Nuclear Energy: To Be or Not To Be?

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Nuclear power has tremendous potential to solve the world's energy needs, yet it remains mostly untapped in the US. The public has feared nuclear radiation since the World War II detonation of two nuclear weapons over Hiroshima and Nagasaki. Later, as the nuclear powers of the world continued to test more nuclear weapons, the fear only escalated. This is probably more true today as we fear terrorist dirty bombs and nuclear power in the hands of so called "rogue" nations, politically incorrect though such classifications may be.

Regarding power from nuclear energy, the public fears are in the categories of radiation leaks from nuclear power plants, power plant meltdown, nuclear waste disposal, terrorist diversion of nuclear fuel for construction of bombs, etc. These and other topics will be addressed here with sufficient facts and data. If there are aspects here that astound you, all the better, please feel free to continue to do your own research.

Today the US consumes 20 million barrels of oil a day, of which half are imported. US reserves are 20 billion barrels, so that is a mere 1000 days worth. In addition of course we use coal and natural gas. All this makes us very dependent on foreign fossil fuel, the vagaries of international politics, price increases that can drive our economy wacko. In contrast, there is sufficient nuclear fuel available today to last us, economically, at least 200 years if not double that. So, should we tap into nuclear power?

Proponents to nuclear power will claim that nuclear power is safe, it is very environmentally friendly, releasing no carbon dioxide whatsoever, nor does it generate the acid rain producing gases such as sulfur dioxide or nitrogen oxides, also that economically it is cheaper. Moreover they will assert, by not emitting any particulates in the form of soot that conventional power plants do, nuclear power is better for your health and that the nuclear waste can be disposed of safely.

Opponents to nuclear power will, equally vehemently, point out all the deleterious implications of nuclear power that have been alluded to above, power plan melt down a la Three Mile Island or Chernobyl or China Syndrome, threat of terrorists getting hold of the material and developing big nukes, the worries about the radioactive waste etc. Plus of course the very word nuclear conjures up visions of two-headed mutant chickens. How bad are the cancer consequences of radiation?

Considering the potential for nuclear power, it behooves us to look into it. Without a doubt today's economy and power requirements, necessitates the exploration of alternate sources of power, be it wind, solar, clean coal, nuclear or some other sustainable energy source. Were you to buy a TV today, you would do the research on brand, cost, pixel refresh rates, frame refresh rates, reliability and other specifications on the product you buy. Similarly with our power supply, we all should feel comfortable with our choices for our country, for our world.

This article will look into many aspects of nuclear power. Most of the negative reaction to nuclear radiation comes about from misunderstanding and from insufficient knowledge of nuclear physics. I hope to present here facts that you will be able to look up yourself and continue to do further research. I will provide sufficient reading material and internet links that you should be able to make your own conclusions. Because of bomb and terrorist threats, I will address the construction of bombs to show that it is not at all easy to make these bombs. Nuclear medicine today is a fundamental part of many treatment regimens. Radiation used for oncological treatment is either in the form of external beam or radio isotopes. So, nuclear radiation can be beneficial too.

Physics of Nuclear Energy

With the exception of solar, most sources of commercial electrical power involve using some form of energy to mechanically turn a turbine that is connected to an electric generator that produces electricity when it spins. Wind power causes a propeller to rotate, hydroelectric uses water flowing by gravity to turn a turbine, and many others utilize a heat source to covert water to steam that then turns a steam turbine. Carbon fuels like wood, coal, and fuel oils are burned to create heat. Nuclear reactors use the energy released during the fission chain-reaction process described below.

Nuclear power in the purest sense can mean two kinds of power, nuclear fission power and nuclear fusion power. The latter is not in use today and is unlikely to come into play anytime soon for energy generation and hence will not be discussed here. In this article nuclear power or energy will solely imply nuclear fission power or energy, what is used today in all our reactors.

It will be necessary to use some nuclear fission equations to explain nuclear energy properly. You may skip the equations and still get the gist of the discussions. However, the equations are really not that difficult. If you are unfamiliar with some of them, it may well be worthwhile to brush up on the structure of the nucleus of the atom before you continue. I promise that is all that will be needed in terms of physics equations.

Traditionally nuclear power is achieved by splitting ${}^{235}_{92}U$, this is the isotope[1] of uranium with 235 nuclear particles, 92 protons and 143 neutrons. A typical reaction could be:

$$ {}^{235}_{92}U + {}^{1}n \Rightarrow {}^{142}_{56}Ba + {}^{91}_{36}Kr + 3\ {}^{1}n + \text{energy} \quad \ldots\ldots\ldots.(1)$$

Here the ${}^{235}_{92}U$ atom absorbs one neutron (${}^{1}n$) and breaks up into two smaller nuclei, releases two more neutrons and a lot of energy.

In the fission given above, if you weighed the particles on the left side of the equation and the fission fragments[2], i.e, the particles on the right side, you would find that the right side particles weighed slightly less. This difference in mass is converted into energy via the most famous physics equation $E = Mc^2$ and manifests itself as the kinetic energy of the fission fragments or as heat. This heat then could be used to produce steam to drive turbines for instance, down the normal power production path.

This above fission of uranium can result in a chain reaction because as you can see the reaction took one neutron to start it, but it releases two additional neutrons which can then activate two more ${}^{235}_{92}U$ atoms. Thus at each step or generation, the number of reactions could potentially double. This a very rapid increase indeed. Such a rapid expansion tends to cause an explosion, as in a bomb. If there are very few atoms of ${}^{235}_{92}U$ you will see that the chain cannot be sustained and one needs “a critical mass” of uranium to create a bomb. At the same time, in reactors, the chain reacction needs to be modulated and “controlled”, staying at the same number of disintegrations at every generation. To do so, control rods are used to absorb the extra neutrons, allowing the reaction to remain at the same rate.

Uranium ore has two types of isotopes in it, the type ${}^{235}_{92}U$ shown above used in reactors as well as another isotope ${}^{238}_{92}U$ which is the pollutant. In naturally occurring uranium ore, 0.7% of the uranium is ${}^{235}_{92}U$ while the majority 99.3% is the pollutant ${}^{238}_{92}U$ variety. Most reactors today need a concentration of ${}^{235}_{92}U$ of between 2%-5%. This is produced in a process called uranium enrichment and is a very tedious process. The two nuclei ${}^{235}_{92}U$ and ${}^{238}_{92}U$ have identical properties and almost similar mass, only 1.3% different, making them very difficult to separate. Successive stages of enrichment are typically done in a thermal diffusion process or a centrifuge process till desired level of enrichment is achieved. Weapons grade uranium to make bombs have to be better than 90% pure ${}^{235}{}_{92}U$ making the bomb material more difficult to produce.

While ${}^{238}{}_{92}U$ is a pollutant, it does play a major role. Fission can also occur in ${}^{238}{}_{92}U$, however the probabilities are low and can be ignored in reactors. What is important about ${}^{238}{}_{92}U$ is that it can absorbs a neutron to form the element plutonium, ${}^{239}{}_{94}P$, a transuranic element, that is an element heavier than uranium and with an atomic number higher than that of uranium. The plutonium can be separated to be used as a nuclear fuel or in the making of plutonium bombs as we will discuss later.

$$ {}^{238}{}_{92}U + {}^{1}n \ \Rightarrow\ {}^{239}{}_{94}P \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

${}^{235}{}_{92}U$ has a half life[3] of 704 million years, ${}^{238}{}_{92}U$ has a half life of 4.5 billion years and ${}^{239}{}_{94}P$ has a half life of 24,110 years, making it the most radioactive of the three.

Health, Radiation and Excess Cancer

Nuclear radiation primarily comes in two varieties, the high speed tiny subatomic particles that get emitted and gamma rays. The first consists of electrons, neutrons and alpha particles. These are stopped very easily, a sheet of paper, a layer of skin, some short distance in air, etc. It needs to be stressed that this type radiation is not toxic unless it is consumed or you come into contact with it very close and in large doses. The second form of radiation, the gamma rays, consists of tiny packets of energy, very much like X-ray or visible light, just a bit higher in energy. These are penetrating, requiring inches of lead to stop them, depending on the energy. The gamma ray can travel far and gets absorbed by the whole body tissue.

In the next section we will discuss nuclear weapons and terrorist bombs etc. In this section let us discuss the health effects of nuclear radiation, how much are we normally exposed to and how much cancer does excess radiation cause.

First a little about the radiation measurement units rad and rem. Rad measures the amount of radiation absorbed by per unit tissue of the body. One rad is 0.01 joules absorbed per kilogram of tissue, or, 100 ergs per gram of tissue. (0.01 joules is about 0.0024 calories.)

The rad however does not reflect the amount of damage or risk to the tissue, for this we use the unit rem. To use an analogy, rad is like the total heat dumped into an area of the skin, it does not measure how much skin burn it causes. The rad is multiplied by the “quality factor” Q or the Relative Biological Factor (RBE) of the radiation in question and the value Q depends on the energy of the radiation. The lower the energy, the higher the value of Q, since low energies get absorbed quickly in a short distance causing more cellular damage. Thus at lower energies, more radiation is dumped into a certain volume. Alpha particles have a Q of 10~20, so that 1 rad in that case can be as much 20 rems. For Xrays and gamma-rays Q is 1 so that the rem and the rad are the same in numbers, i.e. for gamma rays 1 rad is 1 rem[4].

We are bathed in radiation at any minute. These can be due to natural background radiation or human-caused radiation. The natural category will include the radioactivity of the earth around you, radiation from the material of building you are in, cosmic rays and even from carbon or potassium atoms decaying in your body itself. The man made radiation comes from smoke detectors, computer terminals and TVs, cell phones, x-ray equipment, microwave ovens, etc. The natural background varies with geographical location, Denver for instance has a higher background radiation, due to the Rocky Mountains and the uranium deposits there and also because at its altitude it gets more cosmic rays. On the whole it is estimated that Denver gets extra 100 mrem compared to the low lying US areas. The average worldwide background radiation is about 300 mrem including radon, but it can vary anywhere from a low of 150 mrem to a high of 26 rem (2600 mrem) in Ramsar, Iran.

Now, how much damage does radiation cause? Scientists do know a great deal on this subject and can calculate how many cancer deaths a given dose of radiation is likely to cause.

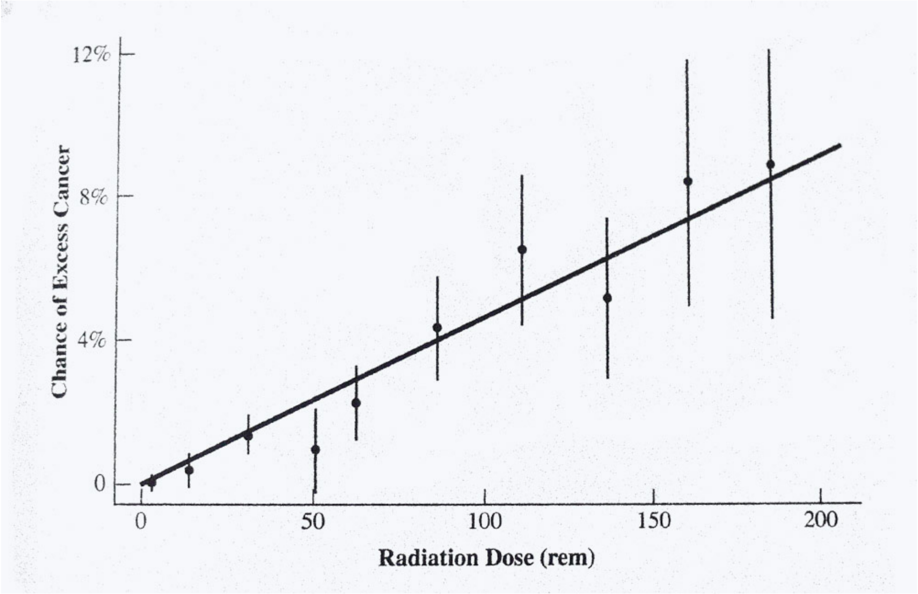

Fig 1. Cancer from radiation: The Linear No-Threshold (LNT) Effect

The above graph is from Richard's Muller's "Physics For Future Presidents". It shows how the cancer rate increases with increasing dose. Note that the horizontal axis is in rems, and we have been talking mostly mrems so far (rem = 1000 mrem). The vertical axis is labeled "excess cancer". Cancer is one of the major causes of death and will occur "naturally" even without any radiation. Here we are only concerned with the excess cancer cause over this background of "natural" cases of cancer. The cancer rate due to genetic and other "natural" causes is 20%, that is 1 out of every 5 deaths is caused by cancer. The above graph says that if you get exposed to about 90-100 rems, then your chances increases by 4% and therefore your chance of getting cancer is now 24%.

Before we go on, one more thing about this graph and the odds of cancer. This graph illustrates what is called the linear no-threshold theory or LNT. This theory says that your chances of getting cancer increases linearly with radiation, and this is true all the way to even minute radiation. Today we know that this is not true, the data is harder to interpret at about 1 rem and there appears to be a threshold of radiation below which the cancer chances do not increase. Most cancers today get treated by many sources of radiation, nuclear isotopes, external beam etc. Obviously these are treating the malignant tumors and suppressing them without causing additional cancer. If all radiation was bad, chemotherapy and other radiation treatment for various cancers would not work. Moreover it is proven that cells have a DNA repair mechanism. During normal cell division, if the DNA was not duplicated exactly right, the DNA repair mechanism kicks in either repairing the cell or cell undergoes apoptosis or cell death. The Hormesis theory proposes that low level radiation triggers the DNA repair mechanisms. This leads to a threshold effect below which carcinogenic effects are not seen[5,6].

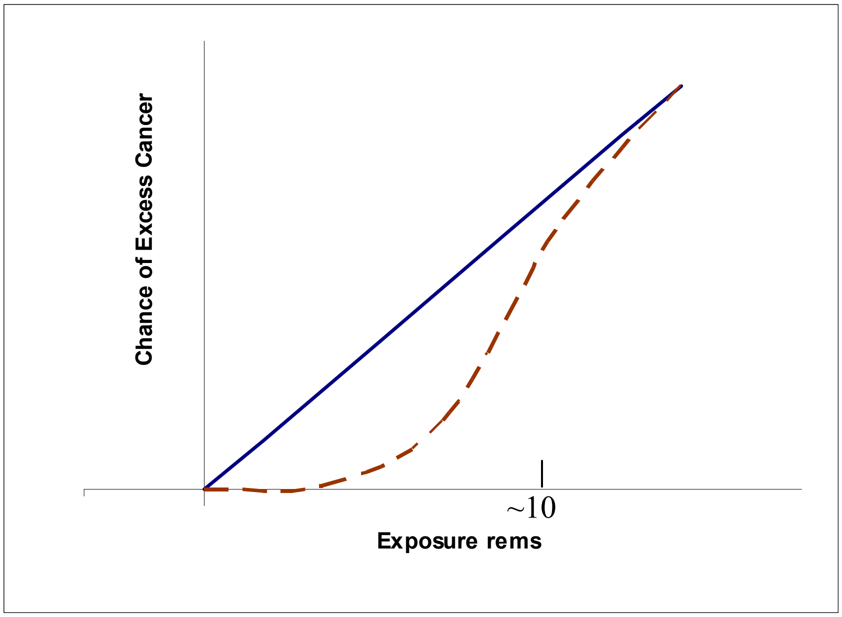

Fig 2. Cancer from radiation: At lower exposure values

This would imply that at low doses the graph should look more like the red dashed curve above. However the blue solid curve, which is the LNT, will overestimate the cancer rate. Hence the LNT will be the conservative exaggerated approach giving the worst case odds and will be used for all calculations in this white article[5] and is used by most government estimations.

Source of Radiation	**Level (rem)**	**Duration**
NRC Occupational worker limit	5	annual
Average US background from all natural sources	0.3	annual
Average US dose from consumer products	0.01	annual
Cosmic ray dose during high altitude flight	0.001	hourly
Estimated maximum dosage from Three Mile Island Incident	0.046	
Radiation at the boundary of a US nuclear plant	0.001	annual
NRC limit for pregnant women	0.5	pregnancy
CT scan[7]	1-3	per study
Chest x-ray	0.01	per study
Kerala, India, background	3.8	annual
Guarapari, Brazil, background radiation	5	annual
Ramsar, Iran, background radiation	16	annual
Radiation sickness due to short-term exposure	50-100	
LD 50/30 from short term exposure	400	
Lethal dose from short term exposure	2500	

Table 1. General Radiation Levels.
(Note : 1 rem == 1000 mrem (millirem) **)**

LD50/30 or Lethal Dose 50/30 is the dose at which the odds are 50% for death in 30 days if untreated.

It is important that we have a rough idea of what the levels of radiation exposure are from various sources before we go on. Table 1 gives some examples. In the US, the yearly dose permitted for radiation workers (at nuclear power plants, hospital personnel etc.) is 5 rem. The LD 50/30 is about 400 rems. The graph in fig 1 saturates at about 2500 rems, which is considered to be the lethal dose. A typical chest x-ray exposure is about 6-12 mrem. A typical CAT Scan(CT imaging) is about 1-3 rem, with about 2-3 scans ordered per study[7].

Given these bounds now let's consider a few events in the recent past like the Three Mile Island and the Chernobyl reactor meltdown cases. Later we will consider what happens in an atomic bomb explosion.

Nuclear Reactor Meltdowns

In 1979 a reactor at Three Mile Island (TMI) in Pennsylvania, near Harrisburg, had a partial core meltdown. This has been the most significant incident on US soil and served to turn many off of nuclear power. The reasons for the meltdown can be read anywhere in umpteen places, here let us focus on the amount of radiation leaked and the danger from it.

According to NRC, the US Nuclear Radiation Commission, "the average dose to about 2 million people in the area was only about 1 millirem" and "The maximum dose to a person at the site boundary would have been less than 100 millirem." [8] You can now decide given the above graph and data how much cancer that could have caused. The data suggests the excess cancer should merely be a blip above the natural cancer cases, if at all.

The official reports were much contested between the officials and the local residents, with the local residents pitted against the officials. The health reports locally were not in line with the official data. The oft quoted major studies that looked into the radiation effects are the Columbia study[9,10], the presidential appointed Kemeny commission results and the Pittsburgh study[11]. The studies could not find any conclusive correlation between the TMI incident and excess cancer rates. According to the NRC, "comprehensive investigations and assessments by several well-respected organizations have concluded that in spite of serious damage to the reactor, most of the radiation was contained and that the actual release had negligible effects on the physical health of individuals or the environment." Remember that cancer is responsible for 20% of the deaths and also that results of radiation-caused cancer shows up in decades over the life time of the exposed population, not in a few years.

Now, let's consider the Chernobyl reactor meltdown. If the TMI incident closed the door on nuclear power in the US, the Chernobyl incident nailed the door shut. This accident occurred, in northern Ukraine, then part of the Soviet Union, on April 26 1986 1:23:45 a.m., and is the most serious nuclear accident ever, resulting in the evacuation of about a third of a million people. The radioactive plume drifted over western Soviet Union, northern and western Europe and as far as eastern North America. Again, the accounts can be read in a myriad of articles, internet sites[12]. Here we will be brief and mostly concern ourselves with the health effects.

The reactor consisted of 4 RBMK (high power channel type reactors) each producing 1 giga-watt[13] of electrical power. The plant was scheduled for a shut down for maintenance and to perform emergency containment tests. These tests had not passed previously and the data had been falsified under pressure in order to not affect bonuses. The day time crew prepared for this scheduled shut down on April 25th, however, during the evening peak power requirements, a separate power plant unexpectedly shut down and the Chernobyl shut down was postponed. This had critical consequences. The evening shift could not complete the shut down and the night shift, not particularly aware of the procedures or the experiments, had to pick up the work. It appears the crew was neither sufficiently trained nor experienced to deal with the experiments and tests. The errors and the mistakes made by the crew can be read elsewhere.

The radiation levels in the worst areas of the reactor are estimated to be a 5.6 rems/sec or about 20,000 rems per hour. In these areas workers will have received the lethal dose in less than 10 minutes. Some dosimeters were inaccessible due to the explosion and some failed to turn on. Evidence of graphite rods etc. were ignored and readings of other dosimeters brought in were dismissed as being defective. The fire fighters who came in were not told the extent and the reason for the damage or of the radiation leak were exposed to the high levels of radiation. 237 people suffered acute radiation poisoning, 31 of whom died within the first three months. These were almost all rescue workers who were called in to manage the fire.

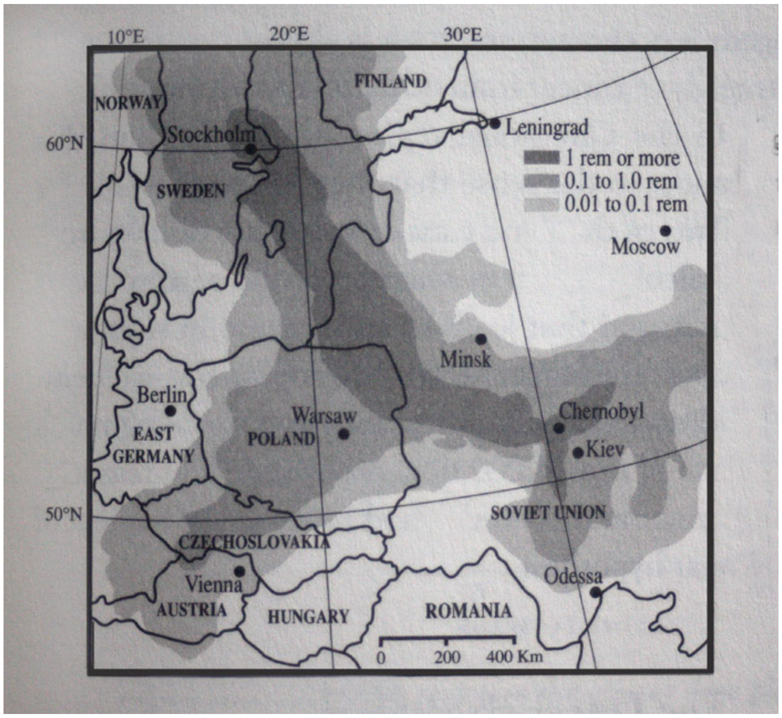

Fig 4. Radiation fallout from Chernobyl over Europe.
(from Richard Muller's Physics for Future Presidents)

Outside the nuclear plant, the exposures were much lower. In the immediate area surrounding the plant, about 30,000 people are estimated to have received 45 rem. From Fig.1, using the LNT hypothesis, this computes to about 2% excess cancer. In a population of 30,000 that equates statistically to 600 extra cancer deaths (30,000 x 0.02) in addition to the 6000 “natural” cancer deaths (20%) that you would expect. For most of the area, the radioactivity has now (2009) fallen below 1 rem per year.

Using the LNT linear hypothesis, the United Nations estimates that the number of excess deaths for the 5 million Western Europeans exposed to the radiation caused by the Chernobyl incident will be about 4,000 deaths over the lifetime of the population[14]. This is in addition to the “natural” cancer deaths of about a million (20% of 5 million) that will occur in that population.

Here it is important to debate the linear hypothesis show in Fig 1. If the graph is more like the red dotted line in Fig 2, the number of deaths drop drastically from 4000 to about 500. This points out that further research in this area is paramount since at some point this will fall in the area of public policy and in order to set proper public policies, we need to have better estimates of health effects of radiation. As mentioned earlier, there are many reasons to conclude that in this low exposure region, the linear theory is incorrect. After all we use chemotherapy to treat cancer with no effects to the rest of the body.

This is not to say that the 500 extra deaths caused by Chernobyl is not tragic. It is, but not as tragic as 4000 extra deaths.

One cost these numbers do not illustrate is the cost of human emotional stress. Take the Three Mile Island incident. It involved a great deal of evacuation, periods of not knowing how bad the radiation leak was, stretches of uncertainty in the public's mind, etc. One cannot put a value on the gut wrenching tragedy of the ensuing emotional roller-coaster. These effects can be mitigated in future by better public knowledge on the effects of nuclear radiation and its consequences, keeping the public better informed during the crisis and having open communication. All of this can be done through public education and non-sensationalizing news reporting.

The Chernobyl incident, I am positive, could not happen in the US. It was the result of earlier bad decisions, bad reactor design cover ups, data cover ups and improper training of the plant personnel. The detection and the first reporting of the incident is a case in point. The first intimation that something had happened came from Sweden. A number of workers at a Nuclear Plant in Sweden detected radioactive particles on their clothing far above contamination levels and first thought it was from a leak in their plant. In their frantic searches for the cause, they looked into the prevailing winds at that time and the Swedes began to suspect an incident in Soviet Russia. There had been some rainfall resulting in local fallout over certain regions of Europe including Sweden. For 12 hours after the Swedes queried the Russians they were met with silence. Finally, at 9 pm on April 28, almost three days after the incident, all that was forthcoming was a terse 4 sentence communication on Moscow television that mentioned the accident at Chernobyl and that a government commission had been set up. After the brief message, the newscaster calmly picked up the next sheet of paper and went on to a story on a Soviet peace fund[15].

Big Nukes

As weapons go, these are the most devastating weapons invented by humans. Our fear of the word "nuclear" without a doubt is a direct result of the bombs exploded by the US on Japan in August of 1945. So, let us see what these atomic bombs entail and how easy or not easy they are to construct.

There are basically 4 types of atomic bombs, these are listed below, in the order of difficulty to construct them. Here I hope to convince you that these large nuclear weapons require the resources of the size of a country to manufacture. These are out of the league of terrorists, who are perhaps more likely to produce a "dirty bomb" which we will discuss next.

1. Uranium Bomb. This is of the type, "little boy" that was deployed over Hiroshima on Aug 6, 1945. Uranium is an ore quite readily available, in the Rocky Mountains near Denver for instance. The isotope ^{235}U is what is used in bombs and is also the isotope

responsible for nuclear power. The ^{235}U nucleus can absorb one neutron to fission, yielding two neutrons and atomic fragments, as given in equation (1) :

$$^{235}_{92}U + {}^{1}n \Rightarrow {}^{142}_{56}Ba + {}^{91}_{36}Kr + 3\ {}^{1}n + \text{energy} \quad \ldots\ldots\ldots(1)$$

The energy is in the form of gamma rays as well as kinetic energy of the fragments. The two extra neutrons can then cause fission in two more ^{235}U nuclei. This multiplication at each generation is required for the explosion, otherwise if you started with 5 nuclei fission, it would remain at 5 nuclei fission which is not an increase in momentum. If the process can be maintained, that is at each stage the neutrons are absorbed by ^{235}U which fissions and the process continues, then we have what is called a "chain reaction".

It is not easy to maintain a chain reaction, which is the essential requirement of the uranium bomb. Imagine going into a small grove of forest and firing randomly with your rifle hoping to hit tree trunks. Your chances of hitting a trunk are not big unless the forest is deep, otherwise the bullets sail through the trees. This is especially true in matter, where the nucleus is very small. For uranium the nucleus size is 1.5×10^{-14} m (15 fm) and the inter-atomic distance is about 3×10^{-10}m (300 pm). That is like, if the trees have trunk sizes of 10 inches and the distance between any two tree is about 3 miles. Bullets can really miss the trunks and the forest has to be really big for the bullets not to escape, assuming that bullets can travel forever, which is roughly true in the case of neutrons inside the uranium block. This gives rise to the concept of the "critical mass", which for uranium is about 440 pounds. So, you need a mass of about 440 pounds of uranium in order to sustain a chain reaction.

There is a clever trick one can use to sustain a chain reaction with a smaller mass of uranium. What if you have a smaller forest, but put a wall around it so that it reflects the bullets back into the forest? Using this technique, you can get by with 33 pounds of uranium to sustain a chain reaction.

It turns out that for the same reason that bullets miss the trunks, you also cannot completely explode all the uranium nuclei. When a portion of the nuclei have exploded the neutrons start missing the trunks and go clean sailing trough the material again. The problem is to design the bomb so that a significant amount of the fuel can be consumed before the bomb destroys itself. This gives rise to the "efficiency" of the explosion.

It happens to be very difficult to get 33 pounds of pure ^{235}U. Natural uranium occurs in two isotopes, ^{235}U and ^{238}U where ^{235}U is only 0.7% of the total. For weapons you need more than 90% purity ^{235}U while for nuclear reactors you need 2-5% pure ^{235}U. To achieve this higher concentration uranium has to go through an enrichment process. Isotope separation or enrichment is not easy to do as the chemical properties cannot be used since both the isotopes have the same chemical property. For the Hiroshima bomb a device called the calutron was used, invented by the Nobel Laureate Ernest Lawrence. In this, uranium is vaporized and accelerated in a magnetic field. ^{238}U which is slightly heavier (by a ratio of 238/235 or 1.3%) tends to travel in a slightly larger arc. By collecting the atoms in the inner arc you "enrich" the ^{235}U fraction. Because of the very slight mass difference, the material has to be passed through the device many times over. Getting the enrichment to 2-5% for nuclear power grade is much easier.

Modern ways of doing this are still as involved though the process may have changed. The newer processes use gas diffusion, again the lighter isotope travels slightly faster through a filter. Again due to the very slight mass difference, the process has to be repeated till the desired purity is achieved.

After you have the material, of course you cannot keep all the material together or it will spontaneously explode. In a bomb, the uranium is kept in two separate portions, and the bomb has a mechanism where, at firing, one fragment is fired into the other fragment, welding the two fragments together to form the critical mass. Thus these bombs need mechanisms inside them that are separate from the launching and timing mechanisms.

In building the Hiroshima bomb, the uranium was so precious that they did not have excess enriched ^{235}U material to test it prior to the final launch. The launch was its test. So, a uranium bomb is easy enough to build, provided you get the material which as you can see is difficult enough. It also goes without saying that this material cannot be stolen from nuclear power plants, which uses a much lower concentration of ^{235}Uranium.

2. Plutonium Bomb. This is of the type "fat man" that was deployed over Nagasaki on August 9, 1945. The fissionable isotope ^{239}P is not naturally occurring (at least not enough) but is produced in nuclear power plants when ^{238}U absorbs a neutron. As a result ^{239}P is part of the nuclear waste in the US. This waste can be chemically "reprocessed" to separate and obtain the ^{239}P. The resultant ^{239}P can be used as fuel for the power plant as it does occur today in France and most other countries. By presidential directive since 1976 US power plants do not reprocess the spent fuel[16]. (This probably is a mistake wasting good fuel and increasing the radioactivity of the waste. This will be revisited in the discussion for nuclear waste.)

   Spent fuel is not something that you can walk into a nuclear power plant and walk out with in your brief case. It is highly radioactive and needs to be transported in heavy casks, as nuclear waste is done. Then to separate it and purify it into ^{239}P, requires radio-chemistry, i.e., chemistry involving radioactivity, not to be fiddled with in your garage.

   Even if you got yourself pure weapons grade plutonium, building the bomb is another matter. Where ^{235}U releases two neutrons in fission, ^{239}P releases three. This means that the chances of premature detonation is high, the chain reaction starting before the whole critical mass is brought together. Thus the simple design used for the uranium bomb cannot work for the plutonium bomb. Instead here the bomb is designed with many small plutonium sections with external conventional explosives. These external explosives are designed to implode and bring all the segments of plutonium together to achieve the critical mass. There are 32 equal sections of plutonium on the surface of a sphere or a ball that have to be precisely brought together at the center with 1 tenth of a millionth of a second precision. This requires many years of systems level testing and if terrorists were to do this, the testing itself would give them away.

   Because the plutonium is more easily obtainable for nations, this is probably the weapon of choice for newer countries trying to develop atomic bombs. However you can see that due to the complication of the design, the resources of a nation are required to go after it. Even then, the chances of the weapon fizzling is high. The North Korean test of the 2006 is estimated to have yielded only 1 kiloton of explosion and has been suggested that this was a fizzle. Compare this to the Nagasaki bomb that yielded 20 kilotons. The Hiroshima bomb yielded 13 kilotons.

3. Hydrogen Bomb. This is a fusion bomb, also called the thermonuclear bomb. This bomb yields the most power, and is the most difficult to build. Not only would you require the resources of a country, you would also require the talents of the many top notch physicists and nuclear design engineers. The fusion is between two isotopes of hydrogen[17], the deuterium ^{2}H and tritium ^{3}H.

$$^{2}H + ^{3}H \rightarrow ^{4}He + ^{1}n + \text{energy} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This is the same fusion reaction that happens in our Sun and all solar objects releasing tremendous energy and power. At very high temperatures and high kinetic energies, example in the sun, the two nuclei collide and fuse and the reaction goes through. Now imagine bringing enough hydrogen of the two types together at high enough speed to mimic the temperature, holding them in place till the reaction occurs. The first trick used is to have a primary stage of uranium or plutonium implosion that will bring the hydrogen isotopes together for the secondary stage. The whole bomb is enclosed in depleted uranium. The x-rays and gamma rays from the primary reaction bounce off the walls and compress the hydrogen to ignition.

All this implosion has to be done without the hydrogen gases flying away. This problem, the second trick, was solved by using LiD. ^{3}H or T is produced when Lithium absorbs a neutron.

$$^{6}Li + ^{1}n \rightarrow ^{4}He + ^{3}H \qquad \ldots\ldots\ldots\ldots(4)$$

The neutron comes from the primary stage. Often there are excess neutrons to ensure that the above reaction goes through. These excess neutrons can also enable a third stage where the neutron is absorbed by the ^{238}U to fission. Typically this third stage provides half of the energy of the H-Bomb. (^{238}U does not emit enough neutrons during fission to sustain a chain reaction, however, given enough neutrons it does fission to provide energy.)

4. Neutron Bomb. This is included for the sake of completeness. The N-Bomb was designed to have less destructive power than the other large nukes. This is still a fission-fusion bomb like the last one, only the fusion reaction is controlled by allowing the neutrons to escape. The shell of the bomb is made of lighter material to help this process. The neutrons escaping have less penetrating power, being stopped after about 100 yards, but can cause intense radiation poisoning and death, even inside tanks.

   This bomb would not have the blast and heat component of the other bombs and therefore leave the infrastructure and buildings intact. The idea was to use it to stop the invading army, in the case of a Soviet invasion of a friendly country. The bomb would kill the soldiers but cause minimal damage otherwise.

The primary reason for use of nuclear weapons is the power it packs in a small volume, not to cause death by radiation. In a nuclear bomb explosion, the majority of the deaths are caused by the blast itself, the high temperatures and the flying debris. One pound of ^{235}U is about 20 million times more explosive than TNT. Thus the Hiroshima bomb at 80 pounds of uranium could have be as powerful as 750 kilo tons of TNT. Due to the efficiency factor it yielded about 13 kilo ton, a 2% efficiency, just about what the scientists expected. On a side note, the mushroom cloud that one associates with nuclear bombs is not unique to nuclear weapons, it can be due to any large powerful blast explosion. Even volcanic eruptions or meteor impacts can produce mushroom clouds.

In the Nagasaki and Hiroshima bombings as many as 80,000 to 140,000 deaths resulted, 15-20% of which were due to radiation illness. The initial deaths due to radiation peaked 3-4 weeks after the blast and ceased 7-8 weeks after the blast. This is the nature of acute radiation poisoning, the deaths occur inside three months. After the immediate casualties, radiation is estimated to have caused an additional 231 leukemia and 334 other cancer deaths over the life time of the survivors. The number of deaths here, horrific as they are, compare in numbers to deaths from fire bombing of Dresden, Tokyo and other cites during the World War II.

The data for the LNT radiation-cancer effects as discussed in the heath section come from studies from the two cities. Studies were also conducted to collect data on birth defects in children born to parents exposed to radiation during the blast. The data showed no significant difference amongst children born to exposed parents as to unexposed parents.

This is not to minimize the effects from the bombs which are absolutely terrifying. Nuclear weapons, these big nukes, pack tremendous destructive capability. However it does illustrate that the major cause of death is not from radiation and after the initial acute poisoning deaths are over, the cancer rate is not excessive. Even in the two cities, the radiation effects, after the blast, died down fast. Yet, the enormity of the destruction will always haunt us and is all the more reason we need to work towards world peace.

Dirty Bombs and Terrorists

So, if you are a terrorist, would you invest your limited resources, more limited than that available to a nation anyway, to making big nukes or the much more easily doable dirty bombs? Perhaps you get more bang for the buck by concentrating on the smaller weapons? After all, your intention is to do as much damage as possible within your budget, get in and out quick. So, you will go for dirty nukes, right? Ok, let's examine what dirty bombs can do.

A dirty bomb is a device to disperse radioactive material using conventional explosives. Nuclear explosives are impractical because they are much more difficult to build as we have seen. The radioactivity then, the thought is in a dirty bomb, would be carried in the wind and settle over a large area.

Let us consider the case where a dirty bomb with 1400 curies of ^{137}Cs (Caesium or Cesium. One curie is the radioactivity of one gram of radium.) is blown up. Let's assume that the dust cloud settles over one square mile. According to Richard Muller, calculations show that after 1 hour in this area, you will be exposed to 5 mrem, in a day to 100 mrem. Presumably evacuation can happen in a matter of days. From all previous discussions remember that the average annual background is 300 mrem. So, there will be no casualties from the radiation. There will be more damage from the blast and shrapnel than the radiation.

However, given the present state of mind, there will be toll from panic and general misunderstanding of consequences from radiation. Which is why, it will be important to educate the public on the effects of radiation. If terrorists do use this method, they will be relying on the after effects of panic to cause general disruption.

It seems that Al Qaeda does understand the limitations of the dirty bomb. From court deposition papers it appears that Jose Padilla approached the Al Qaeda with the concept of a dirty bomb. (Not clear whether he first approached the Al Qaeda with thoughts of an H-Bomb, after all most literature and internet sites seem to imply that these are solved technologies and nuclear bombs are easy to build.) Al Qaeda directed him instead to use natural gas to blow up apartment buildings. Jose Padilla does not fall into the standard profile of a terrorist and it is indeed big Kudos to the CIA and FBI for tracing him down. Dangerous as such individuals are, that is not the issue for this article.

Next, if not dirty bombs, how could nukes be deployed in a more practical way by terrorists? One way could be to do smaller bombs, instead of the megaton bombs perhaps deploy a kilo ton bomb. A 1 megaton bomb can cause destruction over a radius of about 3 miles, a 20 kiloton bomb will cause damage over a radius of 1 mile and a 1 kiloton bomb will cause damage over a radius of 450 feet[18]. Thus a few small tonnage bombs will spread more damage than one large bomb. However, remember that there still is the problem of obtaining the nuclear material and then constructing the bomb. Plus you need rather top level expertise. This can probably be done more by “rogue” nations than by terrorists, whose limited budget is probably better spent, they might conclude, by conventional means.

Nuclear Waste[19]

Nuclear waste is another topic that weighs heavy on most people’s minds. Needless to say, the public needs to be reassured on this and we need policies that will make the public feel reassured and safe.

All industries have waste products, for instance the coal industry has carbon dioxide. In the nuclear industry, the waste product is categorized into two classes, low-level waste (LLW) and high-level waste (HLW). The majority of the waste is LLW, which includes the protective level clothing worn by the personnel, tools, etc. This is identical to the waste product from hospitals and radio-chemical laboratories and does not represent a major hazard and is treated the same way those waste would be treated. In this document we will consider only the HLW.

HLW are the spent fuel rods from the reactors and present a greater challenge. This waste is typically 95% uranium, 1% plutonium, 3.65% fission products and 0.35% other transuranic elements. Transuranic elements are elements like plutonium that are of higher atomic number, i.e. heavier, than uranium. For example, uranium absorbs one neutron and becomes a plutonium which absorbs one neutron and becomes americium which then becomes curium and so on. This spent fuel is very radioactive and needs to be transported and stored with care so that the radiation is not leaked into the environment. As we shall see, this is not that difficult. We need to consider how much waste is produced, how long before they are no longer dangerous and how/where to store them.

Most nations are considering burying the waste, which does seem to be the best idea (the other ideas being to blast it into space, bury under the ocean, under the south pole, …). In the US, the DOE is planning a burial site in the Yucca Mountain range, 1000 feet below the surface.

The HLW components, composed of fission fragments, have short half lives and hence a higher radioactivity at the start. (The good thing about half life[8] is that with each half life the radioactivity reduces to a half and eventually the activity will decay away.) The uranium and the transuranic elements (plutonium onwards) in the HLW, can be separated out from the waste. The remainder of the HLW, the fission fragments have on the average has a half life of about 30 years. This means that in about 300 years, the radioactivity will have halved 10 times. Therefore the radioactivity will be ½ x ½ x ….. 10 times which works out to 1/1000 times what it started with. So, while the initial waste was highly radioactivity, it’s activity goes down by a factor of 1/1000 every 300 years.

Remember, the original ore for the nuclear fuel came from the ground itself, which was radioactive in the mountains of Colorado, or Wyoming or S. Dakota. So, how much more radioactive is the nuclear waste compared to the original ore. Ignoring the plutonium (we will consider plutonium separately) in the waste, it is about 1000 times more radioactive than the original ore. Therefore in 300 years, the waste will have the same level of radioactivity as the original ore. Isn’t that then, the length of time we should aim to store the nuclear waste safely? After 300 years, the waste will be safer than the original ore.

Two fission fragments ^{99}Tc and ^{129}I have half lives of 200,000 and 15,000,000 years but are present in trace quantities. Also the fact that they have long half lives mean that they decay very slowly and the radioactivity from them is very low.

However the public discussions of nuclear waste do not take into account these numbers and the fact that the original ore itself was radioactive. The EPA has set very stringent levels for the Yucca mountain storage site:

- Retain the dose limit of 15 mrem per year for the first 10,000 years after disposal
- Establish a dose limit of 100 mrem per year from between 10,000 years and 1 million years
- Require the Department of Energy (DOE) to consider the effects of climate change, earthquakes, volcanoes, and corrosion of the waste packages to safely contain the waste during the 1 million-year period;

The 15 mrem per year limit is 20 times lower than the original ore and as you know 20 times lower than background radiation. This is the equivalent amount in one chest x-ray and 1/6 the amount of radiation that workers in the US Capitol receive from the granite of the building. The allowance to let it increase after 10,000 years results from fears that the Yucca region has earthquake faults and will result in the radioactivity to be release into the atmosphere or the ground water.

The Colorado river is at present flowing over the uranium ores of the Rocky Mountain and this water supplies Los Angeles and many other urban areas. Regarding the earthquake and volcanic activity in the region, consider that due to such activity, we do not have to ensure that 0% of the radioactivity cannot escape. Say we ensure that due to such natural volcanic or tectonic activities 99% cannot escape. This would still make it very very safe.

I do not at all intend to imply that the nuclear waste can be treated cavalierly. No, it is radioactive and we have to treat it accordingly. However we also have to make sure that the limits set on it are reasonable and not be harsh unnecessarily out of fear.

By setting the extreme limits, EPA has made the whole Yucca mountain project unnecessarily expensive and a project that is an over kill many times over. Many who object to the nuclear waste being buried in the Yucca region had of course the “not in my backyard” syndrome and have a strong voice in the opposition. This has led to much delay in deploying the Yucca Mountain facility as well as tremendous cost over runs.

Shipping the Nuclear Waste

The burial of the nuclear waste will involve shipping the waste. At present the spent fuel rods are first stored in water filled concrete pools at the reactor sites. The rods lose about 95% of the radioactivity in the first few years. When the YM site is ready these will be shipped in specially designed containers with foot thick walls and may in fact be buried in the same containers adding another layer of safety. These containers have to meet the following requirements:

- The equivalent of being dropped several hundred feet onto a hard surface,
- Being immersed in 1475 ºF fire for 30 minutes, and
- Being submersed under water for 8 hours.

Sandia National Lab has extensively tested these casks. In one experiment, a locomotive traveling at 80 miles per hour was smashed broadside into a cask parked in the tracks. The locomotive was demolished with only negligible damage to the cask.

Treatment of the Waste and Reprocessing

plutonium in the waste has a half life of 24,000 years and does not decay fast like the fission fragments, which go to negligible radiation amounts in 300 years. It is also as valuable as uranium as a fuel for reactors. The original reason for not reprocessing it and burying was to assure the public that the terrorists could not divert it to be made into bombs. Another reason was also that reprocessing is more expensive than mining more uranium ore from the ground. However, the cost of not reprocessing it must include the expense of burying it. As mentioned earlier, reprocessing was stopped in the US by a presidential decree. Even though this decree has been reversed, it has not yet restarted.

Most reactors in other countries today reprocess the waste to remove not only the plutonium but also the uranium and other transuranic elements. These are then fed into the reactors and utilized as fuel. This leaves only the fission fragments to bury, making the waste quantity much smaller. Also these have a half life of about 30 years, making the problem much more tractable. Thus, our plan to deal with the long term waste storage should include:

- Separate the uranium from the spent fuel and recycle it in today's reactors.
- Separate plutonium and other transuranic elements and recycle them in fast reactors.
- Bury the remaining fission products.

Plutonium has been called, by Ralph Nader amongst others, the most toxic substance on earth. Plutonium, to be toxic, has to be ingested. Cyanide is about 5 times more toxic than plutonium. The active ingredient of Botox, botulinum toxin is about 1000 times more toxic than inhaled plutonium. The LD50 for botulinum toxin about 10 ng/kg of body weight. In other words, a dose of slight less than 1 micrograms or about 0.00003 oz. has a 50% chance of killing a 200 lb person. Yet it is quite widely used for cosmetic surgery.

Amount of Waste

The volume of nuclear waste is rather small. If the reprocessing of waste is done as optimally described above, then the volume of waste per 1,000 Megawatt power plant is about three cubic yards per year, about 1/5 the size of an automobile. If the reprocessing is not done, then the volume is about 25 cubic yards per year, the size of about 2 cars. Quite a tractable problem. An additional 800 cubic yards of lower-level waste is produced annually which can be treated like normal nuclear medicine waste.

US electrical power consumption is about 4,000,000,000 MW-hr per year. This can easily be satisfied with 500 power plants producing 1,000MW each. Therefore, if reprocessed, the total will produce 1500 cubic yards of HLW. This would the size of 20 yards x 15 yards x 5 yards, about the size of a medium single family home. The total waste would be far less than this since the US is unlikely to be totally nuclear, this is merely an intellectual exercise.

Cost of Nuclear Power

Nuclear power is very cost competitive except where there is abundant fossil fuel availability. The cost of the fuel itself is minimal, the primary cost is in the capital of building the reactor and safety measures. Once this is paid off, the operating costs make it very economical. At present the US nuclear plants are more than 30 years old and have been fully amortized. The chart in figure 3 shows the US power production costs from 1995 to 2008.

Nuclear power plants have in the recent past boosted their efficiency by putting extra efforts into better scheduling and better maintenance reducing plant shutdowns for repairs. Plants have also been upgraded to run at higher efficiency levels. These include better enrichment of Uranium and higher burn-up reducing fuel costs.

In the 1970s nuclear plants could be constructed at about $250 per installed kilo-watt (a typical 500,000 kilowatt plant would cost $125 million). Things changed dramatically after Three Mile Island incident boosting the cost to about $3860 per installed kilo-watt due mainly to legislative delays in granting permits. New regulations were enacted, primarily one that affected the most: after the plant construction was complete, NRC required further hearings before the plant could be commissioned. This meant the plants idled while the permits were being considered. The last Bush administration changed this so that now the permit is granted with the plant blueprints and will hopefully lead to better costs. New plants are being built in Japan in under 4 years and there is no reason why this cannot be done in the US too. US has not built a plant in many years and the first plant will likely incur delays as we debug the process and mainly “relearn” the system. There is a price to putting things in hibermation.

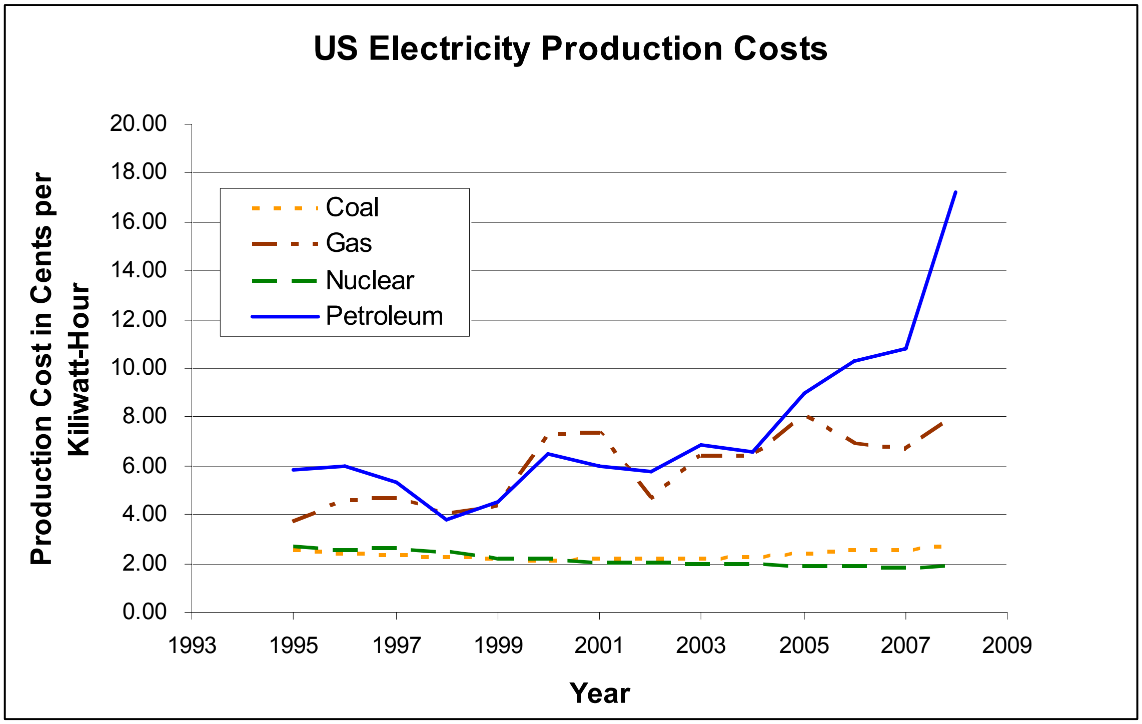

Fig 3. US Electricity Production Costs from 1995 to 2008.
Source: NEI reliable and affordable energy

A study conducted by Chicago University[20] states that “First-of-a-kind engineering (FOAKE) costs for new nuclear designs could increase capital costs by 35 percent, adversely affecting nuclear energy’s competitiveness.” The study states that without any subsidies, loan guarantees, in the next decade, the levelized-cost of electricity (LCOE)[21] for nuclear energy is likely to be $47 to $71 per megawatt-hour (MWh), while the LCOEs for coal- and gas-fired electricity are estimated to be $33 to $41 per MWh and $35 to $45 per MWh, respectively. The latter does not include any costs for clean up of green house gas.

The study concludes that after the first few nuclear power plants, the “LCOEs are expected to fall to the range of $31 to $46 per MWh”. And, “If stringent greenhouse policies are implemented and advances in carbon capture and sequestration prove less effective than hoped, coal-fired electricity's LCOE could rise as high as $91 per MWh and gas-fired electricity's LCOE could rise as high as $68 per MWh."

This would make nuclear power very cost effective indeed. More than that, it would ensure the US to be independent of foreign fossil fuels and would be an investment for the future of US power.

What about other countries that have been investing in nuclear for some time? The following table shows the comparative costs in a few countries:

Electricity Generating Cost Projections for year 2010 [22]

	nuclear	coal	gas
Finland	2.76	3.64	-
France	2.54	3.33	3.92
Germany	2.86	3.52	4.90
Switzerland	2.88	-	4.36
Netherlands	3.58	-	6.04
Czech Rep	2.30	2.94	4.97
Slovakia	3.13	4.78	5.59
Romania	3.06	4.55	-
Japan	4.80	4.95	5.21
Korea	2.34	2.16	4.65
USA	3.01	2.71	4.67
Canada	2.60	3.11	4.00

Table 2. Electricity costs in cents/kWh, 40 year lifetime, 85% load factor.
Source: OECD/IEA NEA 2005.

Coal and gas costs are as shown above and wind is around 8 cents. Nuclear costs were highest by far in Japan. Nuclear is comfortably cheaper than coal in seven of ten countries, and cheaper than gas in all. Nuclear costs always include, by law, waste management and plant decommissioning. These costs are usually not included in other more traditional technologies.

Availability of Uranium

Uranium is a rather ubiquitous mineral roughly as common as tin or zinc, present in rocks and seawater. It's total availability is not fully known, for instance the known resources jumped by about 17% in 2007 due to increased mineral exploration.

Due to the nature of nuclear power, the uranium ore constitutes a minimal fraction of the cost to the nuclear electricity. At $40/Kg of U, this adds 0.1c per Kw-hr or about 1-2% of the total nuclear cost. After the capital cost of building the power plant, nuclear energy is cheap. Even if as more nuclear plants are commissioned and the price of ore increases, it will not affect the cost of the power by much. This is in stark contrast to the fossil fuel generated power where the market price of the barrel dominates the cost.

According to NEA, at present usage patterns, known uranium supplies should last roughly 230 years. This is most likely to increase if there is more demand and explorations are stepped up, similar to what happened in 2007. According to NEA, known supplies are 5.5 million metric tons with likely 10.5 million tons waiting to be discovered. As power plants get more efficient the supply will last even longer, perhaps doubling the estimate of about 200 years. Australia has the largest deposits as of today, 23% of the known reserves. The world production was about 40,000 tons in 2006, of which 25% was mined in Canada. An additional 4.6 billion tons (note, this is with a 'b') are estimated to be in seawater.

Comparison with Other Technologies

Every type of power plant, be it fossil fuel plants or otherwise produce waste. Let's compare the fuel usage and waste production of power plants.

Fuel	**Requirements**
Uranium	33 tons
Coal	2,300,000 tons
Oil	10,000,000 barrels
Natural Gas	64,000 million cubic feet
Solar Cells	39 square miles
Garbage	7,000,000 tons
Wood	3,000,000 cords

Table 4. Annual fuel requirements for a power plant generating 1,000 MegaWatts of Electricity
(Source DOE)

Wastes	**Coal Plant**	**Nuclear Plant**
Sulfur Dioxide, SiO_2	1,000 tons	0
Nitrogen Oxides, NO_x	5,000 tons	0
Particulates	1,4000 tons	0
Carbon Dioxide, CO_2	7,000,000 tons	0
Ashes	Up to 1,000,000 tons	-
Spent Fuel	-	20-30 tons

Table 5. Annual waste quantities from a power plant generating 1,000 MegaWatts of Electricity
(Source: Dr. Hans Blix, former director of IAEA)

The carbon dioxide from fossil plants is released into the atmosphere, contributing to green house gases. In the case of the so called “clean coal” this will have to be sequestered and somehow stored underground “safely”. Sulfur dioxides and the various oxides of nitrogen are also released into the atmosphere and contribute to acid rain. These along with the particulates, tiny soot particles, lead to respiratory problems and are estimated to cause approx 40,000 premature deaths a year in the US alone. The other disadvantage of these waste products compared to the nuclear waste is that they do not decay, there is no half life and they are there forever. The ash waste can contain many contaminants, mercury, arsenic, chromium, lead etc. Also recall the oil tanker related accidents that have occurred, causing great public expense in clean up as well as wildlife casualties.

Conclusions, Executive Summary

So far, I hope to have convinced you that nuclear power and energy can be very safe, practical and environment friendly.

Present day nuclear power is achieved by splitting ^{235}Uranium releasing nuclear fission energy. Uranium ore is mined in the US for instance from the rocks in the Rocky Mountain near Denver where ^{235}U occurs as trace isotope along with the more commonly occurring isotope ^{238}U. ^{235}U is only 0.7% of the total natural uranium. This is too rarefied to be used in reactors and has to be enriched to a concentration of 2-5% before it can be used for power generation. The enrichment process is rather long, tedious and involved and requires specialized equipment. Weapons grade uranium has to be better than 90% pure and is even harder to make requiring further rounds of enrichment. Thus reactor fuel uranium cannot be made into bombs.

While the public has a very strong negative reaction to the concept of nuclear radiation, this radiation is identical to that used in x-rays, cat scans, external beam, chemotherapy, etc. Nuclear medicine today is an integral part of our medical system and has proven its utility. Moreover, we are all constantly exposed to radiation at all times from the natural background minerals, cosmic rays, from the materials of the buildings we are in, smoke detectors, and even the decay of potassium or carbon in our own bodies. Annual background radiation on the average across the world is of the order of 300 mrem, but it can range anywhere from 100 mrem (milli rem) to 16 rem. Table 1 is a summary of average radiation and exposures from natural and other sources. The annual permissible radiation exposure to radiation workers, set by NRC is 5 rem (5000 mrem).

In contrast, the average exposure due to the Three Mile Island was about 1 mrem to the general public outside the plant and was at a peak of 45 mrem at the plant boundary. No cancer deaths have been conclusively linked to the TMI accident. Chernobyl on the other hand exposed it workers and rescue workers to high levels of radiation, mostly by neglecting to tell the rescuers that a power plant accident had occurred, killing some 30 people in 3 months due radiation sickness. Outside the plant, in the nearby area and Western Europe over which the radioactive gases were carried, 500-4000 excess cancers deaths are expected over the lifetime of the population. The “natural” cancer rate is 20%, i.e., 1 out of 5 of us can expect to die of cancer. The 500-4000 extra cases are in a population of about 5 million, therefore this is 500-4000 extra cancers above the “natural” background of about 1 million cancer deaths.

Nuclear power produces no green house gasses like CO_2, the green house gas or the acid rain producing gases like sulfur dioxide and the oxides of nitrogen. See Table 5 for the waste products comparison between traditional power plants and nuclear power plants. The checks and oversight of the nuclear power plants are tremendous and the excess radiation at the boundary of

US nuclear power plants is about 1 mrem. This makes the nuclear power industry indeed very environmentally friendly and green. Nuclear power should also be contrasted to the negative health effects caused by the gaseous and particulate emissions from fossil fuel power plants. These are estimated to cause about 40,000 deaths in the US annually.

Nuclear bombs, terrifying as they are, cause their destruction more from the blast and flying debris than from the radiation. These bombs pack a tremendous power and are indeed a frightening weapon. In a bomb explosion over a dense population, e.g. cases as in Hiroshima and Nagasaki, 15% of the deaths can be expected from radiation sickness and these occur within 3 months of the explosion. In Hiroshima and Nagasaki, it is estimated that an additional 600 deaths were cause due to the cancer from the radiation due to the explosion over the lifetime of the surviving population. There were no excess birth defects in the children born to the survivors from these bomb explosions.

The chances of terrorists building an atomic bomb are slim due to either the lack of availability of the bomb material or due to the intricate mechanisms required in the construction of these bombs and also because such weapons will require lengthy development time and adequate talent resources. The materials require very special handling, enrichment and re-processing. To build such bombs, it would require the resources of a nation or a country. It is unlikely that terrorists will even resort to dirty bombs since, the radiation from a dirty bomb is very unlikely to cause any death, most deaths being caused by the conventional explosives used in the dirty bombs. The terrorist might as well, for their limited budget, stick to the conventional weapons to cause terror.

Nuclear waste is quite a tractable problem. Each 1MW power plant produces about 3 cubic feet of high level waste if re-processed or about 25 cubic feet of waste if unprocessed. Reprocessing is definitely the right step since it yields more reactor fuel, reduces the volume of waste and makes the storage time requirements to be much shorter. The waste reduces to background level in a reasonably short time and should be perfectly safe to store, perhaps in the shipping casks, at the Yucca Mountain site. Towards this end EPA should revisit their extra stringent requirements for the YM storage site and make them reflect reality.

Nuclear power plants have not been built in the US in about the last 25-30 years and nuclear technology has progressed a great deal since then, making the newer plants and reactors much safer than what we have in this country at the moment. Nuclear plants are expensive to build, however they are much cheaper to operate than other types of plants, other than hydro electric. This makes nuclear power very cost effective. See the chart in Fig. 3 for costs of electricity from different sources in the US. Also see Table 2 for comparison of nuclear, coal and gas power from some countries. Nuclear can indeed be very good investment for the future. Since we are at the moment rusty, the first few plants are likely to cost up to 35% more, however as we get the processes ironed out, it is likely to get to parity. Should carbon emission tax etc. be imposed, then nuclear will easily become one of the most cost effective.

The general public indeed has a visceral reaction to the concept of nuclear energy. As a nation we will have to educate the public in order that we make good decisions and more importantly, do not have panic stricken reactions. For instance, should there be a dirty bomb, even though we know that the radiation can cause no lasting harm, the public panic may itself cause much untoward effects.

Discussions

Today, we need new sources of power for multiple reasons. No one will deny that we need to seriously take steps to be independent of foreign oil and gas. US consumption today is 20.8 million barrels a day, half of which is imported. US reserves are 20 billion barrels or just enough for 1000 days usage! Drilling all of Alaska is not going to help more than 1000 days unless we can do a great deal to curtail our consumption and imports. Coal consumption is at 1 billion tons annually but imports are increasing to about 4% of the usage as low sulfur coal is in demand and is getting expensive. This is compounded by the fact that all these, including natural gas power, create acid rain producing gases like sulfur dioxide and the oxides of nitrogen. Plus, not to forget Al Gore, they release tons of green house carbon dioxide gas into the atmosphere.

Nuclear energy, if we go that route, could solve all of this. It would make us energy independent and emit no noxious gases. We have omitted this energy source in the last 30 years from phobic fear of nuclear radiation. We should take a good hard look at this and see if the data warrants this paranoia.

Country	Number of Nuclear Reactors	Net Nuclear Capacity MWe	% of Power from Nuclear
Belgium	7	5,824	54%
Bulgaria	2	1,906	35%
Czech Repuplic	6	3,634	30%
Finland	4	2,696	27%
France	59	63,260	78%
Germany	17	20,470	30%
Hungary	4	1,859	35%
Lithuania	1	1,185	70%
Netherlands	1	482	4%
Romania	2	1,300	20%
Russian Federation	31	21,743	16%
Slovakian Republic	4	1,711	55%
Slovenia	1	666	42%
Spain	8	7,450	20%
Sweden	10	8,958	46%
Switzerland	5	3,238	37%
Ukraine	15	13,107	46%
United Kingdom	19	10,097	22%
Japan	55	58,200	34%
South Korea	20	28,000	40%
US	104	100,000	20%

Table 6. Nuclear Power Plants in use and usage.

Nuclear is a solved fully developed technology, it requires no new research. It is an energy source waiting to be tapped. It can provide continuous base load power regardless of the weather conditions unlike solar power, which requires the sun to be shining, and wind power which of course requires the wind. Moreover, these other technologies require acres of land for installation, not to mention the deaths in hawks and other birds that the wind turbines cause.

Whether the US goes the nuclear power route or not, the rest of the world will and have been making steady irreversible progress in that direction. Today 16% of the global electricity needs comes from nuclear in 30 countries. In France it supplies 77%. The US is lagging behind with 20% of our energy coming from nuclear. History back to the past few thousand years shows us that with new technology and mainly new sources of power, great strides are made in cultural evolution and the human standard of living. For large tracts of impoverished sections of the world, nuclear could just provide the needed power source. The following table shows the capacity and usage across some of the top nuclear countries.

India, Korea, Pakistan, Iran, Israel, in addition to many countries in Europe, are already on their way to nuclear power. Nuclear is a technology that is more than 50 years old. The world, ever since tools or agriculture was invented, has proven that good technologies will be copied, far and wide. As the wheel, agriculture or writing systems developed, they were copied massively leading to advancements across continents. Similarly nuclear power is a clear winner and cannot be confined to the closet. Given that this technology is out there, ubiquitous, in many countries, it is pointless to avoid nuclear power for fear of diversion of nuclear materials by terrorist organizations. Bomb materials may not accessible from the US nuclear plants, but there will be and are plenty reactors available where the security may be more easily breached. As this article is being written North Korea has just tested their second bomb.

The problem of “rogue” nations or worries about nuclear weapons in the hands of rogue dictators will have to be solved by political means, détente, and other pacts. The political powers will have to make the effort to enact EU style multi-country nuclear treaties. A clear distinction has to be made between nuclear weapons and nuclear power and realize that one does not imply the other and that we can use nuclear power for our own energy requirements in the US.

A good hard look is required at all alternates sources of energy, be it wind or solar or nuclear. Remember that all sources have pluses and minuses and let us not be blinded by misconceptions. After all it would not be advantageous to leave a perfectly good energy source on the table.

So, if nuclear energy is safe, cheap, environmentally green and friendly and is a good intermediate alternate power source for at least a couple of hundred years, we should give it a good hard evaluation.

Further Reading

1. The two books that I would highly recommend are Richard Muller’s “Physics for Presidents” (surprise!) and Max W. Carbon’s “Nuclear power: Villain or Victim”.

   The first one covers many topics including solar power, climate changes, space, anthrax attacks, etc., any area in the current news where any calculations or physics can contribute. This book is a good read in general. The second book as the name implies deals only with nuclear energy, from bombs to power. Muller is a theoretical high energy physicist with UC Berkeley. Carbon is a Nuclear Engineering Professor with Univ. of Wisconsin, Madison.

2. www.eia.doe.gov

This is a wonderful site with a great deal of data on energy usage from all different power sources, mostly for the US.

3. http://www.world-nuclear.org/ is a good site to read global nuclear usage and utilization. Also has a great deal of information on uranium availability.
4. Wikipedia is always a good source and covers many of these and other related topics.

Notes:

1. Isotope: Atoms consist of protons and neutrons in the nucleus, these are called the nucleons. The number of protons determine the chemical properties on the atom. However if the nucleus consisted only of protons the repulsive force between the protons because of the positive charge on them would make them fly apart. In order to stabilize them they also need neutrons. Thus an atom is characterized by the number of neutrons and the number of protons it has. When a uranium atom for instance is written as ${}^{235}_{92}U$, the lower left subscript is the number of protons. The atom ${}^{235}_{92}U$ has 92 protons in the nucleus. The upper left superscript denotes the total number of nucleons in the nucleus, or the number of protons + the number of neutrons. Thus the number of neutrons in this nucleus is 235 – 92, or, 143. The atoms ${}^{238}_{92}U$ and ${}^{235}_{92}U$ have the same number of protons but different number of neutrons in the nucleus. When two atoms have the same number of protons but different number of neutrons they are said to be isotopes of each other. The isotopes will have the same chemical properties. Neutrons can be represented as ${}^{1}n$ or ${}^{1}_{0}n$.

2. Fission fragments. They are typically called fragments when the large radio isotope nucleus, in this case ${}^{235}_{92}U$, breaks up into two or more smaller nuclei, here Barium and Krypton. N some cases the radio-isotope can absorb the neutron and become a larger nucleus, which can be stable or decay with its own half life.
3. 1. Half life. Time period in which half the nuclei will decay. Example, if you start with 100 atoms of ${}^{235}_{92}U$, in 704 million years there will be 50 atoms left. Statistics, probability and quantum mechanics work out so well that you cannot predict which of the 50 will remain, but 50 will remain, not that you can see them individually anyway. This does add an advantage to nuclear waste in that it will, in a fashion “decay”. The shorter the half life, the more the disintegration of the nuclei and the more the radioactivity in the original pure state. But this also means it will decay faster and lose its radioactivity faster.

4. There are other units for radiation too. The most likely unit that you will encounter is probably the Sievert (Sv) and the Gray (Gy). Sievert measures the biological equivalent dose while the Gray measures the absorbed dose. You should know that:

1 Sv = 100 rems, or 1 mSv = 100 mrem
(mrem = milli rem or 1/1000 rem)

1 Gy = 100 rads = 1Sv (if Q == 1, i.e., for xrays and gamma rays).

There are also units for activity which measure the number of atoms decaying. These are the Curie(Ci) and Becquerel(Bq). Ci and Bq measure the number of decays rather than energy, 1 Bq is 1 disintegration/sec. In this article we will stick to rems and mrems.

5. There are many authorities who will stress today that the LNT is incorrect because of the no-threshold effect discussed. Amongst them is Bernard Cohen[23] at the University of Pittsburgh. According to LNT, lung cancer rates would increase in counties with higher background radon. In fact Cohen found that counties with higher radon levels have lower lung cancer rates.

   The linear theory came about at a time when tests at low exposures had not been done and people knew that high radiation doses were bad. Thus under lack of experimental data it was assumed that the cancer excess rate extrapolated all the way to very low exposures. This is how science progresses, you make guesses, test your theories and correct old errors.

6. Masahiko Watanabe, Genes and environment, Vol 30, No.1 pp 17-24 (2008)

7. David J. Brenner and Eric J. Hall, Computed Tomography — An Increasing Source of Radiation Exposure, The New England Journal of Medicine, 2007, Volume 357:2277-2284

8. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

9. Hatch MC, Wallenstein S, Beyea J, Nieves JW, Susser M (June 1991). "Cancer rates after the Three Mile Island nuclear accident and proximity of residence to the plant". American Journal of Public Health 81 (6): 719–724.

10. Maureen C. Hatch et al (1990). "Cancer near the Three Mile Island Nuclear Plant: Radiation Emissions". American Journal of Epidemiology (Oxford Journals) 132 (3): 397-412.

11. Evelyn O. Talbott et al., “Mortality Among the Residents of the Three Mile Accident Area: 1979–1992,” Environmental Health Perspectives, vol. 108, no. 6, pp. 545–52 (2000); Evelyn O. Talbott et al., “Long-Term Follow-up of the Residents of the Three Mile Island Accident,” Environmental Health Perspectives, vol. 111, no. 3, pp.341–48 (2003).

12. http://en.wikipedia.org/wiki/Chernobyl_disaster has quite a comprehensive description, detailing what went wrong.

13. In the Ukraine, a giga-watt power plant can supply power for about a million population

14. http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf

15. Time magazine, 5/12/86. http://www.time.com/time/daily/chernobyl/860512.cover.html

16. President Gerald Ford passed the directive in 1976, confirmed by President Jimmy carter in 1977. President Ronald Reagan lifted the ban in 1981 but commercial reprocessing never started. France does reprocess to use the plutonium in the nuclear plants for power generation.

17. There are three isotopes[1] of hydrogen. The most common one is the lightest $^{1}_{1}H$. The next one has one neutron and therefore it is $^{2}_{1}H$, called deuterium, sometimes depicted as D. The third one has two neutrons in the nucleus and is $^{3}_{1}H$, tritium, also depicted as T.

18. http://www.fas.org/irp/threat/mctl98-2/p2sec06.pdf and http://www.fas.org/nuke/intro/nuke/effects.htm

19. The topic of nuclear waste is treated in great detail in many books and articles. Two in particular that would serve as further reading are Richard's Muller's "Physics for Future Presidents" and Max Carbon's "Nuclear Power: Villain or Victim?" Many of the numbers quoted here come from these two sources.

20. http://www.nuclear.gov/np2010/reports/NuclIndustryStudy-Summary.pdf

21. The LCOE is the price at the busbar needed to cover operating costs plus annualized capital costs.

22. http://www.world-nuclear.org/info/inf02.html

23. http://www.phyast.pitt.edu/~blc/