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J-value assessment of relocation measures following the nuclear power plant accidents at Chernobyl and Fukushima Daiichi

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ABSTRACT

The policies of population relocation put in train following the severe nuclear reactor accidents at Chernobyl in 1986 and Fukushima Daiichi in 2011 are examined using the Judgement- or J-value. Here relocation is taken to mean a movement of people that is long-term or permanent. A review is made of a 1992 IAEA/CEC study of the Chernobyl countermeasures, which includes data from which the effectiveness of the 1986 and post-1990 relocations may be judged using the J-value. The present analysis provides endorsement of that study's conclusion that the post-1990 relocation of 220,000 members of the public could not be justified on the grounds of radiological health benefit. Moreover, application of the J-value suggests that the first Chernobyl relocation is economically defensible for between 26% and 62% of the roughly 115,000 people actually moved in 1986. Thus only between 9% and 22% of the 335,000 people finally relocated after Chernobyl were justifiable, based on the J-value and the data available. Nor does the J-value support the relocation of the 160,000 people moved out on a long-term basis after the Fukushima Daiichi nuclear accident. The J-value results for these very severe nuclear accidents should inform the decisions of those deciding how best to respond to a big nuclear accident in the future. The overall conclusion is that relocation should be used sparingly if at all after any major nuclear accident. It is recognised that medical professionals are seeking a good way to communicate radiation risks in response to frequent requests from the general public for information and explanation in a post-accident situation. Radiation-induced loss of life expectancy, which lies at the heart of the application of the J-value to nuclear accidents, is proposed as an information-rich yet easy to understand statistic that the medical profession and others may find helpful in this regard.

1. Introduction

In the event of an industrial accident with off-site consequences, decision-makers must decide who, if anyone, ought to be evacuated from the surrounding area. If the accident results in prolonged restrictions on the normal use of the land, then decisions must be made about who can return to their homes and who should be temporarily or permanently relocated. In the civil nuclear industry, the only two events that have caused the authorities to recommend relocation are the accident at the Chernobyl nuclear power plant in Ukraine in 1986 and that at the Fukushima Daiichi power station in Japan in 2011. This paper assesses how far the relocation programmes following these events were justified and considers the import of the results for future decision making.

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It is important to distinguish between "evacuation", taken for the purposes of this paper and the NREFS study more generally (NREFS, 2016), to be short-term, and "relocation", taken to be long-term or even permanent. Evacuation may be in force for only days or a week or so, allowing for time to establish the extent of the accident, after which a decision may be taken on whether or not to allow return. Temporary relocation is defined in Ashley et al. (2017) as implying an enforced period of absence of up to 3 months, with relocation regarded as permanent if a recommendation to return cannot be made 3 months after the accident. It would certainly seem that resistance to going back and problems with a large-scale return are likely to be encountered once people have stayed away for a year or more, as in the cases of the accidents at both Chernobyl and Fukushima Daiichi.

On 26 April 1986, an accident at the nuclear power plant at Chernobyl, Ukraine resulted in a catastrophic failure of the reactor containment. A fire in the exposed, graphite-moderated core burned for ten days before being brought under control. The accident released into the atmosphere large quantities of isotopes of relatively short half-life such as iodine (^{131}I has a half-life of 8 days), together with much lower quantities, in terms of total activity, of long-lived isotopes such as caesium (^{137}Cs, 30 years), strontium (^{90}Sr, 28 years) and plutonium (^{239}Pu, 24,000 years), although their effective half-lives in man's environment can be shorter. The pattern of radionuclide deposition reflected changes of wind direction and rainfall over the duration of the main release, with 150,000 km^2 of land in Ukraine, Belarus and Russia eventually being classified as 'contaminated' (UNSCEAR, 2008, p. 50).

The population of the town of Pripyat, 3 km from the power plant, was relocated one day after the accident. The following week (2–6 May 1986) the entire population within 30 km of the stricken reactor was relocated. Subsequent radiation monitoring led to further relocations including areas of the Gomel region of Belarus and the Bryansk region of Russia, some 150 km to the northeast of Chernobyl. A total of 116,000 people had been relocated by September 1986 (Smith and Beresford, 2005, p. 6). Mapping of the contaminated regions in the following years led to the establishment of the State All-Union and Republican Programme in 1990, under which another 220,000 people were relocated from areas with elevated readings for caesium-137 ground contamination (Lochard and Schneider, 1992). By 2000, some eight years after the break-up of the Soviet Union and fourteen years after the accident, nearly 4600 people were still waiting for new homes in Ukraine, as were 7000 in Belarus (UNDP, 2002, p. 34).

On 11 March 2011, the Great East Japan Earthquake led to the loss of offsite power at several nuclear power stations. This led to the automatic shutdown of the plants, with the cooling pumps being powered post-shutdown by on-site, back-up generators. However, the earthquake also triggered a series of tsunamis that hit the east coast of Japan, causing the Fukushima Daiichi nuclear power plant to be overwhelmed. The failure of the back-up power supplies led to pumped cooling being lost for three reactors, and this resulted in damage first to the cores and subsequently to the reactor pressure vessels. Operations to reduce pressure in the reactor vessels – or possibly, leaks from the vessels – resulted in the release of radionuclides into the reactor buildings. The over-heated fuel assemblies led to a chemical reaction that produced hydrogen gas in the reactor buildings. This subsequently exploded, releasing radionuclides into the environment (UNSCEAR, 2013, p. 34).

In the hours and days following the accident, the Japanese authorities ordered the progressive evacuation of those living near to the plant. A 20-km 'Restricted Zone' was established around the plant from which 78,000 people had been evacuated by the following day. Further compulsory and voluntary evacuation zones were established, extending as far as 40 km to the northwest (Iitate Village), based on monitoring of the deposition pattern. Between 118,000 and 150,000 people had been relocated from the vicinity of the power plant by the end of 2011 (UNSCEAR, 2013, p. 50; Ranghieri and Ishiwatari, M., 2014, p. 105).

Following both the Chernobyl and Fukushima Daiichi accidents, more than one hundred thousand people were removed from their homes within a few months. Nearly thirty years after the Chernobyl accident, over one-third of a million people have been relocated and few have returned. Four years after the Fukushima Daiichi accident, more than 85,000 people remain in temporary or permanent accommodation away from their former homes (City Population, 2016).

Whilst leaving one's home may provide initial reassurance, an enforced long period away brings disruption and dislocation, with the attendant social and psychological penalties. Moreover, staying away for a substantial time will reduce both social and occupational ties to the original location and engender a general reluctance to return. The evidence from Fukushima Daiichi is that young people, who tend to be more mobile, are even less likely than their elders to wish to return to their original dwelling place (Tsubokura and Morita, 2015). Inevitably this will have an adverse effect on the viability of the towns and villages from which the people were removed even after the authorities have declared them safe for return.

A similar effect has been observed in a non-nuclear context following the evacuation of New Orleans in response to Hurricane Katrina in August 2005. The population of New Orleans 11 months after the hurricane was down 25% on what it had been a year earlier, and had risen to only 90% of the pre-hurricane level by July 2014 (US Census Bureau, 2015). (Some have suggested, however, that part of the eventual shortfall might have been caused by a pre-excising decline in the New Orleans economy).

This paper assesses the extent to which the mass relocations at Chernobyl and Fukushima were justified and what, if any, long-term health benefits resulted from relocation. In particular, the analysis considers whether the very high costs involved could have been better spent elsewhere, including on other, more effective, interventions.

2. The Judgement- or J-value

The J-value framework provides an objective tool that assesses the cost-effectiveness of safety schemes that reduce the risk to human life (Thomas et al., 2006a). It balances the costs of a safety scheme against the improvement in quality of life of those affected as a result of implementing that scheme. The Judgement- or J-value is the ratio of the actual (or contemplated) sum to be spent on protection to the maximum that it is reasonable to spend if the quality of life of those affected is not to be compromised. Ensuring that the safety expenditure is economically and scientifically reasonable implies that this ratio should be less than or equal to unity, $J \leq 1$.

The J-value builds on the ground rule established in welfare economics (see, for example, Boadway and Bruce, 1984) that the sum of money to be spent on mitigating an adverse effect or compensating for it should be the amount that the people affected would themselves be prepared to pay for such mitigation or to receive in compensation. In practice, of course, payment for such a safety measure is often made by another person or body such as a company or Government. The J-value then postulates that the average person affected will be prepared, in principle if not in actuality, to pay for his or her share in a safety measure as long as his/her quality of life is not compromised as a result. Here the quality of life of those affected is measured by the Life Quality Index (Nathwani and Lind, 1997; Thomas et al., 2006a, 2010; Nathwani et al., 2009), which takes account of how much the average individual affected has available to spend and how long he/she can expect to live from now on, with the balance between the two mediated by the appropriate value of risk-aversion (Thomas and Waddington, 2017; Thomas, 2016).

Payment by the organisation owning the plant or by the Government corresponds to a strengthened version of the Kaldor–Hicks compensation principle (Kaldor, 1939; Hicks, 1939), whereby society is judged to be better off if the gainer from some economic activity is able to pay the loser the appropriate compensation and still be better off at the end of the day. Under Kaldor–Hicks the payment is hypothetical, and while it could be made from the extra income that the activity generates for the gainer, he has no obligation to make any such transfer (see, for example, Johansson, 1991). It is possible, especially after a very large industrial accident has occurred that, in the event, there will be no gainer. In such a case we may replace the term "gainer" with "expected gainer", since we can be sure that the firm will only build and run a plant when it expects to profit from it, and would not do so if it expected to make a loss as a result of a severe accident.

Often the state will step in if the owner of the plant is unable to foot all the losses, a position that is given legal status in the case of nuclear plant, where Governments socialise the risk beyond a certain level (Kidd, 2011; World Nuclear Association, 2015). The Kaldor–Hicks criterion, written in terms of "expected gainer", will once again be satisfied since the Government may be assumed to have allowed a regulated plant to operate on the basis that society could be expected to gain from its operation.

The J-value provides an objective criterion against which the reasonable extent of health and safety expenditure can be judged, something that is especially valuable when payment is to be made by a third party, such as an industrial company or Government. It could also be used as a guide by an affected individual wishing to invest in additional protection, for example voluntary relocation even when this course of action is not recommended nor sponsored by Government. Clearly such a person is in sole charge of his/her own resources and there is no onus on him or her to make use of any J-value information. (Interestingly, however, there is evidence that individuals, communities and nations tend, on average, to act as if their decisions on life extending actions were being guided by the J-value (Thomas and Waddington, 2017)).

In Section 3 of the paper it will be shown how the J-value can be applied to assess relocation strategies following a nuclear accident. The second programme of mass relocations from the Chernobyl area (in 1990) coincided with the increasing openness of the Soviet state and consequently the literature contains sufficient technical and economic data to enable a detailed J-value assessment of that relocation programme. Estimates of the economic costs and health benefits are used in Section 4 to provide an assessment of the cost-effectiveness of the relocation strategy after 1990. An attempt has been made in Section 5 to extrapolate the 1990 data back to 1986 in order to estimate the J-value of the first relocation scheme. Section 6 begins with a J-value analysis of the provision of temporary housing following the Fukushima Daiichi accident and goes on to analyse how the radiation risk averted by relocation may be compared with the increased risk to life arising from the relocation process itself. Section 7 discusses the lessons learnt from the relocation strategies at Chernobyl and Fukushima Daiichi. The same Section also discusses how socio-political aspects may be factored into decisions on public safety, and considers, further, how residual radiation risks can be communicated most accurately to members of the general public. Conclusions are given in Section 8.

3. Applying the J-value to assess relocation strategies

The J-value approach balances safety expenditure against the extension of life-expectancy brought about by the introduction of measures to improve safety. In the present context the proposed safety scheme is the relocation of people from their homes near the site of a nuclear accident to somewhere where the risk of harm from radiation exposure is lower. The safety expenditure is likely to be dominated by the construction costs of new housing and infrastructure.

The J-value framework postulates that the fundamental factors influencing the quality of life for an individual are how long he or she can expect to live from now on (his/her life expectancy, X_d) and how much he/she will have available to spend (income, G). The life quality index, Q, can then be defined by (see Nathwani and Lind, 1997; Nathwani et al., 2009; Thomas et al., 2006a, 2010)

$$Q = G^q X_d \tag{1}$$

Here G is normally chosen to be the GDP per head of the nation concerned, which has the effect of valuing the next day of life the same for each person in the nation, rich or poor, male or female, old or young. This ethical decision is regarded as appropriate when safety decisions are being considered that would affect a representative subset of the nation's citizens.

The subscript 'd' on life expectancy, X, allows for the generality of discounting of future utility of income, where the discount factor can be incorporated equivalently into the 'discounted' life expectancy (Thomas et al., 2006a, 2010). Meanwhile the fact that q is a constant means that G^q is a Power utility function of income, $u(G)$. q is the complement of risk-aversion, $\varepsilon = 1 - q$, where the hyphenated noun, risk-aversion, is used to signify the negative of the normalised derivative of marginal utility, m, with respect to income: $\varepsilon = -(G/m)\,dm/dG = -Gu''/u'$. Here $u = G^q$ is the utility of income, while $m = du/dG = u'$. The reader may confirm easily the consistency of these equations that define the dimensionless variable, ε. Pratt (1964), who introduced the concept, called ε the "local proportional risk aversion". Economists use the word, "elasticity", to denote a normalised derivative, so that the same quantity can also be described as the 'negative of the elasticity of marginal utility of wealth'. The 'coefficient of relative risk aversion' is another name used. But the desirability of a shorter title has led the author into using the hyphenated term, 'risk-aversion', ε, here and elsewhere. See Thomas (2016) for a fuller discussion of the history of utility functions and risk-aversion. The same article also explains how ε is well correlated with what we might in normal speech call aversion to risk, thus providing a further justification for the simple term, 'risk-aversion'.

Thomas and Waddington (2017) used pan-national data to derive a common value of risk-aversion, $\varepsilon = 0.95$, finding that the figure reduces to 0.91 in the case of developed countries such as the USA and the UK. Hence $\varepsilon = 0.95$ was used in the characterisation of the USSR and the Former Soviet Union, while $\varepsilon = 0.91$ was adopted for Japan.

The discussion in Thomas and Waddington (2017) of the value of $\varepsilon = 0.91$ used for developed nations includes a comparison with the value, $\varepsilon = 0.82$, derived for the UK from working time data (Thomas et al., 2010). The higher value is shown in Thomas and Waddington (2017) to correspond to an equal, 50:50 deal between the employer and the employee on how much satisfaction the average employee will gain from his work. The figure of 0.91 receives further corroboration in a recent paper (Thomas, 2017a) that uses this value in a successful test of the J-value model against the observed increase in life expectancy at birth in the UK over a 20-year period. The larger figure resolves a potential weakness associated with the earlier, lower figure for risk-aversion which assumed the average employee took no benefit other than economic from his time working. The increase in risk-aversion will lead to higher amounts being sanctioned for safety spending.

An average individual may maintain or improve his or her life quality by giving up part of his/her annual income, δG, to pay for a protection system that restores his/her life expectancy to what it would be in the absence of the risk (e.g. Thomas et al., 2006a, Eq. (14)):

$$\delta G \leq \frac{G}{q}\frac{\delta X_d}{X_d} \tag{2}$$

where δX_d is the loss of discounted life expectancy from exposure to the risk.

A cohort, i, of N_i similarly affected individuals should be willing to spend, per year, up to

$$\delta G_{N_i} = N_i\,\delta G = \frac{GN_i}{q}\frac{\delta X_{d,i}}{X_{d,i}} \tag{3}$$

If an annual amount $\delta\hat{G}_{N_i}$ is actually spent then the J-value for cohort *i* will be ratio of the amount spent to the maximum that it is reasonable to spend,

$$J_i = \frac{\delta\hat{G}_{N_i}}{\delta G_{N_i}} = \frac{q}{N_i}\frac{\delta\hat{G}_{N_i}}{G}\left(\frac{\delta X_{d,i}}{X_{d,i}}\right)^{-1} \tag{4}$$

3.1. *Combining the J-value for multiple cohorts*

An extensive relocation strategy such as that implemented at Chernobyl or Fukushima Daiichi will, in practice, apply to multiple locations each of which may have a different degree of land contamination. The benefits of relocation will therefore vary by initial locality, as will the amount that it is reasonable to spend on the strategy. To calculate the J-value, the maximum reasonable expenditure must be summed over all the locations.

Consider a strategy that relocates some people from an area of relatively high potential dose, others from an area of medium dose, another involving a lower starting exposure, and so on. The population may be divided into *m* cohorts, where all the individuals within the same cohort face the same potential dose. For example, following both the Chernobyl and Fukushima Daiichi accidents, areas were categorized according to surface contamination, allowing a corresponding radiation dose to be deduced.

On average each person in a given area will receive the same effective dose and thus lose the same amount of life expectancy. The maximum that a given cohort should be prepared to spend to avert the risk is given by Eq. (3). The total annual amount, δG_N, that should be spent on the relocation scheme is the sum over all the individual cohorts:

$$\delta G_N = \sum_{i=1}^{m}\delta G_{N_i} = \frac{G}{q}\sum_{i=1}^{m}N_i\frac{\delta X_{d,i}}{X_{d,i}} \tag{5}$$

where the subscript, N, refers to the total number of people, $N = \sum_{i=1}^{m} N_i$. If an annual amount $\delta\hat{G}_N$ is actually spent, then by definition the J-value will be

$$J = \frac{\delta\hat{G}_N}{\delta G_N} = q\frac{\delta\hat{G}_N}{G}\left(\sum_{i=1}^{m}N_i\frac{\delta X_{d,i}}{X_{d,i}}\right)^{-1} \tag{6}$$

In practice, it is convenient to evaluate a potential J_i-value for each cohort separately from Eq. (4) and then to combine the results to give the actual J-value. From Eq. (4), the fractional change in discounted life expectancy for a particular cohort can be expressed as

$$\frac{\delta X_{d,i}}{X_{d,i}} = \frac{q}{J_i N_i}\frac{\delta\hat{G}_{N_i}}{G} \tag{7}$$

Substituting this into Eq. (6) gives

$$J = q\frac{\delta\hat{G}_N}{G}\left(\sum_{i=1}^{m}N_i\frac{q}{J_i N_i}\frac{\delta\hat{G}_{N_i}}{G}\right)^{-1} = \left(\sum_{i=1}^{m}\frac{\delta\hat{G}_{N_i}}{\delta\hat{G}_N}\frac{1}{J_i}\right)^{-1} \tag{8}$$

The relocation costs will be dominated by the capital expenditure of building new housing and infrastructure, so that, neglecting economies of scale likely to have some influence on the overall cost, the amount spent per head may be regarded as constant:

$$\frac{\delta\hat{G}_N}{N} = \frac{\delta\hat{G}_{N_i}}{N_i} \tag{9}$$

for all cohorts, i = 1, 2,. . .,*m*. Re-arranging this and substituting into Eq. (8) gives

$$J = \left(\sum_{i=1}^{m}\frac{N_i}{N}\frac{1}{J_i}\right)^{-1} = \frac{N}{\sum_{i=1}^{m}\frac{N_i}{J_i}} \tag{10}$$

Taking the definition of *N* from above gives a relation between the J_i-values for each of the cohorts separately and the J-value for the combined population:

$$J = \frac{\sum_{i=1}^{m}N_i}{\sum_{i=1}^{m}\frac{N_i}{J_i}} \tag{11}$$

This result shows that it is possible to consider each cohort separately and then combine the individual J-value results in a final step.

3.2. *Amortizing the up-front capital costs*

For the common case where the costs of a safety scheme are dominated by an up-front capital spend, as exemplified by the need to provide infrastructure to facilitate relocation, Thomas et al. (2010) have shown how the expenditure can be amortized. The J-value for an intervention with an up-front cost of δV_N that benefits N people is given by

$$J = \begin{cases} \dfrac{q\delta\hat{V}_N}{NG}\dfrac{X_d}{\delta X_d}\left(\dfrac{r^*}{1-e^{-r^* X_d}}\right) & r^* > 0 \\[2ex] \dfrac{q\delta\hat{V}_N}{NG\delta X_d} & r^* = 0 \end{cases} \tag{12}$$

where the "social discount rate", r^*, is that appropriate for comparing the costs and benefits of schemes that have future societal benefit (corresponding to the "discount rate" of Thomas et al. (2010)).

This formulation conforms to a strong version of intergenerational equity, which requires that those N people alive at the time of the implementation of the safety measure and protected by it should notionally be prepared to pay for it (even when another body will actually foot the bill in practice), spreading their payments over their average discounted life expectancy, X_d, which is about 35 years for the former USSR and 43 years for Japan when a "net discount rate" of zero is applied. The change in discounted life expectancy is found not only for those living at the start of the relocation but also for those born within the relocated community during the period when dose is being averted. (This period ends either when the community returns home or when the dose being averted has fallen to a low level). The N people alive when relocation begins are then assumed, notionally, to regard a weighted average change in discounted life expectancy, δX_d, covering both those already living and those yet to be born, as their own when estimating what they would be prepared to pay for relocation.

3.3. *Economic parameters*

The J-value depends on established actuarial and economic parameters such as the life tables, gross domestic product (GDP) per head, GDP growth rates and discount rates. These parameters vary over time and from country to country, and several sources of data were used to find the appropriate values for each calculation.

The World Health Organisation (WHO) publishes life tables for its member states based on a review of national censuses, surveys, registration records and similar data (World Health Organization, 2012). The abridged life tables provide statistics on the number of deaths per year at age intervals of five years, plus infant mortalities at 0 and 1 year. The life tables for Ukraine, Belarus and Russia from 1990 were used for the J-value life expectancy calculations in both 1986 and 1990. The 2011 life tables for Japan were used for the Fukushima Daiichi analysis (World Health Organization, 2013).

The World Bank publishes GDP per head data for the UN member states. The data are updated annually and at the time of the analysis covered the years 1980–2011 (World Bank, 2012). The data are available both in current US dollars based on market exchange rates and in current international dollars based on purchasing power parity (PPP) calculations (OECD, 2011). The PPP exchange rate can differ from the market exchange rate, which measures the relative value of goods traded between countries and is driven, in practice, by processed and high-value goods. In contrast, the PPP exchange rate also takes into account non-traded goods and services that are produced and consumed within a country. The average person's quality of life in countries with little dependence on international trade is dominated by these, in-country essentials of life (housing, fuel and food). The PPP exchange rate is determined by the cost of purchasing goods and services in the local currency in such a case. On the other hand, in a country that depends on international trade for its essentials (typically high-income countries), the PPP exchange rate is dominated by the cost of obtaining these foreign goods and services and so tends towards the market exchange rate. Thus in both low-income and high-income countries, the PPP data give the best measure of what the average person can afford to buy, and are the data generally used in J-value analyses.

However, the World Bank dataset does not include GDP values from the USSR prior to 1990. Therefore, in order to apply the J-value to the USSR at the time of the Chernobyl accident in 1986, GDP and population values were obtained from the National Accounts Main Aggregates Database of the UN Statistics Division (2013; hereafter "UNSTATS"). Lochard and Schneider (1992, p. 26) used similar figures. An estimate of the GDP growth rates for the USSR in 1986 and 1990 was calculated from the Maddison Project of the University of Groningen (Bolt and van Zanden, 2013). That project provides historical data on GDP and population growth, from an amalgamation of national accounts and estimates. Their data are presented in international dollars at a fixed epoch of 1990, giving what appear to be the most realistic estimate of the USSR growth rate that could be found (the raw values in the UNSTATS data were uncorrected for inflation and exchange rates). However, it should be noted that there is likely to be significant uncertainty in all the USSR economic statistics, given the political structure of the country at that time.

Table 1 – Economic parameters adopted for the USSR in 1986 and 1990 and for Japan in 2011.

Country	USSR	USSR	Japan
Year	1986	1990	2011
GDP per head	2851[a]	3532[a]	34,294[b]
Currency	Rouble	Rouble	International dollar
GDP growth rate (%)	0.9[c]	0.9[c]	0.6[d]
Social discount rate[e] (%)	0.9	0.9	0.6

[a] United Nations Statistics Division (2013).
[b] World Bank (2012).
[c] Averaged over 1975–1989 (Bolt and van Zanden, 2013).
[d] Averaged over 1997–2011 (World Bank, 2012).
[e] Assuming a net discount rate of 0%.

It is common economic practice to discount future costs and benefits, on the basis that people prefer to receive goods and services now rather than later. Discounting enters the J-value framework in two contexts: to discount the utility of an individual's future income, or, equivalently his/her life expectancy (the "net discount rate", r) and to discount the costs and benefits of schemes that have societal benefit (the "social discount rate", r^*). Thomas and Waddington (2017) have argued that the clear correlation of increasing life expectancy with increasing GDP across some 180 countries, can be best explained if the net discount rate is zero for all countries. The social discount rate then becomes equal to the growth rate of the average individual's income, g, equal to the GDP growth rate for a steady-state population. The following discount rates then hold for the J-value calculations:

$$\begin{aligned} r &= 0 \\ r^* &= g \end{aligned} \tag{13}$$

(Thomas and Waddington, 2017, Eq. (66)).

The economic parameters used in the analysis for Chernobyl and Fukushima Daiichi are given in Table 1.

3.4. *Physical data*

The data we have used for the paper are the best we could gather from publicly available reports on the two accidents at Chernobyl and Fukushima Daiichi. There are obviously uncertainties with respect to both the dose received and the harm that radiation causes, although almost certainly both estimates can be made with a better accuracy than for any other industrial carcinogen. Moreover, rather than give a best estimate of radiation harm subject to a variance, the ICRP chooses instead to promulgate a conservative estimate of radiation harm coefficients. Thus, to a large extent, the uncertainty on this part of the radiation harm calculation has been accounted for in a conservative way.

Accordingly the figures for radiation dose should be regarded as best-estimate, but the associated loss of life expectancy is then somewhat pessimistic in that the loss of life expectancy may be overstated.

4. Chernobyl relocation after 1990

There were two relocations after the 1986 Chernobyl accident, with the first, involving 115,000 people, being complete within a few months. The analysis detailed in this paper is based on the best data we could gather after the event and it is clear that the authorities' state of knowledge would necessarily have been much lower in April 1986. It is recognised that they faced a major nuclear accident of unprecedented scale and the study does not seek to judge adversely their action in instituting a very large relocation in 1986, even though this will be shown in Section 5 to be possibly excessive. As a general point, the purpose of the research is to enable lessons for the future to be drawn rather than to give verdicts on the past.

The situation is less clear-cut in the case of the second Chernobyl relocation of 220,000 people which took place four years later in 1990. By this time the radioactive release had long since ceased, and surface radioactivity levels were available for all the districts affected by fall out, both close to and distant from the plant. Moreover, the early results of the work of Lochard and Schneider (1992), discussed next, were also becoming available.

The difference in the information available to the authorities in April 1986 and in 1990 is considered further in the discussion of Section 7, giving additional pointers to the near-term management of any big nuclear accident that occurs in the future.

4.1. *The IAEA/CEC study by Lochard and Schneider, 1990–1992*

The effectiveness of relocation post 1990 was the subject of a detailed study carried out by Lochard and Schneider (1992). The work, which started in 1990, was carried out under contract for the Commission of the European Communities (CEC) within the framework of the IAEA International Chernobyl Project. The IAEA was itself responding to a request from the Soviet Government that an international group of experts should be organised to review and evaluate the measures being taken to assure safe living conditions for the people continuing to live in the affected areas. Lochard and Schneider explained that the work was

> "an attempt to provide a coherent framework for all the available data [in 1990] concerning the costs and doses averted associated [with] various relocation strategies, for the population living in the contaminated areas affected by the Chernobyl accident."

The methodology is summarised in a paper written by Lochard et al. (1992) as a combination of

> "the use of a baseline monetary value of the man-Sievert calculated according to the human capital method with a risk aversion factor, increasing with the level of contamination, to reflect the general attitude of the population living in the contaminated areas".

Lochard and Schneider used a risk aversion exponent, a, to characterise the disproportionate aversion to larger doses of radiation that might characterise people living in the vicinity of Chernobyl. Hence the monetary value, α_i (Roubles), of unit collective dose received in individual doses of d_i (mSv) is related to the baseline monetary value, α_0, received in baseline doses of d_0 of 1 mSv or lower, leading to the equation:

$$\frac{\alpha_i}{\alpha_0} = \left(\frac{d_i}{d_0}\right)^a \tag{14}$$

A unity "risk aversion exponent", $a = 1$, corresponds to risk-neutrality, in which case a dose of 20 mSv would be regarded as 20 times more likely to cause harm than a 1mSv dose. This coincides with the stance prevalent in the scientific community and in general use as the basis for safety regulation in the nuclear industry (see, for example, ICRP, 2007). But putting $a = 1.5$ would mean that a dose of 20 mSv would be perceived as about 90 times more harmful that a dose of 1 mSv.

Lochard and Schneider constructed a paired base-case by first setting $a = 1.2$ to give what may be denoted "Base Case LS1", and then increasing the parameter to $a = 1.5$ to give "Base Case LS2", where the suffix, "LS", denotes "Lochard and Schneider". The range, $1.2 \leq a \leq 1.5$, was considered by Lochard and Schneider to "reflect the uncertainty attached to this key parameter".

It is worth emphasizing at this point that the authors of the present paper are not endorsing the use of a risk aversion exponent, $a{:}a > 1$, as a substitute for the parameter, risk-aversion, ε. The latter, which is integral to the J-value method, is scientifically grounded and provides a general model for human beings' aversion to risk (Thomas, 2013, 2016). Lochard and Schneider were wanting to find some way to compensate for their use of a human capital model in calculating their baseline, monetary value of the man-Sievert since the human capital approach is equivalent to the use of a utility function with a zero risk-aversion (see Thomas and Taylor, 2012). Setting risk-aversion at its risk-neutral value in the utility function, $\varepsilon = 0$, must necessarily entail a low estimate of how much ought to be spent against any given radiation dose, meaning that some mechanism elsewhere in the calculation had to be devised to allow the permissible spend to increase. Lochard and Schneider's chosen method to fulfil this task, a strictly positive "risk aversion exponent", cannot lay claim to any general justification. However, it may be seen as an early attempt to introduce risk aversion into the process of radiation protection.

Lochard and Schneider (1992) found that none of the 220,000 people relocated after 1990 should have been moved under Base Case LS1, when $a = 1.2$. The argument for relocation would be even weaker if a were set to the risk-neutral value of unity:

> "Using a baseline value of the man-Sievert, estimated on the basis of human capital considerations, it is not justified to relocate anyone from the controlled zones". (Section 10, *Conclusion*)

Just 14,700 people should have been moved in Base Case LS2, when $a = 1.5$, specifically those living in areas with a contamination level in 1990 that was higher than 1480 kBq m^{-2}.

Lochard et al. (1992) make it clear that they regard Base Case LS2 as highly conservative:

> "Based on the most conservative assumptions only population above 40 Ci/km^2 [=1480 kBq m^{-2}] should have been relocated."

But even under Base Case LS2, the great majority (205,000 out of 220,000 people actually relocated post 1990) should have been left in place.

Apart from the high-end risk aversion parameter, $a = 1.5$, another of the factors regarded as conservative is the dosimetric model developed at the Moscow Institute of Biophysics (MIB) and used to convert the measured caesium-137 surface contamination (kBq m^{-2}) into dose equivalents (mSv y^{-1}). Lochard and Schneider considered that the estimates of the long-term doses might be as much as 75% too high: the parameter, k, in the denominator of the dose Eqs. (15) and (16) below takes the value, 1.7, for the Base Cases, LS1 and LS2, but the enhanced decline in Caesium-137 in man's environment might make a value of 3.0 more appropriate (see Section 8.1 of Lochard and Schneider (1992), *Conservatism of the model*).

Support for a speedier effective decline comes from later work by Robison et al. (2003) and Paller et al. (2014), who report that while the physical half-life of caesium-137 is 30 years (as reflected in Eqs. (15) and (16) below), its half-life in the environment may be significantly lower. Their studies, based on measurements in the Marshall Islands in the one case and on the Savannah River site in the USA in the other, produces various estimates for the effective half-life depending on the environmental medium under consideration, from less than 9 years up to a maximum of 17 years. Work on Chernobyl post-dating Lochard and Schneider (1992) suggests that the effective half-life of ^{137}Cs for use in calculating external dose is 18.8 years, while the value to be used in calculations of internal dose should be 23 years in the case of mushrooms but 15 years for general agricultural products (Jacob et al., 2009).

Although Lochard and Schneider (1992) advocate caution in their Section 2.1, *Background* [*to Methodology*]:

> "Because of the many simplifications and assumptions adopted in the model, the results have to be interpreted carefully and considered only as indicative estimates of the cost and effectiveness of the protective measures envisaged."

the authors address the simplifications and assumptions by conducting the *Sensitivity Analysis* detailed in Section 8. This examines the effects of variations in:

- the dosimetric model,
- the economic parameters,
- the duration of the protective measures, and
- the internal dose correction factor.

after which Lochard and Schneider comment that

> "The various sensitivity analyses do not significantly change the conclusions of the base case evaluation."

Moreover the authors state, in their Section 10. *Conclusion*, that

> "The model developed has been extensively discussed, and presents what is believed to be the best compromise achievable, taking into account the various uncertainties."

and conclude that

Table 2 – Fractional distribution of population living in each activity band over the Republics of Belarus, Ukraine and Russia.

kBq m^{-2}	Ci km^{-2}	Belarus	Ukraine	Russia	Total
185–555	5–15	0.5065	0.2789	0.2146	1.0
555–1480	15–40	0.5041	0.1075	0.3884	1.0
>1480	>40	0.5663	0.1566	0.2771	1.0

> "With some allowance for risk aversion [$1.2 \leq a < 1.5$] the results suggest that there are no strong arguments for the implementation of further measures other than those already envisaged*, unless relocation costs differ largely from the base case [the paired Base Cases, LS1 and LS2]."
>
> *In their Section 1, *Introduction*, Lochard and Schneider (1992) comment that "At the time the present study started some settlements had already been relocated, but there was a strong on-going debate on the opportunity of future relocations below the criteria stated in the Programme." They were able to recommend the relocation of only the 14,700 people living with a 1990 level of 1480 kBq m^{-2} or higher, and this recommendation was based on the more conservative Base Case LS2.

We know from Lochard, Schneider and Kelly (1992) that the calculations recorded in Lochard and Schneider (1992), were first performed in 1990. But despite their implication that a further mass relocation should not be carried out in 1990 or later, it is a matter of record that 220,000 people were relocated after that date. Lochard and Schneider (1992) include comment relevant to this outturn in their Section 1, *Introduction*:

> "A large fraction of the money already spent (or to be spent in the next few years) on improving living conditions will achieve little or no reduction in dose. In fact, most of the resources already allocated (or to be allocated) need to be seen as direct or indirect compensation for those who may have been affected by the accident, mainly from the psychological point of view, in order to improve the public acceptability of the situation."

4.2. *Applying the J-value*

In addition to its recommendation, not acted on, against a second mass relocation in 1990, the Lochard and Schneider report is valuable in providing a detailed breakdown of the populations, doses and costs, which can be used in J-value analysis. Their paper provides the distribution of the Soviet population in terms of the level of ^{137}Cs ground contamination experienced in 1990. The three Republics of the Former Soviet Union concerned, Belarus, Ukraine and Russia, were not affected uniformly by the accident. Table 2 gives the fractional distribution of population in each of 3 activity bands over the Republics, based on Table 2 of Lochard and Schneider (1992). Making the natural assumption that the fractions of Table 2 apply uniformly within each of the finer contamination bands given in Table 1 of Lochard and Schneider allows an estimation to be made of the number of people within each of the narrower activity bands within the 3 Republics. See Table 3.

The status of 'contaminated' was applied by the Soviet authorities to areas with surface contamination above 37 kBq m^{-2} of ^{137}Cs and was said to correspond to an annual individual effective dose of approximately 1 mSv (or 70 mSv

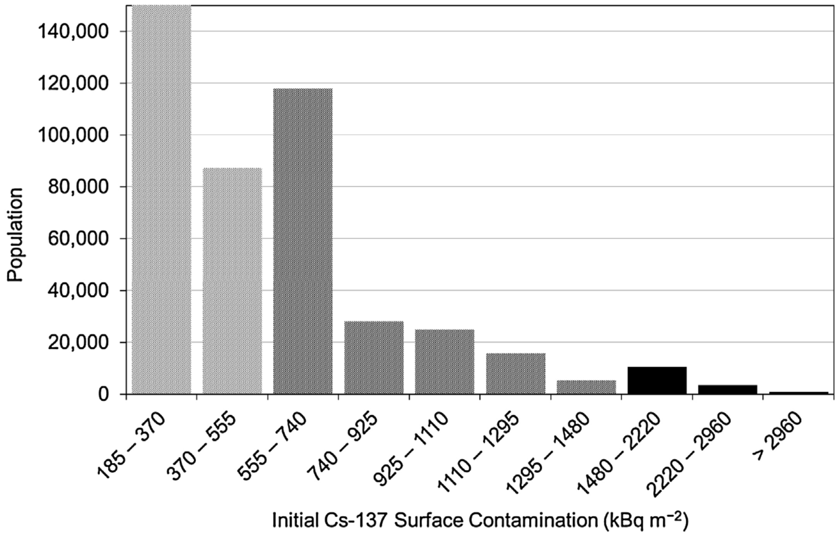

Fig. 1 – The population distribution as a function of ^{137}Cs surface contamination in 1990. Black indicates the official relocation limit at >1480 kBq m^{-2} while the effective limit of >555 kBq m^{-2} is shown in dark grey, corresponding to the strict control zone. The vertical scale has been truncated in order to emphasize the distribution at high activity levels.

Table 3 – Soviet population subject to post-Chernobyl restrictions in 1990, as a function of ^{137}Cs surface contamination.

^{137}Cs surface contamination		Number of people			
kBq m^{-2}	Ci km^{-2}	Belarus	Ukraine	Russia	Total
185–370	5–10	208,371	114,892	88,537	411,800
370–555	10–15	44,123	24,329	18,748	87,200
555–740	15–20	59,422	12,733	45,745	117,900
740–925	20–25	14,162	3035	10,903	28,100
925–1110	25–30	12,550	2689	9661	24,900
1110–1295	30–35	7913	1696	6092	15,700
1295–1480	35–40	2671	572	2056	5300
1480–2220	40–60	5886	1633	2881	10,400
2220–2960	60–80	1924	534	942	3400
>2960	>80	509	141	249	900
>185	>5	357,531	162,254	185,184	705,600

over a lifetime). It may be noted 1 mSv is the current ICRP recommended dose limit for ongoing practices, but not for interventions after an accident, when the post-accident dose optimization exercise may recommend the toleration of higher levels of radiation as a result of additional account being taken of social and economic factors. Then two particular zones were designated for possible further precautionary measures: a ‘control zone’, where the ^{137}Cs concentration was above 185 kBq m^{-2} but below 555 kBq m^{-2}, and a ‘strict control zone’, which covered populations living in areas with a ^{137}Cs contamination level over 555 kBq m^{-2} (Fig. 1).

Lochard and Schneider (1992) presented the MIB dosimetry model, which allowed them to estimate average internal and external effective doses for any given year from 1990 to 2060 from the surface contamination. Starting from $t = 0$ in 1988, the external effective dose equivalent in year t was given by

$$H_{ex}(t) = \frac{0.28C}{k}\left(0.7e^{-0.3t} + 0.3e^{-0.024t}\right) \qquad (15)$$

where H is in mSv per annum, C is the ^{137}C surface contamination (Ci km^{-2}) in 1990, 4 years after the 1986 deposition, and $k = 1.7$ is a correction factor that “only takes account of known conservatisms based on measurements up to 1990”. The internal effective dose equivalent in year t was given by

$$H_{in}(t) = \frac{0.28C + 1.1232}{k}\left(0.43e^{-0.35t} + e^{-0.05t}\right) \qquad (16)$$

The principal components of this model may be identified approximately with the exponential decays of ^{134}Cs (with a natural decay constant of $\lambda = 0.33\,y^{-1}$ or a half-life of $t_{1/2} = 2.1$ years) and ^{137}Cs ($\lambda = 0.023\,y^{-1}$ or $t_{1/2} = 30.1$ years), with modifications due to environmental and biological factors. The total annual dose per year, $H_{ex} + H_{in}$, between 1990 and 2060 is plotted in Fig. 2 as a function of surface contamination in 1990.

The population distributions and effective doses enabled a calculation of the average loss of life expectancy for people exposed to these radiation hazards. Life Tables for Belarus, Russia and Ukraine in 1990 were obtained from the World Health Organization (2012). For each of the thirty population groups from Table 2 the life-table hazard rates were perturbed by the additional radiation hazard for fatal cancers (ICRP, 2007; Thomas and Jones, 2009) due to the effective doses that would have been received in the absence of relocation (Eqs. (15) and (16)). The calculation was carried out for the seventy-one years from 1990 to 2060, assuming a steady-state population over this period. Table 4 presents the expected loss of life expectancy averaged over the three Republics for each of the dose bands, together with the effective doses received. The variation (sample standard deviation) in loss of life expectancy between the Republics was 2% of the mean.

The calculations were carried out using the CLEARE program (Change of Life Expectancy due to Atomic Radiation Exposure) based on the extended Marshall model (Marshall et al., 1983; Thomas et al., 2006c; Thomas and Jones, 2009). Results were compared with the loss of life expectancy reported in Lochard and Schneider’s Table 18 on the basis of “a computer code of the Centre d’étude sur l’Evaluation de la Protection dans le domaine Nucléaire (CEPN)”. It was found that there was a close match, but with CLEARE producing a loss of life expectancy roughly 10% higher than the estimate from the CEPN Program. See Table 5.

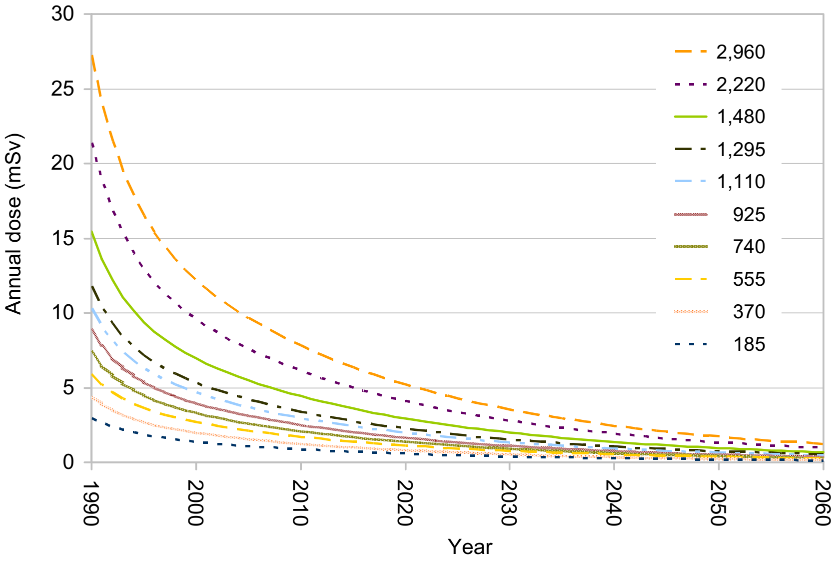

Fig. 2 – Evolution of the effective annual dose for an individual living in areas with initial ^{137}Cs surface contaminations of 185–2960 kBq m^{-2}.

Table 4 – Effective doses and loss of life expectancy within each contamination band over 1990–2060 for the combined populations of the three Republics, in the absence of relocation.

^{137}Cs surface contamination kBq m^{-2}	Effective cumulative dose mSv	Loss of life expectancy days
185–370	50	9.6
370–555	74	14.4
555–740	99	19.2
740–925	124	24.0
925–1110	149	28.8
1110–1295	173	33.6
1295–1480	198	38.4
1480–2220	260	50.5
2220–2960	359	69.8
>2960	458	89.0

Table 5 – Comparison of loss of life expectancy in days against initial surface contamination between CLEARE and the CEPN Program.

	Initial surface contamination (kBq m^{-2})		
	185	555	1480
CLEARE	7.0	16.4	39.9
CEPN Program	6.4	15	35.8

Applying CLEARE, it was found that the average dose for the 900 people living in the most contaminated regions would have led to a loss of life expectancy of 3 months (89 days) if they had not been relocated in 1990. In the lowest band of the effective relocation area (555–740 kBq m^{-2}), the average dose would have caused 19 days to be lost. The average dose for the 207,000 people in all areas with more than 555 kBq m^{-2} activity would have led to a loss of life expectancy of 24 days. Thus the person relocated in 1990 receiving the average dose will have achieved a gain in life expectancy of about 3½ weeks as a result of the decrease in radiation exposure achieved. These figures on reduction of life expectancy may be put into an initial context by noting that, according to Levchuk (2009), preventable alcohol-related deaths in Ukraine reduced male life expectancy by 5.2 years in 1995. Meanwhile the average Londoner currently loses 4.5 months of life through air pollution in the nation's capital (9 months loss of life expectancy at birth (Darzi, 2014)).

In all cases where a life expectancy is quoted for a population there will obviously be a variation in the length of life experienced by different individuals in that population, and the same goes for changes in life expectancy. Thomas (2017) considers the loss of life expectancy for those who suffer a radiation induced cancer, finding that they are likely to lose between 8 and 22 years of life expectancy based on UK life tables, figures that may be compared with the roughly 40 years of life expectancy taken away on average by an immediately fatal accident such as a car crash, rail crash or drowning after a dam collapse. A much smaller figure for the population-average loss of life expectancy implies that the number of victims will be small.

The J-value can improve upon relative measures by providing an objective method with which the cost-effectiveness of any life extending activity may be judged. As noted in Section 3, a J-value of greater than 1 indicates that more is being spent than is warranted by the improvement in safety, with J = 2, for example, indicating that twice as much is being spent as is economically and scientifically justified.

Lochard and Schneider (1992, Table 12) report the cost of relocation as 42,260 roubles per head, about 12 times the Soviet GDP per head in 1990 of 3532 roubles (Table 1). This ratio is significantly higher, for example, than that of average house price to median full-time earnings in the UK, which, in the years since 1983, peaked at 5.86 in 2007 (Lloyd's Banking Group, 2016). However it comprises the construction costs of not only the new dwellings but also shops and other infrastructure, in addition to about 12% in compensation payments (see Table 9 of Lochard and Schneider, 1992). The figures imply that the overall cost of relocation in the USSR was comparatively high. On the other hand, one might question whether this level of compensation would actually have been adequate, given that relocation would have meant that many if not all would need to start a new life from scratch, with farmers, for example, being deprived of the farmland on which they were reliant for their living. Moreover there might be significant

Table 6 – Population, loss of life expectancy and J-values for relocating people from the areas with ^{137}Cs contamination in 1990 above the limits given in column 1.

^{137}Cs contamination kBq m^{-2}	Population	Average loss of life expectancy days	J-value
>185	705,600	14.8	17.5
>370	293,800	22.1	11.7
>555	206,600	25.3	10.2
>740	88,700	33.4	7.8
>925	60,600	37.8	6.9
>1110	35,700	44.1	5.9
>1295	20,000	52.3	5.0
>1480	14,700	57.3	4.5
>2220	4300	73.8	3.5
>2960	900	89.0	2.9

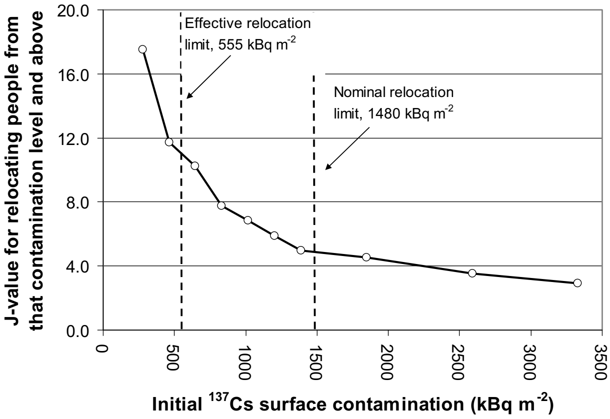

Fig. 3 – J-value as a function of the initial ^{137}Cs surface contamination level in 1990.

loss of life expectancy if the move led to reduced socio-economic status, which seems highly possible after a rapid relocation. A recent study based on data from the UK, France, Switzerland, Portugal, Italy, USA and Australia has shown low socio-economic status to be associated with a 2.1 year reduction in life expectancy between ages 40 and 85 (Strigini et al., 2017). No such effect has been taken into account in the J-value analysis contained in this paper, but it is clear that a reduction of life expectancy of this order associated with relocation would strengthen considerably the argument against moving people away from their homes permanently.

Using the figure of 42,260 roubles together with the economic parameters listed in Table 1, the J-value was calculated for each of the ten individual dose bands. (The effect of a relocation cost per person higher than 42,260 roubles would be to increase the J-values in each case and decrease the incentive to relocate).

Table 6 shows the J-value for relocating all the people initially living in areas with ^{137}Cs surface contamination above the given limits (corresponding to the lower bounds of each band in Table 2). These results are further illustrated in Fig. 3.

For the 900 people living in areas with the highest radio-caesium activity in 1990 (more than 2960 kBq m^{-2}), the relocation had a J-value of 2.9. At the nominal limit of the State All-Union and Republican Programme (^{137}Cs contamination more than 1480 kBq m^{-2}) the J-value would have been 4.5, and for the 206,600 people above the effective relocation limit of 555 kBq m^{-2}, the J-value is 10.2.

This J-value analysis shows that the cost of relocating the 220,000 people who were actually moved following 1990, exceeded the benefit of their increased life expectancy by an order of magnitude. Furthermore, with J-values significantly in excess of unity for even the most contaminated regions, the conclusion must be drawn that, based on the preservation of life quality, as measured by the life quality index, there was no case for relocation post-1990.

The J-value model is a more recent development than the human-capital-plus-radiation-risk-aversion model used 25 years ago by Lochard and Schneider and, moreover, has been validated recently against pan-national data on life extending decision making (Thomas and Waddington, 2017) and against within-nation data on the increase life expectancy at birth with GDP per head (Thomas, 2017a). Nevertheless, it is striking that the J-value conclusions are in close agreement with the findings of Lochard and Schneider (1992), as summarised in Lochard et al. (1992).

5. Chernobyl relocation in 1986

At the time of the Chernobyl accident, the Soviet state had strong powers of compulsion, and true costs were difficult to ascertain in the absence of a market economy. Vast resources were potentially available and a cautious approach was taken towards minimising radiation dose, with limited communication and discussion of measures, concerns, and available scientific information. Against this background there are clear difficulties in assessing the cost-effectiveness of the relocation and relocation strategy in the immediate aftermath of the accident. Nevertheless it is possible to make estimates of the loss of life expectancy and the J-values for the early (pre-1990) relocation measures.

Less effort appears to have been devoted in the very first stages of the accident, as compared with later on, to protecting either the power plant workers and emergency responders or the population of the surrounding areas. Those on-site were subjected to high levels of radiation from the exposed core and from the core debris that was scattered across the site. One hundred and thirty-four workers suffered from acute radiation syndrome, of whom twenty-eight died in the immediate aftermath of the accident. Children were playing outdoors in the nearby town of Pripyat, only 3 km from the site, as the accident unfolded. It was not until the following day that the 50,000 residents of Pripyat and Yanov were relocated in buses (Smith and Beresford, 2005, p. 6). Over the following days and weeks, a total of 116,317 people were relocated from their homes in Ukraine, Belarus and Russia (Table 7, with numbers taken from UNSCEAR, 2000).

There was a clear increase in the incidence of thyroid cancer amongst those aged under 18 at the time of the Chernobyl accident and living in the whole of Belarus, the whole of the Ukraine and in the most affected areas of the Russian Federation (Nuclear Europe Worldscan, 1996). It was possible to deduce from epidemiological data to the end of 1998 that the mean latency period was 17 years, but with a large standard deviation, 10 years, that meant that some cases came to light within 4 years of the accident (Thomas and Zwissler, 2003). The eventual number of victims was predicted to lie between 3300 and 7600, and a total of 6848 cases were reported to the end of 2005 (UNSCEAR, 2008). These cancers, while undoubtedly of concern, are susceptible to medical treatment, which may ensure full remission in 97%–99% of cases (UNSCEAR,

Table 7 – The relocated populations of the USSR in 1986 (UNSCEAR, 2000, p. 472).

Area		Date	Number
Ukraine			**91,406**
	Pripyat & Yanov	27 April	49,614
	10-km zone south	30 April–3 May	10,090
	30-km zone (incl. Chernobyl)	3–7 May	28,133
	Outside 30-km zone	May–September	3569
Belarus			**24,725**
	30-km zone	2–7 May	11,358
	Outside 30-km zone	3–10 June	6,017
	Outside 30-km zone	August–September	7350
Russia			**186**
	Bryansk		186
Total			**116,317**

Table 8 – Distribution of the estimated first-year doses from external irradiation to Belarusians relocated in 1986 *if they had stayed in place.*

External dose experienced by relocated Belarusians if they had stayed in place (mSv)	Number
0–10	1956
10–20	4710
20–30	3726
30–40	2552
40–50	1795
50–60	1226
60–70	961
70–80	726
80–90	565
90–100	453
100–150	1513
150–200	1015
200–250	814
250–300	646
300–350	494
350–400	371
400 + (*mean* = 584)	1204

From Table 24 of UNSCEAR (2000).

2000). Their cause is most likely to have been exposure to ^{131}I, which has a half-life of 8 days, as well as possibly other iodine isotopes with shorter half-lives; a prior iodine deficiency amongst those affected may have been a contributory factor. The early use of prophylactic iodine is the established countermeasure to minimise the prevalence of uptake of radioactive iodine to the thyroid. By contrast, the brief duration of the threat and the large areas and populations involved means that relocation, which may take weeks or months to complete (Table 20 of UNSCEAR, 2000), is likely to be a rather ineffective countermeasure.

5.1. *Optimal number of relocated persons in 1986*

5.1.1. *Sources of data*

Table 24 of UNSCEAR (2000) provides a comparison between the actual external doses received by the population of Belarus relocated from within the 30-km exclusion zone and an estimate of the potential external doses they would have received *had they not been relocated*. The calculated distribution of external dose amongst the 24,725 relocated Belarusians if they had stayed in place is reproduced in Table 8.

The collective external dose aggregated over the 24,725 relocated Belarusians if they had stayed in place is cited in paragraph 105 of UNSCEAR (2000) as 2260 man Sv. This study adjusted the average external dose given to those receiving above 400 man Sv so that the total burden of external dose matched this figure of 2260 man Sv. The result was a mean value of 510 man Sv, which implies an upper limit of 620 man Sv when a piecewise uniform probability distribution is assumed.

There seems, however, to be a degree of ambiguity between Table 24 of UNSCEAR (2000), which gives the “Distribution of estimated first-year doses from external radiation of inhabitants of Belarus evacuated from the exclusion zone”, and paragraph 105 of the same report, which gives 2,260 man Sv as the “collective effective dose from external exposure averted” but suggests that this may be a dose difference, since it is “approximately 75% of the dose that would have been received without evacuation”. On the other hand, it would appear to correspond to the aggregate of the external doses received by the 24,725 Belarusians in the absence of relocation, as found from Table 8 by summing the products of numbers of people and their mid-interval doses and the estimate of 510 man Sv as the average dose above 400 man Sv.

Applying the same estimate of the average dose above 400 man Sv in analysing the actual dose after relocation, also given in UNSCEAR’s Table 24, gives a collective external dose of 699 man Sv in year 1. This figure lies within 10% of the actual estimated external dose of Belarus’s relocated persons presented in Table 23 of UNSCEAR (2000), namely 770 man Sv and within 6% of the revised dose listed in Table B6 of UNSCEAR (2008), namely 742 man Sv, as listed in Table 9. However, the fraction of dose averted by relocation is then: $(2260 - 699)/2260 \times 100 = 69\%$ of what the relocated population would otherwise have faced, rather than the 75% quoted.

It is possible to deal with this uncertainty by assuming that any relocation would have been 100% effective in eliminating exposure. This enables the figure of 2260 man Sv to be regarded as both the total external dose applicable in the absence of relocation and the dose averted by relocation. This procedure is conservative in the sense that it will tend, if anything, to make relocation look more attractive than otherwise. We apply the same assumption of 100% effectiveness to the 1986 relocation from the Ukraine, where the collective external dose averted is stated by paragraph 105 of UNSCEAR (2000) to be “about 6000 man Sv”.

From Table 23 of UNSCEAR (2000), summarised in Table 9, the internal dose in the year beginning 26 April 1986 for the 24,725 Belarusian relocated persons was about 20% of the external dose, while the corresponding fraction for the 91,406

Table 9 – External and internal dose in 1986 for the relocated populations from Belarus, the Russian Federation and the Ukraine.

Country	Population relocated	Collective Dose (man Sv)			Average Individual dose (mSv)			Ratio of internal to external dose, ρ
		External	Internal	Total	External	Internal	Total	
Belarus								
UNSCEAR (2000)	24,725	770	150	920	31	6	37	0.19
UNSCEAR (2008)	24,725	742	148	890	30	6	36	0.20
Russian Federation								
UNSCEAR (2000)	186	10[a]	10[a]	20	54	54	108	1.00
UNSCEAR (2008)	186	5	2	7	25	10	35	0.40
Ukraine								
UNSCEAR (2000)	91,406	1500	1300	2800	16	14	31	0.87
UNSCEAR (2008)	89,600	1792	896	2688	20	10	30	0.50
Total								
UNSCEAR (2000)	116,317	2280	1460	3740	20	13	32	0.64
UNSCEAR (2008)	114,511	2538	1046	3585	22	9	31	0.41

[a] Table 23 of UNSCEAR (2000) gives <10 Sv in each case. The small number of Russian relocated persons means the value is not critical to the discussion of relocation strategy.

relocated persons from the Ukraine was 87%. The much higher fraction in the Ukraine as compared with Belarus conforms to the observation in UNSCEAR (2000), paragraph 100:

> "The main factor influencing the individual dose was found to be the distance of the residence from the reactor".

Table 23 of UNSCEAR (2000) was updated in UNSCEAR (2008), Table B6, and the differences are shown in Table 9 of this paper.

UNSCEAR, 2008 reduced the estimate of the number of relocated persons from the Ukraine by about 2% from 91,406 to 89,600, thus lowering the total number of relocated persons by 1½% to 114,511. Because the difference is small, the original number is retained in this analysis for the sake of consistency. Moreover the dose figures given in UNSCEAR (2000) were chosen in preference to the revised figures from UNSCEAR (2008) because they are generally slightly higher and hence more conservative.

The most important change between the early and later UNSCEAR tables is the reduction in the ratio of the internal to external dose in the case of the Ukrainian relocated persons. Whereas the internal dose was regarded as nearly equal (87%) to the external dose for Ukrainian relocated persons in UNSCEAR (2000), the later document revises the contribution of internal dose down to the point where it is only half the external dose.

The ratio, ρ, of internal to external doses is needed to convert the external doses listed in Table 8 into total effective dose for the first year. However, as shown in Table 9, the actual values of ρ reported in UNSCEAR, 2000 and UNSCEAR, 2008 amongst relocated persons seem *prima facie* to show significant differences with the MIB model, which predicts that the internal dose will be 2–3 times higher than the external dose in the early years. Moreover the model predicts that the time-averaged ratio of internal to external lifetime effective dose equivalent over 70 years will always be greater, with a limiting ratio of $\bar{\rho}_{\mathrm{lim}} = 5.24/3.18 = 1.65$, irrespective of the starting contamination level. (See page 11 of Lochard and Schneider, 1992).

The uncertainty over the relative sizes of the internal and external doses led to a decision to multiply the external dose produced by the MIB model by the average value, $\bar{\rho}$, to estimate the internal dose. Thus, while the MIB model is retained for its description of the time-varying behaviour of external dose, the estimate of the internal dose draws on the empirical evidence of UNSCEAR (2000) when considering the 1986 relocation.

In the Base Case the average internal to external dose ratios, $\bar{\rho}$, were assumed to conform to UNSCEAR (2000), so that $\bar{\rho}_{Ukr} = 0.87$ for Ukraine and $\bar{\rho}_{Bel} = 0.2$ for the more distant Belarus. Then a Sensitivity Study was carried out with double these figures, namely $\bar{\rho}_{Ukr} = 1.74$ and $\bar{\rho}_{Bel} = 0.4$. It should be noted that the Ukraine ratio, $\bar{\rho}_{Ukr}$, used in the Sensitivity Study is greater than the limiting ratio, $\bar{\rho}_{\mathrm{lim}} = 1.65$, for the MIB model discussed above.

The 186 relocated people from the Russian Federation constitute a very small number compared with the tens of thousands being relocated from the other two Republics in 1986, and so the results will be insensitive to the choice of the ratio, $\bar{\rho}_{\mathrm{Rus}}$. Because of the negligible effect on the total number of persons relocated, it was decided to put $\bar{\rho}_{\mathrm{Rus}} = 1$ for simplicity in both the Base Case and the Sensitivity Study.

The whole body collective dose was then formed of the sum of the external and internal doses, where the distribution of external doses in Belarus followed Table 8 (and hence Table 24 of UNSCEAR, 2000).

In the absence of specific figures for the costs of relocating and relocating the population in 1986, it was assumed that the cost of relocation would have been roughly proportional to the GDP per head, with a constant of proportionality of about 12 deduced from the relocation cost and GDP per head at the time of the 1990 relocation. The relocation cost per head in 1986 was then taken to be 34,500 roubles.

5.1.2. *Base Case ($\bar{\rho}_{Ukr} = 0.87$ and $\bar{\rho}_{Bel} = 0.2$)*

A probability density curve may be derived from Table 8 for the size of dose received by the Belarusian relocated persons in the first year under no relocation. For the Belarusian Base Case $\bar{\rho}_{Bel} = 0.2$. The average total dose of the 1200 relocated persons with the highest exposure would then have been $510 \times (1 + \bar{\rho}_{\mathrm{Bel}}) = 612\,\mathrm{mSv}$ *if they had stayed in place*, while the upper limit to the distribution becomes $620 \times 1.2 = 744\,\mathrm{mSv}$. Fig. 4 shows the resulting probability density for individual dose (external plus internal). The average combined dose per head in the first year for all 24,725 Belarusian relocated per-

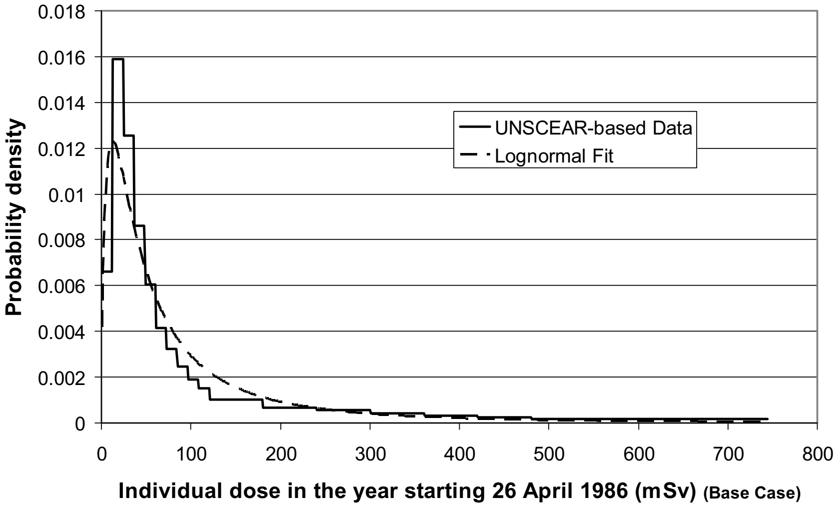

Fig. 4 – Probability density for total dose (external and internal) in year starting 26 April 1986 for Belarusian relocated persons. The stepped full line corresponds to UNSCEAR (2000) data with $\bar{\rho}_{Bel}$ =0.2, while the broken line is a fitted lognormal probability density. Base Case.

sons would then have been 110 mSv if they had been left in place.

As may be seen from Fig. 4, the distribution for individual dose is approximately lognormal, and a lognormal distribution with the same mean value, 110 mSv, was fitted to the data through minimising the integral of the squared error by varying the standard deviation. The best match was achieved with a standard deviation of 189 mSv, which corresponds to a median, 55 mSv, that is half the mean. The matched lognormal probability density is displayed in Fig. 4 also. The two probability densities demonstrate clearly that most people relocated from Belarus would have received doses well below 100 mSv in the first year if they had stayed in place, although the distribution has a long tail. In fact the mean, 110 mSv, of this long-tailed distribution is also the 74% percentile. Hence nearly three-quarters of the affected population would have received a small dose than the mean value of 110 mSv.

The MIB model for external dose was employed to find the 1990 surface caesium contamination, C, that would lead to external doses at the levels given in Table 8 being received in the year starting 26 April 1986. Having established a suitable value of C for a given external dose in 1986, Eq. (15) was then evaluated from $t = -2$ (1986) to $t = 68$ (2056) to give a 71-year long external dose profile. Fig. 5 shows the case where the external dose in the year beginning 26 April 1986 was 100 mSv, illustrating the rapid fall-off in dose during the first few years. This reflects the fact that the caesium radionuclides are decaying initially with an effective half-life of about 3 years as a result of the early dominance of the shorter lived isotope, ^{134}Cs (half life ~2 years) over the longer lived ^{137}Cs (half life ~30 years). [In fact the effective half life for ^{137}Cs in man's environment may be 50% or so lower than the theoretical value of 30 years (Smith and Beresford, 2005; Robison et al., 2003; Paller et al., 2014).]

The external dose profile was then multiplied by $1 + \bar{\rho}_{Bel} = 1.2$ to give the profile for total individual dose (external plus internal). This profile was then entered into the CLEARE program to find the loss of life expectancy that would have occurred without relocation for exposed people with any given starting dose.

By setting $J = 1$ and using the economic parameters from Table 1, the J-value method could then be inverted to find the minimum starting dose above which it would have been justified to relocate people from Belarus, on the basis of maintaining a constant life-quality for the affected people, as given by the life-quality index. By iteratively varying the total individual dose for the year beginning 26 April 1986 and computing the resulting dose profile and J-value, it was found that a dose of 126 mSv in 1986 was required to give a J-value of 1 for the affected Republics within the USSR. A 1986 dose of 126 mSv, together with the associated dose profile over 70 years, falling rapidly over the first 10 years as illustrated in Fig. 5, would have led to a loss of life expectancy of 8.7 months.

A dose of 126 mSv in the first 12 months after the accident corresponds to the guidance given in ICRP (1991), the International Atomic Energy Agency (1994) and a Working Group set up under Article 31 of the Euratom Treaty (European Community, 1993) that relocation will almost certainly be justified if lifetime doses are projected to exceed 1 Sv or dose rates are likely to exceed approximately 10 mSv per month. ICRP (2007), paragraph 278, suggests that, when planning for an emergency situation, a 100 mSv one-off dose should be regarded as an upper limit. However the previous paragraph states that

> "277. In emergency exposure situations particular attention should be given to the prevention of severe deterministic health effects as doses could reach high levels in a short period of time. In case of major emergencies an assessment based on health effects would be insufficient and due considerations must be given to societal, economic and other consequences. Another important objective is to prepare, to the extent practicable, for the resumption of societal and economic activities considered as 'normal'."

where deterministic health effects may be caused by a dose of 400–500 mSv or more received in a short time.

It may be noted that the loss of life expectancy associated with $J = 1$, namely 8.7 months, lies well within the variation in life expectancy seen between different regions of the UK, for example. Thus the average inhabitant of Manchester can expect to live about 3¼ years less than the average person living in Harrow in London (based on the 6½ years difference in life expectancy at birth across the two genders (ONS, 2015) and the average to new-born life expectancy ratio of roughly 0.5 appropriate for the UK (Thomas and Waddington, 2017)). The allowable loss of life expectancy of 8.7 months would have

Fig. 5 – Dose profile for an external dose of 100 mSv in the year beginning 26 April 1986.

been lower but for the fact that relocation, at 34,500 roubles per head, is large by comparison with the GDP per head, in fact twelve times larger. (The relative cost of relocation in the USSR after Chernobyl was thus very large compared with the relative cost of relocation in Japan after the Fukushima Daiichi accident. However the Japanese accommodation was expected to serve for only a few years before the people could return rather than being permanent. This may explain why the cost of relocation in Japan was much lower relative to GDP per head. At about 37,500 international dollars per person, it was little more than Japan's GDP per head of 34,294 international dollars in 2011. See Section 6.1)

Since the J = 1 value of 126 mSv is above the mean dose, 110 mSv, of this Belarusian population, the J-value analysis would not support relocation of the total Belarusian cohort of 24,725. Average values are normally used in J-value calculations, a practice that would seem to fit well with the recommendation of Lochard and Schneider (1992), who maintain in their *Conclusion* that best-estimate models should be used in preference to conservative-estimate models in a public health context:

> "The effectiveness of protective measures should be evaluated on a realistic basis, since overestimation of the potential health impacts could lead to the misallocation of resources; moreover, it may place additional and unnecessary stress on the population."

However, Fig. 4 demonstrates that the dose distribution in Belarus is very long tailed, with some people receiving much higher doses than the mean. Moreover, it is possible to determine, from the probability density of Fig. 4, the fraction of relocated people who would have received at least 126 mSv by remaining in Belarus. This fraction, f_{UNS}, would have been $f_{UNS} = 0.24$ in the Base Case. Thus, based on the maintenance of their notional life quality, as defined by the life quality index, just under a quarter, 5930, of the Belarusian relocated population of 24,725 actually merited relocation.

The fraction, f_{UNS}, of the relocated Belarusians who actually merited relocation based on the UNSCEAR Table 24 data is the same in this case as the fraction, f_{LOG}, calculated from the fitted lognormal distribution. Hence

$$\frac{f_{UNS}}{f_{LOG}} = 1 \tag{17}$$

The number of people in the Ukraine who would have received at least a dose of 126 mSv was calculated by first noting that the mean dose for the 91,406 relocated Ukrainians, if they had remained in place, would have been, after summing the external and internal dose, 123 mSv. The dose distribution for the affected people in the Ukraine, which must have this mean, is assumed to be approximately lognormal, as was the case for the Belarusian relocated persons. Keeping the ratio, σ/μ, of the standard deviation, σ, to the mean, μ, the same as for the Belarusian case (which is equivalent to maintaining a constant geometric standard deviation, g_σ; see Appendix A) produces the probability density for dose in year 1 shown in Fig. 6. Comparing the probability density for the Ukrainian case with the Belarusian, it is noticeable that the fraction of people with low doses is slightly less, with the median dose for the Ukrainian cohort calculated to be 8 mSv higher at 63 mSv. In fact, the mean individual dose of 123 mSv in year 1 lies at the 72% percentile, and it is estimated that two thirds of the relocated persons from the Ukraine would have received a dose below 100 mSv if they had stayed in situ.

The J = 1 dose is slightly greater than the mean dose and so relocation of the whole of the Ukrainian cohort is not supported. But the distribution of individual dose has a long tail, as exemplified by the very large geometric standard deviation, $g_\sigma = 3.23$. Using the lognormal distribution of Fig. 6, we may calculate that 27% of the relocated Ukrainians would have received a first-year dose of 126 mSv or above if they had remained in situ. This corresponds to 24,694 out of the 91,406 Ukrainians who were actually relocated in 1986.

The 186 people relocated from the Russian Federation had an average individual total dose calculated conservatively as 108 mSv in year 1, which is just below that of the Belarusian relocated persons. Applying the Belarusian fraction, 24%, would suggest that 45 people merited relocation from the Russian Federation.

Thus the total of people whose relocation was justified by the J-value is:

5930 + 24,694 + 45 = 30,669, that is to say 26% of the total of 116,317 people actually relocated.

5.1.3. *Sensitivity Study* ($\bar{\rho}_{Ukr} = 1.74$ *and* $\bar{\rho}_{Bel} = 0.4$)

The average ratios of internal to external dose are doubled in the Sensitivity Study for both Ukraine and Belarus, so that $\bar{\rho}_{Ukr} = 1.74$ and $\bar{\rho}_{Bel} = 0.4$.

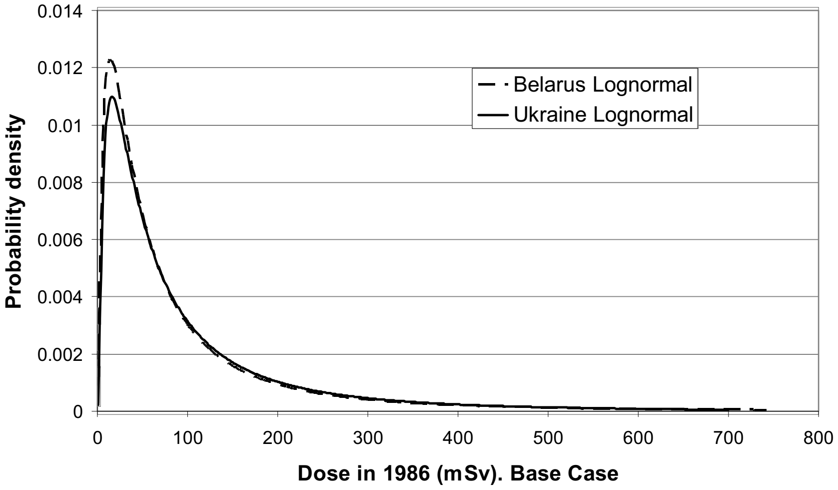

Fig. 6 – Probability density for total dose (external and internal) in year starting 26 April 1986 for Ukrainian relocated persons assuming a lognormal distribution with the same σ/μ ratio as in the Belarusian case. The Belarusian lognormal curve is shown by the broken line. Base Case.

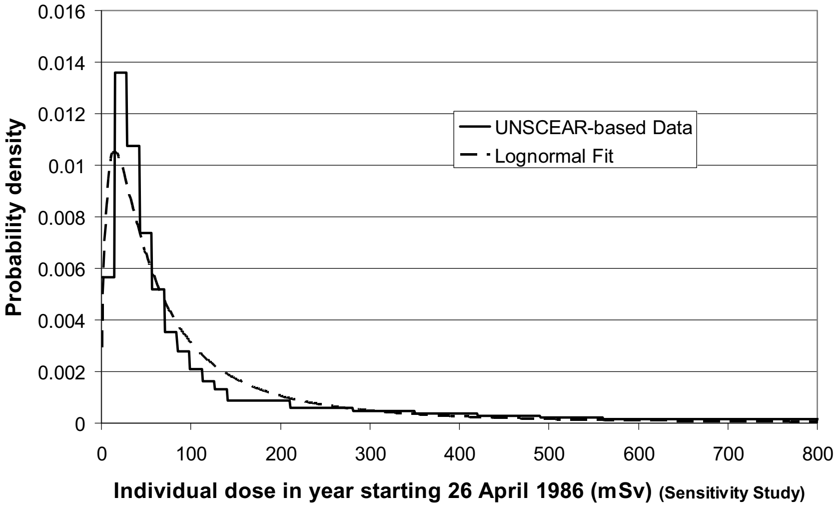

Fig. 7 – Probability density for total dose (external and internal) in year starting 26 April 1986 for Belarusian relocated persons. The stepped full line corresponds to UNSCEAR (2000) data with $\bar{\rho}_{Bel}$ =0.4, while the broken line is a fitted lognormal probability density. Sensitivity Study.

Once again Table 8 is the starting point for a probability density curve to be found for the number of relocated Belarusians in terms of the size of dose received in the first year with no relocation. The average dose of the 1,200 relocated persons who would have received the highest dose if they had stayed in place would have been $510 \times (1 + \bar{\rho}_{Bel}) = 510 \times (1 + 0.4) =$ 714 mSv, and the upper limit to the distribution would have been 868 mSv based on the use of a piecewise uniform distribution. See Fig. 7. The mean total dose per head in the first year for the Belarusian relocated persons *if they had been left in place* would have been 128 mSv.

The mean dose, 128 mSv is slightly higher than the $J = 1$ value of 126 mSv in the first year, and so an argument could be made for relocating the whole cohort. But it is clear from the probability density of Fig. 7 that the spread of doses is very wide, and it is possible to determine the fraction of relocated Belarusians who would have received at least 126 mSv in year 1 by remaining in Belarus. This fraction, f_{UNS}, turns out to be $f_{UNS} = 0.265$ in the Sensitivity Study. Thus based on the maintenance of their notional life quality, as defined by the life quality index, 26.5% of the Belarusian relocated population of 24,725 actually merited relocation, that is to say 6550 under the assumptions of the Sensitivity Study.

A lognormal distribution with the mean value, 128 mSv, was fitted to the data through varying the standard deviation so as to minimise the integral of the squared error. Fig. 7 shows the result. Based on the fitted lognormal distribution, the fraction, f_{LOG}, of the number of relocated Belarusians predicted to merit relocation in the Sensitivity Study is f_{LOG} =0.283, close to the fraction, $f_{UNS} = 0.265$, based on the UNSCEAR Table 24 data. Thus the ratio, f_{UNS}/f_{LOG}, is:

$$\frac{f_{UNS}}{f_{LOG}} = \frac{0.265}{0.283} = 0.94 \tag{18}$$

The number of people in the Ukraine who would have received at least a dose of 126 mSv was calculated by first noting that the average dose for the 91,406 relocated Ukrainians, if they had remained in place, would have been 180 mSv, after summing the external and internal dose, under the assumptions of the Sensitivity Study. Keeping the ratio, σ/μ, of the standard deviation to the mean the same as for the Belarusian case produces a lognormal probability density for dose in year 1 shown in Fig. 8. The median dose is now 90 mSv.

Clearly the average dose, 180 mSv, received by the Ukrainian cohort under the assumptions of the Sensitivity

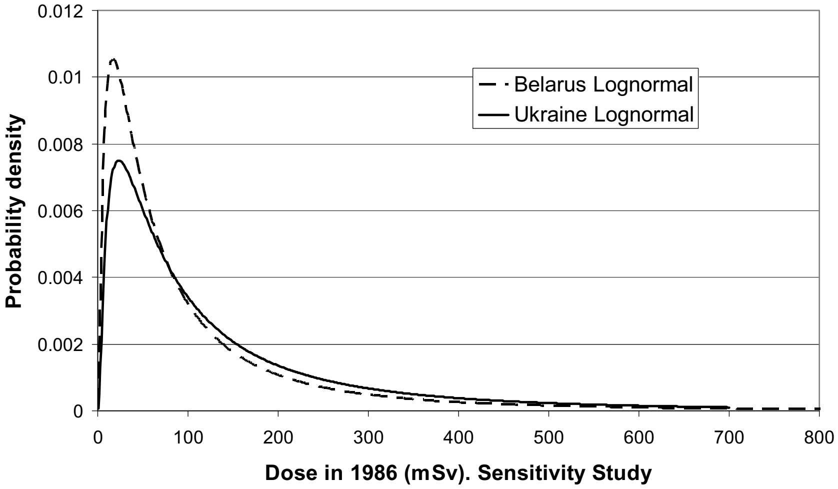

Fig. 8 – Probability density for total dose (external and internal) in year starting 26 April 1986 for Ukrainian relocated persons assuming a lognormal distribution with the same σ/μ ratio as in the Belarusian case. The Belarusian lognormal curve is shown by the broken line. Sensitivity Study.

Study, is greater than the $J = 1$ dose of 126 mSv in year 1, and an argument can therefore be made for relocating the whole cohort. However, the raw fraction of relocated people from the Ukraine with a first-year dose of 126 mSv or above *in the absence of relocation* is found from the lognormal distribution of Fig. 8 to be 38.8%. A corrected figure may be found by multiplying this raw fraction by f_{UNS}/f_{LOG} from Eq. (18) to give a corrected fraction of 36.3%. This corresponds to 33,157 out of the 91,406 Ukrainians actually relocated in 1986.

The Sensitivity Study has made no change to the Base Case assumptions for the doses received in the Russian Federation, and so the same fraction, 24%, merited relocation, implying 45 people.

Thus the total of people who ought to be relocated under the Sensitivity Study is 6, 550 + 33,157 + 45 = 39,751, that is to say 34% of the total of 116,317 people actually relocated.

Comparing the optimal total number of people recommended for relocation under the Sensitivity Study, 39,751, with the number recommended under the Base Case, 30,669, it is clear that the doubling of the ratios of internal to external dose for Ukraine, $\bar{\rho}_{Ukr}$, and Belarus, $\bar{\rho}_{Bel}$, has had only a limited effect on the final fraction meriting relocation.

5.2. *Identification of the people meriting relocation: the 95th percentile heuristic*

The figures of 30,669 (Base Case) and 39,751 (Sensitivity Study) derived in Section 5.1 may be regarded as the optimal range for the numbers to be relocated, based on the maintenance of the notional life quality of the affected persons, as measured by the life quality index. However, it relies on the disaggregation of individual doses, and it is recognised that it will be difficult to identify precisely the people concerned. Lochard and Schneider (1992) were tackling a similar problem when they introduced their “coefficient of relocation”, intended to cover the following two cases:

> “First, for social and economic reasons, the relocation of a given settlement or a set of settlements may necessitate the additional relocation of neighbouring settlements where these are economically dependent on those relocated. Secondly, there may be many people in each Republic who wish to be relocated, even when the level of contamination is below the criterion.”

They set their coefficient of relocation at 1.0 in their paired base cases, LS1 and LS2, a value that implies that relocation should apply only to the people level living in 1990 in an area of sufficiently harmful contamination as identified by their model, and not to social or economic neighbours facing a smaller contamination hazard. However, in a sensitivity study, they set the coefficient at 2.0, thus doubling the number to be relocated, although they reported that this did not make a very big difference to the numbers recommended for relocation, since the base number was either zero or else small.

An alternative approach is put forward here, based on the concept of the “representative person” recommended by the International CommissionInternational Commission for Radiological Protection (ICRP) when assessing countermeasures against radiation exposure. The ICRP defines a “representative person” such that “the probability is less than 5% that a person drawn at random from the population will receive a greater dose” (ICRP, 2006, paragraph 89). It is implicit in the ICRP definition that the representative persons are distributed randomly in the population and assumed impossible to identify. Hence a protective measure, required only for these “high-end” people, will be applied generally, based on the reasoning that any given individual in the population will have a 1 in 20 chance of needing such a level of protection

While retaining the concept of representative persons being randomly distributed in the population, it is possible to divide the population into bands of increasing contamination in the way set out by Lochard and Schneider in their 1992 study. The advantage of this procedure is that the average dose may be found for members of each subpopulation, which will, in practice, correspond to a given settlement or village. Benefit is then taken from the work explained on page 478 of UNSCEAR (2000), which reports on the relative distribution of external doses in 1991 and 1992 for 906 inhabitants of 20 Belarusian villages. It was found that

> “a log-normal distribution with a geometric standard deviation of 1.54 provides a good approximation of the normalized individual doses from external irradiation.”

Assuming as in the previous section that the internal dose is a constant fraction of the external dose allows the same value for geometric standard deviation, $g_\sigma = 1.54$, to be applied in the case of total individual doses (external and internal).

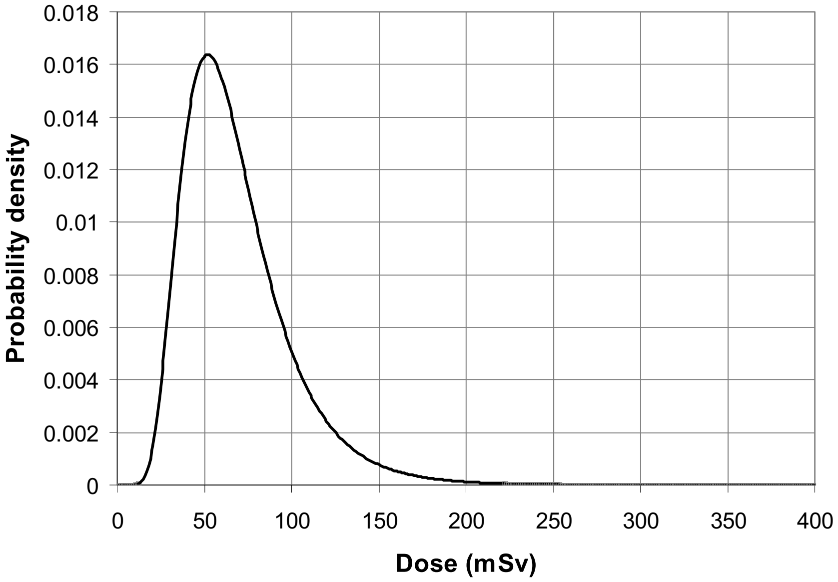

Fig. 9 – Probability density for individual dose in year starting 26 April 1986 when the 95th percentile dose is 126 mSv in the first year.

It may be noted that $g_\sigma = 1.54$ implies a ratio, $\sigma/\mu = 0.45$ (see Appendix A), which is roughly a quarter of the corresponding value, $\sigma/\mu = 1.72$, that applies to dose distribution among the cohort of the 24,725 relocated Belarusians, for whom $g_\sigma = 3.23$. Unsurprisingly the dose variation in a particular settlement is much less than the dose variation over a much bigger region, suggesting that a benefit may be gained in disaggregating the regional population into settlement cohorts before applying the J-value.

J-value analysis may then be applied by taking the maximum permissible dose at J = 1 to refer to the settlement mean dose. Alternatively, if the decision is made to adopt the ICRP's "representative person" instead as a precautionary assumption, then the maximum permissible dose at J = 1 may be assumed to refer to the 95th percentile person rather than the average person in the population group. In this case the corresponding mean for the group may be calculated from the dose at J = 1 using the empirically derived geometric standard deviation in the manner described in Appendix A.

When the dose in year 1 at the 95th percentile is equal to the J = 1 figure of 126 mSv, applying the method described in Appendix A yields a corresponding mean individual dose of 68 mSv. Fewer than 5% of the residents will experience a dose of 126 mSv if their village has a mean dose of less than 68 mSv. Hence the population of such a settlement should not be relocated under the 95th percentile heuristic.

The probability distribution for dose when the 95th percentile is 126 mSv is shown in Fig. 9; its standard deviation is 31 mSv and the median dose is 62 mSv. The mean value, 68 mSv, coincides with the 59th percentile value when the geometric standard deviation is 1.54. For such a cohort, implementing the J-value using the average rather than the 95th percentile value would result in the adoption of a countermeasure that would already exceed what was necessary for 59% of the population.

5.2.1. *Applying the 95th percentile heuristic to the Base Case ($\bar{\rho}_{\mathrm{Ukr}}$ =0.87 and $\bar{\rho}_{\mathrm{Bel}}$ =0.2)*

It is shown in Appendix B that the proportion of the relocated population coming from settlements with a mean dose level above 68 mSv will be very similar to the cumulative probability above a dose of 68 mSv calculated from the stepped probability density for individual dose shown in Fig. 4. This finding will hold when the number of settlements is large and no single settlement dominates the population as a whole. From the probability density function displayed in Fig. 4, 37.5% of the Belarusian relocated persons would have received a dose in year 1 of 68 mSv or more if they had stayed in situ. Thus on this basis, 9272 Belarusians (38%) should have been relocated out of an actual figure of 24,275.

49,360 of the 91,406 Ukrainians subsequently relocated were living in Pripyat at the time of the accident. The dominant fraction (54%) of people living in the same town requires a modified approach as compared with that applicable in Belarus, where the population is roughly evenly spread amongst a large number of small villages. This is explained in Appendix C, where it is shown that under the 95% heuristic, the population of Pripyat as well as 13,632 others from the smaller settlements should have been relocated making 62,992 people in total, which is 69% of the Ukrainian population actually relocated.

Assuming it was justifiable to relocate all 186 people from the 4 settlements in the Russian Federation, the total of people from the 3 Republics who ought have been relocated comes to 9, 272 + 62, 992 + 186 = 72,450. This is 62% of the number actually relocated, implying that the relocation of 43,867 people, 15,453 from Belarus and 28,414 from the Ukraine, may not have been justified. The 1986 relocation exercise was 60% bigger than justified under the J-value plus 95% heuristic.

5.3. *Applying the J-value to Chernobyl relocations in 1986: summary*

The results include both a Base Case and a Sensitivity Study to account for uncertainty on the ratio, ρ, of internal to external dose. In addition, the 95th percentile heuristic has been examined, corresponding to the ICRP's "representative person", where precautions that exceed what is needed by 19 out of 20 people in the population are applied to all. The results are summarised in Table 10.

It is found across all these cases that between 26% and 62% of the number actually relocated in 1986 could be justified on

Table 10 – Number of people in the Republics of the USSR meriting relocation at $J = 1$.

	Base Case $\bar{\rho}_{Ukr} = 0.87$ and $\bar{\rho}_{Bel} = 0.2$	Sensitivity Study $\bar{\rho}_{Ukr} = 1.74$ and $\bar{\rho}_{Bel} = 0.4$	95% heuristic (applied to Base Case)	Actually relocated
Belarus	5930	6550	9272	24,725
Russian Federation	45	45	186	186
Ukraine	24,694	33,157	62,992	91,406
Total	30,669	39,751	72,450	116,317

the basis of maintaining the life quality of those affected, as measured by the life quality index. This suggests that relocation may not have been the best option for between 44,000 and 86,000 of the 116,000 people relocated from the Ukraine and Belarus in 1986.

In terms of the total number, 335,000, relocated in both 1986 and post 1990, the justifiable fraction is found to lie between 9% and 22%.

6. Fukushima Daiichi relocation in 2011

In the hours and days following the Fukushima Daiichi Nuclear Power Station accident, the Japanese authorities ordered the progressive relocation of those living near to the plant. At 20:50 on 11 March, settlements within 2 km of the Fukushima Daiichi Nuclear Power Station were given the order to relocate (Futaba Town and Okuma Town). By 18:25 the following day (12 March) the relocation radius had been expanded to 20 km (the towns of Futaba, Hirono, Naraha, Okuma and Tomioka and the village of Kawauchi, as well as those residents of Minamisoma City, Tamura City, Namie Town and Katsurao Village living within the 20-km zone). On 25 March, residents between 20 and 30 km of the site—who had been sheltering since 15 March—were advised to begin voluntary relocation. On 22 April, compulsory relocation was extended to specific areas to the north-west of the plant beyond the 20-km zone, extending out to 40 km for Iitate Village (UNSCEAR, 2013, para. 31–24). Note also that a relocation order was issued at 17:39 on 12 March to residents within 10 km of the Fukushima Daini Nuclear Power Station (which suffered no radiation release) although this area was mostly subsumed within the 20-km zone of the Fukushima Daiichi Nuclear Power Station (Ranghieri and Ishiwatari, 2014, p. 103).

Approximately 78,000 people had been living in what became the 20-km "Restricted Zone" and about 62,000 were living between 20 km and 30 km of the plant (the "Relocation Prepared Area"). About 10,000 people were relocated from the "Deliberate Relocation Area" beyond the Restricted Zone. The UNSCEAR report gives the total number of relocated persons as approximately 118,000 (UNSCEAR, 2013, para. 76), implying that about 30,000 residents of the voluntary Relocation Prepared Area actually left their homes. The Japanese Reconstruction Agency (2016) cites 154,000. The World Bank report gives the total number of relocated persons from Fukushima prefecture as more than 150,000 by the end of 2011 (Ranghieri and Ishiwatari, 2014, p. 105)—this Figure would seem to imply that all 62,000 residents of the Relocation Prepared Area had in fact left their homes. The report later states that 160,000 people had left their homes by December 2012, of whom 111,000 were from the restricted areas and 49,000 had relocated voluntarily (p332). Meanwhile data taken from the website, City Population (2016), allows the relocation following the Fukushima Daiichi accident to be broken down on a settlement by settlement basis and produces an aggregate number of 162,677. This figure allows for the fact that the 20 km exclusion zone bisected both Minamisoma City and Kawamata Town by making the simplifying assumption that the relocated population was exactly half the population registered on 1 October 2010 in each case. Despite the fairly crude nature of this assumption, the estimated total is usefully close to the figures cited above. See Table 11.

Table 11 – Estimated number of people relocated is the number of inhabitants in the various settlements as of 1.10.2010.

	Inhabitants as of 1.10.2010	Inhabitants as of 1.10.2015	% returned
Tomioka Town	16,001	0	0.0
Okuma Town	11,515	0	0.0
Futaba Town	6932	0	0.0
Naraha Town	7700	976	12.7
Namie Town	20,905	0	0.0
Tamura City	40,422	38,500	95.2
Minamisoma City (half)	35,439	22,314	63.0
Hirono Town	5418	4323	79.8
Kawauchi Village	2820	2021	71.7
Katsurao Village	1531	18	1.2
Iitate Village	6209	41	0.7
Kawamata Town (half)	7785	6695	86.0
Total	162,677	74,888	46.0

Source: http://www.citypopulation.de/Japan-Fukushima.html.

The 20-km relocation zone bisected Minamisoma City and Kawamata Town, and it is assumed that exactly half the population was relocated in each case. It is further assumed that the reduction in population of Minamisoma City and Kawamata Town was caused by the non-return of relocated people.

The number of inhabitants as of 1 October 2015 shows a fall of 87,789, which suggests that less that half the people relocated had returned to their homes 4½ years after the accident. The response at Naraha Town may indicate how there may be problems of returning after a prolonged absence. The Japanese Government had signalled in July 2015 that it would be safe to return to Naraha Town on 5 September 2015, when, according to Demetriou (2015), the dose level had fallen 60% to 0.3 μSv h^{-1} or 2.63 mSv y^{-1}. However less than 1000 out of over 7000 people had returned by 1 October 2015.

6.1. *Loss of life expectancy averted by relocation*

The UNSCEAR report (2013, Table C11, page 191) gives estimates of the radiation doses that were averted by relocating the residents of twelve localities within the Fukushima Prefecture. The external and inhaled doses were based on results from atmospheric dispersion modelling while measurements of activity concentrations in foods were used to estimate ingested doses. A questionnaire issued to all 2 million residents of the prefecture provided information about their location and movements during and after the accident. The National Institute for Radiological Science (NIRS) used these

Table 12 – Estimates of the averted doses during the first year for eighteen representative communities relocated within Fukushima Prefecture (adapted from UNSCEAR, 2013, p. 191, Table C11), together with the gain in life expectancy from averting the first-year dose. (LLE = loss of life expectancy).

Locality	Destination	Dose in First Year (mSv)			LLE averted (days)
		Without relocation	With relocation	Averted	
Tomioka Town	Koriyama City	51	3.3	48	21.7
Okuma Town	Tamura City	47	1.5	45	20.4
Futaba Town	Saitama	38	1.1	37	16.7
Naraha Town 1	Tamura City	7	3.7	3	1.4
Naraha Town 2	Aizimisato Town	7	2.5	4	1.8
Namie Town 1	Nihonmatsu City	25	5	20	9.1
Namie Town 2	Nihonmatsu City	25	7	18	8.1
Tamura City	Koriyama City	2	3.5	(2)[b]	(0.9)[c]
Minamisoma City 1	Fukushima City	4	5.7	(2)[b]	(0.8)[c]
Minamisoma City[a] 2	Minamisoma City[a]	4	4.8	(1)[b]	(0.4)[c]
Hirono Town	Ono Town	4	1.3	3	1.4
Kawauchi Village	Koriyama City	2	3.3	(1)[b]	(0.6)[c]
Katsurao Village 1	Fukushima City	6	4.3	2	0.9
Katsurao Village 2	Fukushima City	6	6	0	0.0
Iitate Village 1	Fukushima City	11	7.8	3	1.4
Iitate Village 2	Fukushima City	11	8	3	1.4
Kawamata Town[a]	Kawamata Town[a]	2	9.3	(7)[b]	(3.3)[c]

[a] The 20-km relocation zone bisected Minamisoma City and Kawamata Town, and some residents were relocated to other areas of the city/town that were outside the zone.

[b] Parentheses indicate groups that received a higher estimated dose after relocation than had they remained in place.

[c] Parentheses indicate a loss of life expectancy as a result of resettlement.

data to estimate the doses with and without relocation for eighteen representative groups of people within the relocation zones. Table 12 summarises their findings. An estimate of the variability about these dose values stated that individual doses could be “about two to three times higher or lower” than the average, due to the variability of deposition rates, food consumption patterns and human behaviour (UNSCEAR, 2013, para. C148). These figure are in good agreement with the lognormal distribution with a geometric standard deviation of 1.54 reported on page 478 of UNSCEAR (2000) and discussed in Section 5.2. The 95% percentile heuristic (see Appendix A) will be used to assess the sensitivity of the results concerning Fukushima Daiichi.

The loss of life expectancy averted by relocation was calculated from the NIRS estimates of the averted doses. These results are also presented in Table 12 and are applicable to the first year after the accident. Residents in the immediate vicinity of the power station (Okuma, Futaba and Tomioka Towns) gained between 17 and 22 days of increased life expectancy in the first year of their relocation. Relocated persons from the nearby town of Namie gained 8–9 days, and those from the wider relocation zones had 1–2 days of life expectancy restored.

The NIRS study suggested that residents of four areas (Tamura City, Minamisoma City, Kawauchi Village and Kawamata Town) actually *lost* 1–3 days of life expectancy as a result of leaving their homes and being moved to locations where they received a higher dose.

Table C6 of the UNSCEAR (2013) report gives estimates of the effective doses received by residents of areas that were not relocated. Those in Fukushima Prefecture received 1–4 mSv in the first year following the accident, which equates to a loss of life expectancy of between 11 hours and 47 hours. In the surrounding prefectures, the effective doses were 0.3–1.4 mSv, corresponding to a loss of 2–15 hours of life, while for the rest of Japan the expected loss of life expectancy was 1–3 hours (from a dose of 0.1–0.3 mSv; UNSCEAR, 2013, Table C6). These effective doses can be put into context by comparing them with the average (pre-accident) background radiation level in Japan of 2.1 mSv per annum (UNSCEAR, 2013, para. E43).

The Fukushima reports contain estimates of the costs of relocation and (temporary) evacuation that enable a J-value assessment to be made. About 52,000 units of temporary prefabricated housing had been built by early 2012 (Ranghieri and Ishiwatari, 2014, p. 195). The World Bank report gives the cost of building this housing as US$71,000–US$80,500 per unit; other estimates suggest US$56,000–US$75,000 (International Recovery Platform, 2013, p. 65). A value of US$75,000 was adopted here. Each of the units houses up to three people, so an average occupancy of two was assumed, giving a housing cost of US$37,500. They were expected to be used for two years (International Recovery Platform, 2013, p. 64) but the relocation has lasted for 5 years at the time of writing.

The dose averted in the first year is taken from Table C11, page 191 of UNSCEAR (2013). The doses averted for the second year were then calculated from the MIB model for dose estimation cited in Lochard and Schneider (1992), making the assumption that the dominant decay processes were the same following the Fukushima Daiichi accident as for the Chernobyl accident, predominantly the radioactive decay of ^{137}Cs ($t_{1/2}$ = 30.1 y) and ^{134}Cs ($t_{1/2}$ = 2.1 y). Iodine-131 has a very short half-life, at 8 days, which means that its effect will have essentially disappeared within a month, as discussed in the final introductory paragraph of Section 5. Its relevance to relocation, staying away for a long time or indefinitely, is thus limited. For example, the time constant associated with the first relocation at Chernobyl has been found to be about 10.5 days (Yumashev et al., 2017). At Fukushima Daiichi the people living between 20 km and 30 km from the site were not asked to relocate until 14 days after the event, while relocation for the population in specific areas to the north-west of the Fukushima Daiichi plant was not ordered until 44 days after the start of the accident, when relocation would have offered no protection against radioactive iodine whatsoever as there would no longer be any risk from that source. The hazard from radioactive iodine is its potential to concentrate in the thyroid gland and increase the chance of thyroid cancer, particularly if there is a shortage of normal iodine in the diet. This was the case near Chernobyl, where an increase in thyroid cancer was observed (Thomas and Zwissler, 2003) in those under 18 at the time of the accident although not in adults. As noted in the final introductory paragraph of Section 5, the best safeguard is the early use of prophylactic iodine. To the extent that a dose from radioactive iodine is added to the first-year dose, this will make the later predictions of the MIB model, which involves decay over years not weeks, more conservative, in the sense of larger doses would be predicted by the MIB model in subsequent years.

The actual dose reduction of 60% after 4½ years in Naraha Town cited in Demetriou (2015) is greater than the 51% fall that the MIB model predicts, suggesting that the model is likely to give conservative (viz. high) dose rates based on the figures cited.

The Japanese Government prescribed 20 mSv y^{-1} as the safe-return dose rate:

> "In December 2011 the government said that where annual radiation dose would be below 20 mSv/yr, the government would help residents return home as soon as possible and assist local municipalities with decontamination and repair of infrastructure. In areas where radiation levels are over 20 mSv/yr evacuees will be asked to continue living elsewhere for 'a few years' until the government completes decontamination and recovery work." World Nuclear Association (2017).

Hence the J-value was calculated by assuming that the inhabitants of affected settlements would stay away until the average dose in the town had fallen to 20 mSv y^{-1} based on the MIB model. This meant that the inhabitants of Tomioka Town would need to stay away 6 years, while those of Okuma Town would need to be away for 5 years. The inhabitants of Futuba Town would need to be absent for 4 years, while those of Namie Town would need to stay away for 1 year. None of the other townships mentioned in Table 12 had doses above this level, and so, logically, their inhabitants should not have been relocated.

It can be seen from Table 11 that Tomioka, Okuma, Futuba and Namie Towns had, in fact, not been repopulated by 1 October 2015. Relocated inhabitants of these and other towns became eligible for "damages for mental anguish", costed at 100,000 Japanese Yen per month during the period of relocation (Matsuura, 2012), equivalent to about US$1000 at an average exchange rate of 0.01 USD per JPY. Those living in an "area where homecoming is difficult" became eligible for an immediate payment of 6 M JPY or US$60,000, the equivalent of 5 years at US$1000 per month, with the payment increasing if the relocation was prolonged (Matsuura, 2012). The area where homecoming is difficult includes the above 4 towns, as well as Naraha Town (Takahashi, 2012). Therefore, in considering these variable periods of relocation, the cost per person is taken to be the cost of temporary housing, US$37,500, plus an additional payment of US$60,000 or US$12,000 times the forecast length of absence, whichever is the larger.

The results are given in Table 13. Since maintenance of life quality amongst those affected and hence cost-effective use of resources requires a J-value of unity or less, this analysis shows that the cost of temporary relocation of these populations was disproportionate to the relatively small improvement in life expectancy achieved by reducing the radiation doses.

It is instructive to calculate the loss of life expectancy associated with a safe-return dose rate of 20 mSv y^{-1}. Those who experience this dose immediately after the deposition of fallout will see the dose rate drop off rather more rapidly than those who return to face the same starting annual dose in a few years time. This is because of the initial presence of the short-lived ^{134}Cs isotope in addition to the more slowly decaying ^{137}Cs isotope. The phenomenon has a small effect on the loss of life expectancy as a result of slightly different profiles of residual doses. Applying the MIB model to calculate dose rates over a period 70 years long, the cohort subject to a dose of 20 mSv in the first year after the accident would lose about 2 months of life expectancy as a result of the residual radiation exposure. This would have fallen to ∼0.5 mSv y^{-1} at the end of that time, about a quarter of the natural background radiation in Japan. Performing a similar, 70-year calculation for those who have stayed away for 6 years and would experience a dose of 20 mSv in year 7 after the accident suggests that the residual radiation dose 70 years after return is now about half the natural background, at roughly 1 mSv y^{-1}. The loss of life expectancy in the latter case would be about 3 months.

It may be concluded that the loss of life expectancy for those experiencing an initial dose of 20 mSv y^{-1} either by staying in situ or by returning up to 6 years after the accident will be between two and three months.

The J-value results suggest that, under the Japanese Government's 20 mSv y^{-1} safe-return criterion, it was not advisable to relocate any of the 162,700 actually relocated. This is because the inhabitants' gain in life expectancy, even in the most contaminated settlements where the dose would have been around 50 mSv in year 1 and falling in the way illustrated in Fig. 10, would have been insufficient to balance the fall in their life quality index caused by their notional payment of the costs of relocation. Attention might have been better focussed on other remedial measures, found in a separate paper to be cost-effective in many cases (Waddington et al., 2017).

A number of further queries may be raised about the size of the relocation. The first is whether it is reasonable to expect people to live in temporary housing for 4–6 years. Spending a significant fraction of one's life in such temporary housing might be seen to be undesirable, even if it can be borne with reasonable equanimity for up to two years. People could be expected to want a more spacious dwelling space after that time, for example, and more amenities. It is a moot point whether the $1000 per month mental anguish payment provides adequate compensation for a life that may well have become quite restricted as well as disrupted by social and economic losses.

There will also be economic costs of relocation associated with the loss of the means of earning a living, and these have not been accounted for here. Nor has allowance been made for those whose relocation led to increases in radiation dose, as shown in Table 12, as a result of the new location having a higher dose rate than that pertaining at their old home. The increased loss of life expectancy caused by being moved by mistake to an area of higher radiation dose is low, of the order of a day or two, but obviously this is not a desirable outcome.

As noted in Section 4.2 above, a recent study has pointed to a reduction of about 2 years associated with low socio-economic status (Strigini et al., 2017), and it is very possible that those relocated after the Fukushima Daiichi accident suffered a reduction in their socio-economic status. An effect of

Table 13 – J-value assessment of the cost effectiveness of providing mental anguish payments and prefabricated temporary housing, assumed to be used until return when the dose in the home location has fallen to 20 mSv per year. (LLE = loss of life expectancy).

Dose averted in year 1 (mSv)	Number of years until home dose rate $\leq 20\,\mathrm{mSv\,y^{-1}}$	Locations	LLE averted (days)	J-value
48	6	Tomioka Town	82	1.5
45	5	Okuma Town	69	1.5
37	4	Futaba Town	49	2.1
20	1	Namie Town	9	11.6

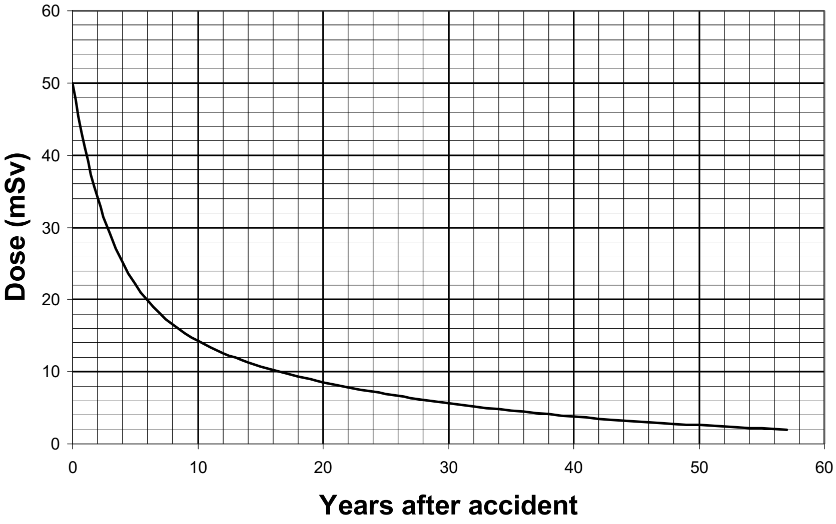

Fig. 10 – Dose received by people in a neighbouring town in the years after an imagined big nuclear reactor accident.

the order cited would outweigh by a significant margin any life expectancy gained by moving away from an affected area, and would strengthen the argument against relocation. This possible effect has not been included in the J-value analysis presented here.

6.2. *Applying the 95th percentile statistic*

Given an average dose in year 1 of 25 mSv in Namie Town if relocation had not taken place, the corresponding across-community variation in dose may be estimated by applying a lognormal distribution with the geometric standard deviation, 1.54, found to characterise 906 inhabitants of 20 Belarusian villages following Chernobyl, as described in Section 5.2. The median dose in year 1 in Namie Town would be 22.8 mSv, while the dose at 95th percentile person, the ICRP's "representative person", is 46.3 mSv. See Fig. 11. If a complete community were composed of people receiving 46.3 mSv in year 1, they would need to stay away for 5 years for the safe-return dose rate to fall to $20\,\mathrm{mSv\,y^{-1}}$. 71 days of life expectancy would be gained by staying away, but the J-value is 1.5. This J-value is higher than unity and thus indicates that relocation should not take place on economic and scientific grounds.

Similar calculations performed for Futuba, Okuma and Tomioka Towns produce J-values that are higher than unity and thus suggest that no relocation should occur, even under the 95th percentile heuristic. See Table 14. The decisions are close for both Okuma and Tomioka Towns, but these throw into sharp relief the implications of applying to all people in the community a protective measure that is required for only a small number of "high-end" people, 575 in the case of Okuma Town and 800 in the case of Tomioka Town. Suppose the J-value had come out just below unity rather than just above, would it be reasonable to expect the whole population of Tomioka Town to wait for another decade before being allowed to return: 16 years as opposed to 6 years? The figures would suggest that effort ought to be devoted to finding a better solution for the small number of "high-end" people that would not disadvantage the rest of the inhabitants so much.

6.3. *Premature deaths due to relocation*

No radiation deaths occurred during or following the accident, however there were a number of deaths directly attributed to the relocation and subsequent relocation of the Fukushima population. Hasegawa et al. (2015) summarise that

> "After the accident, mortality among relocated elderly people needing nursing care increased by about three times in the first 3 months after relocation and remained about 1·5 times higher than before the accident."

The phenomenon of stress-related deaths after Fukushima has been examined in detail by Murakami et al. (2015) for the case of 3 nursing homes that were relocated. These deaths need to be taken into account when considering the impact of the response to the accident.

Following their relocation from the Futaba Hospital, fifty patients had died by 31 March 2011 (Ranghieri and Ishiwatari, M., 2014, p. 103). As of September 2012, there had been 1121 deaths among the relocated persons in Fukushima attributed to physical and mental exhaustion caused by the accident. Of these, 35 had died more than a year after the accident (p332). The World Bank report also notes that the risk of death among the elderly had increased by a factor of 2.7 for those relocated from nursing homes. These figures point to the risk of death from relocation reducing rapidly with time, although it may

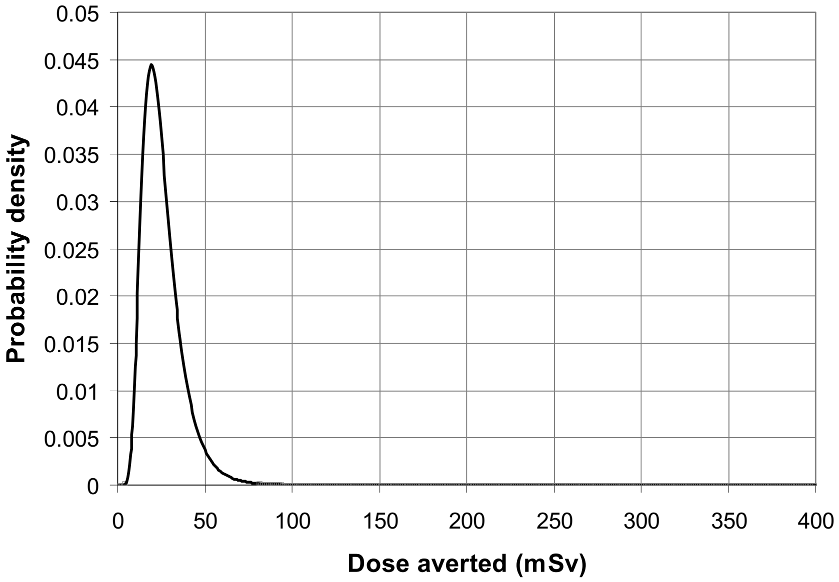

Fig. 11 – Probability density for dose in year 1 in Namie Town based on a geometric standard ratio of 1.54. Average dose = 25 mSv; 95th percentile dose = 46 mSv.

Table 14 – J-value assessment of the cost effectiveness of providing mental anguish payments and prefabricated temporary housing, assumed to be used until return when the dose in the home location has fallen to 20 mSv per year: 95th percentile heuristic. (LLE = loss of life expectancy).

Dose averted in year 1 (mSv)	Number of years until home dose rate $\leq 20\,\mathrm{mSv\,y^{-1}}$	Locations	LLE averted (days)	J-value
95	16	Tomioka Town	240	1.02
87	14	Okuma Town	212	1.04
70	10	Futaba Town	156	1.1
46	5	Namie Town	41	1.5

be mentioned that a report from Parungao (2014) suggests that the problem may continue into the 3rd year, giving an estimate of 1656 premature deaths from the stress of moving recorded in the first 3 years after the Fukushima Daiichi accident.

A generalised and simplified actuarial model was programmed to represent the key features of the situation. Based on the assumption that the premature deaths affected only elderly people, an increase in the hazard rate was calculated for year 1 and year 2 amongst those relocated persons aged 70 years. Japanese demographics determine the fraction, 18%, of the people being relocated who will be 70 or over, that is to say 29,686 out of the total of 162,677 relocated persons. Thus the increase in the hazard rate was taken to be 1086/29,686 = 0.0366 $\mathrm{y^{-1}}$ in year 1 and 70/27,881 = 0.0025 in year 2, where the latter denominator takes into account the number of over 70 s dying in year 1, made up of the expected number of 720 and the 1086 excess deaths. Based on Japan life tables, the average loss of life expectancy amongst the 162,000 relocated persons due to the stress of the relocation programme turns out to be 37.5 days.

Using the MIB model to provide a 70-year dose profile associated with an initial, year 1 dose, it is found that 37.5 days of life expectancy would be lost by the average member of the community for an initial dose of 13 mSv in year 1. The dose, 13 mSv in year 1 followed by a 69-year MIB dose profile, would have caused equivalent harm to relocation. Thus it may be used as a yardstick, independent of the J-value, against which to judge the estimated first-year doses without relocation given in Table 12.

Under the assumption that a full spread of ages typical of Japanese demography is represented in each settlement, relocation becomes more dangerous than radiation exposure for the settlement's inhabitants when the first year's radiation dose lies below 13 mSv. This is the case for all locations except for Tomioka, Okuma, Futaba and Namie Towns. Residents in Naraha Town, Tamura City, Minamisoma City, Hirono Town, Kawauchi Village, Katsurao Village, Iitate Village and Kawamata Town, whose averted doses were less than 13 mSv in the first year, would, by this criterion, have been better off if they had not been relocated.

The simplified model assumes that the old people live within the community, and it is known that many of the old people affected by the Fukushima Daiichi accident were in fact housed separately in old people's homes and nursing homes. Hence it could be argued that a different criterion could and should be set for these older people, allowing them to remain in situ while others around them were evacuated. But there is a limit to the degree of separate living possible for older people in care, since old people's homes and nursing homes are reliant on proper staffing. Those caring staff will need to live reasonably close by, and real problems must occur if the settlements in which the staff live have been issued with an instruction to relocate. How are the service needs of the old people's and nursing homes to be met if everyone around is moving out? This consideration places the old people back in the community, suggesting that the analysis of the simplified model would once again be at least approximately valid.

7. Discussion

In the early stages of a severe nuclear accident, there must always be a degree of uncertainty on the course that the accident will follow. It is accepted that this uncertainty may lead to a desire for precautionary measures that subsequently turn out to be exaggerated in the light of later knowledge that the accident was more limited than previously thought. However, our work is showing the clear difficulty in justifying the very large population relocations instituted following Chernobyl and Fukushima on grounds of radiological risk.

We concur with Lochard, Schneider and Kelly, whose basic finding was that there was no radiological or economic case for a second mass relocation from Chernobyl in 1990. Unfortunately their recommendation was not followed and 220,000 people were relocated post 1990 in addition to the 116,000 relocated in 1986.

We have examined the first, 1986 relocation after the Chernobyl accident, and shown that it is possible to justify the relocation of 31,000 in the Base Case, with an upper bound of 72,500, a number obtained when the 95th percentile heuristic is invoked in addition to the J-value. See Table 10. These numbers represent between 9% and 22% of the 335,000 total of people eventually relocated after Chernobyl. The modelling is subject to inevitable simplifications and approximations and no claim is made that these figures are fully accurate. But the scale of the difference between what actually happened and what both we and the earlier authors, Lochard, Schneider and Kelly, have concluded makes it clear that, viewed from the perspective of radiological health and economics, the actual figure of 335,000 people relocated must be regarded as much too high.

It may be possible to explain the reasons for this apparent overreaction and attendant disruption of people's lives by reference to political considerations. As noted earlier, Lochard and Schneider (1992) suggested that money was being spent on "direct or indirect compensation for those who may have been affected by the accident, mainly from the psychological point of view, in order to improve the public acceptability of the situation." But if this was indeed the case, then those charged with spending the public's money ought to have made it clear that this was their intention, and that their primary purpose was not to reduce exposure to radiation when, according to Lochard and Schneider: "A large fraction of the money already spent (or to be spent in the next few years) on improving living conditions will achieve little or no reduction in dose."

Transparency is required, in conformance with the conclusions of the World Health Organization's Chernobyl Forum Expert Group on Health (2006):

> "What the Chernobyl disaster has clearly demonstrated is the central role of information and how it is communicated in the aftermath of radiation or toxicological releases. ... Nuclear activities in Western countries have also tended to be shrouded in secrecy. The Chernobyl experience has raised the awareness among disaster planners and health authorities that the dissemination of timely and accurate information by trusted leaders is of the greatest importance."

Such transparency could be satisfied by adopting the "balance sheet" approach (Taylor et al., 2003), by which the socio-political concerns are set down clearly before judging how far they should influence the final decision. Thus it is advisable, when taking decisions on public safety, to ascertain the cost effectiveness of actions contemplated by applying the J-value to establish a baseline. Socio-political factors may then be considered, which, in the case of relocation following a nuclear accident, might include:

- allowing for uncertainty regarding costs and projected doses
- avoiding splitting affected communities where possible
- a wish to reduce public anxiety over health impacts from radiation
- a desire to reassure communities that an adequate response is being made

and, possibly,

- a desire to be seen to be going above and beyond the call of duty as regards risk reduction measures.

But it is important that the reasoning be presented transparently to allow a balanced assessment to be made on whether or not to move away from the baseline in making the decision.

Against the socio-political considerations discussed in the previous paragraph must also be set the possibility that actions taken to allay fear may cause more harm than good. There is now considerable evidence to show that using relocation as a means of providing reassurance and minimising initial stress may not necessarily be the best strategy in the longer term. Relocation itself can lead to very significant stress and concern in the longer term. Indeed the World Health Organization (2006) has concluded that for those relocated following the Chernobyl accident

> "Evacuation and relocation proved a deeply traumatic experience to many people because of the disruption to social networks and having no possibility to return to their homes. For many there was a social stigma associated with being an 'exposed person'."
>
> (See also World Health Organisation (2016), which states:
>
> "The psycho-social impact of disasters and emergencies has been well documented. It has been reported to be the Chernobyl accident's main public health impact that affected the largest number of people.")

This would suggest that socio-economic well being may indeed have been reduced for Chernobyl's relocated people. As noted earlier in the text, Strigini et al. (2017) reported a 2-year reduction of life expectancy for 40–85 year olds associated with low socio-economic status. A penalty of this order would outweigh significantly the benefits calculated for moving away from a contaminated area for the overwhelming majority of people relocated after Chernobyl.

The present study suggests that mass relocation after Fukushima Daiichi was also a poor policy response. The J-value analysis shows that relocation option was not justified even for the most contaminated areas of Tomioka and Okuma. Relocation has been shown to have caused a fall in the notional life quality of the residents of these towns, as measured by the life quality index. It is possible that the very extensive population relocations effected in the months and years following the Chernobyl accident set a precedent, now shown to have been largely unjustified.

It is instructive to examine the significant difference between the information available to the authorities just after the Chernobyl accident in April 1986 and what was available to them four years later. The principal uncertainty on 26 April

1986 was how long the release of radioactive material was going to continue and hence how much would be deposited as fallout. This uncertainty was resolved after 10 days when the fires on the stricken plant were extinguished and the release was found to have stopped. However further time was needed to set up the monitoring of radiation levels on the ground for all the districts affected by fallout, both close to and distant from the plant. Developing a model to take the radioactivity readings and then predict doses to the individuals living in the affected areas would have taken additional time.

Clearly such information was not available to the decision makers in the immediate aftermath of the Chernobyl accident, but the necessary radiation monitoring was in place by 1990, allowing spatially distributed readings of ground radioactivity. In addition, the predictive MIB model had been developed, allowing estimates to be made of the radiation doses (external and internal) that people in different areas would receive as the radioactive contamination decayed in each of the succeeding years. The model and these data, both available by 1990, were the basis of Lochard and Schneider's finding against a further mass relocation at the time, a conclusion endorsed by the more modern and validated J-value method, which uses the CLEARE programme to calculate the loss of life expectancy caused by the falling profile of radiation doses over 70 years, for example.

Had both a good monitoring system for surface contamination and an appropriate contamination-to-dose model been available in advance of the Chernobyl accident in 1986, then a good platform for taking sensible decisions on relocation would have been in place and could have been applied as soon the situation stabilised, in the event after 10 days. A similar observation may be applied to the accident at Fukushima Daiichi in 2011, where "after two weeks, the three reactors (units 1–3) were stable with water addition" (World Nuclear Association, 2017). Given such a degree of information-preparedness prior to a big nuclear accident, an on-line J-value decision making tool could be applied to guide decisions on relocation. The decision makers on the ground would then have access in real time to the sort of information contained in this paper, and could take their decisions on relocation accordingly.

A precautionary and temporary evacuation might have been a reasonable policy response in the first phases of the Chernobyl and Fukushima Daiichi accidents, when the final degree of radioactive contamination could not be estimated with a good degree of certainty because the situation had not stabilised, a process that took about 2 weeks in each case. There is a recent precedent for a large-scale but temporary evacuation downstream of the Oroville Dam, a combined water resource and energy generation installation situated on the Feather River in California. Exceptionally high water flows down the main and emergency slipways led to erosion damage in both these overflow channels and the consequent fear that the emergency slipway would fail. This led to a temporary evacuation order being placed on 180,000 people in northern California on 12 February 2017 (BBC, 2017a), an order that was lifted 2 days later when slipway repairs had been effected and a significant amount of water had been drained from the reservoir (BBC, 2017b).

But even before the deposition of fallout is complete or expected to be complete in a big nuclear accident, a process that took about two weeks at both Chernobyl and Fukushima Daiichi, the availability of:

- spatially distributed, real-time measurements of ground contamination (an innovation that modern technology could make viable)
- a prediction model for current and future dose such as the MIB model
- a model, such as CLEARE, to convert dose into loss of life expectancy
- a J-value program to provide evolving J-value guidance

would allow decision makers to make sensible judgements on who should be evacuated on a temporary basis. The number of people asked to leave their homes if only for a short time could then be minimised so as to keep disruption to a minimum.

It is not a good idea to evacuate people unless strictly necessary because evacuation and relocation are not risk-free options in terms of physical well-being. Not only are there penalties in terms of people's life quality, but also directly to their physical health. The simple modelling of Section 6.3, which is independent of the J-value, points to evacuation and relocation having, on average, a higher risk of death than staying in place when the doses averted by moving are low. The evidence points to the need for evacuation to be used carefully and sparingly, and relocation even more so.

Our study provides evidence-based support for the questioning by Japanese medical professionals of the policy of relocation. For example, Ohtsuru et al. (2015) stated that:

> "On the basis of these findings, immediate relocation might not be the best option, especially for vulnerable populations."

They comment, further, that the public is likely to look to medical personnel, in the first instance, for information on radiation risk:

> "In such a disordered situation, doctors, public health officers, and nurses are often asked to explain the risks and provide scientific information to the community as risk communicators."

They highlight the fact that psychological harm may predominate over radiation-induced harm:

> "past experiences of nuclear disasters show substantial effects on health and society, irrespective of the magnitude of radiation effects."

This opinion is endorsed by Hasegawa et al. (2015):

> "past experiences suggest that common issues were not necessarily physical health problems directly attributable to radiation exposure, but rather psychological and social effects."

Linking these effects to fear of the effects of radiation, Hasegawa et al. concluded that:

> "The psychological effect on adults was strongly associated with risk perception."

A similar point is picked up in the Lancet Editorial in the same issue (Lancet Editor, 2015):

> "the understanding of nuclear risk by most clinicians — and especially by the general public — has not advanced as deeply or as widely as has the uptake of nuclear technology."

The tendency to overestimate nuclear radiation risks is highlighted in a recent paper on Hiroshima and Nagasaki survivors by Jordan (2016):

> "In essence, survivors having received 1 Gy irradiation (~1000 mSv) have a significantly elevated rate of cancer (42% increase) but a limited decrease of longevity (~1 year), while their offspring show no increased frequency of abnormalities and, so far, no detectable elevation of the mutation rate. . . . Yet the general public, and indeed most scientists, are unaware of these data: it is widely believed that irradiated survivors suffered a very high cancer burden and dramatically shortened life span, and that their progeny were affected by elevated mutation rates and frequent abnormalities. In this article, I summarize the results and discuss possible reasons for this very striking discrepancy between the facts and general beliefs about this situation."

Part of the problem in understanding the risk from radiation is the difficulty that everyone, including scientists, has in dealing with uncertain hazards. Mathematicians have devised an extensive and powerful theory of probability to describe such situations, but the probability figure in itself is not easy to understand or interpret. Radiation at low doses, the only dose-levels experienced by a member of the public after a nuclear reactor accident, is just such an uncertain hazard in the sense that a small fraction of the people exposed may die from a radiation-induced cancer some decades into the future, but it cannot be predicted in advance which people will be unlucky in this way.

Based on the ICRP recommended risk figure for a member of the general public of 5×10^{-5} per mSv (ICRP, 2007), someone receiving a dose of 10 mSv within a year has a 0.05% chance of dying before his or her natural lifespan as a result. Perhaps that can be understood as a small risk, but even then it is hard for anyone to get an intuitive feel for how different 0.05% is from, say 0.13% or 0.008%, for example. But now suppose that, following a big nuclear accident, the dose affecting people in a neighbouring town is 50 mSv in the first year (similar to the worst affected Japanese towns after the Fukushima Daiichi accident) and then follows the MIB dosimetric model discussed in Section 4.2. Hence the dose falls with time as shown in Fig. 10, taking 57 years to get down to be the same level as the natural background radiation of 2 mSv per year. If probabilities are chosen as the way of communicating the risk, then people might be told that they faced a probability of dying of 0.25% as a result of radiation exposure in year 1, 0.20% as a result of exposure in year 2, 0.17% as a result of radiation exposure in year 3 and so on. A more compact single figure for the overall average probability of dying as a result of radiation exposure could be worked out, but that would still suffer from the disadvantage that most people would struggle to interpret it and put it into context, as discussed above.

A fundamental problem is that a statement of the probability of death from a radiation cancer contains no information on when that death will occur and how much life will be lost. But being killed immediately is a very different proposition from being killed in 60 years' time, say, when the person may have had the chance to live a long and potentially very full life. The probability of radiation-induced death at some unspecified time in the future contains less information than the statistic of life expectancy lost, which is innately more informative as a result of incorporating the additional, actuarial knowledge tabulated in the life tables. Loss of life expectancy provides a scale that is able to differentiate between early and delayed death in a way that the bare probability of death from a radiation cancer cannot.

The J-value has change in life expectancy at its heart, as discussed in Section 4.2, with examples given in Table 5. The calculation for a given population is not trivial, and the loss of life expectancy for a given radiation dose profile will differ somewhat from country to country (although it will be similar for countries at a similar level of development).

But once calculated the change in life expectancy is simple to understand. The basic meaning will be taken on board easily by most people, who gain familiarity from their earliest years with the concept of personal age through celebrating their birthdays.

Thus if a town in the UK were subjected to nuclear radiation with the dose profile shown in Fig. 10, the loss of life expectancy amongst the residents of the town, including those being born during its duration, can be calculated to be 4⅔ months, based on the UK life tables for 2009. This is not a trivial loss, but it may be put in context by comparing it with variations in life expectancy amongst the UK population. As noted earlier, the average person living in Harrow in London can expect to live about 3¼ years longer than the average person domiciled in Manchester (ONS, 2015).

A loss of life expectancy of 4⅔ months does not mean that everyone's life will be curtailed by exactly 4 months and 20 days. Most people in the affected town would live out their full lifespan, but there would be some who would die early. No definite figure can be given to how early, but it has been shown elsewhere (Thomas, 2017b) that the loss of life expectancy experienced by radiation victims will be about half what they would have lost had they been victims of a fatal road or rail accident or a fatal explosion. This is mainly because, although the latency period before the onset of a fatal cancer will be variable, it will usually be long, often decades long.

The loss of life expectancy amongst the affected population caused by a one-off or a continuing radiation dose is proposed as a very good alternative for communicating the size of the risk both to experts and to lay persons.

8. Conclusions

Earlier work (Thomas et al., 2006a,b) has used the J-value to demonstrate that there can be a significant variation in the resources committed to the reduction of risks across a wide range of areas requiring societal judgements, leading to an unintended but inequitable distribution of resources. We contend that proposed decisions should be judged first on the basis of their cost effectiveness, where the J-value provides a baseline for decision making across all sectors.

In the case of the mass relocations after the big nuclear accidents at Chernobyl and Fukushima Daiichi, it is clear that many of the measures taken were not cost effective, resulting in only a small restoration of life expectancy and high J-values. Resources were committed that might have been used to greater effect elsewhere, and there is a danger that misleading precedents might have been set.

While there are uncertainties attached to the doses and costs used, we have used the best estimates available to us. Specific allowance for uncertainties in the doses associated with the first, 1986 relocation at Chernobyl has been made through the inclusion of a Sensitivity Study whereby internal doses are doubled. The numbers justified for the first relocation at Chernobyl in 1986 have been tested further using the 95th percentile heuristic, implying that the countermeasure would exceed what was necessary for 95% of the affected population. The highest number of people who should have been relocated in 1986, based combining the J-value with the 95th percentile heuristic, comes to only about two thirds of the 116,000 who were actually moved out, never to return.

We confirm the earlier work of Lochard, Schneider and Kelly who found that further relocations after 1986 were not justified on radiological health grounds following the Chernobyl accident and concluded against the post-1990 relocation of 220,000 people. We deduce that only between 10% and 25% of the total number relocated in total after Chernobyl can be justified. A quarter of a million or more people appear to have been moved unnecessarily.

Given the Japanese Government's 20 $\text{mSv}\,\text{y}^{-1}$ safe-return dose, we find that no relocation was justified on scientific and economic grounds after the accident at Fukushima Daiichi. This finding is robust against the 95th percentile heuristic.

While inclusion of more precise knowledge on radiation dose profiles, should they become available, might influence exact numbers, any changes are unlikely to affect the main conclusion arising from the J-value analysis, namely that relocation should be used sparingly after a major nuclear reactor accident and quite possibly not at all. It is shown in a companion paper (Waddington et al., 2017) that remediation measures can reduce radiation exposure at reasonable cost, and it is suggested that these may provide a better and more proportionate response after a large nuclear accident.

The availability before the event of a system taking spatially distributed measurements of ground contamination in real time would open up the possibility of developing an on-line J-value tool to aid decision makers at the time of a major nuclear accident.

It is accepted that the number of people actually relocated after a major nuclear accident may be influenced by a range of other socio-political issues. This is particularly the case when, in the words of the Lancet Editor, "the understanding of nuclear risk … by the general public has not advanced as deeply or as widely as has the uptake of nuclear technology".

However it will be best for all concerned if the factors involved in the decision are identified and addressed transparently, including a statement of the J-value figure, so that the effect of each on the final decision can be made clear.

It is plain that medical professionals are seeking a better way of understanding the risk from nuclear radiation both for their own information and so that they can communicate an accurate picture to the people in their care who look to them for impartial advice. While the J-value offers a way of balancing the risk against the amount that should be spent mitigating or countering it, as demonstrated above, it is suggested that providing the calculated loss of life expectancy associated with various scenarios offers a good way of communicating the level of risk to lay people and professionals alike.

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Professor Thomas's contribution to the paper was written mainly since he has been with the Safety Systems Research Centre in the Queen's School of Engineering at the University of Bristol and he is grateful to that University for its sponsorship of open access publication in fulfilment of EPSRC's wishes.

Appendix A. Deriving the mean of a lognormal distribution from a given value for a general percentile given the geometric standard deviation

Let the distribution of the random variable, X, be lognormal, with the mean and standard deviation of X being μ and σ. By definition, the associated natural logarithmic variable, Y,

$$Y = \ln X \tag{A.1}$$

will be normally distributed. Let the mean of $Y = \ln X$ be m and the standard deviation of Y be s. A standard result (see, for example, Weisstein, 2015) gives m and s in terms of the parameters, μ and σ, of the underlying distribution for X as:

$$s = \sqrt{\ln\left(1 + \left(\frac{\sigma}{\mu}\right)^2\right)} \tag{A.2}$$

$$m = \ln\ \mu - \frac{1}{2}s^2 \tag{A.3}$$

The probability that Y lies below $m + ks$ follows from the properties of the normal distribution, so that

$$P\left(Y \le m + ks\right) = f\left(k\right) \tag{A.4}$$

where $f(k)$ is the probability that a normal variable is less than the mean plus k standard deviations:

$$f\left(k\right) = \frac{1}{\sqrt{2\pi}} \int_{z=-\infty}^{k} e^{-\frac{z^2}{2}}\, dz \tag{A.5}$$

where k may be positive or negative. Thus $f(-1.645) = 0.05$, $f(-1) = 0.1587$, $f(0) = 0.5$, $f(1) = 0.8413$ and $f(1.645) = 0.95$, for example. Since $X = e^Y$ from Eq. (A.1), X will be monotonically increasing in Y. Hence the probability, $P(Y \le m + ks)$, is also the probability that X lies below the exponential of $m + ks$:

$$P\left(X \le e^{m+ks}\right) = P\left(X \le e^m e^{ks}\right) = P\left(X \le e^m \left(e^s\right)^k\right) = f\left(k\right) \tag{A.6}$$

Putting $k = 0$ in Eq. (A.6) gives $P(X \le e^m) = f(0) = 0.5$, which defines the median, ϕ, of the underlying distribution:

$$\phi = e^m \tag{A.7}$$

Eq. (A.6) also allows a "geometric standard deviation", g_σ, to be defined as:

$$g_\sigma = e^s \tag{A.8}$$

Thus Eq. (A.6) may be rewritten:

$$P\left(X \leq g_\sigma^k \phi\right) = f(k) \tag{A.9}$$

It may be noted that the median must be less than the mean for any random variable with a lognormal distribution, a result that follows from exponentiating Eq. (A.3) and noting the definition of Eq. (A.7).

Suppose that the geometric standard deviation, g_σ, is given, together with a general percentile level, $x_{\max}(k)$, associated with the number, k, of standard deviations such that $Y \leq y_{\max} = m + ks$. Noting Eq. (A.9), the appropriate constraint on X is:

$$X \leq x_{\max}(k) = \phi g_\sigma^k \tag{A.10}$$

Eq. (A.10) allows the median, ϕ, of the underlying distribution for X to be calculated as

$$\phi = \frac{x_{\max}(k)}{g_\sigma^k} \tag{A.11}$$

It now follows from Eq. (A.7) that

$$m = \ln\ \phi = \ln \frac{x_{\max}(k)}{g_\sigma^k} \tag{A.12}$$

Meanwhile $s = \ln\ g_\sigma$ from Eq. (A.8), and so a rearrangement of Eq. (A.3) gives the mean of the underlying distribution, X:

$$\mu = e^{m+\frac{1}{2}s^2} = \phi\sqrt{e^{s^2}} = \frac{x_{\max}(k)}{g_\sigma^k}\sqrt{e^{(\ln\ g_\sigma)^2}} \tag{A.13}$$

Appendix B. Modelling the effect of discrete population settlements in Belarus

B.1 *General procedure*

Let the population of a region be N, divided among M villages or settlements, each of different size, N_i, and with an average value, $\bar{N}_i = N/M$. Let each settlement be subject to a radiation dose, Z, in year 1 that is lognormally distributed, defined by a mean radiation dose of μ_i mSv and geometric standard deviation, g_σ, that is common to all settlements, as per UNSCEAR (2000), page 478, which gives $g_\sigma = 1.54$. See also Section 5.2 above. The standard deviation, s, of lnZ for each settlement will then be the same for each settlement and follow from Eq. (A.8) as

$$s = \ln\ g_\sigma \tag{B.1}$$

The number of people in settlement, i, expected to receive doses between z_{j-1} and z_j mSv will then be

$$n_{ij} = \frac{N_i}{s\sqrt{2\pi}} \int_{x=z_{j-1}}^{z_j} \frac{1}{x} \exp\left[-\frac{(\ln x - m_i)^2}{2s^2}\right] dx \tag{B.2}$$

The total number of people across all settlements, N_j, expected to receive doses between z_{j-1} and z_j mSv may then be found by addition:

$$N_j = \sum_{i=1}^{M} n_{ij} \tag{B.3}$$

The probability, P_j, that a person selected at random from the whole population of N people would receive a dose between z_{j-1} and z_j mSv may then be estimated as:

$$P_j = \frac{N_j}{N} \tag{B.4}$$

P_j, will be a close approximation to the probability density: $p_Z\left(z_j\right) \approx P_j$ when the dose interval, $z_j - z_{j-1}$, is chosen to be 1 mSv.

The procedure has been applied to the Base Case (Section 5.1.2 and Fig. 4) of the 24,725 persons relocated in 1986 from Belarus.

B.2 *Geometrical progression of mean settlement doses*

The overall distribution of the total doses (internal plus external) received by the relocated Belarusians *if they had not moved* has been shown to be approximately lognormal (see Fig. 4), making it natural to assume that the mean doses in the settlements would have varied in a geometric progression:

$$\mu_{i+1} = r\mu_i \quad i = 1, 2, ..., M \tag{B.5}$$

Here r is a constant and μ_i is the mean radiation dose of settlement i. Hence

$$r = \left(\frac{\mu_M}{\mu_1}\right)^{\frac{1}{M-1}} \tag{B.6}$$

The mean dose for settlement 1 was selected to be the mid point of the first dose interval: $\mu_1 = 6$ mSv, while the Mth settlement was assumed to receive a mean dose equal to the average for the highest dose band and so $\mu_M = 612$ mSv. Then the numbers, N_i, of people in all but one (*viz.* $M - 1$) of the villages were varied so as to achieve a probability distribution for individual dose as close as possible to the stepped distribution shown in Fig. 4.

This process was carried out for cases corresponding to $M = 2, 3, \ldots, 35$ and then for $M = 48$, 49 and 50 and for the individual values, 75, 100 and 108. The number of Belarusian settlements subject to relocation in 1986 was, in fact, 108 (see Table 20 of UNSCEAR, 2000). Putting $M = 5$ produces the probability density shown with the dotted line in Fig. 12, while setting M to 108 gives the probability density shown in Fig. 13.

The match to the stepped curve derived from the UNSCEAR (2000) data is fairly good when $M = 5$, but it is clearly improved when $M = 108$. The much larger number of control variables available in the latter case allow the "higher frequency" variations to be captured more effectively.

Fig. 14 shows the population of each settlement when $M = 5$, while Fig. 15 shows the populations of each village when $M = 108$. After allowing for scaling, the general shape of the two curves is similar, but there is clearly a much finer gradation in mean dose when $M = 108$. This is brought out more clearly in Fig. 16, which graphs mean settlement dose against settle-

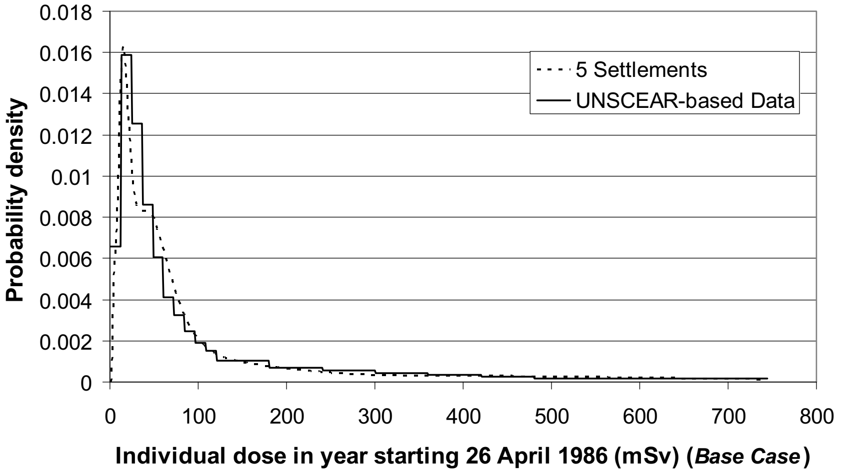

Fig. 12 – The overall probability density for dose in year starting 26 April 1986 found when the number of settlements is $M = 5$ and that derived from the UNSCEAR (2000) data as summarised in Table 8 with $\bar{\rho}_{Bel}$ =0.2. Belarus Base Case.

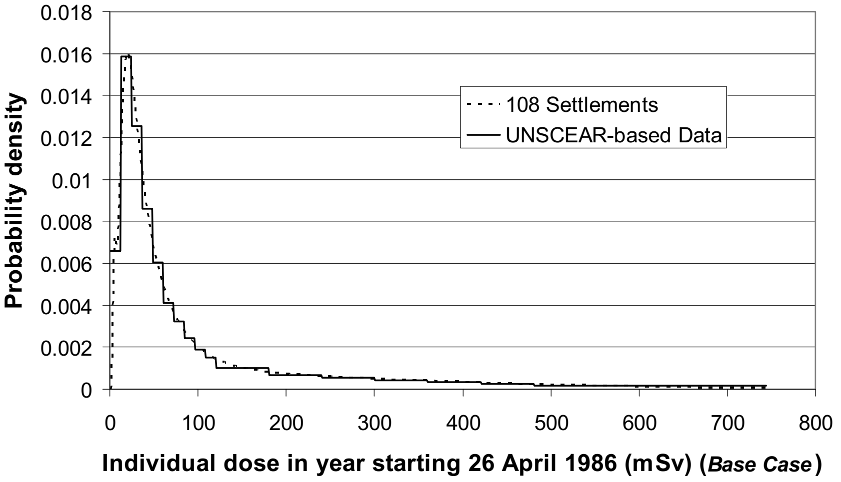

Fig. 13 – The overall probability density for dose in year starting 26 April 1986 found when the number of settlements is $M = 108$ and that directly from the UNSCEAR (2000) data as summarised in Table 8 with $\bar{\rho}_{Bel}$ =0.2. Belarus Base Case.

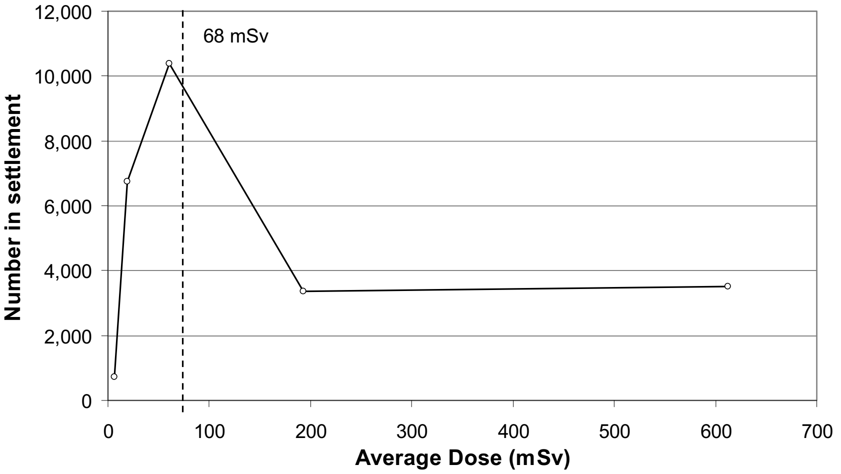

Fig. 14 – The population of each settlement when the number of settlements is $M = 5$. Belarus Base Case.

ment number. The mean dose profile is beginning to resemble a continuum.

The number of people living in settlements with a mean dose of 68 mSv or more (derived under the 95th percentile heuristic; see Section 5.2) is found by summing the numbers in each community with an equal or higher dose—to the right of the 68 mSv line in Figs. 14 and 15:

$$N_{\mu_i > 68} = \sum_{i:\mu_i \geq 68} N_i \tag{B.7}$$

The probability that someone selected at random from the population will live in a settlement with a mean dose of 68 mSv or more will then be $N_{\mu_i > 68}/N$.

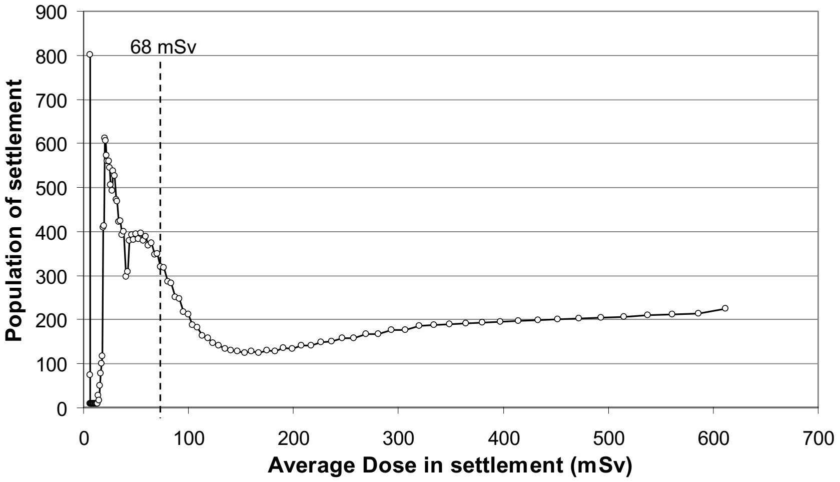

Fig. 15 – The population of each settlement when the number of settlements is $M = 108$. Belarus Base Case.

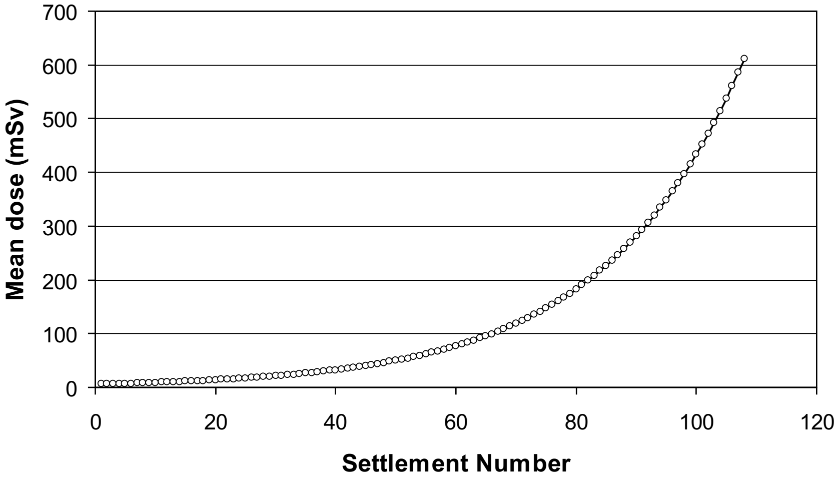

Fig. 16 – Mean dose for year starting 26 April 1986 vs. Settlement number for $M = 108$. Belarus Base Case.

The minimum feasible value of M, namely $M = 1$, corresponds to the case where all the inhabitants belong to the same settlement. Since the mean dose for these people if they had not been relocated would have been 110 mSv (see Section 5.1.2), it follows that $N_{\mu_i > 68} = N$ and so $N_{\mu_i > 68}/N = 1$ at $M = 1$.

The theoretical, maximum value of M corresponds to the situation where the population is so dispersed that there is one village for each person, so that, in the case of the relocated Belarusians, $M = 24{,}725$.

The general behaviour of $N_{\mu_i > 68}/N$ vs. M is shown in Fig. 17, which shows that it falls rapidly for low M before steadying out at an asymptotic value corresponding to the theoretical, maximum value of M, namely 24,725, when the mean dose and the individual dose will converge. At this point $N_{\mu_i > 68}/N$ is equal to the fraction of individual doses equal to or higher than 68 mSv, derived from the stepped probability distribution of Fig. 4 as 0.375.

Fig. 17 shows that there is a good level of convergence for $M \geq 13$. The process of convergence may be understood by deriving the difference, Δ, between the closest mean dose and 68 mSv

$$\Delta = \left(\min_i |\mu_i - 68|\right) \times sgn\,(\mu_i - 68)\,|_i \tag{B.8}$$

and plotting this variable against the number of settlements, M. See Fig. 18, which shows damped oscillations in Δ as M increases. The sequence of high and low values for Δ mirrors that for $N_{\mu_i > 68}/N$ shown in Fig. 17, and, moreover, the amplitudes of the swing are also well correlated. It is clear that the coverage within the range of mean dose values must increase with the number of settlements, M, as may be seen by comparing Figs. 14 and 15. Fig. 16 shows how densely packed the mean values have become at $M = 108$, at which point the mean dose of 68 mSv is bracketed within the interval (67.51, 70.49), so that $\min_i |\mu_i - 68| = 0.49$ mSv. Clearly $\min_i |\mu_i - 68| \to 0$ as M increases to very large values, suggesting that the oscillatory behaviour of Δ and the linked behaviour of $N_{\mu_i > 68}/N$ will both settle as the asymptotes are approached.

B.3 Sensitivity study: arithmetic progression of mean settlement doses

The assumption of a geometric progression of settlement doses was tested by using an alternative, namely an arithmetic progression, so that the mean dose in settlement $i + 1$ is given by

$$\mu_{i+1} = \mu_i + a \quad i = 1, 2, \ldots, M \tag{B.9}$$

where a is a constant dose interval given by

$$a = \frac{\mu_M - \mu_1}{M - 1} \tag{B.10}$$

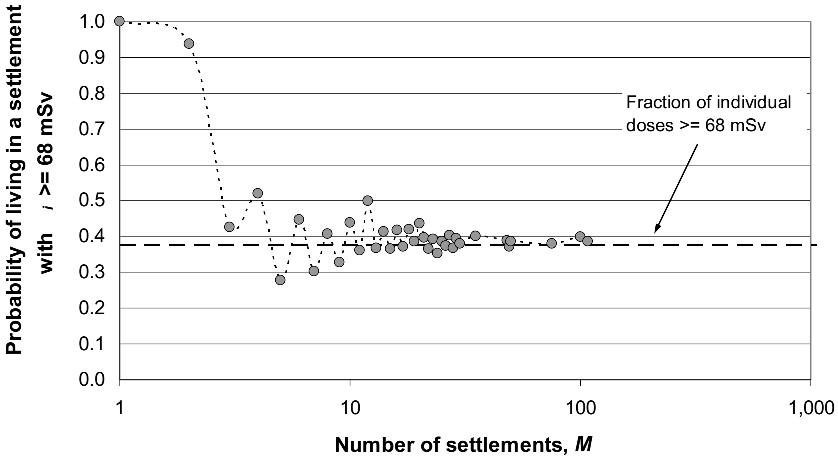

Fig. 17 – Probability of living in a settlement with a mean dose greater than 68 mSv in year starting 26 April 1986, $N_{\mu_i>68}/N$, versus the number of settlements, M. Belarus Base Case.

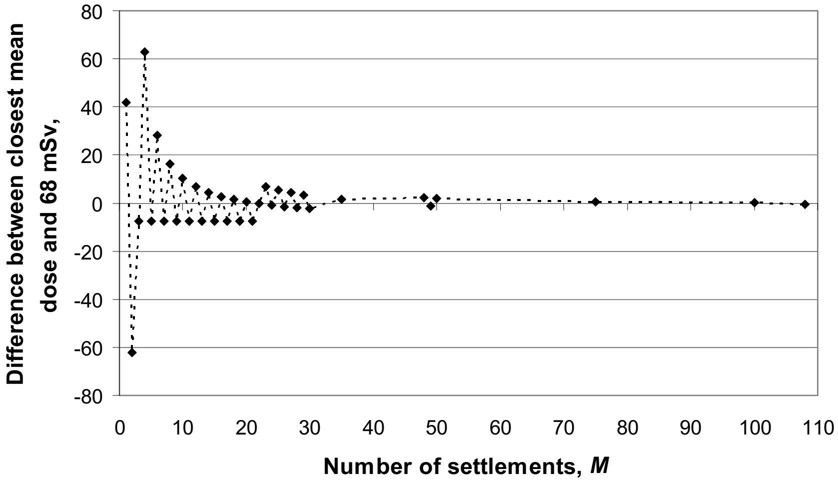

Fig. 18 – Difference between the closest mean dose in year starting 26 April 1986 and 68 mSv versus the number of settlements, M. Belarus Base Case.

The arithmetic progression in mean settlement dose appears to be a poorer model than the geometric progression, as it is unable to provide a good match to the stepped probability density of Fig. 4 for individual dose for values of M below about 30. Nevertheless the arithmetic progression is able to provide a fit that is comparable to that produced by the geometric progression when $M \geq \sim 30$.

But, although it is possible to see some pattern in the populations assigned to the different settlements under the arithmetic and the geometric progressions in mean dose, the populations of the individual settlements differ significantly from one progression to the other. This is illustrated in Fig. 19, which gives results when the total number of settlements corresponds to the Belarusian case, namely $M = 108$.

Despite the wide variation in the settlement populations between the progressions, however, the cumulative number of people living in settlements where the mean dose is less that any specified level is similar under both progressions, as shown in Fig. 20. The fractions of people predicted to be living in settlements with a mean dose at or above 68 mSv are similar under both dose progression models: 0.387 under the geometric progression and 0.399 under the arithmetic progression at $M = 108$. Parallel results come when $M = 30$, where the corresponding figures are 0.379 and 0.372.

These figures are all close to the asymptotic value of 0.375, despite the populations predicted for the individual settlements varying significantly. The locus of $N_{\mu_i>68}/N$ shown in the right-hand half of Fig. 17, where $M \geq 30$, can be expected to be reproduced approximately by a range of possible progressions for mean dose across the Belarusian settlements.

B.4 *General application to Belarus*

The Belarusians relocated in 1986 came from 108 settlements in Belarus, a number well above 30. Hence if the average doses in the settlements lead to a probability density for individual dose that matches the one shown in Fig. 4, the proportion of the relocated population coming from settlements with a mean dose level above 68 mSv will be similar to the cumulative probability above a dose of 68 mSv calculated from the probability density for individual dose shown in Fig. 4. This result is likely to hold for a broad range of distributions for mean doses in the settlements.

Appendix C. Modelling the effect of discrete population settlements in Ukraine

UNSCEAR (2000) Table 20 shows that the 91,406 Ukrainians relocated in 1986 came from a large number of settlements, *viz.* 75, but by contrast with the Belarus case, a dominating fraction, 54%, came from one place, the town of Pripyat (pop.

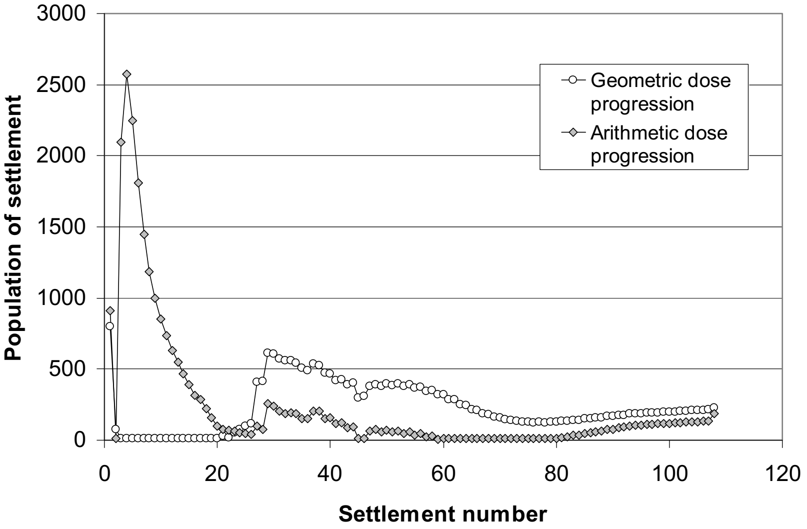

Fig. 19 – Settlement populations under the geometic and arithmetic progressions in mean dose, $M = 108$. Belarus Base Case.

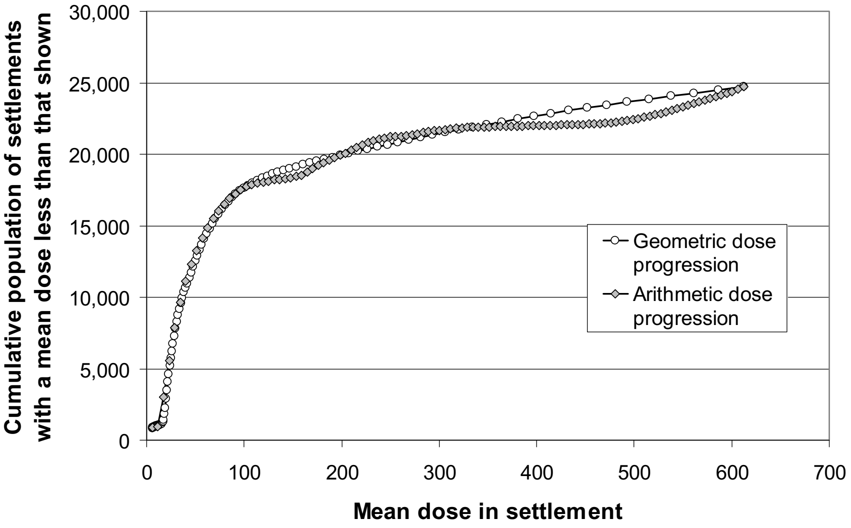

Fig. 20 – Cumulative population of settlements with a mean dose in year starting 26 April 1986 less than that shown on the horizontal axis. Belarus Base Case.

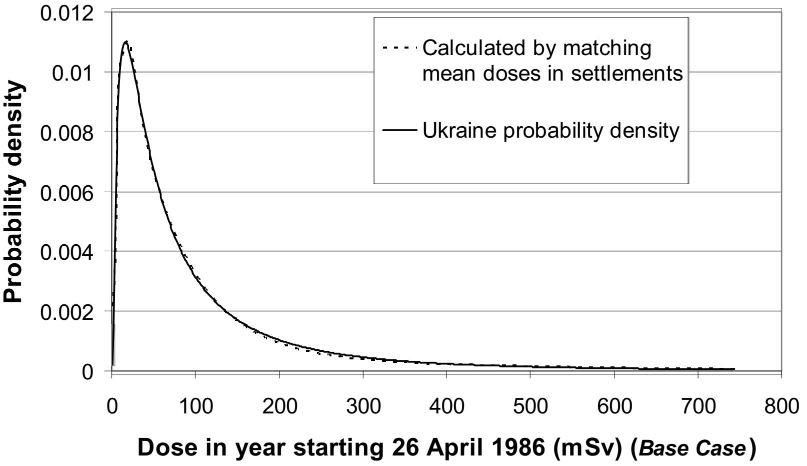

Fig. 21 – Probability density for dose in year starting 26 April 1986 for relocated Ukrainians if they had stayed in situ as in Fig. 6, compared with version derived under the assumptions of Appendix C.

49,360). Thus while Section "General procedure" of Appendix B will still be valid, a modification is needed in the later modelling of the discrete population settlements of Ukraine to account for this concentration of people in one town.

UNSCEAR's Table 20 gives the populations of 5 settlements, Pripyat, Railway Station Yanov (pop. 254), Burakovka Village (226), Chernobyl Town (13,591) and Bober Village (711). The populations of the 70 other settlements are not given and so

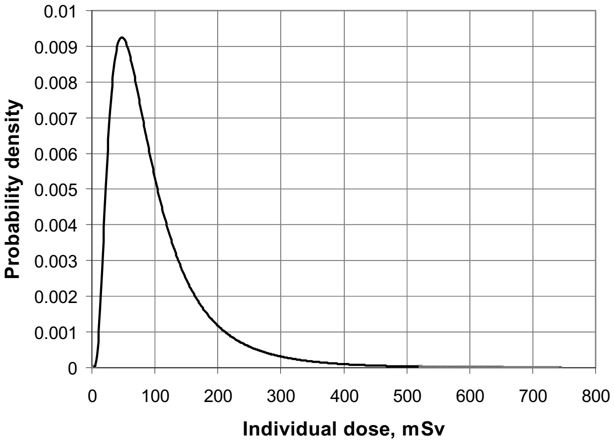

Fig. 22 – Estimated probability density for dose in year starting 26 April 1986 amongst inhabitants of Pripyat if they had remained in situ.

are assumed to have a size equal to the average for these villages, namely 390. With the settlement populations, N_i, $i=1, 2, ..., M$, ($M=75$), now fixed, variations may now be made to the $M-1$ settlement mean doses in year 1, μ_i, $i=1, 2, ..., M-1$ so as to achieve a good match to the Ukrainian probability density for individual dose shown in Fig. 6. The Mth mean dose follows from the constraint that the total manSievert burden is given.

It was found necessary, however, to adjust the geometric standard ratios, g_σ, for both Pripyat and also Chernobyl Town so as to achieve an acceptable match to the Ukrainian probability density. Rather than $g_\sigma=1.54$, the figure found appropriate for small villages, the geometric standard ratio for Pripyat emerges from the optimisation process as 2.04, while that for Chernobyl Town is estimated at 1.81. These higher geometric standard deviations would appear to be reasonable as these settlements are townships rather than the villages. The consequential larger complexity and geographical spread are likely to result in a greater spread in dose.

Fig. 21 compares the Ukrainian Base Case probability density of Fig. 6 with that found by summing the optimised number of people in 1 mSv dose bands and dividing by the total relocated population.

The optimum match occurs when the mean first-year dose is 101 mSv for the inhabitants of Pripyat, under the assumption they had stayed in situ. The town's majority contribution to the Ukrainian relocated persons means that the optimisation exercise is likely to act as a reasonably good estimator for the starting mean dose in Pripyat.

The probability density for dose amongst the citizens of Pripyat, shown in Fig. 22, has a greater spread than that illustrated in Fig. 9, where $g_\sigma=1.54$. The median dose is 78 mSv, and about 25% of Pripyat's inhabitants would have received the $J=1$ dose of 126 mSv, or more. Hence Pripyat's population of 49,360 should be relocated under the 95% heuristic.

A further 13,632 people would have been living in Ukrainian settlements with a mean dose greater than 68 mSv. Thus 49,360 + 13,632 = 62,992 people in all should be relocated from the Ukraine under the 95% heuristic.

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