Responding after a big nuclear accident***

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Managing the aftermath of a major nuclear reactor accident will necessarily take place in the media's spotlight, so it is essential to establish a rational set of accident management principles well in advance. The paper reports on the findings of a multi-university project that used diverse methods to explore how best to cope with a big nuclear accident. The dangers from a big reactor accident are reviewed, the three diverse methods are explained and the results are set out. These turn out broadly consistent with each other, and strongly indicate that the previous practice of moving people *en masse* was misguided. The requirements for online management information are discussed and ways of providing the necessary data are outlined. It is concluded that it is possible to be much more effective in reducing the harm to people living near a nuclear power station than in the past and to simultaneously significantly reduce the cost of an accident.

Keywords: Chernobyl, cost of consequences, evacuation, Fukushima, J-value, optimal control, relocation

1. Introduction

Anxiety about harm from radioactivity after a major nuclear reactor accident constitutes one of the great fears of our age.[1] This makes it inevitable that the aftermath of a big nuclear accident will be managed in the full glare of national and international media attention. Like all big, real-world problems, such management will be a multifaceted process, involving:

- science: nuclear physics
- technology: instrumentation and engineering
- medicine: radiation and psychology
- logistics

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1 Nuttall, W.J., Ashley, S.F. and Heffron, R.J., Compensating for severe nuclear accidents: an expert elucidation. *Process Safety and Environmental Protection* **112A** (2017) 131–142.

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- economics (the current method of managing a big nuclear accident such as Chernobyl or Fukushima costs more than 100,000 million USD)
- the general public
- the media
- politics and politicians.

The multiplicity of different aspects means that managing the situation after a big nuclear accident is a systems problem *par excellence*. One should, moreover, recognize that the problem has been handled far from optimally for the two biggest nuclear reactor accidents the world has experienced to date, Chernobyl (1986) and Fukushima Daiichi (2011).

Finding the right strategy in the event of a severe nuclear accident requires a dispassionate appraisal of the options, conducted well in advance. The paper will outline the findings of the multi-university NREFS project[2] that examined how best to cope after a big nuclear accident. The analysis is retrospective, hence blame is not apportioned to the authorities concerned, neither in the USSR in 1986 nor in Japan in 2011. Nevertheless, it is clear that the response fell well below the optimum in both these cases. The new and, in many ways, iconoclastic findings of the NREFS study[3] need be taken into account in future decision-making if harm to those living near the affected nuclear power plant is to be minimized.

2. What are the dangers from a big nuclear reactor accident?

To address fundamentals first, it is physically impossible for a commercial nuclear reactor to explode like an atom bomb. While explosions occurred at both Chernobyl and Fukushima Daiichi, these were either caused by the violent flashing of water into steam or were chemical in nature. In the latter case, the energy was suddenly released by the violent burning in air of hydrogen previously produced during the course of the accident as a result of the reaction between steam and hot graphite (Chernobyl) or by steam reacting with zirconium alloy (Fukushima). The ensuing blasts were relatively small and, in general, would have a low potential for harming any members of the public living in the neighbourhood of the power station.

Nuclear heat production does not, however, stop immediately the reactor shuts down—it takes 24 hours for the post-trip heat production to fall from 7% to 1% of full thermal power. For a commercial nuclear reactor, this implies heat generation falling from about 210 MW to 30 MW, which still represents a sizeable quantity of heat that needs to be removed. Big nuclear accidents happen when the cooling systems relied on to abstract the nuclear decay heat fail to function, allowing the core to melt. The molten core may then penetrate its containing vessel and open up a path between the highly radioactive core and the outside world.

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2 Management of **N**uclear **R**isk Issues: **E**nvironmental, **F**inancial and **S**afety, EPSRC grant reference number EP/K007580/1, a project involving: City, University of London; Manchester University; Warwick University; the Open University; and the University of Bristol, for which the author was Principal Investigator. See http://www.nrefs.org/. The project formed part of the UK–India Civil Nuclear Power Collaboration.

3 Thomas, P. and May, J. (eds), *Coping with a big nuclear accident; Closing papers from the NREFS project,* Special Issue of *Process Safety and Environmental Protection* **112A** (2017) 1–198. Available at https://www.sciencedirect.com/journal/process-safety-and-environmental-protection/vol/112/part/PA

Radioactive gases, vapours and gas-borne particulate matter can then escape and solid matter may be deposited as nuclear fallout in the immediate environs of the plant and beyond.

People living in the vicinity of the plant can then be exposed to both external radiation and an internal dose. The external dose can come from a layer of fallout deposited on the ground or from "shine" emitted by a transient "cloud" containing radioactive gas, vapour and air-borne particles. The internal dose can come initially from breathing in radioactive gases and air-borne particulate matter and subsequently from eating radioactively contaminated produce, either vegetables or animal products: meat, milk and cheese.

Based on the evidence from the worst-ever nuclear accident at Chernobyl, and the very bad nuclear accident at Fukushima Daiichi, the public will not be subjected to high-dose radiation, which would cause acute effects (radiation sickness, hair loss and, for very high doses, death). Instead they may experience low-dose radiation, where the danger is the induction of a potentially fatal cancer in 10–40 years' time (Figure 1). A mitigating factor is the substantial decrease in this low-level radiation that will occur over time, with the dose following a decay curve similar to that shown in Figure 2. For example, the dose imposed in the worst-affected town near Fukushima Daiichi, Tomioka, will have fallen from 51 mSv in the first year to 1 mSv/year after about 70 years, half the pre-existing background level in Japan (and the UK).

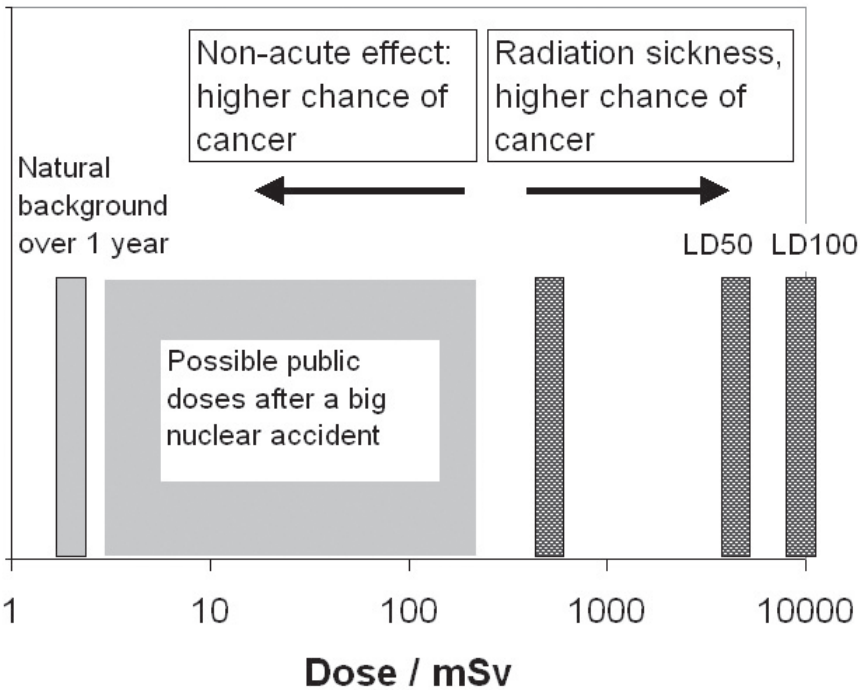

Figure 1. Possible doses to the public after a big nuclear accident.

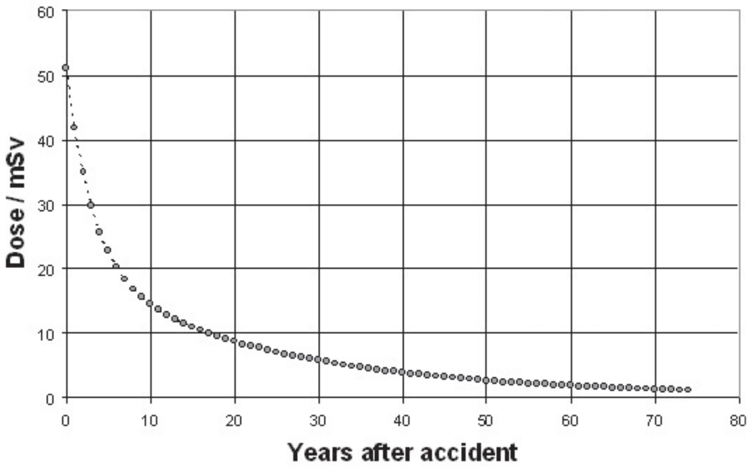

Figure 2. Predicted decay over time of dose from internal and external sources from a starting value of 51 mSv per year, the initial dose rate in Tomioka.

3. Policy options after a big nuclear accident

Possible policy options may be grouped into 6 main categories:

- Sheltering indoors in the early stages of the accident. This protects against cloud shine, ground shine and inhalation of radioactive gas and dust;
- Distribution of iodine tablets to protect against an increased chance of contracting thyroid cancer following the release of iodine-131 (half-life 8 days) and possibly other, shorter-lived iodine isotopes;
- Temporary evacuation. Here people will return to their homes within days or at most a few weeks. (This could be a precautionary measure while the extent of the problem is being determined.)
- Relocation—people are asked to abandon their homes for a long time or for ever;
- Temporary food bans (which may last a very long time);
- Remediation, comprising urban decontamination and agricultural decontamination.

Three diverse quantitative approaches were used in the NREFS study to assess the best way of applying such countermeasures:

- Optimal economic control applied to hundreds of potential reactor melt-downs in reactors under a variety of economic conditions across the world (led by Manchester University);
- Public Health England's nuclear accident consequence codes, PACE-COCO2, applied to a big accident at a fictional, commercial light-water reactor located in Southern England (led by the Open University);
- Judgement—(J)-value analysis of the responses after the Chernobyl and Fukushima Daiichi accidents (led initially by City, University of London and later by the University of Bristol).

4. Optimal economic control for hundreds of conceivable big nuclear accidents worldwide

The analysis[4] calculated the likely economic effects, including health, of a nuclear reactor accident similar in scale to a single reactor meltdown at Fukushima Daiichi, but taking place in different economies in the world. The most appropriate post-accident policy was found for each case.

Equations were developed to model: the deposition of radioactive fallout, radioactive decay and the harvesting of vegetation (see Figure 3); the dynamics of population movement (see Figure 4 for the first evacuation at Chernobyl); and the relationship of crop harvesting to the level of the local population. These features were then assembled into an intentionally simple model consisting of first-order differential equations in the two state variables, dose rate and local population level, together with a number of auxiliary algebraic equations. Three variables control the two model states, namely remediation rate, specific agricultural radioactivity extraction rate and target population level. Optimal control strategies for a range of different conditions were then found in order to maximize a value function using Bellman's principle of optimality.[5, 6]

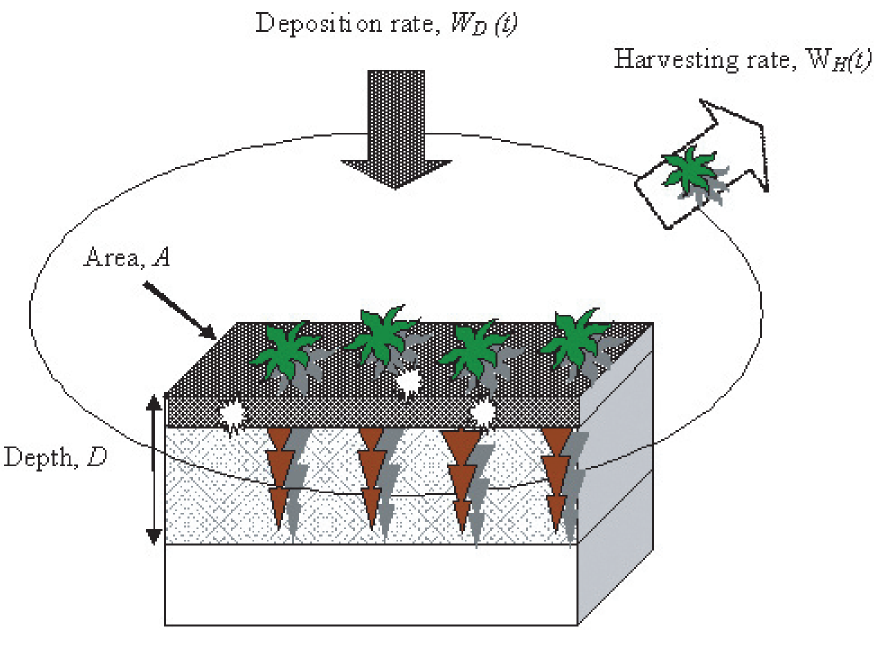

Figure 3. Radionuclide deposition, growth of vegetation and harvesting (directly or via animal produce).

4 Yumashev, D., Johnson, P. and Thomas, P.J., Economically optimal strategies for medium-term recovery after a major nuclear reactor accident. *Process Safety and Environmental Protection* **112A** (2017) 63–76.

5 Bellman, R., Dynamic programming and Lagrange multipliers. *Proceedings of the National Academy of the United States of America* **42** (1956) 767–769.

6 Bellman, R.E., *Dynamic Programming*. Princeton: University Press (1957, 2010).

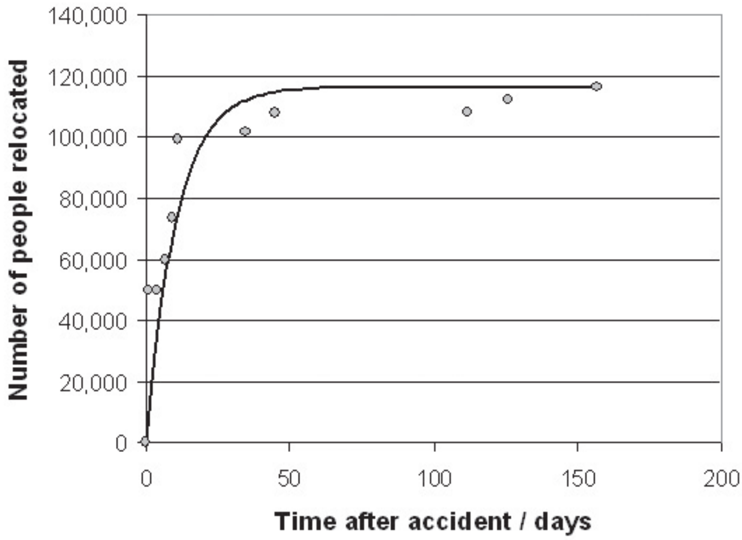

Figure 4. The dynamics of the mass relocation of people, Chernobyl 1986.

Allowing for the different economic conditions that could characterize the location of nuclear reactors worldwide, the optimal strategy for 84% of the base cases comprised:

- early remediation
- no food ban
- partial population relocation followed by full repopulation.

No relocation at all was advised for the remaining 16% of base cases.

A set of sensitivity studies was carried out. Even in cases that were deliberately skewed to reduce or eliminate the costs of moving, permanent relocation was advisable for fewer than 2% of cases.

5. Application of the nuclear accident consequence codes, PACE–COCO2, to a big accident at a fictional nuclear reactor

PACE and COCO2 were applied to estimate the effects of a core melt accident occurring at a fictional light water reactor based on the South Downs of England, 30 miles from Southampton and 45 miles from Central London. PACE is a **p**robabilistic **a**ccident **c**onsequence **e**valuation code, written by Public Health England (PHE), which calculates the spread of fallout from a specified accident and radioactive release. COCO2 is PHE's **co**st of **co**nsequences code, version **2**, which calculates the economic cost of the fallout dispersed (including health costs). The accident specified a release of radioactive material similar to that from a single reactor at Fukushima Daiichi.

The safe-return dose was set at 10 mSv over the ensuing 12 months, with the final test for this condition made 3 months after the accident. This is half the safe-return dose set by the Japanese authorities at Fukushima Daiichi and may be put in context by noting that a dose of 10 mSv per year for 50 years continuously would reduce the life expectancy of people in the

UK by 4½ months. For comparison, this is the life expectancy that Londoners are currently believed to be losing due to air pollution.[7] But such a dose rate in the first year of an accident would fall to a very small fraction by the time 50 years had elapsed, as can be judged from Figure 2. Hence the actual loss of life expectancy corresponding to this safe-return dose would be significantly less.

Even under these rather strict conditions for safe-return dose, the expected number of people needing relocation was found to be only 620, two to three orders of magnitude down on the sizes of population movement recommended by the authorities after Chernobyl and Fukushima Daiichi.[8,9]

6. J-value assessment of the Chernobyl and Fukushima Daiichi accidents

The J-value method,[10–13] based on the life quality index,[14,15] allows for the first time an objective balance to be struck between what is spent on safety and the benefit that will be achieved. The benefit is judged by reference to the satisfaction or utility that the people affected can expect to gain over the rest of their lives; overspending on safety will diminish people's utility. The method has been validated against pan-national data on the revealed preferences of thousands of millions of people all over the world.[16,17] It is this combination of objectivity and empirical validation that constitutes the J-value's unique attraction for conducting cost–benefit analyses to assess the correct level of spending to reduce a threat to human life. It allows both balance and consistency to be extended to safety decisions where people may have less of a historic feel for the level of risk, as in the case of nuclear radiation.

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7 Darzi, A., *Better Health for London* (Report of the London Health Commission). Mayor of London's Public Liaison Unit (2014).

8 Ashley, S., Vaughan, G.J., Nuttall, W.J. and Thomas, P.J., Considerations in relation to off-site emergency procedures and responses for nuclear accidents. *Process Safety and Environmental Protection* **112A** (2017) 77–95.

9 Ashley, S., Vaughan, G.J., Nuttall, W.J., Thomas, P.J. and Higgins, N.J., Predicting the cost of the consequences of a large nuclear accident in the UK. *Process Safety and Environmental Protection* **112A** (2017) 96–113.

10 Thomas, P.J., Stupples, D.W. and Alghaffar, M.A., The extent of regulatory consensus on health and safety expenditure. Part 1: Development of the J-value technique and evaluation of regulators' recommendations. *Process Safety and Environmental Protection* **84** (2006) 329–336.

11 Thomas, P.J., Stupples, D.W. and Alghaffar, M.A., The extent of regulatory consensus on health and safety expenditure. Part 2: Applying the J-value technique to case studies across industries. *Process Safety and Environmental Protection* **84** (2006) 337–343.

12 Thomas, P.J., Stupples, D.W. and Alghaffar, M.A., The life extension achieved by eliminating a prolonged radiation exposure. *Process Safety and Environmental Protection* **84** (2006) 344–354.

13 Thomas, P.J., Jones, R.D. and Kearns, J.O., The trade-offs embodied in J-value analysis. *Process Safety and Environmental Protection* **88** (2010) 147–167.

14 Nathwani, J.S. and Lind, N.C., *Affordable Safety by Choice: the Life Quality Method*. Waterloo, Ontario: Institute for Risk Research, University of Waterloo (1997).

15 Nathwani, J.S., Pandey, M.D. and Lind, N.C., *Engineering Decisions for Life Quality: How Safe is Safe Enough?* London: Springer (2009).

16 Thomas, P. and Waddington, I., Validating the J-value safety assessment tool against pan-national data. *Process Safety and Environmental Protection* **112A** (2017) 179–197.

17 Thomas, P., Corroboration of the J-value model for life-expectancy growth in industrialized countries. *Nanotechnology Perceptions* **13** (2017) 31–44.

The J-value was used to examine the justification for applying the countermeasures of relocation and remediation after the accidents at Chernobyl and Fukushima Daiichi.

6.1 Chernobyl

The Chernobyl accident occurred on 26 April 1986, when the reactor in Unit 4 went super-prompt critical[18] due to operator error during an experiment. The top of the reactor was blown off as a result of the massive power excursion that occurred, the core melted and fires broke out. The contents of the core were exposed, and large quantities of radioactive material were expelled over the following 10 days. There were 28 deaths amongst plant operators and firefighters in the hours following the accident, predominantly from acute radiation exposure, which claimed a further 2 victims in the ensuing 3 months. The Soviet authorities relocated 116,000 people in 1986 and followed this up with an even larger relocation of 220,000 people in 1990.

J-value analysis of the 1st relocation in 1986 showed that it was advisable to move out only those calculated to lose 8.7 months of life expectancy or more. For these people, 31,000 in number, $J \leq 1$, implying that it was sensible for them to be relocated.[19] However, $J > 1.0$ for the remaining 85,000 evacuees, who should not therefore have been asked to move. These 85,000 people would have lost, on average, 3 months' life expectancy by staying in their homes for ever, too small to warrant moving away. As noted above, the inhabitants of London are expected to lose 4½ months' life expectancy today as a result of air pollution levels, and a mass exodus from London is not being advocated (although measures to reduce air pollution are being pursued).

If it was decided to relocate the entire population of a town or settlement even when only 5% of the population merited such a move, then the relocation figure for 1986 rises from 31,000 to 72,500. This is still substantially down on the actual figure, 116,000, of relocated people.

The analysis for the 2nd relocation revealed that the 900 people living on the most contaminated land near Chernobyl in 1990 would have lost 3 months' life expectancy by continuing to live there for the rest of their lives. Relocation for them gave a J-value of 2.9. This is significantly higher than 1.0 and it is therefore clear that none of the 220,000 people should have been moved out. (Interestingly, the Soviet government was advised not to move anyone in 1990 by a contemporaneous French study it had commissioned via the IAEA, but unfortunately it chose not to follow this advice.[20,21])

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18 "Super prompt critical" means that the reaction could be sustained and could grow using prompt neutrons only. The increased fission rate could be maintained for only a few seconds, however, before the high temperature induced in the core caused its reactivity to drop and the reaction to shut down automatically (the Nordheim–Fuchs effect). The disrupted core then stayed subcritical and shut down.

19 Waddington, I., Thomas, P.J., Taylor, R.H. and Vaughan, G.J., J-value assessment of relocation measures following the nuclear power plant accidents at Chernobyl and Fukushima Daiichi. *Process Safety and Environmental Protection* **112A** (2017) 16–49

20 Lochard, J. and Schneider, T., *Radiation Protection: International Chernobyl Project—Input from the Commission of the European Communities to the Evaluation of the Relocation Policy Adopted by the Former Soviet Union. Part A: Countermeasures to be taken after 1990 to ensure safe living conditions for the population affected by the Chernobyl accident in the USSR.* Directorate-General, Science, Research and Development; Directorate-General, Environment, Nuclear Safety and Civil Protection, Report No. EUR 14543 EN. Luxemburg: Office for Official Publications of the European Communities (1992).

21 Lochard, J., Schneider, T. and Kelly, N., Evaluation of countermeasures to be taken to assure safe living conditions to the population affected by the Chernobyl accident in the USSR, *International*

6.2 Fukushima Daiichi

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 after 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 inundated. The ensuing 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. The overheating of fuel assemblies led to meltdowns in the three reactors that had been at power when the tsunami struck. Meanwhile a chemical reaction began between the high-temperature steam and the zircalloy fuel cladding, producing hydrogen gas in the reactor buildings. The reaction product subsequently ignited explosively and radionuclides were released directly into the environment.

18,500 people died as a result of the tsunami, but no radiation-induced deaths have occurred as a consequence of the accident at Fukushima Daiichi. The authorities instructed 111,000 people to leave their homes, and a further 49,000 people self-evacuated. 85,000 people had not returned home 5 years later. There were 1,121 excess deaths amongst the evacuees within 2 years, attributed to "physical and mental exhaustion",[22] a number that has now grown to 2,202.[23]

The Japanese Government specified a safe-return dose of 20 mSv per year. Inhabitants of a town facing such an initial dose, falling over the next 70 years in the way shown in Figure 2, could be expected to lose between 2 and 3 months of life expectancy. Only 4 towns, with a combined population of 55,500, would have experienced a dose at this level or higher in the first year after the accident. The most exposed township was Tomioka, where the dose in year 1 would have been 51 mSv. Keeping the people of Tomioka away for the 6 years needed for the dose rate to decay to 20 mSv per year would have gained the inhabitants 82 days of life expectancy as a result of the radiation exposure avoided. Comparing this relatively small benefit with the cost of relocation using the J-value method gave a J-value of 1.5. As $J > 1.0$, it was inadvisable to relocate the inhabitants of Tomioka.

Since Tomioka was the worst affected town, it follows that no one from the other towns and villages around the Fukushima Daiichi power plant should have been relocated.

6.3 Disruption and dislocation

The J-value analysis summarized above assumed that relocation removed the radiation risk and that its only downside was the monetary cost of relocating. But in fact the relocation at Fukushima is known to have incurred significant non-monetary penalties. As noted earlier, there were premature deaths: 1121 early deaths after 2 years, 1656 after 3 years[24] and 2202 by March 2018.

Radiation Protection Association 8th International Congress (IRPA 8), Montreal, Canada, paper M1-53 (1992).

22 Ranghieri, F. and Ishiwatari, M. (eds), *Learning from Megadisasters: Lessons from the Great East Japan Earthquake*. Washington, DC: World Bank (2014) (http://dx.doi.org/10.1596/978-1-4648-0153-2)

23 Harding, R., Fukushima nuclear disaster: did the evacuation raise the death toll? *Financial Times* 11 March 2018 (https://www.ft.com/content/000f864e-22ba-11e8-add1-0e8958b189ea)

24 Parungao, B., Post-tsunami deaths due to stress, illness outnumber disaster toll in Fukushima. *Japan Today* (February 2014) (http://www.japantoday.com/category/national/view/post-tsunami-death)

Moreover, Chernobyl studies have shown that mass relocation can have a general devastating effect on those moved away for a long time or permanently from their homes, a factor that is now being observed after the Fukushima Daiichi accident.[23] Many relocated people think that they are doomed, a position that has its own internal logic. To understand this, suppose that the relocated people come to see the tens of thousands of millions of dollars being spent on them not as protection from damage but as compensation for the damage inflicted on them. Will they not now back-calculate the extent of their harm from the vast expenditure that they observe? Will they not now conclude, quite rationally, that the likely injury they are facing is enormous? Will they not see themselves as victims, almost certain to die young?

This way of thinking can turn into a self-fulfilling prophecy. After Chernobyl, according to the World Health Organization (WHO):[25]

> The designation of the affected population as 'victims' rather than 'survivors' has led them to perceive themselves as helpless, weak and lacking control over their future. This, in turn, has led either to overcautious behavior and exaggerated health concerns, or to reckless conduct, such as consumption of mushrooms, berries and game from areas still designated as highly contaminated, overuse of alcohol and tobacco, and unprotected promiscuous sexual activity.

The report from the WHO also states:

> More than 350 000 people have been relocated away from the most severely contaminated areas, 116 000 of them immediately after the [Chernobyl] accident. Even when people were compensated for losses, given free houses and a choice of resettlement location, the experience was traumatic and left many with no employment and a belief that they have no place in society. Surveys show that those who remained or returned to their homes coped better with the aftermath than those who were resettled. Tensions between new and old residents of resettlement villages contributed to ostracism felt by the newcomers. The demographic structure of the affected areas became skewed since many skilled, educated and entrepreneurial workers, often younger, left the areas leaving behind an older population with few of the skills needed for economic recovery.

and

> According to the [Chernobyl] Forum's report on health, 'the mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date.' People in the affected areas report negative assessments of their health and well-being, coupled with an exaggerated sense of the danger to their health from radiation exposure and a belief in a shorter life expectancy.

These considerations strongly add to the argument established by using the J-value that relocation should be used sparingly, if at all, after a big nuclear accident.

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[25] World Health Organization, Chernobyl: The True Scale of the Accident. 20 Years Later a UN Report Provides Definitive Answers and Ways to Repair Lives. Answers to Longstanding Questions (2005). Available at: http://www.who.int/mediacentre/news/releases/2005/pr38/en/index1.html (accessed July 2017).

7. Key instrumentation and software to support decision making

The key measurement is of the radioactive contamination (Bq/m^2) across the area. It is quite possible with modern technology to gather spatially distributed measurements of contamination in near-real time using a mixture of fixed and moving sensors, the latter aboard either a helicopter or a drone. Continually updated measurements of contamination could then be supplied to a set of interlinked software models:

- a prediction model for current and future dose for the next 70 years or more
- a model to convert dose into loss of life expectancy, and
- a J-value package to provide evolving J-value guidance.

The provision and interpretation of better measurement data, provided in real time, would promote an orderly reaction to the post-accident situation. The information could be made available not only to the incident controller but also to politicians, the media and the general public.[26] Regularly updated predictions could be given for the loss of life expectancy resulting from living in the towns and villages in the vicinity of the nuclear plant for the next 70 years or more, figures likely to be reassuring in many cases.

The outputs from the models would put the decision makers in a good position to make sensible judgments on key questions such as who, if anyone, should be evacuated. The number of people asked to leave their homes if only for a short time could then be minimized so as to keep disruption to a minimum.

8. Conclusions

Three diverse methods used in the NREFS project have come to very similar conclusions on the best way to recover from a big nuclear accident. The big lesson from past big nuclear accidents and models of possible future accidents is how small the radiation damage has been and is likely to be in the future to members of the public from even the biggest nuclear reactor accidents. Most of the harm from previous big nuclear accidents has come from what can now be seen to be unjustified fear and worry and from the social disruption and dislocation caused by the relocation of hundreds of thousands of people.

The so-called "solution" of relocation applied in the past has become the problem. In fact, remediation should be the watchword for any future big nuclear accidents, not relocation.

We have a duty to cope with any big nuclear accident in the future much more sensibly and effectively than has been the case in the past. Modern instrumentation linked to software to calculate the dose profile over 70 years or more, the associated loss of life expectancy and the J-value for candidate protection measures will enable the incident controller to take sensible decisions, especially on such disruptive choices as relocation.

The opportunity now exists to protect people from a big nuclear accident significantly better in the future and save tens or hundreds of thousands of millions of dollars in the process.

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[26] Thomas, P., Coping after a big nuclear accident (public lecture at the University of Bristol, 20 November 2017). Available at https://www.youtube.com/watch?v=k5eZdutuPVY&t=2s