Electronic Supplementary Information (ESI) for:

Accounting for long-term doses in "Worldwide health effects of the Fukushima Daiichi nuclear accident."

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In what follows, we focus on the mid-range mortality estimates presented by Ten Hoeve and Jacobson (TH&J).[1]

Shielding: Shielding factors account for dose-rate reduction provided by buildings, terrain, and trees relative to the dose rate that would be delivered from radioactivity deposited on a perfectly flat plane. "Effective" shielding is an average, weighted by the fractional times spent indoors and outdoors. TH&J took a modest reduction factor of 0.85 for effective shielding, which tends to underestimate real dose rate reductions. In a recent estimate of individual doses in Japan by the World Health Organization, a factor of 0.6 was used, based on input from unnamed Japanese experts.[2] In 17 detached wooden houses in Marumori, a rural settlement in Japan, indoor dose rates were measured beginning in March, 2012 and found to be about half outdoor dose rates.[3] For 200 days, beginning in Sept 2011, personal dosimeters were worn by residents of the 17 rural buildings, which allowed average dose rates to be extracted that accounted for both activity patterns and self-shielding by the body. Decay of Cs-134 and Cs-137 were taken into consideration. The personal dose rates were even lower than expected from the indoor values; they varied linearly with indoor dose with a slope of 0.77, but there was a positive intercept. Personal dosimeters accumulate higher than average dose contributions while a person is outdoors and generally accumulate lower dose contributions while a person works or attends school in buildings larger than residences.[4] Thus, some dose would be accumulated on the dosimeter, even if indoor dose rates were zero. The existence of an intercept likely reflects the outdoor contribution in residences with low indoor doses, but it complicates the use of a single effective shielding factor. If the intercept is neglected, the net effective shielding factor would be 0.39 (= 0.77 X 0.5); higher if the intercept is included.

As for shielding factors in urban cities, we presume that the reduction in indoor dose would be greater there, where many residents live in multiunit buildings, e.g., condominiums built with reinforced concrete);[3] however, we have not been able to locate any data that would allow quantification of the reduction. If the ratio of urban shielding to rural shielding varies as it did after Chernobyl, the urban shielding factor would be half the rural one. Dose reductions due to shielding were calculated in Russia from an analysis of dose rate measurements taken at a variety of locations and validated by persons wearing TLD dosimeters over a 5-year period after the Chernobyl accident.[5] The reduction factor was found to be 0.16 for urban and 0.31 for rural populations. These measured shielding factors were used in the 2007 assessment of the radiation doses to the population of Europe due to the Chernobyl accident.[6] An additional dose-rate reduction factor of 0.82 was included to account for surface roughness and initial penetration into soil, which leads to an effective urban shielding factor of 0.13.

The 0.13 to 0.6 range of shielding factors are incorporated into our analysis by taking the geometric mean of the range (0.28), and including a factor of two uncertainty. This corresponds to an approximately 3-fold reduction in mid-range groundshine dose rates relative to dose rates computed using the shielding factor assumed by TH&J.

I-131 external ground dose. To simplify the presentation in Table 1 of the main text, we did not include groundshine from deposited I-131. TH&J treated radioiodine as a gas and radiocesium as a particle and thereby treated their dispersion and deposition differently. They do not provide sufficient information to allow us to do a simple scaling to estimate the contribution that I-131 made to their estimates of mortalities from external ground dose. We therefore make an approximate calculation, based on the assumption that iodine and cesium have the same ground deposition patterns. TH&J in their paper estimate that the total I-131 activity released to the atmosphere from the accident was 3.8 times higher than the activity of the Cesium-137 release. The dose rate at 1-meter above ground from an infinite plane source of I-131 is 0.66 of that from Cs-137 for the same number of disintegrations per second per unit area.[7] Using the above information, the vegetation weathering half life of 8-days assumed by TH&J,[5] the physical decay rate for I-131 of 10^{-6} per second (not the typo value in the TH&J paper), and their assumed shielding of 0.85 produces a dose-rate term that can be added to the radiocesium integrand given in Table 1, which leads to an increase in their calculated groundshine dose of 17 percent.

TH&J give a number of sensitivity results in their paper that suggest the actual contribution to their external ground dose is less than 17%, so it is safe to use 17% as a limit, which we round up to 20%. Adding I-131 to the long-term groundshine calculation makes a much smaller difference, which can be neglected, so the net effect of accounting for the I-131 groundshine is to decrease the ratio of our adjusted external ground dose to the TH&J value by a factor of 1.2^{-1}.

Evacuation

After a number of rough starts,[8] the Japanese policy has been to request evacuation from areas where unshielded doses projected for the following year are greater than 20 mSv.[9] To estimate the potential reduction in population dose that might accrue from this policy, we have relied on a report by L'Institut de Radioprotection et de Sûreté Nucléaire (IRSN) that gives population data for zones by first-year doses. In addition to making 1-year dose estimates, IRSN in its Table 2 has made estimates of 70-year external doses from long-term ground contamination for a range of dose categories, using a shielding factor of 0.65.[10] Our Table ESI-1 reproduces the IRSN dose bins and the populations within them. One bin divider is at 16 mSv for the first year, which is 25 mSv/yr before accounting for the IRSN shielding factor of 0.65, which in turn is close enough to 20 mSv to allow it to serve as a proxy for the 20 mSv/year boundary. In order to estimate a population dose for each dose category (population times average dose), we have interpolated within the ISRN-ranges to get an estimate of the average dose in each category. Also, at the end of Table ESI-1, we have added an additional bin for lower doses, with question marks for the populations and resulting population dose.

Table ESI-1 shows that 23,000 Person-Sieverts, more than half of the long-term population dose we derive from the IRSN data, occurs in the first-year dose range 5 to 16 mSv, i.e. outside of the regions targeted by METI for evacuation. Applying a US EPA cancer mortality risk coefficient[11] of 5.8 X10^{-2}/Sv to the 23,000 Person-Sv, after adjusting for our more effective shielding factor, slightly faster weathering time, and assumption of a factor of two reduction from decontamination, gives a projection of 350 excess cancer mortalities among this population of 335,000 living outside of the evacuation zone. (Note that the ratio of 70-year doses to 1-year doses in Table ESI-1 is 8.2, not the value of 6.7 obtainable from Fig. ESI-1, indicating that IRSN used a weathering formula that differs from the European-Assessment (EA) formula presented in Table 1 of the main text. The IRSN ratio of 8.2 is consistent with an effective weathering half-life of 21 years.)

Furthermore, the IRSN Table does not include doses of less than 0.041 Sv accumulated over 70-years. We have found in our work that most of the radiation population dose following simulated releases after accidents occurs at large distances (small doses to large numbers of people.[12] Including doses below the 0.041 Sv level would significantly increase the total population dose beyond the 64% already in the less than 16 mSv first-year dose category, which is not scheduled for evacuation. The number of projected mortalities would rise correspondingly. Also some of the people evacuated will be allowed to return once their future unshielded dose rates are projected to be less than 20 mSv per year, thereafter accumulating doses every year that could add up to 6.7 times 20 mSv, based on Figure ESI-1. Consequently, it does not appear that evacuation policy to date will reduce total projected cancer mortalities (population dose times risk coefficient) by very much.

Of course, those who reject the standard linear no-threshold model for the cancer risk from radiation will not accept the validity of either the TH&J estimates or our adjustments to them.

Table ESI-1. Estimated cumulative, population doses from groundshine in Japan based on Tables 1 and 2 of the 2011 IRSN report,[10] assuming an effective shielding factor of 0.65

Population in dose range	**first-year dose (mSv)**		**70-year dose (Sv)**		
	Range	Mid range	Range (Sv)	Mid range in region (Sv)	population dose (Person-Sv)
2200	100-500	300	0.82-4.0	2.4	5300
3100	50-100	75	0.41-0.82	0.61	1900
21000	16-50	33	0.136-0.408	0.270	5700
				Subtotal:	13000
Population below is outside of evacuation zones					
43000	10-16	13	0.082-0.136	0.11	4700
292000	5-10	7.5	0.041-0.082	0.061	18000
?	< 5	< 5	< 0.041	< 0.041	?
				Subtotal:	> 23,000
				Total:	> 36,000

Dose from consumption of contaminated food

Studies of Chernobyl exposures found that 40-75% of the dose from food was received in the first year.[6, 13-15] Hamada and Ogino have reviewed the food safety regulations put into place in Japan after the declaration of nuclear emergency conditions (March 11, 2011) following the start of the Fukushima nuclear accident.[16, 17] See also, Fukuda and Fukuda.[18] It took 7 days to set provisional regulation values (PRV) for tap water, milk, and some vegetables; it took 11 days to order the first restrictions on distribution and/or consumption of such contaminated food. Consumption restrictions were only set for some subareas of Fukushima Prefecture. PRVs were established on 27 June 2011 for aquatic food, additional vegetables, and major foodstuffs (such as rice). PRVs for beef were added at the beginning of August. New PRVs, 4 to 20 times lower than the originals, went into effect in April of 2012. In general PRVs were not "comprehensive and systematic in terms of coverage of foodstuffs and radionuclides."[17] The time to phase in restrictions, once PRVs were found to be exceeded, varied by foodstuffs, but in all cases the phase-in time was less than a year after the accident. In May of 2011, the IAEA established default intervention levels that can be used immediately in future events.[17]

TH&J estimated the collective food dose in Japan by scaling the external ground dose by a factor derived from the ratio of collective food dose to collective external ground dose estimated after Chernobyl by Anspaugh et al.[19] Overall, the ratio found by Anspaugh et al. was about unity, which is consistent with the most recent assessment of collective Chernobyl doses.[6] However, Anspaugh et al. found the ratio to be only 10% for the Asian part of the former Soviet Union, which at the time of the accident had very few food crops that had grown to the point where they could be contaminated directly. TH&J averaged between this 10% ratio and unity to obtain their 60% scale factor.

The Japanese diet is significantly different from the European diet, [13, 14, 20, 21] which makes it appropriate to discuss methods of assessing dose from food consumption that are independent of the ratio method. The World Health Organization published an order-of-magnitude, first year ingestion dose based on monitoring data for the bulk of the Japanese population of 0.07 to 0.7 mSv in its Table 3.[2] The WHO authors estimated doses based on measurements of contamination that were mainly made of food coming from Fukushima and neighboring prefectures. Even taking the lowest number in the range, 0.07, however, the collective dose in the first year to the 130 million people in Japan is high, namely, 9,100 person-Sv, Assuming the first year dose is half the total ingestion dose implies a total commitment of 18,000 Person-Sv, which means a future excess mortality of about 1100, applying a US EPA cancer mortality risk coefficient[11] of 5.8 $X10^{-2}$ /Sv. Even after reducing by two to account for food restrictions, the number of implied mortalities is considerably higher than the 140-mortalities we obtained using the TH&J ratio method. This does not mean that the TH&J ratio method is wrong. The WHO study made a number of both conservative and optimistic assumptions. Assuming high intake of critical foods at the 97.5th percentile and using medians, rather than means, for food concentrations are respective examples (see their Table 1). But it appears appropriate to assign at this time large uncertainties to any estimate for food ingestion.

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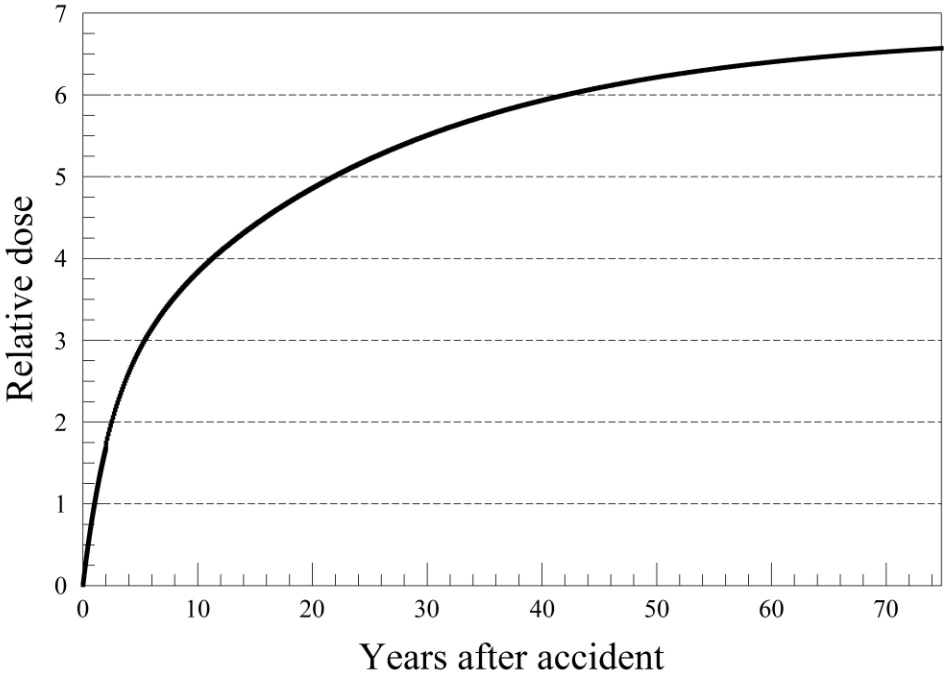

Figure ES-1. Cumulative external ground dose from Cs-134 and Cs-137 relative to first-year external ground dose, using equations in Table 1 of the main text.

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