NUCLEAR SAFETY IN THE AGE OF CHERNOBYL AND FUKUSHIMA

The recent nuclear accident at Fukushima in Japan has focused the world's attention on the safety of nuclear power. As a consequence there have been reports ranging from the outlawing of all future nuclear power plants to proposals suggesting nuclear power is the only available road open to satisfy the world's future energy needs. The arguments on both sides have become very contentious despite of the fact that most participants in these discussions don't seem to understand what type of radiation releases were involved in nuclear accidents such as at Three-Mile Island, Chernobyl, and now Fukushima. Also people are highly confused when radiation terms such as Sievert, Curie, Becquerel, rem, and rad are bandied about. It is our purpose here to briefly discuss what one is dealing with when talking about nuclear power, its concomitant radioactive isotope production, and the unwanted dispersion of some of its more dangerous radioactive isotopes into the environment during nuclear accidents.

The starting point of our discussion is to first look at the basic fission reaction happening in a nuclear reactor (or bomb) when U235 nuclei are bombarded by slow neutrons. A typical reaction goes as -

$${}_{0}n^{1} + {}_{92}U^{235} \rightarrow {}_{36}Ba^{141} + {}_{56}Kr^{92} + 3{}_{0}n^{1} + energy$$

(as first reported by Hahn and Strassmann back in 1939). The superscript represents the atomic weight (total numbers of protons and neutrons) and the subscript the atomic number (number of electrons). Since there are more neutrons produced than go into the reaction, one will produce a chain reaction which makes atomic bombs and nuclear reactors possible. Notice the balance in electronic charge and atomic weight in the reaction. The small difference in total mass on the two sides of the reaction equals Δm and produces an energy of $E=(\Delta m)c^2$, according to Einstein's formulas. Here c is the speed of light. The fission products need not always be barium and krypton as shown above, but rather can be any two unequal mass fragments whose atomic weight is most likely to lie near 95 and 140. This means that typical uranium fission will also produce the three dangerous radioactive isotopes of cesium 137, strontium 90 and iodine 131. Since some of these fission fragments can remain radioactive for many years, they pose a potential threat to living plants and animals including immediate death due to DNA damage and cancers produced many years after exposure. It is imperative that such radioactive waste be safely stored in long term guarded depositories and not be allowed to escape into the environment either through reactor accidents or leakage at intermediate storage sites.

There are essentially three types of radiation emanating from radioactive nuclei. These are the alpha particles, the beta particles , and gamma rays. An alpha particle is a helium nucleus which will not penetrate more than a few sheets of writing paper and so is not a problem for man's health unless ingested or inhaled. Alpha particles emanating from long half-life alpha emitters such as plutonium 239 or polonium210 will cause major destruction of body cells if brought next to these cells. It was recently found that Yasser

Arafat was poisoned with polonium by an unknown adversary. Plutonium 239 is a radioactive nucleus produced by neutron bombardment of regular U238 in nuclear reactors. It is highly toxic when inhaled because of its high alpha particle activity. It is also a potential source for nuclear bombs and can be produced in nuclear reactors requiring only poorly enriched U235 as the starting material. Reactors producing Pu239 are known as breeder reactors. The US used many of these at Hanford during WWII. One of the present worries by Israel (a possessor of over 200 of its own nuclear bombs) and other middle Eastern and European countries is that Iran has, through its low level enrichment of U235 by centrifuges, opened the door for plutonium production and the possibility of building a plutonium atomic bomb without first needing to go to the higher 80 percent enrichment stage needed for a pure U235 nuclear bomb.

Beta particles are high energy electrons ejected from decaying beta emitter nuclei such as Iodine 131, Strontium 90, and Cesium 137. They can penetrate thicker barriers and will also damage and can kill living cells. Beta emitter sources such as strontium90 are used by oncologists to kill cancer cells. Because of their charge their path can be bent by both magnetic and electric fields.

Finally there are radioactive nuclei generated in nuclear fission which emit high energy electromagnetic waves which can penetrate considerable thicknesses of shielding. X rays, which typically have wavelengths of about one Angstrom, can be looked at as low energy gamma rays. The radiation we are being bombarded with at TSA checkpoints at airports are soft x-rays which penetrate only a few millimeters of skin. Still, like all penetrating electromagnetic waves of energies above the typical molecular binding energies of molecules in living cells, they can cause cell damage through cumulative exposure. I anticipate major suits against the TSA in coming years by frequent flyers who have developed cataracts due to repeated exposure to full-body x-ray machines at airports.

In addition to α, β, and γ radiation one needs to also worry about nuclear reaction ejected high kinetic energy neutrons and protons. Both of these have large penetration capabilities in living cells.

To detect α, β, and γ ionizing radiation one uses Geiger-Mueller or scintillation counters. Also for cumulative exposure one can use film badges. A Geiger counter (invented in 1908 by the German physicist Hans Geiger and his student Mueller) is essentially a partially evacuated cylinder filled with argon in which an electric potential is maintained between a central wire insulated from an outer coaxial cylinder. When radiation enters through an end window it will momentarily produce an electric discharge between the cylinder and central wire which registers as a click. A measure of the incoming radiation will be proportional to the number of clicks per second. Unfortunately a Geiger counter does not distinguish what fractions of the incoming radiation is α, β, or γ nor what its energy is. Alpha particles can be prevented from entering the Geiger counter by replacing the thin mica window with thicker glass. Also by blocking the window with metal foil only gamma rays will be detected by the counter. Scintillation counters function by having the incoming radiation produce photons in certain crystals such as zinc-sulfide which can then be amplified by use of a photoelectric multiplier . Different crystals may be used to distinguish between alpha, beta, and gamma radiation. Film badges measure the degree of darkness produced on a piece of film after exposure to radiation for a fixed length of time. Film badges are one of the least accurate measures of radiation but serve the purpose of indicating when there might be a problem for nuclear plant workers. In the language of economics, a film badge can be thought of as a lagging indicator.

We next look at the type of radiation expected from stored spent reactor fuel rods and from the by-products of the nuclear weapons industry. Basically nuclear fission will result in the release of radioactive products which can produce fast moving neutrons, gamma rays , alpha and beta particles. As already discussed above, fission produces, among many other species, radioactive iodine 131, strontium 90 and cesium 137. These products will decay in time following the simple exponential decay law-

$$N = N_0 \exp(-\lambda t)$$

, where N_0 is the original amount, λ the decay constant, and t the time. The half-life of a radioactive nucleus is τ=ln(2)/λ and represents the time it takes for half of its radioactivity to disappear. The half-life of radioactive species can range from fractions of a second to thousands of years. Here is a short table giving the half-lives of various radioactive nuclei encountered in fission reactions-

SPECIES	HALF-LIFE
Iodine 131	8 days
Polonium 210	138 days
Tritium	12.5 years
Strontium90	29 years
Cesium137	30 years
Plutonium239	24 thousand years
Uranium235	704 milion years

Of particular interest for reactor and bomb manufacturing safety are iodine 131, strontium90, cesium 137 and plutonium 239. All have fairly long lifetimes so that once inhaled or ingested can radiate cells for days to many years and thus are likely to cause radiation damage beyond a body's ability to repair the damaged cells. Because of its short half- life, iodine 131 is not a major long term problem although iodine pills are advised for individuals exposed to nuclear explosions so that less radioactive iodine will enter their thyroid glands. Strontium, cesium and plutonium are the real source of potential long term problems for humans as they can cause cell damage over many years especially if they get into the food chain as may be happening at the moment to people in Japan and to fish in the Pacific. Strontium has the tendency to deposit itself in bones while cesium is highly soluble in water and will distribute itself throughout the body. It acts similar to potassium, a main ingredient for running the Na-K pumps in living cells.

Finally we come to the last point before our concluding remarks. It is to briefly discuss the units of radiation intensity. This is an area which can cause a great deal of confusion as most mixtures of nuclear waste consists of a spectrum of radioactive nuclei with widely different lifetimes and different concentrations and effects on living animal and plant tissue. One of the best known measures of radiation is the Becquerel. It is the standard SI unit denoted by Bq and equal exactly to one nuclear decay per second. It has dimensions of reciprocal time. Unfortunately it gives no clue as to what type of radiation one is dealing with nor the energy of this radiation. When talking about the number of Becquerels present in a given mass of radioactive material one speaks of Bq/m^3 . For aerial surveys of a contaminated land surface one talks about radiation in terms of Bq/m^2. An older measure of radioactive disintegration per time is the Curie(Ci) . In its earlier definition one Curie equaled $3.7x10^{10}$ decays per second emanating from 1gram of radium 236. Later adjustments allowed the Curie to be defined as just $3.7x10^{10}$ decays per second so that 1Ci=37G Bq, where G stands for 10^9. The fallout at Fukushima city after the accident was measured at about 8 million Bq/m^2 for Cs137. The radioactive disintegrations per second at Chernobyl were a little smaller than this. The worry at Fukushima at the moment is (1) the leakage of radioactive water into the Pacific ocean , (2) some of the cores melting through their concrete supports to come in contact with the aquifer, and (3) the removal of highly radioactive spent fuel rods from an unstable above ground elevated container.

A better measure of the effect of nuclear radiation on living cells is the Sievert(Sv) It is an SI unit defined as 1Sv=1joule of energy / kg of human tissue. Closely related to the Sv is the Gray(Gy) where 1Gy=deposited energy in Joules per kilogram of any material. Also one has the rem (roentgen equivalent in man) defined as 100 rem=1Sv. Typically the yearly background radiation on man is about 3 milliSieverts (mSv). Radiation poisoning and death will occur for exposures above 1 Sievert (=100 rem). Some of the workers at the Fukushima nuclear plant have received almost this lethal amount. Another radiation measure is the rad. It is related to the gray by the equality 1rad=0.01Gy=0.01J/kg.

With the above information we are now in a position to discuss what we see as the future of nuclear energy throughout the world. First of all it is clear that energy demand will continue to increase with increasing world population and the development of so called “underdeveloped” countries. Also renewable sources such as solar and wind energy are inadequate now and in the immediate future from meeting even a very small percentage of the world’s energy needs. This leaves one with the alternative of using both fossil fuel and nuclear power. Both of these sources have their problems such as global warming produced by the buildup of CO2 due to fossil fuel combustion. For nuclear power it is the potential of radioactive pollution due to reactor accidents such as at Fukushima and the inability to establish a permanent waste storage facilities such as attempted at Yucca Flats, Nevada. The accidents at Chernobyl and Fukushima are indicating that we can expect such accidents to occur once every few decades or so and this will continue unless one comes up with safer reactor designs. I estimate that this will be done in the form of smaller reactor facilities using fail-safe reactor designs different from the light water reactors presently used throughout the world. Also the need for a large storage facility serving the entire world must be established. When this has been done nuclear power will again be considered a safe and indispensable energy source. As far as the use of fossil fuel is concerned, this will remain a major source of energy especially petroleum and coal combustion. Major scrubbing facilities will have to be instituted to remove carbon dioxide and other pollutants from the exhaust gases. Perhaps the captured CO_2 can be used to enhance plant growth and so slow down any atmospheric green-house effects plus produce oxygen.