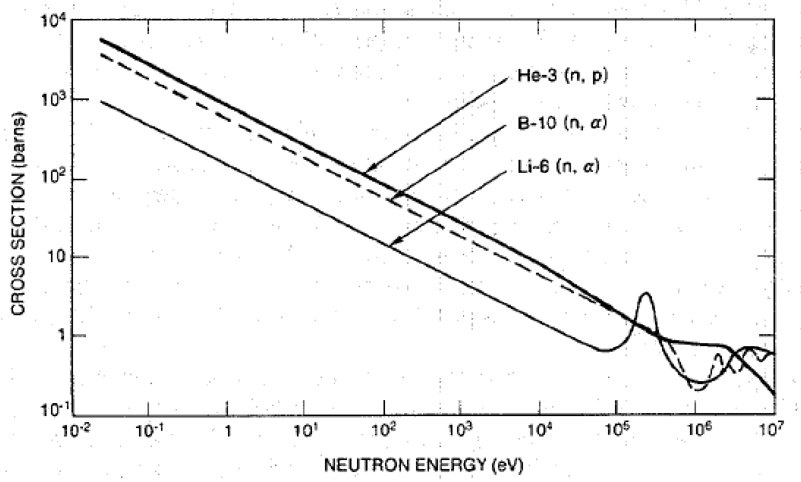
- **Neutron multiplication measurements (passive and active) designed to separate the correlated emission events, e.g., SF, from the uncorrelated events, e.g. , (α,n),**
  - Record time of neutron capture in a neutron detector over a large collection time (e.g. 300 sec)
  - Group these capture times in a large number (e.g. 1 M) smaller time sub-intervals (e.g. 250 μsec)
    - These time sub-intervals are larger than typical neutron detection and lifetimes (~50 μsec)
  - Multiplicity histogram is constructed
    - Obeys Poisson statistics if system is non-multiplying (i.e. neutrons are emitted randomly in time)
    - Data analysis begins…Feynman Variance-to-Mean, CSDNA, etc

Data recorded is neutron detector location and time: list-mode data

Simulations need to produce list-mode data for comparisons

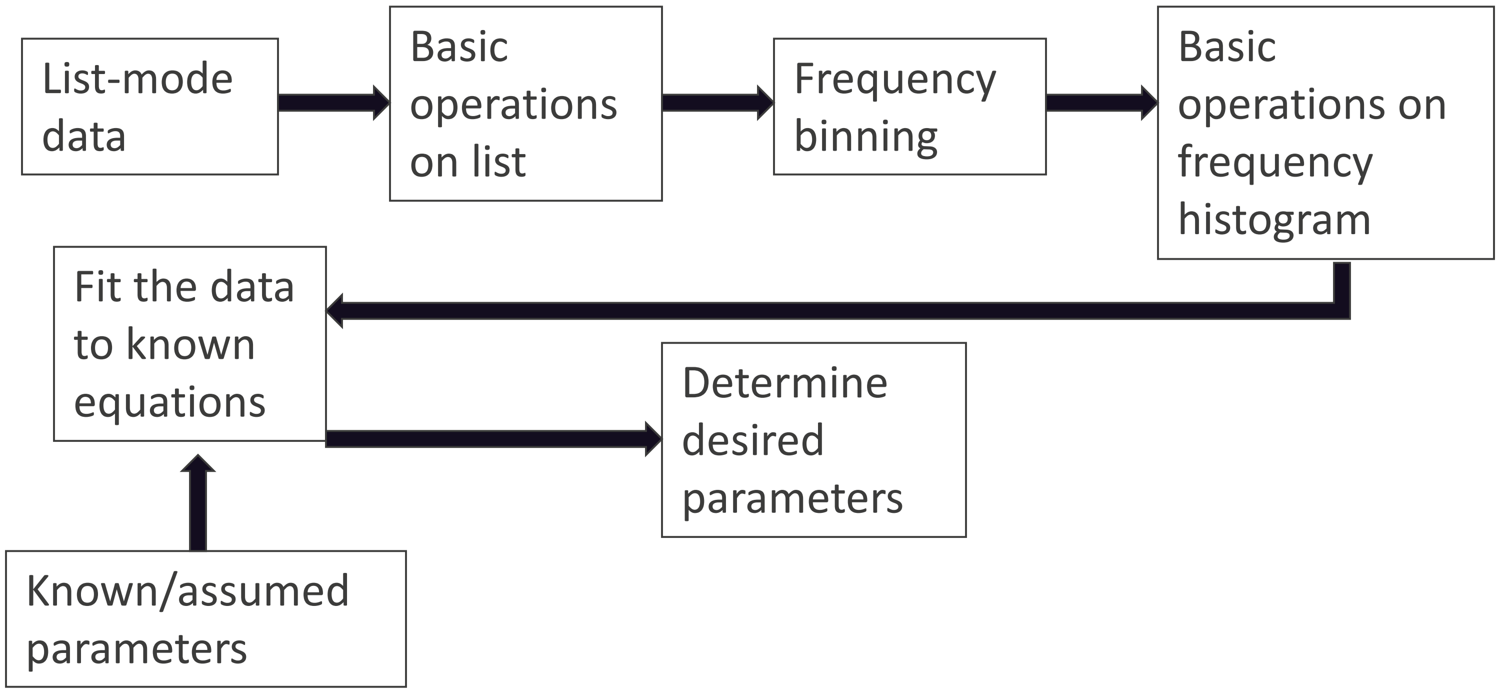
Sub-critical Measurements - Radiation Detection

- **Nearly all neutron detectors actually detect secondary radiation (protons, alpha particles, fission products, etc).**
  – Capture, scattering, and fission based detectors exist.
- **Some have threshold energies but most take place at thermal energies (moderating materials may be used to slow down the neutrons which will increase the detector efficiency) due to the cross-section of the detection media.**
- **Neutron detectors generally give a signal when a neutron is absorbed but most other information is lost (such as energy).**



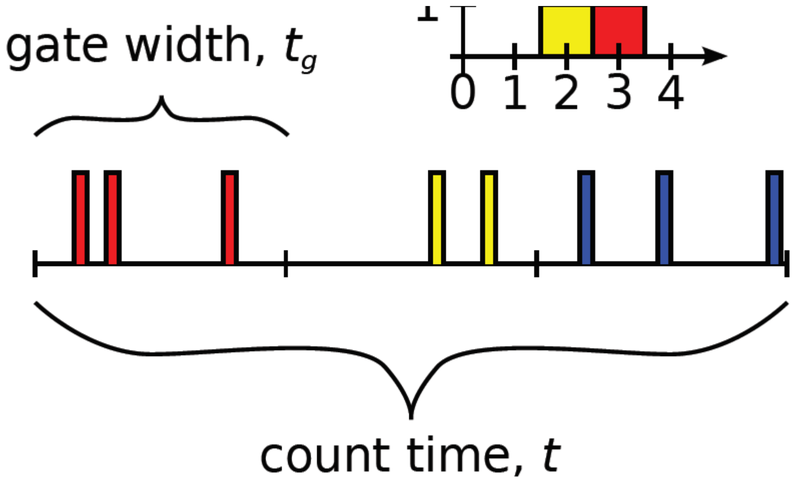
- **Many data acquisition systems exist:**
  - **Scalers/counters**
  - **Coincidence circuits**
  - **Shift-register**
  - **List-mode**

Sub-critical Measurements - Data Analysis

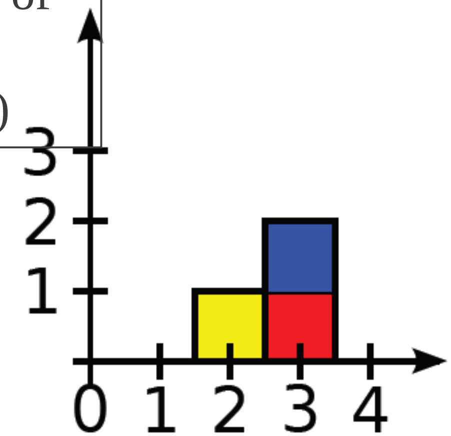


Sub-critical Data Analysis: Construct Feynman Histogram

Data are separated into gates



y-axis is the number of gates that contained exactly n events (C_n)



x-axis is the number of neutrons recorded in the gate (n)

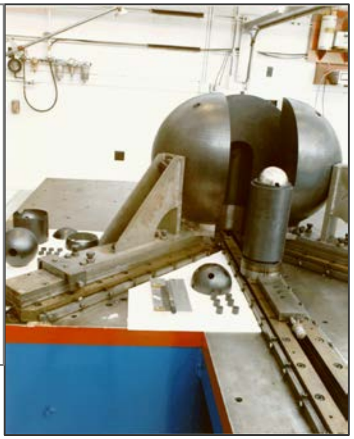
Then frequency binning is performed

National Criticality Experiments Research Center (NCERC)

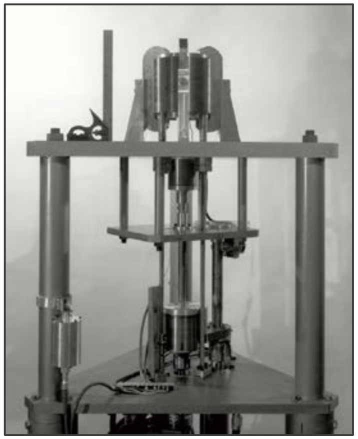
- **Location: Device Assembly Facility (DAF) at the Nevada Nuclear Security Site (NNSS)**
- **Operated by: Los Alamos National Laboratory**
- **NCERC Mission Statement:**
  - The mission of the National Criticality Experiments Research Center (NCERC) is to conduct experiments and training with critical assemblies and fissionable material at or near criticality in order to explore reactivity phenomena, and to operate the assemblies in the regions from subcritical through delayed critical. One critical assembly, Godiva-IV, is designed to operate above prompt critical.

- **Critical Measurements:**
  - Critical Benchmarks (ICSBEP)
  - Sample irradiations (foils, dosimetry, etc.)
  - reactivity worth measurements
  - Reactivity ranges subcritical to prompt critical
  - Thermal, intermediate, and fast neutron energy spectrum
  - HEU, LEU, Pu, etc.

Comet: General purpose, heavy duty vertical lift assembly



Flat-Top: Fast benchmark critical assembly

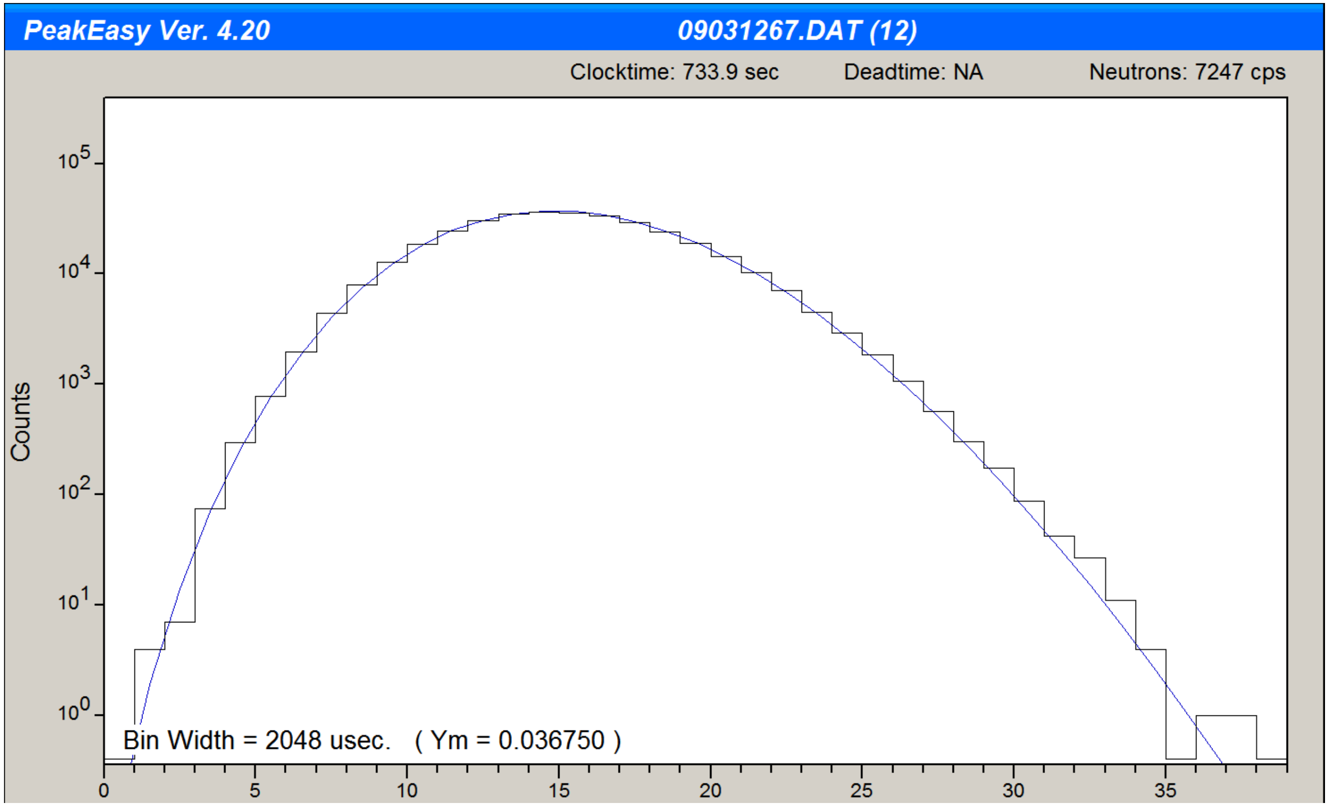


Godiva IV: Fast burst assembly

Why pay attention to sub-critical, multiplying systems, Aren't critical systems more valuable and interesting?

- **Critical experiments have been used to benchmark codes, measure nuclear data, well known, easy to measure, …**
- **Sub-critical, multiplying systems are providing invaluable information select few have examined:**
  - Standard comparison of simulated and measurements (fixed source, eigenvalue)
  - Design of future measurements, approach to critical, POI, …
  - Validation of MCNP, nuclear data, in other regimes.
  - New methods for interpreting measured data (keff, M)
  - *Quantification of uncertainties in inferred values*
  - *Impact on nuclear data (ν, σ_f, …)*
  - Nuclear safeguards
  - Threats from unknown systems…
  - New radiation detector technologies

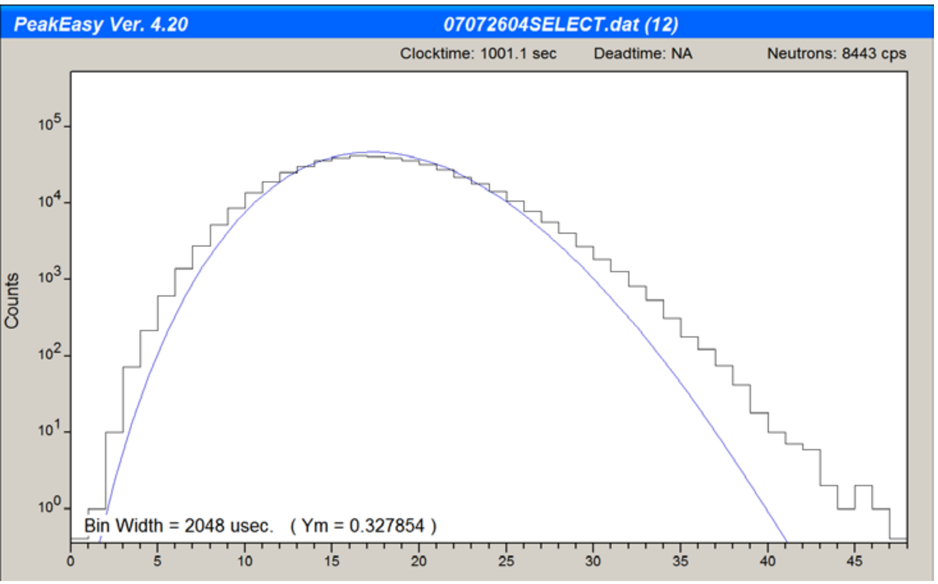
Sub-critical Data Analysis: Feynman Histogram Randomly fissioning source follows Poisson Distribution



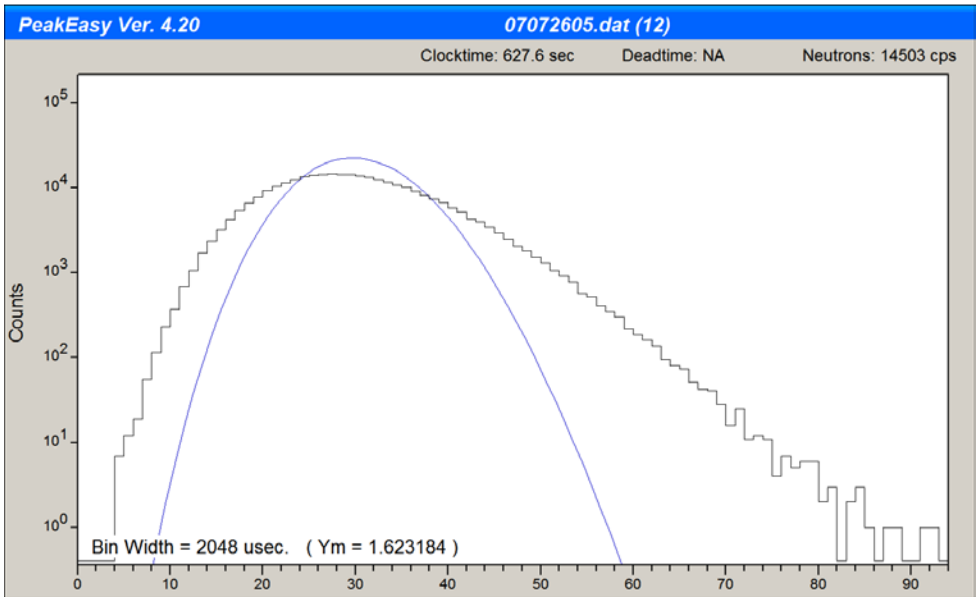
- **Feynman distributions are constructed and the deviation of the distribution from a Poisson gives us information about the multiplication of the system.**

Sub-critical Data Analysis: Feynman Variance-to-Mean Multiplying source Deviates from Poisson Distribution

- **As the multiplication of a system increases, the deviation from a Poisson distribution will increase.**



BeRP Ball (4.5 kg Pu sphere), M=4.4



BeRP Ball reflected by 3” polyethylene, M=13.5

Hage-Cifarelli formulism

- **Moments are a measure of the shape of data points.**
  - 1st moment is the mean, 2nd is the variance or width.
- **Reduced factorial moments:**

$$\overline{m_{1!}} = \frac{\sum nC_n}{1!\sum C_n}$$

$$\overline{m_{2!}} = \frac{\sum n(n-1)C_n}{2!\sum C_n}$$

$$\overline{m_{3!}} = \frac{\sum n(n-1)(n-2)C_n}{3!\sum C_n}$$

Numerator is the total number of neutrons detected.

Hage-Cifarelli formulism

$$R_1 = \frac{\overline{m_{1!}}}{\tau\, \omega_1} \qquad \omega_1 = 1$$

$$R_2 = \frac{1}{\tau\, \omega_2}\left[\overline{m_{2!}} - \frac{1}{2}\overline{m_{1!}}^{\,2}\right] \qquad \omega_2 = 1 - \frac{1-e^{-\lambda\tau}}{\lambda\tau}$$

$$R_3 = \frac{1}{\tau\, \omega_3}\left[\overline{m_{3!}} - \overline{m_{2!} m_{1!}} + \frac{1}{3}\overline{m_{1!}}^{\,3}\right] \qquad \omega_3 = 1 - \frac{3-4e^{-\lambda\tau}+e^{-2\lambda\tau}}{2\lambda\tau}$$

- **R_1, R_2, and R_3 are the singles, doubles, and triples counting rates. R_1 is the count rate in the detector in n/sec.**
- **τ is the gate width.**
- **λ is the decay constant of the of the system (including neutron interactions inside the detector system).**

Hage-Cifarelli formulism

$$R_1 = \varepsilon\left[b_{11}F_S + b_{12}S_\alpha\right]$$
$$R_2 = \varepsilon^2\left[b_{21}F_S + b_{22}S_\alpha\right]$$
$$with$$
$$b_{11} = M_L \overline{\nu}_{S(1)}$$
$$b_{21} = M_L^2\left[\overline{\nu}_{S(2)} + \frac{M_L - 1}{\overline{\nu}_{I(1)} - 1}\overline{\nu}_{S(1)}\overline{\nu}_{I(2)}\right]$$
$$b_{12} = M_L$$
$$b_{22} = M_L^2 \frac{M_L - 1}{\overline{\nu}_{I(1)} - 1}\overline{\nu}_{I(2)}$$

The subscripts S and I refer to s.f and induced fission.

- **ε is the detector efficiency.**
- **F_s is the spontaneous fission rate of the system.**
- **S_α is the (α,n) neutron emission rate.**
- **M_L is the leakage multiplication of the system.**
- **Four unknowns (ε,F_s,S_α,M_L) and only two equations.**
  - R_1 and R_2 are measured
  - Estimate: M_L and ε
  - Use additional moments of the counting distribution (R_3 and/or R_4).

Hage-Cifarelli formulism

- **(α,n) neutron emission rate (S_α):**
  - For "pure" metal systems S_α is approximately 0.
  - For systems in which $S_\alpha > 0$ it may be possible to estimate S_α using other methods (gamma spectroscopy).
- **Detector efficiency (ε):**
  - Calibration measurements with neutron sources can be performed.
  - Efficiency determined via gross counting (detected neutron count rate/"known" neutron emission rate) or using the singles and doubles counting rates (in this case the neutron emission rate does not need to be known).
- **The downside to this approach is that it may be difficult to accurately determine the (α ,n) emission rate or the detector efficiency for some measurements.**

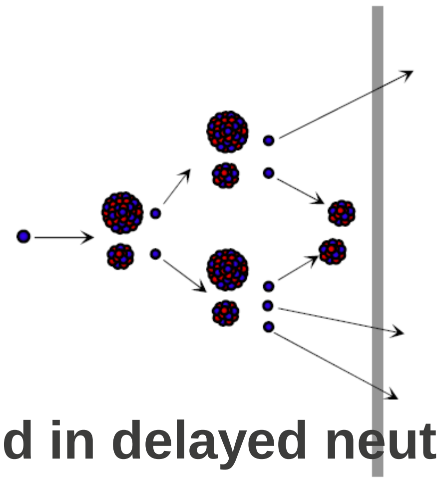
- **After the approach is decided we can rearrange the equations and will then have solutions for ε, F_s, S_α, and M_L.**
- **What about M_T, keff, SNM mass…**
- **What else can we learn about the system now that we know these parameters:**
  - Total multiplication (M_T).
  - Mass

Hage-Cifarelli formulism: What about M_T, k_{eff}, SNM mass…?

- **Serber Equation:** $$M_T = 1 + Q_f \bar{\nu}_{I(1)}$$
- **Q_f is the number of fissions produced when one neutron is introduced in the system.**

$$M_T = \frac{M_L \bar{\nu}_{I(1)} - 1 - \frac{\sigma_c}{\sigma_f}}{\bar{\nu}_{I(1)} - 1 - \frac{\sigma_c}{\sigma_f}}$$

$$M_T = \frac{1}{1-k_p}$$



- **Measurements are for prompt neutrons. To add in delayed neutrons we look to the case in which a system is at prompt critical:**

$$k_p = 1$$

$$\rho = \beta$$

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \Rightarrow k_{eff} = \frac{1}{1-\rho} \Rightarrow k_{eff} = \frac{1}{1-\beta}$$

$$\frac{k_{eff}}{k_p} = \frac{\frac{1}{1-\beta}}{1} \Rightarrow k_{eff} = \frac{k_p}{1-\beta}$$

Hage-Cifarelli formulism

- F_s is the spontaneous fission rate of the system.
- The number of neutron per second produced by spontaneous fission is equal to
- The spontaneous fission yield is known for many isotopes of interest.
- Dividing the number of neutrons per second from spontaneous fission by the spontaneous fission yield gives the mass of the isotope which is undergoing spontaneous fission.

Isotope	Total Half-Life	Spontaneous Fission Half-Life (yr)	Spontaneous Fission Yield (n/s·g)
^{232}Th	1.41×10^{10} yr	$> 1 \times 10^{21}$	$> 6 \times 10^{-8}$
^{232}U	71.7 yr	8×10^{21}	1.3
^{233}U	1.59×10^{5} yr	1.2×10^{21}	8.6×10^{-4}
^{234}U	2.45×10^{5} yr	2.1×10^{21}	5.02×10^{-3}
^{235}U	7.04×10^{8} yr	3.5×10^{21}	2.99×10^{-4}
^{235}U	6.8×10^{8} yr	1.8×10^{21}	8.0×10^{-4}
^{236}U	2.34×10^{7} yr	1.95×10^{21}	5.49×10^{-3}
^{238}U	4.47×10^{9} yr	8.20×10^{21}	1.36×10^{-2}
^{238}U	4.5×10^{9} yr	8.0×10^{21}	1.6×10^{-2}
^{237}Np	2.14×10^{6} yr	1.0×10^{21}	1.14×10^{-4}
^{238}Pu	87.74 yr	4.77×10^{21}	2.59×10^{3}
^{239}Pu	2.41×10^{4} yr	5.48×10^{21}	2.18×10^{-2}
^{239}Pu [a]	2.4×10^{4} yr	5.5×10^{21}	3.0×10^{-2}
^{240}Pu	6.56×10^{3} yr	1.16×10^{21}	1.02×10^{3}
^{240}Pu [a]	6.6×10^{3} yr	1.2×10^{21}	1.0×10^{3}
^{241}Pu	14.35 yr	(2.5×10^{21}) [b]	(5×10^{-2}) [b]
^{242}Pu	3.76×10^{5} yr	6.84×10^{21}	1.72×10^{3}
^{241}Am	433.6 yr	1.05×10^{21}	1.18
^{242}Cm	163 days	6.56×10^{21}	2.10×10^{7}
^{244}Cm	18.1 yr	1.35×10^{21}	1.08×10^{7}
^{249}Bk	320 days	1.90×10^{21}	1.0×10^{5}
^{252}Cf	2.646 yr	85.5	2.34×10^{12}
^{252}Cf [a]	2.65 yr	66.0	2.3×10^{12}

Data are from the PANDA manual (1991), p. 339, unless otherwise noted.

[a] Data from *DOE Fundamentals Handbook, Nuclear Physics and Reactor Theory*, Module 2, p. 2.

[b] Parameters in parenthesis have estimated accuracies of 2 orders of magnitude.

Summary of Correlated Neutron Analysis

- **Passive neutron analysis can help provide information on many systems of interest. In particular it can give information on:**
  - The location of sources, absorption properties of materials, room return information, the multiplication (total or leakage), neutron or fission rates, and mass.
- **Things that it cannot provide include:**
  - High-quality isotopic information.
  - Elemental information about reflector or moderator materials.
- **Neutron measurements can provide useful information on their own but are even more effective when coupled with other measurement methods (such as gamma spectroscopy).**

MCNP Simulations of Sub-Critical Measurement

- **MCNP simulation of neutron sources and detection**
  - User can define location, direction, energy, time, and intensity of SF, (α,n) neutron sources
  - User **cannot** define fission events
    - e.g. sample number of neutrons emitted from ν_{bar}
  - User **cannot** define correlated (time, location) neutron sources
    - MCNP samples these values from user's input
  - User cannot (easily) record location and time of detection.
    - Possible using MCNP's PTRAC capability and a user-created external script to extract this information

Standard MCNP is not microscopically correct enough to compare with current sub-critical measurements:

The goal of our simulations is to be predictive!

- **MCNP – well suited for comparing results of sub-critical measurements**
  - Calculates relevant quantities for fixed-source, eigenvalue problems
    - How faithfully is MCNP simulating fission process and what we measure?
    - Correct for averaged values but **<u>not microscopically correct</u>**

- **Other MCNP-like capabilities exist:**
  - MCNP-PoliMi
  - MCNP-DSP
  - Others?
  - We are currently evaluating these capabilities.

MCNP

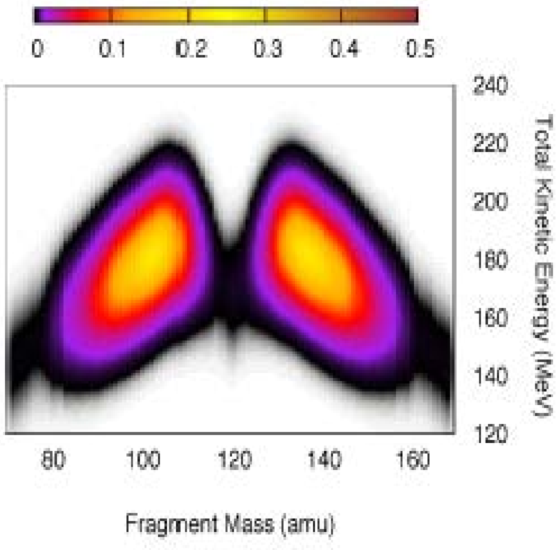
- **In tabulated nuclear data libraries (i.e. ENDF/B-VII.1):**
  - Average secondary neutron and photon information can be available
    - Average multiplicity,
    - Average spectrum,
    - Average energy-angle spectrum,
  - Generally, high-dimensional distributions of secondary particles are unavailable
    - Multiplicity distribution,
    - Multiplicity-dependent emission spectra,
    - Multiplicity-dependent energy-angle emission spectra,
    - Neutron-neutron, neutron-photon and photon-photon correlations
    - Too much data to tabulate!
- **Default MCNP uses average quantities**
  - Consider this a nuclear data “variance reduction” technique
  - Good for integral quantities, like flux and effective multiplication
  - Bad for studying detailed particle emission physics

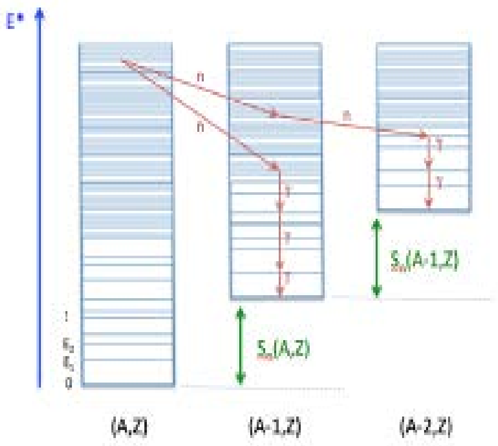
Secondary Particle Event Generators

- **MCNP6.1.1 contains two event generators:**
  - **LLNL Fission Library**
    - Spontaneous, neutron-induced and photo-fission
    - Fission Reaction Event Yield Algorithm (FREYA)2 isotopes
      - Spontaneous: 238U, 240Pu, 244Cm and 252Cf
      - Neutron-induced: $_{233}$U, $_{235}$U and $_{239}$Pu
    - When available, FREYA generates secondary neutrons and photons
  - **Cascading Gamma-ray Multiplicity (CGM) – LANL**
    - Generates secondary particles from a variety of reactions
    - No fission! (CGMF under active development)

Secondary Particle Event Generators: CGMF

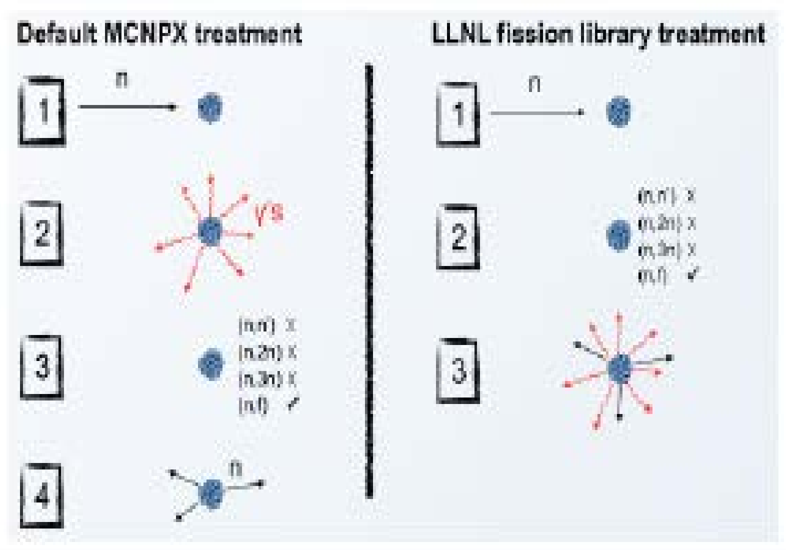
- CGMF is a superset of CGM with an addedfission reaction capability
- Fission fragments are sampled from a joint probability distribution function of mass (A),charge (Z) and total kinetic energy (TKE)
- Uses Hauser-Feshbach statistical theory of nuclear reactions
- Neutron / photon competition is treated during evaporation from fission fragments
- Monte Carlo is used to sample each step in the de-excitation process





Secondary Particle Event Generators: FREYA

- **FREYA is LLNL's fission event generator**
- **In MCNP6, it is accessible through LLNL Fission Package**
- **The LLNL Fission Package includes more tabulated and fitted data used for lesser known isotopes FREYA can't presently handle**
- **FREYA uses a Monte Carlo Weisskopf approach**
  – Neutrons emitted by sampling from Weisskopf spectrum
  – After neutrons are done emitting, gamma rays are emitted from residual energy
- **Computationally more efficient than Monte Carlo Hauser-Feshbach**



Upcoming modeling / simulation work

- **Many applications are in need of high fidelity physics models**
- **Fission event generators are under active development**
- **When implemented in MCNP a predictive capability may be possible**
- **SNM signature detection with code validation will soon be possible**

- **Future work:**
  - Finish implementation and improvements to fission event generators in MCNP
  - Develop verification tests for all these new features
  - Need experimental measurements to compare against
  - Validate the new physics features with experiment
  - Compare against MCNP-PoliMi and other specialized codes

Summary

- **We have reviewed some of the current missions and scope of Los Alamos National Laboratory**

- **Additionally, we have reviewed some of the enduring and impactful consequences of the 1930's and 1940's on:**
  - High performance computing
  - Monte Carlo invention and development
  - Nonproliferation and nuclear safeguards
- **We have also covered some of the methods and simulation procedures involved in analyzing multiplying sub-critical systems.**

- **I have found the historical accounts both informative and enjoyable but also re-emphasizes the breadth and impact of nuclear engineering.**

Thank you!

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