



 **Los Alamos**
NATIONAL LABORATORY
— EST. 1943 —

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



Nuclear Safeguards, Monte Carlo Method, and MCNP – A Brief Review of Our 70 Year History

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XCP-3 Group Leader

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Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

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 Alamogordo, 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.

Nuclear Deterrence: the US has 11 nuclear weapon types, LANL has responsibility for 8 of the weapons.

B61-3,-4,-7



B61-11



LANL Weapons

W76-0
W76-1



W78



W88



LLNL Weapons

W80-1



B83



W87



Adapted from M. Bernardin's ADX talk to LANL post docs

LANL: Helping to shape a globalized nuclear world

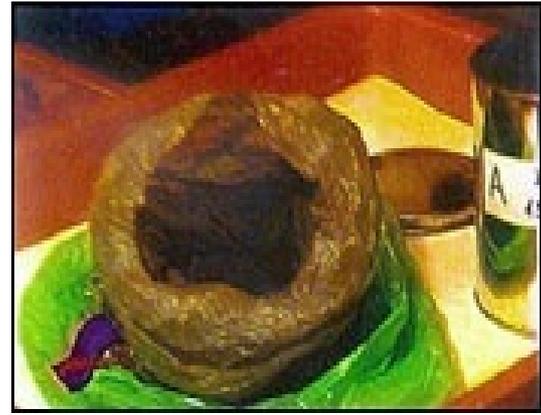
Foreign Nuclear Threats



Nuclear Counterterrorism



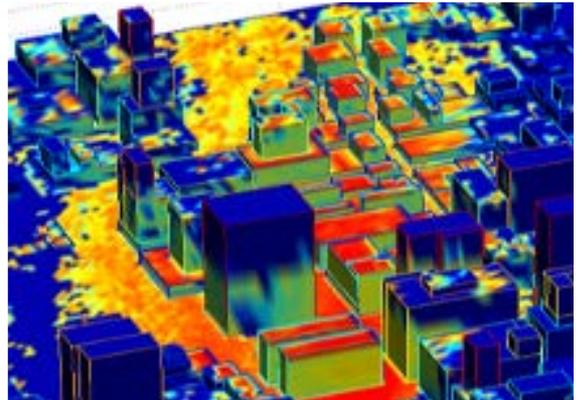
Nuclear Nonproliferation



Nuclear Forensics



Nuclear Consequence Management



Nuclear Emergency Response



SSP: Assessment of the current stockpile, projecting stockpile lifetimes, and designing tomorrow's stockpile

Physics

High Explosives

- Detonation characteristics
- Energetics, EOS

Material Properties

- Equation of State
- Strength
- Damage

Hydrodynamics

- Material deformation, fracture, spall, & ejecta
- Elastic & plastic flow, friction
- Laminar to turbulent fluid flow
- Material mixing, morphology
- MHD

Transport

- Methods (Monte Carlo, Sn)
- Neutrons, Gammas, Photons, Charged Particles

Atomic Physics

- Opacities
- LTE / NLTE

Nuclear Physics

- Cross sections
- Reaction rates
- Energetics

Thermonuclear Physics

- Reaction rates
- Energetics
- Plasma physics

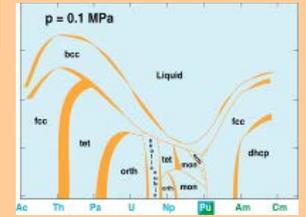
SSP Research & Development

Theory and models

Theory

$$\frac{1}{c} \frac{\partial E_v}{\partial t} + \frac{1}{c} \vec{\nabla} \cdot \mathbf{F}_v = \left(\frac{4\pi\eta_v}{c} \right) - \chi_v E_v$$

Physics Model



Development of large, 3D weapon simulation codes



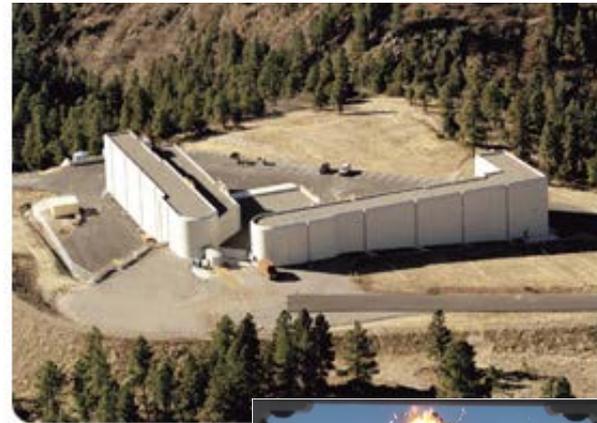
Experimentation



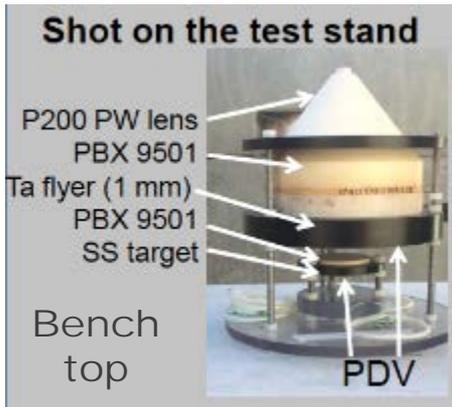
Our Mission is accomplished through broad expertise, a broad range of cutting-edge experimental facilities



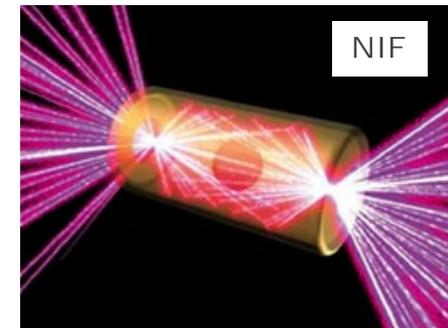
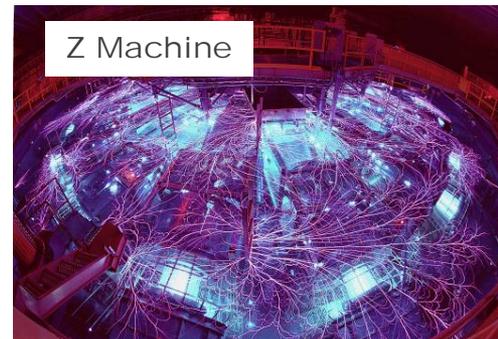
DARHT radiographic facility



pRad, nuclear X-sections, material research

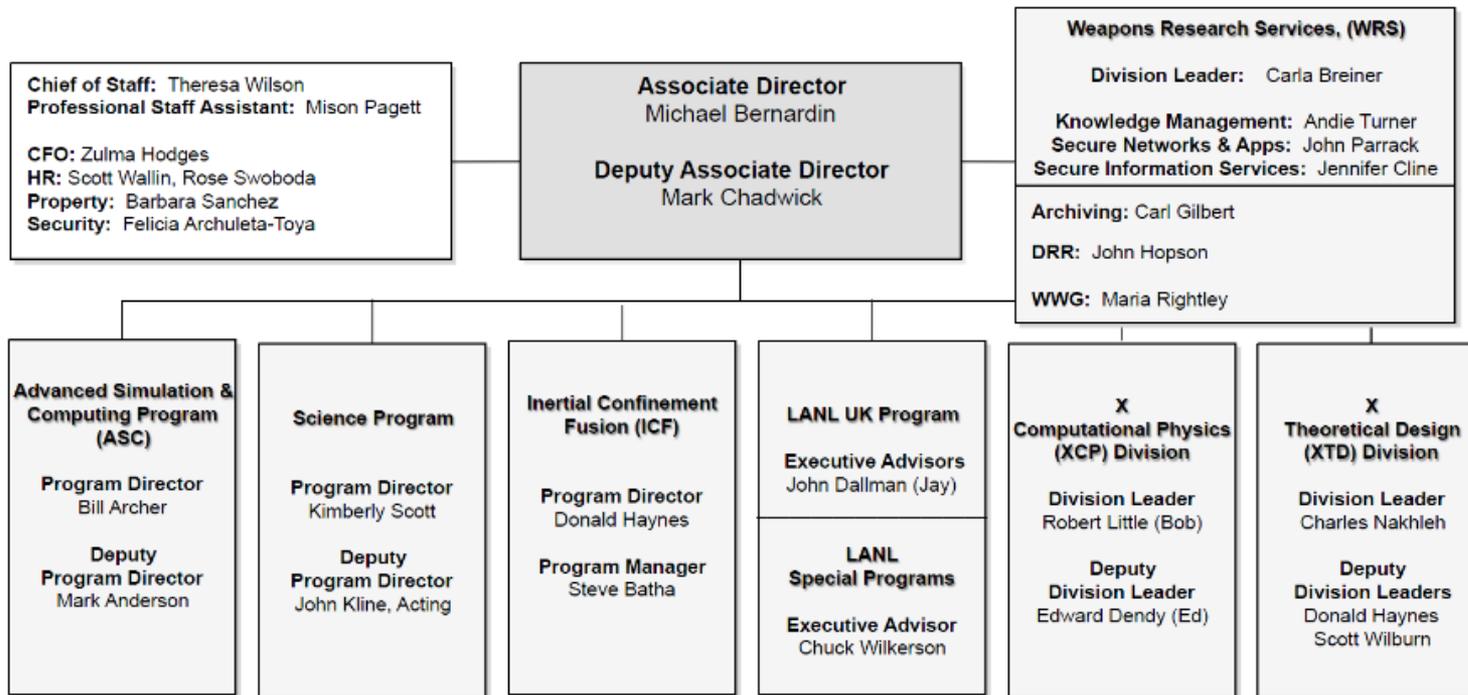


- Centrifuge Machines
- Thunder Pipe
- ACRR
- Hermes, Saturn
- Omega



High-energy density (HED) physics experiments

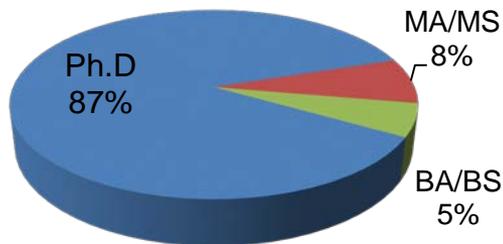
Weapon's Physics Directorate (ADX)



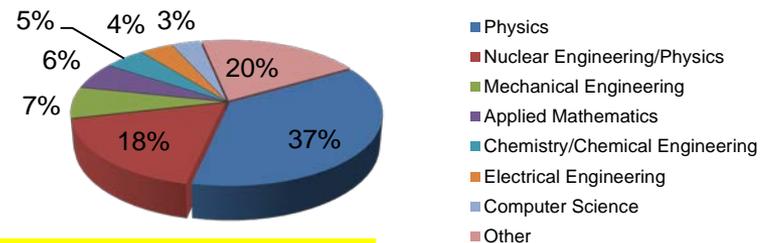
Weapon Physics programs manage budget of \$428M

- 75% funding goes outside ADX
- Supports work in 50% of Lab's Divisions

Highest Degree of our Technical Staff



ADX Ph.Ds by Discipline



45% of our technical staff held a Post Doc position prior to being hired as a TSM/R&D

What does LANL's XCP Division Do?

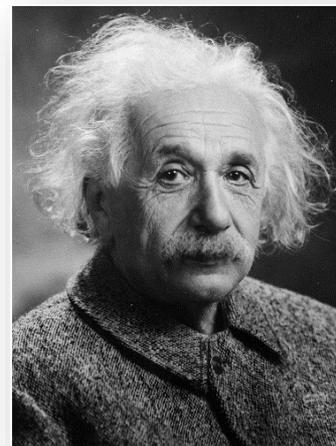
- The X Computational Physics Division (XCP) develops and uses multiphysics simulation codes, as well as underlying physics models and numerical algorithms, to support basic science and applications in national nuclear security.
- We take advantage of some of the world's fastest and most advanced computing platforms running state-of-the-art simulation codes to study a variety of complex physics problems.



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.
Massena Point
Pasadena, 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 unofficial 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 Weizsacker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

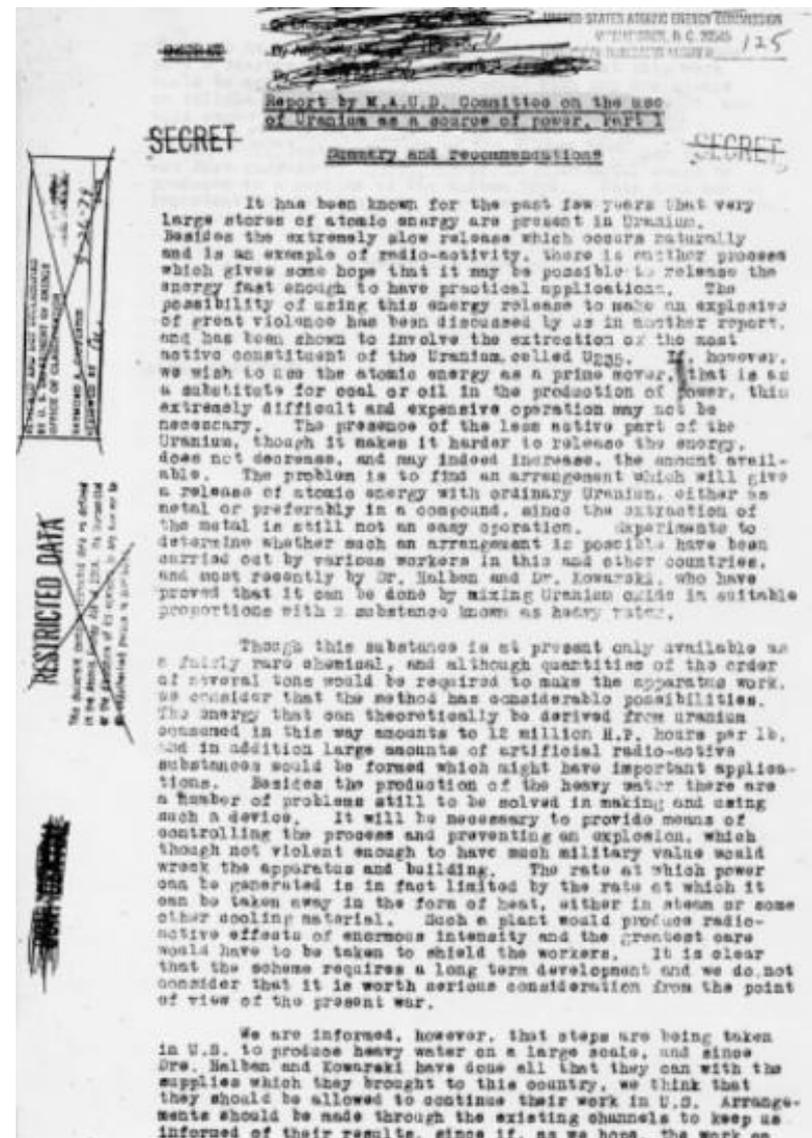
Yours very truly,
A. Einstein
(Albert Einstein)

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

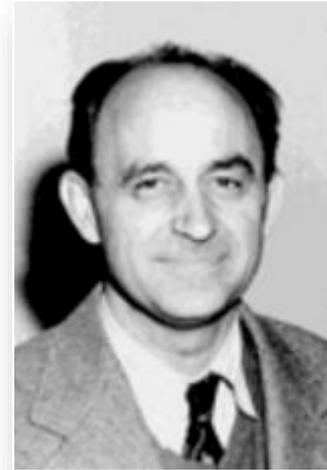
Source:

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



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

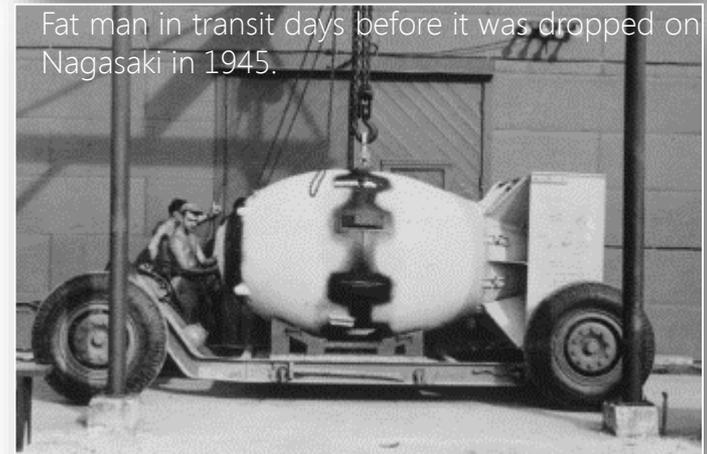
https://www.osti.gov/opennet/manhattan-project-history/Events/1942-1944_pu/1942-1944_plutonium.htm

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>

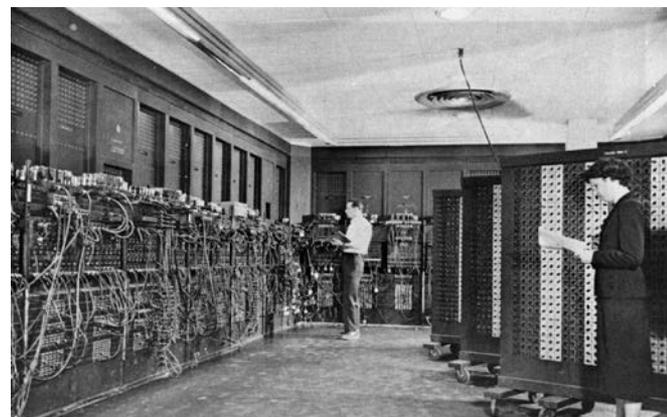
Out of WW II comes computing and the Monte Carlo Method

The Origins of Monte Carlo – 1946 Stanislaw Ulam

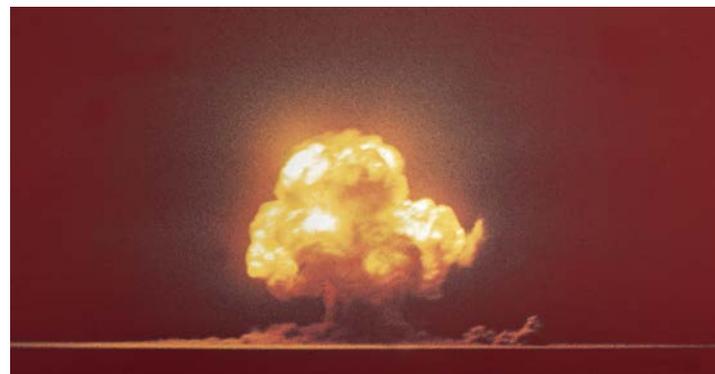
- “*The year was 1945. Two earthshaking events took place: the successful test at Alamogordo and the building of the first electronic computer*” – N. Metropolis
- **The method was invented by Stanislaw Ulam in 1946 playing Solitaire while recovering from an illness.**
- “*After spending a lot of time 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

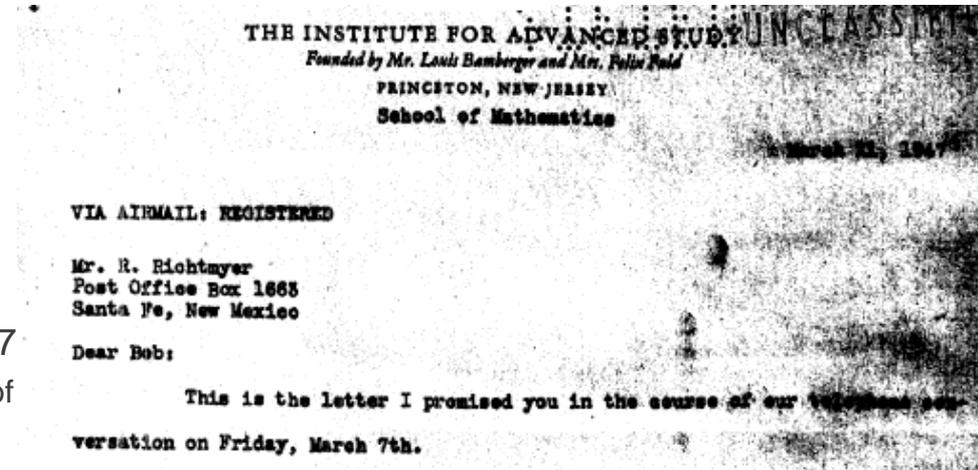


John von Neumann

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 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.

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

	Instructions:	Calculations:	Explanations:
	1 r of $C_1 - 1$, see (1)		r_{i-1}
	2 r of C_2 , see (1)		r_i
	3 $(C_2)^2$		s^2
	4 $(C_1)^2$		r^2
	5 $3 - 4$		$s^2 - r^2$
	6 $C_2 \begin{cases} \geq 0 \Rightarrow vt \\ < 0 \Rightarrow sb \end{cases}$		$s \begin{cases} \geq 0 \Rightarrow vt \\ < 0 \Rightarrow sb \end{cases}$
Only for sb :	7 $(1)^2$		r_{i-1}^2
Only for vt :	8 $5 + 7$		$r_{i-1}^2 + s^2 - r^2$
Only for sb :	9 $8 \begin{cases} \leq 0 \Rightarrow sb' \\ > 0 \Rightarrow sb'' \end{cases}$		$r_{i-1}^2 + s^2 - r^2 \begin{cases} \leq 0 \Rightarrow sb' \\ > 0 \Rightarrow sb'' \end{cases}$
	10 $vt \text{ or } sb' \Rightarrow 2$ $sb'' \Rightarrow 1$		$vt \text{ or } sb' \Rightarrow r_i - \}$ $sb'' \Rightarrow r_{i-1} - \}$ r^*
	11 $vt \text{ or } sb' \Rightarrow +1$ $sb'' \Rightarrow -1$		$vt \text{ or } sb' \Rightarrow +1 - \}$ $sb'' \Rightarrow -1 - \}$ E
	12 $(10)^2$		r^{*2}
	13 $5 + 12$		$r^{*2} + s^2 - r^2$
	14 $11 - 1 - \sqrt{13}$		$- *$

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

April 2, 1947

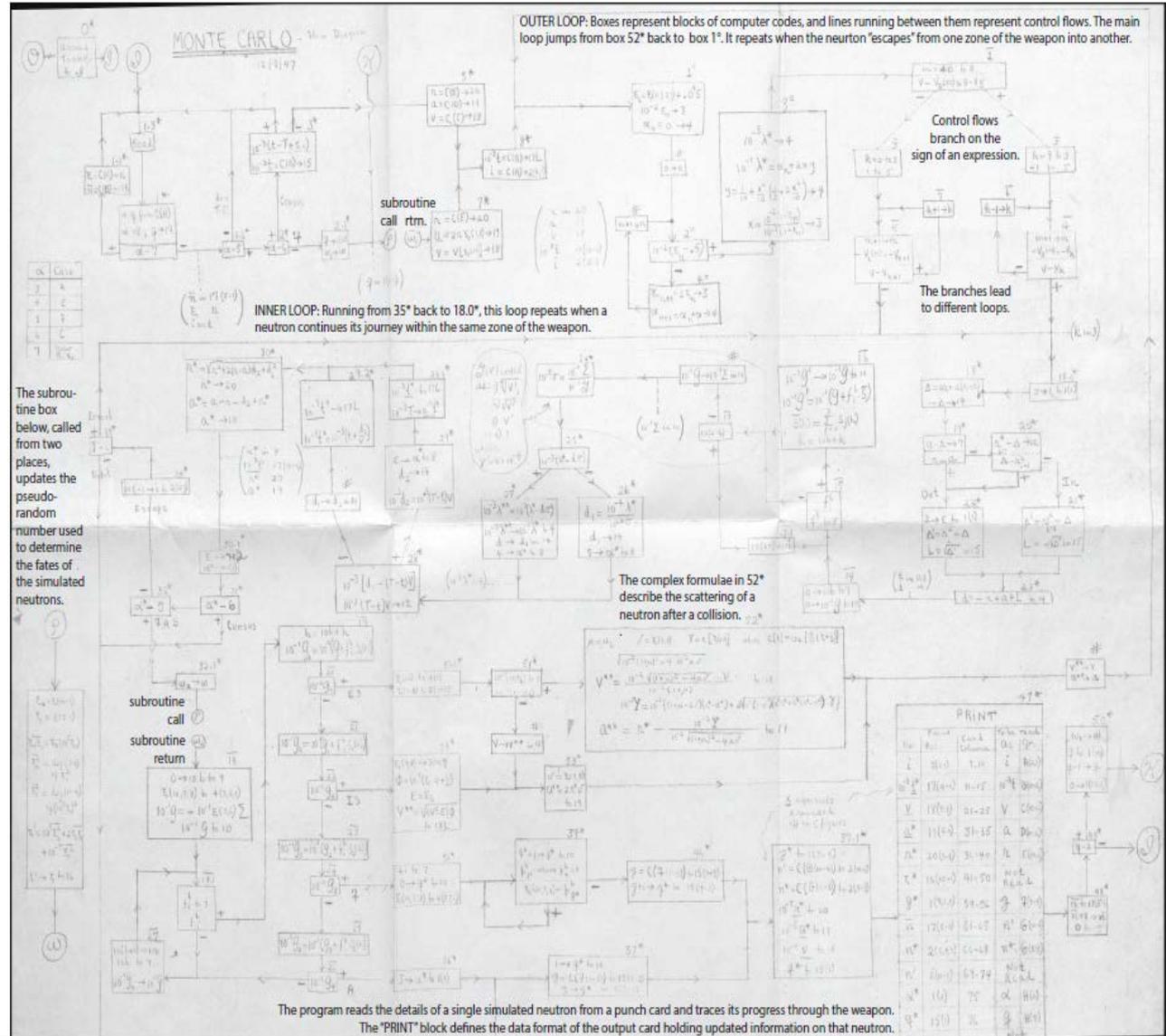
Professor John vonNeumann,
The Institute for Advanced Study,
School of Mathematics
Princeton, New Jersey

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 Carlsson has even set to work to test it out by hand calculation in a simple case.

ENIAC in Action: MC Program / flowchart

Boxes	Function
1* - 8*	Read a card and store neutron characteristics
1* - 4*	Calculate random parameter λ^*
$\overline{1-7}$	Find neutron's velocity interval
18* - 23*	Calculate distance to zone boundary
$\overline{14-17.1}, 24^*$	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
$\overline{18-27}$	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



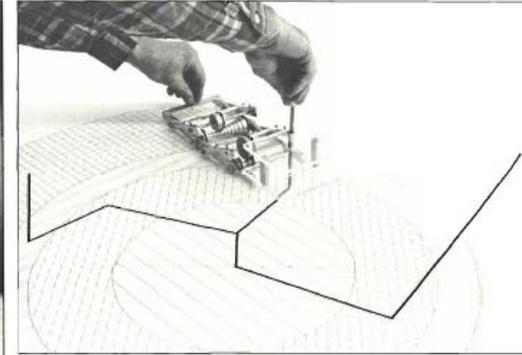
Thomas Haight, Mark Priestley, and Crispin Rope, "ENIAC in Action: Making and Remaking the Modern Computer," MIT Press 2016

Enrico Fermi: Independently developed Monte Carlo!

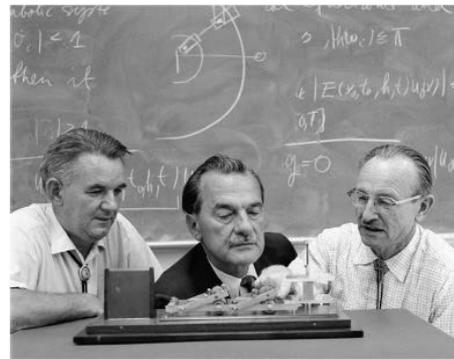
- **Emilio Segrè, Fermi's student and collaborator:**
 - *"Fermi had invented, but of course not named, the present Monte Carlo method when he was studying the moderation of neutrons in Rome. He did not publish anything on the subject, but he used the method to solve many problems with whatever calculating 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



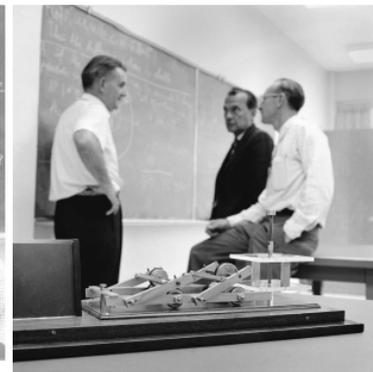
Enrico Fermi



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

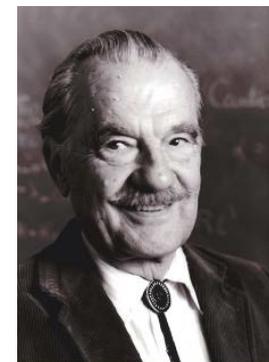
SEPTEMBER 1949

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)
- Universality 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!

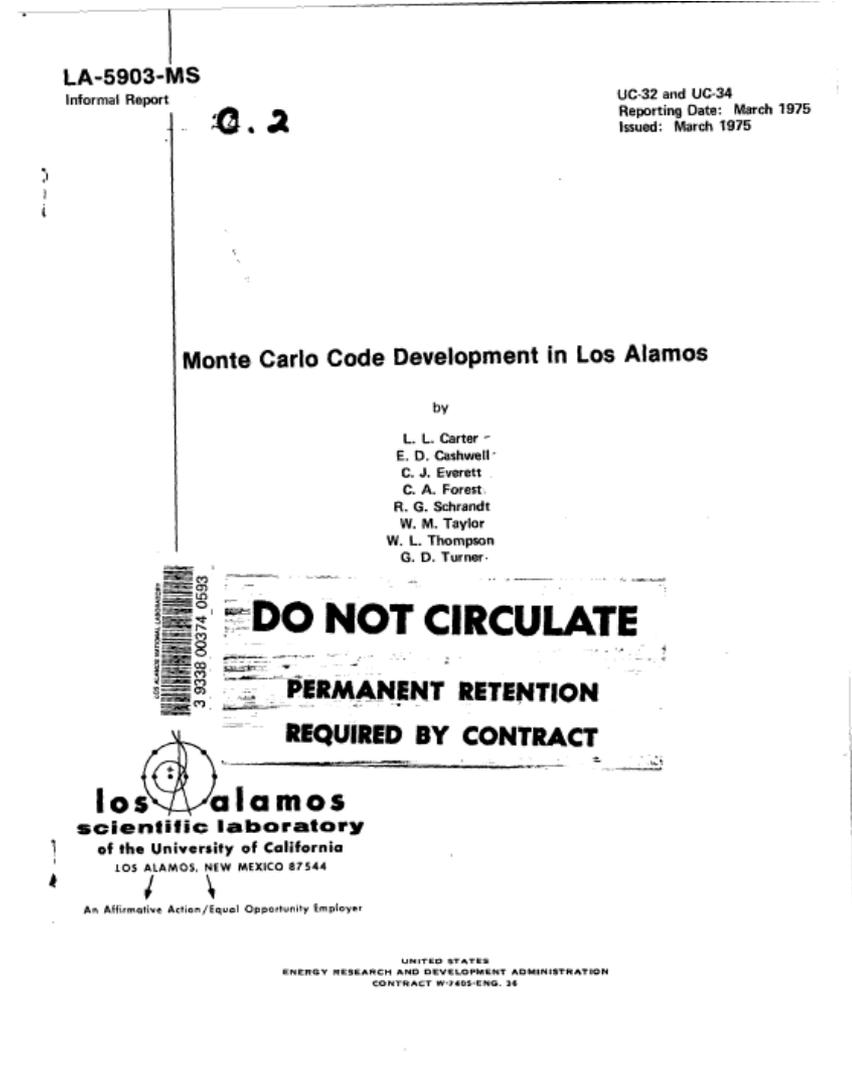
- **Herman Kahn, “Applications of Monte Carlo,” AECU-3259 (April 19, 1954).**
 - General and not specific to radiation particle transport
 - Direct sampling for common distributions
 - Rejection sampling – if direct sampling does not work
 - Use a simple, easy to sample distribution, to get an estimate 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 production
 - Particle direction after collision – direction cosines
 - Did not deal with thermal neutron collisions nor pseudo-random number generation

1960's: Initial work on Criticality and Reactor Calculations

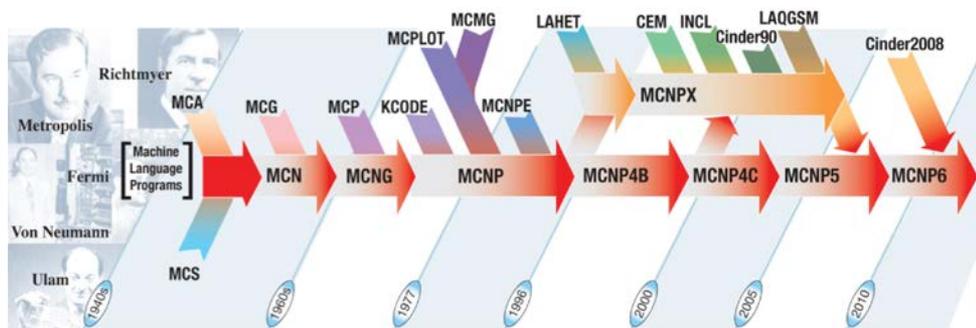
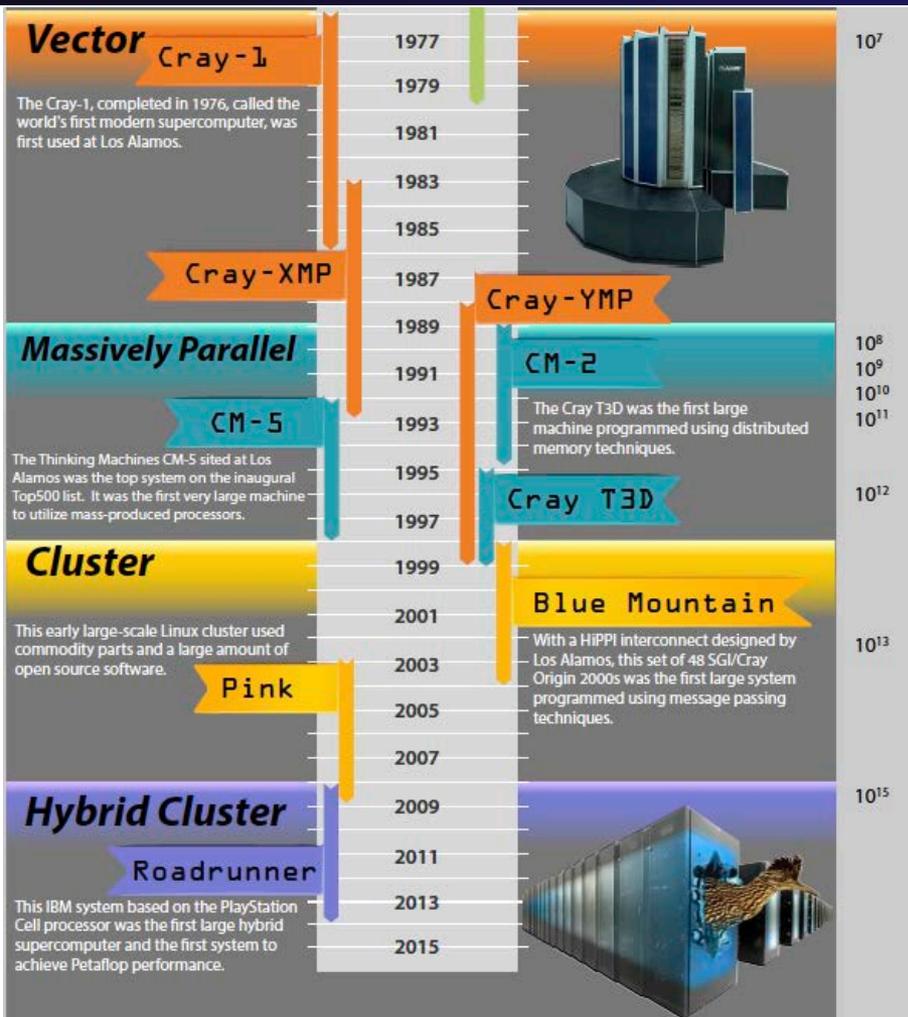
- **JJ.B. Parker, and E.R. Woodcock, “Monte Carlo Criticality Calculations,” Prog. In Nucl. Ener, 4 (1961).**
 - Introduced concept of neutron generations or batches of particles as histories
- **E.R. Woodcock, T. Murphy, P.J. Hemmings, and T.C. Longworth, “Techniques Used in the GEM Code for Monte Carlo 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).**

1970: MCNP first emerges

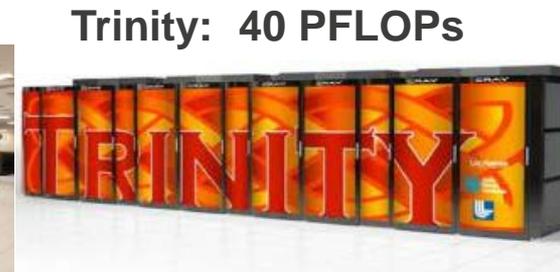
- **1974 – NEA Committee on Reactor Physics (NEACRP)**
 - E.D. Cashwell presented a paper on Monte Carlo development at Los Alamos
 - MCN – neutrons
 - MCNA – neutron adjoint
 - MCG – gamma rays
 - MCP – general photons
 - MCNG – coupled neutron-gamma ray
 - MCMG – multi-group coupled neutron-gamma ray
 - 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



Monte Carlo & MCNP History



70 years of Monte Carlo methods development



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.

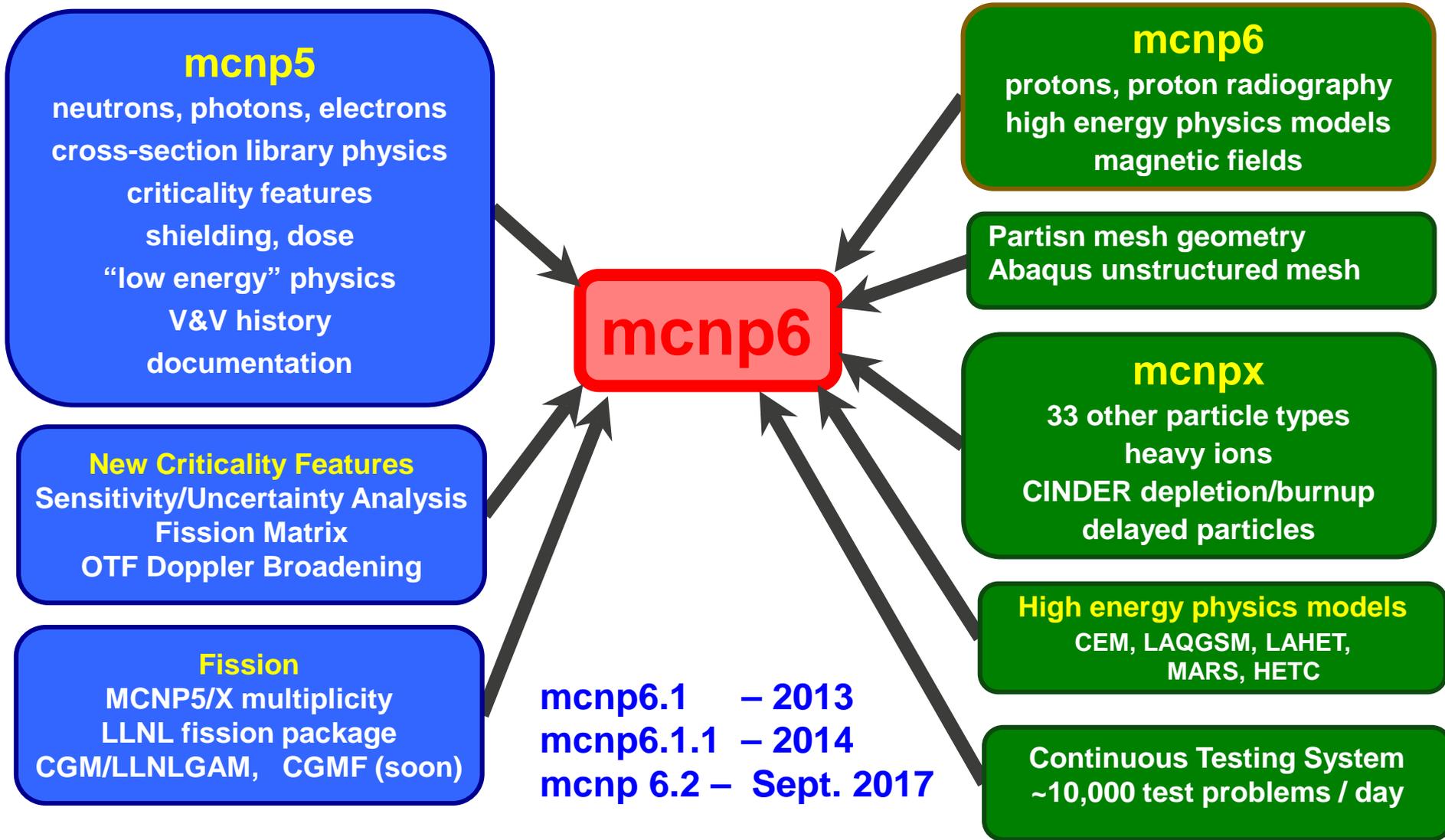
T. Goorley, et al. "Initial MCNP6 Release Overview," LA-UR-13-22934 (2013)

- **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



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:**

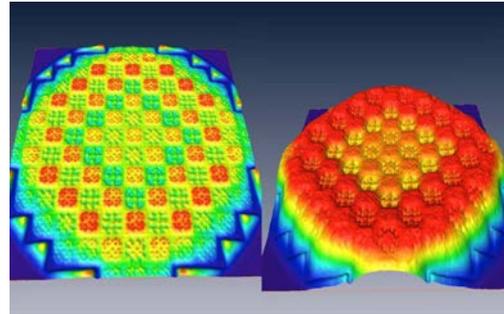
- Unstructured mesh transport
- Electric and magnetic field transport
- High-energy physics models
- 33 additional particle types
- Reactor fuel depletion and burnup
- Radiation source and detection capabilities
- Sensitivity and uncertainty analysis for nuclear criticality safety

- **Extensive Variance Reduction**

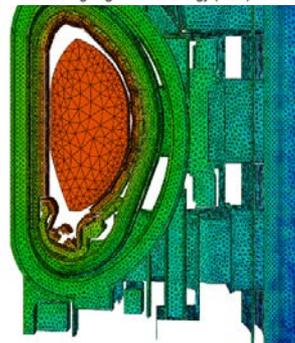
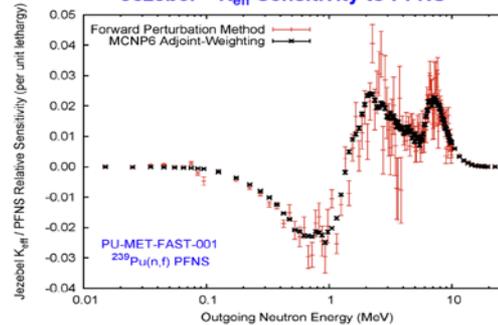
- Weight Windows
- DXTRAN

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Whole-core Thermal & Total Flux



Jezebel – K_{eff} Sensitivity to PFNS



ITER Neutron Flux Calculations

Experimental Benchmarks with Critical Assemblies

HEU-MET-THERM-003

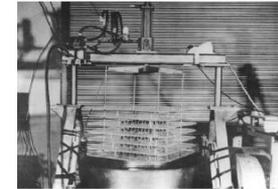
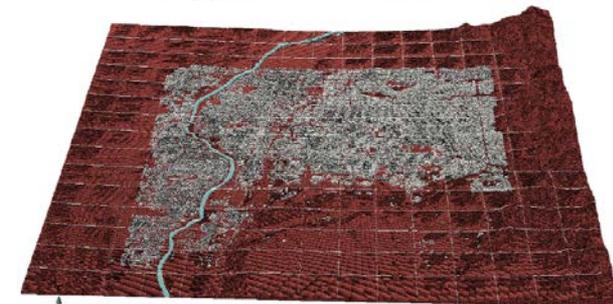
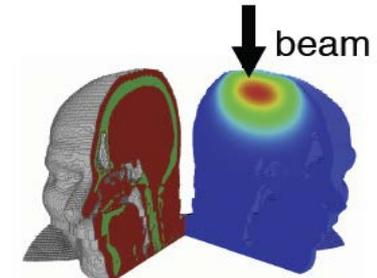
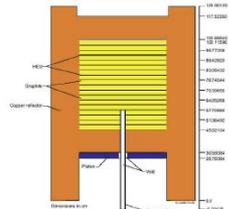


Figure 2. Array of 8 Six-Cable Piles to Immersion.

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)

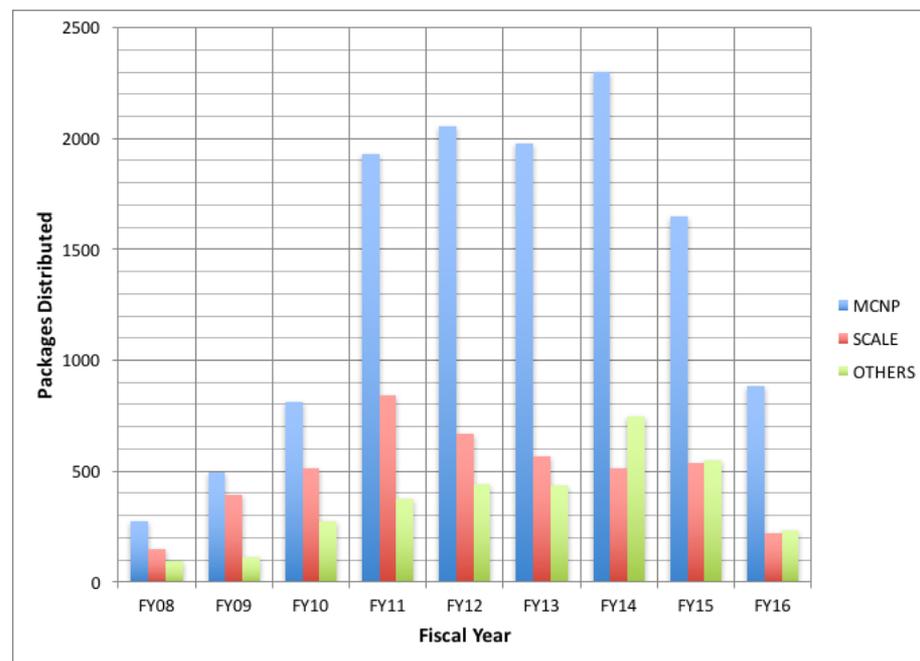
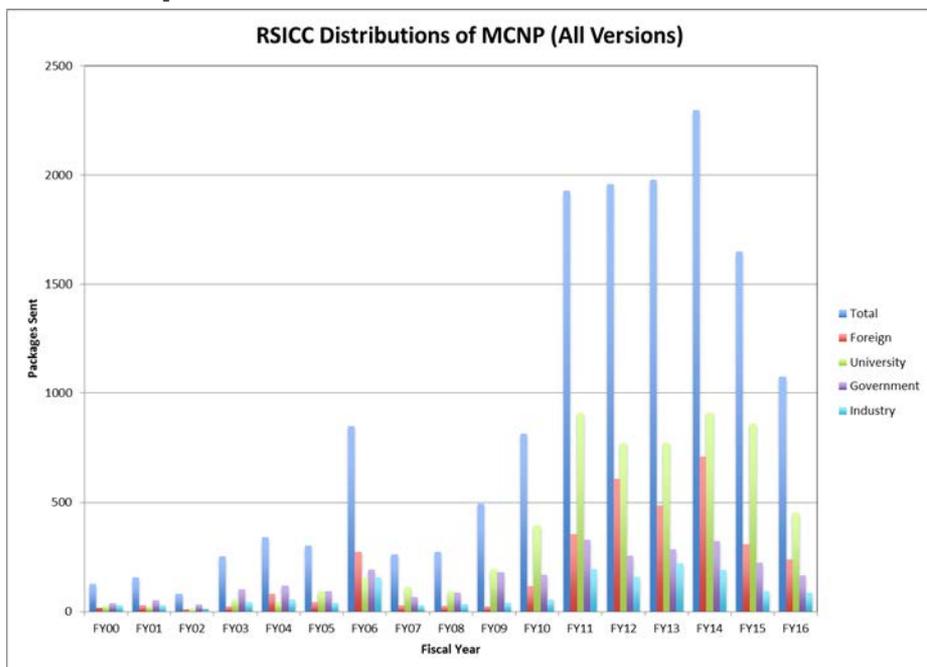
code	institution	
ARCHER	RPI	USA
COG11	LLNL	USA
DIANE	CEA	France
FLUKA	INFN & CERN	Italy & CERN
GEANT4	GEANT4	International
KENO and MONACO	ORNL	USA
MC21	Naval Nucl. Lab.	USA
MCATK	LANL	USA
MCCARD	Seoul Natl. Univ.	ROK
MCNP6	LANL	USA
MCU	Kurchatov Inst.	Russia

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 and Safeguards

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

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

f t e ...

1,799 74

Source: Orbital Mechanics

Thursday 13 August 2015 21:38 EDT



24-JUL-1957 03:03:29

02:07 / 13:42

</> Embed 🔊 + ↶ ↷

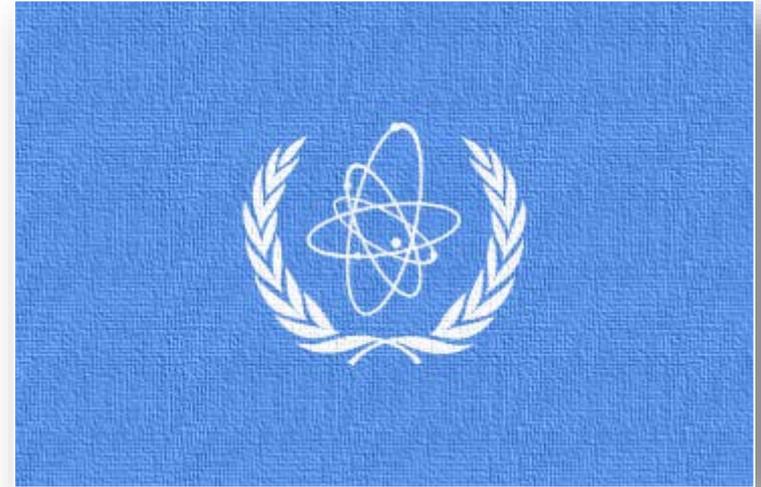
This eerie visualisation was created by [Orbital Mechanics](#), an audiovisual collective based in Montreal. It begins in 1945, before picking up speed with thousands of detonations over the following decades. Each one is colour-coded: red for atmospheric, yellow for underground, and blue for underwater.

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**

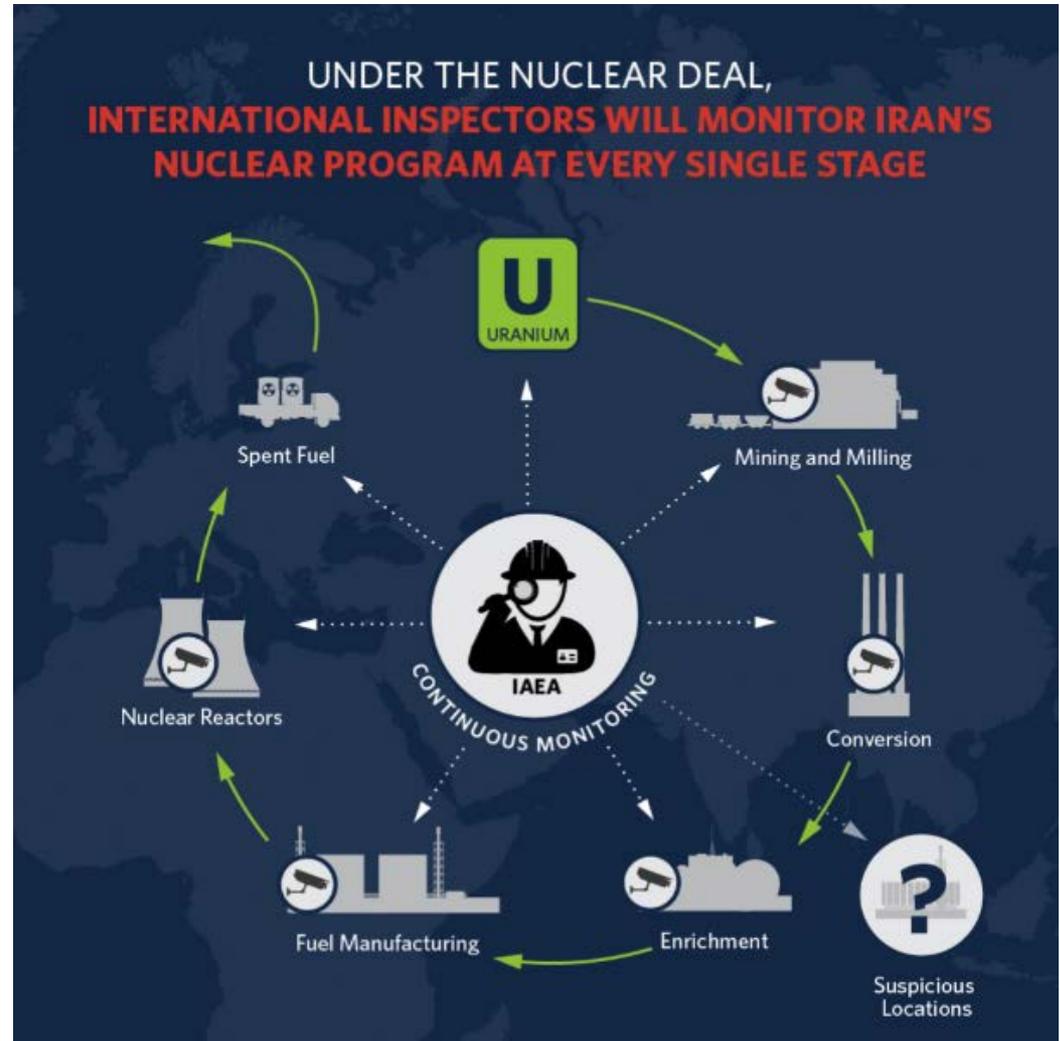
- Further sanctions and asset freeze, extended to 2016

- **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)

THE U.S. JUST SECURED A DEAL THAT ACHIEVES WHAT WE ASKED FOR:
PREVENTING IRAN FROM OBTAINING A NUCLEAR WEAPON

- ✓ Increase the time it would take Iran to acquire enough material for 1 bomb from 2-3 months to at least 1 year
- ✓ Reduce Iran's stockpiles of enriched uranium
- ✓ Reduce the number of Iran's installed centrifuges by two-thirds
- ✓ Prevent Iran from producing weapons-grade plutonium
- ✓ Track Iran's nuclear activities with robust transparency and inspections

WH.GOV/IRAN-DEAL

#IranDeal

- 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

Resolution endorsing the deal goes to U.N. Security Council for quick adoption.

Likely September

Congress's deadline to vote on the deal. President Obama has vowed to veto any rejection.

Likely late October

90 days after U.N. Security Council resolution, the agreement comes into effect.

December 15

Deadline for IAEA chief to report on Iran compliance with its efforts to investigate Tehran's past nuclear activities.

Likely early 2016

The IAEA reports Iran has carried out all first-stage actions. Europe and U.S. suspend most nuclear-related sanctions.

Five years after adoption

Arms ban expires.

Eight years after adoption

EU and U.S. will terminate sanctions—subject to congressional approval in U.S. The U.N.'s ballistic missile ban ends.

Ten years after adoption

Special U.N. channel for Iran to buy nuclear-related goods ends.

Fifteen years later

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

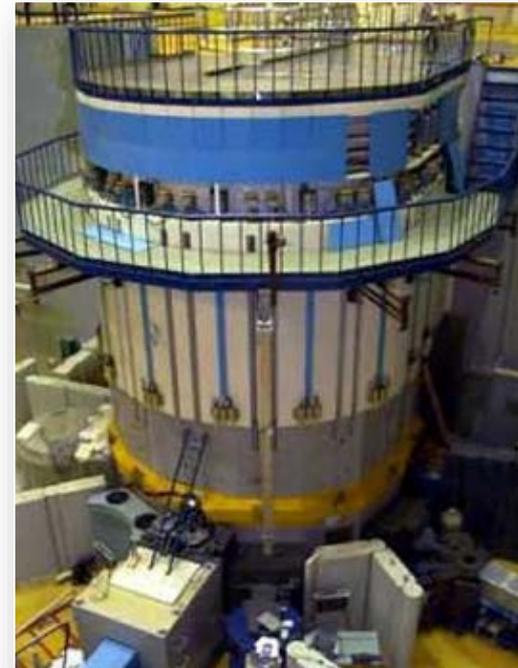


Source(s):

<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):

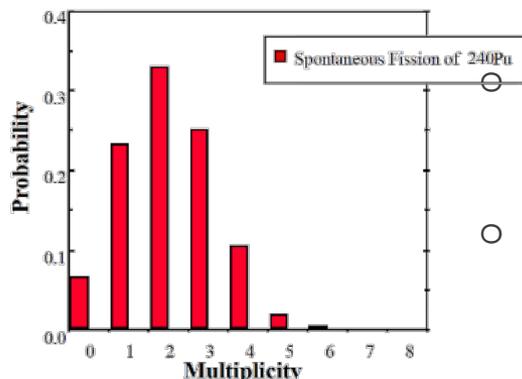
<http://fas.org/nuke/guide/libya/iaea0804.pdf>

<http://carnegieendowment.org/2009/08/28/libya-iaea-reports>

<http://www.nti.org/analysis/articles/was-libyan-wmd-disarmament-success/>

Verification Science and Technology: Safeguards

- **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)**



Coincidence counting

Most probable number of neutrons released by ^{240}Pu is 2

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



Finding Hidden SNM

- The primary distinguishing characteristic of SNM is fission.
- Fission releases several photons and neutrons simultaneously; this is called a signature.
- Observables detected by using multiple detectors synced in time.

Source(s):

<http://www.lanl.gov/orgs/n/n1/panda/00326406.pdf>

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
- **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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sooda@lanl.gov**