Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

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

I. Waddington[a], *P.J. Thomas*[b,*], *R.H. Taylor*[b], *G.J. Vaughan*[c]

[a] *Ross Technologies Ltd., City Point, Temple Gate, Bristol BS1 6PL, UK*
[b] *Safety Systems Research Centre, Queen's School of Engineering, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK*
[c] *Department of Natural Sciences, School of Science and Technology, Middlesex University, The Burroughs, Hendon, London, NW4 4BT, UK*

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form 20 February 2017
Accepted 4 March 2017

Keywords:
J-value
Chernobyl
Fukushima
Relocation
Risk management
Major accidents

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.

* *Corresponding author*.
E-mail addresses: philip.thomas@bristol.ac.uk, pjt3.michaelmas@gmail.com (P.J. Thomas).
http://dx.doi.org/10.1016/j.psep.2017.03.012

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