Nuclear Power

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Winter, 2009

Nuclear Power
Review of principles

Energy is the ability to do work

Energy can have many forms
- Gravitational energy
- Kinetic energy
- Chemical energy
- Nuclear energy
- Heat

Heat Example 1

Heat Example 2

Heat Example 3

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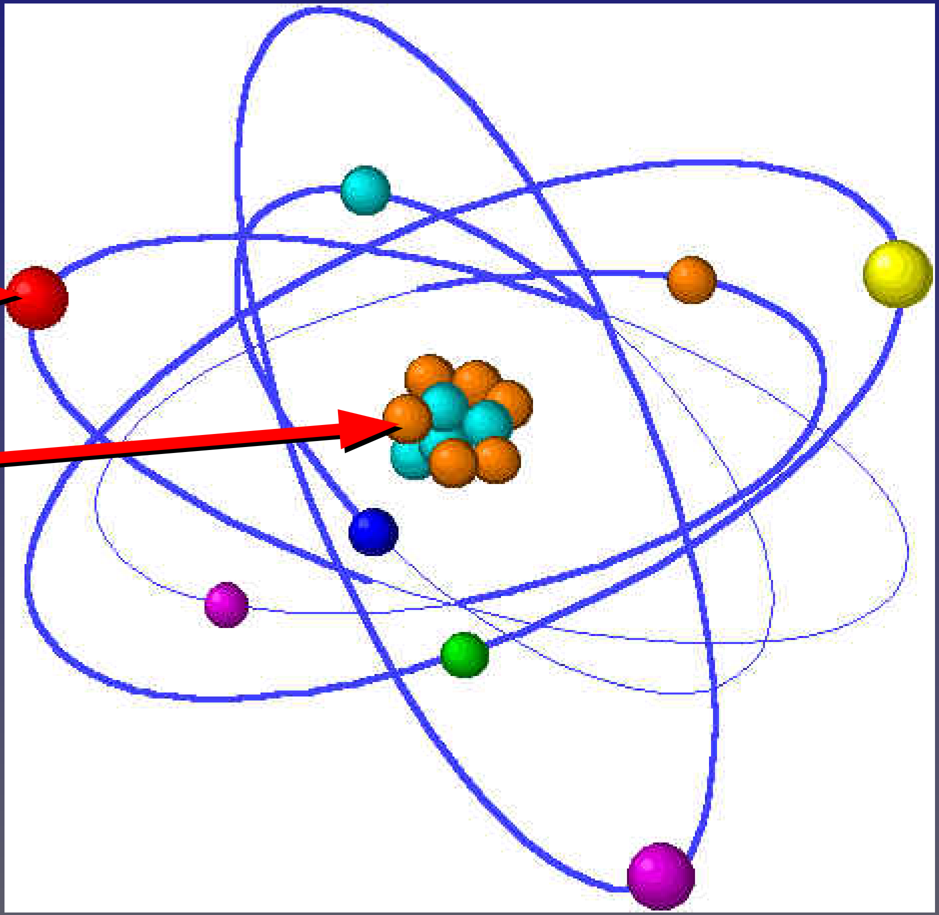
Review of principles

- Matter is composed of atoms which are held together by electromagnetic force



- Electrons(-)
- Nucleus

  { protons(+) and Neutrons(0) }

Nuclear Power
Review of principles

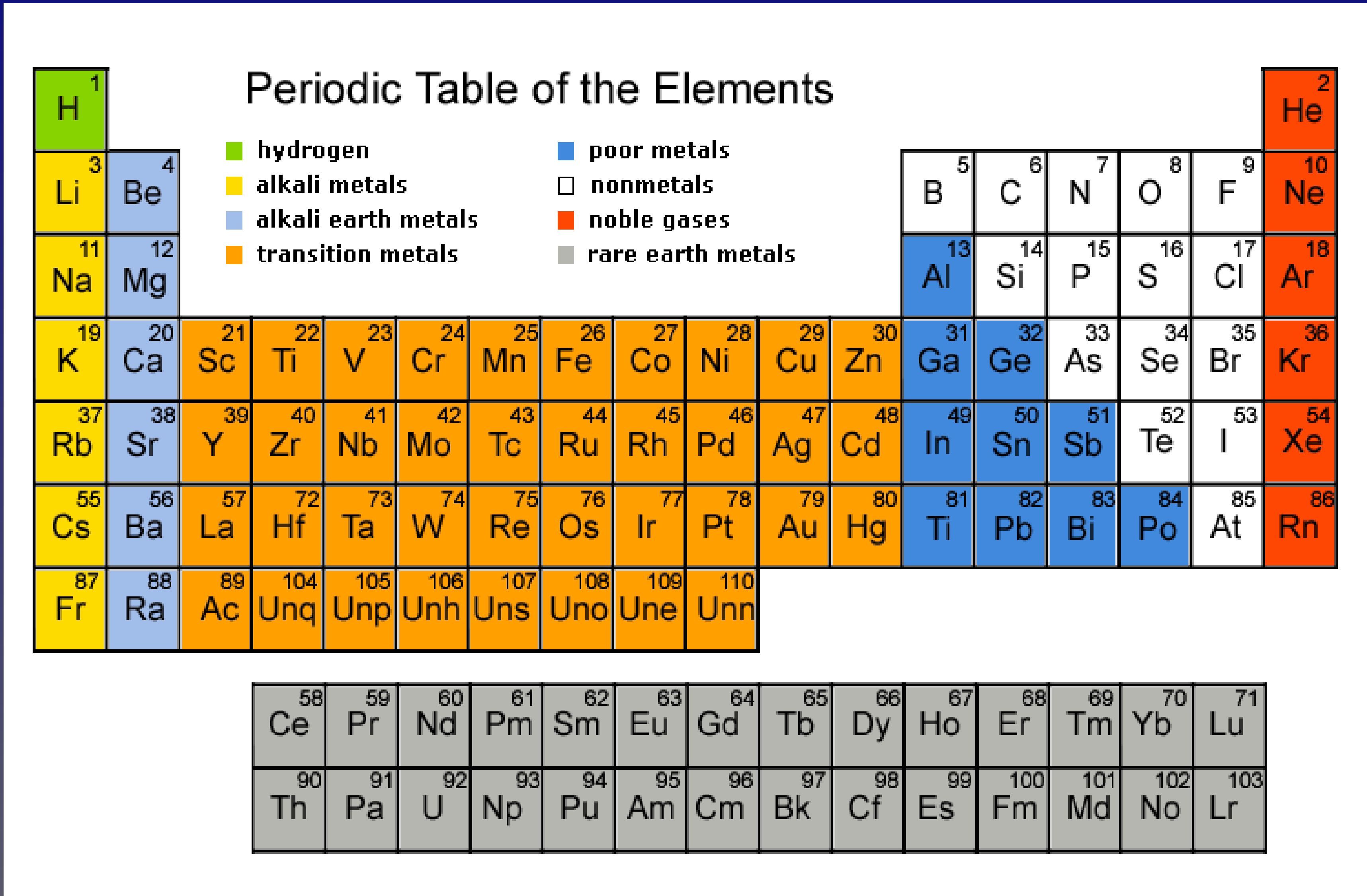
Physical forces

- Gravity
- Weak nuclear force
- Electromagnetic
- Strong nuclear force: holds nuclei together

Nuclei = plural of nucleus

Nuclear Power

Review of principles



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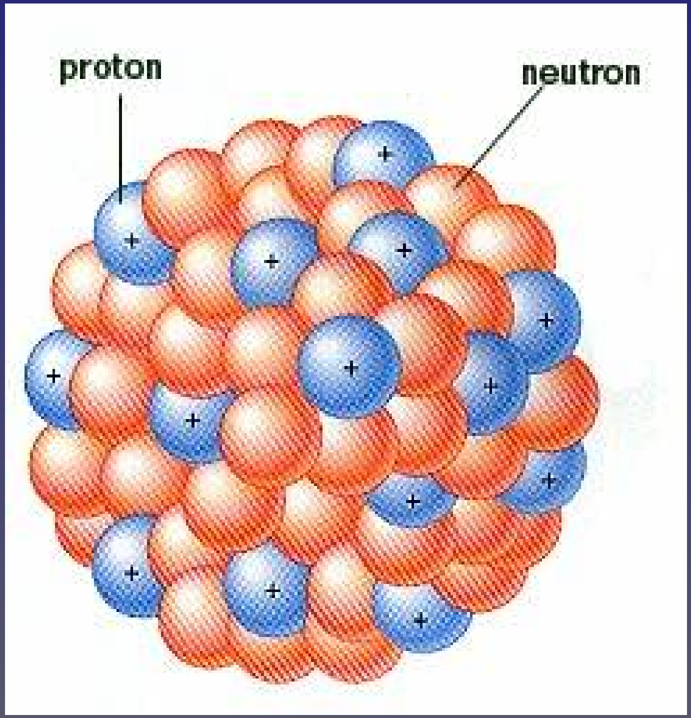
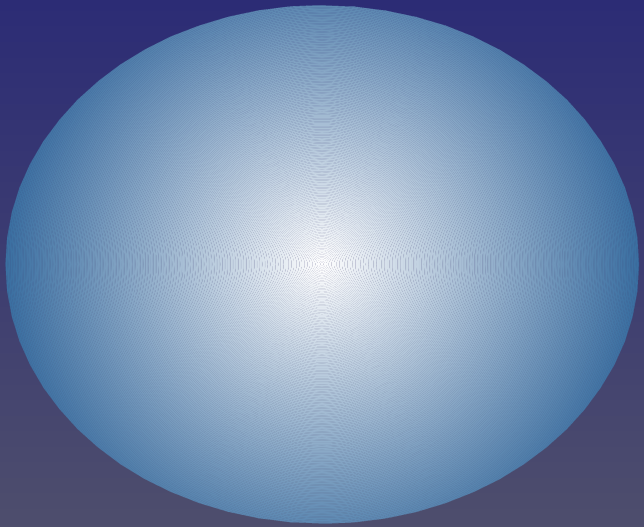
Review of principles

- The atomic nucleus is held together by the *strong* and *weak* nuclear forces, but the *weak* force makes some nuclei unstable





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Review of principles: Isotopes

- The number of protons and neutrons determines what *element* and *isotope* the atom is
-
- 1 p → normal hydrogen
- 1 p, 1 n → heavy H or deuterium
- 1 p, 2n → tritium
- 2p, 1n → ^{3}He or helium 3
- 2p, 2n → ^{4}He or normal helium

Table of nuclides

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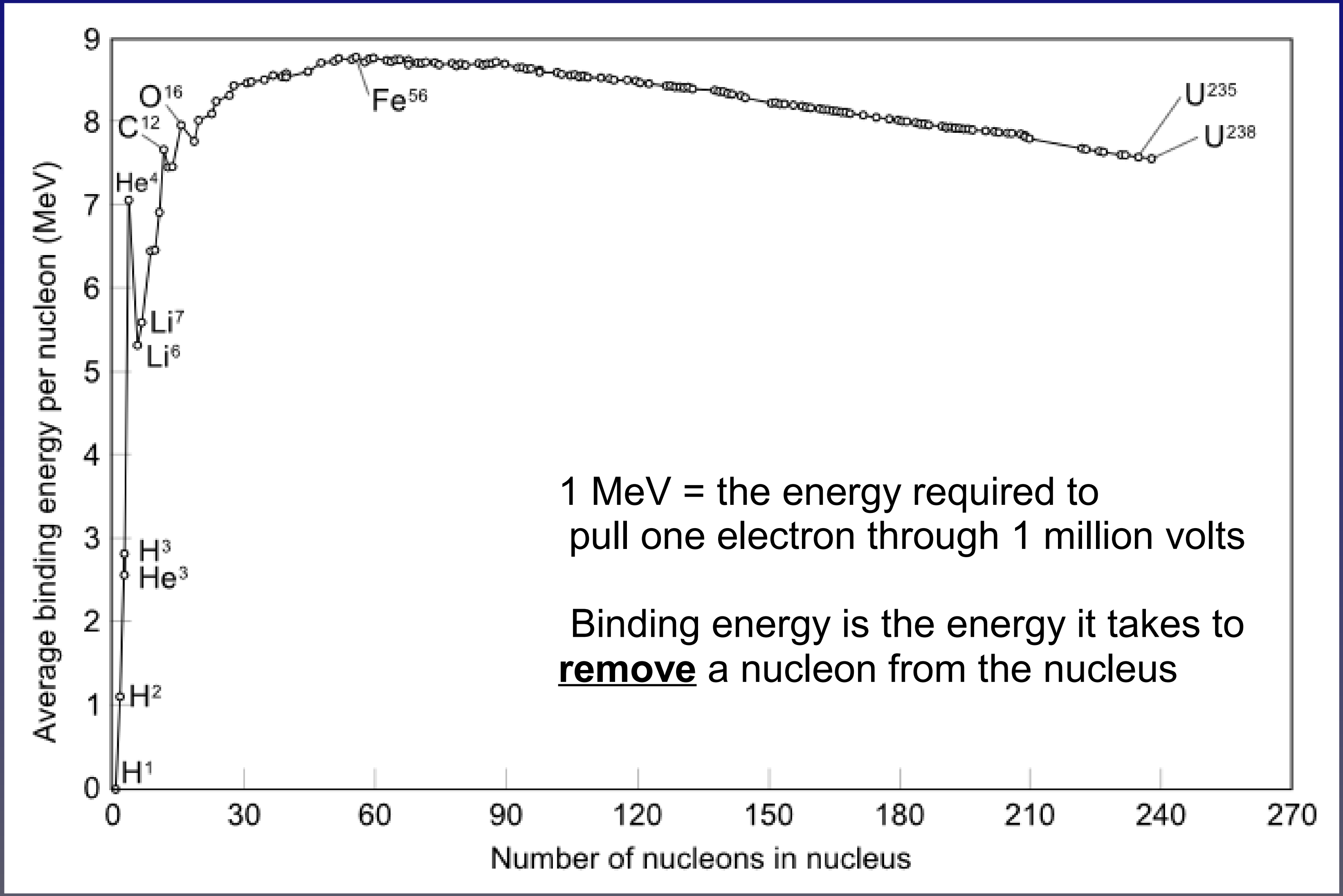
Review of principles: Binding Energy



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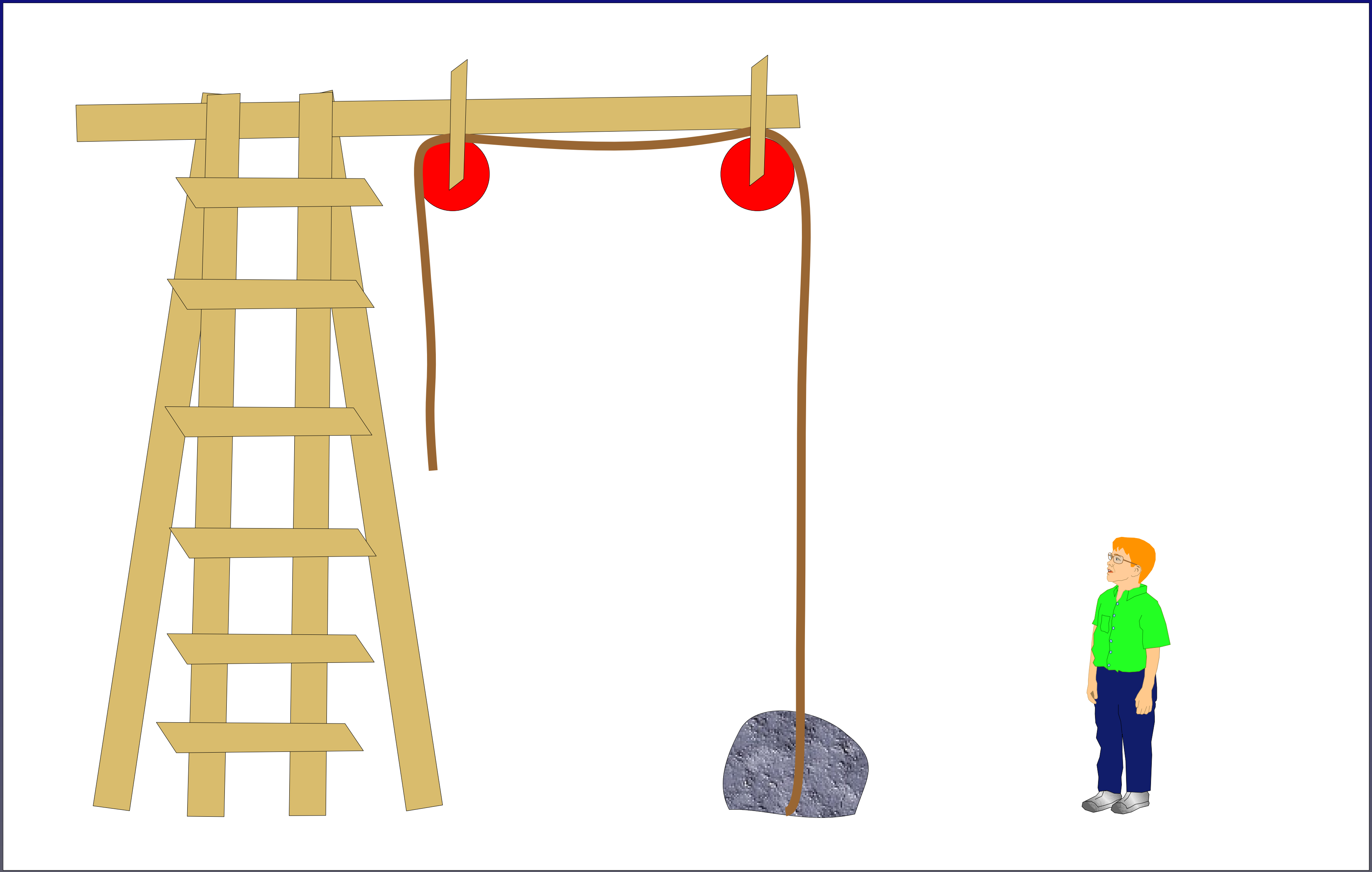
Review of principles: Binding Energy



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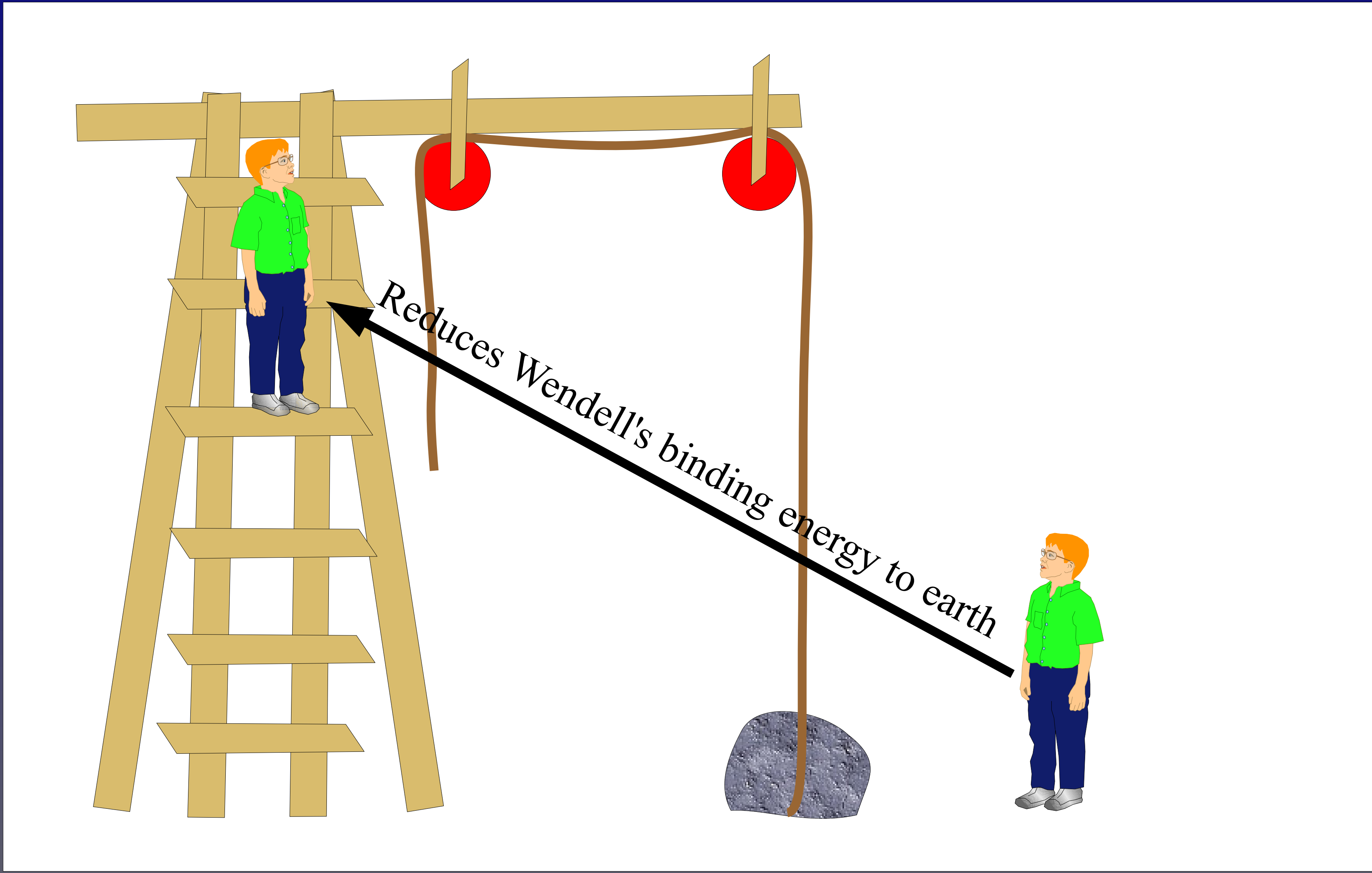
Review of principles: Binding Energy



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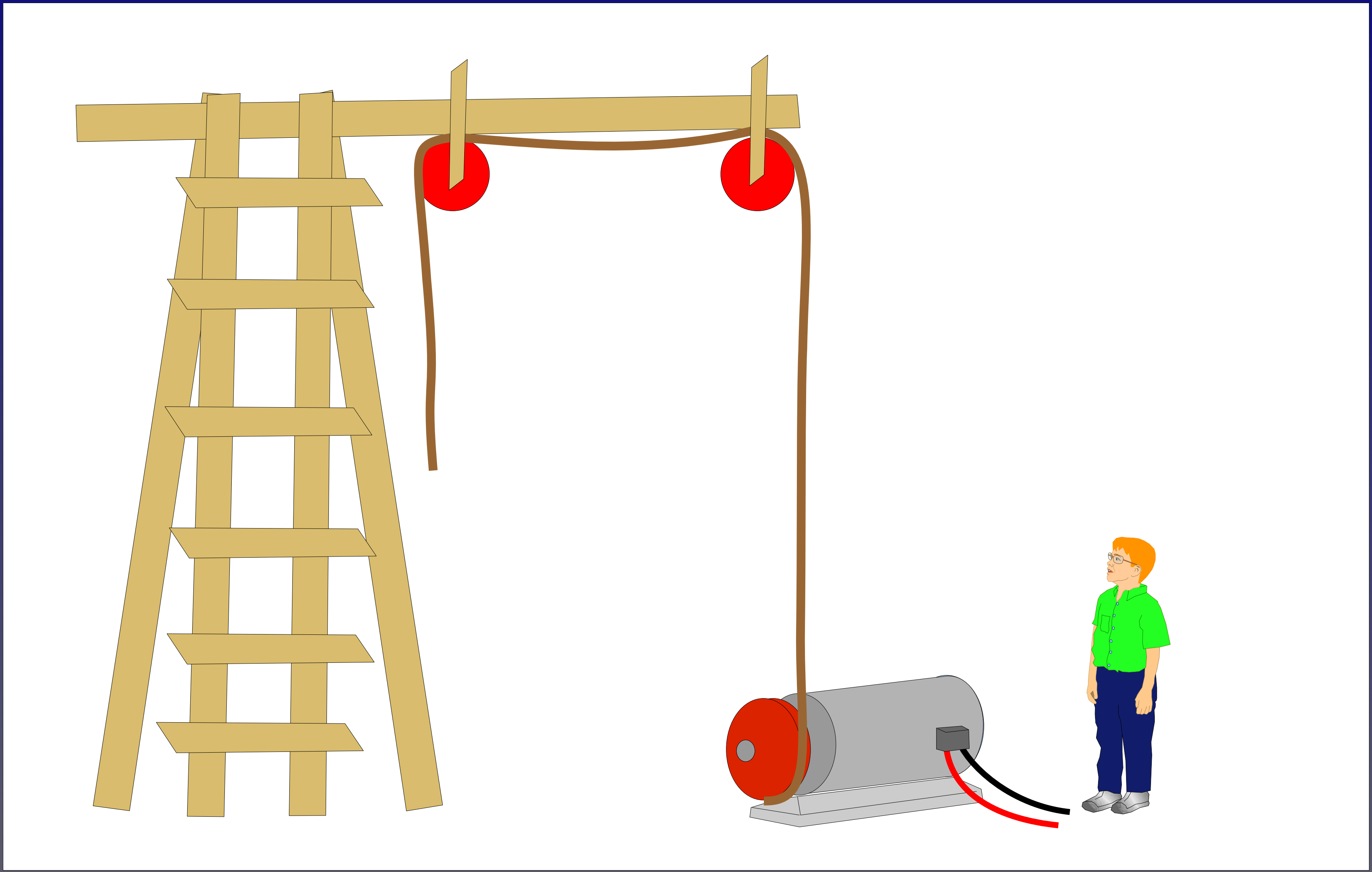
Review of principles: Binding Energy



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Review of principles: Binding Energy

- When nucleons combine into a single nucleus (fusion) or break up to form two nuclei (fission), the excess energy is released as gamma rays and other radiation
- Gamma rays are electromagnetic radiation like light, but more energetic
- $^2H + {}^2H \xrightarrow{\text{fusion}} {}^4He$ + lots of gammas

LOTS OF HEAT

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Review of principles: Binding Energy

The energy carried by the initial products of a nuclear reaction--fast electrons, gamma rays, fast alpha particles—is converted to heat by a sequence of events:

- One gamma produces multiple lower-energy gammas
- A gamma produces an electron and its antiparticle (a positron) or vice versa
- The conversions produce light and heat
- Light is converted to heat
- The final product is heat

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Review of principles: Binding Energy

Energy and mass are interchangeable, but the sum is always conserved

- $E = mc^2$
- mass of a nucleus = mass of protons + mass of neutrons – the binding energy of protons and neutrons
- Mass of two protons + two neutrons = 4.03188 amu
- Mass of ^{4}He = 4.00153 amu

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Review of principles: Nuclear decay

Some isotopes are stable and some *spontaneously* decay

Example of α decay:

$$^{238}U \xrightarrow[t_{1/2} = 4.5 \text{ billion years}]{} {}^{234}Th + \alpha(\text{at high speed}); \quad \alpha = {}^{4}He$$

Example of β decay:

$$^{234}Th \xrightarrow[t_{1/2} = 24 \text{ days}]{} {}^{234}Pa + \beta(\text{at high speed}); \quad \beta = \text{electron}$$

$t_{1/2}$ is the half life, the time in which half of the material decays

Pa = Proactinium

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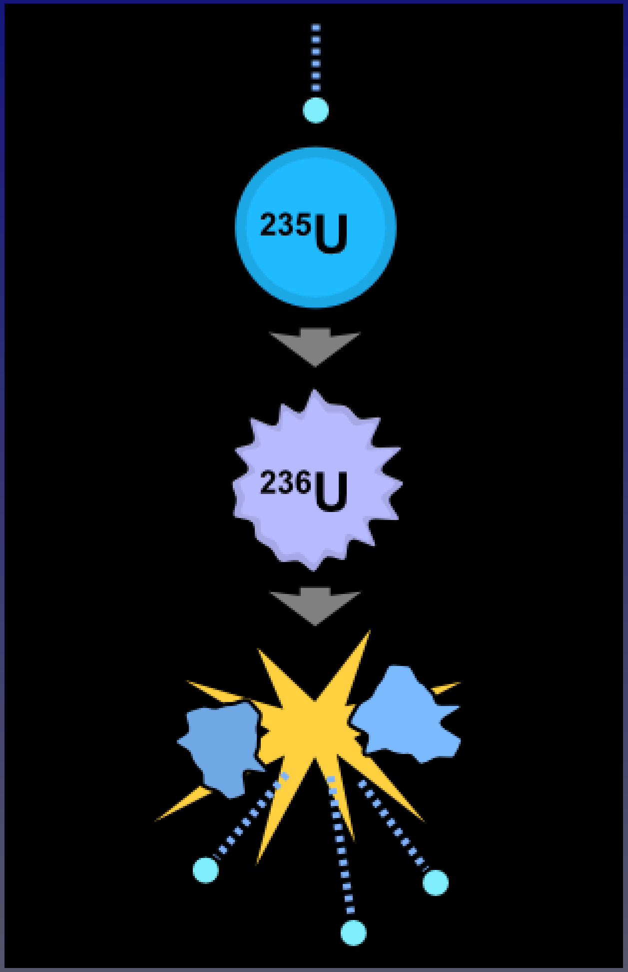
Review of principles: Induced nuclear decay

Nuclear decay can be induced

$^{235}U + n \rightarrow {}^{236}U$
$^{236}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3n + \text{energy}$

The production of three neutrons allows for the production of a *chain reaction* and lots of energy



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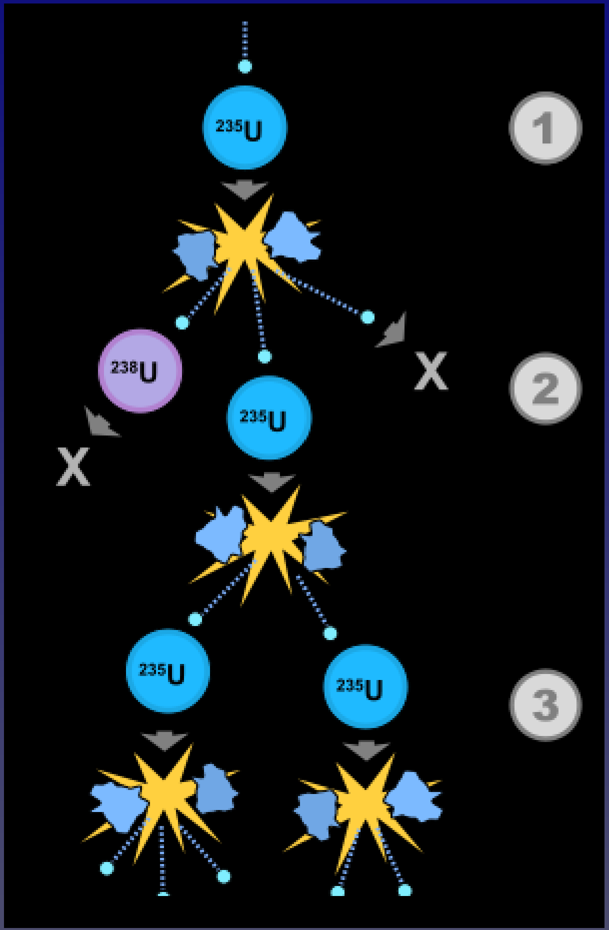
Review of principles: Nuclear decay

Chain reaction

Small piece of Uranium→
Noncritical reaction (slow and stable)

Bigger piece of Uranium→
Critical reaction (fast and marginally stable)

Bigger piece of Uranium→
Supercritical reaction (grows until..........)



Chain reaction

Chain reaction

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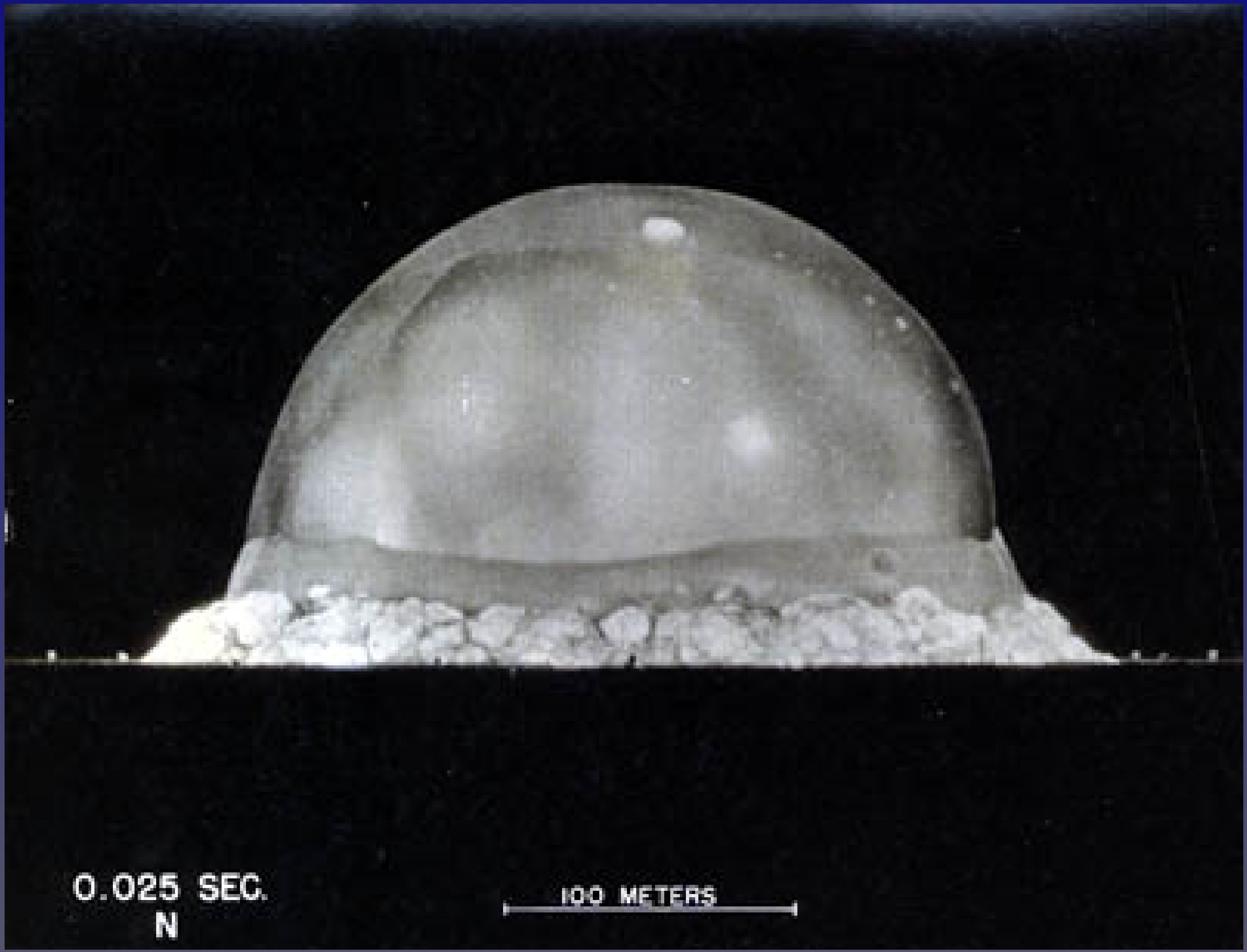
Review of principles: Chain reaction



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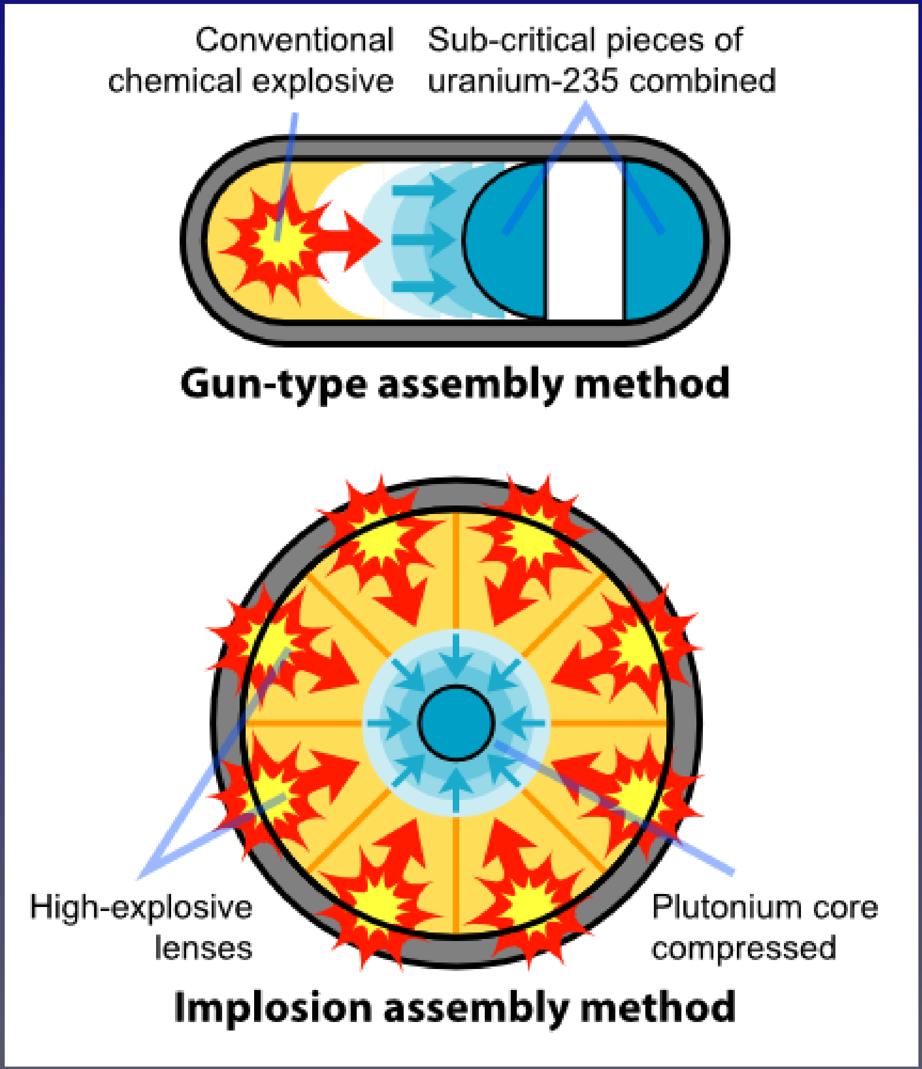
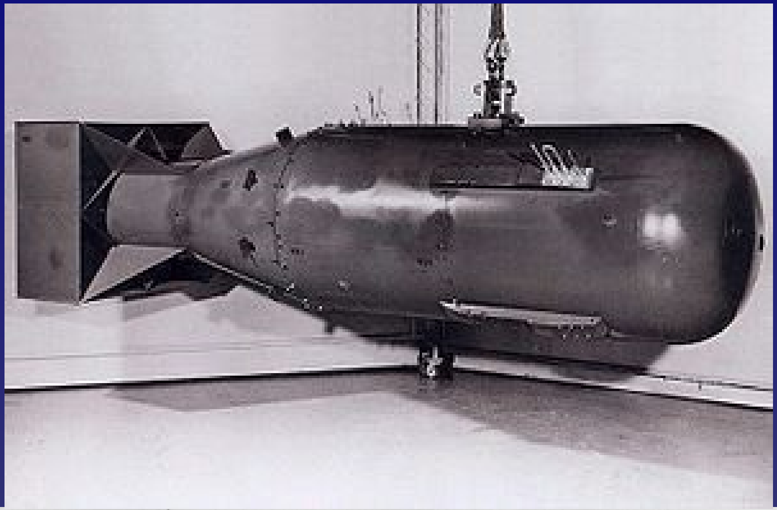
Fission Bombs (A bombs)





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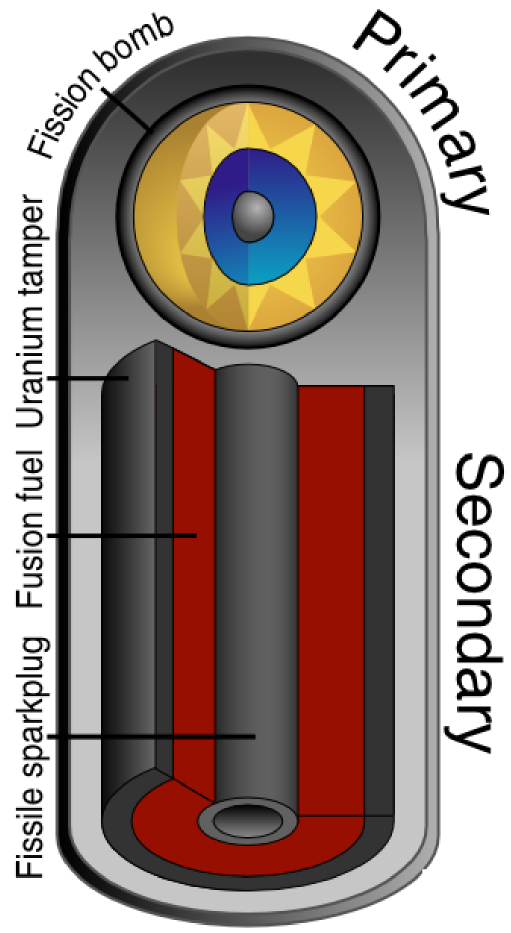
Fusion Bombs (H bombs)



$$^{2}H + {}^{3}H \rightarrow {}^{4}He + n + 17.6\ MeV$$

Deuterium + Tritium → Helium + Neutron + Energy

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Review of principles: Nuclear decay

Chain reaction

Small piece of Uranium→
Noncritical reaction (slow and stable)

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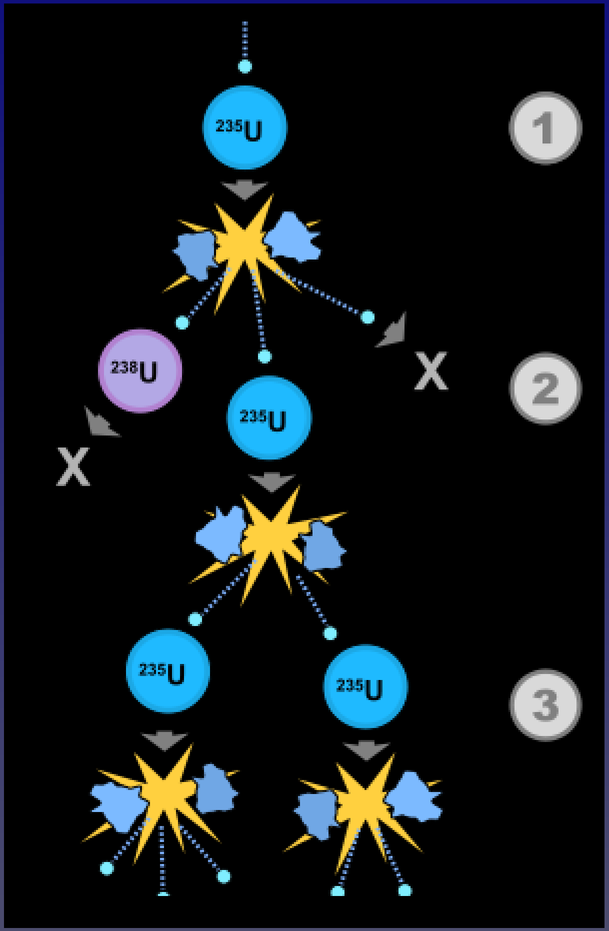

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Nuclear reactors

- A device that sustains a rapid, controlled nuclear chain reaction is called a nuclear reactor or just reactor

Diablo Canyon Reactors, California

Cooling Tower

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Nuclear reactors

Uranium ore, mostly ^{238}U and a little ^{235}U

Uranium fuel pellets with concentrated ^{235}U

BW Reactor

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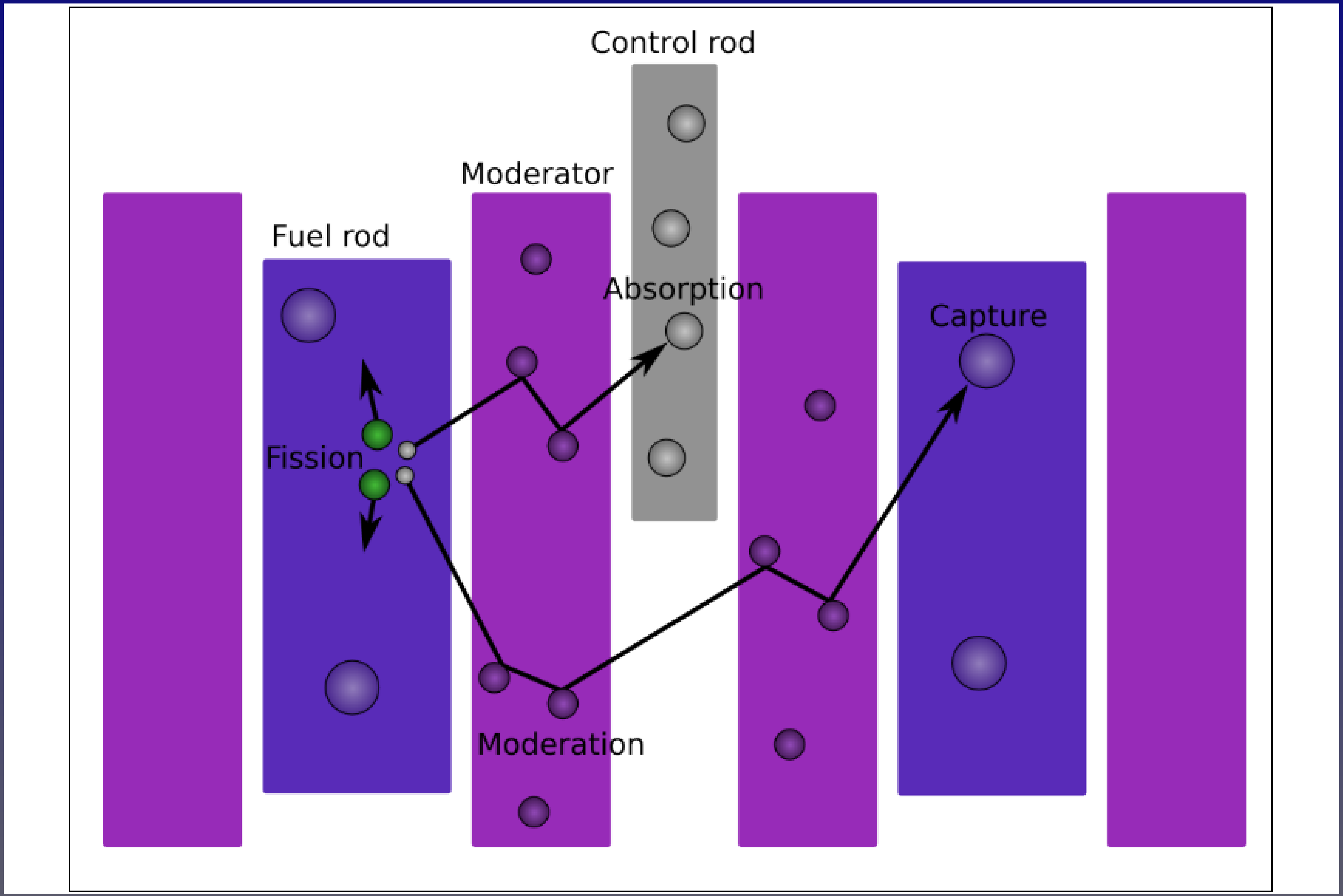
Nuclear reactors

PW Reactor



Animation

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Dangers: Reactor Failure

Three Mile Island nuclear power plant

Three Mile Island unit 2
underwent a
partial meltdown
in 1979

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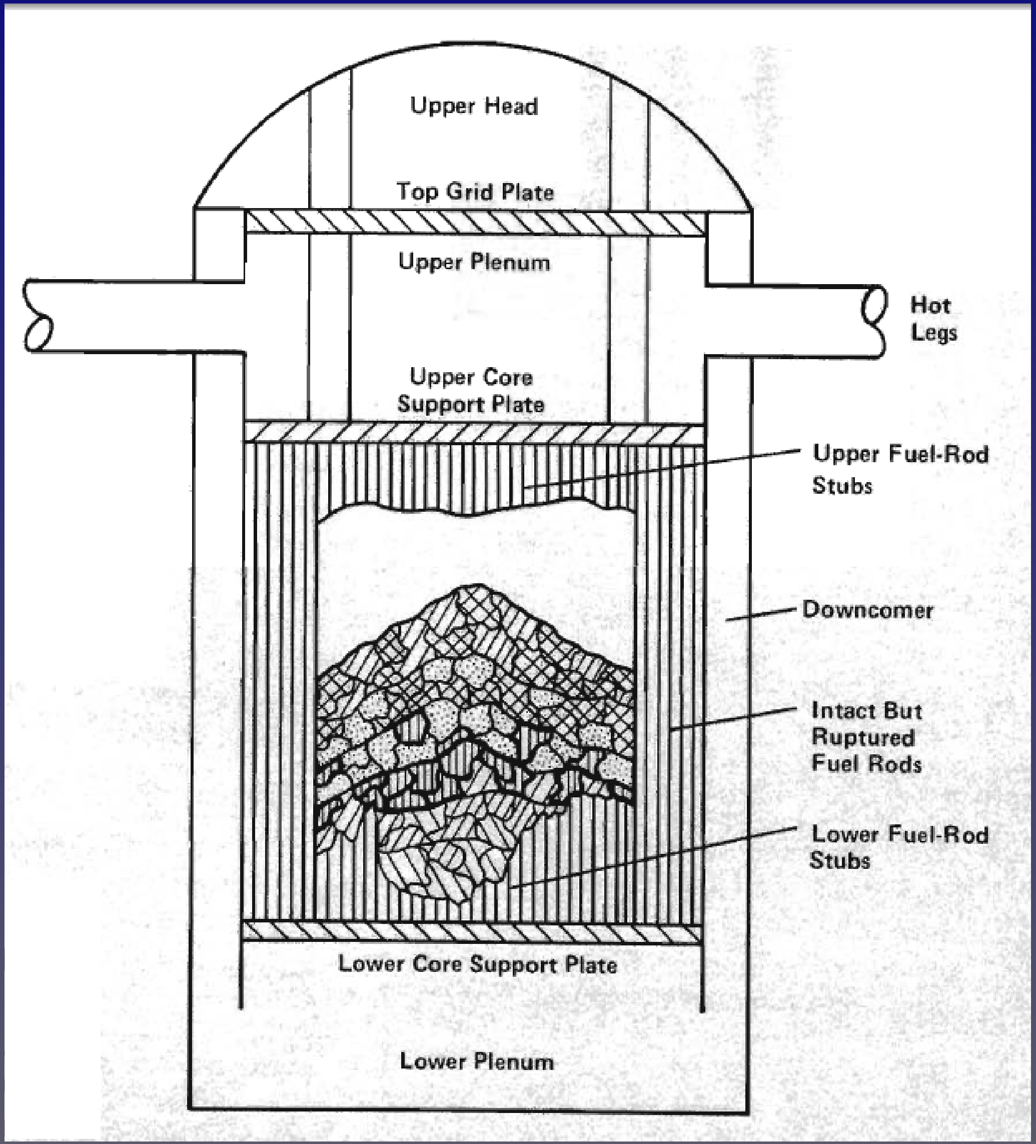
Dangers: Reactor Failure



TMI-LANL.pdf

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Dangers: Reactor Failure

- The operators were inadequately trained and their data was inadequate or wrong
- Scientists at Los Alamos and other national laboratories were unprepared and lacked the knowledge to be of significant help
- No one knew what was happening for over two hours
- A measure of luck was involved in avoiding a much greater disaster
- In fact, such a disaster was avoided by the conservative design of the reactor
- Events could have led to rupture of the primary containment system
- The resulting spread of radioactivity would have produced an unknown large number of deaths and illnesses
- In fact, little or no health effects resulted from the radioactivity that was released
- An unknown part of Pennsylvania and surrounding states would have been made uninhabitable and likely still would be
- Such a large disaster happened in Ukraine in 1986

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Dangers: Chernobyl

- Chernobyl was a city in northern Ukraine
- On April 26, 1986, one of four reactors exploded, releasing huge amounts of radioactivity
- As at Three Mile Island, inadequate operator training was cited as a primary contributing factor in the accident
- The reactor design was very different than any in the US
- There have been 56 fatalities officially confirmed, but large areas of Ukraine, Belarus, Russia, and Scandinavia were contaminated
- People living within 18 mi were evacuated (161,000 people) and the area was later expanded to about 40 mi. About 1000 people have illegally returned, but the area is still officially uninhabitable
- Actual damage and casualties may be much larger due to government suppression of information

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Dangers: Chernobyl

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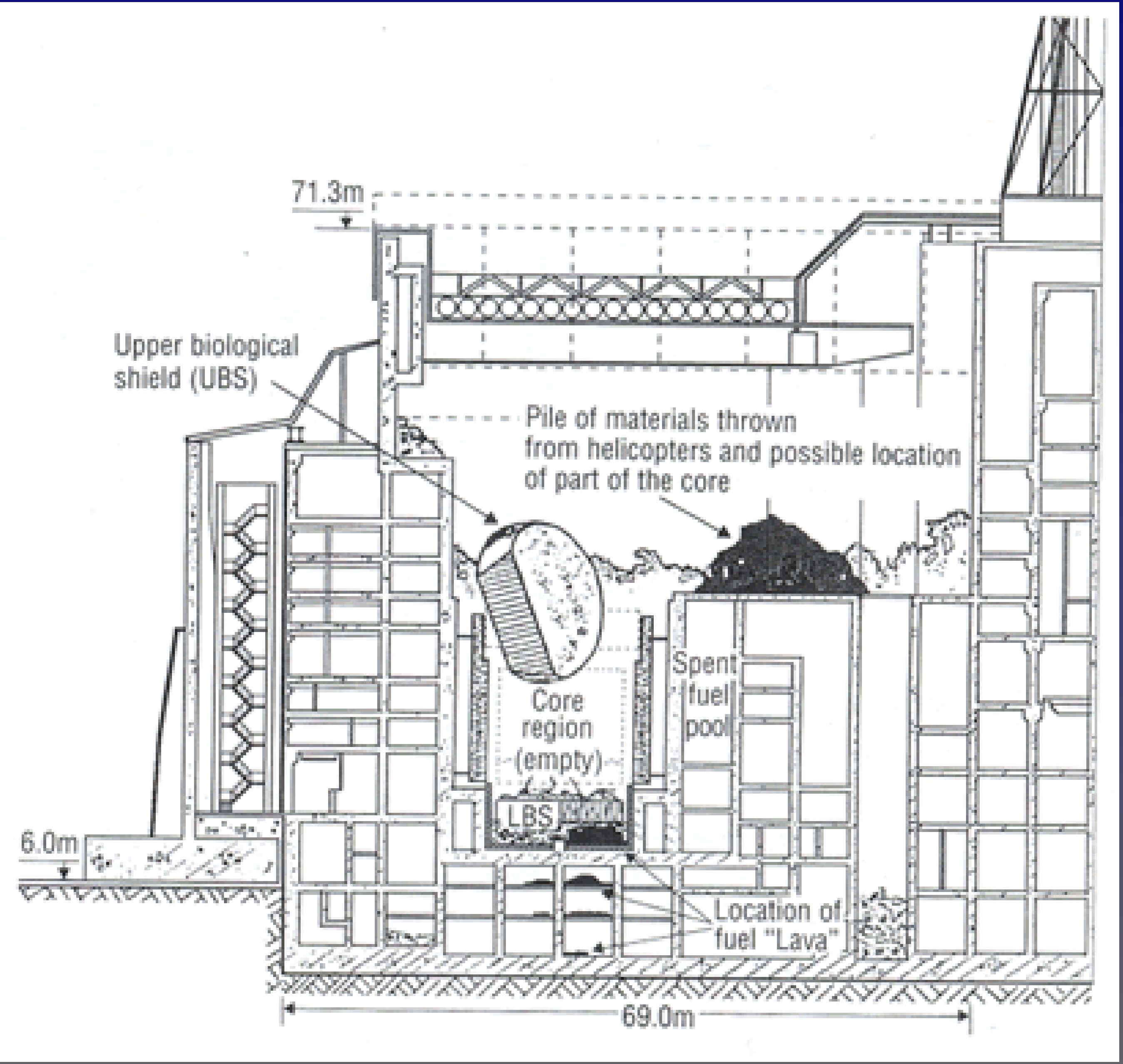
Dangers: Chernobyl



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Dangers: Chernobyl

- The remains of the reactor were encased in a temporary enclosure
- About 200,000 people participated in the attempted clean up and received up to maximum nonfatal radiation doses.
- 600,000 others participated and received lesser radiation doses
- Over 5 million people living nearby received significant radiation (more than a few x-rays)
- By 2000, around 4000 cases of juvenile thyroid cancer were reported
- A few percent of the 800,000 cleanup participants are expected to die of some radiation-induced cancer
- Around $1Billion has been spent on keeping the damage contained, but more will be needed for a long time

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Dangers: Chernobyl

- A new enclosure planned for 2011 will cost roughly another $1.5 billion
- Other significant amounts of money have been spent to close and dismantle the other three reactors. No permanent storage or disposal of the used fuel from the reactors has been achieved
- These statements about Chernobyl were all taken from (http://www.world-nuclear.org/info/chernobyl/inf07.html) published by The World-Nuclear Organization, an organization sponsored by the nuclear industry and likely to be very conservative in its assessment

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Waste Disposal

- The operation of a nuclear power reactor generates a huge amount of radioactive waste
- The first sources are mining tailings and depleted Uranium

- Processing steps

  Mining → dump low-grade rock and soil

  Extracting ^{235}U → depleted Uranium (^{238}U + ~0.5% ^{235}U)

  Scraps of contaminated materials and equipment from processing

  - Depleted Uranium, even though it is radioactive, is used in artillery shells and in numerous places where high density is desired; e.g. in the keel of a yacht

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Waste Disposal

- The fission products created by reactor operation absorb neutrons and slow or stop the fission process
- Fuel rods have to be replaced while they contain substantial amounts of unused Uranium
- Used fuel rods contain unused ^{235}U, ^{234}U, ^{237}Np, ^{238}Pu and ^{241}Am and fission products, all of which are extremely radioactive
- Used fuel rods are usually placed in a “swimming pool” next to the reactor
- If they are stolen, they could be used to make bombs or just spread around to make a water supply unusable, a city, or other area uninhabitable

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Waste Disposal: Reprocessing

- Used fuel rods can be dissolved, the isotopes separated chemically and physically and the extracted materials used to make new fuel rods
- Reprocessing is very expensive. It is not done in the US at present
- Reprocessing produces more potentially misdirected material
- Nuclear reprocessing produces:
  - Reprocessed uranium
  - Plutonium
  - Minor actinides
  - Fission products
  - Activation products (structural materials made radioactive)
  - Cladding leftovers

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Waste Disposal: Yucca Mountain

- Yucca Mountain, Nevada has been proposed as an underground storage facility for spent nuclear fuel
- Many people oppose the project on many grounds

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Waste Disposal: Long term storage

- Storage has to be permanent: for at least several thousand years
- The materials must be kept dry to prevent dissolving in ground water
- The heat from the radioactivity must be carried away to prevent melting
- The material must be guarded from terrorists for its entire life
- Cost of all this waste disposal is part of the overall cost of nuclear power

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Waste Disposal: Yucca Mountain

- A shipping cask for fuel rods

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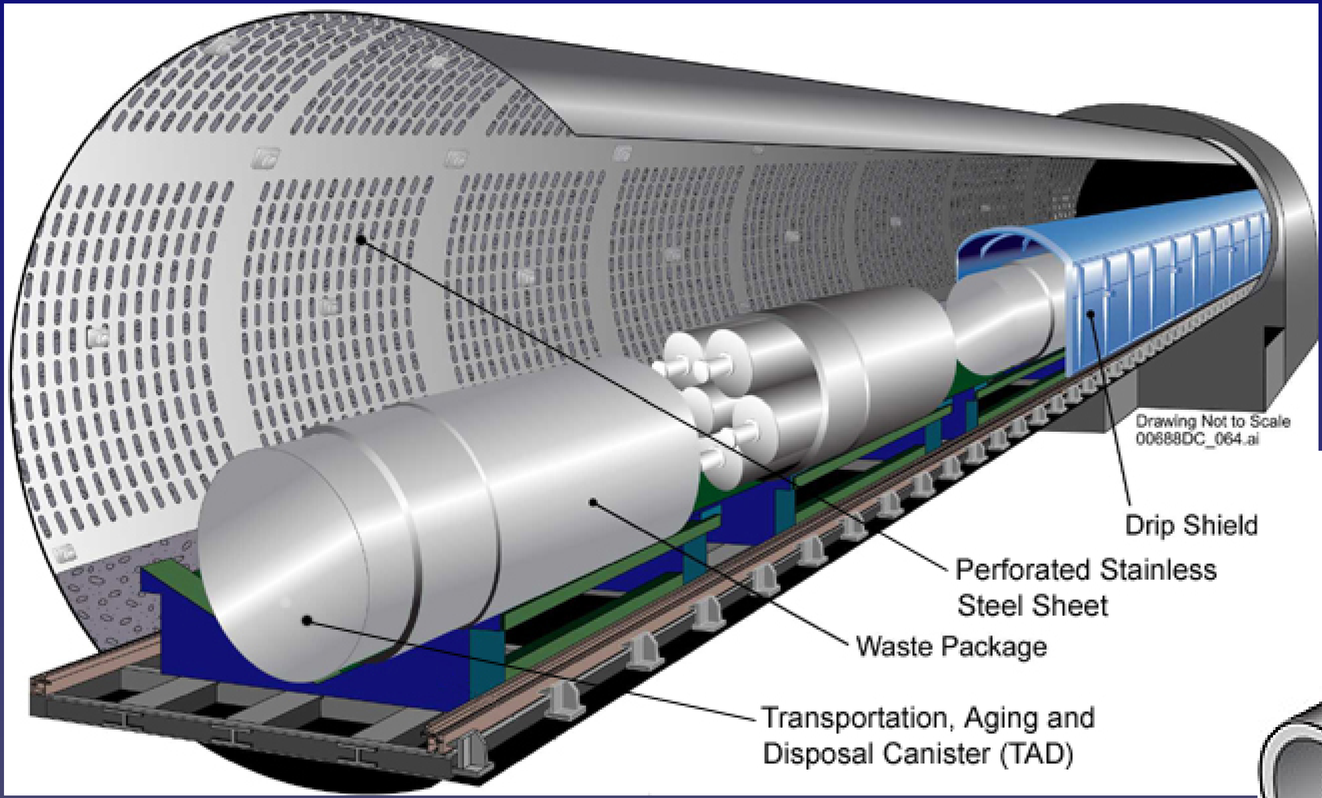
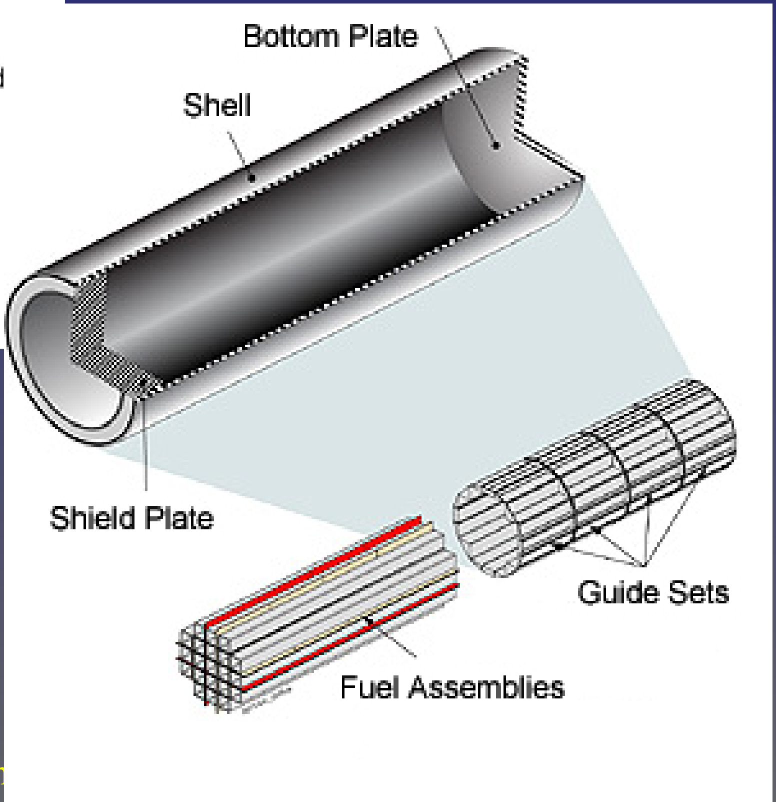
Waste Disposal: Yucca Mountain





- Storage plan

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Cost

- Table taken from *The Future of Nuclear Power, An Interdisciplinary MIT Study,* 2003

- The costs do not include "external costs" including waste disposal
- Recycling the fuel extends the life of nuclear power but does not make it any cheaper

Table 5.1 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) Advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%).	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)

	$50/tC	$100/tC	$200/tC
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Nuclear Power

Wendell's personal opinions

- Currently used costs of nuclear energy do not include large amounts required for waste disposal or fuel reprocessing. When these costs are included, it's just too expensive
- We should not continue to build and operate reactors without a working waste disposal plan
- Risk analysis should consider the *worst case accident,* which is unacceptable for current reactor designs (other designs might be acceptable)
- Nuclear power is not renewable without reprocessing
- Other sources of renewable energy have become much more feasible over the last decade