Lecture Notes

(Fission & Fusion)

Nuclear Fission History:

- in the 1930s, German physicists/chemists Otto Hahn and Fritz Strassman attempted to create transuranic elements by bombarding uranium with neutrons; rather than the heavy elements they expected, they got several unidentified products

- when they finally identified one of the products as Barium-141, they were reluctant to publish the finding because it was so unexpected

- when they finally published the results in 1939, they came to the attention of Lise Meitner, an Austrian-born physicist who had worked with Hahn on his nuclear experiments

- upon Hitler's invasion of Austria, she had been forced to flee to Sweden where she and Otto Frisch, her nephew, continued to work on the neutron bombardment problem

- she was the first to realize that Hahn's barium and other lighter products from the neutron bombardment experiments were coming from the fission of U-235

- Frisch and Meitner carried out further experiments which showed that the U-235 fission yielded an enormous amount of energy, and that the fission yielded at least two neutrons per neutron absorbed in the interaction

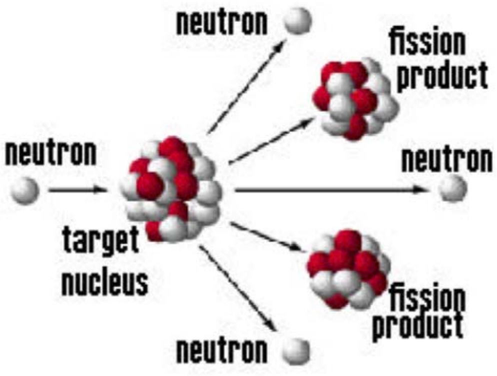
- they realized that this made possible a chain reaction with an unprecedented energy yield

Nuclear Fission Basics:

- nuclear fission is the process of splitting the nucleus of a heavy atom (target nucleus) into two or more lighter atoms (fission products) when the heavy atom absorbs or is bombarded by a neutron

- a few radionuclides can also spontaneously fission

- fission releases a large amount of energy along with two or more neutrons; the large amount of energy released is due to sum of the masses of the fission products being less than the original mass of the heavy atom



- this 'missing' mass (about 0.1 percent of the heavy atom mass) has been converted into energy according to Einstein's equation, $E = mc^2$

Nuclear Chain Reaction:

- when a heavy atom fissions, it releases neutrons which can be absorbed by other heavy atoms to induce further fissions; this is called a chain reaction

- if each neutron releases two more neutrons from a fission, then the number of fissions doubles each generation; in that case, in 10 generations there are 1,024 fissions and in 80 generations about 6 x 10^{23} (a mole) fissions

- the process may be controlled by neutron-absorbing materials (as in nuclear power reactors) or uncontrolled (as in nuclear weapons)

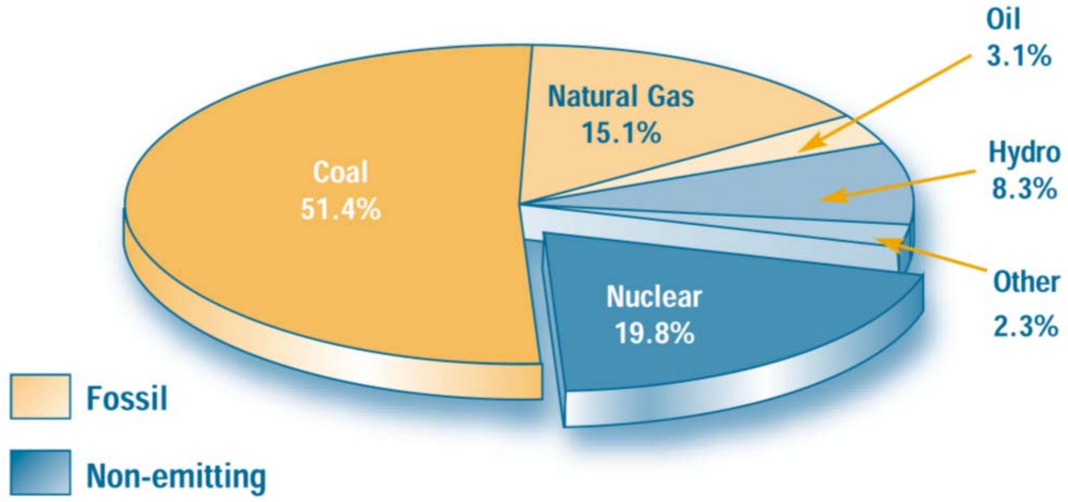
- if the chain reaction rate is capable of being sustained at a constant level, the rate of neutron production equals the rate of neutron loss, the reaction is termed critical

- if the chain reaction rate rises, the rate of neutron production is greater than the rate of neutron loss, the reaction is termed supercritical

- the world's nuclear power industry is based upon nuclear fission

Nuclear Power Facts:

- nuclear energy is the second-largest source of electricity in the United States, after coal



Second Largest Source of Electricity in the U.S.

Figure 1

Source: Department of Energy/Energy Information Administration

- nuclear energy is the largest emission-free source of electricity, because it does not burn anything to produce energy

- the US has more than 100 licensed nuclear plants that provide about one-fifth of the nation’s electricity

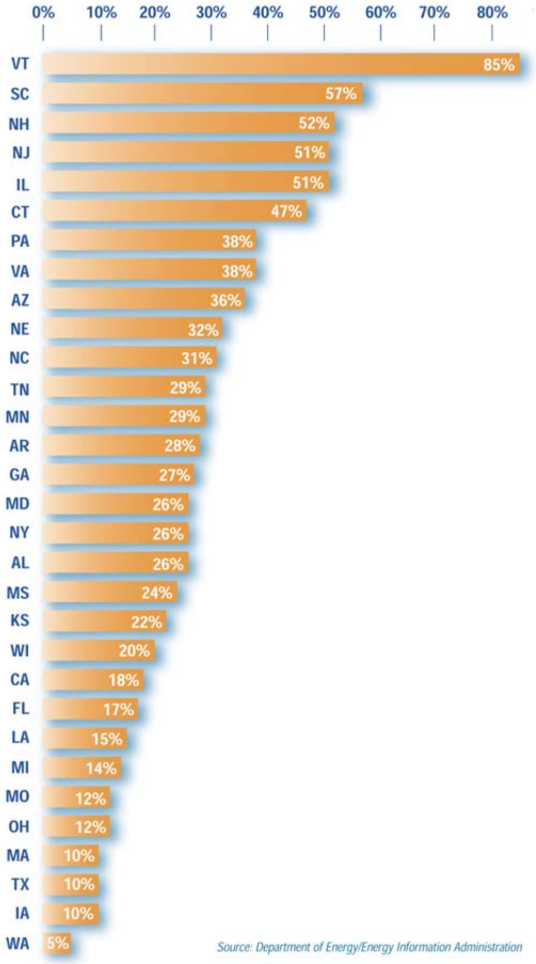
- these nuclear plants have a capacity of more than 97,000 megawatts (MW), and they provided 728 billion kilowatt-hours in 1999

- that was almost as much electric energy as our entire national electric system was generating when nuclear energy was introduced in 1957 with the startup of the first commercial nuclear generating station in the western Pennsylvania town of Shippingport

- today, almost every American home, business and industry receives part of its electricity from nuclear power plants through a nationwide, interconnected transmission system

Nuclear Power Produced in 1999

Figure 2



Source: Department of Energy/Energy Information Administration

- the last nuclear power plant to be completed in the United States came on line in 1996

- the yearly carbon avoided by U.S. nuclear plants amounts to almost 60 percent of the target level required in the Kyoto Protocol on climate change

- the carbon avoided is equivalent to the carbon emissions that would result from 170 coal-fired power plants with generating capacities of 500 megawatts or from 300 gas-fired plants of the same size

- globally, 432 nuclear power plants generate 16 percent of the world's electricity

Nuclear Power Worldwide

Figure 3

Top Ten Countries by Number of Operating Reactors in 2000	
United States	103
France	59
Japan	53
United Kingdom	35
Russia	29
Germany	19
South Korea	16
Canada	14
Ukraine	13
Sweden/India	11

Top Ten Countries by Percentage of Electricity Supplied by Reactors in 1999	
France	75%
Lithuania	73%
Belgium	58%
Bulgaria	47%
Slovak Republic	47%
Sweden	47%
Ukraine	44%
South Korea	43%
Hungary	38%
Armenia	36%

Source: International Atomic Energy Agency

- in electricity production, nuclear energy essentially has replaced the use of oil

- between 1973 and the early 1990s, nuclear energy's share of U.S. electricity increased from 4% to 20%; oil's share dropped from 17% to 4%

- the shift to nuclear generated electricity has saved American consumers $65 billion since 1973 by avoiding the cost of using oil

- U.S. nuclear power plants are using fuel derived from Russian weapons-grade uranium to generate electricity, earning back most if not all of the purchase price, while destroying fissile material from warheads that once were aimed at U.S. cities

- U.S. experts say the equivalent of more than 1,800 nuclear warheads already have been destroyed by blending down weapons-grade uranium to the very dilute fuel used for energy production

Nuclear Power Generation:

- a nuclear power plant is a way to boil water to generate steam without the use of fossil fuels; the steam turns a turbine to produce electricity, just as it does in any power plant

- the difference is that in a nuclear plant, the heat used to generate steam is produced by a nuclear reaction involving uranium, instead of by the combustion of fossil fuel

- the reactor’s uranium is manufactured in solid pellets, each about a half-inch long; the pellets are stacked by the hundreds into long, thin fuel rods bundled to form fuel assemblies, with the number of assemblies in the typical reactor ranging from 550 to 800

- all the fuel assemblies together are referred to as the reactor “core”

Nuclear Power Safety:

- a nuclear plant in the United States has multiple backup safety systems to provide “defense in depth”

- safety features are built in to control the chain reaction; control rods absorb tiny subatomic particles called neutrons and control the reaction

- the reactor core itself is contained within a steel pressure vessel with very thick walls; water helps moderate the reaction inside the reactor

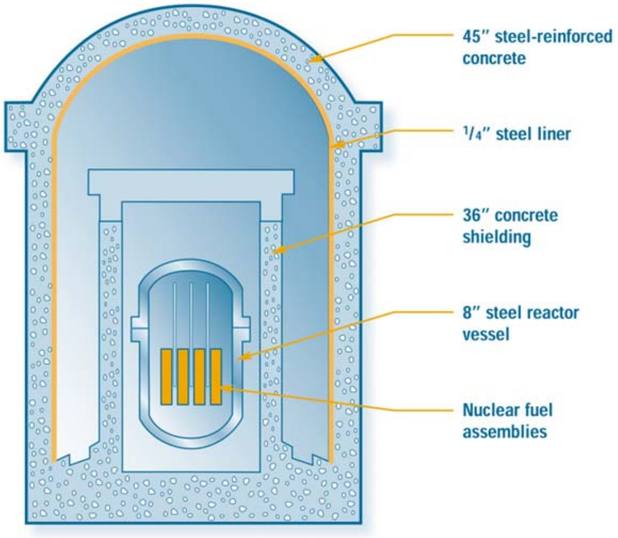
- although the control rods are the main way to control the nuclear reaction, the water helps, too

- the greater the nuclear reaction, the more heat is produced; the increasing heat turns more water to steam, which slows down the nuclear reaction

- the water works like a brake; it prevents the nuclear reaction from running out of control; if the water were ever lost, multiple emergency cooling systems would keep the reactor from overheating

U.S. Style Nuclear Reactor—Defense In Depth

Figure 4



- the many thick layers of the containment building keep radioactive materials safely inside

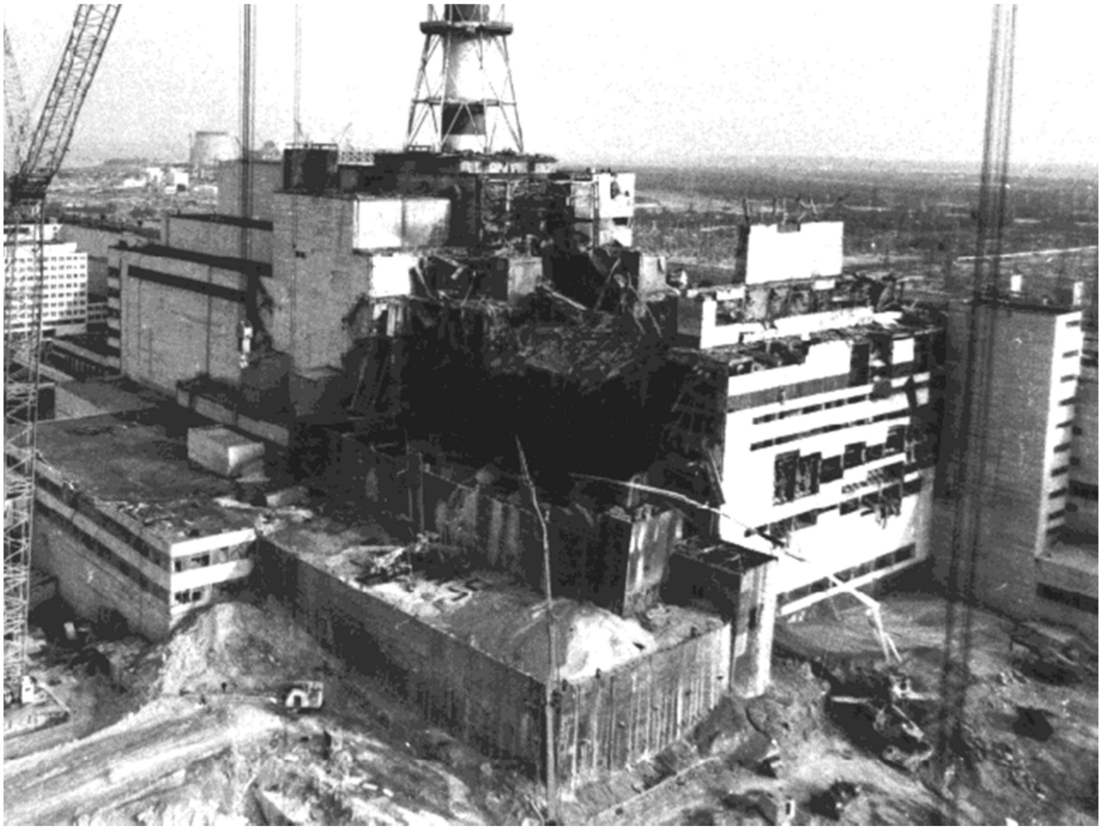
<u>Chernobyl</u>:

- the 1986 accident at Chernobyl in the former Soviet Union could not happen in the U.S.; that basic design would not be licensed by the U.S. Nuclear Regulatory Commission

- the Chernobyl reactor had no containment structure, so radioactivity did escape

- safety systems that, at a minimum, could have reduced the severity of the accident had been ordered shut off while a test of plant equipment was conducted; Ukraine closed the last operating Chernobyl reactor in December 2000

A map of eastern Europe and Russia.



The photo shows reactor No. 4 of the Chernobyl nuclear power plant after the explosion.

The photo taken on April 14, 2006 shows reactor No. 4 of the Chernobyl nuclear power plant, 130 kilometers north of Kiev, capital of Ukraine. Ukraine prepares to mark the 20th anniversary of the world's worst nuclear leakage triggered by an explosion happening at reactor No. 4 on April 26, 1986.

<u>Three Mile Island</u>:

- the U.S. nuclear energy industry learned many lessons from the Three Mile Island accident near Harrisburg, Pa., in March 1979

- although it did not result in a single injury, the accident aroused public fears concerning nuclear safety

- the accident began with a single pump failure; as the operators addressed this rather routine problem, an important valve failed to work the way it was designed, causing a leak in the reactor's cooling system; more than two hours passed before the faulty valve was discovered and shut

- during this time, thousands of gallons of radioactive water passed into the reactor building, but still within the containment; some of the water was pumped to storage tanks in an auxiliary building, but these tanks quickly spilled over

- the plant's operators were being misled by inadequately designed instrumentation that provided ambiguous indications of plant conditions; the operators believed the cooling system contained too much water, when in fact there was far too little

Three Mile Island, on the Susquehanna River at Harrisburg, Pennsylvania. On the right is mothballed Unit 2, which almost completely melted down in 1979, and is now is owned by FirstEnergy. Unit 1, to the left, is owned and operated by a subsidiary of Exelon Corp.

- because of this faulty reading, the operators took actions that essentially eliminated the system’s ability to remove heat from the reactor core

- although the nuclear reaction had ceased, heat in the fuel continued to increase, causing the metal grid work and supports that hold the fuel in place to melt and, according to research commissioned by the U.S. Department of Energy, the pellets themselves began to disintegrate

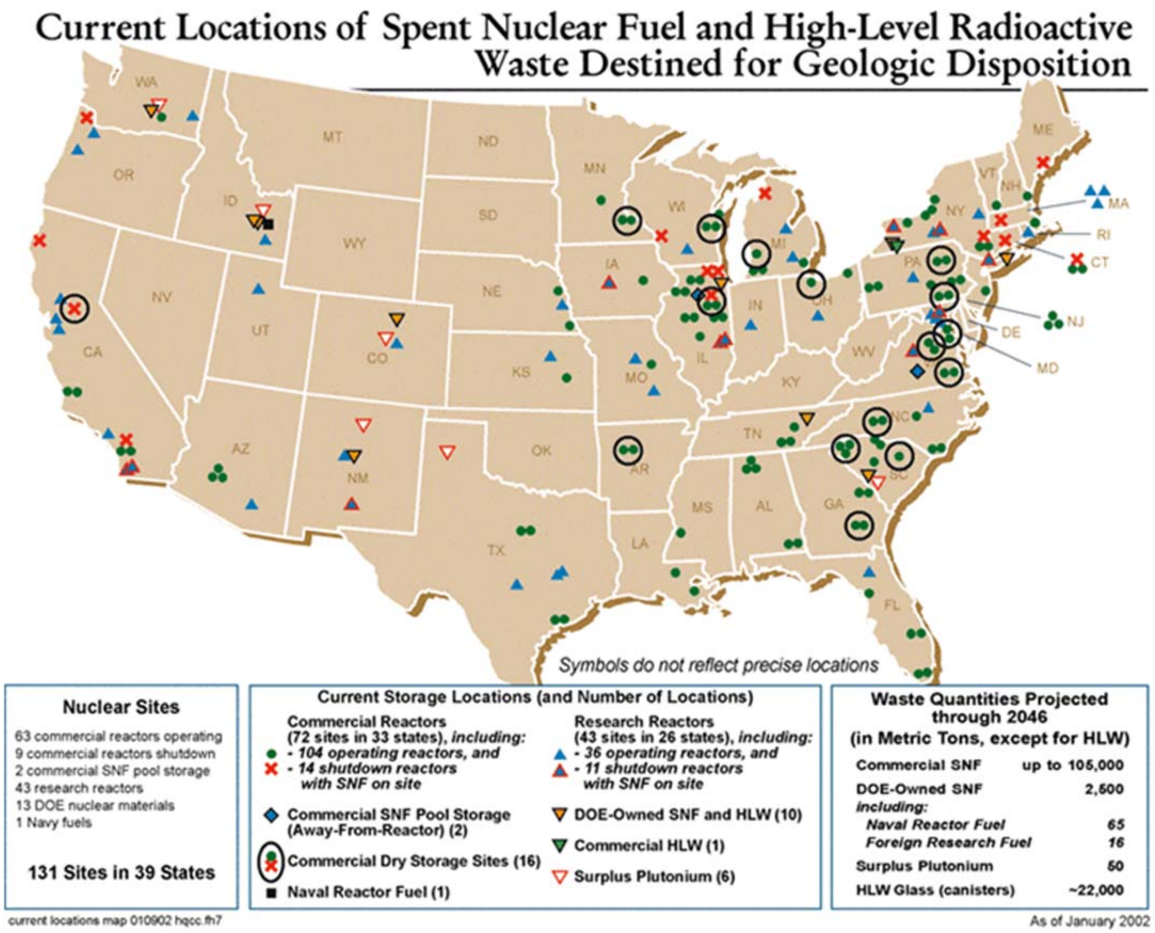
- three mile island restarted in 1985 and began its climb to world-class performance; in 1989, TMI-1’s capacity factor—a measure of reliability and safe operation—reached 100.03 percent, the best in the world

Nuclear Waste:

- used nuclear fuel is stored at nuclear power plants in 34 states

- it has been national policy that the federal government has responsibility for retaining control and disposing of used fuel

- U.S. Department of Energy has refused to meet its contractual obligation to take possession of used fuel beginning Jan. 31, 1998; the used fuel is still being stored at more than 75 nuclear power plant sites around the country

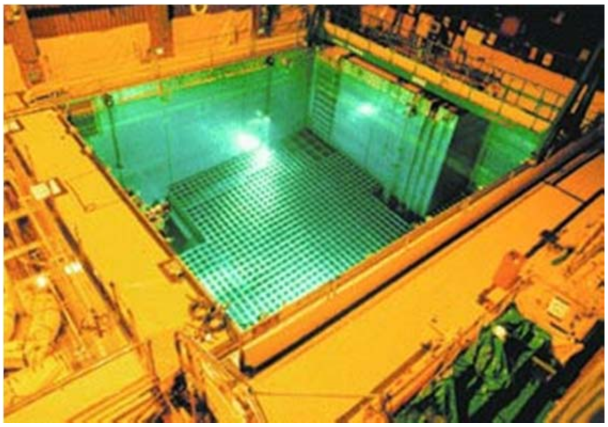


Current Locations of Spent Nuclear Fuel and High-Level Radioactive Waste Destined for Geologic Disposition

- the Energy Department claims that it cannot take the used fuel because the federal government has no place to store it

- temporary storage of spent fuel-rods is achieved by using pools of water; rods are placed under at least 20 feet of water, which provides adequate shielding from the radiation for anyone near the pool

- the rods are moved into the water pools from the reactor along the bottom of water canals, so that the spent fuel is always shielded to protect workers



- the long-lived elements in used nuclear fuel constitute the high-level radioactive wastes that must be disposed of permanently

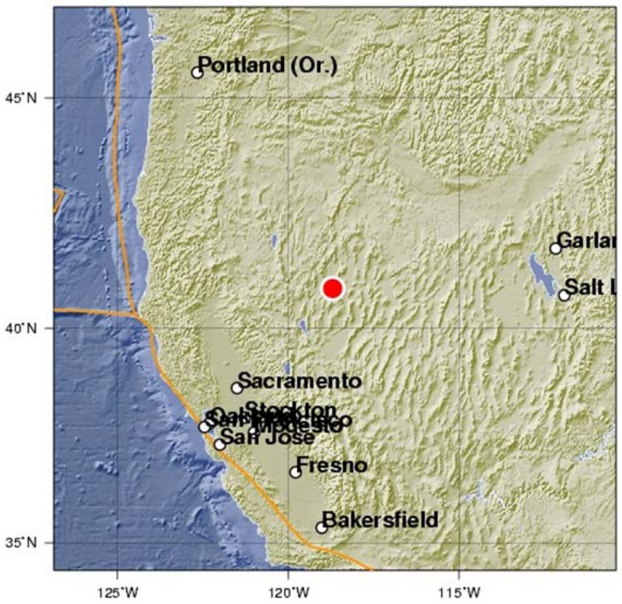
- some of these radioactive isotopes—plutonium-239 and iodine-129, for example—have half-lives that are measured in many centuries

- because it is a solid, used fuel is easy to manage and control; it can't spill or leak the way a liquid or a gas can; and because of its physical and chemical characteristics, used fuel cannot explode

- a typical nuclear power plant produces about 20 tons of used fuel each year

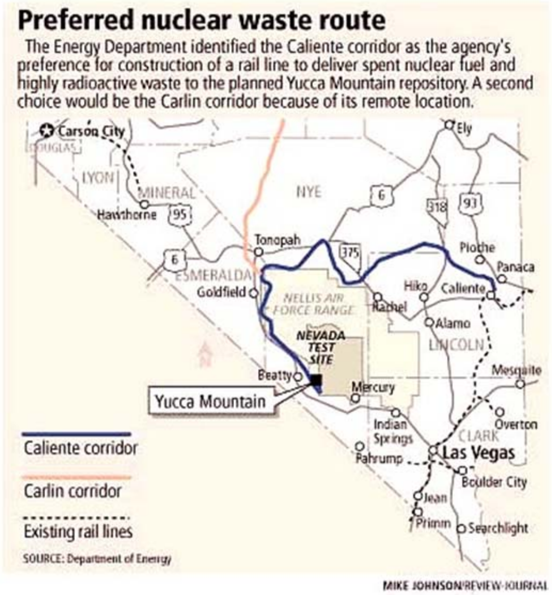
- all the used fuel produced by U.S. nuclear plants since the first commercial units began operating in the early 1960s—almost 40,000 tons—would cover an area the size of a football field to a depth of about five yards

- Yucca Mountain was officially designated as the site to store the nation's spent fuel and high-level radioactive waste in 2002



- Energy Secretary Spencer Abraham recommended the site to President George W. Bush, who approved it; Nevada Governor Kenny Guinn vetoed the decision, but the veto was overturned by Congress in July 2002

- in terms of transportation, the DOE has not yet identified specific rail and highway routes to be used for shipping waste to Yucca Mountain, with the exception of the Caliente corridor in Southern Nevada; waste shipments will not begin until 2010 at the earliest


Preferred nuclear waste route

The Energy Department identified the Caliente corridor as the agency's preference for construction of a rail line to deliver spent nuclear fuel and highly radioactive waste to the planned Yucca Mountain repository. A second choice would be the Carlin corridor because of its remote location.

SOURCE: Department of Energy

MIKE JOHNSON/REVIEW-JOURNAL

Nuclear Fusion:

- fusion events release the energy that powers the sun and other stars

- to release appreciable fusion energy requires high temperature plasmas confined for times long enough for sufficient fusion reactions to occur

- the results of research in nuclear and plasma physics are being used to create controlled fusion on earth as a possible source of energy to supplement other sources in meeting the world's needs

Energy Sources & Conversions:

- modern society relies on the availability of many forms of energy and must convert these into useful forms

- in most power plants, thermal energy is produced by energy-releasing reactions such as chemical, fission, and − in the future − fusion reactions

- the thermal energy is then converted to other useful forms in a cycle following the basic laws of thermodynamics

- limits in the efficiency of these conversion processes are formalized in the 2nd Law of Thermodynamics; invariably waste energy and waste material are produced

- the energy generated per kilogram of fuel, which is typically much larger for the nuclear processes, is based on the reactions and inputs shown on the chart

- in the most likely first-generation fusion plant, the reaction will actually be the fusion of deuterium, which is plentiful on the earth, and tritium

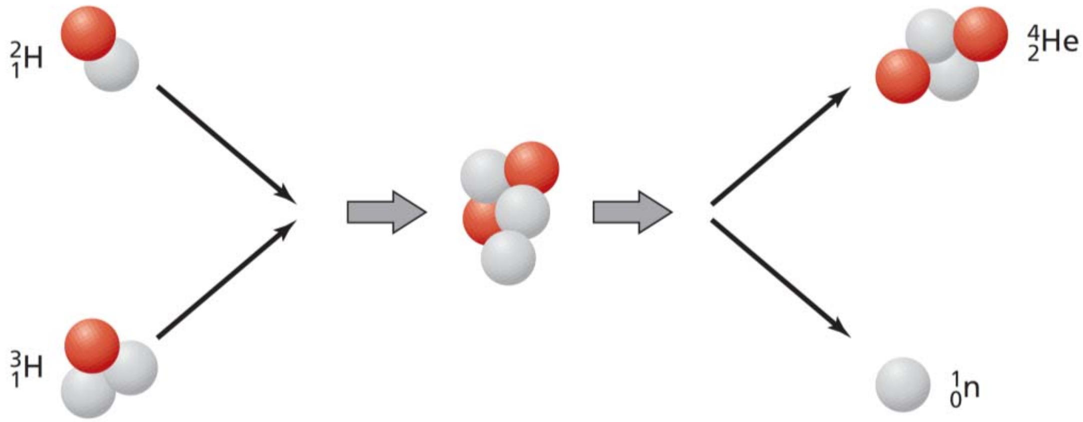
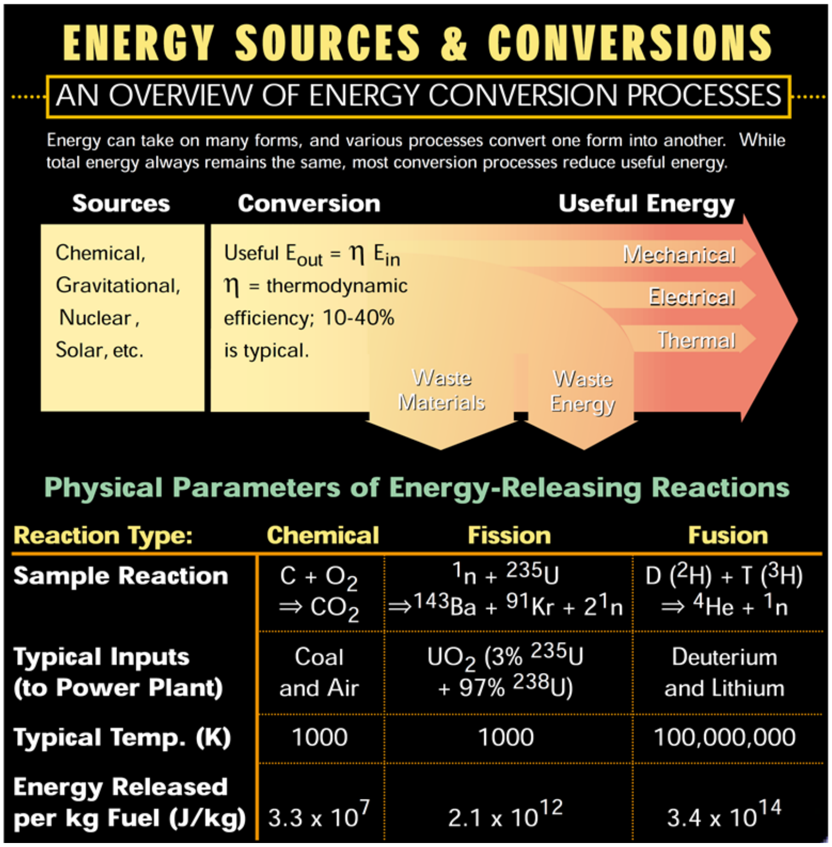


Figure 30-9 The fusion of deuterium and tritium produces helium. Protons are red and neutrons are gray in the figure.

- the tritium will be produced in the same reactor, since lithium absorbs neutrons from this “D-T” reaction and splits into tritium and helium



ENERGY SOURCES & CONVERSIONS

AN OVERVIEW OF ENERGY CONVERSION PROCESSES

Energy can take on many forms, and various processes convert one form into another. While total energy always remains the same, most conversion processes reduce useful energy.

Sources	Conversion	Useful Energy
Chemical, Gravitational, Nuclear, Solar, etc.	Useful $E_{out} = \eta E_{in}$ η = thermodynamic efficiency; 10-40% is typical.	Mechanical Electrical Thermal

Physical Parameters of Energy-Releasing Reactions

Reaction Type:	Chemical	Fission	Fusion
Sample Reaction	$C + O_2 \Rightarrow CO_2$	$^1n + {}^{235}U \Rightarrow {}^{143}Ba + {}^{91}Kr + 2\,{}^1n$	D (^2H) + T (^3H) $\Rightarrow {}^4He + {}^1n$
Typical Inputs (to Power Plant)	Coal and Air	UO_2 (3% ^{235}U + 97% ^{238}U)	Deuterium and Lithium
Typical Temp. (K)	1000	1000	100,000,000
Energy Released per kg Fuel (J/kg)	3.3×10^7	2.1×10^{12}	3.4×10^{14}

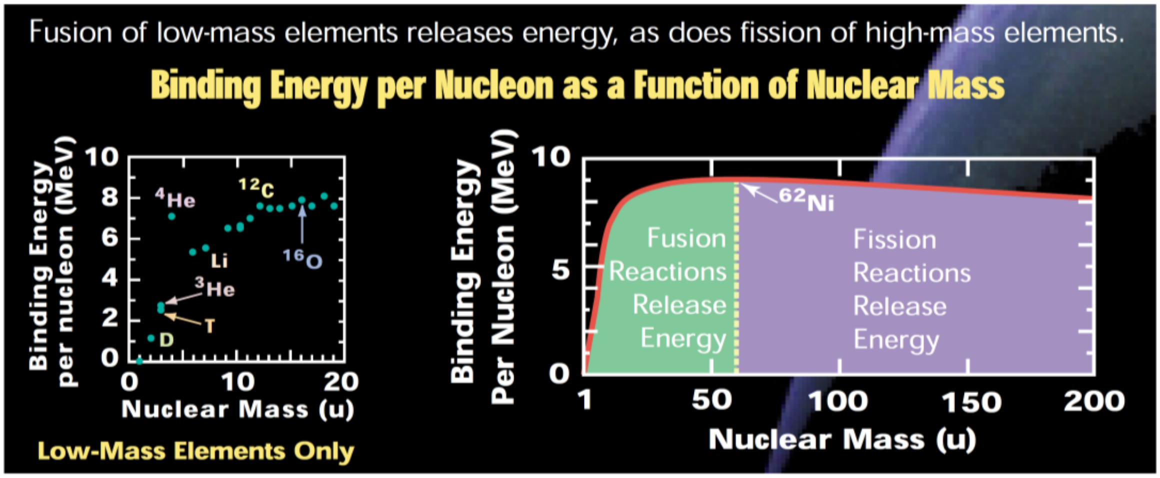
- thus deuterium and lithium are the actual input materials

How Fusion Reactors Work:

- kinetic energy is released by the mass differences of reactants and products

- the binding energy of a nucleus is the difference in the mass of the nucleus compared to the sum of the masses of its constituent nucleons (protons and neutrons)

- a larger binding energy represents a greater difference; the shape of the graph of binding energy per nucleon shows that combining low mass elements (fusion) yields a nucleus with greater binding energy per nucleon and thus releases energy



- for larger mass elements (above about mass 62 u), splitting the nucleus into smaller parts (fission) gives less massive nuclei thereby releasing energy

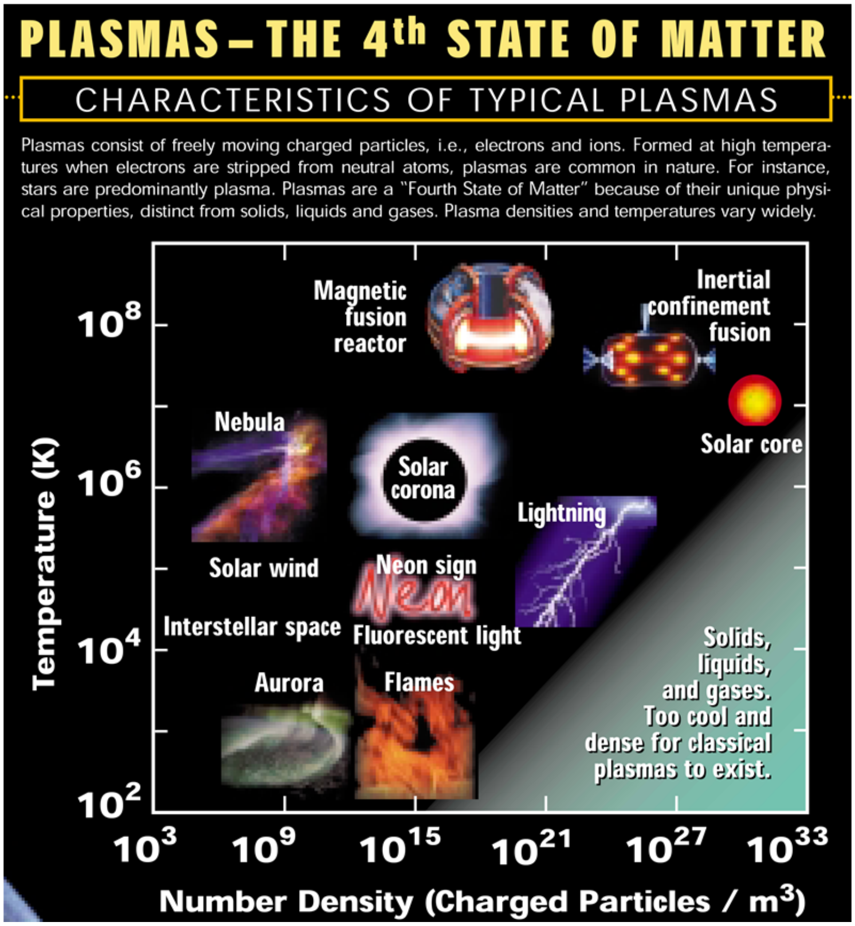
- because the curve is steeper on the “fusion” side (masses below 62 u) than the “fission” side, there is more energy released per nucleon in fusion than in fission

- high temperatures are necessary because the nuclei must approach to within about 10^{-15} m to fuse, so that the attraction from the strong force between the nuclei overcomes the electromagnetic repulsion between the protons

Plasmas - the 4th State of Matter:

- plasmas, collections of freely moving charged particles, occur in many contexts, spanning an incredible range of densities and temperatures

- plasma science provides one of the cornerstones for our knowledge of the Sun, the stars, the interstellar medium, galaxies, neon lighting, lightning, the aurora and techniques for controlling the fusion process



PLASMAS – THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.

- plasmas are influenced by the long-range electrical interactions of ions and electrons and by the presence of magnetic fields, either applied externally or generated by current flows within the plasma

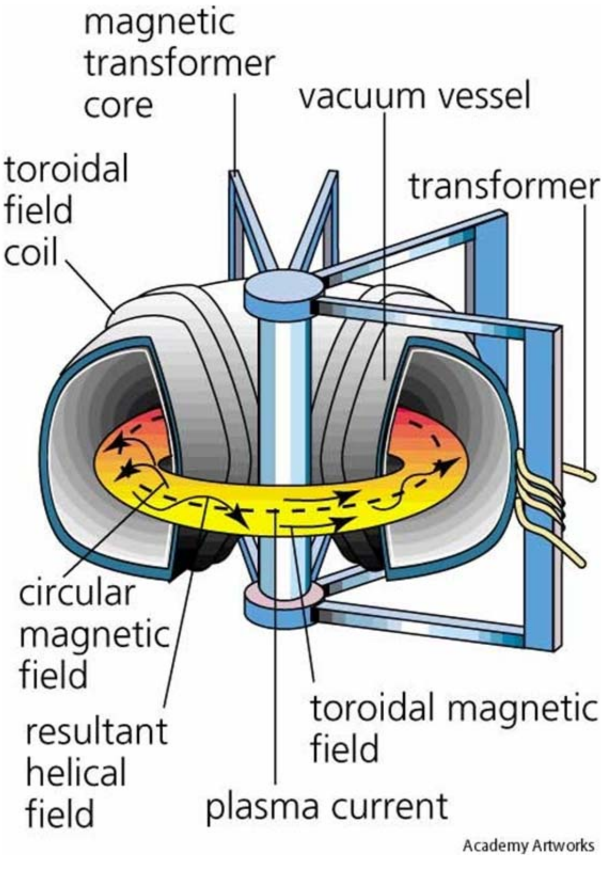
- the dynamics of such systems are complex and must be well understood for the development of fusion energy

<u>The Conditions for Fusion</u>:

- refinements in the techniques for heating and confining plasmas are necessary to achieve controlled fusion

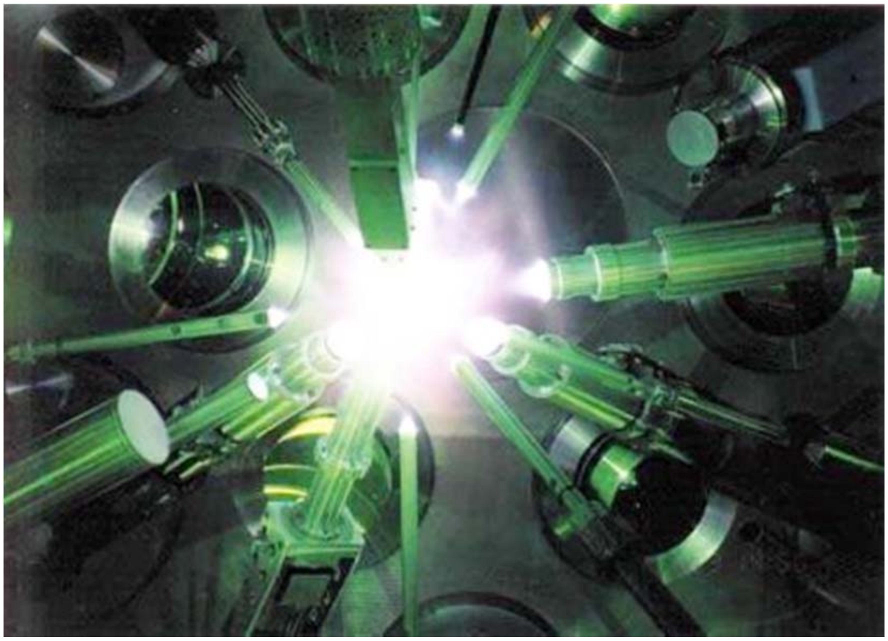
- for the deuterium-tritium plasma which must be at temperatures of about 108 K, the two most promising confinement techniques are magnetic and inertial

- the tokamak, a toroidal device comprising a hollow doughnut shaped vessel through which magnetic fields twist, is the most common magnetic confinement device under study

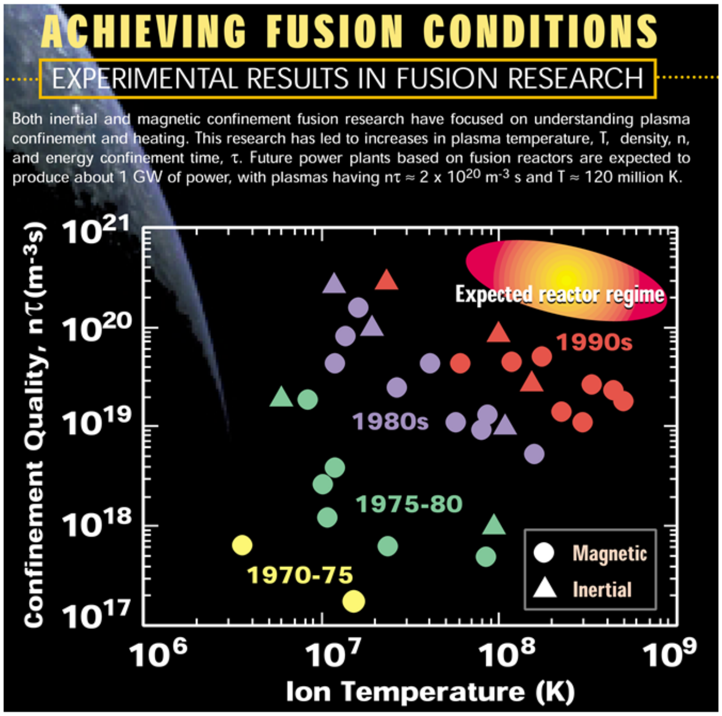


Academy Artworks

- in inertial confinement, intense lasers or ion beams compress a pellet to extremely high plasma densities and temperatures which will allow significant amounts of fusion in the short time the imploding pellet is confined by its inertia



- to achieve controlled fusion, a plasma at a given temperature must be confined at a high enough density for a sufficiently long time



ACHIEVING FUSION CONDITIONS

EXPERIMENTAL RESULTS IN FUSION RESEARCH

Both inertial and magnetic confinement fusion research have focused on understanding plasma confinement and heating. This research has led to increases in plasma temperature, T, density, n, and energy confinement time, τ. Future power plants based on fusion reactors are expected to produce about 1 GW of power, with plasmas having $n\tau \approx 2 \times 10^{20}$ m^{-3} s and T ≈ 120 million K.

- this criterion is expressed in terms of the confinement quality: the product of the plasma density and energy confinement time

- recent experiments have produced plasmas with either confinement time, the plasma density, or plasma temperature at values near or exceeding those needed for self-sustaining controlled fusion, but all three have not been achieved simultaneously