Nuclear Energy

Mechanical Engineering 694C

Seminar in Energy Resources, Technology and Policy

Larry Caretto

September 25, 2002

California State University
Northridge

Remind students to turn in homework.

Reading for this week is pages 120 to 140 in Fay and Golomb.

No class next week, October 2. Work on project proposals. Proposals due October 9.

Reading for next class is pages 143 to 183 in Fay and Golomb.

Problems for this week, due October 9: 6.1, 6.2, and 6.5

Main Ideas

- Current and projected use
- Basic physics
- Nuclear electricity generation methods
- Regulation of nuclear energy
  - Nuclear safety
  - Nuclear waste disposal
- Fusion Energy and Prospects for the future

California State University Northridge

2

Nuclear energy now accounts for a significant fraction of electrical energy produced in the world. In France, the vast majority of electrical energy is produced by nuclear power. Since the accidents at Three Mile Island and Chernobyl there has been an increased public concern about the risks of nuclear energy. In addition, the costs of nuclear power are now higher than other power generation methods.

Recently there has been an increased interest in nuclear generation. In the deregulated power market several older nuclear power plants have been recently sold at a significantly higher price than their previous sale. Increasing concerns about global warming caused by emissions of CO_2 from combustion of fossil fuels have increased the attractiveness of nuclear power.

These notes present an overview of nuclear power generation starting from the basic physics, leading through nuclear plant designs and regulations of nuclear power.

Finally we will discuss the prospects for fusion power and some of the current thinking about the future of nuclear power generation in the US and in the world.

Nuclear Power Share1999

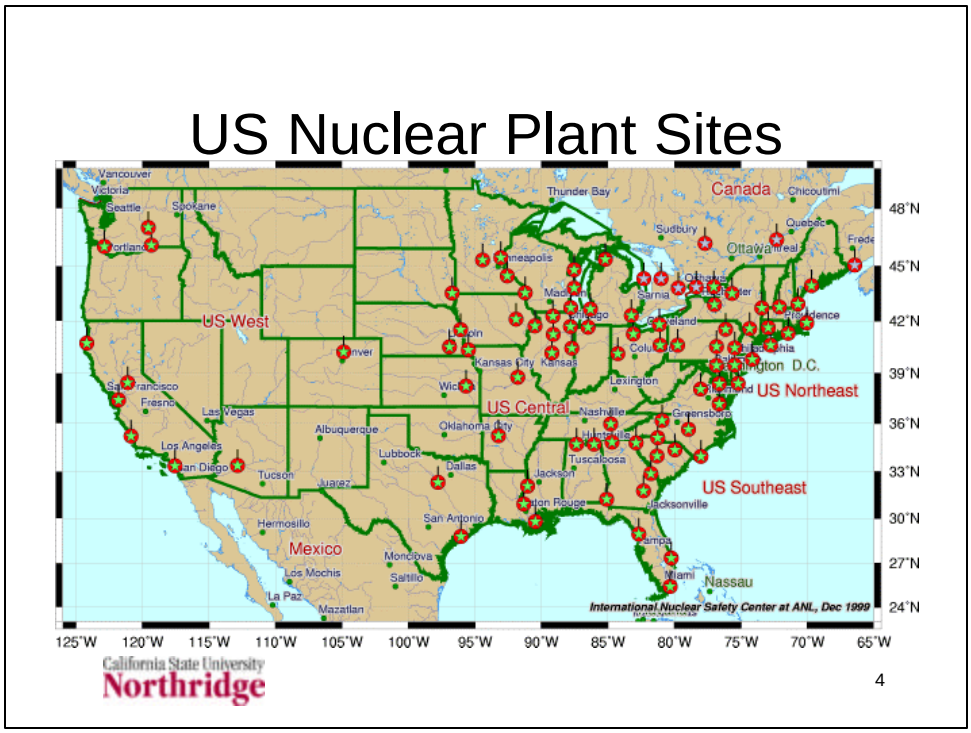
North America	18.1%
Central and South America	1.4%
Western Europe	30.4%
Eastern Europe and Former Soviet Union	16.4%
Middle East	0.0%
Africa	3.2%
Asia and Oceania	12.3%
World Total	17.9%

California State University Northridge

3

The slide shows the percent of a region's total electrical energy that is produced by nuclear power. The nuclear proportion of electrical energy for individual countries having the highest values for this figure is shown below. The percent of the world nuclear electrical energy is also shown for each country. The world total nuclear energy generation for 1999 was 228.3 TWh.

Country	**%nuclear**	**%world**	**Country**	**%nuclear**	**%world**
Lithuania	76.1%	0.4%	Spain	28.2%	2.3%
France	75.1%	15.7%	Taiwan	26.4%	1.5%
Belgium	58.2%	1.9%	United Kingdom	26.1%	3.8%
Slovakia	47.5%	0.5%	Czech Rep	20.7%	0.5%
Sweden	44.2%	2.8%	United States	19.7%	30.5%
Ukraine	41.6%	2.8%	Russia	13.8%	4.6%
Bulgaria	41.4%	0.6%	Canada	12.3%	2.9%
Korea, South	39.1%	4.1%	Romania	9.9%	0.2%
Hungary	38.1%	0.6%	Argentina	9.0%	0.3%
Slovenia	35.9%	0.2%	South Africa	6.9%	0.5%
Switzerland	35.2%	1.0%	Mexico	5.2%	0.4%
Armenia	33.2%	0.1%	Netherlands	4.3%	0.2%
Germany	30.4%	6.7%	India	2.5%	0.5%
Japan	29.6%	12.6%	China	1.2%	0.6%
Finland	29.4%	0.9%	Brazil	1.2%	0.2%



http://www.insc.anl.gov/pwrmaps/map/united_states.html is the source for this map and information below on California reactors.

Humboldt Bay 3 in Eureka is 63 MW(e) BWR that operated from 1963 to 1976 is permanently shut down.

Rancho Seco in Clay Station (near Sacramento), PWR 913 MW(e). operated from April 1975 to June 1989.

The location near San Francisco is called Vallecitos; there is no further information about this site.

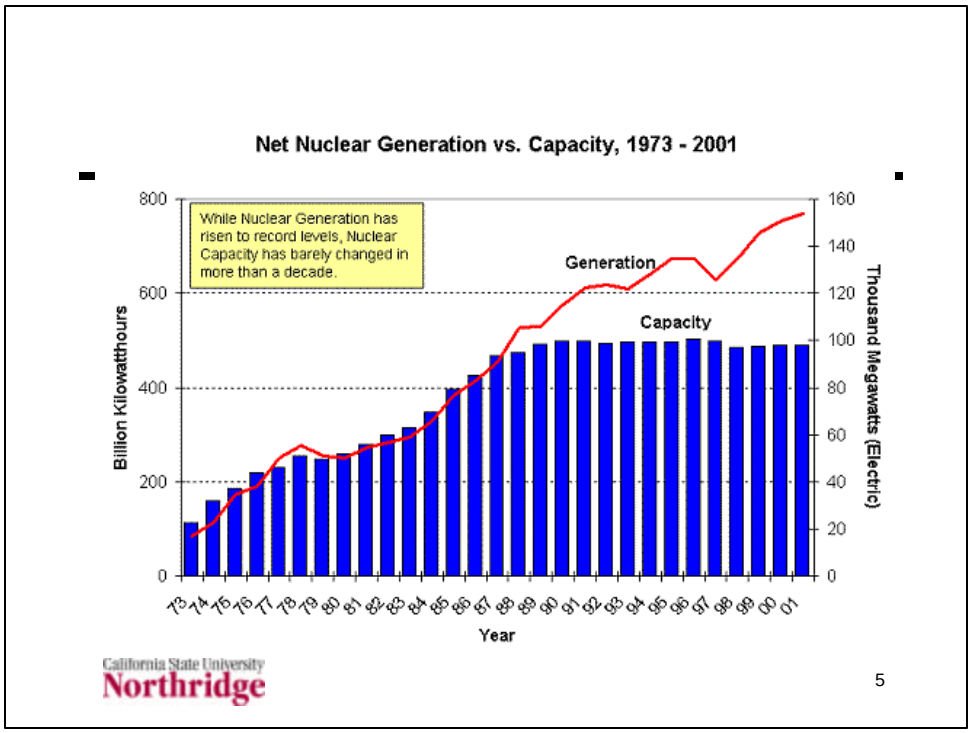
The Palo Verde plant in Arizona has three PWRs each rated at 1,243 MW(e). This is the largest nuclear facility in the US. **Operator:** Arizona Nuclear Power Project **Owners:** Arizona Public Service Co. (29.1%); Salt River Project Agricultural Improvement & Power District (17.5%); Southern California Edison Co. (15.8%); El Paso Electric Co. (15.8%); Public Service Co. of New Mexico (10.2%); Southern California Public Power Authority (5.9%); Los Angeles Department of Water & Power (5.7%) **Reactor Supplier:** Combustion Engineering, Inc.

Unit 1 in 2001: 9.46 billion kWh **2001 Average Capacity Factor:** 86.9%

Unit 2 in 2001: 9.98 billion kWh **2001 Average Capacity Factor:** 91.6%

Unit 2 in 2001: 9.29 billion kWh **2001 Average Capacity Factor:** 85.0%

Data on San Onofre and Diablo Canyon are on the notes page for the next chart.



The chart of nuclear capacity and generation shows the increased generation while having constant capacity. This indicates a increase in capacity factor.

Diablo Canyon San Luis Obispo County, California. Construction of the units may have been the longest in U.S. history at 15 and 16 years due to regulatory concern for its ability to withstand seismic activity. Cooling water for the units is obtained from the Pacific Ocean. **Operator:** Pacific Gas & Electric Company
Owner: PG&E Corp. (100.0%) **Reactor Supplier:** Westinghouse Corporation
Unit 1:1,073 net MWe PWR **Date of Operation:** November 1984 **License Expiration Date:** 09/22/2021 **2001:** 9.47 billion kWh **Average Capacity Factor:** 100.8%

Unit 2 Capacity: 1,087 net MWe PWR **Date of Operation:** August 1985 **License Expiration Date:** 04/26/2025 **2001:** 8.61 billion kWh **2001 Average Capacity Factor:** 90.4%

San Onofre 3-unit site near San Clemente. Unit 1, shutdown in 1992, was a first generation Westinghouse commercial unit that operated for 25 years.

Units 2 & 3 Operator: Southern California Edison Co. **Owners:** Edison International (75.1%); San Diego Gas & Electric Co. (20%); Anaheim Public Utilities Dept. (3.2%); Riverside Utiltities Dept. (1.8%) **Reactor Supplier:** Combustion Engineering, Inc.

Unit 2 capacity: 1,070 net MWe PWR **Date of Operation:** September 1982 **License Expiration Date:**10/18/2022 **2001:** 9.49 billion kWh **Average Capacity Factor:** 101.3%

Unit 3 Capacity: 1,080 net MWe PWR **Date of Operation:** September 1983 **License Expiration Date:**10/18/2022 **2001:** 5.65 billion kWh **verage Capacity Factor:** 59.7%

Source: http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html

Basic Physics

- Einstein: $\Delta e = \Delta mc^2$
- $^{235}U + n \quad ^{144}Ba + ^{89}Kr + 3n + 177MeV$
- Nuclear energy units
  - 1 atomic mass unit =1.660 538 73x10^{-27} kg
  - 1 eV = 1.602 176 462x10^{-19} J
- Energy comparison
  - ^{235}U fission = 7.3x10^{13} J/kg
  - Carbon combustion = 3.3x10^{7} J/kg

California State University Northridge

6

Einstein's formula $e = mc^2$ can better be written in terms of Δe and Δm. It is the change in mass in a nuclear reaction that produces a certain amount of energy. Atomic masses are measured in terms of the atomic mass unit or amu. One amu is exactly 1/12 the mass of a C^{12} atom. (Recall that the atomic mass system is defined such that the atomic weight of of C^{12} is exactly 12; one amu is approximately the mass of a proton or the mass of a neutron.) Since 12 grams of C^{12} is exactly one mol with Avagadro's number (6.02214199x10^{23}) of atoms, one atom of C^{12} has a mass of 12g/(6.02214199x10^{23}). So the amu is1/12th of this mass or 1.66053873x10^{-27} kg.

The energy unit of electron-volts is the energy generated when one electron moves through an electric field of one volt. The change on an electron is 1.602176462x10^{-19} coulombs, and one coulomb-volt = 1 joule. (Recall that 1 ampere = 1 coulomb/s and the product of amps and volts is watts or joule-seconds.) Thus the energy in one eV is 1.602176462x10^{-19} J. The speed of light is 299,792,458 m/s, so the annihlation of 1 emu of mass produces (1.66053873x10^{-27} kg) * (299,792,458 m/s)^2 =1.49241778308056x10^{-10} J = 931495084.5 eV = 931.4950845 MeV. In the fission of ^{235}U into ^{144}Ba and ^{89}Kr, the mass difference is 0.19 amu producing the energy shown.

In this reaction the energy release per unit mass of ^{235}U is 177 MeV / 235.04394 amu; this is equivalent to 7.3x10^{13} J/kg compared to 3.3x10^{7} J/kg for carbon combustion.

Mass Defect

- Isotopic mass less than mass of constituents
- Difference is binding energy
- $D = Z(m_p + m_e) + (A - Z)m_n - M$
- Where D = mass defect, m_p, m_e, and m_n are masses of proton, electron and neutron, Z = protons, A – Z = neutrons

California State University Northridge

7

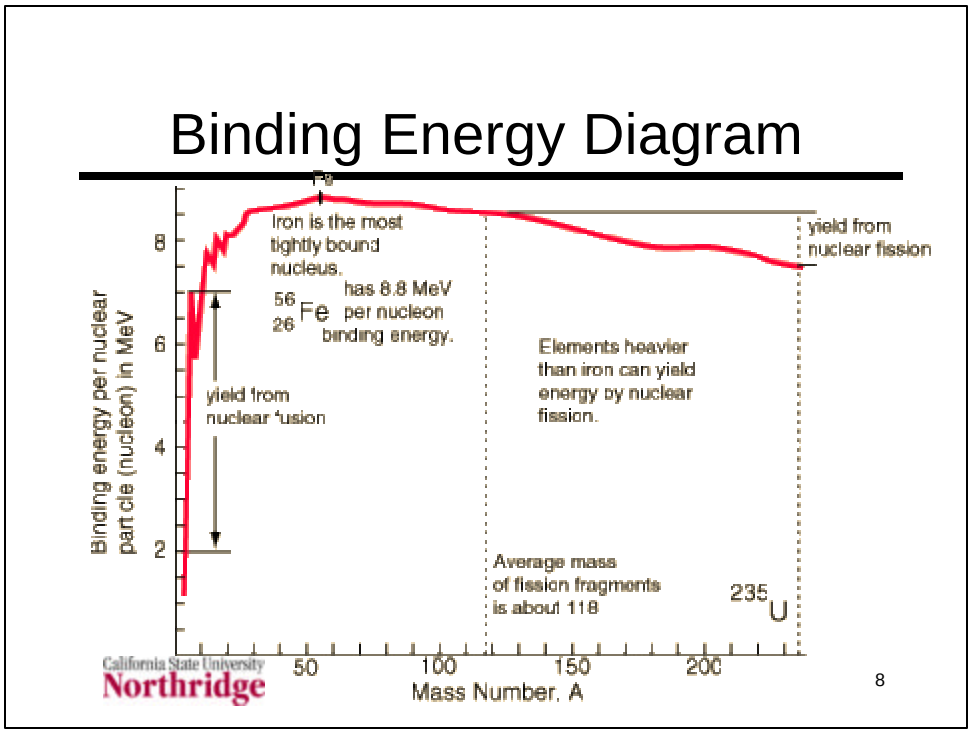
M in this chart is the mass of the nucleus with Z protons and A – Z neutrons.

The concept of a mass defect recognizes that the binding energy of the nucleus, BE, can be written in terms of this defect as $BE = Dc^2$. From the conversion factors on the previous chart, a mass defect of 1 amu is equivalent to a binding energy of 931.4950845 MeV.

With the units of amu, the mass of one atom or molecule is just the atomic or molecular weight expressed in amu. For example the mass of ^{235}U is 235.04394 amu. The mass of a neutron is 1.008665 amu; the masses of a proton and an electron are 1.007276 amu and 0.000549 amu, respectively.

The binding energy is commonly expressed as the average binding energy divided by the total "nucleons", A, which is the sum of protons and neutrons. The equation for this term is simply the equation on the chart divided by A.

The binding energy is the energy produced in a hypothetical reaction where the protons plus the neutrons combine to form the actual isotope.



Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html#c1

We see that the binding energy per nucleon is a maximum for iron. This chart allows us to see the effects of fission or fusion. We start with a certain binding energy in the initial element(s). When we have a nuclear reaction to another set of elements (with a certain average binding energy per nucleon), we have the possibility of releasing energy if the binding energy of the products is greater than the binding energy of the reactants.

This occurs because we can write, for example

92 protons + 143 nuetrons U-235 + 235(7.6 MeV)

For the average fission products we can write

92 protons + 143 neutrons Fission products + 235(8.6 MeV)

Subtracting these two expression gives

U-235 Fission products + 210 MeV

For elements lighter than iron, we can produce nuclear energy when we combine lighter elements into heavier ones. This is known as nuclear fusion. For elements heavier than iron, nuclear fission, the separation of a heavier element into two (or more) lighter ones will produce energy.

Nuclear Radiation

- Spontaneous decay of nuclei can yield other nuclei and radiation
  - Alpha particles $^{239}Pu \rightarrow {}^{235}U + \alpha(^{4}He)$
  - Beta particles $^{90}Sr \rightarrow {}^{90}Y + \beta(^{0}e)$
  - Gamma radiation $^{60}Co \rightarrow {}^{60}Co + \gamma$
- The α, β, and γ radiation have different energy levels that affects their impact

California State University Northridge

9

In addition to nuclear fusion and fission, we can have a series of other nuclear reactions. In these reactions different kinds of radiation are released. Note that beta radiation, although it is equivalent to an electron, comes from the nucleus, not from the outer shell of the atom. Release of an electron from a nucleus with Z protons and A – Z neutrons increases the number of protons by one and decreases the number of neutrons by one. Decreasing the number of protons changes the chemical identity of the nucleus. Thus the beta decay of strontiun-90 into yttirium comes because the number of protons in the nucleus has increased from 38 to 39.

Gamma radiation is high energy electromagnetic radiation. The wavelength region for gamma rays is between 10^{-10} and 10^{-12} meters.

In a nuclear reaction a complex series of changes can occur. Not only does the basic fission reaction take place, but products from the original fission, called daughter products can under go other reactions. The complexity of the reaction schemes produces a large amount of different isotopoes, with varying degrees of radioactivity in the spent fuel from the nuclear reactor.

Chain Reactions

- $^{235}U + n \rightarrow {}^{144}Ba + {}^{89}Kr + 3n + 177MeV$
- Product neutrons, called fast neutrons, have MeV range energies
- Slow or thermal neutrons energies are in the eV range
- In a nuclear reactor the fast neutrons may be moderated into slow neutrons

California State University Northridge

10

The equation at the top of the page is taken from a previous slide. It shows the basic notion of a chain reaction. The reaction not only produces energy, but it also produces additional neutrons to carry on the reaction.

Some of the neutrons may be absorbed and some may leave the reactor. A critical mass is one in which the chair reaction can be sustained.

Additional reactions can take place in a nuclear reactor from the product neutrons. One of these is the production of plutonium-239 by the reaction of a neutron with U-238 that is usually present. Here is the sequence that produces plutonium

$^{238}U + n \rightarrow {}^{239}U + \gamma$

$^{239}U \rightarrow \beta + {}^{239}Np$

$^{239}Np \rightarrow \beta + {}^{239}Pu$

The first reaction in this sequence changes the number of neutrons in the nucleus, but it does not change the number of protons; thus we still have element the element with 92 protons in the nucleus, uranium. In the second reaction, the ^{239}U releases an electron from the nucleus. This does not affect the total number of nucleons in the nucleus; instead it converts a neutron to a proton. We thus have 93 protons in the nucleus so we have formed element 93 which is called neptunium. The neptunium then undergoes a subsequent beta decay with the same effect. The number of protons in the nucleus is increases giving element 94 which is Plutonium.

Plutonium is the main element used in nuclear weapons. The design of nuclear reactors depends on their purpose. Reactors to produce nuclear weapons are designed to produce significant amounts of plutonium. Civilian reactors are designed to avoid the production of plutonium.

Radioactive Decay

- Decay proportional to amount present
- $dN/dt = -kN$ so $N = N_0e^{-kt}$
- $t = (-1/k)\ln(N/N_0)$
- Half life, $t_{1/2}$, is point where $N/N_0 = ½$
- $t_{1/2} = (-1/k)\ln(1/2) = \ln(2)/k$
- $N = N_0e^{-\ln(2)t/t_{1/2}}$

California State University Northridge

11

The decay rate of spontaneous radiation is directly proportional to the amount present. The time required for half of the initial radiation to decay is known as the half life. Half lives for various isotopes can range from centuries to microseconds.

The calculation of how much of the original amount of a radioactive isotope is present after a certain period of time is computed in terms of half lives:

½ present after one half life

¼ present after two half lives

1/8 present after three half lives

1/16 present after four half lives

1/1024 present after ten half lives

1/1048476 present after twenty half lives

The proposed nuclear waste storage facility in Ward Valley Nevada is designed to store the nuclear waste that will be radioactive for a long time.

Radiation Measurements

- Units for rate of decay
  - becquerel (Bq) = 1 disintegration per sec
  - curie (Cu) – older unit; 1 Cu = 3.72×10^{10} Bq
- Units for energy deposited in matter
  - 1 gray (Gy) = 1 J/kg in water
  - 1 roentgen (R) = .008 J/kg in air (approx)
  - 1 rad =.01 Gy (radiation absorbed dose)

California State University Northridge

12

The curie is defined as the amount of radiation from one gram of radium. Thus one gram of radium has 3.72×10^{10} disintegrations per second.

The gray is defined as the amount of energy absorbed in water, where water is used as a surrogate for human tissue. The gray is really trying to measure the amount of energy absorbed in human tissue.

The roentgen (R) is a measure of radiation intensity of X-rays or gamma rays. It is formally defined as the radiation intensity required to produce and ionization charge of 0.000258 coulombs per kilogram of air. It is one of the standard units for radiation dosimitry, but is not applicable to alpha, beta, or other particle emission and does not accurately predict the tissue effects of gamma rays of extremely high energies. The roentgen has mainly been used for calibration of X-ray machines. (Quoted from http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html.)

Biological Effectiveness

- The sievert (Sv) is the new measure of effective radiation dose
  - Replaces the former unit of rem (roentgen equivalent man)
- Biological equivalence coefficient, Q, accounts for different radiation effects
  - 1 rad delivers Q rem
  - 1 Gy delivers Q Sv

California State University Northridge

13

There are two approaches to defining standards. The first uses direct measures of the radiation in terms of grays (or the older units of rads). The other uses the notion of biological effective dose described here. Again, there is a new unit, the sievert, and an old unit, the rem. The conversion between these two is the same as the conversion between grays and rads:

1 gray = 100 rads or 1 rad = 0.01 gray

1 sieverts = 100 rem or 1 rem = 0.01 sievert

The Q factor is not constant. For alpha particles it is about 20. For X-rays it is defined to be one.

Although the sievert is now the preferred unit for radiation exposures, there is still a large amount of data in rems and, more commonly, millirems.

Natural Radiation Doses

• Cosmic rays	0.38 mSv/yr
• Internal to human body	0.19 mSv/yr
• Environmental minerals	0.46 mSv/yr
• Radon and daughters	1.3 mSv/yr
• Medical/dental X-rays	0.54 mSv/yr
• Total natural plus medical	2.87 mSv/yr

California State University Northridge

14

These data were taken from Table 4-1, page 89 in the book *Megawatts and Megatons*, by Garwin and Charpak. Recall that 1 seivert = 100 rem so these numbers would be multiplied by 100 to get the doses in millirem.

This chart shows the normal exposure that the typical US resident has to radiation from natural and medical sources. This is an average and there are large differences in the various exposures depending on your individual living situation.

People in Denver get more cosmic rays than people in Los Angeles. (So do people who fly a lot compared to people who don't.)

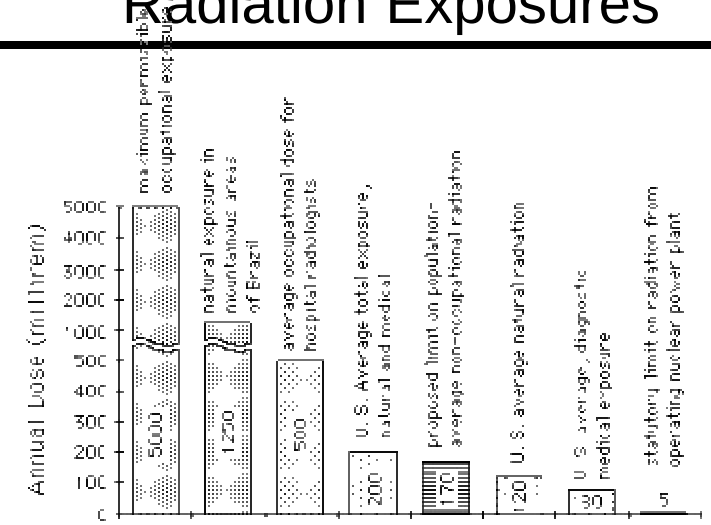
People who live in brick houses get radon exposure. Other get significantly less.

The exposure to environmental minerals depends to a large degree on where you live. At one time there were attempts to mine uranium in the Antelope Valley; I would guess that there may be larger mineral background radiation in parts of the Antelope Valley than there are in the Los Angeles Basin.

X-ray exposure is obviously dependent on the amount of X rays one receives. This is a risk benefit calculation that all individuals subconsciously make to have the benefits of medical diagnosis traded against the risks of radiation exposure.

Note that all such data are subject to approximations and the data here differ from those on the next slide taken from a different source.

Radiation Exposures



California State University Northridge

15

Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html which attributes the figure to Nave, C. R. and Nave, B. C., *Physics for the Health Sciences*, 3rd Ed, W. B. Saunders, 1985.

In this chart medical X-rays are said to contribute 80 millirems which is equivalent to 0.8 mSv in contrast the estimate of 0.54 mSv on the previous chart. Similarly the total exposure to natural and medical radiation is listed here as 200 millirems per year as compated to 2.87 mSv = 287 millirems on the last chart.

http://www.nrc.gov/what-we-do/radiation/sources.html#member says that the total natural dose is about 360 millirems/year or about 3.6 mSv/yr. Of this total, natural sources of radiation account for about 81% of all public exposure, while man-made sources account for the remaining 19%. Natural and artificial radiations are not different in any kind or effect. Above this background level of radiation exposure, the NRC requires that its licensees limit maximum radiation exposure to individual members of the public to 100 mrem (1 mSv) per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000mrem (50 mSv) per year. (NRC regulations and radiation exposure limits are contained in Title 10 of the Code of Feral Regulations under Part 20).

NRC Exposure Data (mrem)

Source	Population	Dose	per capita dose
Radon	230	200	200
Other Natural	230	100	100
Occupational	0.93	230	0.9
Nuclear Fuel Cycle[1]		- - -	0.05
Tobacco [2]	50	- - -	- - -
Other Prod	120	5 - 30	5 - 13
Environment	25	0.6	0.06
Medical			53

California State University Northridge

16

[1] Collective dose to regional population within 50 miles of each facility.

[2] Difficult to determine a whole body dose equivalent for tobacco use. However, the dose to a portion of the lungs is estimated to be 16,000 millirems/year.

In the data on medical exposures, then umber of persons unknown. However, 180 million X-Ray examinations were performed with an average dose of 50 millirems per examination. In addition, nuclear medicine treatments had 7.4 million examinations performed with an average dose of 430 millirems per examination.

Health Risks

- Cumulative risk of getting a disease at any time is lifetime risk (0.25 for cancer)
- Relative risk: ratio of incidence from some cause to normal incidence
  - Relative risk of smoking for lung cancer 9.9
  - Cohort studies measure relative risk
  - Case control studies measure odds ratio
  - Excess relative risk = relative risk minus 1

California State University Northridge

17

Health risks are measured in the terms shown here.

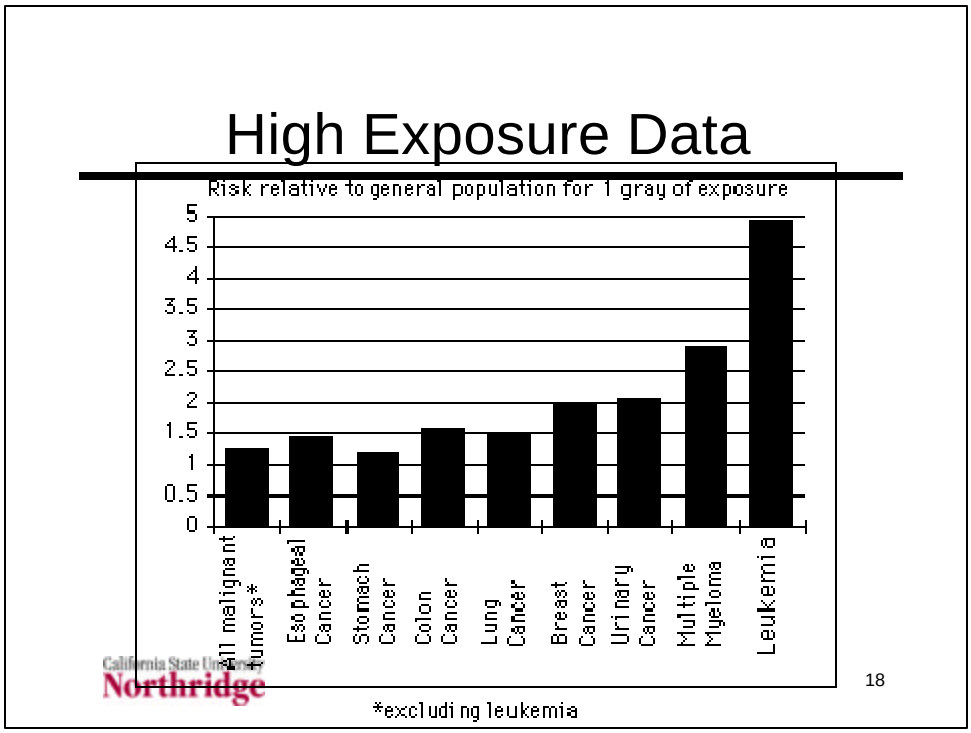
The difference between an odds ratio and a relative risk is a formal one which recognizes the differences in two kinds of studies. In a cohort study, sometimes called a prospective study, two groups are selected. One group receives a "treatment" and a second group does not. The groups are followed for some period of time and the incidence of the disease under study is measured in both groups. The incidence rate of some disease in the group with the "treatment" is then compared to the incidence rate in the group which did not receive the treatment. The cohorts are designed to have similar activity patterns so the differences in the disease rate will be due to the treatment.

The second kind of study, the case control study, sometimes called a retrospective study, is one in which two groups are selected (e.g. people who worked with radiation and those who did not). The incidence rate of certain diseases is then compared for the two groups. Other factors which may affect the results are controlled for in the study.

Both types of studies are known as epidemiological studies. These are studies on human populations. Ethical issues govern these studies and limit the kinds of exposures that can be provided.

Other types of studies, known as toxicological studies, use laboratory animals. In such studies it is possible to use exposures to large doses that would not be used on humans. The problem is in extrapolating results to humans. This is usually done by studying the effect in terms of units like grams of dose per kilogram of body weight. The easiest subjects to use are mice, but these have a metabolism that is not like humans. Studies on larger animals are more expensive and usually not done.

My favorite quote from an epidemiologist is the following: "Epidemiology uses the right species but does not always have accurate dose data; toxicology uses the wrong species but has accurate dose data. I'll take the right species any time."



Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html which attributes the chart to the Atlanta Journal, March 20, 1993, page F1.

The health effects associated with exposures to radiation are uncertain. Although we know that large doses have the results shown in the table below, we do not know what the long term effects to low does of radiation over long times are. The standards for radiation exposure are based on a linear, no-threshold hypothesis. This means that high does exposures for which we have data are extrapolated to zero effect at zero dose, without assuming a threshold. Some health scientists have argued that this is too conservative, but it has been used to provide protection to the public.

Effect	Dose (rems)
No observable effect	0-25
Slight blood changes	25-100
Significant reduction in blood platelets and white blood cells (temporary)	100-200
Severe blood damage, nausea, hair loss, hemorrhage, death in many cases	200-500
Death in less than two months for over 80%	>600

Nuclear Reactors

- Classified by neutron energy
  - Fast versus slow
- Moderators reduce neutron energy
- Fast breeder reactors
- Light water reactors
- Gas cooled rectors
- CANDU reactors

California State University Northridge

19

Nuclear reactors have fissile fuel that undergoes nuclear fission and produces energy. Once a chain reaction is started many different reactions can take place in the reactor. If the majority of the fission reactions are done by fast neutrons, the reactor is called a fast reactor. When moderators are used to absorb the energy of the fast neutrons, most of the fissions are done by slow (or thermal) neutrons. Such reactors are called thermal reactors (because they use thermal neutrons).

All nuclear rectors have the following an active core in which fissile fuel undergoes fission. The core may also contain a fertile material that can be converted to a fissile material. If the reactor is to use slow or thermal neutrons, a moderator is required. The core is surrounded by a reflector to prevent neutrons from escaping from the core.

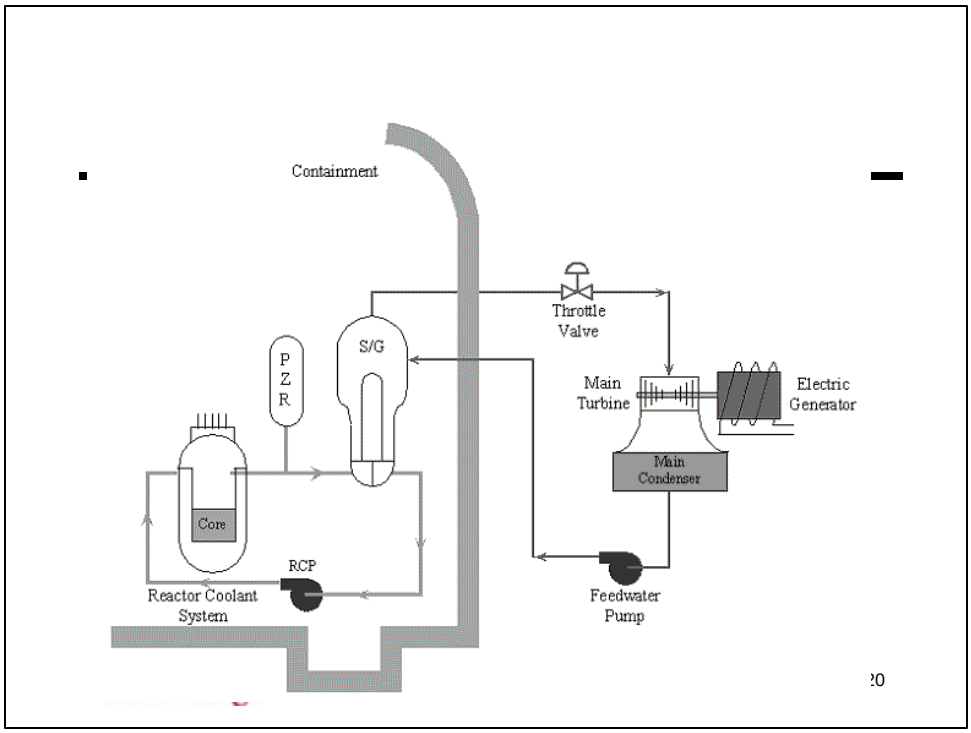
The heat produced in the core is removed by a coolant. The energy added to this coolant is then used to produce useful power from the reactor.

The reaction is controlled by rods inserted into the core that absorb neutrons. Such rods, called control rods, are neutron poisons such as boron or cadmium.

Fast breeder reactors use both a fertile and a fissile material. Such a reactor can produce more fuel from the fertile material than it consumes from the fissile material.

Most commercial reactors are light-water reactors in which H_2O, with its natural isotopic composition acts as both the moderator and the coolant. Such reactors have a fuel that is about 2% to 4% U-235.

The CANDU reactor uses natural uranium as the fuel with heavy-water (deuterium oxide or D_2O) as the moderaor.

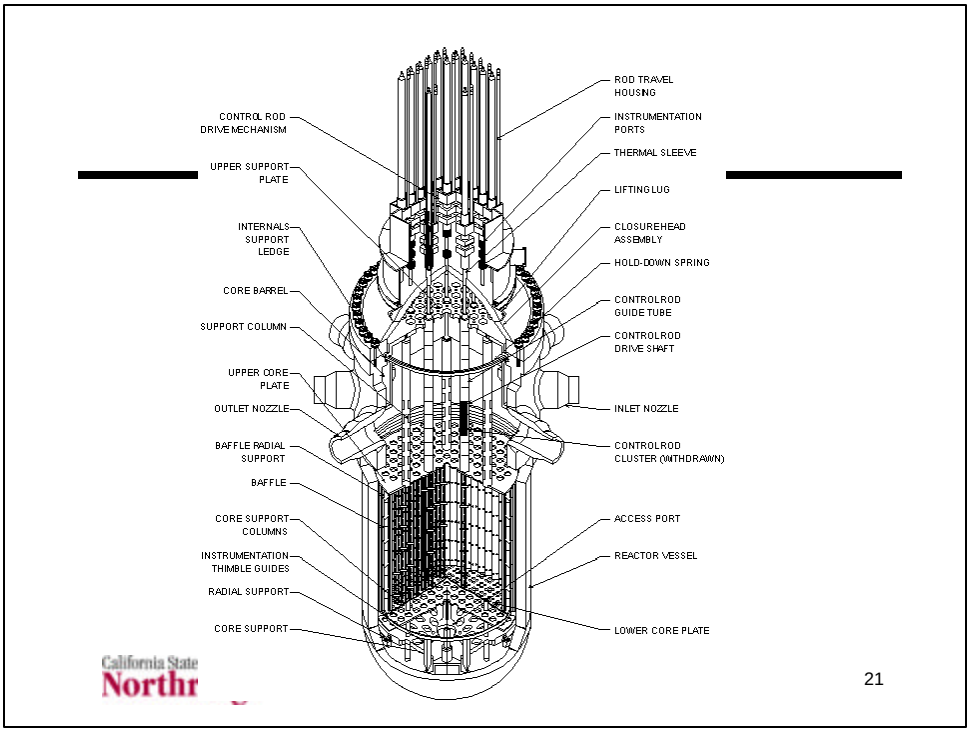


This diagram shows a pressurized water reactor. In this reactor there is a separate coolant loop of high pressure water that receives heat from the reactor and then exchanges heat with the working fluid in the steam generator (SG). Both the reactor and the steam generator are located within the containment vessel that is designed to contain the debris from a nuclear accident. Steam produced in the steam generator then is used in a steam turbine as in a fossil-fueled power plant.

In this diagram RCP is the reactor coolant pump and PZR is the pressurizer, a tank or vessel that acts as a head tank (or surge volume) to control the pressure in a pressurized water reactor.

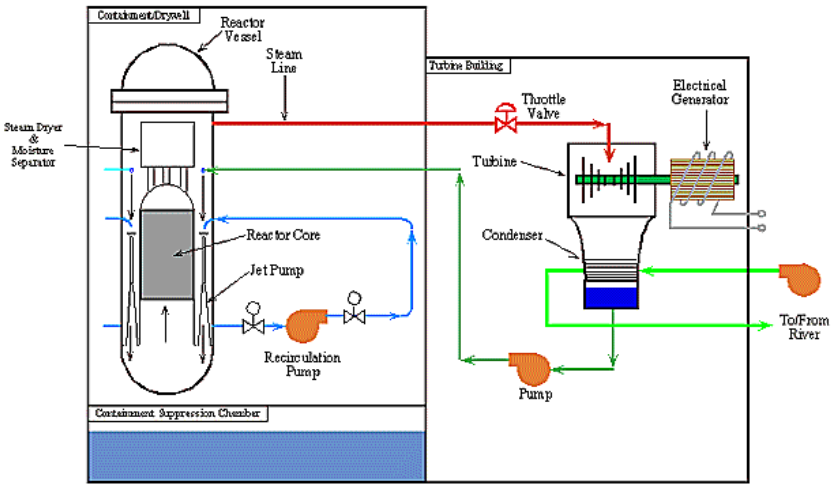
The diagram was found at http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html

In the US 69 units are pressurized water reactors (PWRs) totaling 65,100 net megawatts (electric) and 35 units are boiling water (BWR) totaling 32,300 net megawatts (electric).



This detailed diagram of a reactor vessel for a pressurized water reactor was found at http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html

Boiling Water Reactor



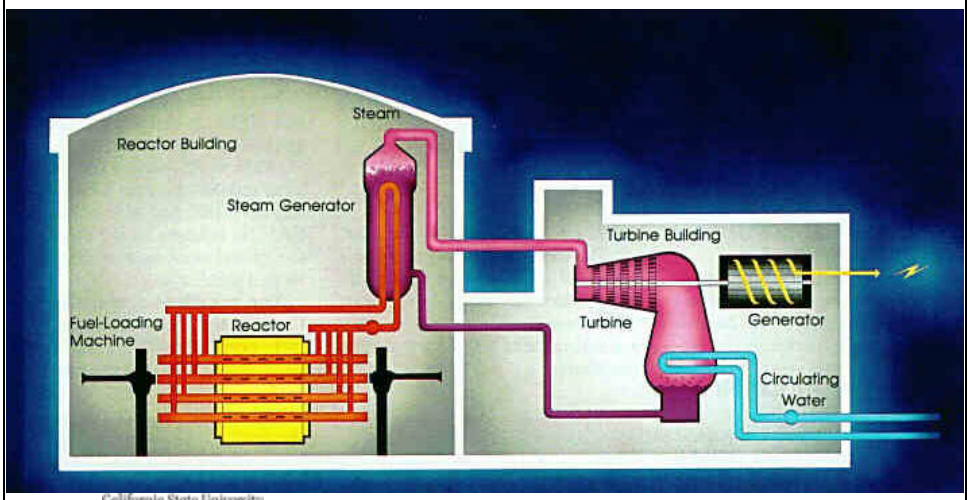
Northridge

22

Reference: http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/

In the boiling water reactor, the heat from the reactor core is used to produce steam. In order to keep the core cooled, additional water circulation is used.

CANDU Reactors



California State University Northridge

23

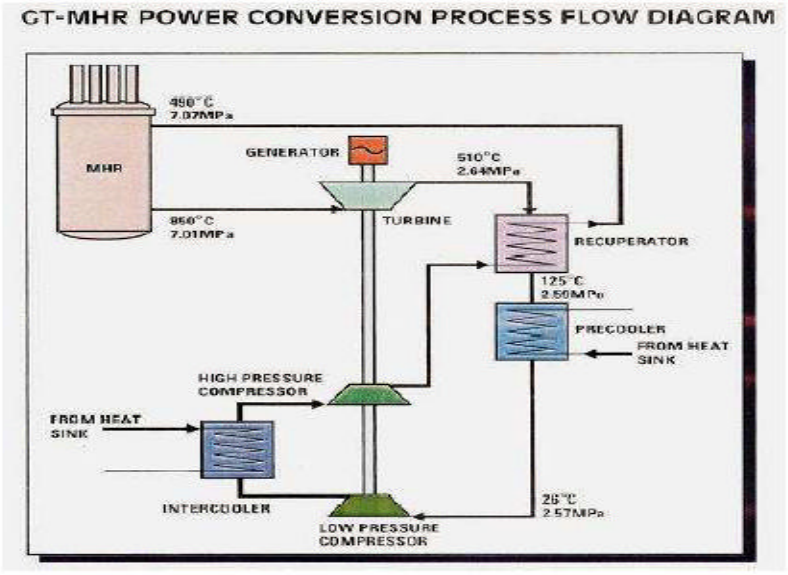
Reference: http://www.ncf.carleton.ca/~cz725/cnf_sectionA.htm#a

CANDU (a registered trademark) stands for **"Canada Deuterium Uranium"**. It is a pressurized-heavy-water, natural-uranium power reactor designed first in the late 1950s by a consortium of Canadian government and private industry. All power reactors in Canada are of the CANDU type (of varying vintage). It is also the power-reactor product marketed by Canada abroad

The CANDU reactor uses **natural uranium** fuel and **heavy water** (D2O) as both moderator and coolant (the moderator and coolant are separate systems). It is **refuelled at full-power**, a capability provided by the subdivision of the core into hundreds of separate **pressure tubes**. Each pressure tube holds a single string of natural uranium fuel bundles (each bundle ishalf a meter long and weighing about 20 kg) immersed in heavy-water coolant, and can be thought of as one of many separate "mini-pressure-vessel reactors" - highly subcritical of course. Surrounding each pressure tube a low-pressure, low-temperature moderator, also heavy water, fills the space between neighboring pressure tubes.

Heavy water is about eight times worse than light water for slowing down ("moderating") neutrons, but its macroscopic absorption cross-section (i.e. probability of absorption) is over 600 times less, leading to a *moderating ratio* (the ratio of the two parameters, a useful measure of a moderator's quality) that is 80 times higher than that of light water.

Heavy water's low absorption cross-section permits the use of natural uranium, which is low in fissile content and would not attain criticality in a light-water lattice. The lower slowing-down power of heavy water requires a much larger lattice than in light-water cores; however, the larger lattice allows space at the core endfaces for on-line refuelling, as well as space between channels for control rods, in-core detectors, and other non-fuel components.



California State University Northridge

24

Reference: http://www.iaea.org/programmes/ne/nenp/nptds/htgr/technology.pdf

High temperature gas (cooled) reactors HTGR or HTGCR uses graphite as the moderator and some gas such as helium as the coolant. The power conversion uses a closed Brayton cycle. (Typical Brayton cycle engines that use the combustion gases as the working fluid simply dump the waste heat in the form of exhaust gas to the atmosphere.

This diagram shows the GT-MHR development program has started in 1993 in a venture involving MINATOM of Russia and General Atomics (GA) of the US, together with Framatome of France and Fuji Electric of Japan. The proposed plant, rated at 600 MWt/293 Mwe will be utilized for weapons Plutonium destruction with a long-term goal of commercial development. The final design is expected in 2005, with construction planned for 2009.

Claimed efficiencies for the advanced reactor types are of the order of 50%.

Nuclear Reactor Fuel

- Light water reactors require enriched uranium fuel
- Natural uranium has about 0.7% ^{235}U
- Power plants require enrichment to about 5% ^{235}U or less
- Uranium purchased in terms of separative work units

California State University Northridge

25

Reference: http://www.urenco.de/pdf_archiv/uran_enrich.pdf

In order to start and sustain a chain-reaction in a light water reactor, the uranium isotope 235 (U235) in nuclear fuel must have a concentration of up to 5% depending on reactor-type and design. U235 is the only isotope of uranium which can be split by thermal neutrons. However, naturally occurring uranium, contains only 0.71% of the U235 isotope. The remaining portion is overwhelmingly made up of the U238 isotope which cannot be split. The enrichment of the somewhat lighter U235 is thus a technically necessary step in the manufacture of nuclear fuel from natural uranium. For the annual reload of a standard pressurized water reactor of 1300 MW electrical capacity and a burn-up of 50 GWd/tU today some 24 tonnes of uranium with an average U235 concentration of 3.95% are required.

Assuming depletion to 0.3% U235 some 213 tonnes of natural uranium must be used and some 124 tonnes of separative work are required for the enrichment. Separative work is a measure of the amount of effort required for enriching uranium and is explained in more detail in the next chapter. For the enrichment of uranium a number of separation processes have been invented and in part further developed. The main processes used today are gaseous diffusion and centrifugation. Both of these take advantage of the differences in mass between the uranium isotopes.

Separative Work Unit

- Have feed stream, F, with $N_F = 0.0071$ and product stream P, with N_P, and waste (tail) stream, T, with N_T
- Mass balance $F = P + T$
- Balance on ^{235}U: $F N_F = P N_P + T N_T$
- $SWU = PV(N_P) + TV(N_T) – FV(N_F)$
- V(N) is the value function

California State University Northridge

26

Declining Spot-Market Prices Like the uranium market, the enrichment market since the beginning of 1998 has experienced a further decline in both spot and long-term contract prices that began in mid-1996. In mid-1996, the spot-market price for the restricted U.S. enrichment market was $98.00 per separative work unit (SWU). By the beginning of 1998, the restricted price had dropped to $86.00 per SWU. The restricted enrichment spot-market price was $84.00 per SWU in June 1999. During the same period, the unrestricted price fell from $92.00 per SWU to $83.00 per SWU. Major reasons for the decline in prices are:

Since 1996, the U.S. dollar has appreciated against most European currencies, meaning that European enrichers Urenco and Cogema could sell more competitively in the U.S. market, were they were able to gain additional market share. European enrichers also made additional inroads to the Japanese market.

Urenco, a European-based enricher, embarked on a program to expand its production capacity. Even though there is a large surplus of enrichment capacity versus requirements, by having low-cost gaseous centrifuge capacity, Urenco was able to both expand production and sell this additional production at the expense of its competitors. While Urenco benefited from the strong dollar, this expansion probably had more to do with a restructuring of the company that centralized management decisions.

As long-term contract prices dropped, spot inventory holders had to reduce prices in order to compete with these supplies. They also had to compete with primary enrichers for spot sales opportunities, especially those that resulted from utilities exercising quantity flexibility provisions under existing long-term contracts. By and large, developments in the long-term contract market dictated spot price trends, as only a small percentage of overall enrichment volume is transacted on the spot market.

Calculating SWU

- Value function defined and tabulated $$V(N) = (2N-1)\ln\left(\frac{N}{1-N}\right)$$

N	V(N)	N
0.001	6.892941	0.999
0.002	6.187756	0.998
0.005	5.240372	0.995
0.01	4.503217	0.99
0.02	3.736147	0.98
0.05	2.649995	0.95
0.1	1.75778	0.9
0.2	0.831777	0.8
0.5	0	0.5

California State University Northridge

27

The value function is a measure of the work involved in obtaining pure components from a binary mixture. It depends only on the concentrations. The work is defined to be zero for a 50:50 mixture. As the degree of purity of the components in the separated stream increases, the separative work increases.

The symmetry about N = ½ can be expressed by the following equation V(1/2+x) = V(1/2 – x).

Note that there are two effects taking place here, concentration and recovery. For a given concentration of U235 in the product stream, it takes more work to produce a lower concentration in the tailings. This recovers more of the uranium, reducing the initial material cost. The optimum tailing concentration is a trade off between the material cost and the separation costs.

Uranium Hexafluoride UF_6

• Triple point at 1516.5 mbar	64.02 °C
• Density (solid) at 20.7°C	5.09 g/cm3
• Density (liquid) at 64.02°C	3.668 g/cm3
• Density (liquid) at 148.9°C	3.043 g/cm3
• Heat of sublimation at 64.02°C	11.4 kcal/mol
• Melting heat at 64.02°C	4.5 kcal/mol
• Vaporizing heat at 64.02°C	6.8 kcal/mol
• Reaction heat with water at 25°C	50.4 kcal/mol
• Critical pressure	45.6 bar
• Critical temperature	230.2 °C
• Vapor pressure at 20°C	106.7 mbar
• Molecular weight	352.07 kg/kmol
• Sublimation point at 1013.5 mbar	56.4°C

California State University Northridge

28

Reference: http://www.urenco.de/pdf_archiv/uran_enrich.pdf

Separation processes use gaseous UF_6. The uranium has to be converted to uranium hexafloride for the separation process.

Nuclear Energy Regulation

- Nuclear Regulatory Commission (NRC)
- International Atomic Energy Agency (IAEA)
- Environmental Protection Agency (EPA)
- Department of Energy (DOE)

California State University Northridge

29

NRC has responsibility for regulating the use of—

Source material (uranium and thorium)

Special nuclear material (enriched uranium and plutonium)

Byproduct material (material made radioactive in a reactor, and residues from the milling of uranium and thorium)

The NRC regulates the use of radioactive materials through 10 CFR Part 20, "Standards for Protection Against Radiation." Part 20 includes agency requirements for —

Dose limits for radiation workers and members of the public

Monitoring and labeling radioactive materials

Posting radiation areas

Reporting the theft or loss of radioactive material

Part 20 also includes—

Penalties for not complying with NRC regulations

Tables of individual radionuclide exposure limits

The IAEA is responsible for setting international programs for nuclear energy. Much of their effort is directed towards a comprehensive program of nuclear safety and avoiding the diversion of nuclear materials from civilian reactors into weapons programs.

The EPA has responsibility for environmental radiation standards and one of their major efforts has been in addressing the problem of radon exposure in homes and offices.

The DOE, NRC, and EPA share responsibility for the development of the Ward Valley Waste Disposal Site.

Waste Disposal

- Permanent repository for high-level nuclear waste scheduled to start accepting waste in 2010
- Location in Ward Valley, NV
- Present operation of Waste Isolation Pilot Plant (DOE/DOT/EPA/NRC)
- 10,000 year standard

California State University Northridge

30

Reference: http://www.epa.gov/radiation/wipp/faq.htm#general_1

What is the WIPP?

"WIPP" is the abbreviation for the Waste Isolation Pilot Plant, a U.S. Department of Energy (DOE) facility located in southeastern New Mexico, 26 miles southeast of Carlsbad. The site chosen for the 2,150-foot-deep WIPP is a 16-square-mile tract of federal land that consists of a thick layer of rock salt deposited about 225 million years ago. The facility is the nation's first geological repository for permanent disposal of transuranic (TRU) radioactive waste. Congress authorized the development of WIPP in 1980 to demonstrate the safe disposal of radioactive waste resulting from defense programs of the United States.

What is Transuranic Radioactive Waste?

The term "transuranic" is derived from trans, meaning beyond, and uranic, meaning uranium. TRU waste, which contains manmade elements heavier than uranium (and therefore "beyond uranium" on the periodic chart) is produced during nuclear fuel assembly, nuclear weapons research, productions, and cleanup, and as a result of reprocessing spent nuclear fuels. The waste generally consists of protective clothing, tools, glassware, and equipment contaminated with radioactive materials.

TRU waste consists of materials containing alpha-emitting radio-isotopes, with half-lives greater than twenty years and atomic numbers greater than 92, in concentrations greater than 100 nano-curies per gram of waste. The WIPP Land Withdrawal Act specifically excludes high-level waste and spent nuclear fuel from the definition, as neither is allowed to be disposed of at the WIPP.

EPA and the WIPP

First, EPA was required to finalize regulations which apply to all sites -- except Yucca Mountain -- for the disposal of spent nuclear fuel, transuranic and high level radioactive waste. The regulations, located at Subparts B and C of 40 CFR Part 191 (disposal regulations), limit the amount of radioactive material which may escape from a disposal facility, and protect individuals and ground water resources from dangerous levels of radioactive contamination.

EPA Process for WIPP

- Set environmental standards
- Monitor DOE activities
- DOE runs WIPP
- DOT is responsible for setting transportation standards
- Ward Valley site continues to be controversial

California State University Northridge

31

EPA's final certification of compliance will allow the emplacement of radioactive waste in the WIPP to begin, provided that all other applicable health and safety standards, and other legal requirements, have been met. at waste generator sites.

Panel Closure System - Condition 1 of the certification relates to the panel closure system, which is intended over the long term to block brine flow between waste panels in the WIPP.

Waste Characterization and Quality Assurance - Conditions 2 and 3 of the final rule relate to activities conducted at waste generator sites that produce the transuranic waste proposed for disposal in the WIPP. The compliance criteria require DOE to have in place a system of controls to measure and track important waste components, and to apply quality assurance ("QA") programs to waste characterization activities.

Passive Institutional Controls - Condition 4 of the certification relates to passive institutional controls ("PICs"). The compliance criteria required DOE to use both records and physical markers to warn future societies about the location and contents of the disposal system to deter inadvertent intrusion into the WIPP. return to: [top] [previous location]

Throughout its operation of the WIPP, DOE must submit a recertification application to EPA every five years, documenting the WIPP's In the immediate future, EPA will conduct inspections at waste generator sites in order to implement Conditions 2 and 3 of the compliance certification.

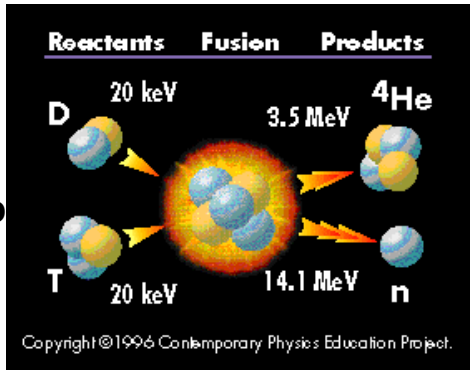
There is world-wide scientific consensus that 10,000 years is a time over which we can reasonably predict geology, hydrology and climatology (we extrapolated backwards to the last ice age, 10,000 years ago). If WIPP can meet the standards for 10,000 years, then it is highly likely that it will survive beyond that.

The current defense-generated transuranic waste is temporarily stored at federal government facilities in California, Colorado, Idaho, Illinois, Nevada, New Mexico, Ohio, Tennessee, South Carolina, and Washington.

Regulations issued by the Department of Transportation set guidelines for routing waste to the WIPP, but give the states and Indian tribes authority to designate routes within their borders. Different departments make the decision in each state, ranging from the Department of Health in Texas to the Public Service Commission in Indiana.

Fusion Power

- **Two Important Fusion Reactions**
- **D + T => ^{4}He + n**
- **For first generatio fusion reactors**



California State University Northridge

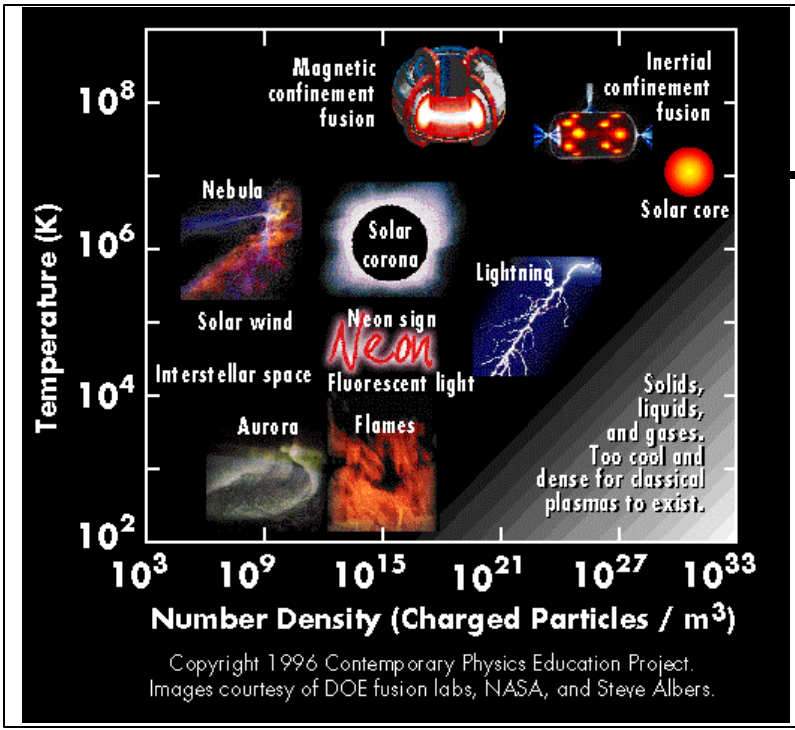
32

http://fusedweb.pppl.gov/CPEP/Chart.html

Energy-Releasing Reactions

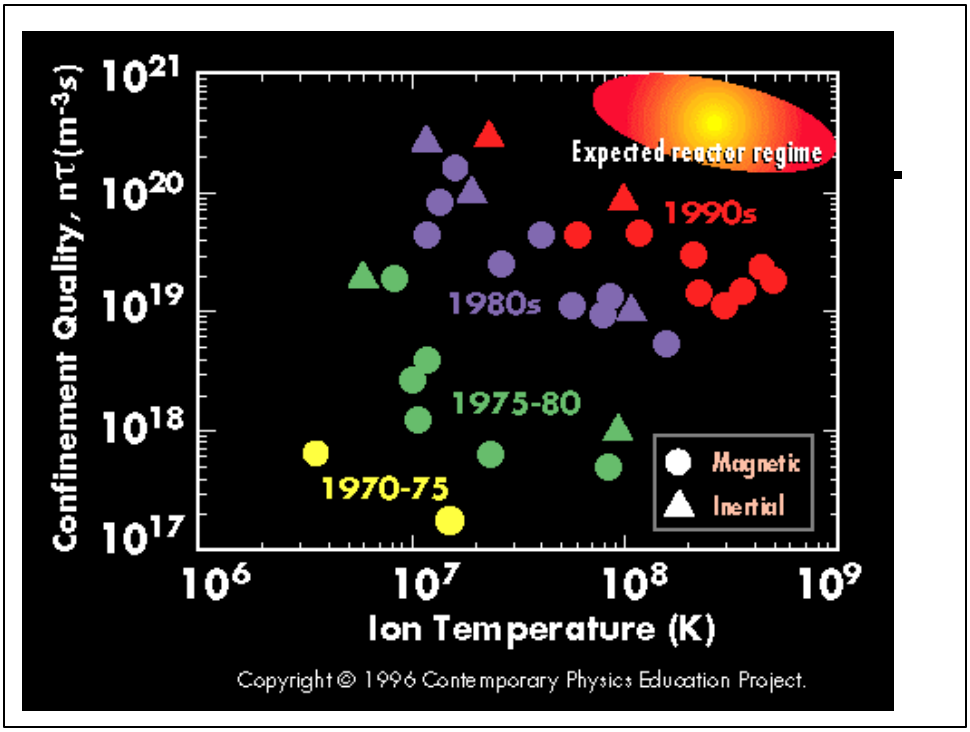
	Chemical	**Fission**	**Fusion**
Reaction	C + O2 -> CO2	U-235 -> Ba-143 + Kr-91	H-2 + H-3 -> He-4
Inputs	Coal	UO2 (3% U-235)	Deuterium & Lithium
Temp(K)	700	1000	10^8
Energy(J/kg)	3.3×10^7	2.1×10^{12}	3.4×10^{14}

The "D-T" reaction has the highest reaction rate at the plasma temperatures which are currently achievable; it also has a very high energy release. These properties make it the easiest reaction to use in a man-made fusion reactor. As the figure shows, the products of this reaction include an alpha particle (Helium-4 nucleus) with 3.5 MeV energy, and a neutron with 14.1 MeV energy. The neutron escapes from the plasma (it has no charge and is not confined) and can be trapped in a surrounding "blanket" structure, where the n + Li-6 => He-4 + T reaction can be used to "convert" the neutrons back into tritium fuel.



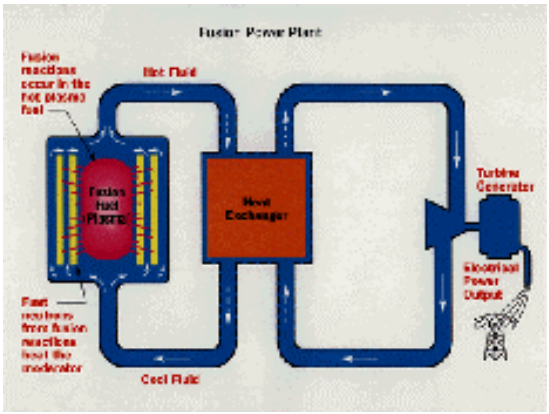
Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are the "Fourth State of Matter" because of their unique physical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

One approach to fusion reactions is to create a magnetically confined plasma in which the fusion reactions take place. The magnetic field allows the high temperature reactions to take place without melting the walls of the reaction chamber.



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, tau. Future power plants based on fusion reactors are expected to produce about 1 GW of power, which requires plasma parameters of n*tau ~ 2x1020 s/m3 and T ~ 120 million K.

Fusion Power Plant



California State University Northridge

35

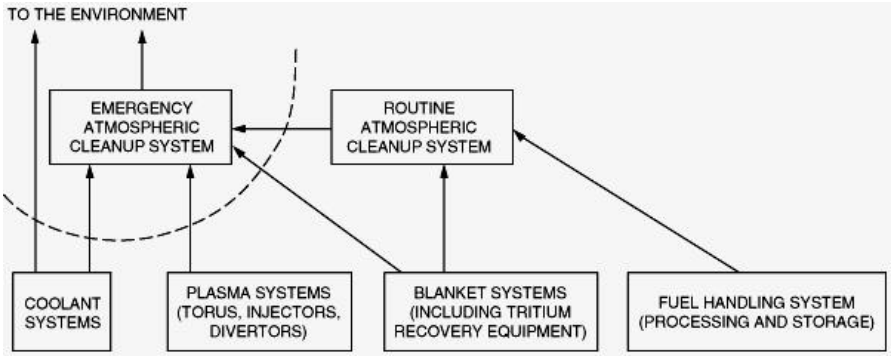
Reference: http://fusedweb.pppl.gov/

In the most likely scenario for a fusion power plant, a deuterium-tritium (D-T) mixture is admitted to the evacuated reactor chamber and there ionized and heated to thermonuclear temperatures. The fuel is held away from the chamber walls by magnetic forces long enough for a useful number of reactions to take place. The charged helium nuclei which are formed give up energy of motion by colliding with newly injected cold fuel atoms which are then ionized and heated, thus sustaining the fusion reaction. The neutrons, having no charge, move in straight lines through the thin walls of the vacuum chamber with little loss of energy.

The neutrons and their 14 MeV of energy are absorbed in a "blanket" containing lithium which surrounds the fusion chamber. The neutrons' energy of motion is given up through many collisions with lithium nuclei, thus creating heat that is removed by a heat exchanger which conveys it to a conventional steam electric plant. The neutrons themselves ultimately enter into nuclear reactions with lithium to generate tritium which is separated and fed back into the reactor as a fuel.

The successful operation of a fusion power plant will require the use of materials resistant to energetic neutron bombardment, thermal stress and magnetic forces. Additional work also needs to be done on the design of fuel injection systems and systems for removing spent gas.

Tritium Hazards



California State University Northridge

36

Reference: http://www.esd.ornl.gov/iab/iab1-13.htm

Tritium will be a fuel at future fusion reactors, but health risks for tritium differ between its form as T2 gas and its form as HTO. Because tritium in the water form is about 25,000 times more hazardous than in the gas form, evaluation of human health risks for a number of situations around future fusion reactor plants depends on knowledge of how tritium converts from T2 to HTO. A series of experimental and theoretical studies were undertaken to measure needed parameters and to calculate others. This effort resulted in the development of validated rate equations, which spanned more than seven orders of magnitude in tritium concentration. Health risks from a wide variety of possible situations can now be calculated. These calculations provide input for future design and siting requirements for tritium-fueled fusion reactors.

Future Prospects

- Current nuclear reactors will continue to operate
- Plans underway for deployment of new nuclear reactors in the US by 2010
- Certify designs in advance to reduce regulatory burden
- Improve design safety

California State University Northridge

37

See the report, “A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010m” Prepared for the US DOE, Office of Nuclear Science and Technology. October 31, 2001.