Notes on the economic valuation of nuclear disasters.

by

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Abstract:

We provide an overview of methods used to assess the economic impact of nuclear accidents, along with a summary of attempts to date to estimate the costs and policy responses to accidents.

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JEL Codes:

1 Introduction.[*]

Nuclear accidents such as Chernobyl or Fukushima are examples of slow-moving but persistent disasters. *Slow-moving* because, unlike say earthquakes or industrial explosions, typically the accident unfolds over a timescale which allows most local residents and workers to abandon the affected area safely. The disasters are *persistent* because of the nature of radioactive materials released which often have half-lives that are significant compared to the typical life span of humans.

Thankfully major nuclear accidents are rare events. In the sixty or so years in which nuclear power has been used to generate electricity, there have only been 2 events that merit a '7' on the International Atomic Energy Authority's event scale for accidents The sole 6 event was the Kyshtym disaster at Mayak in the Soviet Union, in 1957, the causes of which are not currently clear. The IAEA lists 3 accidents labelled 5, including the Three Mile Island (TMI) accident in the USA and the 1957 Windscale Fire in the UK[1] (IAEA, 1996)..

There is very little work done on the economic valuation of nuclear accidents and as I argue in more detail below, most of this work is inappropriate in terms of its economic methodology. The key problem with existing works are:

1. many lost benefits lost are estimated using the cost of damaged or abandoned assets.
2. some lost benefits are measured twice – by the cost of the damaged assets and by the cost of their replacement.
3. many costs are in fact transfers
4. many costs remain unestimated – this particularly applies to health and labour market costs.

As a result these notes are incomplete, in the sense that sufficient data is not available to provide a complete picture of the economic costs of nuclear accidents.

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[*] Prepared for the Environmental Economics course on the Masters in Public Policy at the National Graduate Institute of Policy Studies, Tokyo. Please do not quote without permission.

[1] Level 7 represent an extremely large release of radioactivity causing widespread health and environmental effects. Described as a major accident. Level 6: A very large release of radioactivity (about 1/10 of scale 7) likely to require the full use of planned countermeasures. Described as a serious accident. Level 5: A limited release of radioactivity (about 1/10 of scale 6) likely to require partial use of planned countermeasures. This involves severe damage to the reactor. Described as an accident with off-site risk (IAEA). The other 5 rated event is Goiânia, Brazil, 1987, where 4 people died after an abandoned radiotherapy device was broken open and the active materials removed.

2 Background.

The boxes contain some basic terminology.

Box 1 Radiation.

There are 3 types of ionizing radiation. Directly ionizing particles. Alpha particles are helium nuclei and consist of two protons and two neutrons. They therefore carry a positive charge. Beta particles are electrons and therefore carry a negative charge. Neutrons are indirectly ionizing particles. They are indirect because they do not carry a charge, instead creating ionizing particles through collisions with atomic nuclei. High energy photons, such as gamma an x-rays are the third type of ionizing radiation. Again, they are indirectly ionizing. A large proportion of gamma and x-rays pass through without interaction with the tissues of the body. At the other extreme, apha particles penetrate much shorter distances. They can be stopped by a sheet of paper.

Measurements of radiation

Becquerels. A becquerel is defined as the radioactive decay of 1 nucleus per second. The units are therefore 1/seconds. Becquerel figures are often quoted in the form of Becquerel per kg (of a material) or some other measure of quantity such as litres or cubic metres (e.g. of soil). A giga becquerel is 10^9 becquerels. A tera Becquerel (TBq) is 10^{12} Becquerels.

Sieverts are a measure of biological dose. The units are joules per kg. A millisievert is 1/1000 of a sievert (written as mSv). A microsievert is one millionth of a sievert (or μSv). The equivalent dose for an organism is defined by,

$$E = \sum_T W_T \sum_R W_R D_{RT}$$

Where W_T is the proportion of tissue type T (in a kg of body mass), W_R is the weighting factor for different types of radiation, R and measures the relative damage caused by each type, while D_{RT} is the absorbed dose of radiation type R in tissue type T. W_R varies considerably according to the type of radiation. For instance, electrons and photons have a weight of 1, while alpha particles have a weight of 20. (Harley, 2008, Newman 2010).

Dose levels and acceptable dose levels are often reported in terms of sieverts per unit of time. For instance, in Japan, the normal legal limit for a nuclear industry worker is 50 millisieverts per year under normal circumstances. However, once the Fukushima accident occurred the emergency limit was increased twice, to 100 millisieverts, and then to 250 millisieverts per year. Within the European Union, the European Council Directive 96/29/Euratom of 13 May 1996, requires that workers are not exposed to 100 mSv over a period of five consecutive years and must not exceed 50 mSv per year in any one year. Background radiation is the exposure to ionising radiation from during normal life. It varies according to lifestyle, latitude and geology, but for instance, worldwide the average background dose is 2.4mSv per year (Green et al, 1992). Some of this typical dose is due to earlier nuclear accidents and nuclear weapons tests.

Radio-nuclides.

All atoms of a given element have the same number of protons, but different isotopes have different numbers of neutrons in the nucleus. As a result isotopes differ in their atomic mass and may also differ in their stability. Unstable isotopes may lose energy by emitting ionizing particles spontaneously. Isotopes have different patterns of decay. For instance, Iodine-131 (i.e. Iodine with an atomic mass of 131), decays to Xenon-131 by gamma and beta particle emission. Meanwhile, uranium-238 normally decays by emitting an alpha particle.

Half-life. Radioactive decay is stochastic. The half-life of an isotope is the length of time after which the rate of decay has fallen by 50%. Iodine-131, for instance has a half life of 8 days. This means that after 64 days, say, the rate of radioactivity has fallen by $½^8$ = 1/256 of its original level.

In nuclear reactor accidents, commonly released radionuclides include iodine-131 (half life of approximately 8 days), caesium-134 (2 years), caesium-137 (half life of 30 years), strontium-90 (half-life of 29 years). In the case of Chernobyl (see below) significant quantities of isotopes of tellurium and rubidium were also released. Three-mile Island produced large quantities of noble gas isotopes while Polonium-210 was a significant factor in the releases caused by the Windscale fire.

3 General valuation issues.

The economic cost of a nuclear accident is the value of the benefits lost from destroyed or damaged assets + costs of adaptation and mitigation – benefits from adaptation and mitigation + spillover costs

Mitigation means measures taken to lessen the impact or severity of the accident. Adaptation means measures taken to adapt to the new situation. The slow-moving nature of nuclear accidents creates opportunities for both adaptation and mitigation.

For instance, placing a protective shield over a destroyed reactor to protect against further releases of radionuclides would count as mitigation. Buying foreign spinach instead of locally grown produce would represent adaptation. In some cases, it is not clear whether an act is truly mitigation or adaptation. For instance, in the wake of the Chernobyl accident some milk has been used for cheese production rather than being consumed directly. The discarded waste from the process contains a disproportionate share of the original radioactive material (Chernobyl Forum, 2006). The switch to cheese production represents both mitigation and adaptation. Acts of mitigation or adaptation are typically choices made by individuals, companies and government. So we might question whether to include them in the baseline estimate of costs.

Lost assets typically include physical assets (e.g. the reactor, machinery, housing abandoned or destroyed), natural assets such as forests and fisheries as well as human capital. Obviously, the most extreme form of lost human capital is death itself.

Figure 1 summarises the loss of benefits from the destroyed assets. The horizontal axis shows time and the vertical axis shows costs. A negative value for cost is a benefit. The loss of benefits is shown as constant per unit of time, but could of course vary. The net present value of the loss of benefit is the sum of the area under the line, with each value discounted at the appropriate discount rate.

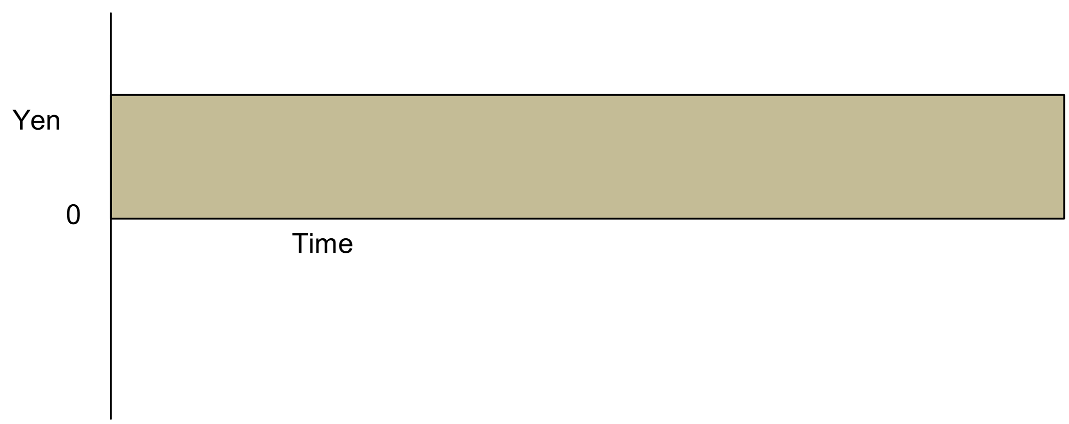

Figure 1. Destroyed benefits.

For an infinite stream of t lost benefits of b per unit of time, t, discounted at a rate of r this is just

$$\int_0^\infty b(t)e^{-rt}\,dt$$

When b is constant, this reduces to:

$$\int_0^\infty be^{-rt}\,dt = \frac{b}{r}$$

It is often the case that assets are replaced or rebuilt at some stage. Figure 2 summarises the amended story. In this diagram the cost of the accident consists of two parts. There is the period of lost benefits from the destruction of assets which lasts from period 0 until period T. In addition there is the cost of restoring or replacing these assets which in the diagram occurs over some period at a rate of c from T-x to T. If, as in the diagram, b and c are constant, then the amended cost is therefore:

$$\int_0^T b(t)e^{-rt}\,dt + \int_{T-x}^T c(t)e^{-rt}\,dt = \frac{b}{r}\left(1 - e^{-rT}\right) + \frac{c}{r}\left(e^{-r(T-x)} - e^{-rT}\right)$$

Note that if the investment occurs over a short period of time just prior to T, its net present value is approximately Ce^{-rT}/r where C is the cash value of the investment ($\approx$ cx).

There are two further important features of the sum. First, the original cost of constructing the assets is not a cost in the destruction – that cost is accounted for by the loss of benefits. Secondly, there can be different plausible scenarios for the eventual replacement of the original services. They might not be replaced; they might be replaced at different dates and they might be replaced in an enhanced form or the services provided may subsequently be provided by substitute assets.

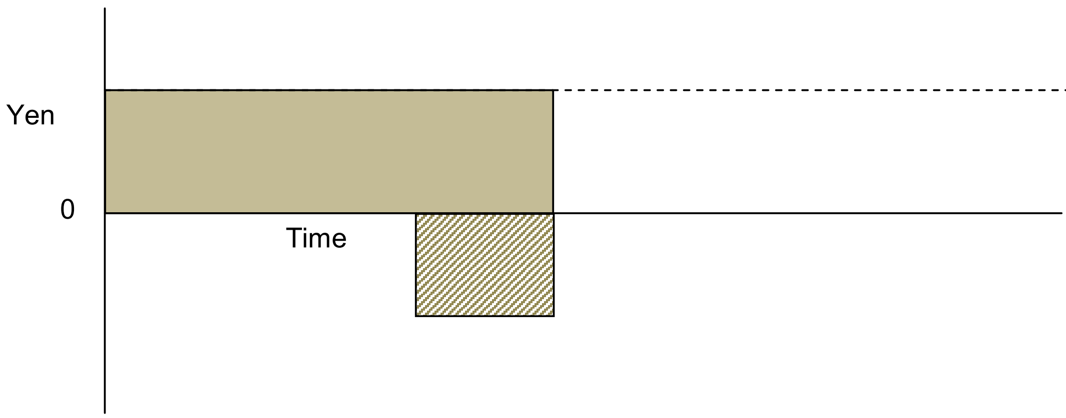

Figure 2. Destroyed benefits with replacement

Is it ever reasonable to include the sunk cost of the original asset in the estimation of the costs of the accident? In some cases it might not be feasible to measure directly the benefits lost. All we 'know' is that at the time of construction the anticipated benefits of the asset exceeded the original costs. If these benefits are now lost then the cost of the asset may provide a lower bound for the lost benefits. In other words, the cost is only used if it is needed to provide an estimate of lost benefits. But it is readily seen that the argument is loose and easily challenged. For instance, even if the benefits at the time of construction exceeded the costs, that does not mean that the lost future stream of benefits would necessarily be greater than costs. If the asset is old, superseded or unnecessary then it is entirely possible that the lost value is smaller than the construction cost.

If investment in the capital asset is continually being made and the asset is tradeable in a perfectly competitive market and the damage to the asset is marginal, then in theory the lost value of the asset will be equal to the lost discounted sum of future benefits. In this case, the asset value will be suitable proxy for the benefits lost. However, this is not typically the case for large or lumpy assets, for public infrastructure or for capital goods owned by households (including human capital).

Three other factors to consider:

- Transfers and compensation payments. In some cases payments were made to individuals or producers by government as compensation for illness or for disruption to lifestyle or to encourage producers to remove their contaminated products from circulation. In all these cases, the actual payments are transfers. In other words, setting aside issues of redistribution, the benefit to individuals receiving the payments cancels out the costs of the money spent. The appendix sets out a simple diagram summarising the (non)-relationship between economic costs and compensation paid.
- Deadweight loss. An amendment to the conclusion of the previous point must be made when funds for compensation are raised by distortionary taxes such as a rise in income tax or a consumption tax. When this occurs there is a deadweight loss from the tax which must be accounted for. Yet the actual compensation payments themselves are still transfers.
- If there are significant discharges of radioactive material into the environment, the effects of nuclear accidents can be long-lived. In these circumstances calculations of the cost of the accident will be sensitive to the discount rate used. In general, the lower the discount rate, the higher the estimate of the costs. (This need not be true if there are subsequent investments in replacement assets. Our first formula for the cost of the accident is clearly monotonically decreasing in r, but the second formula is not necessarily monotonic). [2]

3.1 Human capital.

The major damage to human capital is in 3 forms:

- Mortality – either at the time of the accident or subsequently perhaps by radiation-induced cancer.
- Morbidity – reduced health or quality of life. E.g. due to a non-fatal cancer. Morbidity also includes psychiatric conditions such as anxiety or depression
- Stigma - the negative reaction of other people to experience of exposure to radiation[3]

Within economic valuation, the most common approach to costing mortality is based on the value of a statistical life (VSL).

[2] Gollier and Weitzman, 2010 present a summary of the case for the use of the lowest possible discount rate for long-lived projects, when there is a range of possible future values for the marginal productivity of capital. In their model, a decision-maker switches one unit of resources to invest in a project. The value of the project is known, but there is uncertainty about the opportunity cost of the project. They demonstrate that as the time horizon increases, the lowest possible opportunity cost dominates the calculation.

[3] Remennick, 2002, quotes one emigrant to Israel from the Chernobyl zone: “The shadow of Chernobyl will hang over our lives forever, you cannot run from it—to Israel, America or elsewhere. When your blood and bone are poisoned by radiation you become different, and somehow it shows. There is this morbid spirit of hopelessness around you. Chernobyl victims live here under a double stigma—as Russian immigrants and as radio-zombies…”

An example illustrating the idea.
Suppose there are two states of the world: death and life. Normalise the utility of death at 0, then the expected utility of a world with a probability 1-p of death and income when alive, y is,

$$EU = pu(y)$$

In the VSL approach we ask what decrease in income would offset a small decrease of Δ in the probability of death. In other words, find w such that,

$$pu(y) = (p + \Delta)u(y - w)$$

For infinitesimal changes in Δ, we can obtain,

$$\frac{dw}{d\Delta} = \frac{u(y - w)}{u'(y - w)p}$$

VSL can typically be estimated in one of two ways. One is via revealed preference, by looking at the observable trade-offs between income and risks of fatal accidents made by workers in their choice of occupations or by households in their choice of location. This method is not suitable for estimating the VSL for children or non-workers (or non-householders in the case of location choice). An alternative method is through stated preference, where a sample of individuals is asked to state their willingness to pay for a small, decrease in the risk of death or their willingness to accept a small rise in death risks.

Similar stated and revealed preference methods can be used for changes in morbidity. Using stated preference for mortality and morbidity changes brings with it all the familiar problems of stated choice methods. Bateman et al, 2002, provides a thorough discussion.

VSL is widely employed in cost-benefit analysis and public policy. For instance, in the US a figure of $5.8m is the standard used in public policy by the Federal Government. Viscusi and Aldy, 2003, use data from several countries in a meta-analysis to calculate income elasticities for wtp to save a statistical life. Their preferred figure is 0.51. In other words, a 1% rise in income is associated with a 0.51% rise in wtp for a given reduction in risk. We can use this elasticity model to produce some crude cost figures for lives lost in other countries at other times.

Dread risks. The most basic VSL model assumes that the cause of death does not matter. More sophisticated models allow for the possibility that individuals care about the causes of risks as well as the risks themselves). There is some evidence (e.g. Savage, 1993) that many individuals dread particular risks – in other words they are willing to pay more to prevent or reduce some risks for a given change in the probability of death or ill-health. Jackson et al, 2006, consider the evidence in a radiation context while NERA 2007 is a background report on the economic valuation of radiation risks prepared for the UK's Health and Safety Executive.

3.2 *Spillovers and Macroeconomic effects.*

Large scale accidents can have consequences throughout the economy.

- Supply chain effects.
- Uncertainty shock (see Bloom, 2009, for example for a general discussion of an uncertainty shock).
- Domestic confidence. Uncertainty shocks may be one source of a loss of confidence generally in the domestic economy, which can have widespread macroeconomic consequences.
- Overseas demand. Fear of contamination and fear of contaminated products can lead to a drop in export demand. For instance, tourist numbers coming to Japan dropped sharply after the earthquake and nuclear accident on 11th March 2011 (see figure) and have been slow to recover. Meanwhile some well publicised cases of contaminated goods shipped abroad may have wider implications for the demand for Japanese foodstuffs.

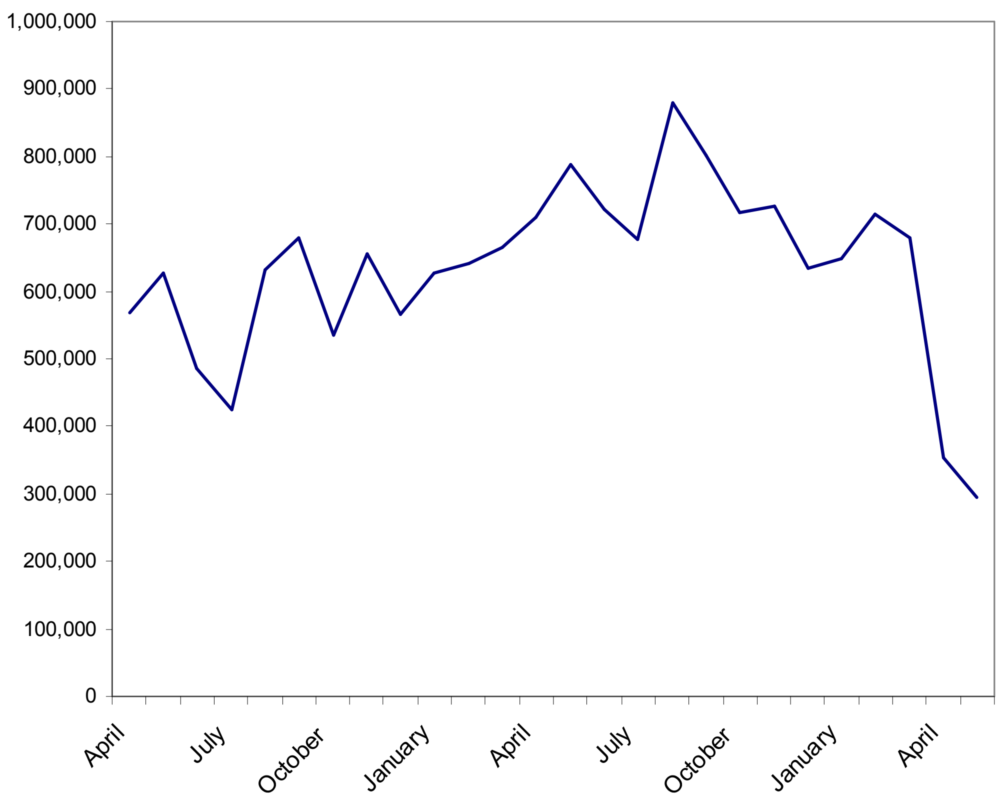

Figure 3. Visitor Numbers to Japan, 2009-2011. Source: JNTO

4 The impacts.

4.1 Ex ante estimates.

There are a small number of studies in which economists have used stated preference data to estimate wtp for insurance or protection against a nuclear disaster. Note that in general, unless individuals are risk neutral, wtp is not equal to the expected compensating surplus from a disaster (Graham, 1981).

Peter Zweifel et al, 2005 conduct a 500 person contingent valuation study in Switzerland on willingness to pay for insurance against a nuclear disaster. Their major finding is that, residents were willing to pay (on average) $2,280 for full insurance at zero distance from nuclear power plants, with mean WTP estimates falling by $24 per km to zero at a distance of 95 km. This rate of distance decline is gentler than that found in US hedonic studies and suggests to the authors that “Data on housing prices, being contaminated by regional supply shift effects, are unlikely to permit discovering the demand effects caused by the sorting in space performed by individuals when choosing their residential location.” P. 23.

Takaaki Kato, 2006, reports a contingent valuation experiment conducted on people living in three small municipalities within 10 km of the Kashiwazaki–Kariwa Nuclear Power Station in Niigata prefecture, Japan. As with other locations that are close to nuclear power stations, residents receive ‘compensation’ in the form of tax transfers to local governments and some (small) payments to local householders and businesses, funded by the owners of the station. The sums vary. [4] Kato examines the willingness of residents to accept a further year of existing payments for an extension of the lifetime of the facility. Approximately 520 residents respond to a mailshot survey. It is not possible to estimate a mean willingness to accept compensation based on the format used, but around 62% did not disagree that the existing payments were adequate compensation in Kariwa, while roughly 55% in the other two towns held the same view. Working for the nuclear facility was linked to the acceptability of the payment. [5]

In July 2007 a magnitude 6.6 earthquake centred 15km out in the neighbouring Sea of Japan shut the plant for 21 months. There was no significant damage to the operating facilities of the

[4] For instance, according to Kato, 2006, the direct payment in 2002-03 was ¥19,000 per annum for households in either Kariwa Village or Kashiwazaki City and half that amount in nearby Nishiyama Town. Meanwhile the indirect payments (some of which are received at the prefectural level, but spent locally) are estimated to be ¥ 706,000, ¥103,500 and ¥25,500 per capita per annum for residents in Kariwa, Kashiwazaki and Nishiyama. All three settlements are roughly the same distance from the 7-reactor nuclear power plant which is owned and operated by the Tokyo Electrical Power Company (TEPCO).

[5] The highest indirect payments, to residents in Kariwa, exceed $7,000 per annum. The refusal to see this as adequate compensation may indicate that some residents have lexicographic preferences, but of course the fact that they continue to live locally suggests otherwise.

plant, but TEPCO undertook significant upgrades to the safety systems. Kato, 2010 reports on a follow-up survey that took place in the wake of the earthquake.

A choice experiment is the vehicle chosen by Kenshi Itaoka et al, 2006 to estimate wtp for reductions in the risks of death from nuclear accidents in Japan. The figure below (figure 1 in the original) shows a typical question (translated into English by the authors). A professional survey firm was used to deliver questionnaires to a random sample of 1500 Tokyo residents and 1000 Gifu residents. The following day 1513 surveys were returned. Of these, approximately 29% of subjects chose the status quo in all 6 questions they faced. In all, 639 surveys were used for the statistical analysis.

		Attributes	Current situation	Program 7	Program 8
PRODUCT	Break-down of effects of Nuclear power sector	(a) Annual probability of a severe accident	30 / 1 million	30 / 1 million [No change]	30 / 1 million [No change]
		(b) Lives lost <u>if a severe accident happens</u>	4000 persons	1500 persons [2500-person reduction]	1500 persons [2500-person reduction]
SUM	Nuclear power sector	(c) Lives lost per year Calculated by (a)×(b)=(c)	0.12 person	0.05 person [0.07-person reduction]	0.05 person [0.07-person reduction]
	Thermal power sector	(d) Lives lost per year	1000 persons	990 persons [10-person reduction]	998 persons [2-person reduction]
		Total reduction of lives lost per year	0	10.07-person reduction	2.07-person reduction
		More tax per household per year (Costs for new public policies)	0	8000 yen	2000 yen
		Which one of these three options would you vote for?			

1000 yen per year = About 80 yen per month

Figure 4. Example choice Set in Itaoka et al, 2006.

There was no evidence that subjects valued lives lost in ‘disasters’ and through ‘routine’ events differentially, but individuals who faced questions where the nuclear disaster was labelled as such were willing to pay 34,700 Yen in extra taxes per year to save a life, compared to only 300 for lives in a non-labelled disaster. Probability was not a significant factor in choices, suggesting that subjects focused only on the number of deaths – not their likelihood.[6]

[6] It is worth noting that 34,700 Yen per year per respondent is a huge figure (around 300 Euros). When aggregated across the whole of Japan, it would produce a sum in excess of 27bn Euros per year to save one life. Itaoka et al, 2006, suggest that some of their more extreme results are because “At least part of this effect appears to be due to an inability to process probabilities of the size relevant to the analysis of nuclear sector disasters.” (p. 395).

5 Specific Events – Ex Post Analysis.

5.1 Windscale Fire, UK 1957.

Windscale (also called Sellafield) is a large scale nuclear plant situated in the north-west of England. At the time of the fire, the reactor was used to produce plutonium for military use. As a by-product some electricity was also being produced. Errors made during a period of routine maintenance on October 7-8th, 1957, led to a fire in the graphite core which burned for nearly 3 days before being noticed on the 10th October. On the 11th October the fire was extinguished, but by then large quantities of radioactive materials had been released into the atmosphere in a plume that spread south and east across the UK and into continental Europe.

Estimated figures for the materials released (Chernobyl figures in parentheses) from Cooper et al, 2003:

- 740 TBq of iodine-131 (1.76m TBq),
- 22 TBq of caesium-137 (79500 TBq)
- 12,000 TBq of xenon-133 (6.5m TBq)[7]

Consequences.

- At the time there was very little guidance on the likely medical impact of a significant release of radioactive nuclides. Locally, authorities quickly banned the distribution of milk in a strip of farming land 10 km north of Windscale to some 20 km to the south.
- Doses received by the workforce were less than 15mSv. Subsequent investigation using propensity matching has found little evidence for a long term impact on the health of Windscale workers. (McGeoghegan, 2010), though with a small sample of 473 the power of statistical tests used is limited.
- The reactor is itself was unusable and for safety reasons it is not yet fully decommissioned.
- Clarke, 1990, estimates the long-run wider impact on mortality as follows: 100 fatal cancers (largely lung cancers attributable to ingestion of the Polonium 210) and 90 non-fatal cancers (of which approximately 55 are thyroid cancers largely attributable to Iodine131).

[7] Johnson et al, 2007, incorporate some more recent evidence for large-scale releases of polonium at Windscale. See also Crick and Linsley, 1983. Other isotopes released in large quantities from Chernobyl include, 80,000 TBq strontium-90 and 6100 TBq plutonium.

5.2 Three Mile Island, USA, 1979.

On March 28th, 1979, mistakes made during routine maintenance of an electricity-generating nuclear power plant (TMI-2) in Pennsylvania, USA, led to a partial meltdown of the reactor core. In the process of controlling the overheating unit, large volumes of radioactive but chemically inert isotopes of Xenon and other noble gases were released into the atmosphere. Smaller quantities (425-629 GBq) of Iodine 131 were also released, but in the weeks after the accident, the US Environmental Protection Agency found no evidence of contamination in water and soil samples taken from around the plant (USNRC, 2009). No casualties at the time of the emergency and there is no reported evidence of any subsequent physical health impact. The reactor itself was rendered unusable, but the neighbouring facility (TMI-1) remains in use.

Jon Nelson, 1982, conducts a hedonic price exercise using residential property values in the Three Mile Island vicinity in the period after the accident. He finds no evidence of price falls in the May-December period following the accident. Later work by Sherman T. Folland and Robbin R. Hough, 1991, uses a similar hedonic pricing method to examine the impact of a nuclear power station on the value of neighbouring agricultural land, using data from 494 markets in the USA. They find a significant negative effect on land prices from proximity to a nuclear power station. A later study by the same authors (Folland and Hough, 2002) examining house prices found a persistent negative effect of proximity to nuclear power stations even after allowing for possible endogeneity in house-building activity.[8] The order of the effect was large, around 10% of asset values over a 60 mile radius for the installation of a nuclear power station.

5.3 Chernobyl, 1986.

The largest civilian accident to-date occurred at the Chernobyl plant in what is now Ukraine in 25th April 1986. During a planned experiment on the reactor, there was a sudden and unanticipated power surge. In response workers attempted an emergency shut-down of the plant, but this led to a further sharp rise in power output and sequence of violent explosions which released a large amount of radioactive material into the atmosphere. Once exposed to the air, the graphite in the reactor vessel caught fire and over several days fire released plumes of smoke which drifted over much of the local area and then across large parts of northern Europe.

In the map the location of the reactor is shown by a yellow star. The shaded areas represent

[8] Endogeneity issues here come in two major forms: first nuclear power stations may well be built where land prices are relatively low. Secondly, housebuilders may be attracted to locations close to nuclear power stations where land is relatively cheap, thereby lowering relative prices further.

different levels of radioactivity from caesium-137 as of 1996. It is readily seen that deposits do follow an even pattern and that the most heavily affected areas do not form a connected set. Instead they are scattered as a result of fluctuations in patterns of wind, rain and emissions over the days following the initial explosion. Some locations close to the plant , to the south and west, experienced very little deposition compared to the north.

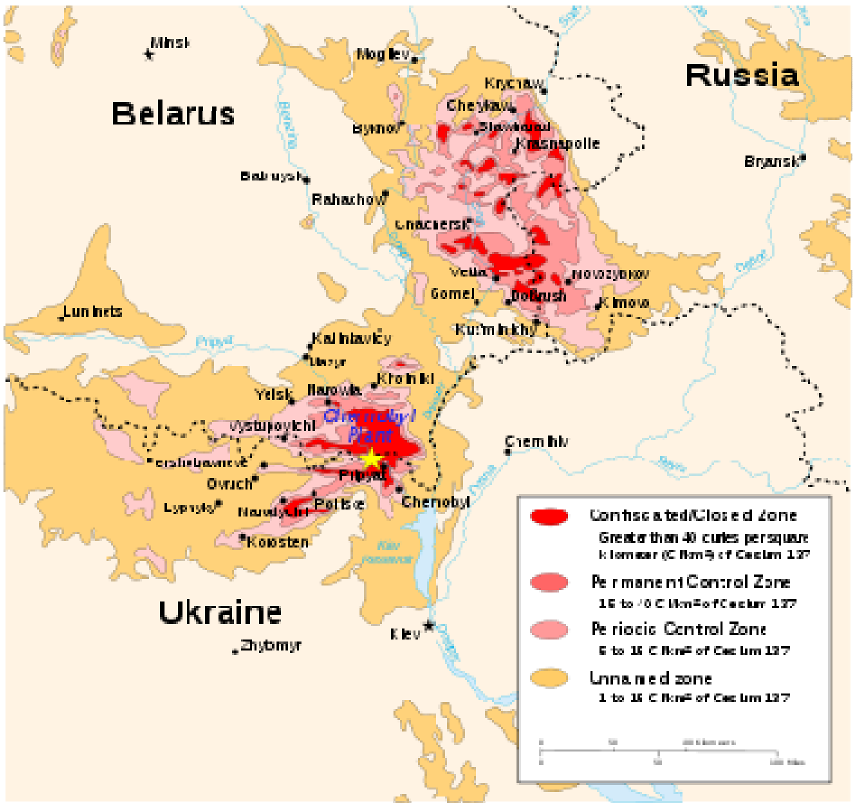

Figure 5. Caesium-137 around Chernobyl. Source: *UNEP/GRID-Arendal Maps and Graphics Library*

During the course of the event, over 200 people were hospitalized for acute radiation exposure and other injuries incurred as a result of the blast and attempts to fight the subsequent fires. Thirty-one people died, most of them fire-fighters brought in to bring the disaster under control. The authorities locally were slow to act. Despite the large-scale release of Iodine-131, restrictions on milk consumption and animal fodder in the region were not brought in for several weeks. Other neighbouring countries acted more swiftly. Approximately 115,000 people were eventually evacuated from the immediate area, including 50,000 from the nearby town of Pripyat, Ukraine. A 30km exclusion zone was established and another 220,000 people were eventually resettled (UNSCEAR, 2008).

Thyroid cancer cases amongst children shot up in the 10 years after the accident. Approximately 6,848 cases in total and 10 deaths were reported in the 3 countries by 2005 for children under aged 18. The overwhelming majority of these cases were in 1991-1995 and after 2005 levels of incidence were close the pre-Chernobyl period.

Estimates for the long-term mortality impacts are extremely varied. Apart from ideological biases there are several sources for this variation, including

- Poor data. The authorities were not open about the disaster and this hindered serious research. In the aftermath of the disaster, the doses received by individuals has rarely been accurately monitored. After the collapse of the Soviet Union and the subsequent collapse of local economies there were few resources to collect accurate data.
- Incomplete life histories. Fortunately, the majority of people living around Chernobyl have yet to die, but this means that data on causes of mortality is incomplete.
- Assignment of causes. Pointing to the Chernobyl as the cause of death for the workers who died from acute radiation poisoning was simple. Childhood thyroid cancer is also sufficient rare for changes in incidence to be easily spotted. However, in modern societies a large proportion of adults suffer from cancer at some stage in their lives and many die from it. Spotting relatively small changes in cancer incidence can therefore represent a challenge to statistical models.[9] Assigning causation to the cancer is even more difficult, particularly when there is only data on geographical deposition of radio-nuclides and not individual exposure. The picture is further clouded by the dramatic changes in socio-economic conditions faced by citizens in Belarus, Ukraine and Russia after the collapse of the USSR.
- Theoretical model. In the threshold model, there is a minimum level of exposure to ionizing radiation below which adults face no enhanced risk of harm from rises in exposure. In the linear model, there is no threshold and risks of harm are proportional to dose. Scientists disagree on the most appropriate model and therefore disagree on the population at risk etc.

A report sponsored by the United Nations (WHO, 2005 or Chernobyl Forum, 2006) estimates a total of 4,000 excess deaths from the accident out of a considered population of 600,000. In contrast, the TORCH report, an unofficial investigation sponsored by a Green Party Euro-MP considered a much larger population, across the whole of Europe and proposed that excess deaths would be between 30,000 and 60,000. (Fairlie and Sumner, 2006).

5.3.1 Costs.

The estimated costs are based on a report prepared for the Government of the Ukraine

[9] For instance, the UN summary report on likely death rates notes, “As about quarter of people die from spontaneous cancer not caused by Chernobyl radiation, the radiation-induced increase of only about 3% will be difficult to observe.” UN 2005, p. 4

(2002). The costs are confined to the value of the lost assets, using their historical cost of consumption or in some cases, their estimated construction costs at the time of the accident.

Table 1. The costs of Chernobyl. Estimates from the Ukrainian Government.

	Year used for estimate	Rubles (1,000s)	US $ (1,000s)
Chornobyl NPP (III turn)	86	99.028	136.12
The fourth block of Chornobyl NPP	64	201	223.33
The object «Chornobyl 2»	84	97.7	137.027
Enterprises of the communication industry (1)	86	51.07	70
Enterprises of metallurgy industries (1)	86	44.7	61.443
Enterprises of the building materials industry (1)	86	7.75	10.653
Enterprises of river transport (2)	86	21.05	28.935
The highways with hard surfaces (353 km)	86	60.55	83.23
Enterprises of the woodworking industry (1)	86	4.72	6.488
Enterprises of the feed mill industry (1)	86	4.55	6.254
Enterprises of primary processing of agricultural raw materials(1)	86	4.9	6.735
Enterprises of the food industry	86	5.01	6.887
Enterprises of repair of tractors and agricultural machines (1)	86	0.76*	1.045
Enterprises of woodlands (1)	86	4.7	6.46
Collective farms (14)	86	79.693	109.544
State farms (2)	86	18.659	25.648
Coagricultural enterprises	86	18.694	25.696
Infrastructure and network of water supply	86	4.405*	6.055
Infrastructure and networks of sewerage	86	3.85	5.292
Electrical networks for lighting	86	0.315	0.433
Infrastructure and networks of heat supply	86	3.39	4.66
The available housing:			
– state (402)	86	209.75	288.316
– private (2.278)		7.101	9.761
– rural houses (9.050)		28.2	38.763
Recreation departments (10); medical stations (44); Schools: trade schools (3);secondary schools (34); musical schools (2); Palaces of culture (16); cinemas (2); clubs (39)	86	29.104	40.005
TOTAL		1010.649	1338.78

Note: Source: Government of the Ukraine, 2002. from Table 7.2.1. * Given as 1,000 times this figure in the original English version table.

The major problems with this approach:

1. many costs are omitted (e.g. health costs)
2. lost asset are valued by their construction costs or equivalent and not by the value of lost benefits.
3. historical costs are used in some cases.
4. there are no on-going costs in the calculation.

These problems are not minor. There is an additional issue that in the USSR markets were not used to clear many markets, so the prices used in cost calculations often do not represent scarcity prices.

A 2002, UN-sponsored report put the accumulated costs at $235bn for Byelorussia over a period of 30 years. Meanwhile a figure of $148bn for 1986-2000 for Ukraine is quoted in the same source (UN, 2002). However, most of these 'costs' are financial payments to household living in the three main affected countries (Chernobyl Forum, 2006). To a significant degree they are therefore transfers and not costs (except of course to government). The UN report does not endorse the estimates and does not offer an alternative set of figures. It identifies the items in Figure 6.

Box 5.1: Losses resulting from the Chernobyl accident

* Direct damage caused by the accident
* Expenditures related to
  a) Actions to mitigate the consequences in the exclusion zone
  b) Social protection and health care to affected population
  c) Research on environment, health and production of clean food
  d) Radiation monitoring of the environment
  e) Radioecological improvement of settlements and disposal of radioactive waste
  f) Resettlement of people and improvement of their living conditions.
* Indirect losses relating to the opportunity cost of removing agricultural land and forests from use and the closure of agricultural and industrial facilities.
* Opportunity costs, including the additional costs of energy resulting from the damage and eventual closure of the Chernobyl complex and the cancellation of Belarus's nuclear power generation programme.

Figure 6 Costs of Chernobyl. Source: UN 2002

The potential scale of these costs is illustrated by Table 2 which shows that the major impact fell on Belarus and the Ukraine.

Table 2. Quantitative estimates of resources removed from service.				
	Belarus	Russia	Ukraine	Total
Agricultural Land (Ha)	264,000	17,100	512,000	784, 320
Forest	200,000	2,200	492,000	694,200
Agricultural and Forest enterprises	54	8	20	82
Factories, transport and service enterprises	9	0	13	22
Raw material deposits.	22	0	0	22
Source UN, 2002, Table 5.2				

We can use the Viscusi elasticity of 0.51 and estimated number of excess deaths to produce a crude estimate of the mortality costs which takes no account of the timing of the deaths. The current official VSL for the USA is $5.8m. We use the Penn World tables to obtain PPP GDP per capita figures for Ukraine in 1993, the first year for which they are available and use this figure as representative. With excess deaths of 4,000 we obtain $7.01bn. For excess deaths of 60,000 (the Torch report upper figure) we get, $105.2bn.

There have been a number of attempts to estimate the non-mortality impacts on lives after the accident. Lehmann and Wadsworth, 2011, is a recent thorough examination of self-reported health and employment patterns using longitudinal data for 8,800 Ukrainian individuals for 2003, 2004 and 2007. In common with most studies they fail to find significant impacts on physical health that can be robustly attributed to the direct consequences of radiation exposure. However, exposure, as instrumented by geographical location at the time of the accident, is correlated with poorer mental health and significantly worse employment prospects.

5.3.2 The wider impact.

Over a period of several weeks, wind and rain spread the radiation across large parts of Europe with northern and upland areas most affected. In fact it was raised radioactivity levels at the Forsmark Nuclear Power plant in Sweden several hundred kilometres to the north that first alerted the wider world to the accident. Figure 7 shows the deposition of Caesium-137 (i.e. it excludes Iodine 131 and other radionuclides). Note that limited monitoring means it is possible that some other countries (e.g. Kazakhstan, Turkey or Spain) were also affected but there is no systematic data for these countries.

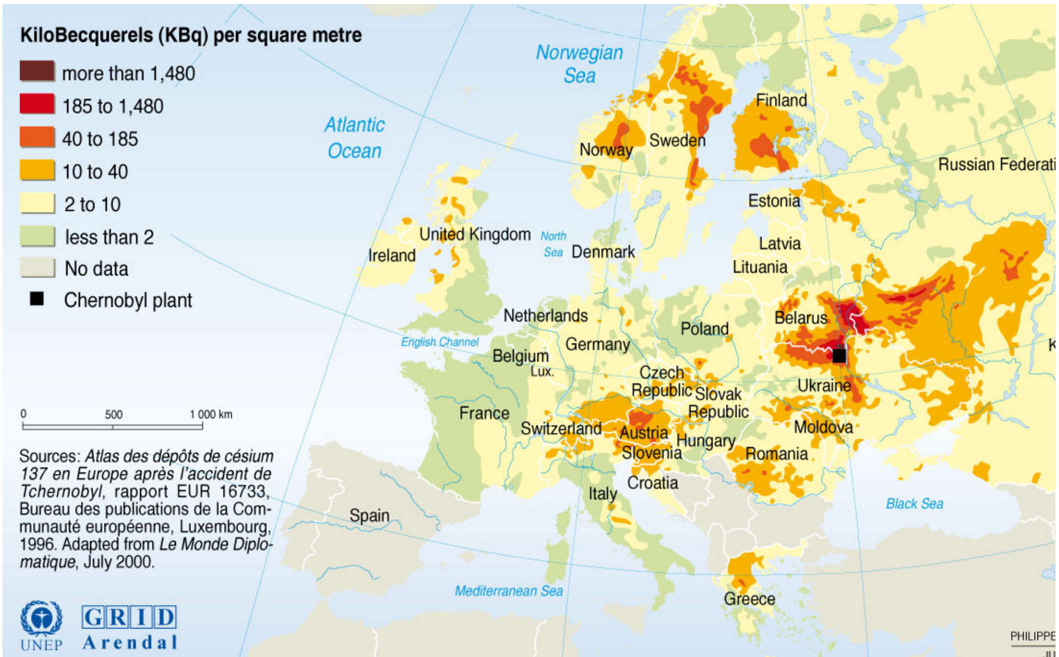

Figure 7. Radiation from Chernobyl. Source: UNEP/GRID-Arendal, Radiation from Chernobyl, *UNEP/GRID-Arendal Maps and Graphics Library*, http://maps.grida.no/go/graphic/radiation-from-chernobyl (Accessed 25 June 2011).

A number of European countries responded by restricting market access for affected foodstuffs such as lamb, wild boar and mushrooms. The raised level of radioactivity has persisted and as a result many EU countries still have significant controls on food produced in affected areas:

Table 3. Restrictions on foodstuffs in selected European countries.

Example Foodstuffs	Country	Restrictions
Reindeer, Boar, Freshwater fish, berries	Sweden	>1500 Bq/kg banned from market; refunding system for producers
Game (e.g. wild boar and deer), wild mushrooms	Germany	>1500 Bq/kg banned from market; refunding system for producers
Reindeer	Norway	Intervention limit of 600Bq/kg in 1986 raised to 6,000Bq/kg then dropped to 3,000Bq/kg for reindeer meat.
Sheep	UK	Testing system for specific upland areas. Refund system for producers
Source: UK Defra; Germany: Ministry of the Environment. Sweden, Tveten, 1990. Norway: Tveten et al, 1998.		

Tveten et al, 1998, document interventions costing 110Nok over the first ten years of intervention in Norway. The use of other mitigation measures was investigated and applied selectively (e.g. Strand, 1995):

- Reducing uptake from the soil to plants by land use changes, fertlizier applications and ploughing
- Using feedstuff additives to limit transfer from plant to animal
- Methods to increase excretion rates from animals
- Processing of contaminated crops.

Strand et al, 1990 and Strand, 1995, estimate that in Norway significant falls in lamb consumption of 5-10% occurred in the first few years after Chernobyl. They estimate that farmer revenue loss was 50-100m NOK, but in the absence of mitigation measures beyond selective bans, the lost revenue would have been 100-400mNOK per year. Strand conducts a cost-effectiveness analysis amongst differ mitigation measures. The most expensive option is interdiction (selective bans on marketing) of sheep at 1,000,000 NOK per manSv; reindeer interdiction costs 340,000, special feeding is 250,000, changing slaughter time is 94,000 and then there are 3 significantly cheaper measures: feeding Prussian blue boli (4,000NOK/manSv), feeding Prussian blue concentrate and offering dietary advice (40 NOK/man Sv).[10]

For Sweden, Tveten, 1990,[11] estimates the costs of Chernobyl mitigation measures as,

- agriculture and horticulture 218.7 Millions Swedish Krona (MSEK)
- reindeer breeding 137-6
- fish 4.3
- game (moose) 6.4

or, 367 MSEK in total over the years 1986 and 1987. Once other items, such as research costs and compensation to reindeer breeders are included the total rises to 491-501MSEK. However, it appears that many of these figures include compensation payments. A further 557-663MSEK of 'indirect costs' are estimated including the loss of tourist trade and the lost value of wild berry and mushroom consumption due to consumer resistance.

Meanwhile Hanley et al, 2001, conduct a contingent valuation survey amongst Scottish citizens to elicit willingness to pay for remediation that changes the type of vegetation in the wake of Chernobyl-like patterns of fallout.[12] They find, for instance, a wtp of £243 – £486 per

[10] 1 manSv is number of people in the affected population x average dose. Prussian blue traps radioactive caesium (134 and 137) in the bowels. The material moves through the intestines and is then excreted, lowering the biological half life of caesium-137 from approximately 110 to 30 days.

[11] This report is notable for outlining a proto-macro model for assessing the impact on the four Nordic countries, Finland, Norway, Sweden and Denmark.

[12] The point of the remediation is to lower human exposure by changing land use directly or by adding chemicals or nutrients that indirectly change the landscape (e.g. soil application of potassium or lime to compete chemically with the analogous Cs-137 and Sr-90.

affected hectare to change heather moor to managed grassland but only £33-£66 to change the same land to forestry. Consumers expressed some scepticism about the effectiveness of remedial measures. Meanwhile, in a connected study, consumers in Scotland and Norway expressed a wtp for certified uncomtaminated lamb , 31% and 46% respectively above normal prices (Grande et al, 1999).

The long-term health impacts of the accident across Europe is unclear. We noted above the Torch reports assessment of raised mortality in countries outside the former Soviet Union but this has been difficult to establish statistically especially given that caesium-137 exposure in northern Europe was of a similar order to the exposure from earlier nuclear weapons tests. A controversial study by Tondel et al, 2004, estimates that 849 cancer cases in Sweden were attributable to the event, controlling for lifestyle factors and historical trends in the data. Meanwhile Almond et al, 2009, examine the impact on health and educational achievement for Swedish children who were in utero at the time of the accident. For children who were at 8-25 weeks of gestation they find a significant negative effect on maths scores at aged 16 and predict a lifetime reduction in wages of approximately 3% for the most affected group. [13]

5.4 Fukushima dai-ichi.

On the afternoon of the 11th March, 2011, an earthquake of magnitude 9 struck off the eastern coast of Tohoku. A subsequent tsunami inundated large areas of the coastline in Iwate, Miyagi and Fukushima prefectures. At Fukushima dai-ichi power plant the waves overwhelmed the coastal defences and flooded the site, depriving the facility of the power to run cooling systems for the reactors that had been in operation and for the cooling ponds where spent reactor fuel was being kept. Rapid rises in temperature followed at four of the reactors (Dai-ichi 1-4), followed by hydrogen explosions at two of the buildings and a partial melt-down of the core in two of the reactors. Over a period of weeks then months, the situation slowly stabilized, though the destruction of the original cooling systems meant that large volumes of water were irradiated over the subsequent months. Some of the water was released into the sea, producing significant contamination of the neighbouring shore and seabed. Figure 8 shows the on-land deposition of Caesium 137, as summarised by the Ministry for Science and Technology.

[13] There are significant differences in the approach that economists and epidemiologists typically take to establish causation in the absence of a clear natural experiment.

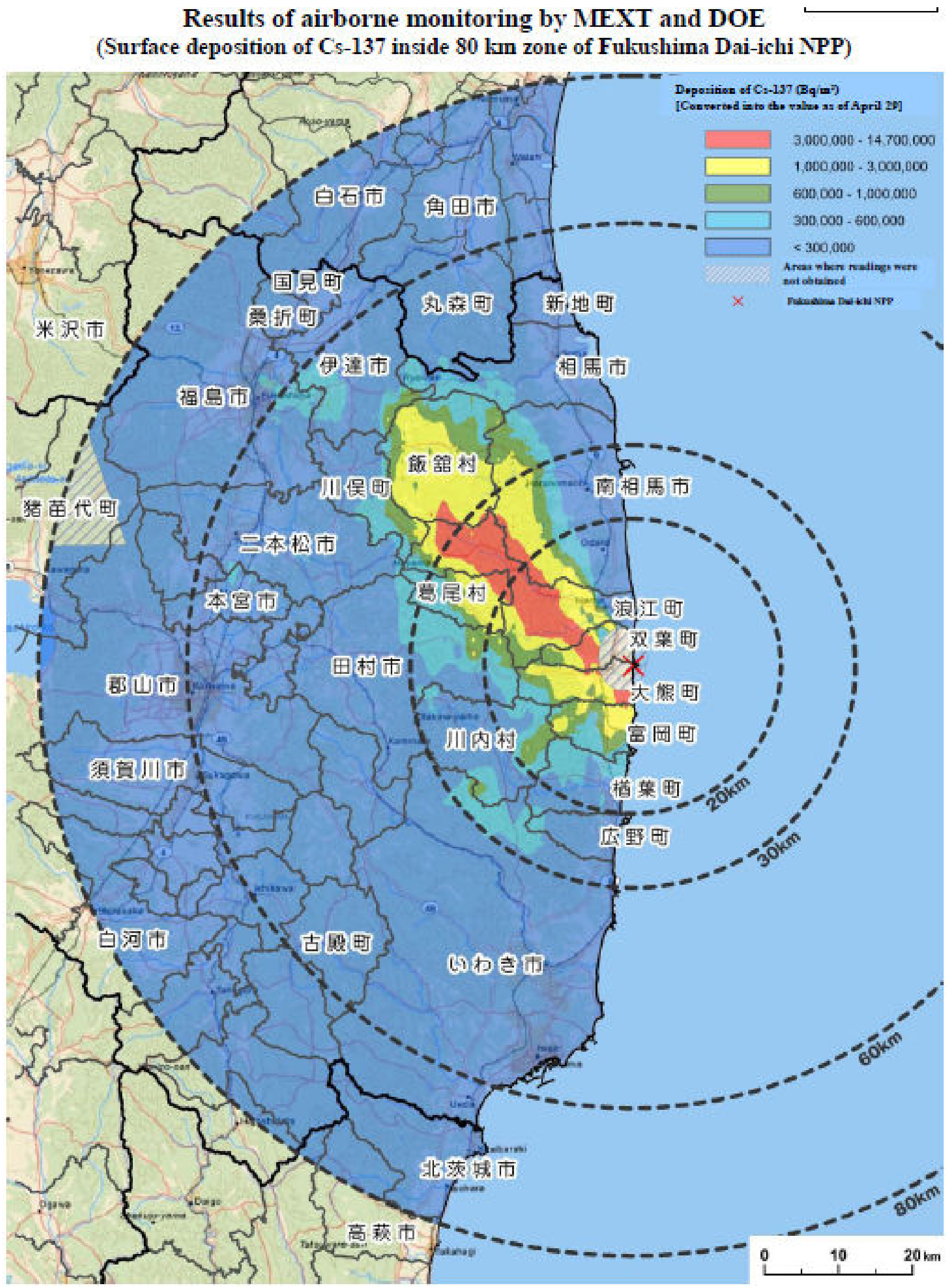

Figure 8. Deposition of Caesium-137 around Fukushima Dai-Ichi. Source: MEXT

It is difficult to make an exact comparison of the maps for Chernobyl and Fukushima. First though we should acknowledge the difference in scales. The height of the Fukushima map is roughly the distance between the labels ‘Belarus’ and ‘Ukraine’ on either of the Chernobyl-Europe maps. Second the Fukushima map is for a period approximately 1.5 months after the initial accident at a time when further releases of radionuclides were still occurring, albeit on a small scale. The Chernobyl map is from 10 years after the accident, but it is retrospective, plotting deposition in the aftermath of the accident. The highest intensities on the Fukushima map are 3,000kBq/m^2 to 14,000kBq/m^2 which is higher than the plotted scale for the European map (the highest level there is ‘more than 1,480kBq/m^2). The higher scale map for Chernobyl uses a different measure, of Curies per sq km. [14] If we convert between the measures, we get that the 15 Curies per km^2 contour in the first map is equivalent to 555,000Bq/m^2 in the immediate aftermath of the release. Thus the green, yellow and orange shaded areas in the Fukushima map all represent higher concentrations of Caesium-137 than the Permanent control zone in the Chernobyl map. The orange and some portion of the yellow shaded areas in Fukushima represent higher concentrations of Caesium-137 than the excluded zone in the Chernobyl map.

6 Conclusions.

Why is it useful to have economic cost figures for major nuclear accidents? There are essentially four reasons,

1. To consider the value of precautions against accidents
2. Comparison with other sources of risk
3. As a guide for insurance markets
4. For cost benefit analysis of post-accident interventions such as,
    1. Food protection measures
    2. Soil remediation
    3. Cancer screening and treatment services

The current data from past major events is very poor quality and does not provide a clear guide for Fukushima. For instance we don’t have any good guide to the relative sizes of health and non-health costs. There is little cost-benefit evidence on food protection measures and no macroeconomic data. In short, accurate estimates of historical nuclear accidents are not possible, though it may be feasible to produce realistic figures for some of the policy choices that were made in their wake. Nevertheless, what we know is that the methods used to estimate the costs of the Chernobyl accident are wrong in principle.

Estimating the cost of the Fukushima accident may be easier, though given the enormous loss of life and infrastructure damage that occurred at the same time in the Tohoku earthquake, it may not be possible to disentangle the consequences of the two tragedies. Nevertheless for the reasons given above, it would be valuable to have some reasonable range of values for the cost of the accident.

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[14] 1 Curie is 3.7×10^{10} Becquerels. So, 1 Curie/km^2 = 3.7×10^4 Bq/m^2 = 3.7×10^1KBq/m^2. With a half life of 30.07 years, Caesium 137 radioactivity will have reduced by 20.6% after 10 years.

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May 2011

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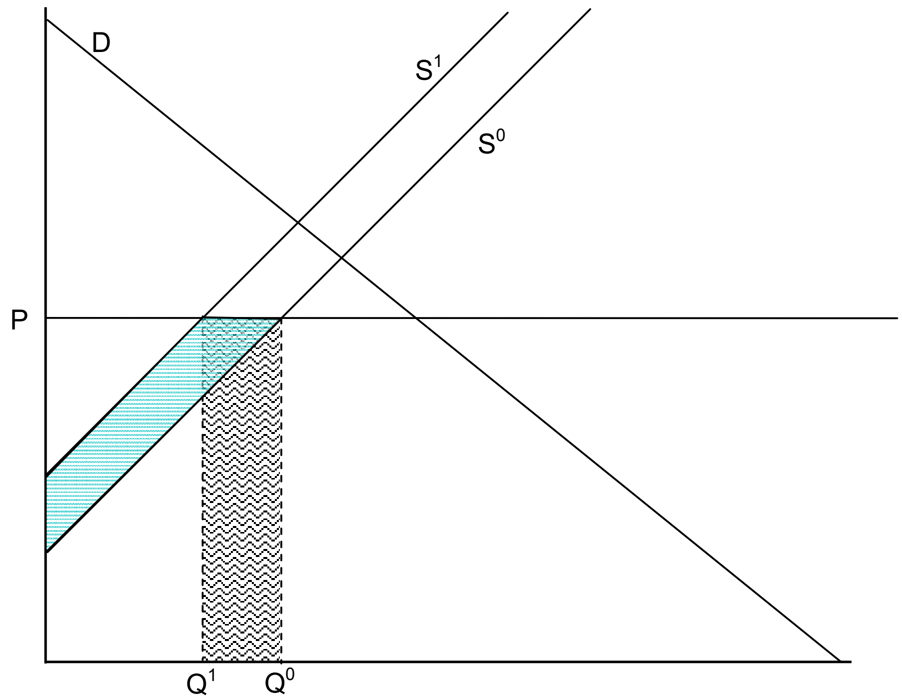
9 Appendix. Costs and compensation.

A simple model summarising the relationship between a shock to domestic quality and compensation payments.



The partial equilibrium diagram shows price (p) and quantity q of a good that can be imported uncontaminated at a price P. Domestic supply prior to contamination is S^{0}. The effect of the shock is to contaminate a proportion of the domestic supply, reducing uncontaminated domestic supply to S^1. In this situation, if domestic consumers cannot identify which of the domestic products are affected, then imports supply the whole market.

Suppose compensation is offered to affected producers in return for which they voluntarily withdraw their product. If p is the compensation price then the compensation paid and received is $p(Q^0-Q^1)$. But this is a transfer. The true cost of the shock is the loss of producer surplus for the domestic industry, given by the blue shaded area. As long as there is no domestic supply at a price of zero, then the compensation paid exceeds the loss of producer surplus in this diagram.

The apparent bound on the cost of the shock is the result of simplifying assumptions in the diagram and should not be taken as a particularly useful guide or rule of thumb. For instance, if import elasticity is less than infinity or compensation paid is not exactly equal to the prevailing market price, then this neat relationship between compensation payment and economic cost is lost. Compensation can be less than the economic cost and it may be more.