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Title: Nuclear Weapons Fundamentals

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July 20, 2011

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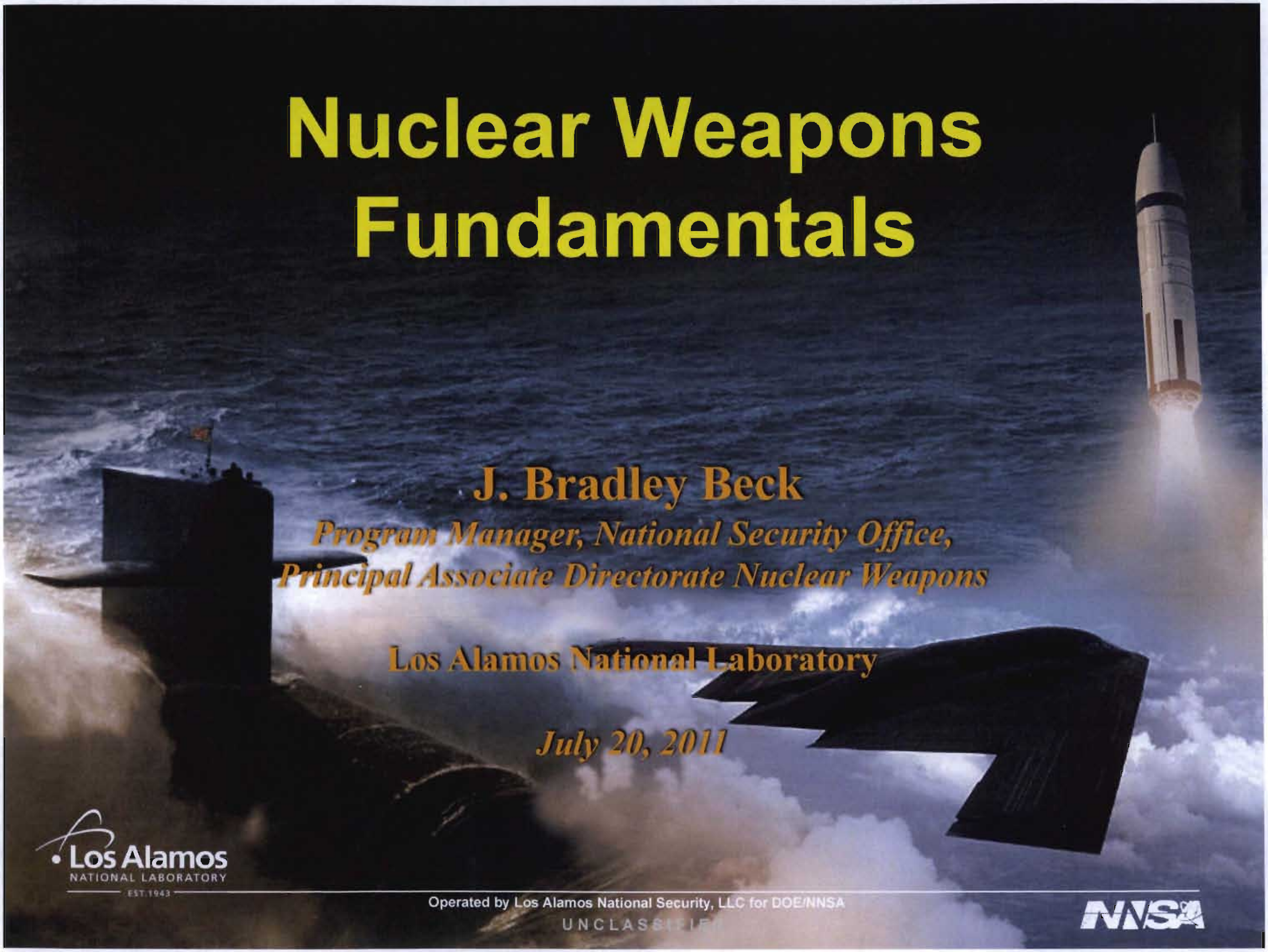
Nuclear Weapons Fundamentals
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Los Alamos National Laboratory
July 20, 2011
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Las Conchas Fire

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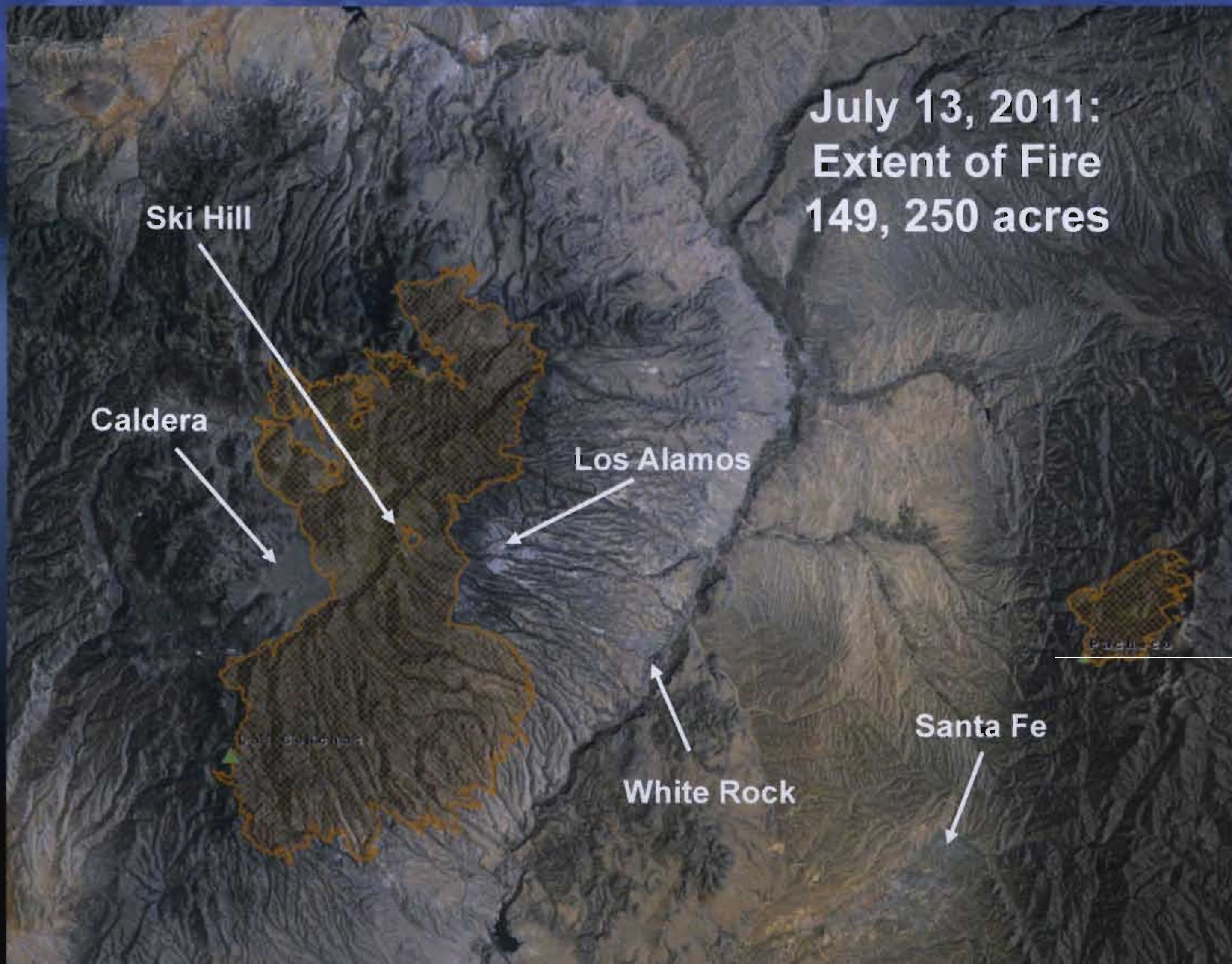

Las Conchas Fire

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Outline

1. Review of nuclear physics
2. Fission weapons
3. Advanced weapons
4. Stockpile Stewardship

[redacted]

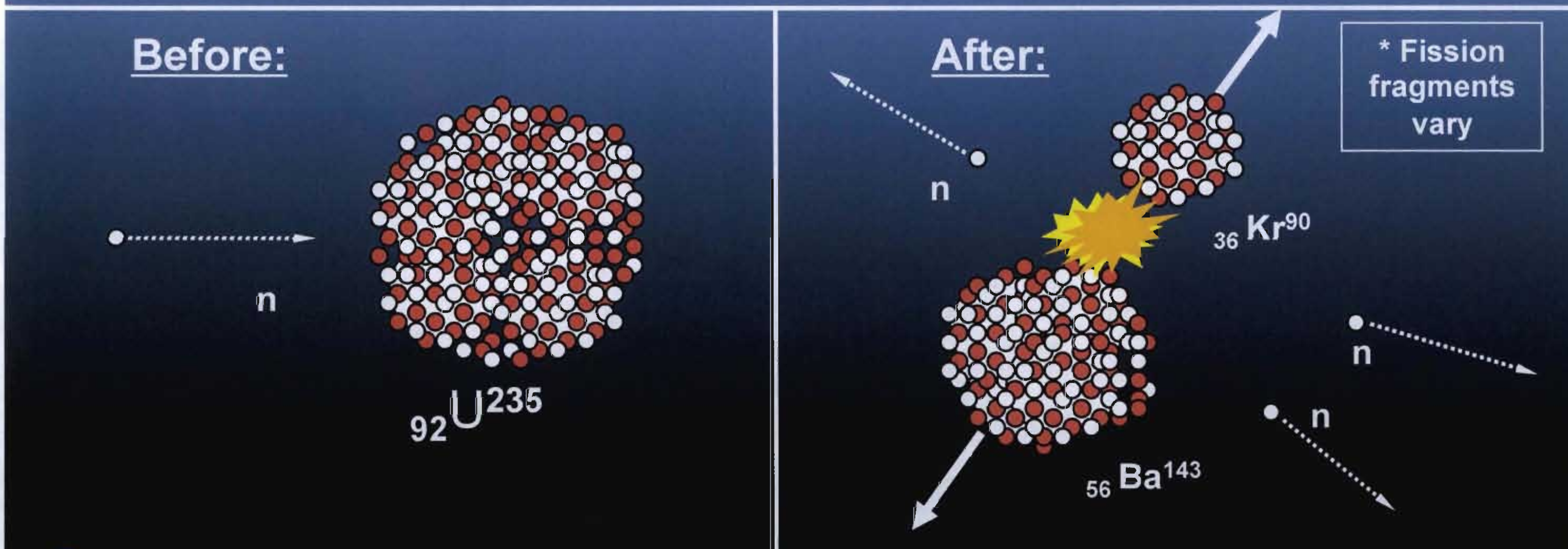
Review of Nuclear Physics

The feasibility of nuclear explosives rests on several properties of nature

- details of the fission process (chain reaction)
- shape of the nuclear binding energy curve (large energy release for fission and fusion)
- magnitudes of the nuclear cross sections

Fission (Neutron-induced)

- One of many possible reactions that can occur when a neutron interacts with a ^{235}U nucleus
- Large energy release per reaction
- Additional neutrons released (opens possibility of a fission chain reaction)

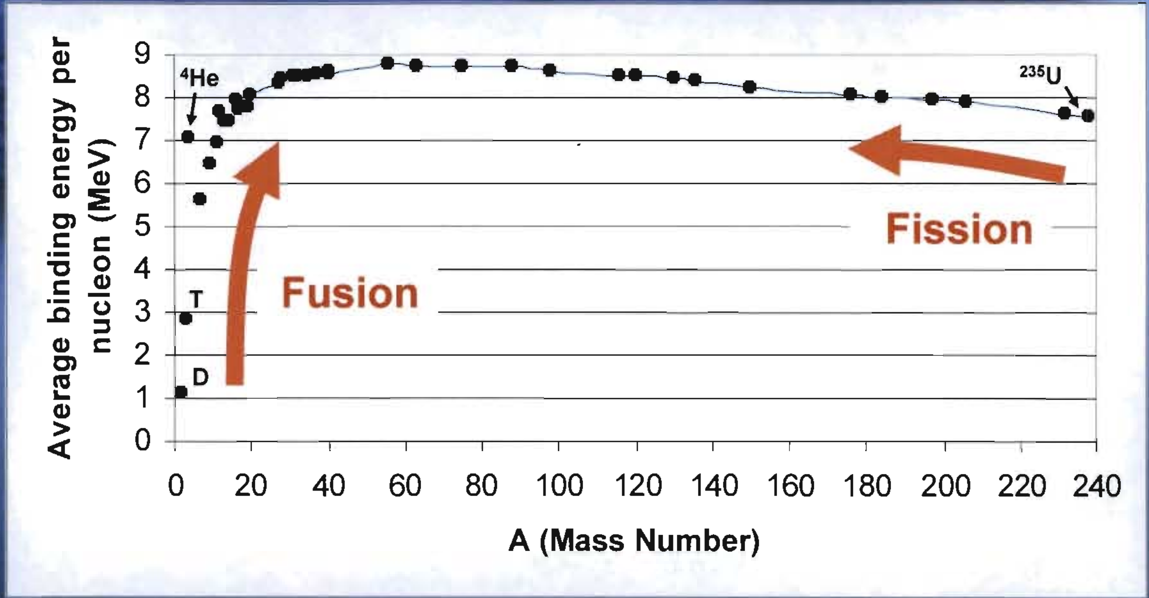


Binding Energy

<u>Fundamental Law:</u>
The rearrangement of a system to a more tightly bound state results in the release of energy

↓

Energy released is equal to the change in binding energy



<u>An example, fission energy release:</u>

$^{235}U + n \rightarrow {}^{236}U \rightarrow$ 2 Fission Fragments + 2n

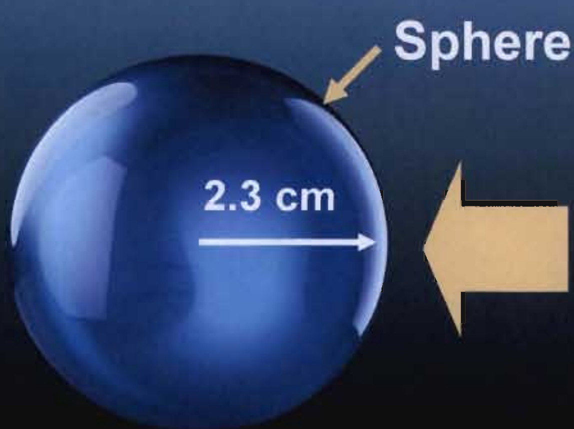
Mass (235U + n): 1996.0 MeV

Mass (after Fission): 1793.6 MeV

Change in B.E. = 202.4 MeV per fission

Comparative Energy Release

	Energy/Reaction	Energy density*
Combustion (Chemical)	4 eV	4.1×10^4 J/cm^3
Fission	200 MeV	1.5×10^{12} J/cm^3



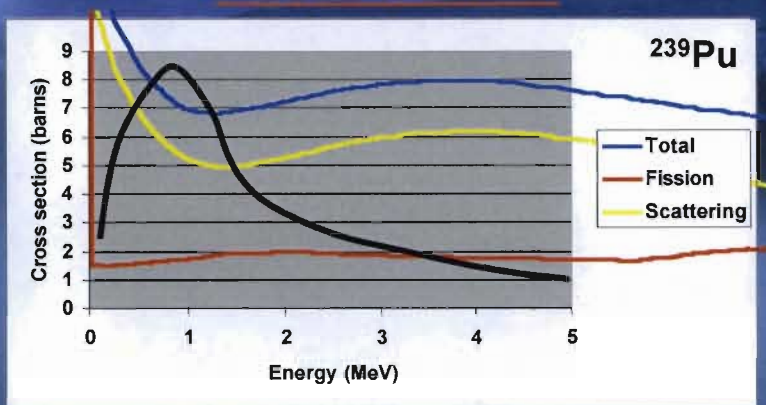
	Energy Available*	100 Watt (J/s) bulb would burn for:
72 g coal	2.2×10^6 J (~1 lb. TNT)	~6 hours
or		
1 kg U	80×10^{12} J (19 kt TNT)	~25,370 years

* Complete combustion or fission is assumed

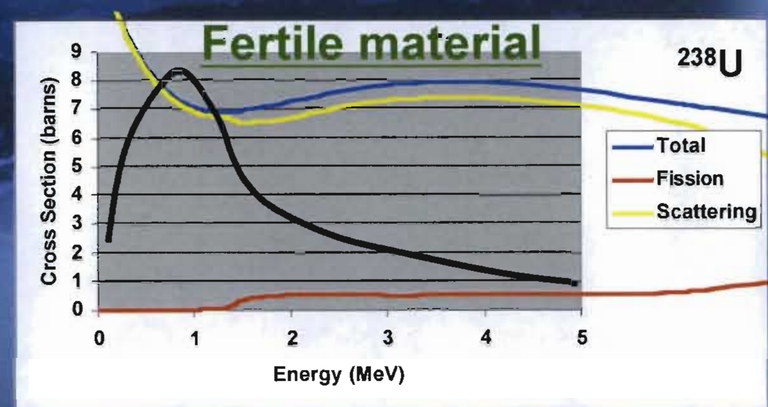
Neutron Cross Sections

(related to probability of reaction)

Fissile material

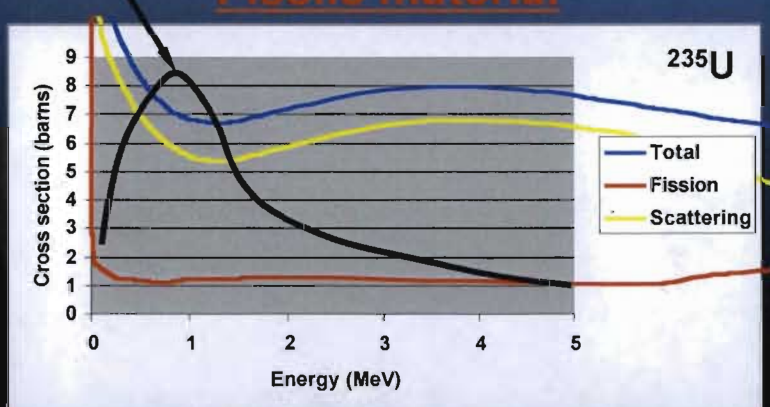


Fertile material

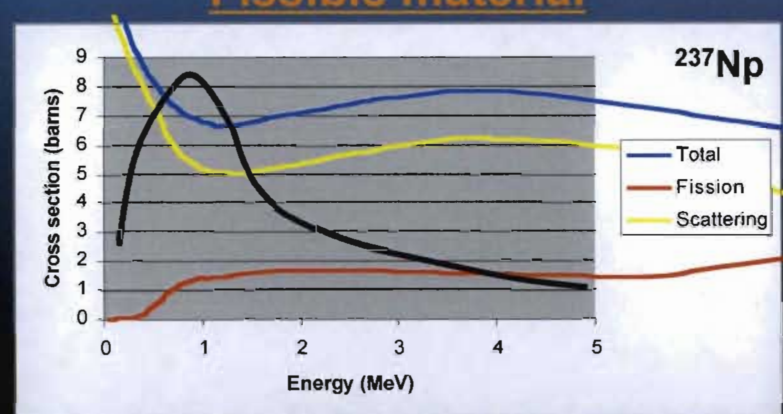


Fission neutron spectrum

Fissile material



Fissible material



1 barn = 10^{-24} cm^2

Fusion Reactions

- Can be thought of as the opposite of fission
- High temperatures ("thermonuclear") and densities needed for reaction to proceed
- Large energy release per reaction
- High-energy neutrons can be released

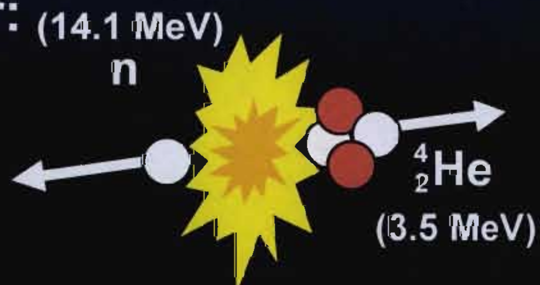
Example: $^{3}_{1}H + ^{2}_{1}H \longrightarrow ^{4}_{2}He + n$

$(T + D \longrightarrow ^{4}_{2}He + n)$

Before:

$^{3}_{1}H$ $^{2}_{1}H$

After:



17.6 MeV released

Other reactions of interest:

$D + D \longrightarrow ^{3}_{2}He + n + 3.2\ MeV$

$D + D \longrightarrow T + p + 4.0\ MeV$

$D + ^{3}_{2}He \longrightarrow p + ^{4}_{2}He + 18.3\ MeV$

$T + T \longrightarrow ^{4}_{2}He + 2n + 11.3\ MeV$

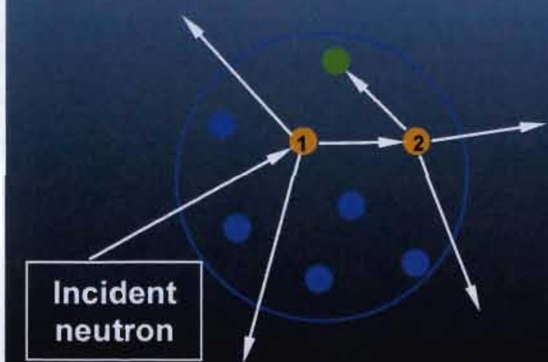
Criticality

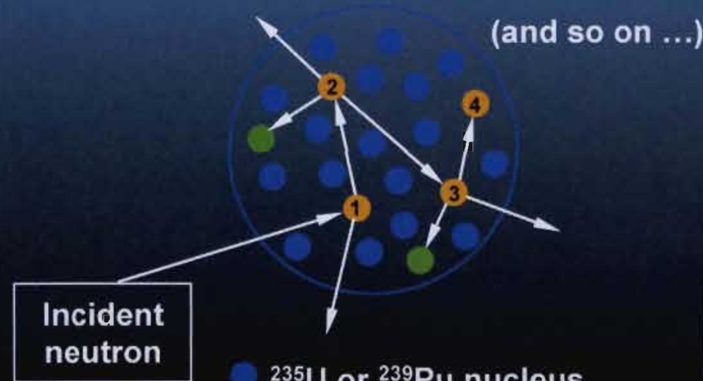
Criticality is a measure of how the number of neutrons (and energy release) in the system (e.g., reactor or nuclear weapon) will change over time

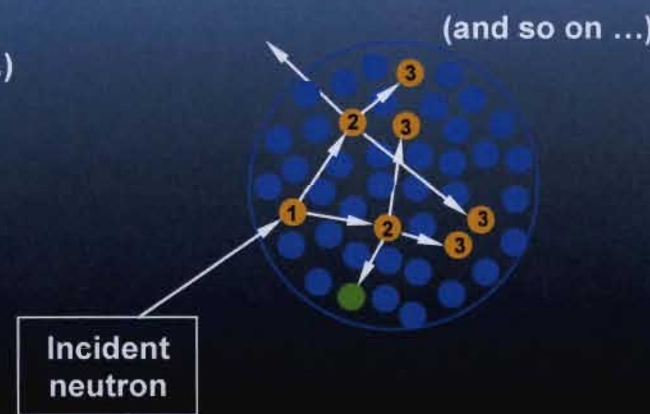
Subcritical system:
number of neutrons (and energy release) decrease with time

Critical system:
number of neutrons (and energy release) constant with time

Supercritical system:
number of neutrons (and energy release) increase with time







- ^{235}U or ^{239}Pu nucleus
- fission
- neutron capture

Factors Affecting Critical Mass

Critical mass – amount of material needed to just sustain a fission chain reaction (and constant neutron population)

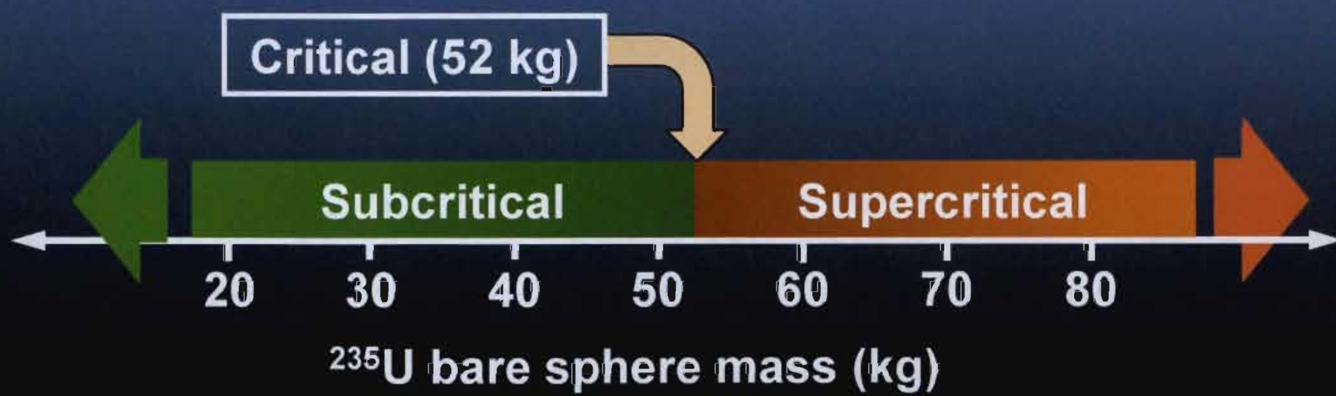
Material - ^{239}Pu has a smaller critical mass compared with ^{235}U

Bare sphere critical mass

* Colors not indicative of true material

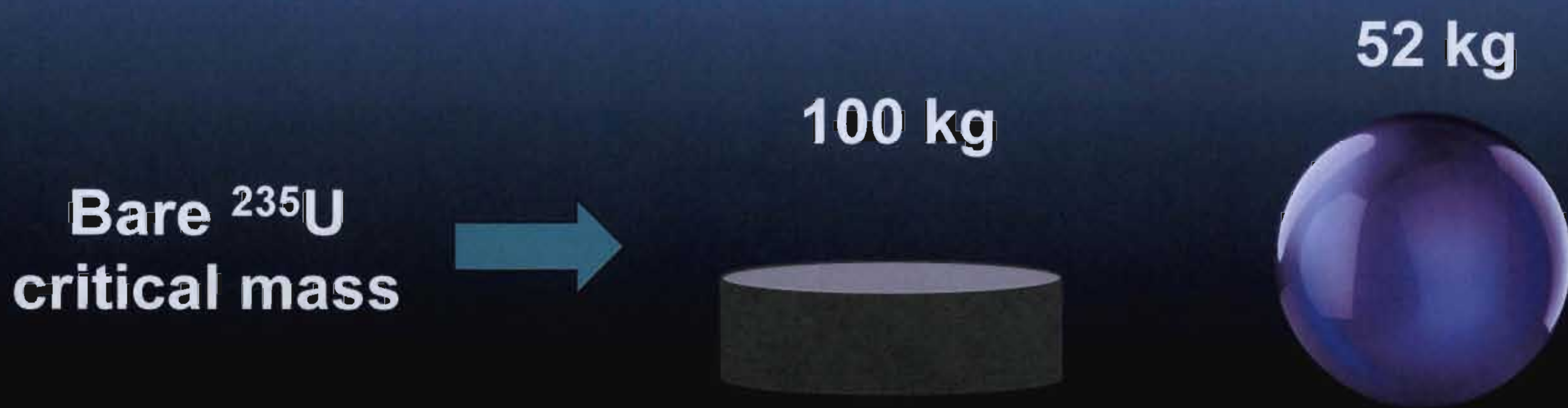
Factors Affecting Critical Mass (Cont.)

Mass – for a given shape and density, a larger mass of material has a higher criticality



Factors Affecting Critical Mass (Cont.)

Shape – for a given volume, shapes with smaller surface area have a smaller critical mass; sphere is optimal



Factors Affecting Critical Mass (Cont.)

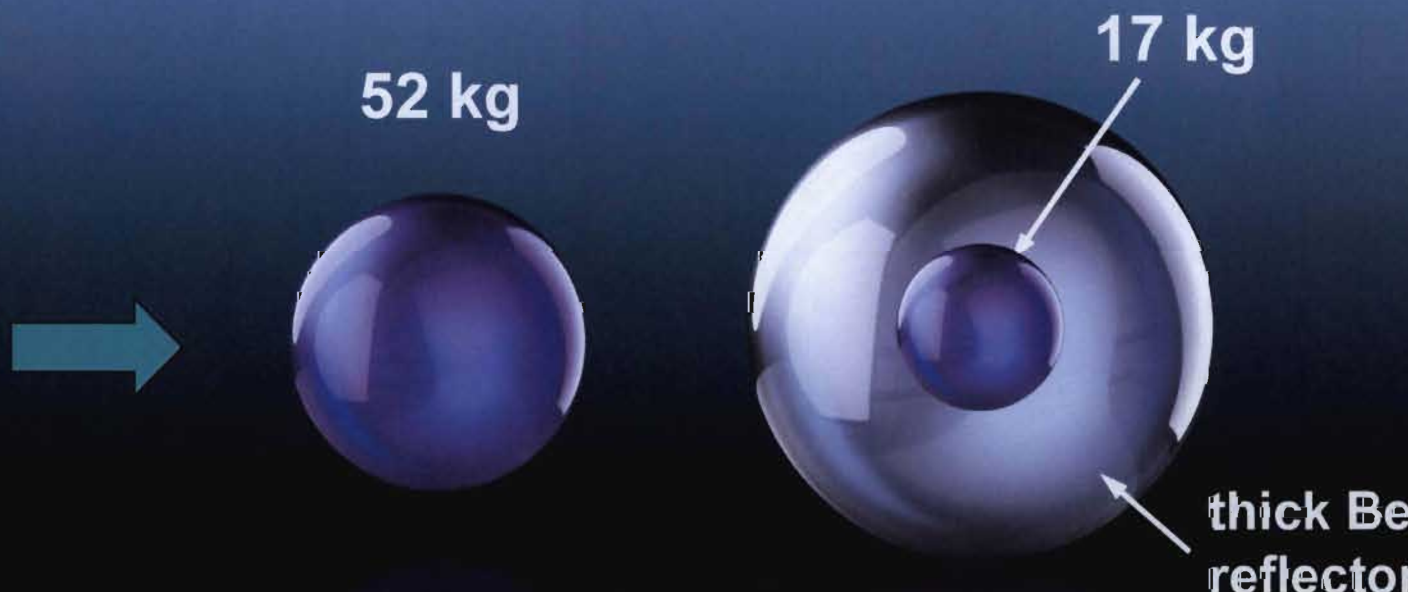
<u>Compression</u> – increases in material density result in smaller critical mass

	18.8 g/cm^3	37.6 g/cm^3
	52 kg	13 kg
Bare sphere ^{235}U critical mass →		

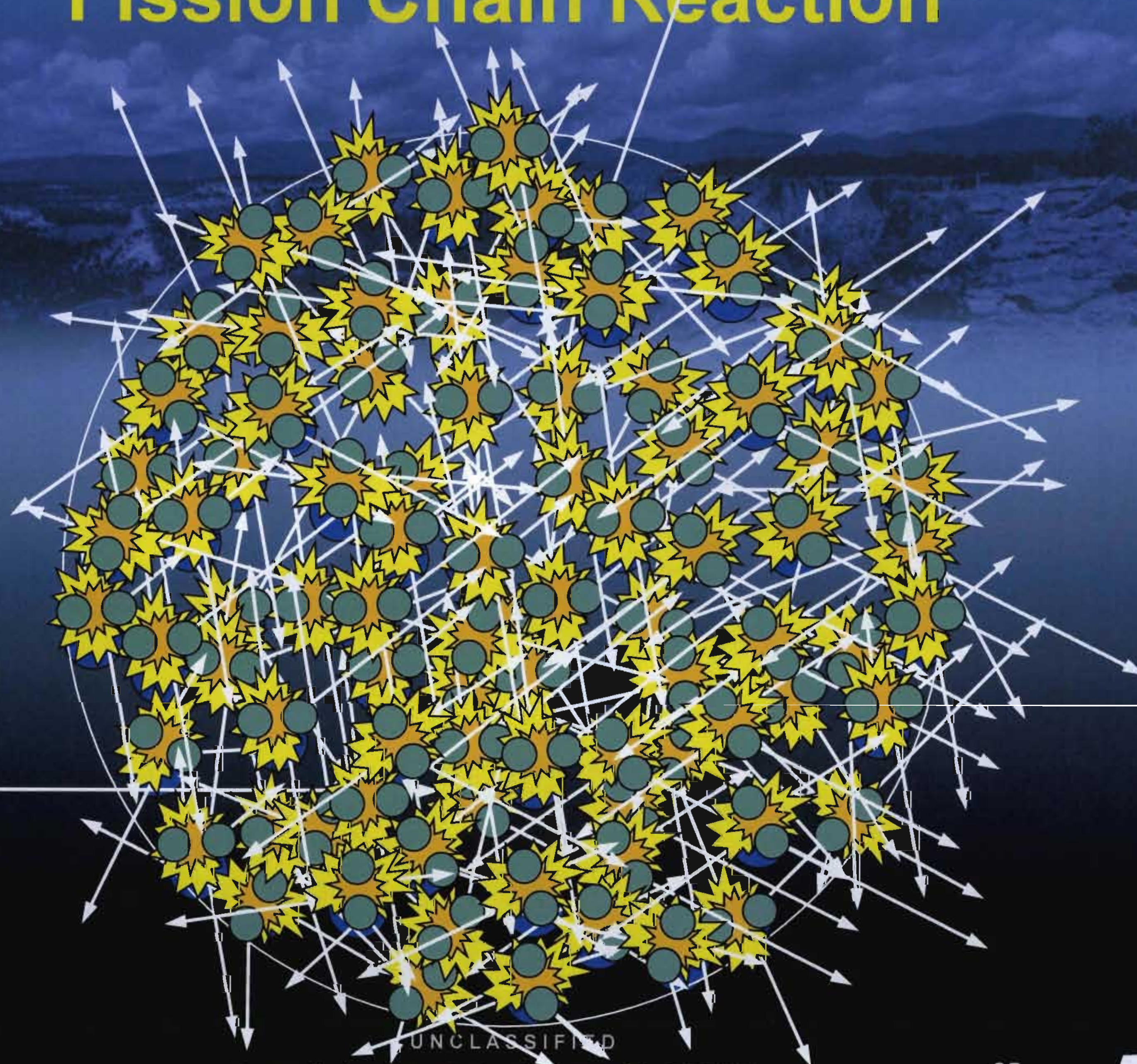
Factors Affecting Critical Mass (Cont.)

Surroundings – surrounding a system by a strong neutron reflector results in a reduced critical mass

^{235}U critical mass



Fission Chain Reaction



Explosive Fissionable Material

- Any material that can be assembled into a supercritical mass, supporting a fast neutron chain reaction
  - » Weapon-grade materials
    - highly enriched uranium, >93% ^{235}U
    - weapons-grade Pu, ^{239}Pu with 6% ^{240}Pu
  - » Alternatives
    - ^{233}U
    - reactor-grade Pu
    - uranium with < 93% ^{235}U
    - fissible isotope ^{237}Np (neptunium)

Plutonium

- Essential material to make a nuclear weapon
  - » 25 kg ^{235}U or 4 kg Pu can be enough

Outline

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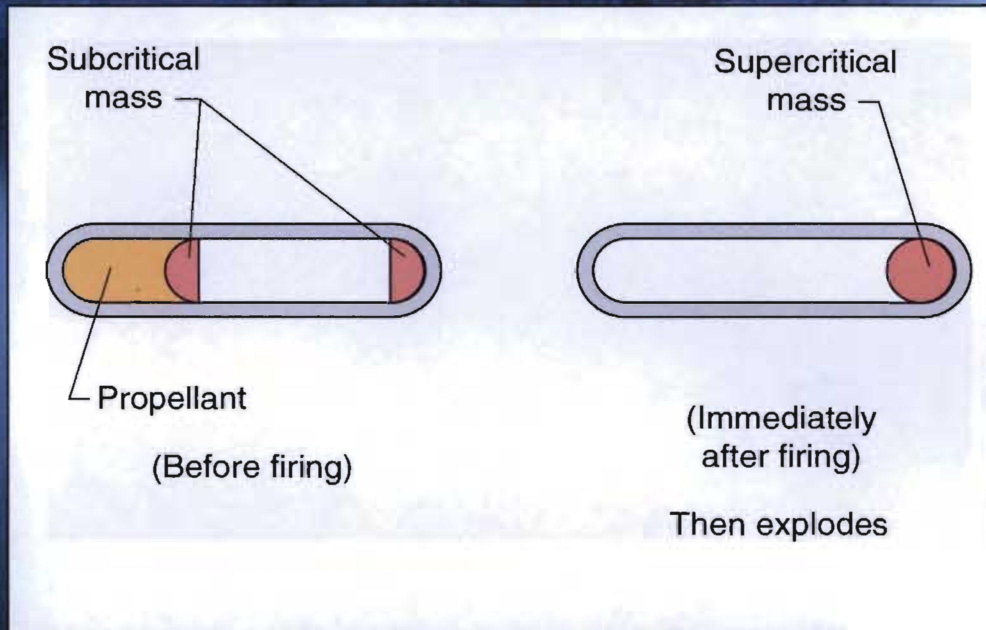
Fission Weapons

- A system for rapidly transforming a mass of 'explosive fissionable material' from a subcritical configuration to a highly supercritical configuration
- Initiation of a runaway neutron chain reaction while in supercritical configuration
- Maintain supercritical configuration long enough to allow large fission energy release

Gun Assembly

- Simple design
- Assemble subcritical masses together into a supercritical mass using propellant
- Inefficient use of material
- Slow assembly time necessitates use of a material with a very low neutron background (e.g., ^{235}U) to avoid pre-initiation; plutonium is precluded



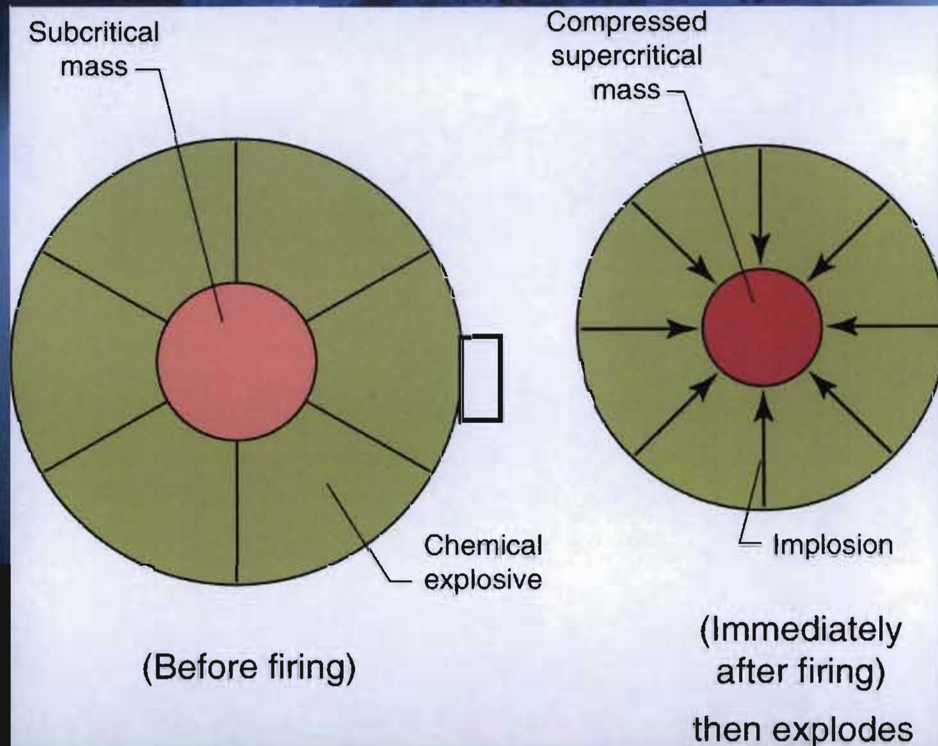
Compare:
HEU : ~1 neutron/kg/second
WGPu : ~60,000 neutrons/kg/second

Little Boy

Untested prior to being dropped over Hiroshima on August 6, 1945 (15 kt)

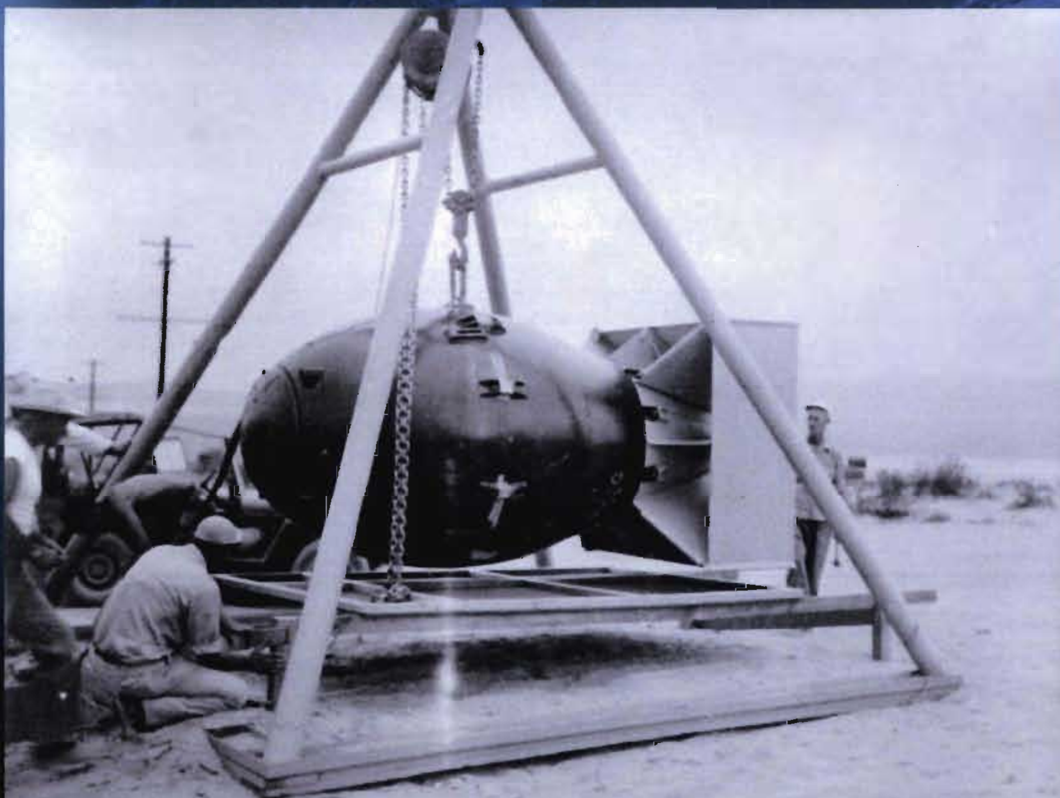
Implosion Assembly

- Complex design – involves precision application of high explosive (HE)
- Symmetrical explosion of the HE implodes pit, compressing fissile material into a supercritical configuration
- More efficient use of material than gun-assembled weapon
- Fast assembly speed allows use of plutonium



Fat Man

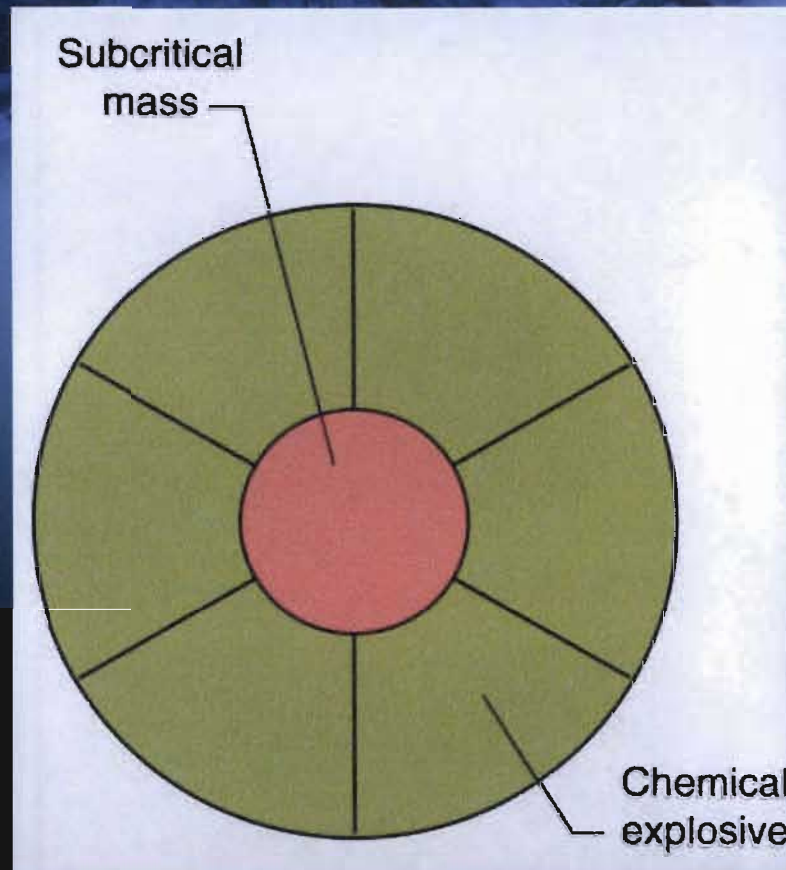
Tested in Trinity shot 7/16/45 at Alamogordo; dropped over Nagasaki on 8/9/45 (21 kt)



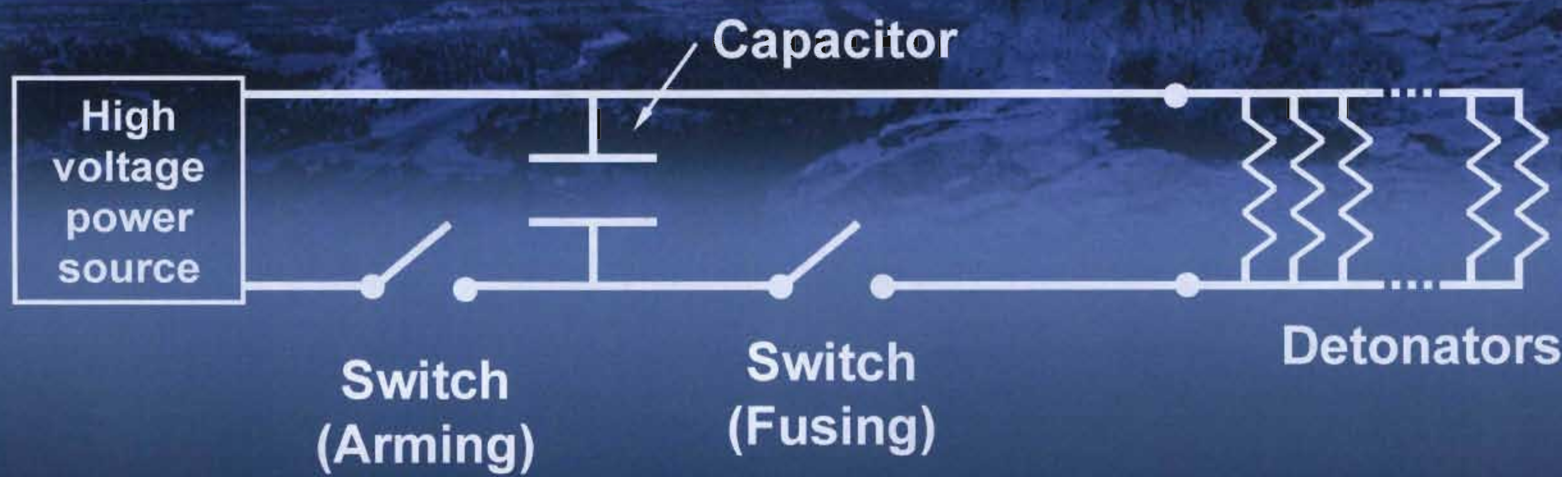
Ivy/King – tested on 11/15/52 at Enewetak; largest US fission only device (500 kt)

Implosion Assembly – before firing

- Must symmetrically initiate outer surface of high explosive charge
  - » Firing system
  - » High explosive lenses



Simplified Firing System



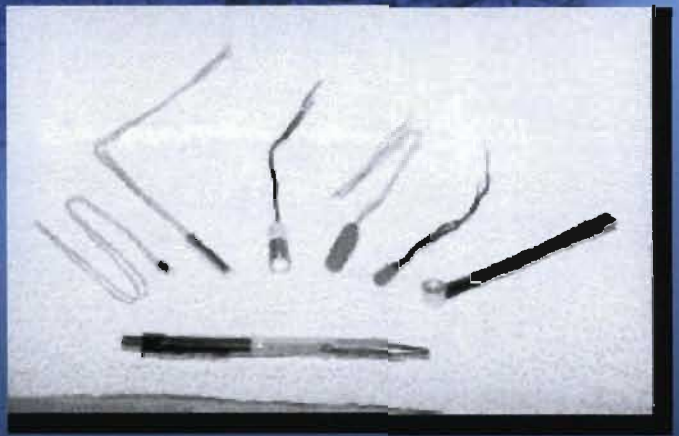
- Arming signal closes switch resulting in slow charging of capacitor
- Fusing signal closes "fast" switch, rapidly delivering stored capacitor energy to detonators

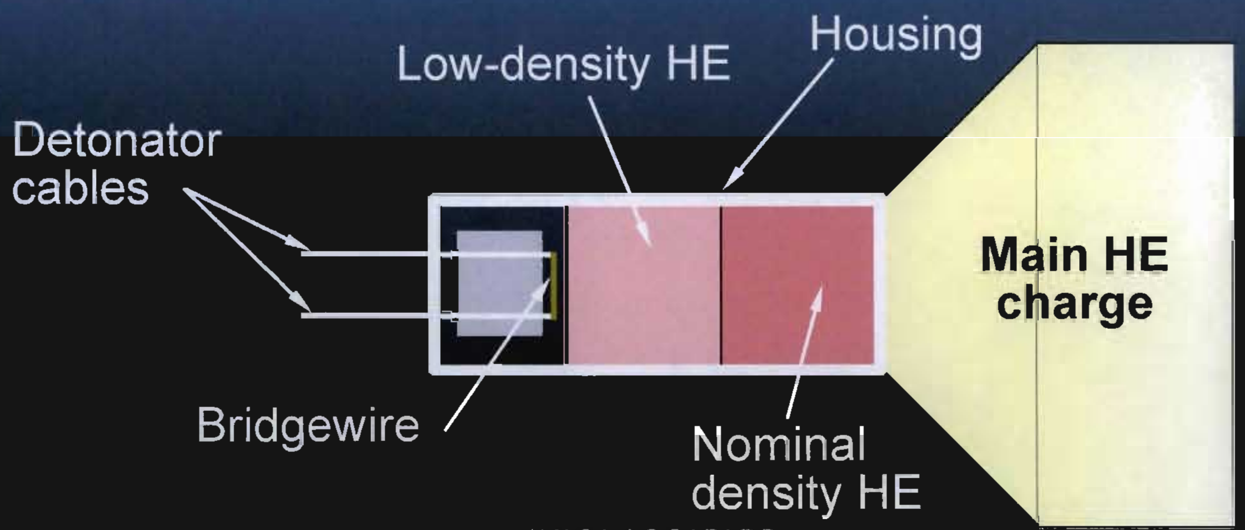
Detonators

- Used to initiate larger high explosive charges
- Convert electrical power into high explosive detonation
- Repeatability must be within small fraction of a second

Exploding Bridgewire (EBW) Detonators

- Large pulse of electric current vaporizes thin bridgewire, producing shock wave
- Shock wave initiates adjacent low-density HE pellet
- Detonation propagates thru HE pellets, strengthening in nominal density HE
- Initiation of main HE charge follows





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High Explosives (HE)

- **Castable**
  - TNT (trinitrotoluene)
  - Composition B-3 (60% RDX, 40% TNT)
- **Plastic-bonded**
  - mostly HMX or RDX based
  - hydrostatic or isostatic press
- **Final machining required for both types**

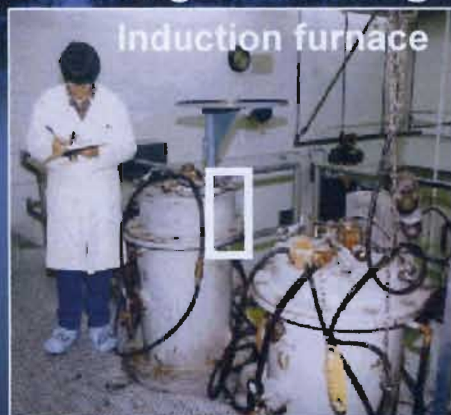
HE melting kettle

Hydrostatic press

Pit Fabrication

Explosive Fissionable Material

Melting & Casting



Billet

Rolled & Hydroformed

Cast Part

Note:
Plutonium operations performed in glovebox

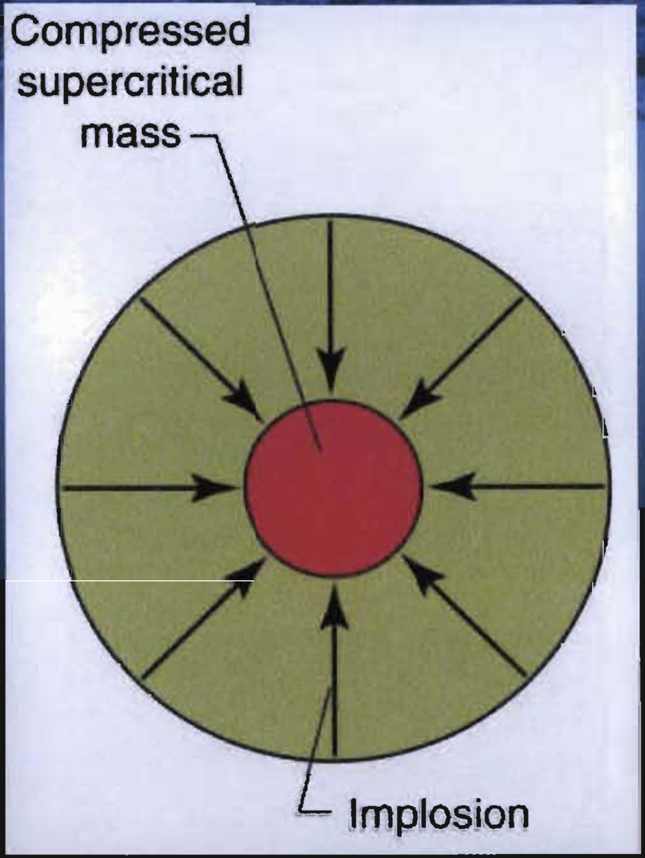
Finish machining

Inspection

Final Part

Implosion Assembly – after firing

- Following implosion, pit will reach a point of maximum supercriticality
- At this time, neutrons must be introduced into pit to begin fission chain reaction (this is called neutron initiation)
  - » Internal initiators
  - » External initiators



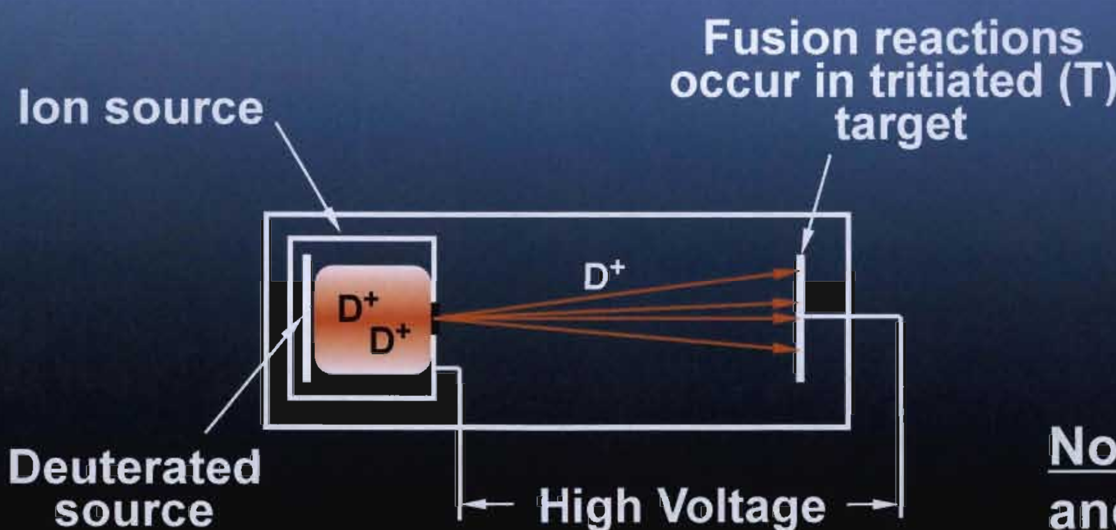
Internal Neutron Initiators

<u>(α,n) Initiator</u> – based on the reaction in which α particles from a radioactive isotope (e.g., polonium-210) interact with a light element (e.g., beryllium), thereby releasing neutrons

$$^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + \alpha({}^{4}_{2}\mathrm{He}) \rightarrow \alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + \boxed{n}$$

External Neutron Initiators

Neutron generator tube - based on fusion of deuterium and tritium produced in a small accelerator



Note: tritium is radioactive and must be replenished

Outline

1. Review of nuclear physics
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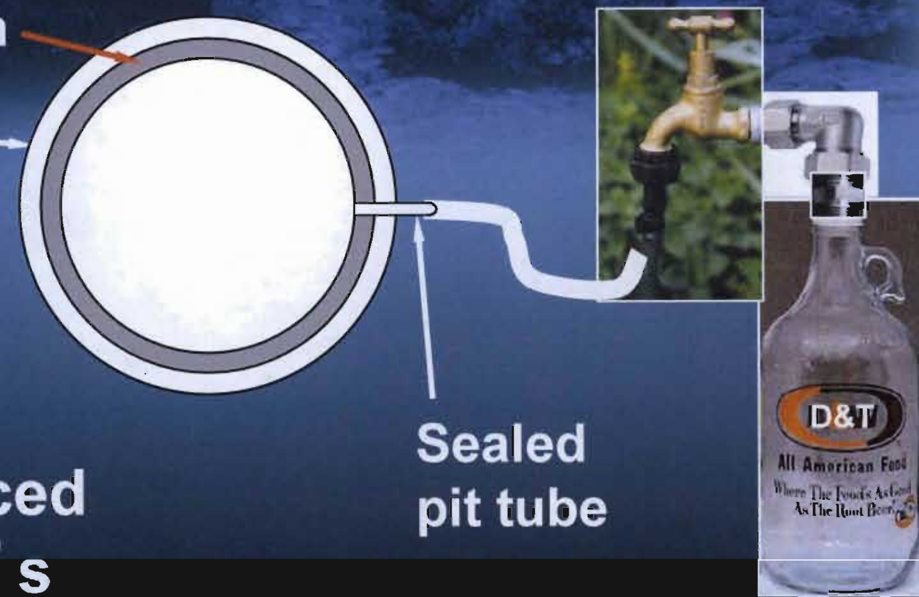
[redacted]

Boosted Fission Weapons

- Fusion produces energetic neutrons which cause further fission. This is called *boosting*.
- Boosting is used in primaries of thermonuclear weapons and can also be used in fission only weapons.

Boosted Fission Weapons (Cont.)



1. Mixture of deuterium and tritium (boost gas) is introduced from a reservoir to pit' s central cavity
2. During implosion, boost gas is compressed along with the fissile material

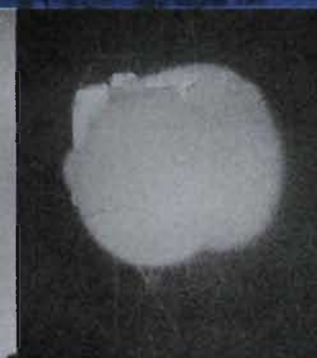
Boosted Fission Weapons (Cont.)

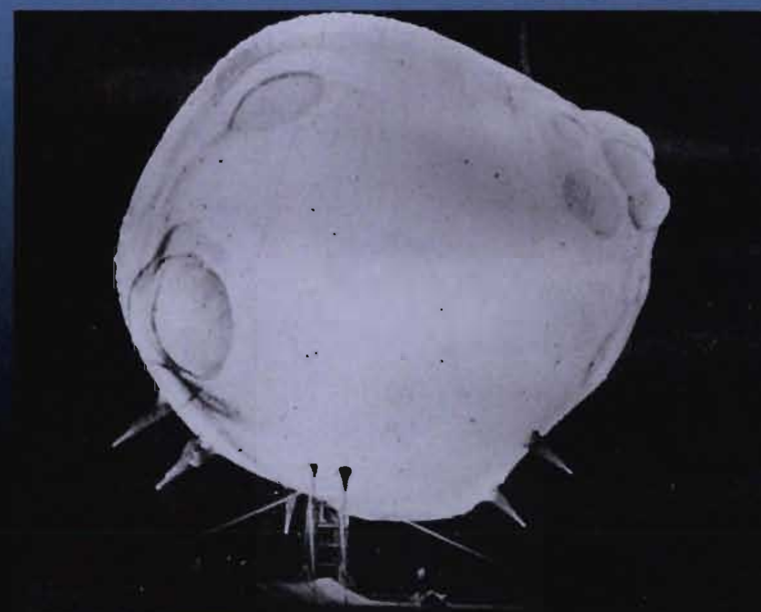
3. Driven by energy from fission, D-T fusion occurs, flooding compressed pit with high energy neutrons

4. These neutrons produce additional fissions, driving nuclear yield to much higher values

Note: Bulk of the yield is from fission; thermonuclear fusion yield is a few percent of the total

Greenhouse/Item – tested on 5/24/51 at Enewetak
First US boosted device (45.5 kt)





Additional Nuclear Physics

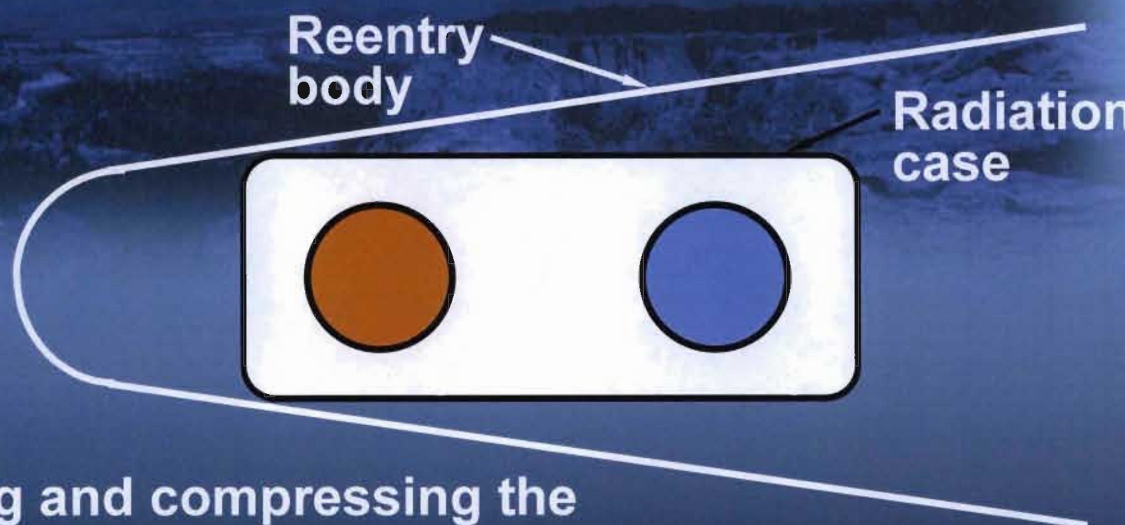
- Isotopes of lithium absorb neutrons resulting in the production of tritium

$${}^{6}_{3}Li + n \longrightarrow T + {}^{4}_{2}He + 4.8\ MeV$$

$${}^{7}_{3}Li + n \longrightarrow T + {}^{4}_{2}He + n - 2.5\ MeV$$

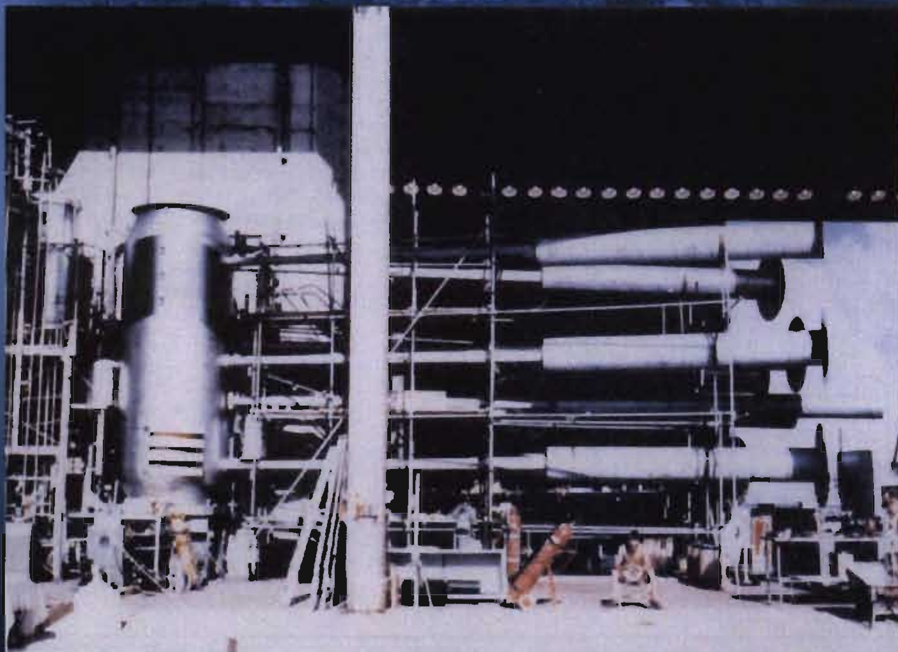
- Tritium can undergo subsequent fusion with deuterium
- Unlike tritium, lithium is a stable compound

Thermonuclear Weapons



- Radiation energy produced by primary stage is contained by radiation case
- X-ray energy flows toward and around the secondary stage heating and compressing the thermonuclear fuel (e.g., lithium deuteride)
- While thermonuclear fuel is undergoing heating and compression, neutrons are interacting with lithium, creating tritium
- Tritium and deuterium subsequently undergo fusion producing high-energy neutrons, producing additional fissions and tritium

Ivy/Mike – tested on 10/31/52 at Enewetak/Elugelab; 10.4 Mt



- "Experimental" thermonuclear device
- TN fuel was liquid deuterium
- Complex and bulky cryogenic equipment

Castle/Bravo - tested on 2/28/54 at Bikini; Largest US detonation at 15 Mt

- Used lithium deuteride as a thermonuclear fuel

"Why buy a cow when powdered milk is so cheap?"

Harold Agnew,
South Pacific
(~1952-1954)

Largest Weapon Detonation

- Soviet test at Novaja Zemlya on 30 October 1961
- Fired at: ~58 Mt
- Design yield: 100 Mt

Dr. Edward Teller (5' 8")
at Snezhinsk (C-70)

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Stewardship of the stockpile includes many activities

- Annual Assessment
- Developing baseline models
- Support of surveillance program
  - Random selection from stockpile
  - Unit Disassemblies
  - Non-destructive testing such as radiographic imaging
  - Component testing of non-nuclear components
- Resolution of significant findings
- Surety studies
- Emergency Response
- Archiving
- Diagnostic reassessment
- Test readiness
- Training / mentoring

LANL's science and engineering infrastructure a critical component of U.S. nuclear deterrent

Metropolis Center for Modeling & Simulation

High Explosive laboratories

Los Alamos Neutron Science Center

Plutonium Processing Facility

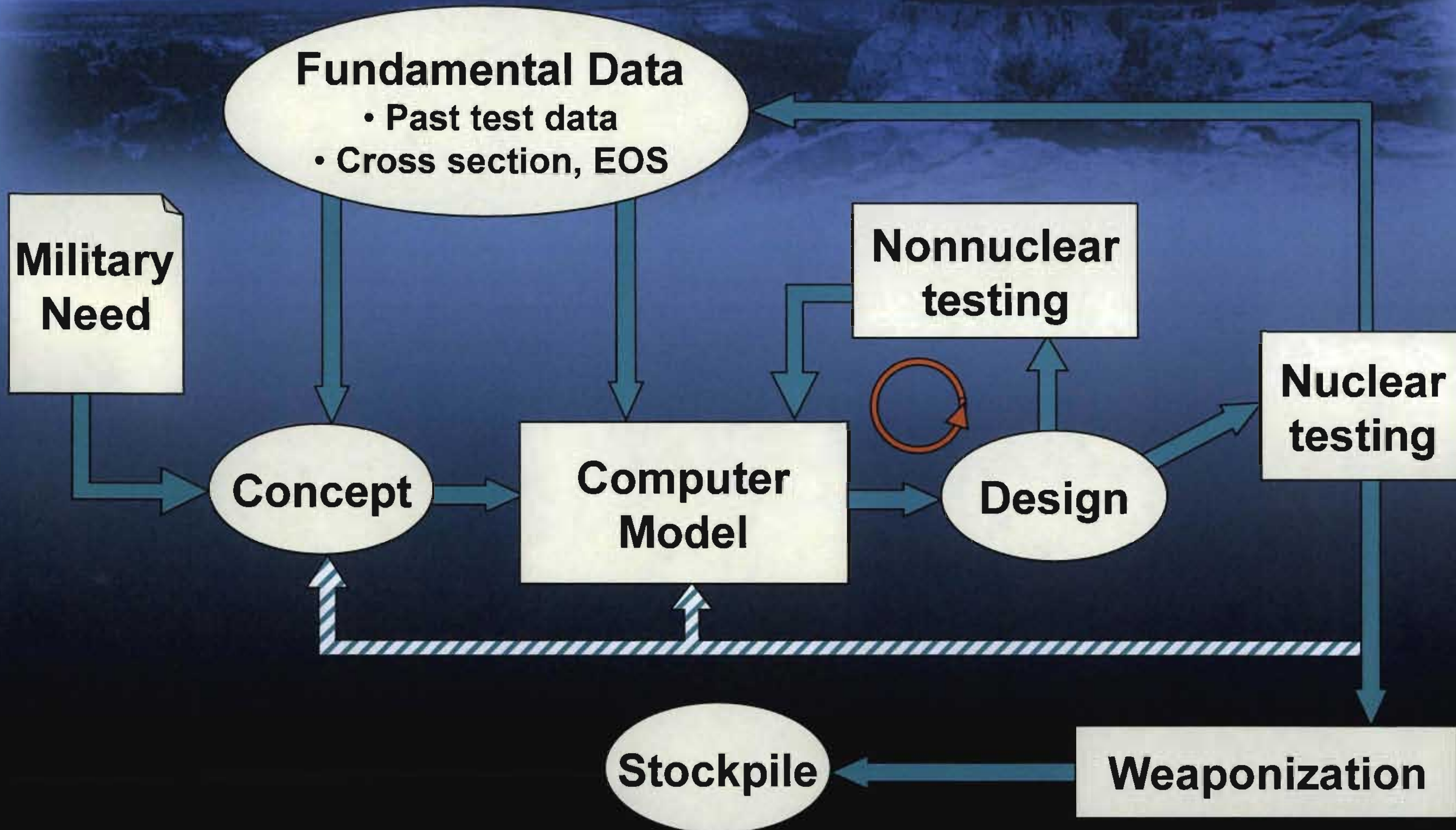
Chemistry and Metallurgy Building

Dual Axis Radiographic Hydrotest Facility

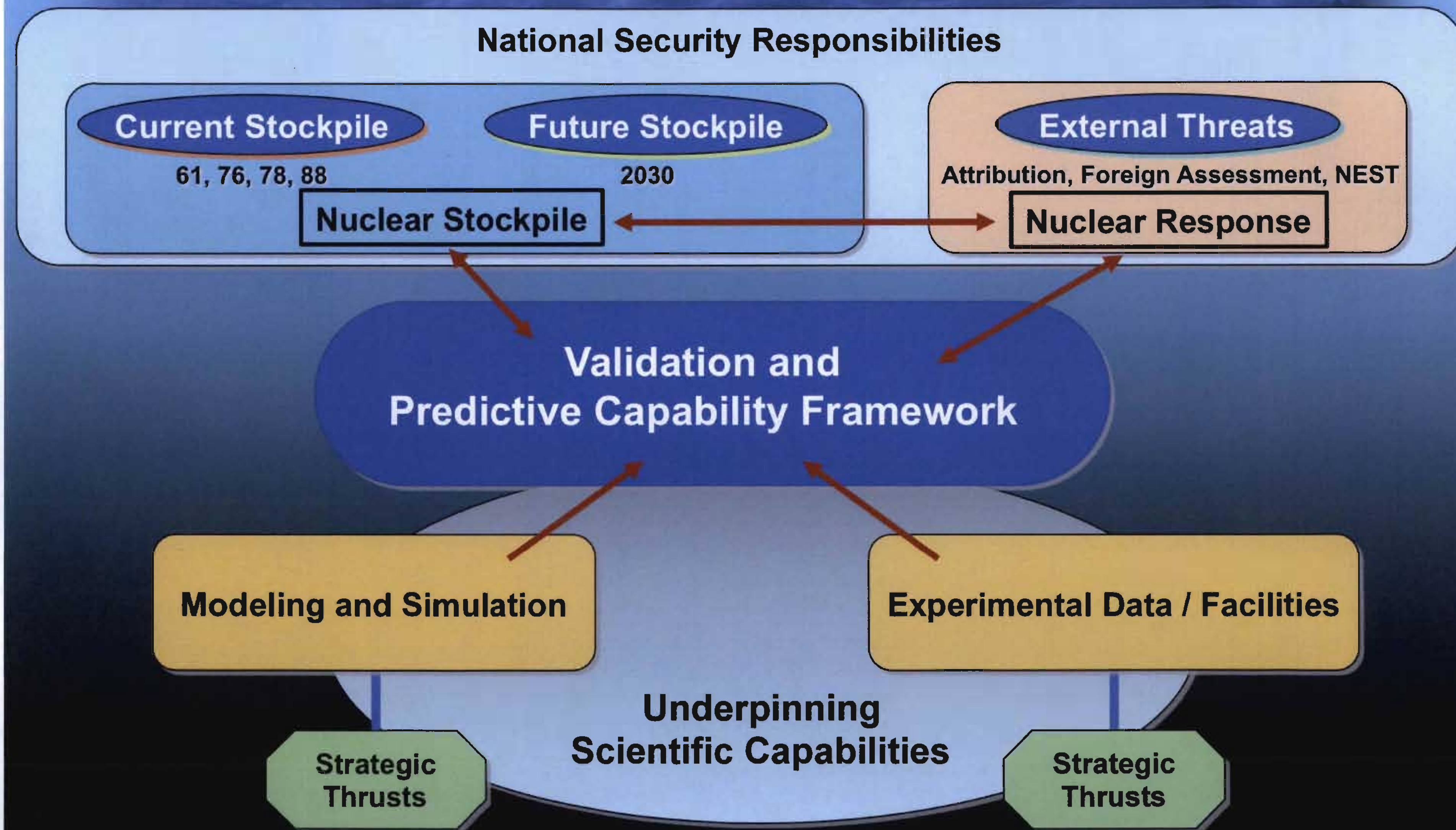
SIGMA Building

Chemistry & Metallurgy Research Replacement (RLUOB)

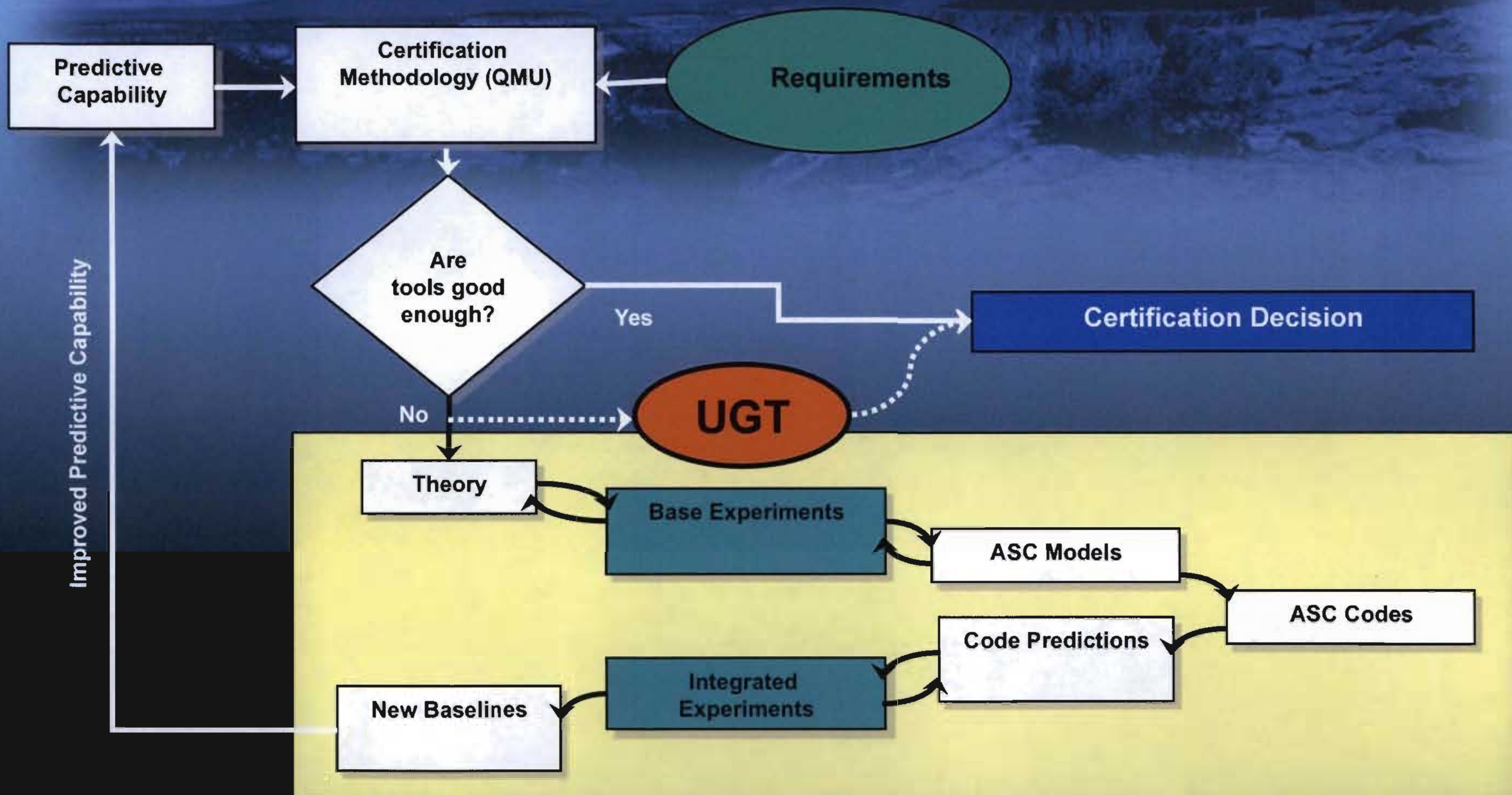
Traditional Design and Development



We will meet our National Security responsibilities through Validated Predictive Capability

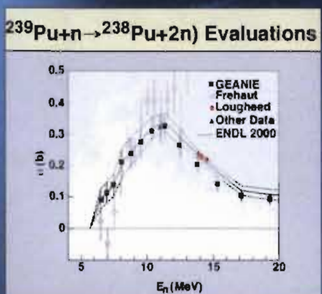


How does predictive capability fit in the big picture?

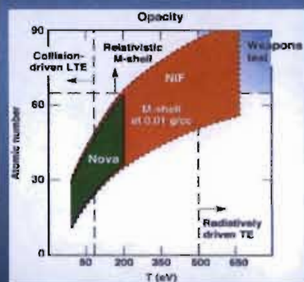


Range of Length Scales
From the size of the nucleus to the size of the weapon

Nuclear Structure



Atoms



Molecules and Shocks

Materials Strengths

High Explosive Constitutive Models

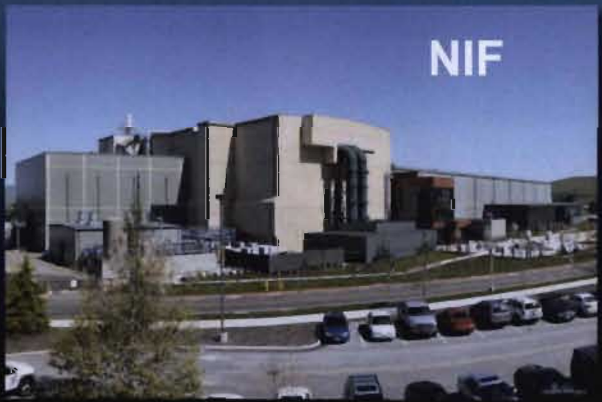
Full System

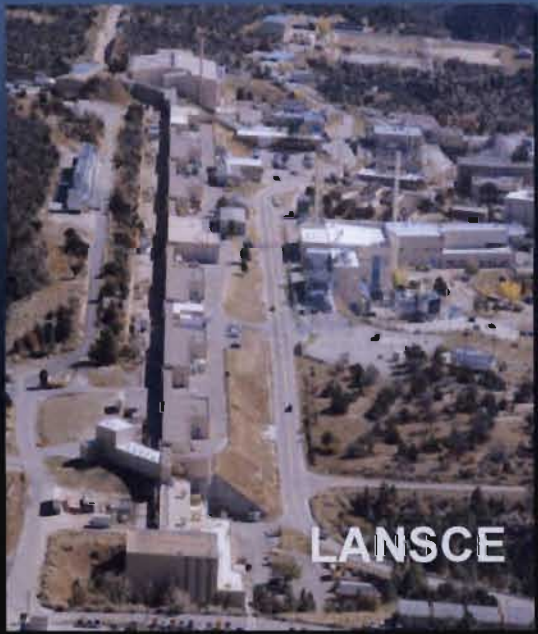
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1

Characteristic Length Scale (m)

LANL utilizes world-class experimental facilities to accomplish mission

- Science is underpinning for assessments & is key to recruiting
  - Facilities just becoming available to the scientists after investments
  - NIF (LLNL)
  - DARHT (LANL)
  - ZR (SNL)
  - LANSCE (LANL)





Nonnuclear Testing

- Instrumented HE tests, possibly including mock fissile material (hydrotest)
  - » Characterize detonators, HE, and firing set
  - » HE system performance and pit behavior
  - » Gas cavity formation
  - » Radiation case dynamics

Pin Diagnostics

- Measure implosion velocity and symmetry
- Pins produce signals when struck by moving material
  - » Electrical
  - » Optical
  - » ~500 pins typical

Pin dome

- Oscilloscopes capture timing of signals

Oscilloscope

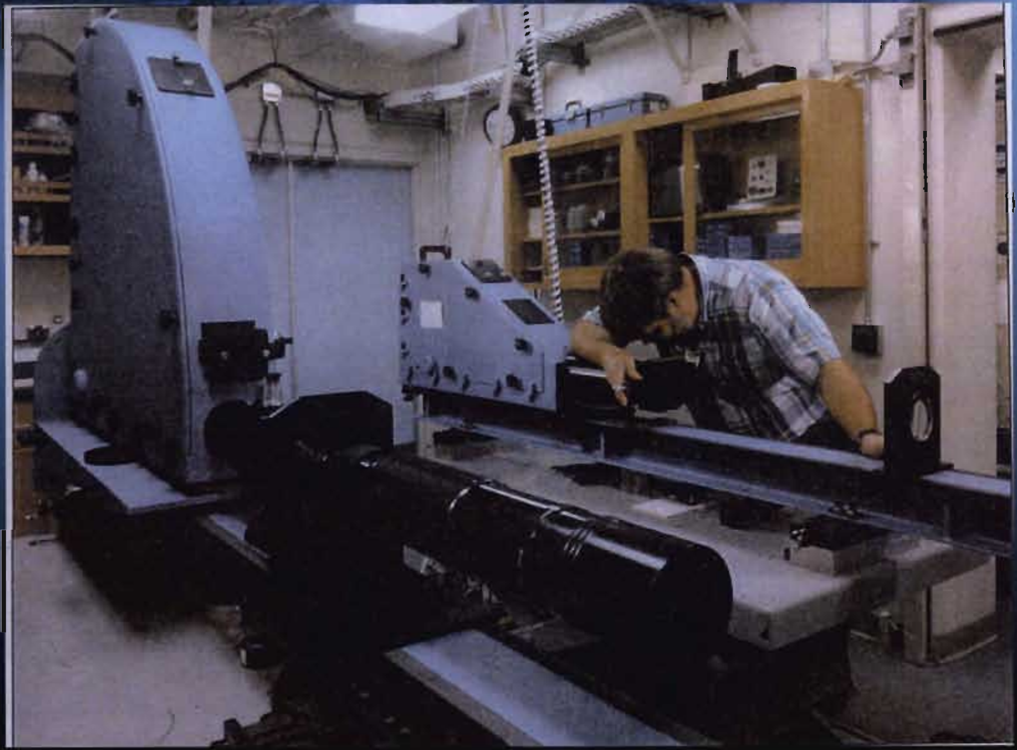
High-Speed Photography

- Image high-speed events
  - » HE detonation waves (7-9 km/s)
  - » HE-driven plates (1-6 km/s)
- Used for the development of HE components and initiation systems
- Film and electronic cameras are used

High-Speed Photography (Cont.)

Rotating mirror cameras

Framing camera (left)
Streak camera (right)

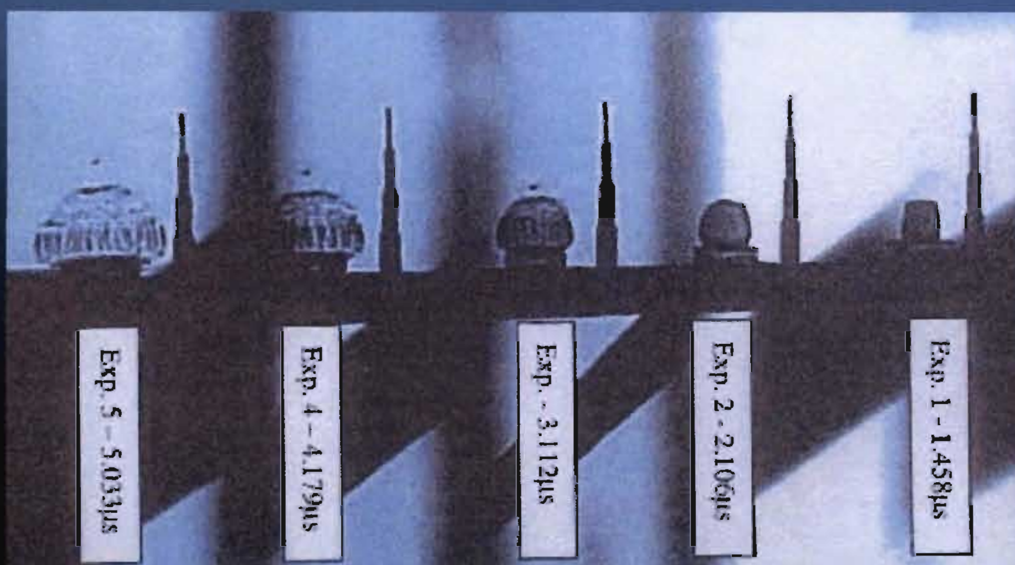


Inside a rotating mirror framing camera

High-Speed Photography (Cont.)

Rotating mirror framing camera images of exploding hand granade (~1 million frames per second)

Courtesy of David J. Fisher and Rodney L. Robbs, Naval Weapons Center, China Lake, CA. Official US Navy photographs.



Electronic framing camera images of exploding detonator

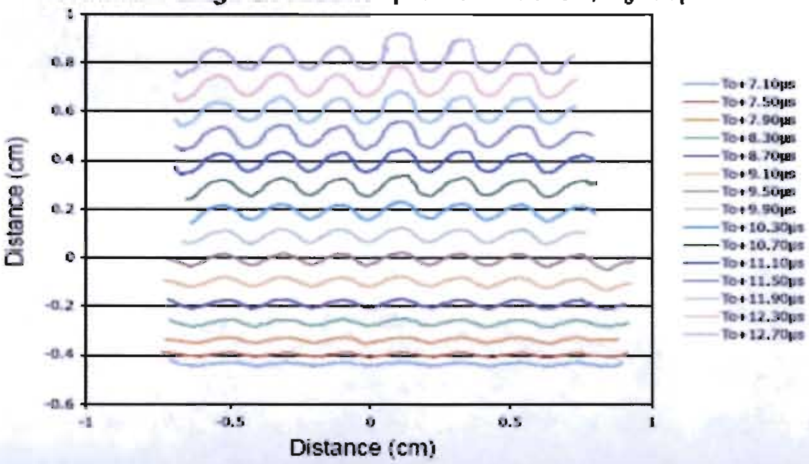
DARHT provides experimental data on the health of the deterrent

- World class X-ray radiography for hydrodynamic tests to gather data to support stockpile
- Axis 1 single image, operational since 1999
- Axis 2 up to four images
- World's first dual axis experiment successfully executed December 2009
- Experiments fully contained to reduce environmental impacts and increase shot rate

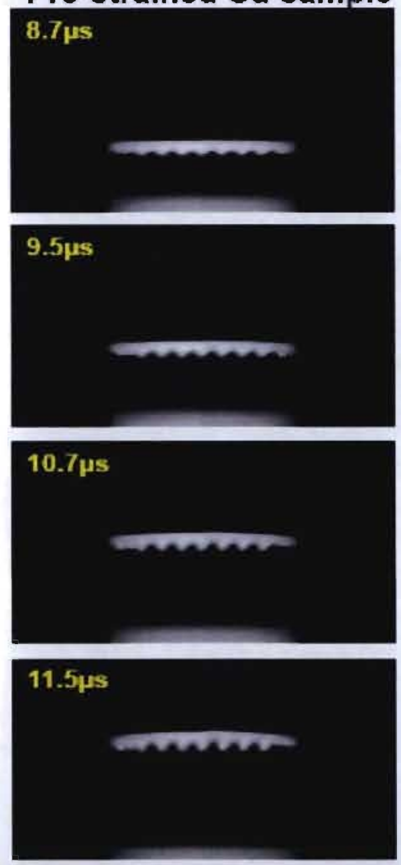
pRad studies of perturbation growth rates as a function of time demonstrate a strong influence of materials processing

- **Comparison between fully annealed and cold worked copper samples.**
  - 55μm sinusoidal initial perturbation imposed on each sample.
  - Identical sample acceleration.
- **Significant reduction in growth rate is observed for cold worked Cu samples.**

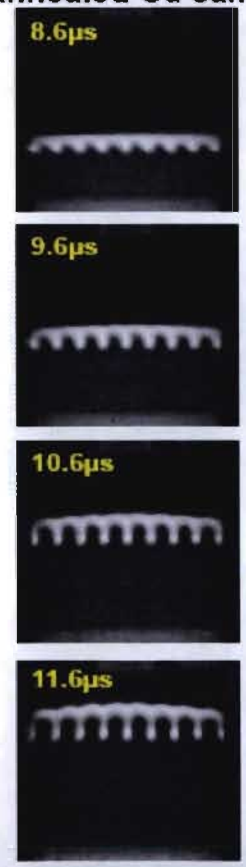
Extracted Edge Locations: pre-strained Cu, A_0=55μm



Pre-strained Cu sample



Annealed Cu sample



Supercomputing essential to Stewardship and other scientific missions

- Stockpile challenges are increasingly complex as systems continue to age
- Experimental tools are providing large data sets to resolve stockpile challenges
- Data sets require ever more capable machines that can quickly process information
- Road Runner world's first machine to operate at 1.105 Petaflops

Computer Codes

- *Computational Models* – sets of equations describing various weapons phenomenology and numerical solution techniques
  - » Radiation/Hydrodynamics
  - » Neutronics
  - » Thermonuclear burn
- *Physical Data* – unique for each material
  - » Neutron cross sections
  - » Equation of state
  - » Opacities
- *Nuclear test data* – needed to overcome our lack of full physics understanding (phenomenology and data)

Computers, Codes, and Nuclear Testing

- Manhattan Project work relied heavily on experimental and analytical programs – hand computing and electromechanical machines used
  - » produced workable unsophisticated designs (heavy, inefficient use of nuclear material)
  - » nuclear test of gun-assembled weapon not performed prior to dropping Little Boy
  - » if enough enriched uranium is available, gun designs are relatively easy

Computers, Codes, and Nuclear Testing (Cont.)

- Supercomputers and complex codes are used to make weapons lighter, smaller, safer, more efficient
  - » Classified nuclear test data essential to process (still lack understanding of full physics)
  - » US stockpile was designed with "supercomputers" equivalent to today's desktop PCs

Computers, Codes, and Nuclear Testing (Cont.)

- Advanced weapon states will continue to pursue larger computers to further understand weapon physics and operation
- Understanding stockpile aging issues without nuclear testing will require massive computational resources; success is not assured
- Supercomputers are of little value to beginning proliferants lacking nuclear test data

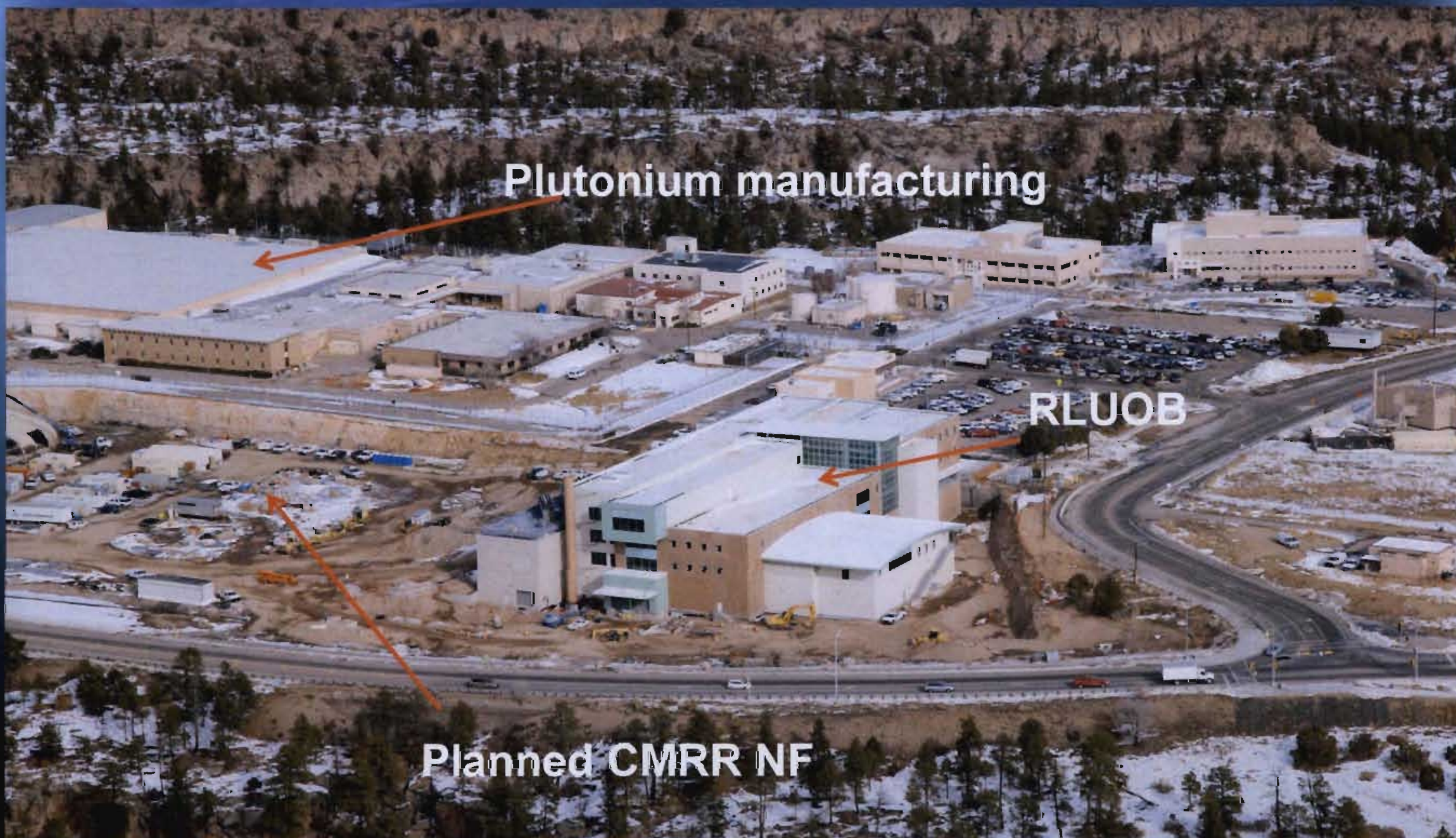
Nuclear Weapon Design is Unique

- Range of operating conditions within a nuclear weapon is greater than in anything else, manmade or natural, existing on earth
- Processes are very complicated and occur in extremely harsh environments
    - » extreme temperatures (>100 million degrees)
    - » high material velocities (>1 million miles/hour)
    - » very high pressures (>10 million atmospheres)
    - » small time scales (measured in billionths of a second)

Nuclear Weapon Design is Unique (Cont.)

- Forces are so large that the strongest metals compress and flow like fluids.
- Designing a machine that by its very nature destroys itself in a fraction of a second (and everything within a kilometer or more over the next several seconds) obviously complicates the process of understanding its reliability and of refining the design.
- Some parts of the device will be vaporized in an explosion while other parts only a few centimeters away must remain intact and function under the harsh environmental conditions described.

TA-55 the Nation's center of plutonium science and manufacturing



CMRR will provide 21st century actinide science capabilities supporting a variety of national security missions

- Phase 1 of CMRR—RLUOB completed on time/ budget
- Phase 2 (equipment install) underway on schedule and budget
- CMRR will support a broad range of LANL activities including:
  - non-proliferation/IAEA training
  - nuclear energy R&D
  - space power
  - homeland security
- CMRR NF will improve site security and allow for SNM consolidation
- CMRR NF adds @ 20,000 square feet of Cat I/2 lab space to support operations in PF-4
  - Analytical chemistry
  - Actinide R&D
  - Materials characterization
  - Vault storage

Annual Assessment– A statutory requirement and the highest priority of the Lab Director

- Detailed reports are prepared by lab staff on each warhead
- Lab Director briefed in detail by staff
- Lab Director issues letter to Secretaries of Defense & Energy and Chair of the NWC
- Lab Director briefs the Secretary of Energy
- STRATCOM prepares separate report and briefs the Secretary of Defense
- Secretaries of Defense & Energy brief the President
- President advises Congress





Key Questions for a Capability-Based Deterrent

- How agile do we need to be?
  - 3 – 5 – 10 years?
- How do we assess this?
  - historic weapon development times?
  - expert assessment?
  - negotiated via arms control?
- What about military readiness?
  - Dual use delivery platforms?
  - Dedicated platforms?
- How will capability be perceived by –
  - Allies? Adversaries? The rest of the world?
  - Must linkage to stockpile goals and a CTBT be explicit?
  - Will transparency play an important role?
  - Do we design transparency into weapons? The complex?

TA-55 Plutonium Complex at Los Alamos

B-61 Nuclear Bomb (>4000 parts)