NUCLEAR POWER AND PUBLIC HEALTH
By Peter Karamoskos MBBS, FRANZCR

"... [T]here is a linear dose-response relationship between exposure to ionizing radiation and the development of solid cancers in humans. It is unlikely that there is a threshold below which cancers are not induced." – National Academy of Science, BEIR VII report, 2006.

"We need to develop a very firm commitment to the elimination of nuclear power as a source of energy on the earth." – Russell Train, former US Environmental Protection Agency administrator, 1977.

"[The economic] failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale." – Forbes, 1985.

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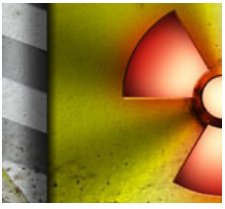
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1. INTRODUCTION

The public health implications for a resurgence of nuclear power appear to have taken a subordinate position to the economic and global warming arguments that the industry has advanced to justify its expansion. The purpose of this essay therefore is several-fold: to review the scientific evidence for public health impacts of nuclear power, to assess occupational hazards faced by nuclear industry workers involved in the nuclear fuel cycle, to assess the evidence for nuclear reactor safety and critically challenge the underlying assumptions which may be less than adequate. It will also examine the public health risks of spent fuel from nuclear power reactors. The common thread linking these safety issues is the risk posed to public health by ionising radiation[1] and in particular the cancer risk. The nuclear industry and our understanding of radioactive[2] health hazards, developed in tandem during the twentieth century, however, the relationship to this day has always been uneasy and often in conflict. A brief historical narrative of this joint evolution is reviewed as it is essential to understanding the context and scope of the public health issues at the heart of the nuclear power debate.

If we are to believe the nuclear industry, nuclear power is both safe and vital to our future, yet over half a century of nuclear power has proven both contentions as false. In the last decade the nuclear power industry has undergone a 'renaissance' of interest and hype, spurred along by the claim that it is vital to combating global warming. Of course, the nuclear power industry has had many false starts, each time failing to live up to its promises. At its inception, it sold itself as providing limitless electricity too cheap to meter. When this was proven false, it attempted to recreate itself as the key to energy security during the oil shocks of the 1970's. However, it foundered again on the grounds that not only was it too expensive, and that most electricity did not rely on imported oil, but that it was so economically unattractive that financing was virtually impossible to come by without heavy tax-payer subsidies and loan guarantees. Throughout this period however, public health concerns increased on a backdrop of reactor safety concerns and the effects of ionising radiation on the surrounding populations, with ten core meltdowns in various nuclear reactors, including several in nuclear power reactors, culminating in the Chernobyl disaster of 1986.

The link between nuclear power and nuclear weapons however is critical in understanding the context of its development and its impact on public health and safety. Nuclear power followed the development of nuclear weapons in the USA, in an attempt to garner public support for nuclear technology which had shown how destructive it could be and how much of a threat it posed to humanity. Public tax-payer support was critical to facilitate further weapons development. Nuclear power was the product of the 'Atoms for Peace' program in the 1950's to achieve this end leading to the export of nuclear reactor technology, as well as bomb grade highly enriched uranium as reactor fuel to many countries. In their attempt to highlight the 'peaceful atom' therefore, the nuclear establishment propelled by the 'more is better' hubristic military commanders and civilian nuclear boosters, inadvertently although not unpredictably, led to illicit weapons programs around the world.

The original drivers of nuclear power therefore, were not a need for electricity, environmental concerns, or the need for energy security, but political and military imperatives which dominated and spurred its development. In this climate, safety issues were not paramount. Indeed, how could they be if the science of the human effects of ionising radiation was still in its infancy, and the safety of nuclear reactors was unknown? If anything, safety concerns posed potential obstacles to its development and thus needed to be managed, as they were by savvy media men. It was a climate of 'electricity today, and (maybe) safety' tomorrow.

So the lingering questions are: what is different now? Is nuclear power now safe? The history of human health and the safety of nuclear power is also inexorably intertwined with the evolving history of the health effects of ionising radiation (IR). Whereas the science underpinning the generation of electricity from nuclear power is well established, the health effects on humans of ionising radiation (IR) is still evolving. This is not to undermine the voluminous research and findings clearly documenting the adverse effects of ionising radiation on human beings. That much is well documented and understood. The uncertainties lie in precisely quantifying the effects of IR including defining with greater precision the risks at ever decreasing doses. This is key in attempting to understand the direct adverse health effects of nuclear power on two groups; nuclear industry workers, and populations in the vicinity of nuclear reactors and subject to their radioactive emissions.

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[1] Ionising radiation: radiated energy which has the potential to cause electrical charges in living tissue.

[2] The form of ionising radiation produced from nuclear decay.
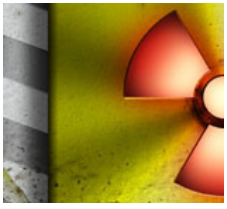
2. IONISING RADIATION AND   PUBLIC HEALTH

Ionising radiation arises from many sources. Nuclear fission which powers nuclear reactors is one. It is postulated ionising radiation imparts its deleterious health effects through two mechanisms: transference of its energy to atoms in biological tissue which then becomes electrically charged leading to the formation of free radicals which then damage the cell's genetic blueprint (DNA) leading to genetic mutations; and direct DNA disruption along the track the ionising radiation traverses through the cell's nucleus. The most mutagenic (causing genetic mutations) of these are double stranded breaks (DSB) where both strands of the double helix DNA molecule are simultaneously disrupted resulting in a high likelihood of mutations. This then predisposes to the initiation of cancer when the regulatory mechanisms of the cell fail. Cancer may not appear for 10-40 years (latency), although can be as short as 5 years for leukaemia. Ionising radiation is classified as a Class 1 carcinogen by the International Agency for Research in Cancer (IARC) of the World Health Organisation (WHO), the highest classification consistent with certainty of its carcinogenicity.
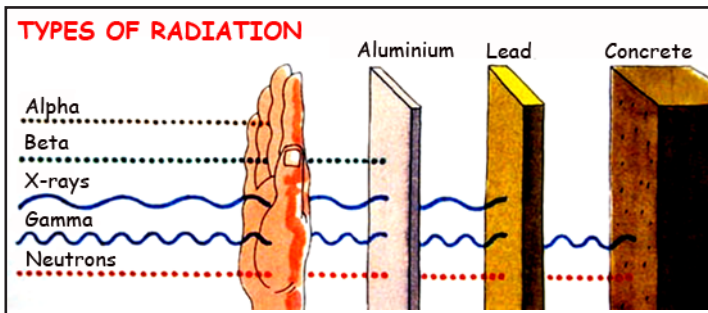
Two types of IR health effects are recognised. The severity of deterministic effects is directly proportional to the absorbed radiation dose. These include skin damage and blood disorders. The higher the dose, the worse, for example is the skin radiation burn. These have a threshold below which they do not occur, although this may vary between individuals. This threshold is around 100mSv at which blood production begins to be impaired.[3] Stochastic effects are 'probabilistic' in nature. In other words, the higher the dose the greater the chance of them occurring, however, one they occur their severity is the same irrespective of the original dose. The main stochastic effect is cancer. The lower the dose of IR, the lower the chance of contracting cancer, however, the type and eventual outcome of the cancer is independent of the dose. It can thus be seen that the high dose deterministic effects of IR were readily observable early after the discovery of radioactivity, however, the concept of a stochastic effect as a mechanism for the development

of cancer, took several decades to be understood. The quantification of stochastic effects has occupied scientific debate throughout most of the twentieth century and is still being played out. The distinction is critical to understanding the health impacts of low-dose[4] radiation, particularly with nuclear power and radiation doses to workers and the general population are below deterministic levels, and why there is considerable controversy over its significance.
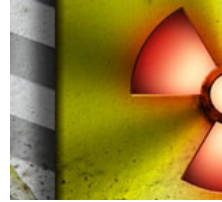
3. A BRIEF HISTORY OF RADIATION SAFETY AND THE   NUCLEAR INDUSTRY[5]

The hazards of IR were inadvertently demonstrated by the pioneering researcher Marie Curie who identified the radioactive element radium three years after Wilhelm Roentgen discovered x-rays, another form of IR, with Curie subsequently dying of leukaemia, and Roentgen of cancer. Many more workers over the ensuing years experienced skin burns and deep tissue trauma, blood diseases and cancers, most famously the radium dial workers.[6] Carcinogenicity was observed as early as 1902. Still, it was not until 1925 that the first protective limits were suggested for workers (the public would have to wait until 1959 before general public limits were enacted in the USA, earlier in Europe). For three decades these limits were based on the concept of a 'tolerance dose' which, if not exceeded, would result in no demonstrable harm to the individual and implicitly assumed a threshold dose below which radiation effects would be absent. This tolerance dose was determined by the concept of 'minimum erythema dose' which related to skin reddening after exposure to IR. This was initially 1% of this dose and corresponded to approximately 2 mSv per day[7] (current occupational limits are 20mSv per annum). This was further halved in 1936. After World

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[3] Compared with a current per capita average of approximately 2mSv from natural background radiation.

[4] Low-dose is defined as less than 100mSv for the purposes of this paper in keeping with the BEIR VII report (2006),

[5] Samuel Walker, J. Permissible dose: A history of radiation protection in the 20th century. Univ. of California Press, 2000. National Academy of Sciences.

[6] Radium was used on watch dials for luminescence and was painted on by (usually female) painters who would sharpen their paint brush bristles by putting them in their mouth thus ingesting toxic doses of radium (a powerful radiation emitter and the same substance that killed Marie Curie).

[7] Actually 0.2R/day; mSv is the unit of biological effective dose. The distinction although important in radiation protection, is of no significance in this case except to the purists.

War II, largely because of genetic concerns related to atmospheric weapons testing, radiation protection dose limits were expressed in terms of a risk based maximum permissible dose (MPD). Of course, this was an arbitrary limit based on the unsubstantiated assumption that any hazards below this level were not significant and represented a reasonable compromise between safety and pragmatism. In effect, the public wore the burden of proof for demonstrating significant harm below these limits. It is important to note that the concept of stochastic risk was not even considered. In 1946, the National Committee for Radiation Protection (NCRP) reduced the MPD in the USA to an annualised limit of 150 mSv per person per annum. Furthermore, these limits only applied to external radiation i.e. x-rays and gamma rays. They did not apply to internal emitters (those ingested or inhaled) such as radon and radium since there was no way of measuring radiation dose from these. The radiation dose from internal emitters was finally determined by the infamous 'radiation experiments' where subjects unknowingly were administered plutonium and uranium without awareness of the nature of the experiment or with informed consent.

The 1927 discovery by Muller of x-ray induced genetic mutations in fruit flies, linear with increasing dose and with no apparent threshold, was an important underpinning of the standards. However, during this era when business and the medical profession were trumpeting radium as a miracle cure, even adding it to bottled drinking water and chocolate bars, it was easy and convenient to dismiss his findings as irrelevant to humans. This was the case for at least four decades after his discovery.
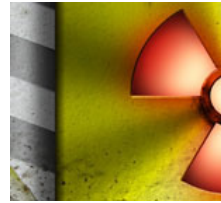
4. NUCLEAR WEAPONS GIVE RISE TO NUCLEAR POWER – PEACE NOW, WAR LATER?

The Manhattan Project was the codename for the project conducted during World War 2 to develop a nuclear bomb. It was a collaborative project led by the USA, with participation by the UK and Canada. It achieved its first controlled chain reaction of a nuclear reactor in 1942, designed and led by Enrico Fermi, and finally developed and detonated an explosive device, Trinity, in July 1945.

The atomic bombs detonated over Hiroshima and Nagasaki less than one month after Trinity were a watershed. Radioactivity would no longer have the lustre it once had; it became synonymous with death and destruction, particularly after the Soviet Union also succeeded in acquiring nuclear weapons. Seven years after nuclear weapons were used in war, Dwight Eisenhower set the US government on a new course, intended to show the world that nuclear weapons, radioactivity and radiation were not harbingers of death but in fact benign forces for the betterment of mankind. The 'Atoms for Peace' program was thus born to convince Americans that these new technologies were full of hope and that nuclear reactors should be developed with tax dollars to generate electricity. The vision was of electricity "too cheap to meter."[8] Of course, the underlying rationale of the 'Atoms for Peace' program was to garner public support for the nuclear

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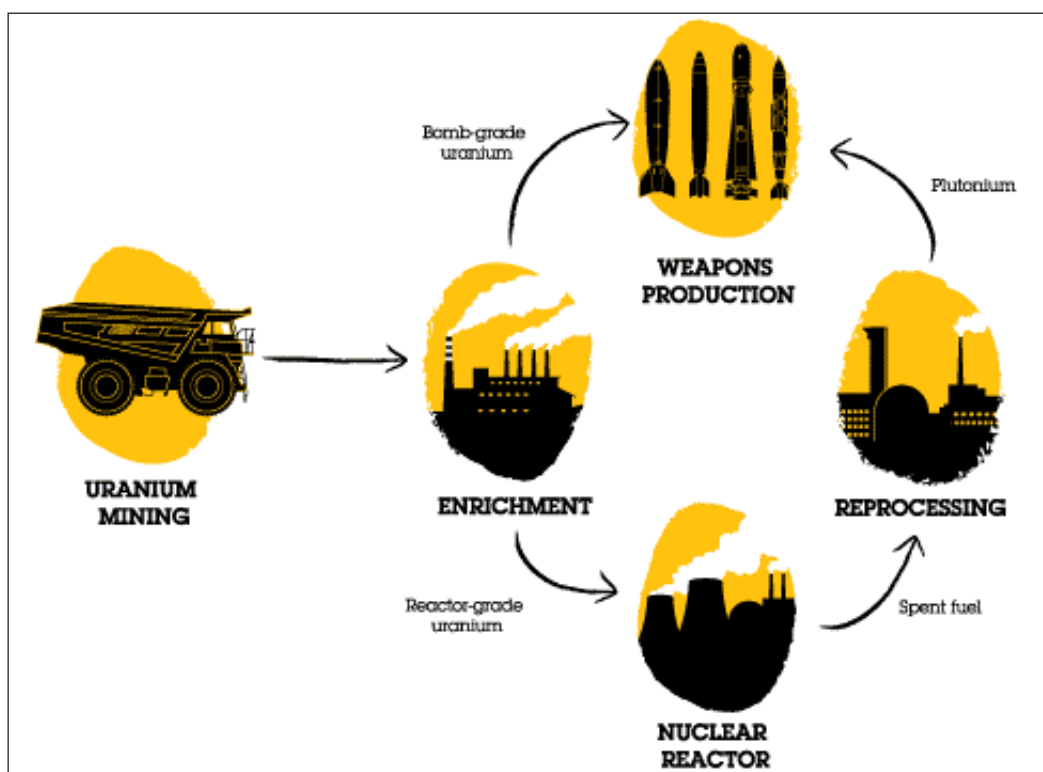
[8] AEC (Atomic Energy Commission) Commissioner Lewis Strauss, 1954.
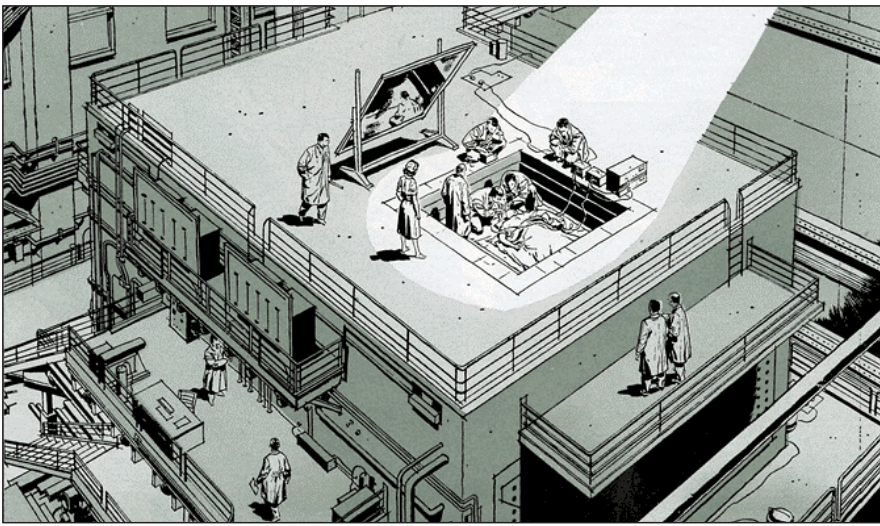
IN 1952, MEDICAL SCIENTISTS AT THE BROOKHAVEN LABORATORY ON LONG ISLAND TOOK THE DARING AND REVOLUTIONARY STEP OF EXPOSING A PATIENT DIRECTLY TO THE RADIOACTIVITY FROM A NUCLEAR REACTOR. FOR FOUR YEARS, THIS TECHNIQUE WAS CAREFULLY TESTED. IN 1956, BOTH THE GOVERNMENT AND PRIVATE INDUSTRY BEGAN DESIGNING NUCLEAR RECTORS TO BE USED SOLELY FOR MEDICAL PURPOSES. ALTHOUGH THE ATOMIC WAR ON DISEASE HAD JUST STARTED, BEFORE LONG MORE LIVES MAY BE SAVED BY ATOMIC ENERGY THAN WERE DESTROYED BY THE TWO BOMBS AT HIROSHIMA AND NAGASAKI.

1957 NUCLEAR INDUSTRY PROPAGANDA 'Atomic revolution', www.ec.tc/atmc

weapons program which relied on large amounts of tax payer dollars. In equal measure, Eisenhower cynically manipulated Cold War fear of attack by the Soviet Union, with the countervailing hope of the promises of peaceful nuclear energy. The process of persuasion was controlled by savvy media men, led by Charles Douglas Jackson, an expert in wartime psychological operations. Eisenhower set the stage for the eventual formation of the International Energy Agency (IAEA), a key step in the government-backed worldwide promotion of civilian nuclear energy. Domestically, the power utilities were reluctant to embrace a risky and undoubtedly expensive new technology. In 1954, there were a lot of unknowns about nuclear safety. Nevertheless, the USA provided funding, research reactors, and bomb-grade highly enriched uranium to forty-two countries to kick-start interest, and heavily subsidised the domestic utilities. It furthermore offered them liability protection (Price-Anderson Act) in the case of a nuclear accident, transferring the risk to the public.[9] To this day private nuclear energy utilities worldwide rely on liability protection emphasising they would not be generating nuclear power without it. Inspired by Eisenhower's example, the nuclear establishments in Britain and France misleadingly promoted the 'peaceful' face of the nuclear industry in order to conceal the true purpose of the early reactors which was to produce plutonium for weapons. In every country where nuclear power was under development, the public was misled into thinking that the separation between military and civilian purposes was real. This was clearly evident in countries with reprocessing plants which highlighted (and still does) the duality of the technology. However, any country with a reactor, even those designed for electricity generation, had the means to produce plutonium. One could easily surmise that nuclear power was nothing more than a fig leaf to hide the true military intentions of the atomic establishments from the public. Gullible politicians aided and abetted the subterfuge through their ineptness and reluctance to question the nuclear establishments in most countries,

which in turn provided phony economics and false book-keeping in order justify their large expenditures.

5. THE REGULATION (SELLING) OF NUCLEAR POWER IN A CLIMATE OF INCREASING PUBLIC HEALTH CONCERN

The Atomic Energy Commission was conceived as a result of the Atomic Energy Act of 1946, as the successor to the wartime Manhattan Project, with the conflicted role of overseeing the development of nuclear weaponsand testing and to convince the public of its safety. In 1954 its mandate expanded to promoting and regulating nuclear industries, particularly nuclear power and certifying safety. As a practical matter, though, given its military origins, the AEC was subjected to close control by top military commanders. Thus, by a series of accidents all major sources of ionising radiation fell under the remit of people and institutions that had no reason to want to explore the early knowledge that IR was harmful. The AEC was always subjected to oversight by its (military) commissioners who often over-ruled recommendations to decrease the MPD's. The conflicts of interest led to public clamour for change, particularly noting that the MPD's were constantly subject to change and furthermore varied from one institution to another. The conflicts were no better illustrated and its credibility no more harmed than by the AEC's anodyne interpretations of nuclear fallout studies, contrary to the results which were quite concerning, and which

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9 The current Price-Anderson Act requires nuclear power utilities to carry $300 million in public liability insurance from private insurers, with the nuclear power industry itself required to provide further coverage up to a total of $10 billion. Most importantly, the nuclear power industry has secured legislation prohibiting liability claims above this $10 billion limit. With losses in a major nuclear accident estimated at over $300 billion, the balance would be shouldered by taxpayers. **6**

their critics readily seized on. Atmospheric nuclear testing, more than any issue, brought the issue of the health effects of low-level radiation to the mass media. In 1956, as the fallout controversy intensified, the AEC appointed the National Academy of Sciences, a prestigious non-governmental scientific panel to assess the current evidence for the effects of nuclear fallout (and more pointedly comment on the health effects of low-level radiation). Their conclusions were that atmospheric nuclear testing at that point in time, did not pose a 'significant' hazard. Yet they also foresaw the dangers of radiation exposure from nuclear power and called for careful control of radiation in this sector. However, and more disturbingly, they concluded that exposure to radiation, even in small doses, could cause genetic consequences that would be tragic in individual cases and harmful for the long term for the entire population over generations. "We ought to keep all our expenditures of radiation as low as possible. From the point of view of genetics, they are all bad."

Partly as a result of the fallout controversy and the National Academy of Sciences report, the NCRP revised its permissible occupational doses down to 50mSv (or 120mSv if past records of exposure existed). Note, however, this permissible limit applied to external radiation (x-rays and gamma rays) and internal emitters (ingested radioactivity) independently, so that in total a worker was permitted to be exposed to 100mSv in total (50mSv from each source). The International Committee on Radiological Protection (ICRP) usually matched and often set the levels used by the NCRP. However, unlike the NCRP it used public radiation levels which were one-tenth that of the occupational permissible doses, which the NCRP finally issued in 1959 jointly with the ICRP, therefore at 5mSv (and 1.7 mSv across population groups to minimise heritable genetic effects) exclusive of background (natural) radiation.
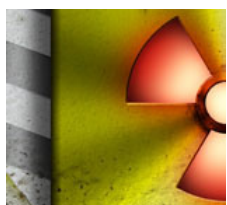
6. NUCLEAR CRITICS – NO 'SAFE' THRESHOLD

The concept of MPD's implicitly acknowledged there was no threshold below which radiation could be said to not cause harmful effects, only that the magnitude was not known although it was assumed to be minimal. Certainly, the somatic effects of low dose radiation, mainly cancer, had not been quantified at low doses due to a paucity of data. Increasingly influential though was the extrapolation of somatic effects from higher dose levels in a linear fashion. This was the 'linear no-threshold' dose-response model (LNT).[10]

In this environment, the potential health impacts of emissions from nuclear power plants were gaining unprecedented national attention. In the late 1960's and early 1970's two scientists affiliated with and funded by the AEC, were instrumental in putting enormous pressure on the nuclear power industry and regulatory agencies, and led to the introduction of the LNT model as a means of numerically estimating cancer risks. Arthur A. Tamplin, a biophysicist and a group leader in the biomedical division of the Lawrence Livermore Laboratory funded by the AEC, and his supervisor John W. Gofman, a chemist with a medical degree, who co-founded the division and was a former alumnus of the Manhattan Project, argued that the then MPD's were too high and advocated reducing them by a factor of ten. They looked at health studies of the survivors of Hiroshima and Nagasaki, as well as other epidemiological studies, and conducted research on radiation's influences on human chromosomes. On this basis, they argued that if the MPD of 1.7 mSv were applied to the whole population, this would result in 17,000 additional cases of cancer in the USA annually. They further argued that it was not obvious that the benefits of more nuclear power outweighed the risks. Ironically, and unbeknownst to the two scientists, the AEC's own regulators were internally simultaneously advocating similar reductions in MPD's, despite publically vilifying them.

In 1972, the Biological Effects of Ionising Radiation (BEIR-I) report of the National Academy of Sciences, declared that nuclear plants generated concern because of their growth and widespread distribution, and that the current limits of 1.7mSv across populations was "unnecessarily high." The BEIR report also found that the somatic risks (cancer) of low dose radiation were appreciable, and further that the LNT model was "the only workable approach to numerical estimation of the risk in a population." It also pointed out the need to evaluate the risks from radiation of nuclear power. The AEC, NCRP and other expert groups now accepted the LNT model that assumed no level of radiation exposure was certifiably safe. Eventually, this led to further reductions of nuclear plant effluent (gas and liquid) emissions limits.[11] Ultimately, Tamplin and Gofman's arguments were vindicated, but not until they were forced to leave the Lawrence Livermore Laboratories. It was not until 1974 that the AEC was disbanded and replaced by the Nuclear Regulatory Commission and the short-lived Energy Research and Development Corporation. A Joint Committee on Atomic Energy

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[10] This is now the established conventional scientific view and most recently endorsed by the National Academy of Science, Biological Effects of Ionising Radiation (low dose) VII (phase 2) report, 2006.
[11] 0.03 mSv whole body dose per annum across a population for liquid effluents, 0.05 mSv for gaseous , and 1.5mSv thyroid gland dose for Iodine 131 (a potential thyroid carcinogen).

oversaw radiation related issues in all federal agencies. However, frequent tension and disagreement prevailed partly due to a paucity of firm data to base MPD's and policy, and more than likely, the political desire to expand the number of nuclear power stations throughout the USA which by this stage had stalled due to cost blowouts and revised estimates of electricity demand downwards. The importance of radiation to national security, energy policy, and environmental health has always made the determination of the effects of low-dose radiation on health a difficult problem. To establish regulations for the safe use of radiation, federal agencies had to balance the uncertain health consequences of radiation against the government's interest in nuclear weapons and nuclear power.

The creation of the US Environmental Protection Agency in 1970 created an organisation whose remit included the protection of the population from environmental radiation, including radioactivity, and almost immediately came into conflict with the AEC (and its immediate successor, the NRC).[12] The EPA published a report in 1974 on the possible long-term hazards of nuclear power plants and which argued that the cost of radiation releases from nuclear plants from 1970-2020 were estimated at up to 24,000 deaths (including a period of up to one hundred years after the releases took place). The EPA further acknowledged that the radiation burden on the population related to the entire nuclear fuel cycle which included not only nuclear plant operation, but also fuel fabrication, reprocessing, and other processes, which enraged the AEC. Contemporaneously, the oil embargo of the early 1970's shifted the focus of the US government to becoming energy independent, which they determined required a major expansion in nuclear power. The EPA's plans for fuel cycle regulation of emissions were thus seen as compromising this and were curtailed. Instead their activities were restricted to oversee an ambient standard for the amount of environmental radiation from fuel cycle activities, rather than set standards for individual fuel cycle facilities. Russell Train, the former EPA administrator, declared a short time after leaving the EPA in 1977, "We need to develop a very firm commitment to the elimination of nuclear power as a source of energy on the earth." [13]

Over the ensuing several decades, three further BEIR reports were released. In addition, several nuclear accidents and incidents including Three Mile Island and Chernobyl (discussed later) damaged the safety credibility of the operation of nuclear power plants are increased public concern and scrutiny which had partly died down during the latter 1970's. The NRC in 1986 reduced its permissible limits for workers to 50mSv (combined internal and external sources) and the exposure of the general public from nuclear plants to 1mSv per person. The BEIR V report (1990) concluded that risks of cancer and leukaemia were three to four times greater than suggested in the BEIR III (1980) report. As a consequence, the ICRP reduced its occupational exposure limits to 20mSv per annum averaged over five years (within which up to 50mSv in a single year was permitted), however, the NRC retained their limits.[14] The NRC argued that the principle of 'as low as reasonably achievable' (ALARA),[15] which the ICRP had introduced in 1977, whereby the aim of good radiation protection was to attempt to reduce the doses as far as was achievable resulted in occupational levels far below regulatory limits obviating the need for revision. Australian occupational regulatory limits reflect the ICRP limits. There is a 1mSv limit per annum to the general public.

The BEIR VII report (2006) defined low dose as less than 100mSv. Since the previous report in 1990 much new information had come to light reinforcing their original heightened assessment of the risk of cancer and leukaemia, and stated:

"… there is a linear dose-response relationship between exposure to ionizing radiation and the development of solid cancers in humans. It is unlikely that there is a threshold below which cancers are not induced."
The report relied on updated data from the Hiroshima and Nagasaki atomic bomb survivors, medical exposure studies, and nuclear workers exposed at low doses and dose rates. Importantly, and contrary to previous assertions that most of the risk estimates were mere extrapolations from very high doses in atomic bomb survivors, more than 60% of exposed survivors experienced a dose of less than 100mSv, and 45% less than 50mSv, well within current cumulative occupational regulatory limits.

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[12] Nuclear Regulatory Commission. Simplified, the NRC was responsible for radiation protection deriving from what occurred inside a nuclear power plant boundary, and the EPA everything external to it. In practice, this was not as clear cut and turf battles and acrimony were the rule.

[13] "Russell Train gives views on the environment." Conservation Foundation Newsletter, January 1977, p3.

[14] These remain current.

[15] In 1977, the ICRP introduced a system of dose limitations based on the principle of keeping exposures to radiation 'As Low As is Reasonably Achievable' (ALARA). This system included (1) justification – no practice (causing exposures of people to radiation) shall be adopted unless its introduction produces a positive net benefit (should not cause more harm than good), (2) optimisation – all exposures should be kept as low as reasonably achievable, economic and social factors being taken into account, and (3) dose limits – the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances. The ALARA system is now established best practice in radiation protection worldwide. The fundamental principle is to consider dose limits as upper bounds rather than goals. No workplace or environmental exposure should be considered best practice if the limits are just met. **8**
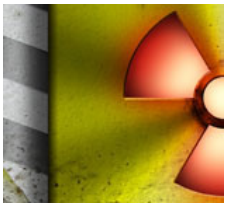
7.NUCLEAR POWER REACTORS AND CANCER

The radioactive burden of nuclear power is not merely from the operation of the power plants. There is an entire nuclear fuel cycle to consider. The potential health impacts of the nuclear fuel cycle not only concern the general public but also nuclear workers.

The nuclear fuel cycle includes the mining and milling of uranium ore; fuel fabrication; production of energy in the nuclear reactor; storage or reprocessing of irradiated fuel; and the storage and disposal of radioactive wastes. The doses to which the public is exposed vary widely from one type of installation to another, but they are generally acknowledged to be small and decrease markedly the further the distance from the facility.

The nuclear reactor core containing nuclear fuel rods and where heat is generated through nuclear fission is highly radioactive, and hence is heavily shielded accounting for virtually no ionising radiation to the surrounding region. Every day, however, in the course of their activity nuclear reactors routinely produce radioactive gases and liquids which are captured[16] and stored on-site until their activity decays to a sufficient level to enable their release into the environment ensuring the activity is below regulatory limits. These amounts are highly regulated and tritium is the largest of the nuclide emissions, by activity, from civilian reactors, apart from noble gases in some types of reactors. The radioactive effluents almost completely account for all radioactive emissions from nuclear power plants. The per capita dose to regional populations (less than 50km) surrounding nuclear power plants is 0.0001mSv (compared to around 2mSv natural background dose) and up to 0.02 mSv for specific groups up to 1km from a nuclear reactor (UNSCEAR, 56th session, 2008).. These are thus very small doses. Doses from nuclear power reactors to local and regional populations decrease over time because of lower discharge levels.

The carcinogenicity of ionising radiation is well established. BEIR VII assigns a risk factor of 5% per Sv, or roughly 1:25000 chance of contracting cancer per mSv dose per annum. On this basis alone, the cancer risk from the documented exposure to ionising radiation from nuclear power stations to the regional general population is 1:250,000,000 per person per annum (or 1:1,250,000 for the specific groups within 1km of the plant). This would equate to one extra cancer per annum for the whole of the USA if the regional population dose was hypothetically generalised to all US citizens. However, epidemiological studies are disturbingly demonstrating otherwise, and the causes are yet to be determined.

8. DO NUCLEAR POWER PLANTS CAUSE CANCER IN LOCAL POPULATIONS?

The role of civilian nuclear power in the induction of cancer, and specifically leukaemia, in the general public has been a major controversy over the last three decades and remains unresolved. Leukaemia is malignancy of the blood forming cells and is notable in the context of IR induction in appearing before solid cancers with a latency of around 4 years (compared to >10 years for solid cancers). Although there is little doubt that exposure to radiation increases the risk of developing leukaemia (BEIR VII 2006; Preston et al. 1994; United Nations Scientific Committee on the Effects of Atomic Radiation 2006; IARC 1999), there is disagreement as to whether the amount of exposure received by children living near nuclear sites is sufficient to increase risk.

The first epidemiological study to raise concern of a link was in Great Britain. This addressed an unexpected observed increase in cases of leukaemia in children aged under ten between 1954 and 1983 at Seascale, three kilometres from a reprocessing plant and other nuclear facilities at Sellafield.[17] Published by the epidemiologist, Martin Gardner in 1990[18], it suggested there was a connection between the increased incidence of leukaemia and Sellafield. Specifically, preconceptional exposures of the fathers of 46 cases of leukaemia, born in west Cumbria and diagnosed there between 1950 and 1985, were compared with those of 564 controls. An association was found between the exposure and leukaemia (Gardner's hypothesis), but this was dominated by four case fathers with high exposure (> 100 mSv). In 1993 a new report by the British Health and Safety Executive found the rate of childhood leukaemia in Seascale was fourteen times

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[16] Nuclear power plants operate under negative pressure.
[17] Committee on the Medical Aspects of Radiation in the Environment (COMARE): The implications of the new data on the releases from Sellafield in the 1950s for the possible increased incidence of cancer in west Cumbria. First report. London: Her Majesty's Stationery Office; 1986
[18] Gardner MJ, Snee MP, Hall AJ, Powell CA, Downes S, Terrell JD. Results of case-control study of leukaemia and lymphoma among young people near Sellafield nuclear plant in west Cumbria.BMJ 1990;300:423-9.

the national average. Two further studies examined leukaemia clusters in Dounreay and Aldermaston although could not correlate paternal exposure levels and leukaemia incidence at these nuclear sites. Furthermore, the increased incidence of leukaemia at Seascale was also occurring in children of unexposed fathers. Additionally, children born outside of Seascale, to Sellafield workers did not have an increased incidence to leukaemia. A further study in Canada also failed to demonstrate a link between childhood leukaemia and preconceptional paternal irradiation, or even ambient radiation.

Several studies since 1990 have found mixed results. A congressionally mandated study by the US National Cancer Institute studied the incidence of cancers including leukaemia in 107 counties with nuclear facilities within or adjacent to their boundaries, assessing incidence before and after commencement of operation from 1950-1984. Each county was compared to three similar 'control' counties. There were 52 commercial nuclear reactors and 10 Department of Energy facilities. It found no evidence to suggest the incidence of cancer or leukaemia was higher in the study counties compared to the control counties. It did however, acknowledge shortcomings in its methodology including not accounting for the potential for at risk populations to be smaller than the specific county study populations, and thus potentially masking underlying increases. Many studies confirmed increased rates of childhood leukaemia in proximity to nuclear power plants, however, could not confirm a correlation with radiation dose. A meta-analysis of 17 research studies involving 136 nuclear sites in the UK, France, USA, Spain, Japan, Germany and Canada [19] of the incidence and mortality of childhood cancer in relation to their proximity to nuclear power plants confirmed an increased incidence of leukaemia. The significance of this meta-analysis is that it not only stratified the distance from the nuclear plants, albeit in coarse terms, but also stratified the age groups of children, arguing that since the peak susceptibility to childhood leukaemia is under the age to ten, this group should be independently assessed. Therefore, any broader age groups could conceal an increase in incidence. They found in children up to 9 years old, leukaemia death rates were from 5 to 24 per cent higher, and leukaemia incidence rates were 14 to 21 per cent higher. The most recent of these studies and also the most compelling was sponsored by the German government in response to public pressure to examine the issue of childhood leukaemia and nuclear power reactors.[20]

This was commissioned by the Federal Office for Radiation Protection (BfS) in 2003. The KiKK case–control study examined all cancers near all of the 16 nuclear reactor locations in Germany between 1980 and 2003, including 1592 under-fives with cancer and 4735 controls, with 593 under-fives with leukaemia and 1766 controls. The main findings were a 0.61-fold increase in all cancers, and a 1.19-fold increase in leukaemia among young children living within 5 km of German nuclear reactors. These increases are statistically significant and are much larger than the cancer increases observed near nuclear facilities in other countries. The study is notable also for measuring the distance of each case from the nuclear reactor so that a distance-risk relationship could be computed. This was the first study of this kind, previous studies having either grouped all cases or coarsely stratified the distance data. The study found not only that risk is greatest closest to the plants but that small increased risk extends up to 70km from the nuclear power plant. Their conclusions discounted the role of radiation in the development of leukaemia due to the emissions being too low. However, an independent review panel appointed by the BfS criticised them for this conclusion arguing that the dose and risk models assumed by the Kikk authors did not necessarily reflect the actual exposures and possible radiation risks, and thus warranted further research before being dismissed as a cause. In other words, they implied that doses might be higher than are currently being measured.

There is reasonably strong evidence now of a link between the proximity of nuclear power plants and childhood leukaemia. There is no significant evidence for solid cancers either in children or adults. Clearly further research is warranted, particularly to elucidate the leukaemia causation. Policy makers therefore need to factor this increasingly strong scientific evidence, consider these health implications. Nuclear regulators also need to revisit their assumptions and consider revising standards at existing nuclear plants.

9. OCCUPATIONAL RISKS IN NUCLEAR POWER

The complete nuclear fuel cycle poses health risks at every stage. Of course hazards exist in every industry particularly the fossil fuel and general mining industries

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[19] Baker PJ, Hoel D. Meta-analysis of standardized incidence and mortality rates of childhood leukaemias in proximity to nuclear facilities. Eur J Cancer Care. 2007;16:355–363.

[20] Kaatsch P, Spix C, Schulze-Rath R, Schmiedel S, Blettner M: Leukemias in young children living in the vicinity of German nuclear power plants. Int J Cancer 2008, 22:721-726. Spix C, Schmiedel S, Kaatsch P, Schulze-Rath R, Blettner M: Case-control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980-2003. Eur J Cancer 2008, 44:275-284.

with deaths occurring not infrequently. However, most industries in developed countries have legislated requirements to minimise the risks to their workers. Furthermore, most responsible industries would have a zero tolerance policy to workplace deaths. In several Australian states, legislation places a liability on the employer to prevent workplace deaths. Furthermore, an employer is guilty of a crime if there is demonstrable negligence or culpability in relation to a workplace death if appropriate policies and implementation of workplace safety practices are not in place. In fact, the burden of proof is on the employer to demonstrate the existence and implementation of such policies and practices, reversing the legal principle of a presumption of innocence. The repercussions of inadequate workplace safety may not be apparent for decades as asbestos-related deaths now bring to light the scandalous disregard for employee health and welfare in the asbestos mining industry despite the medical evidence at the time which clearly demonstrated a major health hazard to asbestos workers. The employer obligation to preventing workplace related deaths has no time limit as deaths may occur many years after employment has ceased. The nuclear industry is no exception to this principle. In many ways it may actually be considered a pre-eminent example of this principle, due to the established carcinogenicity of IR, the lack of a risk-free threshold, and the long latent period before cancer appears (several decades). Furthermore, it raises questions concerning whether miners are given accurate and complete information from their employers concerning radiation induced cancer risks.

Cancer is a common disease accounting for 25% of all mortality in the general population. Therefore, there is much statistical noise obscuring small relative increases in cancer mortality consequent to ionising radiation exposure. In fact, the size of the study population required increases exponentially at lower radiation doses (because the number of cancer cases is commensurately less). In other words, if we are to detect a small increase in cancer risk at low doses, we need very large study populations to achieve statistical significance. Furthermore, given the latency period for radiation induced cancer, long follow-up periods are required. Occupational studies therefore can be difficult to perform and often have weak statistical power to prove a detriment. It is thus important to note that failure to establish statistical significance does not rule out the existence of a detriment, merely that the sample size was not large enough or the follow-up was not long enough.
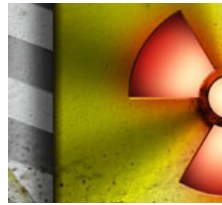
10. RADIATION RISKS TO URANIUM MINERS

The link between uranium mining and lung cancer has long been established.[21] Certain groups of underground miners in Europe were identified as having increased mortality from respiratory disease as early as the 16th century. Lung cancer as the cause was not recognised until the 19th century. The radioactive gas, radon[22], was identified as the cause in the 1950's. Studies of underground miners, especially those exposed to high concentrations of radon, have consistently demonstrated the development of lung cancer, in both smokers and non-smokers. On this basis, the International Agency for Research on Cancer (IARC) classified radon as a carcinogen in 1988. In 2009, the ICRP stated that radon gas delivers twice the absorbed dose to humans as originally thought and hence is in the process of reassessing the permissible levels. At this stage, however, previous dose estimates to miners need to be approximately doubled to accurately reflect the lung cancer hazard.

The Biological Effects of Ionising Radiation VI report (1999) reviewed eleven cohort studies of 60,000 underground miners with 2,600 deaths from lung cancer, eight of which were uranium mines[23] in Europe, North America, Asia and Australia. These found a progressively increasing frequency of lung cancer in miners directly proportional to the cumulative amount of radon exposure in a linear fashion. Smokers had the highest incidence of lung cancer, as would be expected,

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[21] National Research Council. Committee on health risks of exposure to radon (BEIR VI). Health effects of exposure to radon. Washington, DC: National Academy Press, 1999. Lyons: IARC, 2001. International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risks to humans. Vol 78. Ionizing radiation. Part 2: Some internally deposited radionuclides. Lyons: IARC, 2001. UNSCEAR 2006 Report Annexe E. Handbook on Indoor Radon. World Health Organisation. 2009.
[22] Radon-222 arises naturally from the decay of uranium-238, which is present throughout the earth's crust. It has a half life of four days, allowing it to diffuse through soil and into the air before decaying by emission of an alpha particle into a series of short lived radioactive progeny. Two of these, polonium-218 and polonium-214, also decay by emitting alpha particles, a potent form of ionising radiation with twenty times the dose equivalence of gamma or x-rays. If inhaled, radon itself is mostly exhaled immediately. Its short lived progeny, however, which are solid particles, tend to be deposited on the bronchial epithelium, thus exposing cells to alpha irradiation.

however, the greatest increase in lung cancer was noted in non-smokers. The highest percentage increase in lung cancer was noted 5-14 years after exposure and in the youngest miners. Uranium miners are also exposed to IR directly from gamma radiation and the dose from this is cumulative to that from radon. At the Olympic Dam underground uranium mine, the total dose per miner is approximately 6mSv, of which 2-4 mSv (allowing for the new ICRP dose coefficients) are due to radon and the balance due to gamma radiation. Workers at the smelter receive annual doses which may exceed 12mSv.

Most modern uranium mines have air extraction systems and monitored ambient measures of radon concentrations to ensure levels remain low. Current levels of radon in underground uranium mines are only a fraction of mines over one hundred years ago. Furthermore, miners are given personal protective equipment (PPE) including masks to filter out the radioactive particulate matter. However, many underground miners find the masks extremely uncomfortable, especially in the hot underground environment they must contend with. It is estimated that around 50% of underground uranium miners in Australia do not use their masks, and thus drastically increasing their risk of lung cancer, and underestimate their actual radiation dose (since this is calculated assuming PPE's are used). [24]

The Olympic Dam doses mentioned above are typical of modern mine practices. The average miner at Olympic Dam is in his twenties and stays on average five years at the site.[25]   A typical calculation using the linear no threshold model and the latest BEIR-VII figures of radiation carcinogenesis risks indicates miners at Olympic Dam therefore have a 1:670 chance of contracting cancer, most likely lung cancer. Note that as the research demonstrates risk of developing lung cancer is greater for younger workers. These risks are not insubstantial and it is debatable whether miners have the training to understand such explanations, or are even informed of these risks in a full and accurate manner that they can comprehend and make an informed work decision.
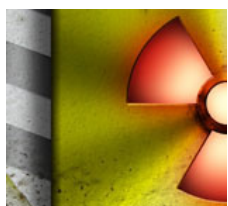
11. RADIATION RISKS IN THE NUCLEAR FUEL CYCLE

Many studies of mortality, and in some instances cancer, have been made over the last twenty years among nuclear industry workers (excluding mining).

Studies have covered workers in Canada, Finland, France, India, Japan, Russia, Spain, the United Kingdom, and the United States. In general, exposure in most of these studies was due to external radiation (x-ray and gamma ray). Internal contamination (through inhalation, ingestion, skin absorption, or wounds) by tritium, plutonium, uranium, and other radionuclides occurred in some subgroups of workers but attempts to reconstruct internal doses have been incomplete.

Studies of nuclear industry workers are unique in that personal real time monitoring of exposure has been occurring since the 1940's with personal dosimeters. More than 1 million workers have been employed in this industry since its beginning. However, studies of individual worker cohorts are limited in their ability to estimate precisely the potentially small risks associated with low levels of exposure. Risk estimates from these studies are variable, ranging from no risk to risks an order of magnitude or more than those seen in atomic bomb survivors.

However, the 15-country study of nuclear industry workers (excluding mining) published in 2005[26] the largest study of nuclear industry workers ever conducted, was able to arrive at statistically significant conclusions confirming the increased risk of cancer and leukaemia in nuclear industry workers, even at low dose. This involved analysing dosimetric records of over 407,000 workers and correlating with solid cancer and leukaemia mortality with a total followup of 5.2 million person years. The average cumulative dose was 19.4mSv, with 90% receiving less than 50mSv. Recall these are within the current permissible dose limits (50mSv in any one year, provide that there is no more than 20mSv per annum averaged over five years ie 100mSv total). The results indicated that there was an excess risk for solid cancers of 9.7% per 100mSv exposure, and an excess risk of 19% for leukaemia. The risks were dose related and they were consistent with the estimates from the Atomic Bomb studies. They estimated that 1-2% of all nuclear worker deaths were probably radiation related.

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[23] The others were, tin, fluorspar and iron. Although radon is a decay product of uranium, many other minerals are sourced in uraniferous sites. For example, the Olympic Dam mine in South Australia which produces the vast bulk of Australia's uranium is predominantly a gold and copper mine.
[24] Personal communication.
[25] Personal communication.
[26] Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. BMJ. June, 2005.
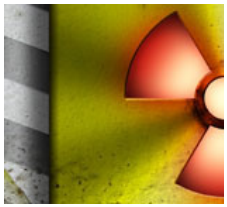
12. NUCLEAR REACTOR SAFETY AND THREATS TO PUBLIC HEALTH[27]

The public health risks of nuclear reactor accidents are potentially catastrophic. Unlike virtually any other major industrial accident,[28] the impact of a nuclear reactor core accident, and specifically, an uncontained meltdown, can span multiple continents through the potential for contamination over vast distances. This, in turn, can eventually lead to thousands of cancer deaths over the ensuing decades.

Whichever way one looks at nuclear reactors, they are enormous. Their magnitude, scale and complexity put them in an industrial category of their own. A typical nuclear plant sits under approximately four acres of roof alone, with the reactor core enclosed by masses of steel and concrete for protection from the deadly levels of radioactivity A vast amount of electrical wiring snakes its way throughout the complex. Huge steam carrying pipes and machinery the length of city blocks are easily consumed by the enormity of the structure. Few people occupy a nuclear plant because it mostly runs itself, with most of the human activity centred on the control room from which engineers monitor and occasionally inspect systems inside the plant. Visual inspection is impossible for the most critical and dangerous part of a plant; its core. Control room operators are more akin to pilots flying on instruments. Unable to visually inspect to any substantive extent the critical components of the reactor, they rely on interpretive analysis of the control room gauges to assess whether the reactor is functioning appropriately. If the readings are abnormal, their job is to analyse why not and then synthesise appropriate responses. It is one thing to read gauges, however, it is another skill to correctly analyse their meaning. Different people may interpret the data very differently – with catastrophic results. Skilled engineers with logical, linear thinking patterns can find themselves lacking the critical skills required when the linearity unravels in a crisis. Such was the fate at the Three Mile Island plant in Pennsylvania which suffered a partial core meltdown in 1976:

"One malfunction led to another, and then to a series of others, until the core of the reactor itself began to melt, and even the world's most highly trained nuclear engineers did not know how to respond. The accident revealed serious deficiencies in a system that was meant to protect public health and safety."

The Nobel laureate, Friedrich Hayek, received his prize on complexity theory. One of Hayek's main contributions to early complexity theory is his distinction between the human capacity to predict the behaviour of simple systems and its capacity= to predict the behaviour of complex systems through modelling.[29] He believed that economics and the sciences of complex phenomena in general, which in his view included biology, psychology, and so on, could not be modelled after the sciences that deal with essentially simple phenomena like physics.
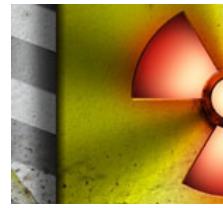
13. PROBABILISTIC RISK ASSESSMENT – LIES, DAMN LIES AND STATISTICS

Probabilistic Risk/Safety Assessment (PRA/PSA) is used to examine how the components of a complex system operate and attempts to quantify risk and identify what

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[27] The proliferation dangers associated with nuclear power are well established and significant although beyond the scope of this paper. The historical interrelationships between the civilian and military sectors exist to this day. They include, but are not limited to, the dual nature of uranium enrichment capabilities (it is easier to enrich low enriched fuel grade uranium to weapons grade uranium than it is to produce the fuel enriched uranium), the ability to extract plutonium from nuclear reactor fuel rods (for maximum plutonium production the fuel rods are normally kept in the core for no longer than ninety days and then sent to a reprocessing plant, compared to around 18 months for exclusively electricity production), and the difficulty in thus determining the true intentions of a country's nuclear program, as evidenced by the nuclear program in Iran. Often the first indication that a country has developed weapons-grade uranium is their announcement. The IAEA acknowledges it is underfunded for the task, and furthermore, can only engage in physical inspections of a miscreant state if they grant permission. Even if a state with nuclear power has not developed nuclear weapons, the infrastructure's dual purpose means that weapons development is only months to a few years away if desired.

[28] A number of Russian nuclear submarines have experienced nuclear meltdowns. The only known large scale nuclear meltdowns at civilian nuclear power plants were in the Chernobyl disaster at Chernobyl Nuclear Power Plant, Ukraine, in 1986, and the Three Mile Island accident at Three Mile Island, Pennsylvania, USA, in 1979, although there have been partial core meltdowns at:
•NRX (military), Ontario, Canada, in 1952
•EBR-I (military), Idaho, USA, in 1955
•Windscale (military), Sellafield, England, in 1957
•Santa Susana Field Laboratory (military), Simi Hills, California, in 1959
•SL-1, Idaho, USA in 1961. (US military)
•Enrico Fermi Nuclear Generating Station (civil), Newport, Michigan, USA, in 1966
•Chapelcross, Dumfries and Galloway, Scotland, in 1967
•Lucens reactor, Switzerland, in 1969
•A1 plant at Jaslovské Bohunice, Czechoslovakia in 1977. 25% of the fuel elements in a heavy water moderated carbon dioxide cooled 100 MW power reactor were damaged due to operator error.

[29] http://nobelprize.org/nobel_prizes/economics/laureates/1974/hayek-lecture.html April 9, 2010

[30] These include very large pipe breaks, and especially reactor pressure vessel failure, large earthquakes, and failures of the reactor protection system function.

could have the most impact on safety, particularly in the operation of nuclear reactors. Complex computerised modelling is used to assess various scenarios and combinations of events. PRA results are therefore complex and imprecise giving rise to a spread of results rather than an exact measure of risk. The imprecision and uncertainty in the result is partly because reality is more complex than any computer model, partly because modellers do not know everything, and partly because of chance. In essence, information is incomplete on the most serious or catastrophic events[30] because they have not occurred with a large enough frequency to provide enough data to be statistically useful. As a consequence analysts need to make estimates (which often may be little more than guesses) of the related probabilities which therefore lead to large uncertainties. Therefore, there continues to be large uncertainties in core melt frequency and off-site risks (risks arising external to the reactor such as earthquakes). However, the most catastrophic events can and do occur, even if infrequently, and these are the events which PRA is weakest in predicting, and even weaker in predicting the ultimate economic losses and health impacts on large populations.[31] Additionally, human interactions are extremely important contributors to safety and reliability in nuclear plants, and modelling human behaviour is fraught with uncertainties, yet can significantly impact the frequency or consequences of an accident sequence. PRA assume rational actions by humans and cannot model irrational or malign activities or a cascade of incorrect actions and responses. Most nuclear plant incidents and accidents[32] are due to human error, including the Chernobyl disaster. As summarized by Edward Hagen[33]:

"There is not now and never will be a "typical" or "average" human being whose performance and reactions to any operating condition, let alone an abnormal operating condition, can be catalogued, qualitatively defined, or quantitatively determined. There are no human robots."

Finally, new reactor designs increasingly rely on computer software for their operation. However, the National Research Council notes that there remains an ongoing "controversy within the software engineering community as to whether an accurate failure probability can be assessed for software or even whether software fails randomly."[34] This has led to inconsistent treatment of software failure modes in PRA's for nuclear plants.[35]

Statistical modelling is able to predict the 'known unknowns', however, the complexity of nuclear power reactors and the uncertainties inherent in their operation involves 'unknown unknowns' or what the author and professor of risk engineering at New York University, Nassim Nicholas Taleb, refers to as 'Black Swan Events' – high impact, hard to predict, and rare

events.[36] By definition, these are statistical outliers and not captured on PRA models. In essence, statistical modelling marginalises or even excludes Black Swan Events, often with catastrophic consequences.[37]

In any case, most risk assessments are not really risk assessments, but merely probability assessments, because actual accident consequences are not evaluated in most cases. Thus they only cover half the risk assessment process. Furthermore, the risk assessments are based on several convenient but unrealistic assumptions. For example, the assessments assume nuclear plants always conform with safety requirements, yet each year more than a thousand violations are reported in the USA. Plants are assumed to have no design problems even though hundreds are reported every year. Ageing of equipment is unrealistically assumed to result in no damage. Reactor pressure vessels are assumed to be fail-proof despite evidence of embrittlement.[38] Risk assessments assume plant workers are far less likely to make mistakes than actual operating experience demonstrates. Finally, the majority of risk assessments are based on core damage

[31] US Nuclear Regulatory Commission factsheet: Probabilistic risk assessment.
[32] Over 90%, personal communication.
[33] E.W. Hagen, "Common-Mode/Common Cause Failure: A Review", Nuclear Safety, Volume 21 Number 2, March-April 1980.
[34] Douglas Chapin et al., Digital Instrumentation and Control Systems in Nuclear Power Plants: Safety and Reliability Issues, National Academy Press, Washington, DC (1997)
[35] Smith, B. Insurmountable risks: The dangers of using nuclear power to combat global climate change. Takoma Park: IEER Press. P10-12; 2006. [36] N.N. Taleb, The Black Swan, Penguin, 2007
[37] The Global Financial Crisis (GFC) and the September 11, 2001 terrorist attacks in New York are examples of Black Swan Events that were thought impossible. The sinking of the (unsinkable) Titanic is also an example. The GFC resulted in multi-billion dollar losses by banks in loans that were seriously mispriced due to the employment of a PRA like method called Value at Risk (VaR) which used statistical modelling to determine the likelihood of loss. The risks of such events were found to be many orders of magnitude greater than predicted from statistical modelling.
[38] The reactor pressure vessel is a large stainless steel vessel, much like a large pot, which houses the reactor core. A typical pressure vessel operates at 300 degrees Celsius and at 70 atmospheres pressure. The majority of the plant's emergency systems are designed to prevent cooling water leaking from the vessel or to replenish any leaks, otherwise the core would overheat risking a core meltdown. However, if the reactor vessel fails and breaks open, water would pour out faster than all the emergency systems could replenish it virtually guaranteeing a core meltdown. There is no backup to the reactor pressure vessel. Risk assessments assume there is zero probability of pressure vessel failure, however, this is not realistic. Reactor pressure vessels are subject to embrittlement, whereby due to hydrogen penetration of the stainless steel in the process of the reactor's operation, the vessel becomes brittle predisposing to cracks and eventual shattering. The Yankee Rowe plant in Massachusetts, USA closed in 1992 because its reactor pressure vessel had become brittle over time, and there has been documented embrittlement at numerous other plants.

and ignore the serious health hazards from spent fuel in cooling ponds, ignoring the possibility of the fuel igniting if there is a loss of water, or there is a rupture of a large tank filled with radioactive gases. Researchers at the Brookhaven National Laboratory have estimated that a spent fuel accident could release enough radioactive material to kill tens of thousands of people. [39]

Of course, the irony is that the fundamental tenet underlying the rationale of using PRA in nuclear reactor operations is that nuclear reactors are too complex to guarantee absolute safety. It is an admission of the inherent risk in their operation and so, given this risk, mathematical modelling is employed to try to estimate it. [40] The US Nuclear Regulatory Commission's basic job as mandated by the US Congress (and which mirrors most nuclear regulatory organisations around the world) is to ensure only that the plants it licenses and regulates will provide "adequate protection" to public health and safety, and that the operation of nuclear plants presents no "undue risk." There is no requirement that there be absolute protection, because clearly by their admission, the nuclear power industry cannot provide this. Whilst one may argue that there is no absolute protection to public health in any industry, only the nuclear power industry threatens such potential catastrophic consequences for the public in the case of a core meltdown with failure of containment, that to expect such a level of protection is axiomatic.
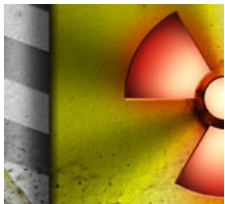
14. CONSEQUENCES OF A NUCLEAR ACCIDENT

Most (nuclear industry) experts consider a 1:10,000 chance of core damage per reactor-year based on historical data. [41] The MIT study, the Future of Nuclear Power (2003) stated in its global growth scenario leading to a tripling of the number of nuclear power reactors to 1200 worldwide:

"With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario with current technology would be 4 [using the PRA estimates].We believe that the number of accidents expected during this period should be 1 or less, which would be comparable with the safety of the current world LWR[Light Water Reactor] fleet. A larger number poses potential significant public health risks and, as already noted, would destroy public confidence." [42]

The US government calculated lifetime core melt probability for all 104 US-commercial reactors is 1 in 5. [43] In 1982, the government's Sandia National Laboratories modelled a study [44] of the effects of a core meltdown and radioactive release at one of the Indian Point nuclear power plants north of New York City. The study estimated 50,000 near term deaths from acute radiation and 14,000 long-term deaths from cancer. A later study (2004) estimated 44,000 near term deaths and as many as 518,000 long-term cancer deaths within fifty miles of the plant. Estimates of economic losses indicate $50 to $100 billion in business losses, and as much as $300 billion in human death costs.

The Chernobyl disaster at the Chernobyl Nuclear Power Plant, in the Ukraine in 1986, was the worst nuclear accident in history. On April 26, the reactor number four exploded, ironically following a safety test. The ensuing fire and core meltdown exposed the reactor core resulting in a massive release of radioactive material into the atmosphere which drifted over large parts of the western Soviet Union, Eastern Europe, Western Europe, and Northern Europe. Large areas in Ukraine, Belarus, and Russia had to be evacuated, with over 336,000 people resettled. Although no more than

[39] Nuclear Regulatory Commission, "A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants," NUREG/CR-6451, Washington, D.C., August 1997.

[40] The rate of accidents at nuclear plants follows the "bath-tub curve."(Lochbaum, D. Nuclear Plant Risk Studies: Failing the grade. Union of Concerned Scientists. UCS Publishing. 2000). This states that the accident rate is higher during the initial operating period of a plant as operators gain experience and the equipment is tested and broken in, finally reaching a lower accident frequency plateau until its later life when equipment wearing out and operator overconfidence leads to increased accident rates and eventual shutdown. PRA's however, only take into account the plateau phase of operation and thus underestimate the true whole-of-life risks of nuclear plant operation and particularly the higher accident rates at the commencement and later periods of operation. All seven nuclear accidents to have occurred so far in the USA have happened within one to seven years of the reactors first achieving criticality. Overall, the average length of time that these reactors had been operating before suffering their respective accidents was less than three and a half years. As the current fleet of US reactors has aged, the number of incidents caused by equipment wearing out has grown.

[41] The nuclear industry quotes 1:1,000,000 for newer reactors and 1:10,000,000 for the next generation reactors, however, these have no reliable evidence base or operational validation, being merely statistical modelling based on dubious assumptions.

[42] The Future of Nuclear Power: an interdisciplinary MIT study. MIT, 2003.

[43] Shrader-Frechette, K. Climate Change, nuclear economics, and conflicts of interest. Sci. Eng. Ethics. 2009

[44] Sandia National Laboratories. 1982. Technical Guidance for Siting Criteria Development, Sandia National Laboratories Report no. SAND81-1549, in, WMD Terrorism: Science and Policy Choices. Stephen M. Maurer (ed.). MIT Press, 2009, p.267.

around 50 people were initially killed, the International Agency for Research in Cancer (IARC) which is part of the World Health Organisation, predicts that there will be up to 41,000 excess cancers as a consequence by 2065, with 16,000 fatal.[45]
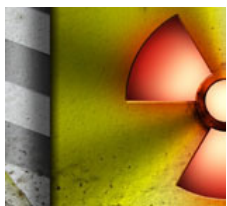
15. TERRORISM AND NUCLEAR POWER PLANTS

In addition to accidents, a successful terrorist attack on the scale of those carried out on September 11, 2001, could also lead to a major release of radiation. The Nuclear Regulatory Commission (NRC) considers the likelihood of this kind of attack occurring as small. The NRC furthermore, considers that nuclear power plants are difficult targets due to them being low lying and the reactor core being a small target. However, we should not forget that the probability of the World Trade Centre towers collapsing due to the impact of civilian aircraft was also considered to be small before they fell. Furthermore, more reactors mean more targets. The Design Basis Threat (DBT) of all US nuclear reactors refers to the general characteristics of adversaries that nuclear reactors and nuclear fuel cycle facilities are meant to defend against. It is a defensive characteristic of the required design, dating from the Cold War era. However, no reactor has an aircraft impact as part of its DBT. The last reactor to come online in the USA was in 1996. Therefore no reactor is adequately defended against such a terrorist threat. It is thus disingenuous for the NRC to surmise firstly that the risk of such an event is low. The most that can be reliably stated is that the probability might be low, however, we just don't have the data to make anymore than educated guesses. Secondly, it is equally fallacious for the NRC to claim that the consequence of an aircraft impact is unlikely to lead to a breach of containment. For example, a sudden shutdown of a nuclear reactor ('scram') in the event of a terrorist attack does not necessarily guarantee the reactor core will not continue to increase in temperature and melt, particularly if the impact has disabled the emergency cooling systems. If the containment structure has been breached from an aircraft impact, this could lead to a major release of radioactive contaminants into the atmosphere.

Additionally, it does not consider the consequences of an impact on the spent fuel cooling ponds which may ignite if there is a loss of cooling water and disperse radioactivity into the atmosphere. As a result of the World Trade Centre attacks, the DBT of US nuclear reactors was upgraded in 2007 to include various terrorist attacks. However, controversially the NRC did not include aircraft attacks, despite internal staff strongly advocating it although being overruled. It

instead insisted ambiguously that only new reactors be able to withstand an aircraft attack. *If this had been included in the upgraded DBT all existing reactors would have been required to be retrofitted accordingly, which the NRC insisted was not required.* Hence, ironically, all current US reactors are vulnerable to commercial aircraft terrorist attacks and will be for their operational life due to the nuclear regulator's opposition to safety upgrades.[46]

Yet, despite all the evidence to the contrary, the nuclear industry claims nuclear power is safe. If nuclear plants are as safe as their proponents claim, why do utilities need the U.S. Price-Anderson Act, which guarantees utilities protection against 98 percent of nuclear-accident liability and transfers these risks to the public? All U.S. utilities refused to generate atomic power until the government established this liability limit and continue to do so without it. Why do utilities, but not taxpayers, need this nuclear-liability protection?

16. NUCLEAR WASTE AND PUBLIC HEALTH

The average nuclear power reactor produces 300 m3 of low and intermediate level waste per year[47] and some 30 tonnes of high level solid packed waste per year. Every year, there is 12,000 tonnes of spent fuel (high level) being produced, which will triple if the so-called nuclear renaissance occurs.

As of 2010 there exists approximately 350,000 tonnes of nuclear fuel derived waste around the world. Currently this is being stored on-site in dry casks at most nuclear power plants, or at reprocessing facilities such as La Hague (France), as an interim solution. Greatly complicating this task are the very long half-lives of some of the radionuclides present in this waste (for example plutonium-239 – half-life of 24,000 years, technetium-99 – half-life of 212,000 years, cesium-135 – half-life of 2.3 million years, and iodine-129 – half-life of 15.7 million years). These are highly hazardous to humans and require ultimately isolation from the biosphere for hundreds of thousands to a million years.

[45] Cardis E, Krewski D, Boniol M, Drozdovitch V, Darby SC, Gilbert ES, Akiba S, Benichou J, Ferlay J, Gandini S, Hill C, Howe G, Kesminiene A, Moser M, Sanchez M, Storm H, Voisin L & Boyle P. Estimates of the Cancer Burden in Europe from Radioactive Fallout from the Chernobyl Accident. Int J cancer.
[46] Holt, M & Andrews, A. Nuclear Power Plant Security and Vulnerabilities. Congressional Research Service. 2009
[47] http://www.iaea.org/Publications/Factsheets/English/manradwa.html#note_c

The aim is to prevent water reacting with the waste since this is the main mechanism by which the waste can re-enter the biosphere. The IAEA states that deep geologic disposal using a system of engineered and natural barriers to isolate the waste is the best method. The principal features of the geological repository concept is to place packaged waste in a stable formation several hundred meters below the surface with engineered barriers around and/or between the waste packages and the surrounding rock. There is no deep geological repository currently in operation despite the nuclear power industry being in existence for over 50 years. With the projected tripling of nuclear power by 2050, a new repository will need to come online every six years somewhere in the world to keep pace with demand. Internationally, no country currently plans to have a repository in operation before 2020, and all proposals have encountered problems.

High level waste (including spent fuel) accounts for 2% by volume although 90% by radioactivity requires permanent storage in deep geological formations for a few hundred thousand years.[48] Due to the complexity of the problem and the long time periods considered, the ability of a repository to retain radioactivity has a significant degree of uncertainty. Similar to assessing the safety of a nuclear reactor, conceptual and statistical models are employed. Furthermore, similar assumptions usually based on insufficient or absent data are made to simulate the behaviour of a repository over an arc of time orders of magnitude beyond that of recorded human history. The process requires the designers of the repository to know what they don't know about chemical and geological processes at a given site over this time. As summarized by the US National Research Council:[49]

"Simply stated, a transport model is only as good as the conceptualizations of the properties and processes that govern radionuclide transport on which it is based. If the model does not properly account for the physical, hydrogeochemical, and when appropriate, biological processes and system properties that actually control radionuclide migration in both the near- and far-fields of the repository, then model-derived estimates of radionuclide transport are very likely to have very large -- even orders of magnitude -- systematic errors."

Numerous examples exist to demonstrate the failures of such analysis in current nuclear waste management. In July 2008, at the German nuclear waste dump in Asse, it was revealed the former salt mine has leaked radioactive brine for two decades and threatened major groundwater contamination. It was designed to last several hundred years. When many of the sites of the US nuclear weapons complex were founded, it was believed that their arid climates and thick

unsaturated zones would protect groundwater from hundreds to thousands of years. These assumptions have been proven wrong. The transit time for several of these sites has been reduced to only several decades underscoring the invalid underlying assumptions in the original modelling. Another example is the discovery of the mobility (leakage and contamination) of radionuclides below the high-level waste tanks at Hanford, Washington.[50]

The large time scales considered necessary also exceed the rise and fall of many civilisations together with their linguistic, cultural and artistic legacies leaving a hiatus in our understanding of these civilisations much less their physical legacies. Information transfer is a key factor, with the management system more important than the media used, and that the greatest threat to information transfer is institutional change. A number of external events, such as climate change, natural disasters, wars, and civilisation collapse could all affect the long term management of radioactive wastes, but it is the more 'trivial' causes such as destruction of archives by paper decay or disruption of electronic media that could lead to problems. Committing to a large increase in the rate of waste generation based only on the potential plausibility of a future waste management option would be to repeat the central error of nuclear power's past. The concept for mined geologic repositories dates back to at least 1957, but turning this idea into a reality has proven quite difficult, and a solution to the waste problem remains elusive to this date. Even more disturbing is the prospect that our highly toxic waste will be our future generations' liability.

[48] To put this in perspective, the Egyptian pharaohs were in power only five thousand years ago, and homo sapiens are understood to have appeared in East Africa between 100,000 and 200,000 years ago.
[49] D. Warner North et al., Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges, National Academy Press, Washington, DC (2001).
[50] Shrader-Frechette, K. Climate Change, nuclear economics, and conflicts of interest. Sci. Eng. Ethics. 2009.
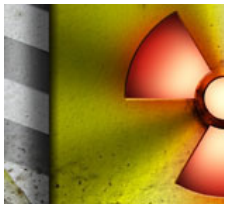
17. CONCLUSION

The nuclear power industry is bedevilled with a military pedigree responsible for the worst weapons of mass destruction. The marketing gurus would say they have a 'branding' problem, and that they need to be rebranded. The nuclear power industry furthermore would distance itself from this pedigree claiming that it has an impeccable record of operational safety. However, the evidence contradicts their claims and furthermore underscores much of the uncertainty that shrouds their estimates for future safety. Of course, the 'branding' problem is ironic since the creation of a nuclear power industry was an attempt to rebrand the nuclear weapons industry and give it legitimacy and underscore public support for it, by emphasising the perverse dichotomy of the need to prepare for nuclear war, and the peaceful promise of the energetic atom – a peace now, war later scenario.

The enthusiastic public relations driven motives of politicians and the military to pursue nuclear power, therefore presupposed the development and expansion of nuclear power, with safety as an afterthought and little tolerance to safety and public health concerns. Indeed, the history of nuclear power is riven with conflicts of interest, understatement of risks, vilification of critics and masterful spin, adapting itself to perennially solving the next environmental problem or energy concern lest it be accused of creating it.

So what is different now? We could facetiously, although equally credibly, argue not much in that the nuclear power industry has now put its hand up to solve the environmental problem du jour, climate change, with claims of cost effectiveness and safety. The rhetoric is redolent of its 1970's mantra of saving us from fossil fuel pollution and establishing energy independence, just before the Three Mile Island and later Chernobyl accidents, and ultimately *"[t]he [economic] failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale."*[51]

Yet perhaps the most glaring concern is that the nuclear power industry developed with safety concerns trailing a distant second. The science of radiation safety and health effects of ionising radiation were still evolving as the civilian nuclear boosters and industry vested interests encouraged further expansion, the motto being, 'electricity now, safety later.' We now have voluminous evidence of public health risks of low levels of ionising radiation, even within occupational regulatory limits. In fact, we also know that there is no 'safe' level of radiation exposure below which radiation does not lead to a risk of cancer – there is no safe threshold. Although the measured doses on surrounding populations from nuclear power plants are very low, we also have strong evidence of a link between increased rates of childhood leukaemia and proximity to nuclear plants. We acknowledge that nuclear power reactors operate within a nuclear fuel chain that commences with mining of uranium and ends with decommissioning of nuclear reactors, with occupational risks at every step. The long association with uranium mining and lung cancer is unequivocal, due to radon gas exposure. Recent evidence however points to radon gas being twice as hazardous as first thought. There is also increasing evidence of an increased rate of solid cancers in nuclear industry workers throughout the nuclear fuel chain proportional to their radiation dose.

Statistical risk modelling to determine nuclear reactor safety has been found wanting and prone to too many uncertainties leading to orders of magnitude variations in likely reactor accidents. Add to this the potential catastrophic consequences of a core meltdown with failure of containment, and the industry's entreaties of excellence and safety ring rather hollow. Maybe we should stop listening to them and instead infer from their actions their true beliefs of the likelihood of a major accident – utilities refuse to operate without the liability of a major accident being transferred to tax-payers. Now who really needs protection?

Lastly, the ultimate in public health and safety concerns is the intergenerational legacy of billions of tonnes of toxic nuclear fuel waste that needs to be sequestered from the biosphere for hundreds of thousands of years using questionable statistical modelling of deep geological repositories which have not yet been prepared. Four decades ago, the then-director of the US government's Oak Ridge National Laboratory, Alvin Weinberg, warned that nuclear waste required society to make a Faustian bargain with the devil. In exchange for current military and energy benefits from atomic power, this generation must sell the safety of future generations.

'OFFICIAL RADIATION WARNING OF THE INTERNATIONAL ATOMIC ENERGY AGENCY'.

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[51] Forbes 1985.