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COPING WITH A BIG NUCLEAR ACCIDENT; CLOSING PAPERS FROM THE NREFS PROJECT

P.J. Thomas. *Quantitative guidance on how best to respond to a big nuclear accident*. Pages 4-15.

A review is made of the quantitative methods used in the NREFS project (Management of Nuclear Risks: Environmental, Financial and Safety) set up to consider how best to respond to a big nuclear accident. Those methods were: the Judgement- or J-value, optimal economic control and a combination of the computer codes PACE and COCO2 produced at Public Health England. The NREFS results show that the life expectancy lost through radiation exposure after a big nuclear accident can be kept small by the adoption of sensible countermeasures, while the downside risk is less severe than is widely perceived even in their absence. Nearly three quarters of the 116,000 members of the public relocated after the Chernobyl accident would have lost less than 9 months' life expectancy per person if they had remained in place, and only 6% would have lost more than 3 years of life expectancy. Neither figure is insignificant, but both are comparable with life expectancy differences resulting from the different day-to-day risks associated with living in different parts of the UK. It is clear in hindsight that too many people were relocated after both the Chernobyl and the Fukushima Daiichi accidents. Remediation methods can often be cost-effective, but relocation of large numbers following a big nuclear accident brings its own risks to health and well-being and should be used sparingly, a message coming from all three of the quantitative methods. There is a need to understand and hence demystify the effects of big nuclear accidents so that decision makers are not pressurised into instituting draconian measures after the accident that may do more harm than good.

- **Keywords:** Big nuclear accidents, Chernobyl, Fukushima, J-value, Optimal control, Cost of consequences, Evacuation, NREFS

I. Waddington, P.J. Thomas, R.H. Taylor, G.J. Vaughan. *J-value assessment of relocation measures following the nuclear power plant accidents at Chernobyl and Fukushima Daiichi*. Pages 16-49.

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.

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

I. Waddington, P.J. Thomas, R.H. Taylor, G.J. Vaughan. *J-value assessment of remediation measures following the Chernobyl and Fukushima Daiichi nuclear power plant accidents*. Pages 50-62.

Actions set in train shortly after the accidents at Chernobyl (1986), and Fukushima Daiichi (2011) had the aim of reducing the more immediate health effects on people living near the plants, with population relocation being especially prominent. The important topic of relocation is the subject of a companion paper, and this article will concentrate on other measures, such as soil treatment and urban decontamination, that have been put in place to reduce the radiation risks in the medium and long term to people living and farming in areas subject to some degree of radioactive contamination. The J-value method of risk assessment has been used to judge the cost-effectiveness of a range of agricultural and urban remediation actions. Many remedial measures instituted after the Chernobyl and Fukushima Daiichi accidents have been found to be highly cost-effective.

- **Keywords:** Risk management, J-value, Disaster recovery, Chernobyl, Fukushima Daiichi, Nuclear remediation

D. Yumashev, P. Johnson, P.J. Thomas. *Economically optimal strategies for medium-term recovery after a major nuclear reactor accident*. Pages 63-76.

The dynamic process of ground contamination after a major nuclear accident is modelled, and the system is then extended to include the transient equations describing the three broad countermeasures: food bans, remediation and population movement (relocation and repopulation). Countermeasures are assumed to be applicable once the deposition period has ended and surface contamination measurements have stabilised. A value function is constructed to account for the major economic factors, including allowance for the detrimental effect on human health of radiation exposure. The principle of optimality is then applied by requiring the value function to satisfy the Hamilton–Jacobi–Bellman partial differential equation, yielding an economically optimal combination of the countermeasures at any given moment of time within the recovery period. A classification into Broad Strategies is made in order to explore the similarities in structure

of optimal strategies for wide ranges of economic parameter values. Population relocation forms no part of any optimal strategy in the Base Case (or Case I) as parameters are varied over a wide range. Strategies incorporating relocation have a low probability of being optimal even in the low-probability sensitivity studies of Case II, where relocation is imposed immediately the accident happens, and Case III, where the Base Case assumption is reversed of lower economic productivity awaiting those moving from the original to the new area. It is concluded that relocation is almost certain to be a less than optimal response after a great many large-scale nuclear accidents.

- **Keywords:** Nuclear accident, Accident modelling, Optimal control, Principle of optimality, Hamilton–Jacobi–Bellman equation, Economic optimality

S.F. Ashley, G.J. Vaughan, W.J. Nuttall, P.J. Thomas. *Considerations in relation to off-site emergency procedures and response for nuclear accidents*. Pages 77-95.

The operation of nuclear facilities has, fortunately, not led to many accidents with off-site consequences. However, it is well-recognised that should a large release of radioactivity occur, the effects in the surrounding area and population will be significant. These effects can be mitigated by developing emergency preparedness and response plans prior to the operation of the nuclear facility that can be exercised regularly and implemented if an accident occurs. This review paper details the various stages of a nuclear accident and the corresponding aspects of an emergency preparedness plan that are relevant to these stages, both from a UK and international perspective. The paper also details how certain aspects of emergency preparedness have been affected by the accident at Fukushima Dai-ichi and as a point of comparison how emergency management plans were implemented following the accidents at Three Mile Island 2 and Chernobyl. In addition, the UK's economic costing model for nuclear accidents COCO-2, and the UK's Level-3 Probabilistic Safety Assessment code "PACE" are introduced. Finally, the factors that affect the economic impact of a nuclear accident, especially from a UK standpoint, are described.

- **Keywords:** Nuclear energy, Emergency management, Chernobyl, TMI-2, Fukushima Dai-ichi, Accident costs

S.F. Ashley, G.J. Vaughan, W.J. Nuttall, P.J. Thomas, N.A. Higgins. *Predicting the cost of the consequences of a large nuclear accident in the UK*. Pages 96-113.

Nuclear accidents have the potential to lead to significant off-site effects that require actions to minimise the radiological impacts on people. Such countermeasures may include sheltering, evacuation, restrictions on the sale of locally-grown food, and long-term relocation of the population amongst others. Countries with nuclear facilities draw up emergency preparedness plans, and put in place such provisions as distributing instructions and iodine prophylaxis to the local population. Their plans are applied in simulated exercises on a regular basis. The costs associated with emergency preparedness and the safety provisions to reduce the likelihood of an accident, and/or mitigate the consequences, are justified on the basis of the health risks and accident costs averted. There is, of course, only limited actual experience to indicate the likely costs so that much of the costing of accidents is based on calculations. This paper reviews the methodologies used, in particular the approach that has been developed in the UK, to appraise the costs of a hypothetical nuclear accident. Results of analysing a hypothetical nuclear accident at a fictitious reactor site within the United Kingdom are discussed in relation to the accidents at Three Mile Island 2, Chernobyl and Fukushima Dai-ichi.

- **Keywords:** Nuclear power, Economic assessment, Post-accident analysis, Level-3 PSA, Fukushima Dai-ichi, Chernobyl

I. Waddington, R.H. Taylor, R.D. Jones, P.J. Thomas. *J-value assessment of the cost effectiveness of UK sheep meat restrictions after the 1986 Chernobyl accident*. Pages 114-130.

Following the accident at the Chernobyl Nuclear Power Plant in 1986, the United Kingdom Government imposed restrictions on the consumption of sheep meat that became contaminated by nuclear fallout to ensure it was extremely unlikely that any consumers would receive an unacceptable dose. The international context for the restrictions is summarized and a brief review of the strategies employed by the UK is presented. An analysis using the J-value framework, including the *de minimis* quantum of life expectancy, is made of the cost effectiveness of the sheep meat restrictions in force until 2012, in terms of 4 categories of consumer ranging from the average to the extreme. The paper shows that the risk to the general population was very low indeed at the time the restrictions were removed in 2012. Retaining the restrictions for an extra year, would have averted the dose to the average consumer by a fraction of a microSievert, corresponding to a gain in life expectancy of 8 s. Meanwhile for the ICRP Representative Person, the gain in life expectancy from retaining the restrictions for an extra year ranged between 17 and 25 s. These gains are nugatory, as they are a factor of between 8 and 23 below the *de minimis*quantum of life expectancy. This new measure provides a meaningful quantitative criterion for judging when the radiation exposure of a large population is trivial in the sense used by the ICRP. The gains in life expectancy for the Field Representative Person and the Extreme Consumer were above the trivial level, but the associated J-values were 10 and 40, an order of magnitude or more above the value of unity where a case could be made for retaining the restrictions for another year. The high J-values and/or *de minimis* life expectancy ratios suggest that the food restrictions could almost certainly have been ended earlier. Also discussed are: the choice of the Representative Person, the role of intervention levels, the extent to which conservatisms in analysis are warranted and how socio-political factors in decision making can be taken into account in a transparent way.

- **Keywords:** J-value, Chernobyl, Intervention levels, Sheep meat, Risk management, *De minimis*quantum of life expectancy

William J. Nuttall, Stephen F. Ashley, Raphael J. Heffron. *Compensating for severe nuclear accidents: An expert elucidation*. Pages 131-142.

We present the results of a structured discussion held in London in July 2014 involving a panel of experts drawn from three communities: specialists on aspects of risk and insurance; lawyers concerned with issues of nuclear law; and safety and environmental regulators. The discussions were held on the basis of participant anonymity. The process emphasised three considerations: conceptions of loss arising from a severe nuclear accident; the specifics of the Fukushima-Daiichi accident and what it means for policy and strategy going forward; and the future of liability regimes. We observe some stoicism from those closest to implementation of policies and procedures associated with nuclear risks, but a lower level of certainty and confidence among those concerned with nuclear energy regulation.

- **Keywords:** Fukushima-Daiichi, Nuclear risk, Nuclear insurance, Nuclear regulation, Expert elicitation, Nuclear energy safety

P.J. Thomas. *Age at death from a radiation-induced cancer based on the Marshall model for mortality period*. Pages 143-178.

Results presented elsewhere in this issue of *Process Safety and Environmental Protection*point to the radiation-induced loss of life expectancy following severe nuclear accidents being lower than generally feared. But this leaves open the question of the loss of life expectancy amongst radiation cancer victims, even if fortunately there are likely to be few of them. Addressing this question, the research presented here finds that the average radiation cancer victim will live into his or her 60s or 70s, depending on how long the radiation exposure lasts, based on data from the UK life tables. Between 8 and 22 years of life expectancy will be lost, well below the 42 years taken away on average by an immediately fatal accident, such as a car crash or rail crash. Not only are the results useful in their own right, but they inevitably call into question once again the concept of the Value of a Prevented Fatality still used for cost-benefit analyses in the UK on a "one size fits all" basis, which disregards the amount of life expectancy lost. This problem with applying the VPF in the context of radiological protection is additional to the gross flaws previously uncovered in the value assigned to the VPF in the UK. It is clear that the VPF should not be used as a criterion for cost-benefit analysis in radiological protection.

An important feature of the results presented is that they apply to any exposure to radiation between a point dose and a constant annual dose that does not cause radiation sickness. The figures presented, for both point and constant annual exposures, are equally valid whether the dose is a few mSv or a few hundred mSv. Nor is the outcome affected by the magnitude of the coefficient used to convert radiation dose into risk.

- **Keywords:** Risk, Radiation cancer, Age at death, Loss of life expectancy, Value of a prevented fatality, VPF

P.J. Thomas, I. Waddington. *Validating the J-value safety assessment tool against pan-national data*. Pages 179-197.

The J-value is an objective method for determining when life extending measures are sensible, applicable to both manufacturing and service industries, including public health and healthcare. A model of human decision making based on the J-value is able to explain the shape of the Preston curve that relates life expectancy at birth and gross domestic product (GDP) per head for all the nations in the world. Making a number of reasonable assumptions, a J-value model produces a population-average life expectancy, which may be translated easily into a corresponding life expectancy at birth when life expectancy is not modified by discounting (net discount rate equals zero). The resultant values may be tested against pan-national data, showing a very good match. Thus the shape of the Preston curve has been explained and, at the same time, validation has been provided for the J-value model. A perturbation analysis shows that the J-value explanation for the Preston curve starts to break down as the net discount rate is increased above zero. Thus the Preston curve may be seen to validate the J-value model at a net discount rate of zero, but not at higher net discount rates. The result allows a closed-form expression to be derived for the first time for the pure time discount rate, namely the product of the rate of economic growth and the complement of risk-aversion. A further conclusion from the work is that no discernable limit is apparent before the age of 100 to the process by which people live longer as they get richer; such an intrinsic limit might be overcome by future improved medical technology.

- **Keywords:** J-value, Validation, Preston curve, Bristol curve, Net discount rate, Pure time discount rate