WNA Personal Perspectives

Public Trust in Nuclear Energy

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Summary

A list of the pros and cons of nuclear energy is straightforward; we need it, it is safe, but people are frightened of it. The need to replace fossil fuels with another large base-load source is widely understood and the safety of the nuclear solution has been demonstrated many times; even in accidents in which reactors suffer irreparable damage, the impact on human health has been minimal. For example, at Fukushima there has been no death, or even extended hospitalisation, due to radiation, nor is this likely to be responsible for any cancer deaths in 50 years.

The reasons for the fear of radiation are instinctive and historical. It is natural to shun what is powerful and unseen, and the legacy of the Cold War with its weapon of nuclear fear has added to that. Although the public accepts moderate to high doses of radiation when used benignly for their own health, non-medical international safety standards are set extremely low to appease popular concerns - these specify levels found in nature or as low as reasonably achievable (ALARA). Yet modern biology and medicine confirm that no harm comes from radiation levels up to 1000 times higher and realistic safety levels could be set as high as relatively safe (AHARS). Indeed the local damage to public health and the social economy caused by ALARA regulations imposed at Chernobyl and Fukushima has been extremely serious and without benefit.

Global damage to future prospects for nuclear power is avoidable. Public trust in nuclear energy should be rebuilt on the existing acceptance of beneficial clinical radiation dose levels through a programme of open and explanatory public education at all levels. Science, not the result of litigation or a popular political vote, is the only firm basis for radiological safety and genuine reassurance. The international authorities (ICRP, UNSCEAR and IAEA) should change the philosophy of their recommendations in order to relate to real dangers (ALARA to AHARS), which would ensure that the world does not continue to be "spooked" by the one major energy source that could support future economic stability without damage to the environment.

Introduction

A powerful giant, however benign, is viewed with fear, especially if first encountered suddenly and without explanation. For reasons set by quantum physics, nuclear energy is such a giant, a million times more powerful than chemical fire. It was introduced to the world in 1945 without understanding and without warning. So the public reaction of distrust and repulsion, still evoked by the words "nuclear" and "radiation", comes as no surprise. However, this apprehension is not justified by current knowledge. Furthermore, nuclear power is needed as a carbon-free energy source that is sympathetic to the environment and available as a major base-load supply. There is no downside to nuclear energy except the need for widespread explanatory education to answer the public concerns raised by its history and its invisibility.

Nuclear energy is exceptionally safe in two distinct ways, firstly in physics and then in biology. The concealment of nuclear energy within physics is almost total; it is hidden so well that it was only in 1896 that this million-fold increase in energy reserves was even discovered. The extent of the biological protection and how it works has been fully appreciated only more recently. In the past 60 years there have been several nuclear power accidents in which expensive reactor plants have been destroyed. But, while the public reaction has become more shrill in each successive case, there have been a tiny number of known deaths due to radiation -- in fact, none at all except at Chernobyl where about 50 died -- and none is to be expected at Fukushima either, even in the next 50 years. That such a powerful agent should have such a small effect on human life shows that the protection in biology is quite as remarkable as that on the side of physics.

Personal interlude

Born in April 1941 I have spanned the nuclear age, although I have never worked for, or had any contract with, the nuclear industry, commercial utilities or government. My concern as an academic has been to understand the physical world through experiment, mathematical calculation, statistical inference and computer simulation. I have lectured and taught much of the subject of physics and its application for 40 years, in particular the areas of radiation, nuclear and medical physics. In 2006 I published *"Fundamental Physics for Probing and Imaging"*, an advanced textbook on medical imaging, radiotherapy and safety, among other matters. Discussions with practising radiologists and others lead to concern about the mismatch between radiation levels, first as used carefully and properly in clinical medicine to further patients' health and second as proscribed as dangerous by environmental regulations, often a thousand times lower. How had this happened? A few observations may explain why nobody has spoken out:

- few scientists have a range of knowledge that spans this extensive problem -- in lauding specialisation of study, modern scientific education has become compartmentalised so that few individuals can see the wood for the trees;
- those in the nuclear industry are seen by the press and public opinion as having a vested interest, and therefore unlikely to express an unbiased view;
- the first duty of any clinician using radiation is to reassure and treat his or her patient with an optimal dose -- raising wider considerations of safety could put at risk patient acceptance of this treatment;
- in 60 years a successful worldwide industry, dedicated to quelling public concerns about nuclear safety, has blossomed, but the professionals in this industry (to whom politicians and the media naturally turn for advice) are reluctant to consider major readjustments -- jobs, status and careers would be at risk;
- most members of the public have almost no knowledge, having never been tempted to study a subject seen as intimidating, avoidable and distasteful -- and this is most true of politicians and journalists who are least likely to have any scientific background;
- any ambitious young scientist entering this academically dangerous field, high in controversy and low in stimulating science, would be risking his or her career.

But none of these restrictions applied to me in my later years. Could I write an account of radiation and its safety so as to expose the arguments in a way that most people might understand? The science is not too challenging but that is not true of the explanations needed. In 2009 with help from many people I published a popular book, *"Radiation and Reason: The Impact of Science on a Culture of Fear"*. In Jan 2010 Simon Jenkins, writing in the Guardian, bracketed it with another book, Atomic Obsession by John Mueller, professor of political science at Ohio State University:

> *"Radiation and Reason narrates the history and nature of nuclear radiation, culminating in an attack on the obsessive safety levels governing nuclear energy. These overstate the true risk... rendering nuclear prohibitively expensive and endangering the combat of global warming. ... The books jointly undermine conventional wisdom on the two greatest political challenges of the day, in the fields of energy and defence. As such, they are sensational. As Allison and Mueller argue, nothing is as potent as the politics of fear, and there is no fear as blind as that which comes from a bomb and a death ray."*

Perhaps the media was beginning to understand the message.

And then in March 2011 came Fukushima. My book was available in Japanese translation by July 2011 and I visited the affected area in September, discussing with doctors, teachers and community leaders. The lessons of

Chernobyl in respect of public communication and public health, openly published by IAEA and others, had not been learnt. The tragedy of radiation misunderstood has been played out once more with appalling consequences. Japanese officialdom has responded to media panic by imposing unwarranted draconian regulations, thereby maximising suffering and misery without good reason. The result has been worthy of a Shakespearean tragedy with its suspicions, good intentions and complete misunderstandings.

Physical nuclear safety in nature

Although nuclear energy is immensely powerful, it is far safer than expected because each nucleus lives an isolated celibate life with its nuclear energy securely locked - the nucleus of one atom never meets the nucleus of another. In fact, only about one nucleus in a million has changed since the Earth was formed more than 5,000 million years ago, and then only by decay[1]. They are held apart from one another, each at the centre of its own atom, by an intense electrical repulsion force that dominates right down to the nuclear radius, 100,000 times smaller than the size of the atom, defined by its enveloping cloud of electrons. So nuclei are prevented from releasing their energy under any circumstances - almost. Only at the centre of the Sun at a temperature of about 15 million degrees does any nucleus get enough energy to meet another, and even there, only once every few billion years. Before the Earth was formed there was much nuclear activity and the vast majority of the atoms with their nuclei around us today were made then. Many were unstable and have since decayed. Although that was a long time ago there are a few exceptional isotopes with lifetimes so long that they are still around and decaying today, notably uranium-235, uranium-238, thorium-232 and potassium-40. These are the sources of natural radioactivity. They are scattered everywhere at low or very low concentrations. Potassium-40, naturally present in all life, gives about half of the internal radiation dose to the human body, that is 7,500 Bq[2] or 0.24 mSv per year[3] (another internal source is carbon-14, discussed below). These natural radioactive nuclei are present in rocks, soil and water and give much of the *external* dose to the body (about 1.5 mSv per year [4]). The energy that they release, spread throughout the Earth, is sufficient to maintain its high internal temperature - it would otherwise cool down in about a million years. This radioactive heat powers the movement of tectonic plates and all geological activity, including earthquakes and tsunamis.[5]

The only way around this embargo on social activity between nuclei is provided by the neutron. This was not discovered until 1932 because it too decays (in a few minutes) and does not exist freely in the wild at all. Because it is not electrically charged it can pass through the intense electrical force field unimpeded and enter a nucleus to release nuclear energy. However, free neutrons only exist in working nuclear reactors and, fleetingly, in exploding nuclear weapons.[6] When a nuclear reactor is shut down, as at Fukushima immediately following the earthquake, the neutrons are all absorbed and the only further energy release is by nuclear decay.

Radioactivity has an important physical safety feature not shared by chemical fire and biological agents; it does not propagate. Fire can catch and spread to make an enlarged conflagration; so also can disease, which multiplies

[1] Apart from moving about passively at the centre of its atom, the only activity possible for some nuclei is rotation. The dynamics of this rotation is the basis of MRI, more fully described as nuclear magnetic resonance imaging. The adjective nuclear has been omitted from the name out of a misguided sensitivity to popular nuclear phobia!

[2] A becquerel (Bq) is a measure of the radioactivity of a source, thus 1 Bq = 1 decay per second.

[3] A milli-sievert (mSv) is a measure of radiation dose (energy) per kg, thus 1 mSv = 1 milli-joule per kg. Note that mSv is not a rate, unlike the becquerel. Strictly this is for gamma radiation and electrons. For alpha radiation it is a bit more complicated, see Radiation and Reason.

[4] including Radon.

[5] True but curious, the Japanese earthquake and tsunami of 11 March 2011 were caused by the Earth's own natural decay heat, vastly more damaging than the man-made decay heat released by the Fukushima reactors!

[6] Also, a tiny number of neutrons are released at the top of the atmosphere by cosmic radiation, just enough to make the few atoms of Carbon-14 (about 1 part in 10^{12}) whose measured concentration is the basis of radiocarbon dating. This internal radioactivity is no threat to life - any archaeologist can confirm that any body that does not have it must have been dead for at least 20,000 years.

and spreads by infection. Radioactivity cannot be caught, it can only be transported. It does not increase, it only diminishes with its particular lifetime. Each nucleus emits radiation just once as it changes to a lower different nucleus. Such decay may be contrasted with the persistence of chemical poisons such as arsenic or lead that remain hazardous indefinitely. There were sad stories in the Japanese press in the months following the Fukushima accident of people being ostracised on the basis that they might have been irradiated in a way that could infect others. Such infection is not possible and normal radiation does not cause radioactivity.

So the public should understand that, from a physical point of view, nuclear power is extraordinarily safe at the point of production -- in fact, so safe that only with considerable large scale investment and great technical expertise is it possible to realise any energy at all! Man-made regulation of nuclear material is a pale shadow of the protection with which nature has surrounded this energy source.

When ionising radiation does enter material, whether from an internal radioactive source or from an external beam, the damage initially caused is quite indiscriminate - it is not tuned or targeted to damage any particular molecule. The damage occurs as a sequence of collisions -- the distance between which varies with the energy and type of radiation but the spectrum of energy delivered in each collision does not change much. This collision energy is much larger than the typical chemical or biological energy that keeps ordinary molecules or delicate biological molecules together. However, the resulting damage is purely molecular - no radioactivity is created and the nuclei of the material take no active part. The only nuclear role was as a source of the radiation in the first place. The next question is what happens to living tissue when hit by radiation in this way.

Radiation doses for medical health

Most people know at first hand about the damage caused by excessive exposure to the sun, that is to ultraviolet ionising radiation. They are aware that this causes sunburn in the short term - damage to the skin which is repaired in a few days without long term consequences. They have learnt about barrier creams and may have understood the benefits of Vitamin D production by sunshine. They have been warned of the danger of skin cancer, years later, caused by repeated over-exposure. Most are sensible and enjoy their summer vacations in the sunshine. Certainly any travel agent would go out of business if he advertised holidays, a week in total darkness buried in a luxurious hole deep underground to avoid any possible exposure to sunlight! People have learnt how to balance risk and benefit for this form of ionising radiation - what is needed is to extend this appreciation to other varieties of radiation too.

With today's high standard of medical care many people have experience of radiation scans, taken with the advice of clinicians. Some scans use other technologies, ultrasound or radio frequencies (MRI), that do not involve ionising radiation. Each type of scan has its strengths and weaknesses and clinicians choose the technique to suit the purpose of the examination. In the case of ionising radiation there are two types of scan: those that use a beam of external X-rays (CT or CAT), and those that use the radiation from a radioactive source injected into the blood stream (PET or SPECT), sometimes called nuclear medicine. Either way, high definition 3-D images incur moderate doses of 5-10 mSv. There are a couple of points about the radiation used in scans:

- While the type and energy of the radiation makes some difference, where it comes from does not matter. For example, a 1 MeV gamma ray from a nucleus has exactly the same effect as a 1 MeV gamma ray from an electron accelerator.
- Although the radiation of a CT scan comes in a single short pulse, that of a SPECT or PET scan comes over a period of a few hours. Thanks to stories of "lingering radiation" it is natural to imagine that a dose drawn out in time is more hazardous than the same dose delivered all at once. In fact the opposite is the

case. A given dose is always more hazardous when received in a short time, as with a large exposure to sun on a single day.[7]

Large radiation doses are fatal. For example, among the 237 workers who bravely put out the fire at the Chernobyl accident, most of those who received an acute dose of more than 4,000mSv died within a few weeks of acute radiation syndrome (ARS) which is due to cells dying. Cell death from radiation is used beneficially in the treatment of cancer. High doses are delivered during a course of radiotherapy (RT) by aiming beams of radiation to kill the tumour cells. Millions of patients each year around the world receive such treatment and most return home thankful for more years of fruitful life. Such a course may last 4-6 weeks with a daily dose of 2,000mSv given each time to the tumour. Unfortunately it is not possible to restrict the radiation to the tumour alone and neighbouring tissue and organs may get as much as 1,000mSv each day - and these can indeed survive the RT course. Over a month the tumour gets more than 40,000mSv and the peripheral healthy tissue as much as 20,000mSv - that is five times the fatal dose experienced by some Chernobyl workers! Here is a very simple sketch of how it works. Each day the cells attempt to repair the damage caused by the radiation (as discussed below). For the tumour cells the repair mechanisms are marginally overwhelmed, and for the peripheral tissue with its lower dose the mechanisms are just able to complete repairs before the next day. This separation of the dose into daily treatments is named *fractionation*. After 4 to 6 weeks the tumour is hopefully dead and the peripheral tissue survives. Evidently, the success of such courses with their multiple doses is witness to these repairs.[8] And everyone knows a friend or relative who has experienced this if they have not themselves.

Although radiotherapy treatment, sometimes with external beams and sometimes with internal radioactive sources, is used to kill cancer in this way, paradoxically such radiation can also cause cancers too. At the high doses used in RT the chance of getting a new cancer while the existing one is being cured is no more than a few percent, otherwise such treatment would not be given! If the peripheral dose was more than 100 times smaller, say 100mSv per month, one might guess that the risk was much less than 1 in a thousand. Support for the idea that such a dose carries practically no risk, and may even be beneficial, comes from biology.

Hidden biological radiation protection

People worry that radiation and radioactivity are invisible and cannot be felt. Not knowing whether they are getting a dose makes it difficult to avoid the danger, if any. There are two points to make in reply and each offers useful reassurance.

In a darkened room and unable to see, rather than getting worried, it is normal to search for a light switch or a flashlight. In a similar way what is needed is a detector to show the presence of radiation. Such detectors do not seem to be available in every hardware store, but there is no reason why they should not, because radiation is easy and cheap to detect. A simple domestic smoke alarm is based on a radiation detector that could be redesigned to indicate and log radiation at low cost. So in a real sense radiation is as simple to detect as burnt toast! Radiation is almost too easy to detect - reports from Japan and elsewhere that sources of radioactivity have been detected usually refer to levels that are quite inconsequential.

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[7] Doses do not just add up, their effect depends on when they are received This is an example of the failure of the simplistic Linear-No-Threshold (LNT) theory, an unsupported dogma behind the formalisation of current overly cautious radiation regulations. There is more about this below and in the book Radiation and Reason.

[8] Radiotherapy of deep cancers would not be possible if LNT was applicable.

The other reassuring point is that modern biology has shown that the cells of our bodies detect the effects of radiation very well, although we are unaware of that. They also send chemical messages that alert other cells and then set about repairing or replacing the damage using a number of overlapping strategies. These include

- the quenching of hot chemical radicals generated by the action of radiation on water and other molecules;
- the regular cell cycle whereby new cells are produced from existing viable ones, whether there is radiation or not;
- apoptosis, a process in which cells are killed off and disposed of;
- the repair of breaks in the strands of DNA, both single breaks and, with more difficulty, multiple breaks;
- when radiation damage is detected, increasing the supply of enzymes and other agents to improve protection in the event of subsequent radiation exposure (an adaptive reaction named hormesis);
- the various mechanisms of the immune system that target cells seen to be foreign, thereby inhibiting precancer developments.

These protection mechanisms are parts of the extraordinary resilience given to life through evolution. They are not peculiar to the impact of radiation and act to protect against other causes of cancer too. We leave aside the details, some of which are only now being unravelled, with more to be discovered in future, and simply note how responsibility for this active radiation protection has been devolved to the local cellular level. The conscious brain plays no part, it should relax and stop panicking! The "worried well" should not try to micro-manage their own health; at least for low and moderate dose rates of radiation nature already has outstanding levels of protection in hand.

Of Hiroshima and Nagasaki

The principle effect of a nuclear weapon is a blast, a fireball and a prompt pulse of radiation. At Hiroshima and Nagasaki these promptly killed at least a quarter of the population of 429,000. In 1950 when reliable records were compiled, only 283,000 survivors could be traced, and their medical health has been followed ever since. Individual doses have been reconstructed for 86,955, knowing where they were when the bomb detonated and checked with their radiation history as recorded by chromosome abnormalities and unpaired electron densities (ESR) in their teeth. The average whole body dose was 160mSv from the acute X-ray and neutron flux. An unknown number of citizens succumbed to ARS and some will have died of cancer before 1950, but most cancers would be expected in the period 1950-2000 and these data are available. Similar data for inhabitants of other Japanese cities have been analysed for comparison.

Of those with a reconstructed dose 10,127 died of solid cancers compared to 9,647 expected from data on other cities; for leukaemia the numbers are 296 and 203. These numbers mean that overall cancer rates increased by 1 in 15 due to the radiation. For the 67,794 survivors with doses less than 100mSv the numbers are 7,657 and 7,595, and for leukaemia 161 and 157. The extra deaths (measure as 62 and 4) are smaller than the typical random error to be expected statistically (90 and 13), and so cannot be considered significant measurements at all. So for these 67,794 people all that we can say is that the cancer risk is not much more than 1 in 1000. For comparison, the chance of dying in a road accident in a lifetime varies between 3 and 6 in 1000. So for all practical purposes there is a threshold of risk at 100mSv - what happens at lower doses is unmeasurable, even when nuclear bombs are dropped on two major cities and the health of the survivors is followed for 50 years.
The dose at Hiroshima and Nagasaki was a prompt radiation pulse with little contribution from residual lasting radioactivity. This is the worst case; a chronic dose due to radioactivity, spread over days, months or years, as at Fukushima, would be substantially less dangerous thanks to the action of biological repairs.

Towards a fresh view of radiation protection regulation

The efficacy of RT shows strong evidence that if a dose is spread in time, repairs can be effected, not perfectly perhaps, but sufficiently to make nonsense of any safety assessment based simply on a measurement of dose accumulated over a long time. The actual repair times vary from minutes up to days and weeks, and some allowance should be made for repairs that are never effected. This suggests a safety regime that places limits on the size of:

- any single acute exposure;
- the exposure accumulated in any month;
- a life-long accumulated dose (to cover the damage that never gets repaired).

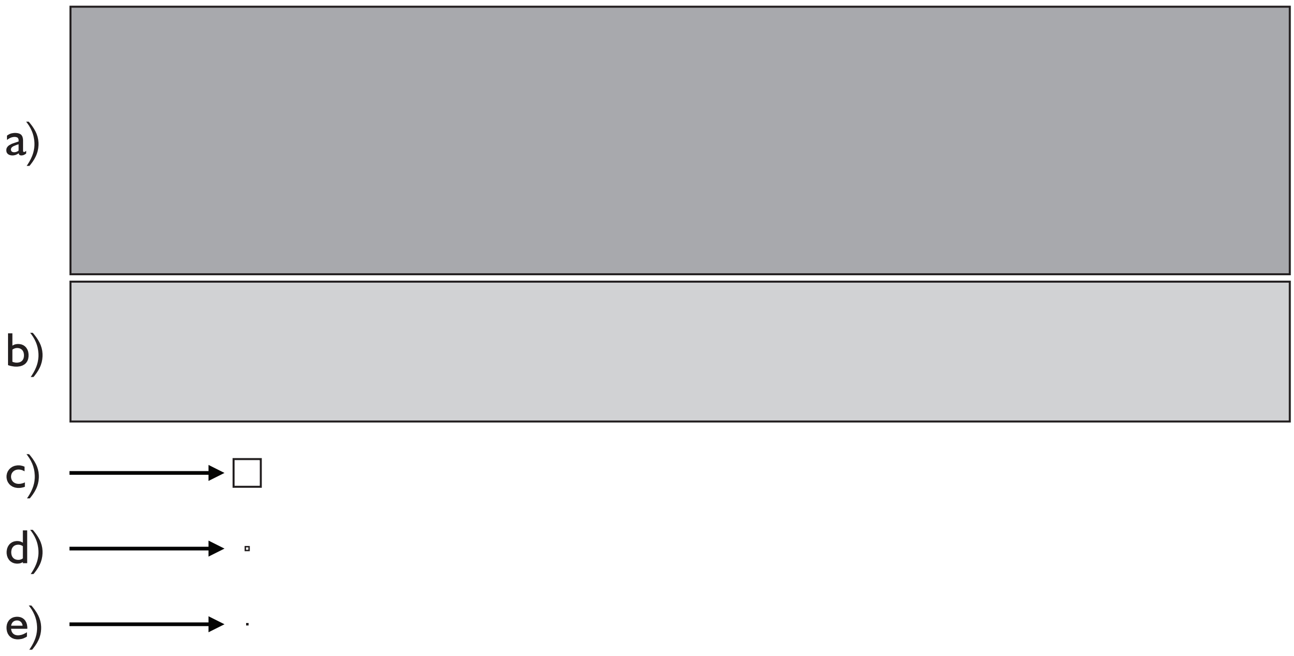
What the value of these limits should be is a matter for discussion based on scientific data, conservatively interpreted. As data improves these limits should be relaxed, science permitting. If people want to impose tighter limits in their own lives or in the care of their own families, they should do so freely. What they should not do is require that unscientific criteria be imposed on the lives of others to appease their personal angst.

When a new technology is introduced, risks are poorly understood, monitoring and control are weak and it is reasonable to take a precautionary view of safety. So it was, for instance, when "locomotives" first appeared on public highways, propelled initially by steam and later by internal combustion engines. Under the influence of popular pressure (in the UK), safety laws restricting speeds to 2 or 4 miles per hour were enacted in the "Red Flag" Act of 1865. Fortunately for modern civilisation, in 1896, coincidentally the same year in which radioactivity was discovered, these traffic restrictions were relaxed by factors of 20 or more. Initially the public thought such traffic unacceptable (and liable to frighten the horses), but progressively the technology improved and accident rates fell. Mankind learnt to accept the risks and reap the benefits, even though traffic still gives rise to extreme potential danger, just a few metres away in the path of an oncoming vehicle - but people avoid these. The caution that prevailed in the 19th century seems unthinkable today, and nobody would suggest special measures for children, such as preventing them travelling by road.

There is no reason to handle the safety of ionising radiation any differently in principle. It should be a matter of balancing risks against benefits in the light of experience, but unfortunately that is not what has happened. In 1951 the safety level was set at 3 millisievert per week (12 millisievert per month). Although the civil nuclear radiation safety record has remained exceptionally good, since 1951 the maximum dose recommended for the general public has been reduced by a factor 150 in pursuit of levels that are As Low As Reasonably Achievable (ALARA). In the light of current knowledge of the effect of radiation on human life the recommendations might reasonably have been increased by a factor of about 8. Coincidentally, such a factor would have been similar to the relaxation of traffic speeds following the repeal of the "Red Flag" Act. Interestingly, of the Nobel laureate husband and wife team who elucidated the science of radioactivity, Pierre Curie died in a horse-drawn traffic accident in Paris in 1906, whereas Marie Curie, despite receiving an untold radiation dose throughout her working life, lived on to 1934 -- but it is not scientific to draw conclusions from individual cases, even of the most famous scientists!

Where did the ALARA suggestion come from? It says nothing about safety. It is a policy that maximises reassurance about exposure to radiation - a policy of appeasement, in fact. This was based, not on science but on fear of a nuclear holocaust in the Cold War era. This fear was then a daily threat and reaction to it has since been assimilated into popular thought and language. Attempts are still made to use it as a political weapon, such as threats of "WMD" and "45 minutes" used to justify the Iraq War. The science and truth behind such propaganda should be questioned. Radiation safety should be a matter of maintaining radiation exposures safely below the level at which it can be shown that actual harm might result. These should be As High As Relatively Safe (AHARS). The implementation of unjustifiable low levels results in unnecessary expense and human suffering. That is what has happened.

Monthly radiation doses represented by areas



a) 40,000mSv per month, a lethal RT dose given to a tumour is at least this large;
b) 20,000mSv per month, a survivable RT dose received by peripheral healthy tissue;
c) 100mSv per month, a suggested safe limit per month (AHARS);
d) 0.7mSv per month (or 1micro-Sv per hour), the level in the Sellafield and Sizewell-B waste storage halls, about 3 times average background;
e) 0.08mSv per month (or 1mSv per year), the public safety limit over background currently recommended by ICRP (ALARA).

Exactly what AHARS levels might be is for discussion, but suggestions good to within a factor of 2 or 3 can be made. A maximum single acute dose of 100mSv seems quite firm. A limit for chronic or protracted doses of 100mSv in any month would be conservative -- a radiotherapy patient receives 200 times that, although not to the whole body. The Figure shown on the next page is drawn to illustrate the relative sizes of these monthly doses, shown as areas.

In addition, a whole-of-life limit of about 5,000mSv is suggested. This is a fraction of a single radiotherapy course and much smaller than the few sources of life-long chronic doses that have been shown to increase the risk of cancer. These include the radiation experienced years ago by the painters of luminous dials. In the future, as more is known and accepted, especially on adaptive mechanisms or hormesis, these limits might be relaxed further.

Doses, food, evacuation and lessons unlearnt

The accident at Chernobyl was more than 25 years ago and what happened, who suffered and how, has been extensively reported in publications by the World Health Organisation, the United Nations and the International Atomic Energy Authority. The known loss of life as a result of radiation exposure includes the 28 firefighters who died of ARS and 15 children who died from thyroid cancer. They report that there is no firm evidence for any other loss of life due to radiation, either individually identified or statistically shown. The higher numbers sometimes reported are based on paper calculations simply multiplying risk coefficients (eg 5% risk of death per Sv) with low doses rates near natural levels accumulated by many people and added up over many years. Such coefficients are a feature of the discredited LNT model. But even the International Commission for Radiological Protection (ICRP) that still champions LNT has cautioned that such calculations "should be avoided".

With a nucleus about half the size of uranium, iodine is one of the many products of fission. It melts at 114C and boils at 184C, so hot spent fuel can release it rather efficiently if allowed to do so. It is an active chemical easily assimilated into the food chain. The most significant radioactive isotope is iodine-131 which has a half-life of 8 days; this means that it loses its potency a few weeks after a reactor shuts down and is not a continuing component of spent fuel. Regular iodine is an important trace element in the thyroid gland and, for children in particular, if the normal diet is iodine deficient, the gland concentrates any fresh iodine entering the body. If iodine-131 is concentrated in this way, it decays rapidly within a small volume, the very conditions under which repair mechanisms may fail. The deficient diet in the Chernobyl region, and the fact that few children were given prophylactic tablets of stable iodine, resulted in about 6,000 extra cases of child thyroid cancer. Most of these were treated but there were 15 deaths. At Fukushima the release of iodine-131 was smaller, the diet includes seaweed (rich in natural iodine) and tablets were distributed to children in most areas. It is unlikely that there will be extra cases of thyroid cancer and there should be no deaths.

Most of the other radioactive isotopes that were present in the Chernobyl reactor have much higher melting points and so were released in smaller quantities than iodine. The exception was caesium which is volatile, soluble in water and easily absorbed. With a chemistry like sodium and potassium it can spread throughout the body without major concentration and is excreted on a time scale of about four months. Its two radioisotopes have half-lives of 2 and 30 years. No deaths at Chernobyl have been linked to caesium and none should be expected at Fukushima.

Although there has always been particular popular sensitivity to risks of genetic errors that might be handed down to later generations, no evidence for these in humans, even at Hiroshima and Nagasaki, has been reported by the BEIR Committee of the National Academy of Sciences (BEIR7 2005), and in 2007 ICRP gave new risk coefficients some 20 to 40 times smaller than for cancers.

The international reports confirm that the most serious effects at Chernobyl have been caused not by the radiation but by the fear of it. The hurried evacuation of 116,000 local inhabitants caused social and economic stress that resulted in depression, suicides, alcoholism, family breakup and broken livelihoods. People who are told that they have received a radiation dose and must abandon their homes, jobs and way of life, naturally develop an attitude of hopelessness and a victim culture. Even those far away can be affected in this way. For instance, studies have shown an increase of about 2,500 abortions in Greece associated with an irrational fear of radiation from Chernobyl.

Further social and economic damage resulted from restrictions on the sale of food. For example, in June 1986 in Norway the maximum activity permitted for food stuffs was set at 600Bq/kg. The economic effect on the reindeer industry was so severe that in November 1986 this was relaxed to 6,000Bq/kg. In Sweden 16 years later on the 24 April 2002 the Swedish Radiation Protection Authority published an apology in the daily press. They admitted that the intervention level had been set too low and that 78% of all reindeer meat had been destroyed at great expense to the taxpayer and adversity to the industry.

But it seems that these lessons were not learnt in Japan. In July 2011 the "Measures.... to Ensure Safety of Beef" issued by the Japanese Government set a maximum of 500Bq/kg, stating that the consumption of 1 kg would give a dose of 0.008mSv, a correspondence that I have checked. This means that you would have to eat 1,000kg of meat in 4 months to get the same dose as that received within a couple of hours during a regular scan. This shows that the regulation is quite inappropriate, and it has been causing great hardship and alarm among the people for no good reason.

The evacuation criteria and public exposure limit at Fukushima were based on 20mSv per year. There has been public pressure to lower the figure to 1mSv per year. (Such a limit can only be interpreted as additional to natural levels which themselves average 2.4mSv per year and show large variations with soil type, altitude and latitude.) Even 20mSv per year as a chronic dose is 10,000 times lower than the monthly dose to some healthy organs accepted by radiotherapy patients in Japan (as elsewhere) - and standards of medical care in Japan are of the highest. The 20mSv per year dose is 60 times lower than the suggested conservative limit of 100mSv per month suggested in this article. The evacuation and clean-up regime imposed at Fukushima has had serious socio-economic consequences for the whole region without benefit of any kind and has been a tragic mistake. To this should be added the major economic and environmental cost of failing to restart the existing nuclear power plants and the related import of fossil fuel.

How many deaths due to radiation might there be as a result of the Fukushima accident? Thirty workers received doses as high as 100-250 mSv but the lowest dose suffered by any worker at Chernobyl who died of ARS was 2000 mSv and that was within 3 or 4 weeks. So it is no surprise that no death at Fukushima from ARS has been reported and none will be in the future. What about cancer in years to come? Of the 5,949 survivors of Hiroshima and Nagasaki who received doses in this range 732 died of solid cancer (and 14 of leukaemia) against expected numbers 691 (and 15). The difference, 40, is a measure of the number of cancer deaths caused by radiation for an acute dose in this range - as a proportion it is 1 in 150. That proportion of 30 people is less than 1, meaning that it is unlikely that any worker will die of cancer from radiation in the next 50 years. The public at Fukushima have received far lower doses and are in no danger at all, except through the punitive effect of the regulations themselves. Something is fundamentally wrong with this safety culture. It was wrong at Chernobyl and the same errors have been repeated at Fukushima with tragic consequences for peoples lives and the Japanese economy.

Let us go back a step. Radiation safety covers two quite separate concerns -- the safe control of the reactor and the protection of people, described as Radiological Protection. Since a typical fission reactor has up to 3-years of fuel loaded at any time, if control is lost, there is potentially a very large release of energy. Further, the act of shutting down a reactor by absorbing all free neutrons and stopping all further nuclear fission leaves the energy release from radioactive decay, the "decay heat", unquenched. It is like driving a car with very efficient brakes which only work above 5 miles an hour. At Fukushima the consequences of not being able to remove this decay heat resulted in the destruction of several reactors. Stabilising the operation of a reactor and providing cooling to remove the decay heat are important and expensive engineering problems. They were overwhelmed by exceptional conditions, far beyond the design specifications of the old reactors at Fukushima Daiichi, of the kind that used to be labelled as an Act of God. Nobody was to blame for this -- indeed those who worked under very difficult circumstances and took important decisions, such as to release the excessive reactor pressures, deserve praise and thanks.

Our mistake, our correction, our survival

Why have the authorities applied such draconian and inappropriate regulations? Actually they had no choice. Only the bravest government could ignore the guidance provided by the ICRP, backed by the IAEA - and this guidance is based on ALARA, as we have seen. A government that ignored such advice would be pursued by a frightened populace and soon be out of office. So, if the government is not to blame, it must be the fault of the ICRP who made such recommendations! Well, yes, but the original fault should be laid at the door of all those around the world with a democratic voice who demonstrated, marched, sat in, chanted and voted for a world with minimal radiation - for ALARA is the result. It is the fault of all.

What should now be done? If we do not want to succumb to the worldwide catastrophes that seem likely to accompany ever more global warming, we should reverse public perceptions and engage with nuclear energy right away and without fear. That will require a culture of public trust based on a vigorous but sympathetic educational programme about radiation science. Why should that be difficult? The public already has a fairly balanced attitude to radiation from the Sun and a degree of confidence about radiation in clinical medicine. Public perceptions can switch much faster than many imagine - think how fast attitudes to smoking have turned around.

New realistic safety regulations should bring large cost savings to any nuclear programme. While no corners should be cut in respect of the control of reactor stability and its heat output, with fresh justifiable safety standards many costs of nuclear power could be reduced dramatically and safely - and that does not depend on which flavour of future nuclear technology is chosen. Matters of nuclear waste, reprocessing and decommissioning should take their place alongside other environmental problems requiring responsible and transparent solutions such as the disposal of hazardous chemical and biological waste. They should not be major problems.

We have survived on planet Earth more successfully than other animals through an ability to think rationally. In the past 60 years we have stopped thinking and become scared of the solution to our predicament. Now we should turn around.

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