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Fukushima Dai-Ichi and the Economics of Nuclear Decontamination.

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Abstract:

Economic analysis of nuclear accidents and their aftermath is comparatively rare. In this paper, in the light of the Japanese government's intensive efforts to decontaminate areas affected by radioactive Caesium from Fukushima dai-ichi nuclear power plant, we create a cost-benefit framework for assessing the merits of decontamination strategies. Using some benchmark data for Japan we estimate that optimal delay is positive for most reasonable parameter values. For low value land, optimal delay could be in excess of 30 years. For higher value, urban land, optimal delay generally lies in the range of 5-10 years.

Keywords: Nuclear accident, environmental valuation, radiation, decontamination, Fukushima Dai Ichi, Chernobyl, Windscale, 除染対策

JEL Codes: D61, Q51, Q53

1 Introduction.

On the afternoon of the 11th March, 2011, an earthquake of magnitude 9 struck off the eastern coast of Tohoku, Japan. A subsequent tsunami inundated large areas of the coastline in Iwate, Miyagi and Fukushima prefectures. At Fukushima dai-ichi nuclear power plant the waves overwhelmed the coastal defences and flooded the site, depriving the facility of the power to run the cooling systems for three operating reactors and for the cooling ponds where spent reactor fuel was being kept. Rapid rises in temperature followed at four of the reactor sites (Dai-ichi 1-4), followed by hydrogen explosions in three of the buildings and a melt-down of the core in unit one and partial melting in units 2 and 3 (TEPCO, 2011). Over a period of weeks then months, the situation was 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.

Nuclear accidents such as Fukushima or the earlier event at Chernobyl 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 (USNRC, 2009) and the 1957 Windscale Fire in the UK[1] (IAEA, 1996).

There is relatively little work done on economic valuation of the costs of nuclear accidents and the policy responses to them. Furthermore, as argued in Munro 2011, some work (e.g. United Nations, 2002, Chernobyl Forum, 2006 or WHO 2005) is inappropriate in terms of its economic methodology, because it often omits important costs, measures benefits by costs and treats transfers inconsistently. In this paper I create a basic model to assess

[1] The other 5-rated event is Goiânia, Brazil, 1987, where four people died after an abandoned radiotherapy device was broken open and the active materials removed (ICRP 2009).

decontamination and resettlement strategies for land affected by the release of radioactive materials. In particular, I focus on the merits of delayed intervention. It should be stressed that I am not here concerned with the decommissioning of the plant itself, but with policy towards the surrounding towns and villages, many of which are currently evacuated. While there are other important aspects of nuclear accidents that await economic analysis, this particular issue seems especially pertinent given the firm commitment made by the Japanese government to the quick, but potentially costly, clean-up of the regions that neighbour Fukushima dai-ichi nuclear power plant. It also seems an important margin for policy decisions, because on the one hand the costs of evacuation are ongoing, while for some important sources of radioactive exposure the costs of decontamination fall over time.

2 The costs of nuclear accidents.

In the wake of nuclear accidents such as Chernobyl or Fukushima a large part of the economic cost arises from the evacuation of contaminated land and cities, together with the abandonment and destruction of capital and infrastructure. 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 in the form of increased morbidity and in some cases, increased mortality. Large scale accidents are significant shocks and can of course have spill over consequences throughout the economy, through demand changes and the disruption of the supply chain. In addition a major unforeseen event may be followed by a period of increased uncertainty which itself affects economic activity (Bloom, 2009). Uncertainty shocks may be one source of a loss of confidence generally in the domestic economy, which can have widespread macroeconomic consequences. With nuclear accidents, a 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 1) 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.

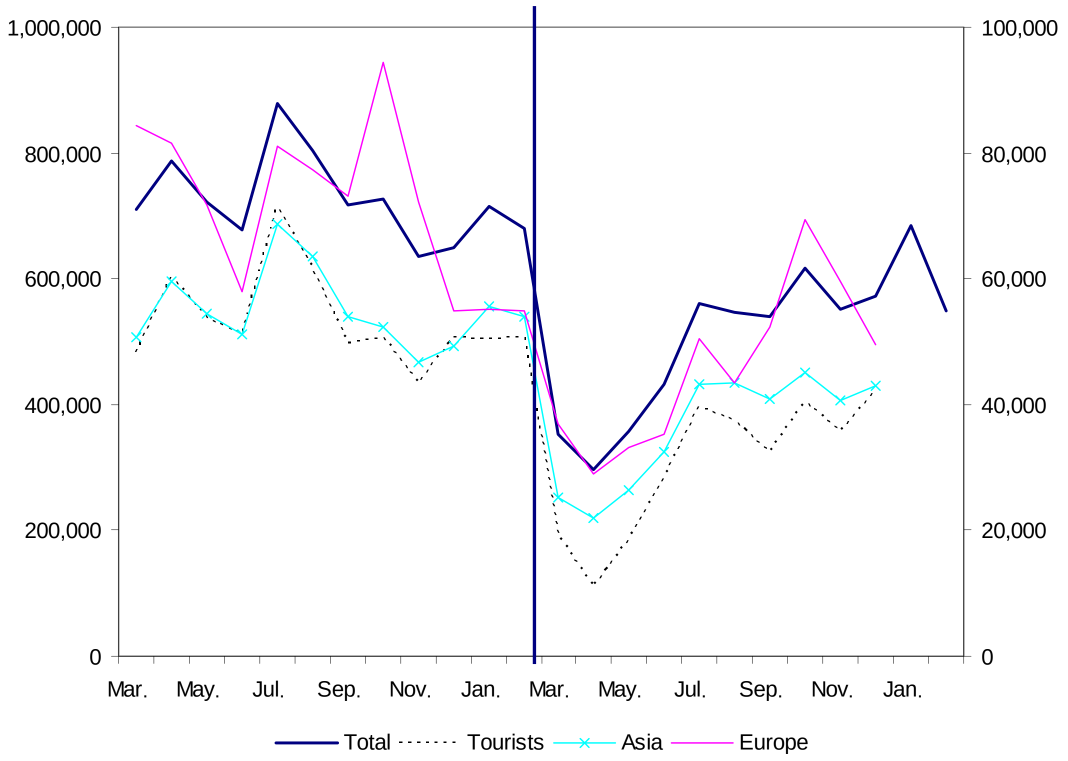

Figure 1. Visitor Numbers to Japan, March 2010-2012. Source for data: JNTO Website. Europe on right-hand scale; others on left-hand scale.

In this context, decontamination is one of a number of possible strategies that can be employed to mitigate the costs of an accident. Prior to Fukushima it has not been used on a significant scale. For instance, in the earliest significant nuclear accident, at Windscale (also called Sellafield) in the UK, errors made during a period of routine maintenance of a nuclear reactor, on October 7-8th, 1957, led to a fire in the graphite core which burned for nearly three days. 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 are provided in Cooper et al, 2003 and included iodine-131, caesium-137 and xenon-133.[2] At the time there was very little guidance on the likely medical impact of a significant release of radioactive nuclides. So that while 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 (Crick and Linsley, 1983) no significant offsite attempts at decontamination were

[2] Johnson et al, 2007, incorporate some more recent evidence for large-scale releases of polonium at Windscale. See also Crick and Linsley, 1983.

conducted. [3]

The largest civilian accident to-date began on 25th April 1986at the Chernobyl plant in what is now Ukraine. Around Chernobyl, management has been by containment, evacuation, abandonment and exclusion from the affected zone (United Nations, 2002). Attempts at decontamination have been limited (WHO 2005). In part this may reflect the low population density and low income and the economic disruption that accompanied the break-up of the Soviet Union. Outside the former Soviet Union, a number of other European countries responded to the emergency by restricting market access for affected foodstuffs such as lamb, wild boar and mushrooms (see Table 1), but again outright decontamination has been comparatively rare.

Table 1. 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.

In Norway and Sweden some attempts have been made to decontaminate land (Tveten et al, 1998). The use of mitigation measures was investigated and applied selectively (e.g. Strand, 1995) and included reducing uptake of radioactive nuclides from the soil to plants by land use changes, fertilizer applications and (deep) ploughing. 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 Norwegian Krona (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

[3] Subsequent investigation using propensity score matching methods 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. 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). No economic valuation of this accident is available.

analysis amongst mitigation measures. The most expensive option is interdiction (selective bans on marketing) of sheep at 1,000,000 NOK per manSv[4]; 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).[5] For Sweden, Tveten, 1990, estimates the financial 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.

2.1 Fukushima dai-ichi.

It is difficult to make an exact comparison of the scale of release of radioactive materials for Chernobyl and Fukushima, but according to Stohl et al, 2011, emissions from the latter are approximately 42% of the former. However, only 19% of emissions or 6.4 PBq were deposited over Japan. Most of the remaining emissions were deposited in the sea, with approximately 2% landing on other countries (Stohl et al, 2011). Nearly all of the current dose exposure in Fukushima is by isotopes of Caesium (134 and 137) which were originally

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[4] **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). One manSv is number of people in the affected population x average dose. 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. (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 mSv per year under normal circumstances. However, once the Fukushima accident occurred the emergency limit was increased twice, to 100 mSv, and then to 250 mSv 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).

[5] Prussian blue traps radioactive caesium (134 and 137) in the bowels (Strand 1995). The material moves through the intestines and is then excreted, lowering the biological half life of caesium-137 from approximately 110 to 30 days.

deposited in the ratio 1:1. The former has a 30.17 year half-life whereas Caesium-134 has a half life of 2.06 years. Because of the short half-life of Caesium-134, exposure falls rapidly (see Figure 2 below). After 10 years or so, Caesium 137 becomes the dominant isotope and as a result the average rate of decay falls.

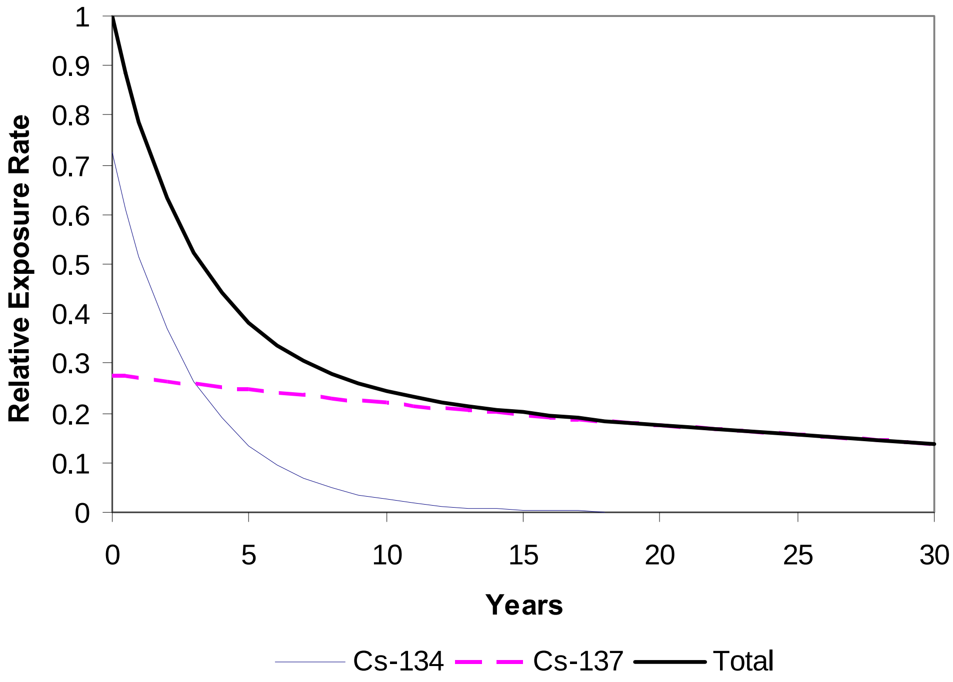

Figure 2. Reduction of the relative external exposure rate subsequent to deposition of Cs-134 and 137 (original ratio = 1:1) due to radioactive decay. Source: IAEA 2011

The pattern of restrictions and evacuations is shown in Figure 3. Note that the Evacuation prepared area notice was removed in September 2011, but evacuation and restricted access was still in force as of January 2012 and for the foreseeable future, with approximately 90,000 people moved out of the area (other families in adjacent areas may have also relocated). There are approximately 500 km^2 where radiation dose levels are above 20 mSv per year (or 20mSv/a) and about 1300 km^2 where radiation dose levels are between 5 mSv/a and 20 mSv/a (IAEA 2011).

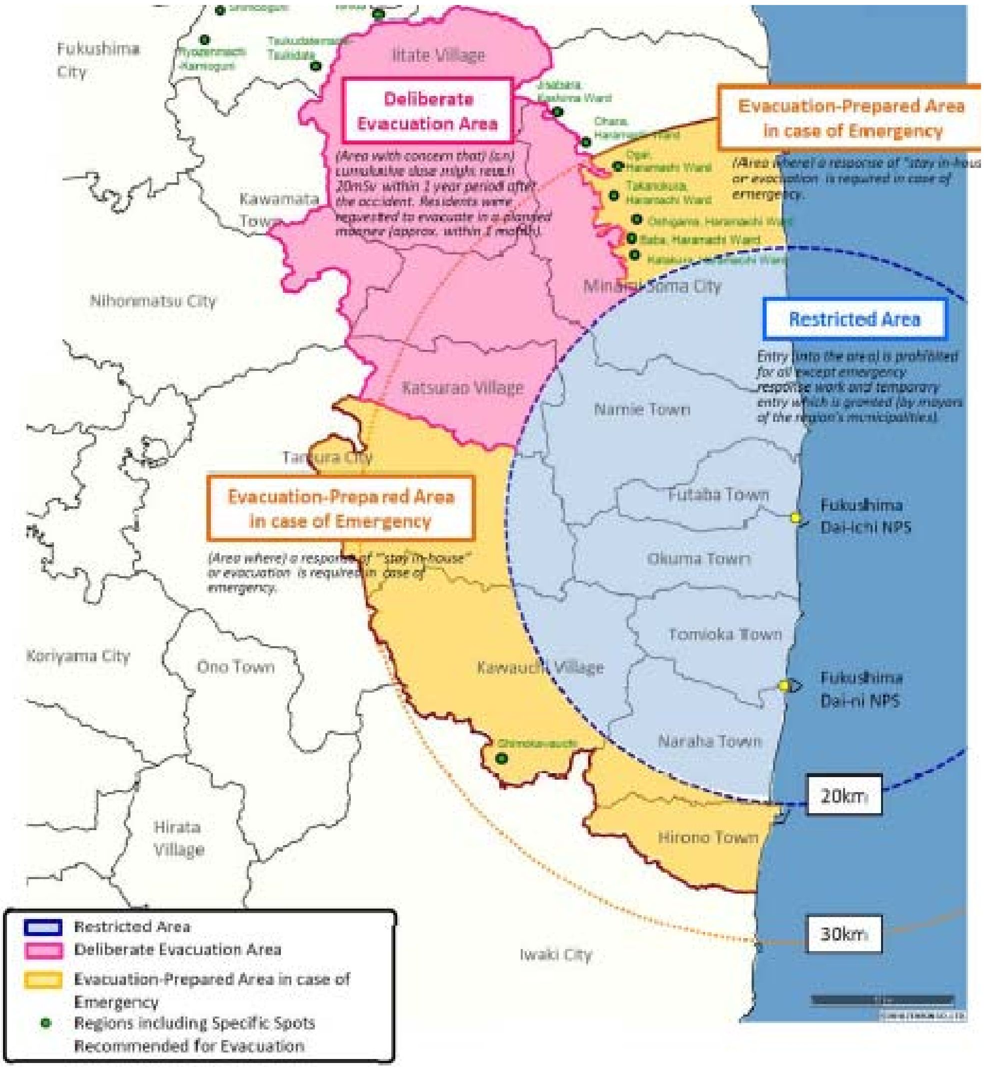

Figure 3. Restrictions around Fukushima in 2011: Source: IAEA

3 Decontamination.

In contrast to Chernobyl, from an early stage the Japanese government has committed to large-scale decontamination of the areas surrounding Fukushima.[6, 7] In addition, citizen's groups and volunteers have also been active, often without prior approval or guidance by local government (IAEA 2011). The currently declared aim of the Japanese government is to reduce quickly the theoretical exposure in affected areas to 20 mSv per year (Ministry of

[6] On 26 August 2011, The Parliament (Diet) of Japan approved the *"Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011"*. This sets out the current legal framework.

[7] There is no current strategy for decontamination for the adjacent sea-bed.

Environment, 2011a). Meanwhile long-term exposure should be reduced to 1 mSv per year.[8] Within this broad framework, special focus has been placed on the exposure of children where through school and school yard decontamination, the aim is to reduce the exposure to an effective dose of 1 mSv per year during the time children are at school.[9] Plans for restoring economic activity and residence in the currently-evacuated areas are not finalised, but there is a suggestion that once the 20mSv limit is reached some re-settlement will occur, albeit with ongoing restrictions on activity (MOF, 2011). As summarized in Figure 4, the plan divides responsibilities between the national ministries and local governments. The former will handle evacuated and restricted areas with exposure levels above 20mSv while the prefectures (and local municipalities) will supervise decontamination efforts for areas where exposure is below 20mSv. In the third supplementary budget of 2011, 249bn Yen (approx 2.45bn Euros) was set aside for 2012 for decontamination efforts for 2012 (MOF, 2011).

A notable feature of the current plan, criticized by the IAEA, (IAEA, 2011), is the aim to remove large volumes of low-radiation topsoil and waste and to store them in secure facilities for an extended period. If zones with contamination levels above 5mSv are cleaned up the estimated volumes range from 20.8m m^3 to 28.8m m^3 – enough to cover a 1 km square 20.8 to 28.8 metres deep (IAEA, 2011, Table 1). Storing materials for an extended period of time underground or in specially built shelters is expensive, and according to the IAEA, unnecessary for the vast majority of the waste.

[8] These target figures are for the excess over any pre-existing natural exposure and medical exposure.

9 What the ICRP states is that, "The reference level for the optimisation of protection of people living in contaminated areas should be selected in the lower part of the 1–20 mSv/year band recommended in Publication 103 (ICRP, 2007) for the management of this category of exposure situations. Past experience has demonstrated that a typical value used for constraining the optimisation process in long-term post-accident situations is 1 mSv/year." P. 11. in ICRP, 2009.

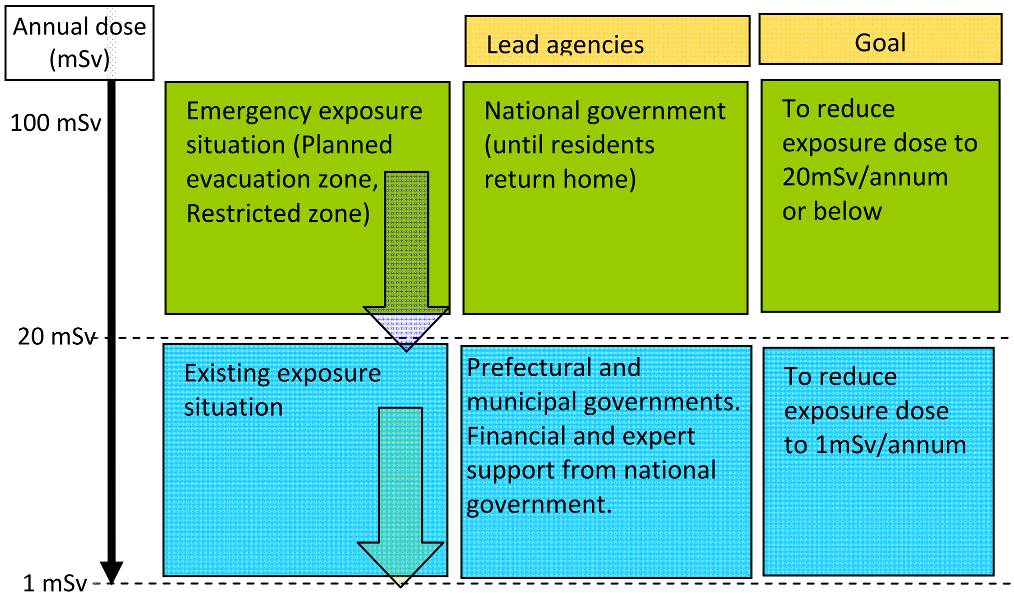

Figure 4. Remediation plans around Fukushima (From Figure 2, Moriya 2011).

3.1 The value of delaying decontamination.

In the face of contaminated land, there are two basic dimensions to the policy choice set. One dimension represents the period of relocation for affected residents and business. At the extreme of this spectrum we have permanent relocation. At the other extreme there is no relocation even of the temporary kind. The major costs of evacuation include the flow of lost benefits from temporarily abandoned assets such as houses, roads, farms and schools. In addition there may be costs of rehousing relocated individuals. Against this tally, relocated individuals receive benefits from their temporary accommodation and of course from the reduction in health risk associated with lower radioactive exposure. The other policy dimension represents the intensity of decontamination strategy. The extremes of this dimension are: do nothing and restore radioactive exposure to the pre-release level immediately. At the risk of some simplification, we can summarize the choice variables as T, the time for resettlement after evacuation and s, the target level of dose exposure below which clean-up efforts cease.

In modelling the economics of decontamination there are obviously different approaches. One option is to fully endogenous the benefits associated with s and to choose both the optimal long-term value for s and the approach path. It is questionable whether this is realistic given the policy context. Major decisions on the management of radioactivity tend to be set with regard to pre-existing international norms on safe levels of exposure (e.g.

IAEA, 1994 and Figure 4 above). Moreover, policy tends to be discrete in nature. For instance, individuals are either evacuated or not from a contaminated zone. So, in the approach adopted here, for the most part I take it that target levels of radiation exposure for resettlement and long-term exposure are given and this frames the policy options. However, I do also consider the optimal level for s.

There are therefore two cases that we consider (alongside a combined case that I consider subsequently).

Case 1. evacuation followed by re-use. Benefits flow from the time at which exposure reaches acceptable levels, resettlement occurs and assets are re-useable. Costs are proportional to the amount of radiation to be removed.

Case 2. in-situ clean-up with stochastic benefits. Costs are proportional to amount of radiation to be removed. Benefits flow from clean up time and are proportional to amount of radiation removed.

There is a simple pre-existing framework set out by the IAEA (e.g. IAEA 1994) that focuses primarily on the relocation decision or on in situ clean-up (Hedemann-Jensen, 1999 and Hedemann-Jensen 2004) . The IAEA's approach to the benefits of reducing exposure is based on the associated, stochastic health benefits using a simple human capital method. The basic model is one in which the risks of death and increased morbidity are linear in exposure (IAEA, 1994) with no lower threshold. The gain, b, from a reduction in exposure of Δ (measured in 'man Sieverts' or manSv) is then given by formulae,

$$B = \Delta\alpha(1+\beta+\delta)p$$

Where p is the probability coefficient for fatal cancer induced by radiation (per^{-1}Sv^{-1}), β is the relative weight put on a non-fatal cancer relative to a fatal cancer and δ is the relative weight put on hereditary consequences relative to a fatal cancer. In the IAEA formula, it is taken that roughly 13 years of life are lost from a fatal cancer. Meanwhile p = 0.05, β=0.01 and δ=0.013. The coefficient α ($/life year) is the monetary value of a statistical life year. [10] In the model there is no explicit treatment of the gains from delay, but the benefits from

[10] In the original IAEA estimates this is taken as GDP per person in the affected country. Obviously this is much smaller than is standard in the modern VSL literature, but this advice was formulated in the 1980s and early 1990s. It is worth noting that the model is for stochastic rather than what the IAEA terms 'deterministic effects', meaning the formula is based on the underlying notion that individual doses are less than 0.1 Sv.h^{-1} and total less than 0.2Sv per person.

particular interventions (i.e. values of Δ) can be compared to the costs. While this framework might be reasonable for in-situ reductions in exposure it is not applicable when the affected area has been evacuated. In such a case, the gains from decontamination arise through any associated reduction of the period of costly evacuation and the consequential return of benefits for individuals living in their own homes, businesses and farms, using local schools and infrastructure etc.

To take the IAEA model further, consider a unit area of contaminated land where the excess radiation exposure is initially x, decreasing exponentially at the rate of a, so that at time t, in the absence of any decontamination efforts, the excess exposure is xe^{-at}. The target level is s, which is greater than or equal to zero. In case 1, the target is the level of exposure at which resettlement is allowed. In case 2, s is the level of exposure at which decontamination efforts cease. The cost of cleaning (e.g. by removal of soil) an excess dose of y is c(y). [11,] The evidence on the functional form of c is scanty. (Brown et al, 1996, Thiessen et al, 2009). As a simplifying feature of the model we take it that c(y) is proportional to the radioactivity removed. So costs are cy, with c > 0. [12]

We define the net flow of benefits from resettled assets as b(t) per unit area and the discount rate as r. The functional form of b depends on the case, but for both cases, the problem is to choose y(t) to maximize the welfare function, W:

$$W = \int_0^T -y(t)ce^{-rt}dt + \int_0^\infty b(t)e^{-rt}dt.$$

subject to $s = e^{-aT}\left(x - \int_0^T y(\tau)e^{a\tau}d\tau \right).$

The constraint implicitly defines T, the first date at which the land meets the target.

Case 1.

For the case of evacuation, b(t) has the following functional form:

[11] In the case of soil removal, the contaminated material may be placed indefinitely elsewhere in which case the function c must include removal and storage costs.

[12] A plausible alternative functional form is one in which each action (e.g. fire-hosing or street-sweeping) removes a more or less constant fraction of the remaining exposure. In this case, marginal costs are increasing in y, making the case for delayed clean-up generally stronger.

$$b(t) = \begin{cases} 0 & t < T \\ b_0 - b_1 e^{-at}\left(x - \int_0^t y(\tau) e^{a\tau} d\tau\right) & t \geq T \end{cases}.$$

We interpret this as follows: prior to resettlement at time T, there are no benefits from decontamination. After, T, the first term in the equation represents the net flow of benefits from the re-use of the assets,[13] but any return to a partially contaminated site may also be associated with elevated risks compared to the evacuation site and this gives the second, negative term in the benefit equation. In case 1, since there are no benefits from decontamination efforts prior to re-settlement and since costs are linear in y then all decontamination will occur at date, T. Thus, the problem is reduced to finding the date at which the decontamination meets the target and land becomes settled again. The benefit equation then simplifies to,

$$b(t) = \begin{cases} 0 & t < T \\ b_0 - b_1 s e^{-a(t-T)} & t \geq T \end{cases}$$

The equation for W is then,

$$W = -(xe^{-aT} - s)ce^{-rT} + \frac{b_0}{r}e^{-rT} - \frac{b_1 s}{a+r}e^{-rT}$$

Unless $s \geq xe^{-aT}$ $s = xe^{-aT}$ or $T \geq \frac{1}{a}\ln\left(\frac{x}{s}\right)$ in which case,

$$W = \frac{b_0}{r}e^{-rT} - \frac{b_1 s}{a+r}e^{-rT}$$

For, $T \leq \frac{1}{a}\ln\left(\frac{x}{s}\right)$ the first order condition is,

$$\frac{dW}{dT} = acxe^{-aT-rT} + (xe^{-aT} - s)rce^{-rT} - b_0 e^{-rT} + \frac{rb_1}{a+r}se^{-rT} = 0.$$

Simplified this becomes,

[13] For simplicity I keep b_0 as constant, but over extended periods, assets may depreciate and this may lower the benefits of resettlement.

$$acxe^{-aT} + (xe^{-aT} - s)rc - b_0 + \frac{rb_1 s}{a+r} = 0.$$

We note that $d^2W/dT^2 < 0$ for $T \geq 0$, so that there is a unique maximum. Solving the first order condition, we get,

$$T = \frac{1}{a}\ln\left(\frac{(a+r)^2 cx}{(b_0 + src)(a+r) - b_1 sr}\right)$$

This interior solution holds unless, $\frac{b_0 - b_1 rs/(a+r)}{c} \geq (a+r)x - rs$, in which case it is optimal to clean up and resettle at time 0. Alternatively, when a > 0, if $\frac{b_0 - b_1 rs/(a+r)}{c} < -sr$, then it is optimal not to actively clean the land at any time, but to delay resettlement until the time when radiation naturally falls to s. Thus there are three sub-cases: (i) immediate restoration; (ii) delayed clean-up and (iii) let nature take its course (i.e. no active clean-up).

For the delayed clean-up sub-case, the comparative statics for T are as follows:

$$\frac{\partial T}{\partial c} = \frac{1}{a}\left(\frac{1}{c} - \frac{(a+r)sr}{(b_0 + src)(a+r) - b_1 sr}\right) > 0$$

$$\frac{\partial T}{\partial x} = \frac{1}{ax} > 0$$

$$\frac{\partial T}{\partial s} = -\frac{1}{a}\left(\frac{(a+r)rc - b_1 r}{(a+r)(b_0 + src) - b_1 sr}\right) < 0$$

$$\frac{\partial T}{\partial b_0} = -\frac{1}{a}\left(\frac{a+r}{(a+r)(b_0 + src) - b_1 sr}\right) < 0$$

$$\frac{\partial T}{\partial b_1} = \frac{1}{a}\left(\frac{s}{(a+r)(b_0 + src) - b_1 sr}\right) > 0$$

$$\frac{\partial T}{\partial r}=\frac{1}{a}\left(\frac{(b_0+src)(a+r))-2b_1sr-sc(a+c)^2+b_1s(a+r)}{(a+r)((a+r)(b_0+src)-b_1sr)}\right)>0$$

$$\frac{\partial T}{\partial a}=-\frac{T}{a}+\frac{2}{a+r}-\frac{b_0+src}{(b_0+src)(a+r)-2b_1sr}$$

In other words, the optimal delay rises with the discount rate, the benefits from reduced exposure and the unit cost of cleaning and falls with the threshold for resettlement and the benefits from resettlement. (The ability to sign ∂T/∂r comes from the fact that in sub-case (ii) $\frac{b_0-b_1sr/(a+r)}{c}\geq(a+r)x-rs$.) It is only for a that the sign of the impact changes is ambiguous. For a, an increase in the rate of natural decay means waiting leads to lower costs of clean-up. This factor pushes up T. On the other hand, higher a means that the time at which the site reaches a certain level of exposure is shortened and this also means that it is more advantageous to begin decontamination sooner rather than later.

Case 2.

For case 2, $b(t)=b_1e^{-at}\left(\int_0^t y(\tau)e^{a\tau}d\tau\right)$ - in other words the benefits from intervention are proportional to the reduction in exposure achieved by the clean-up operation. Overall, W is therefore,

$$\begin{aligned}W&=\int_0^\infty -y(t)ce^{-rt}dt+b_1\int_0^\infty\left(\int_0^t y(\tau)e^{a\tau}d\tau\right)e^{-at}e^{-rt}dt\\&=\int_0^\infty -y(t)ce^{-rt}dt+b_1\int_0^\infty y(\tau)\int_\tau^\infty e^{-a(t-\tau)}e^{-rt}dtd\tau\\&=\int_0^\infty -y(t)ce^{-rt}dt+b_1\int_0^\infty y(\tau)e^{a\tau}\int_\tau^\infty e^{-(r+a)t}dtd\tau\\&=\int_0^\infty y(t)e^{-rt}\left(-c+\frac{b_1}{a+r}\right)dt\end{aligned}$$

This is linear in y(t), so a clean-up that completely meets the target s at time 0 is optimal provided $b_1/c \geq (a+r)$. If this inequality is not satisfied, then no intervention is optimal. Generically, therefore, the linear nature of the cost function means that case 2 falls into one of two sub-cases, both of which involve corner solutions to the optimization problem.

Before proceeding to simulation, there is one adjustment that needs to be made to the model. As we noted above, in the case of Fukushima there are two main sources of ongoing radiation exposure: Caesium 134 and 147. Since they have different half-lives, dose at time t is a weighted average of the dose from the remaining quantities of the two isotopes as in Figure 2. This makes the model slightly more complicated in that we need to replace xe^{-at} by xf(t,α) where f is a weighted average of the doses from the component nuclides and α is a shift parameter. The function f is continuous in t and since f is a weighted average of decreasing and convex functions, then f is decreasing and convex in t. If the function, f is used, then T solves:

$$\frac{b_0}{c} - \frac{b_1 s}{c}\left(1 - \int_T^\infty \frac{\partial f(\tau - T, \alpha)}{\partial T} e^{-r(\tau - T)} d\tau\right) = -x\frac{\partial f(T,\alpha)}{\partial T} + r(xf - s)$$

Ultimately, in the derivation of the optimal delay the basic analysis is the same: there are three possible sub-cases to consider and all the comparative statics for T are unambiguous except for α.

3.2 Parameter values.

Finding reasonable values for some of the parameters is not always straightforward given the paucity of data on previous incidents and attempts at clean-up. The function f = (0.74exp(-0.3356αt)) + 0.26exp(-0.0230αt) with α=1 corresponds to the IAEA, 2011, exposure decay curve shown in Figure 2 and provides a benchmark figure for this parameter. With this function, the first order equation for welfare maximization is,

$$\begin{aligned} &x\left(0.74(0.3356\alpha + r)e^{-(0.3356\alpha)T} + 0.26(0.023\alpha + r)e^{-(0.023\alpha)T}\right) - sr - \\ &\frac{b_0}{c} + \frac{b_1 sr}{c}\left(\frac{0.74}{0.3356\alpha + r} + \frac{0.26}{0.023\alpha + r}\right) = 0. \end{aligned} \quad (1)$$

In practice α might differ from 1 according to the nature of the terrain, weather etc. For r, given Japanese interest rates, a range of 0.01 to 0.10 per annum seems reasonable with a central figure of 0.04. [14]

[14] Gollier and Weitzman, 2010 present a 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

For s and x a number of combinations are possible. As noted above, the ultimate target level for radiation exposure is 1mSv per year, whereas in the excluded zones the theoretical exposure level was largely above 20mSv per year in 2011. However, in some parts of the excluded zone, current exposure levels are well above 20mSv per year with annualised figures exceeding 100mSv per annum at a few monitoring sites (http://www.r-monitor.jp/). Meanwhile, it is possible that the Japanese government will allow some access to the excluded zone well before the eventual target of 1mSv per year is reached. Thus for case 1, setting x = 20-100 and s = 1-20 provides a reasonable range with x = 20 and s = 1 as a benchmark combinations. Outside the excluded zone, exposure is already typically below 20mSv, yet intensive decontamination is also planned for these areas (Moritani, 2011). So for case 2, values of x=2-10 and setting s=1 are in keeping with the current policy framework.

Estimating c and b with precision is possibly the most difficult issue. Although we noted that a decontamination budget has been set by the Japanese government for 2012 there are no associated estimates of costs per hectare at the national level. Indeed, it is anticipated that the largest part of the budget for 2012 will be on demonstration projects (MOF, 2011). The cost per hectare is also likely to vary with terrain type and land use. One source is Hedemann-Johnson, 2003, which conducts simulations of clean-up costs for urban and semi-urban areas using some earlier cost figures for the UK set out in Brown et al, 1996 converted into GNP per capita units. These figures are a fraction (about 1/10) of the current indicative prices set by Fukushima prefecture in its invitation to tender documents (Fukushima, 2011) and the values of the winning bids for model clean-up operations. For this reason we centre our figures on the Fukushima data, limited though it is. The tender documents suggest a cost of approximately 9 million Japanese yen per hectare for farmland clean-up, though the figures do not include long time storage costs for any material removed from the site. As such they may be an underestimate.[15] The same documents provide a figure of approximately 700,000 Yen for cleaning up a residence which occupies a land area of 400m^2. In February 2012 the first major contracts were implemented for model clean-up operations. In these awards, for instance, Mitsui Sumitomo Corporation won a contract to decontaminate 267 houses for Fukushima prefecture at a price of 200m Yen (about 1.95m

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.

[15] Of course, conversely the guide prices may include rents.

Euros) or 795,000 per house.[16] Since the prefecture is responsible for decontaminating areas with exposure levels below 20mSv per year, then the costs of clean-up for more contaminated sites may be significantly higher. For instance, in the first round of contracts for areas under national government control, the construction company Taisei Ltd successfully bid to clean up 62 hectares at a price of approximately 51.6m Yen per hectare, which is well above the 9m yen guide price quoted by the Fukushima prefecture prospectus.

Although we have information on decontamination costs for specific items, an important question concerns how costs should be aggregated, given that individuals typically divide their day between different locales, including home, roads, work and shopping etc. Two strategies are employed. The first is to use the individual figures for homes, farmland etc. and suppose the individual does not use other assets. The second is to calculate an approximate weighted average. In this calculation, prefecture level figures on population, households and land use are assumed to be representative of the affected areas.[17] The formula I use for the unit cost of clean up is,

$$C = \frac{1}{A_F}\left(R_F c_r + A_f c_{fa} + H_F c_H + \gamma A_W c_w + U_F c_u\right)$$

In this expression, A_F is the total area of Fukushima, R_F is the kilometres of paved roads in the prefecture, A_f is the area of farmed land, H_F is the number of households, A_w is the area of woodland and U_F is the area of urban land. Cost per unit are, c_r for roads, c_{fa} for farmland, c_H for housing, c_w for woodland and c_u for non-housing urban sites. The symbol γ represents the fraction of woodland that is actively cleaned (implicitly for other assets γ=1) and η is the efficiency of the clean-up – i.e. the fraction of the excess dose that is actually removed. The cost c is therefore in units of Yen per hectare. Alternatively we could replace A_F by H_F in the denominator to get a figure per household.

For c_w, Fukushima 2011, provides guide prices of 60,000 Yen per hectare for

[16] According to the Asahi Shimbum newspaper, a number of the contract winners bid below cost in order to acquire experience and establish a track record for decontamination. See http://www.asahi.com/business/topics/economy/TKY201201310154.html (in Japanese).

[17] The affected zones do not include the largest urban areas for Fukushima or the highest upland regions. As such, using prefecture level estimates will tend to overestimate the urban clean-up costs and underestimate farmland costs.

removing leaves and loose material from contaminated areas adjacent to housing. For typical roads, the quoted figure is approximately 240000 Yen per kilometre. I set $\gamma=0.1$ on the basis that 10% of forest lies adjacent to built up areas (a figure used in the bid documents) and will be cleared of debris. I include estimates for non-housing buildings using the same source. I then calculate an average cost at the household or hectare level. Using the Fukushima invitation to tender figures this gives a range of 1.38m to 3.49m Yen per household (0.75 to 1.89m Yen per hectare) depending largely on whether a high or low figure for farmland clean up is used. Using the actual winning bid figures for the Taisei bid for instance would push up the cost per household to 14.2m Yen – i.e. several times annual income per capita.

A final uncertainty over costs is that the quoted tender figures are for C and not for c (Yen per mSv per annum per hectare). Since we are using mostly prefectural-based figures and the contracts are for 2012, we take it that $c = \frac{C}{\eta x}$ with $x \approx 20$ mSv. In this expression, η is the efficiency of the clean up operation in terms of the fraction of dose removed. Some estimates of clean-up efficiency based on experimental evidence are available, (e.g. Hedemann-Johnson, 2003) and are typically well below 100%. I use an efficiency of η=70% which has been used in estimates for soil removal (Brown et al, 1996). This yields values of c of 50,000 Yen per mSv per annum for a 400m^2 residence to 0.1m Yen-0.25m Yen per mSv per annum per household based on the average cost figures or 1m Yen per household per mSv per annum using the Taisei figure quoted above. I use the range 0.05m Yen to 1m Yen with a central figure set at 0.175m Yen.

What are good values for benefits, b_0 and b_1? Again this is uncertain and likely to depend on post-resettlement land use, whether activities (e.g. outdoor play by children) are restricted, but also the costs of supplying alternative assets during the period of evacuation and the associated benefits from these assets. My approach here is to suppose that the evacuation costs cancel out the benefits from temporarily supplied assets. In other words, b_0 is well-approximated by the prior flow of benefits from the evacuated areas. In the case where meeting the target ends evacuation and leads to the full restoration of benefits, some figures for b_0 can then be estimated from the flow of farm income, and from house prices and rents. We do not have any estimates of value derived from nearby public buildings and infrastructure such as roads or for other types of land use such as woodlands although at least in theory, the value of these un-priced assets may be capitalized in house prices and rental rates.[18] Net farm income is approximately 1m Yen per hectare per annum for rice farming in Fukushima. A significant portion of this figure is composed of the various subsidies given to farming in Japan and therefore should properly be deducted from the net benefits of clean-up.[19] However if we take the figure at face value, it suggests an estimate for b_0/c of approximately 1.55 for agricultural land using the tender guide prices. For non-farms, average prices for housing in Fukushima in 2009 were approximately 8.8m Yen for a $400m^2$ residential site (Japan Statistical Yearbook 2010). If r =0.04 this would suggest a b_0/c ratio of 5.3 using the single dwelling clean up cost estimate. If we use the weighted average cost estimate, then consistency dictates that we should also use a weighted average for benefits. For this I assume that the benefits from workplace, forests and roads are capitalized in the values for farmland and households. Using this approach produces b_0/c = 3.5 using the low-cost weighted average value, 2.1 for the high cost tender figure and 0.51 if the average based on winning bids is used. I also assume that there are no restrictions on land use after resettlement, so that farm produce can be freely sold. If farm income was zero after resettlement then these three figures become, 1.8, 1.1 and 0.2 respectively. As an alternative to house values we can use rental figures for homes. Mean rental values for homes in Fukushima (Japan Statistical Yearbook 2010) were 39,160 yen per month in 2008, the last year for which figures are available. This rental-based figure yields b_0/c values of 4.9, 2.9 and 0.72, using the weighted average cost estimates (and assuming farm income is restored) or 9.4 if the cost figure used is 700000 yen per dwelling. Overall therefore a range of 0.2 to 10 is used for b_0/c, with a central figure of 2.0.

For b_1, a starting point is the framework set out in the IAEA, 1994, where the effect of 1 man Sv is taken to be roughly equivalent to the loss of one life year. In this case, the value of a 1 m Sv/annum reduction in exposure for a household of n people is vn/1000 where v is the value of a statistical life year (VSLY). According to the Japan Statistical Yearbook, 2010, the average household size in Fukushima was 2.83 in 2009. For v, no official figure is available for Japan. The IAEA guidance sets v = GNP/capita, but this is low compared to many estimates used in the modern risk literature. For instance, Viscusi 2012, finds a range of values of VSLY US $ 150,000 to $400,000 for working age Americans (i.e. roughly 3 to 8 times GNP per capita). Abelson, 2007, offers a survey of international evidence and proposes a

[18] For woodlands etc. some of the benefit flows of ecosystem services are unlikely to have been disrupted by the accidents. Recreation activities and forestry production will however be suspended during the period of evacuation.

[19] OECD 2010, suggests that on average 47% of farm income comes from government support. The figure is typically higher for rice farming.

figure of AU $151,000 (approximately 3 x GNP per capita) for official use in Australia. We therefore use a range of v = 1-5 per capita income with a central value of 3, using Yen 2.7m as a guide for per capita income in Fukushima (Japan Statistical Yearbook, 2010). This gives a range for b_1 of 7,760 Yen to 38,800 Yen per mSv per annum per household. To get a figure for b_1/c per mSv per annum again we need to divide the cost figures referred to above by some estimate of y for a typical clean up operation. If y is again approximately 70% of 20mSv per annum, and for a 400m^2 house a reasonable central estimate of c is 700,000/14 = 50,000 Yen, then combined with estimates of b_1 it suggests a range of 0.15 to 0.78 for b_1/c, with a central figure of 0.45. On the other hand if we use the averaged cost estimate of 3.49m Yen per household, the range is 0.03 to 0.15 with a central figure of 0.09. The much higher estimate for costs based on winning bids, pushes the central figure down to 0.02. In what follows I use the range 0.02 to 0.8 with a central figure of 0.09.

There is ample 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 for this 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 that also mentions the possibility. Takaaki Kato's (2006, 2010) relatively high contingent valuation figures for willingness to accept nuclear power risks in Japan is also consistent with dread risks for exposure to elevated radiation doses. The psychological after-effects of Chernobyl have been stressed in WHO, 2005 and Danzer and Weisshaar, 2009, while Lehmann and Wadsworth, 2011, provide quantitative evidence of the impact of Chernobyl-related psychiatric illnesses on subsequent labour market experience. In addition, some individuals may over-estimate risks, creating a question whether subjective or objective risks should be used in policy analysis (see Johansson-Stenman, 2008, or Munro, 2009). In this context, lost benefits from living in a contaminated area may not be fully restored when evacuation notices are removed and individuals are allowed to return home. The estimates of b_1 that I use omit this important but difficult to quantify element of stress and anxiety associated with raised exposure. Since, $\partial T / \partial b_1 \geq 0$ the omission yields a potential underestimate of optimal delay in case 1. For case 2, the omission potentially leads to an undervaluation of the case for intervention. Arguably, benefits are fully restored only when the anxieties and fears associated with contamination are also removed. Specifically, there may be a premium for restoring exposure levels to their pre-accident levels.[20] All these potentially important aspects are set to one side in the initial simulations, but are obviously significant when the optimal value of s is discussed subsequently.

Table 2. Parameters

Parameter	Value or range	Basis for estimates
Discount rate, r	1-10% per annum	Japanese long-term interest rates
α, decay rate shift parameter	1	Caesium decay rates, IAEA, 2011.
s, target	1-20 mSv per annum per person	Japanese government policy, Moriya 2011
x, starting point	10-100 mSv per annum per person	Current exposure (2011) in restricted and evacuated zones
c, cost	0.05m Yen – 1m Yen per mSv per household	Estimated clean-up costs (Fukushima, 2011)
b_0/c, benefit/cost	0.5-10 per mSv per annum per household	Estimated clean up costs (Fukushima, 2011), House and land income or values
b_1/c	0.02-0.8 per mSv per annum per household	IAEA equation and estimated clean up costs (Fukushima, 2011).
n, person per household	2.83 people	Japan Statistical Yearbook, 2010 for Fukushima
v, value of a statistical life year	1-5 GNP per capita	GNP: Japan Statistical Yearbook, 2010 for Fukushima,

We concentrate first on case 1. The first simulation illustrates the potential for a non-monotonic relationship between α and T (see Figure 5). Throughout this example we set r = 0.04, x = 20 and s = 1. Optimal delay curves are shown for three combinations of b_0 and b_1. We set b_1/c=0.09 for two curves with the corresponding value of b_0/c indicated by the label.

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[20] It may not be simply the dose level that creates psychological problems for some individuals, but also the departure from historical or reference levels of risk. Certainly, it is well-documented (e.g. Harley, 2008) that background dose vary significantly across the world, but I know of no evidence that, anxiety-related psychological problems are generally correlated with background radiation risks. It is also reasonable that at least for some individuals, psychological stresses arises from being away from the family home (Neria et al, 2008).

For one simulation curve $b_1/c = 0.5$, $b_0/c = 1$. As a guide we also add the time it would take to meet the target exposure through natural processes of decay (which is shown on the right hand scale). With regards to optimal delay, for low values of α, no delay is optimal. At these very low rates of α, the natural rate of decay of the radioactive exposure is very limited. For instance for the unrealistically low α = 0.2 it takes the site 358 years to attain the target naturally. As a result there is little advantage in delaying site remediation. For some parameter combinations, T is increasing in α, initially, but then falls. At the benchmark value of α=1, which corresponds to the IAEA chart, the optimal delay is 6.04 years when $b_0/c = 1$ and 2.75 years when $b_0/c = 2.5$. Immediately around the benchmark the optimal delay is relatively insensitive to changes in α. For instance, on the $b_0/c = 1$ curve, T = 6.7 for α = 0.8 and T = 5.8 for α = 1.2. In this example the optimal delay is also insensitive to changes in the ratio of b_1 to c around α=1. This is principally because s=1, meaning that the costs from contamination that occur after resettlement are comparatively low.

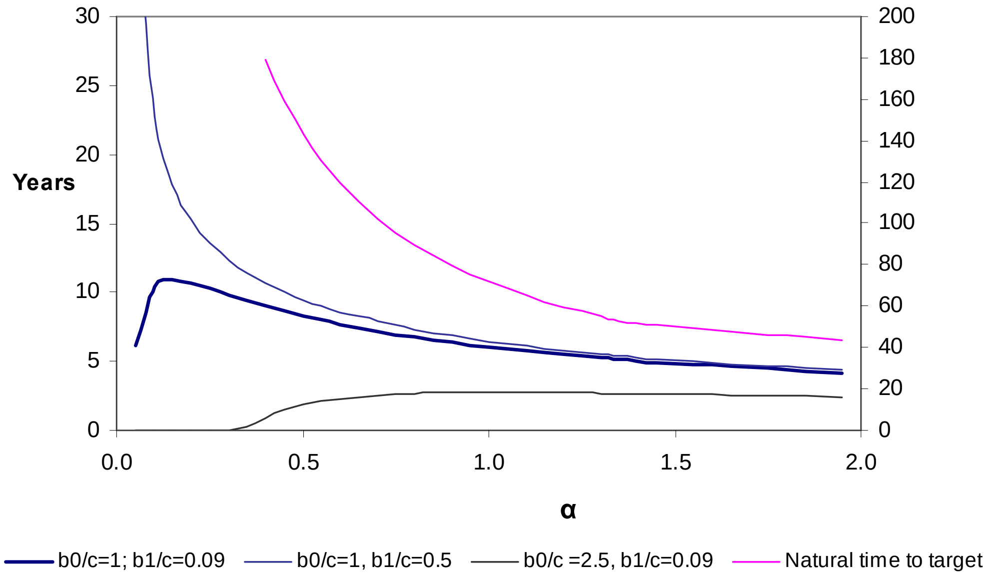

Figure 5. Optimal delay as a function of α. (Natural time to target on the right hand scale.)

Figure 6 illustrates the relationship between delay time and the discount rate for three values of the b_0/c ratio, a value of s = 1 and x = 20 and with $b_1/c = 0.09$. At a discount rate of 4%, the optimal delay ranges from 9.2 to 0.5 years in this example and suggests the value of T is sensitive to changes in the b_0/c ratio.

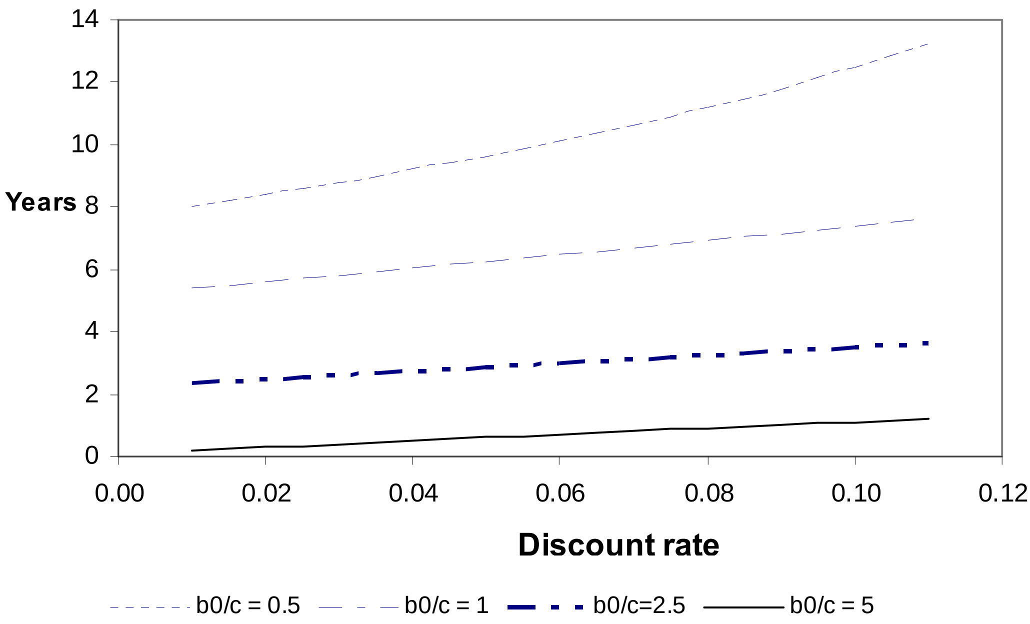

Figure 6. Optimal delay and the discount rate.

We consider the effect of changes in b_0/c for the optimal delay in Figure 7. For these illustrations, we set r = 0.04, α = 1 and b_1/c = 0.09. Curves for four combinations of x and s are shown. When x is high there are some values of b_0/c for which the optimum strategy is no active decontamination. In particular, for cases where b_0/c is less than 0.5 and with x = 100 and targets s = 20, then it is optimal to wait the 13.3 years required for the site to reach the target naturally. Similarly, when s = 5 and x = 50, non intervention is optimal when costs exceed 10 times the annual benefits. For values below b_0/c optimal delay is sensitive to changes in the cost to benefit ratio and can be as high as 40 years for b_0/c=0.2 (which corresponds to a case where farmland was economically unproductive after resettlement. For values of b_0/c above 0.5, the optimal delay time is relatively insensitive to changes in the exact ratio of costs and benefits. However it is sensitive to changes in s and x. At b_0/c = 2.5, the optimal delay is 8.6 years for the s=20, x = 100 case, but only 2.8 years when the starting level of exposure is 20 and the target is 1 mSv per annum. It is worth noting therefore that most of the higher estimates for b_0/c derive from strategies that concentrate on cleaning up urban assets such as housing and roads.

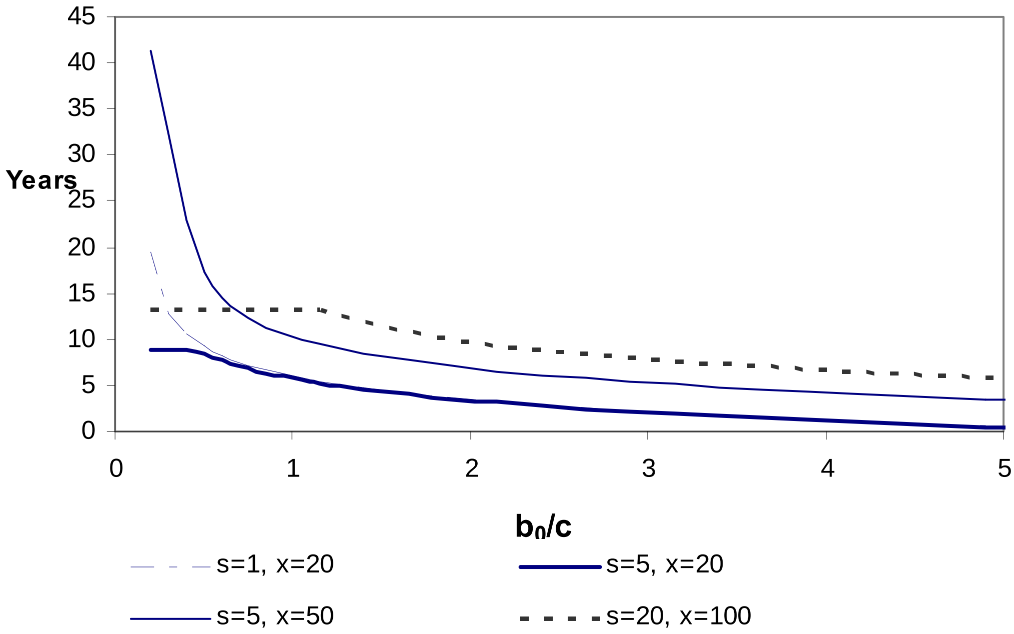

Figure 7. Optimal Delay and b_0/c .

For the next figure I vary b_1/c, keeping b_0/c=2. As in the previous case, for high x/s ratios the optimal strategy can be one of waiting for remediation to occur naturally. This explains the shape of the optimal delay curve for the s=5, x=50 case. For reasonable parameter values immediate clean-up is not optimal. Meanwhile, around the value for b_1/c of 0.09 the optimal delay time varies little but this is not true at the lower end of the scale. As was shown in the previous example, delay is sensitive to changes in the values of x and s.

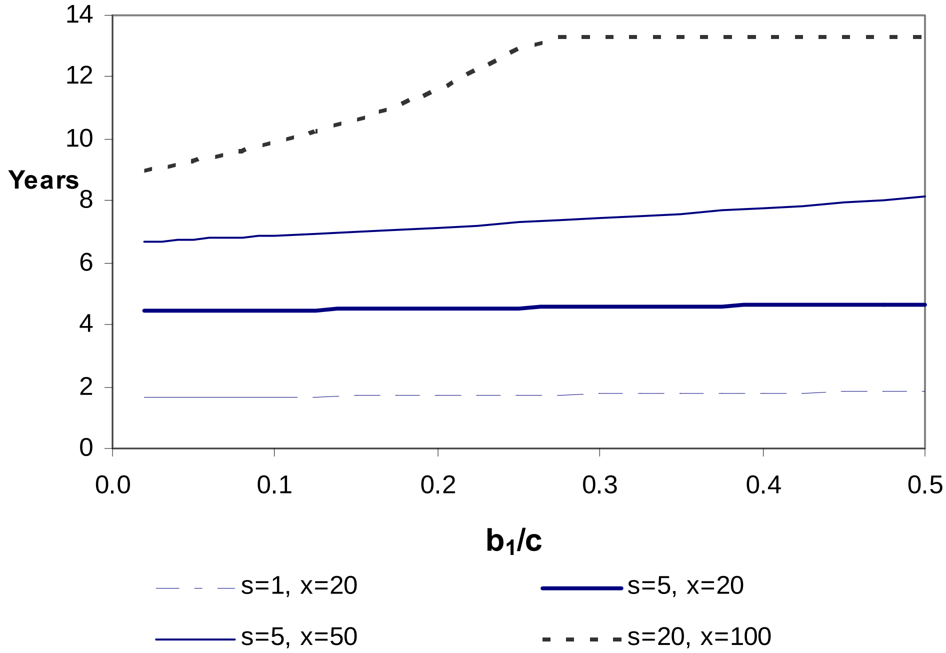

Figure 8. Optimal Delay and b_1/c

One feature that emerges from all the examples is that for most reasonable parameter values immediate action (i.e. T = 0) is not optimal. Some delay almost always enhances the payoffs from decontamination. The scale of the gain from delay varies according to the parameter values, but for instance, for r=0.04, s=1, x =20, b_0/c = 2 and b_1/c = 0.09, the welfare gains from decontamination are reduced by 15% when intervention occurs at T=0, rather than at the optimal date.

Case 2. In case 2, intervention to reduce contamination is optimal provided,

$$b_1\left(\frac{0.74}{r+0.3356\alpha}+\frac{0.26}{r+0.023\alpha}\right)-c\geq 0 \qquad (2)$$

For higher values of b_1/c (e.g. b_1/c >0.164, with r = 0.04 and α=1), this equation is satisfied, but for some of the bigger cost estimates the inequality is not met for non-zero discount rates. In other words, for higher cost estimates a policy of non-clean up would be optimal. On the other hand, we noted above that historically, elevated radiation levels induced fear and anxiety. If there is a fixed 'premium' F (per unit of time), for returning radiation levels to their background level, and thereby eliminating the fear, then a sufficient condition for intervention to be optimal is,

$$\frac{F}{c}\geq ry\left(1-\frac{b_1}{c}\left(\frac{0.74}{r+0.3356\alpha}+\frac{0.26}{r+0.023\alpha}\right)\right) \qquad (3)$$

If for instance, b_1/c = 0.09, α=1, r=0.04 and y=20, then F/c≥0.36. In other words, for the central estimates of costs, the benefits of eliminating fear must be about four times the standard estimates of per mSv benefits from risk reduction.

Combining cases 1 and 2 is relevant for a scenario in which it is possible to choose the value of s optimally. Because of the large amount of international advice on reasonable thresholds for policy interventions (e.g. IAEA 2011) which has now been incorporated into domestic plans (e.g. Ministry of the Environment, 2011a) this may be unrealistic politically, but it gives a perspective from which to judge the optimality of specific policies. In the combined case, both equation (1) and (2) apply. Equation (2) is independent of T (and b_0). If it is satisfied then the optimal value of s is zero. For s=0, equation (1) becomes,

$$x\left(0.74(0.3356\alpha+r)e^{-(0.3356\alpha)T}+0.26(0.023\alpha+r)e^{-(0.023\alpha)T}\right)-\frac{b_0}{c}=0. \qquad (4)$$

So, even if it is optimal to eliminate all the elevated risk, it can still be desirable to wait before returning to the contaminated area. In particular, optimal delay is strictly positive provided,

$$xc\left(r+0.74\left(0.3356\alpha\right)+0.26\left(0.023\alpha\right)\right)-b_0>0.$$

When equation (2) is not satisfied, it is not optimal to clean-up in-situ. For an interior solution for T, optimal delay is given implicitly by the equation,

$$b_1 x\left(0.74\left(0.3356\alpha\right)e^{-(0.3356\alpha)T}+0.26\left(0.023\alpha\right)e^{-(0.023\alpha)T}\right)-b_0=0. \qquad (5)$$

In other words, resettlement occurs when the lost benefits of staying out of the zone for one more unit of time equals the increased costs of returning. Under this condition there is no active decontamination. Under this scenario, for values of x=20, $b_1 / b_0 = 0.045$, $\alpha = 1$ then $T \approx 43$. In short therefore, even when s can be chosen freely, it is generally optimal to have some delay before resettlement.

4 Conclusion.

In the wake of the recent accident at Fukushima-dai-ichi nuclear power plant, the Japanese government has engaged in a high profile and swift attempt to decontaminate affected land. In this paper I have set out a framework for evaluating the economic value of rapid decontamination. The model set out is basic, but captures some of the major dimensions of the policy issue for a general case and for the specific case of Japan. What stands out is the lack of data particularly on costs, both from Fukushima but also from previous incidents. Given this important caveat, it still seems that for most reasonable values of the parameters it is optimal to delay contamination for a period of 2-10 years. For extreme values of resettlement benefits, immediate action is effectively optimal. These values of b_0/c correspond to situations where only housing is decontaminated, but nevertheless the full benefits of life are restored by resettlement.

In the discussion of possible parameters we saw that reasonable figures for the b_0/c ratio differed between strategies that concentrated on urban assets and plans which also cleaned up farmland and adjacent woodlands. This suggests that it may be optimal to have different policies for urban land and farmland, with greater delay for the latter. I am cautious about such a conclusion for at least two reasons. First, the policy may not be feasible in areas where individuals are constantly moving between small villages and farmland. Secondly, it may not be optimal if the presence of nearby, untouched farm and woodland had significant negative external effects on resident's mental health. At the same time, the optimal resettlement dates are sensitive to the twin assumptions that farm income is restored upon resettlement and that farm income is unsubsidized. The second of these assumptions is not true and the first may be viewed as unlikely at least in the short term. The final point of the paper is the role of fear, anxiety and dread in resettlement and decontamination decisions. It is clear from Chernobyl that the psychiatric impact of elevated radioactive exposure can be significant. What is not so clear is the relationship between policy choices and psychological stresses and this requires more research.

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Appendix The IAEA Model.

The basic source is IAEA, 1994, particularly Annex I. The actual, illustrative dollar figures used in that annex are based on numbers for the early 1990s and so would need to be updated to apply to a current emergency.

The basic model is set out on pages 76 and 77 of the Annex and we use the same notation as far as is possible.
S = avertable dose (Sieverts)
α = cost to averting a unit of collective dose
Y = cost equivalent of the averted radiation detriment

$$\Delta Y = \alpha \Delta S$$

Cost of the measure, $X = X_0 + X(I)$ where X_0 is a fixed element from intervention and X(I) is a function of the scale of the intervention. I.e. X(I) is the variable cost element. The optimal intervention is,

$$\frac{d(\Delta Y - X)}{dI} = 0$$

For moving people, B(t) is the net benefit at time t, so that B(t) = ΔY-X=αΔS(t) –X(t). In the annex the term for X is approximated by $n(X_0+at)$. Putting this together gets,

$$B(t) = \alpha \Delta S(t) - (X_0 + at)n$$

Where a is the accommodation cost per unit of time per person. According to the annex, moving people is desirable when B(t) > 0. Return is optimal when 'averted per caput dose per unit time… equals the continuing costs per unit time' p. 77. At this point we have,

$$\dot{B}(t) = \alpha \Delta \dot{E}(t) - an = 0$$

The averted dose per unit time from this equation will then be,

$$\Delta \dot{E}(t) = \frac{\Delta \dot{S}(t)}{n} = \frac{a}{\alpha}$$

A critical number in this calculation is α. The figure is calculated using averted health care costs, though in the accompanying text there are a series of notes and comments on the flaws and caveats with such an approach.

Particular ingredients:

- Average loss of healthy life associated with one 'radiation induced fatal cancer' is approximately 13 years
- The probability coefficient for fatal cancer is $5 \times 10^{-2}\ Sv^{-1}$
- The 'detriment' coefficient for non-fatal cancer is $1 \times 10^{-2}\ Sv^{-1}$
- The 'detriment' coefficient for sever, induced hereditary damage in all future generation is given as 1.3×10^{-2} per manSv

Detriment coefficients 'comprise two terms representing the frequency of occurrence of an effect and the other weighting its severity'

These terms are weighted and added to create a figure for the loss of life quality for 1 man Sv:

$$(5 \times 10^{-2}\ Sv^{-1} + 1 \times 10^{-2} + 1.3 \times 10^{-2}) \times 13 \text{ year} \approx 1 \text{ year}.$$

The figure is based on the underlying notion that individual doses are less than 0.1 $Sv.h^{-1}$ and total less than 0.2Sv per person).

What is the value of a loss of 1 year of life? The annex uses mean GNP per capita for rich countries or approximately $20,000. In subsequent discussion, it is noted that there are a wide range of uncertainties and nuances to be considered. So, in sensitivity analysis a range of $10,000-$40,000 per man Sv is used for α.

Four interventions are then considered:

1. sheltering
2. urgent evacuation (i.e. to an emergency centre for a few days or weeks)
3. temporary relocation (several months or more)
4. permanent resettlement

The basic methodology in all cases is the same.

Costs/ intervention level	*Sheltering*	*Urgent evacuation*	*Temporary relocation*	*Permanent resettlement*
Meaning	Staying indoors with doors, windows closed	Emergency centre such as school	Tolerable, temporary accommodation	New homes at new location
Transport out/return		'a few tens'	'a few hundreds'	
Loss of income	GNP per capita per day	GNP per capita per day	'several tens to a few 100s of $ per month'	
Accommodation/ food		A few tens per day	$100-200 per month rental	
Depreciation/ maintenance			'a few tens to several tens of $ per month'	
Average (1)	$55	$100-125 per day	$400-900 for first month; $200-500 per month thereafter	$10k-30k (mostly new housing costs)
Alpha (α) (2)	$10k-40k /Sv	$10k-40k /Sv	$10k-40k /Sv	$10k-40k /Sv
Intervention level (mSv per unit time) (1)/(2)	1.5-6mSv per day	3-12mSv per day	10-90 mSv first month	'A few hundred mSv to a few Sv'
Return to normal level (mSv per unit time) (1)	-	-	'A few to a few tens of mSv in the month'	-
Generic avertable dose figure	10mSv in 2 days	50mSv (in a week)	80 mSv (over 6 months)	1 Sv (in a life)