Comments on the radiation levels resulting from the damaged nuclear power plants in Fukushima and the impact of these levels on human health.

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Overview:

The radiation doses and dose-rates experienced by residents of Japan, particularly those in Fukushima prefecture, are examined and the expected impact of these elevated radiation conditions on human health is discussed. Overall, doses are very low and the impact on health, *if any*, is expected to be minimal for reasons outlined within.

A similar examination is performed for the most heavily exposed workers at the Daiichi nuclear power plant. Elevated risks of a fatal cancer that might be diagnosed years or decades in the future are calculated using standard risk models utilized in occupational radiation protection.

(i) Radiation doses to the Japanese public:

To discuss the health impact of the radiation doses received by some people in Japan, I have focused on the region receiving the highest dose-rates in Fukushima prefecture (Iitate Village)[1]. Since my conclusion is that the dose-rates and the total accumulated dose received to date in the most dose-intensive region are no cause for alarm or fear, it follows that the same conclusion holds for other regions of Japan where the doses and dose-rates are substantially lower.

Radiation dose-rates measured in several locations within the Fukushima prefecture are shown in Figure 1. The highest dose-rates outside the 20 km evacuation zone have been measured in Iitate Village; here the dose-rates following the radionuclide release on 15 March were initially measured to be ~46 microSievert/hr for about 12 hours. Dose-rates fell steadily with readings dropping below 30 microSievert/hr after 24 hours, and below 20 microSievert/hr after 5 days.

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[1] I have used data provided on the AIF (Atomic Industrial Forum) website which cites MEXT (the Japanese Ministry of Education, Culture, Sports, Science and Technology) as the source of their data. MEXT data show a range of ~7 – 80 microSievert/hr at various locations with most readings below 25 microSievert late on March 16. While the IAEA have not reported dose-rate data for Iitate Village, a comparison of IAEA data for other locations with those provided by MEXT show reasonable agreement.

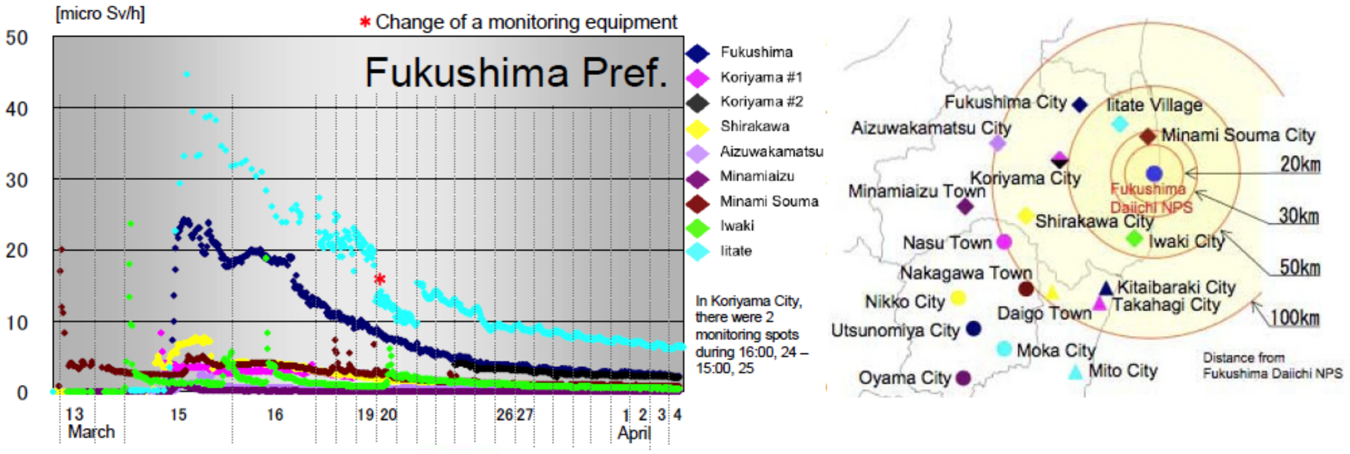

Figure 1. Gamma dose-rates measured in several locations in Fukushima prefecture http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1302054182P.pdf (accessed 4 April 2011). Normal gamma background, which represents roughly 20% of natural background is somewhat less than 0.1 microSievert /hr. [Other components of background are cosmic rays (16%), internal radionuclides (12%), and Radon daughters (52%).]

Elevated gamma dose rates are primarily from two radionuclides: 131-Iodine and 137-Caesium. Both are volatile fission products. This means that they easily are in vapor form at normal temperatures and pressures and can quickly leave a compromised fuel element. Both are combination beta- and gamma-emitters and therefore represent both an internal hazard (ingestion and inhalation) and an external hazard[2]. During the immediate period following radionuclide releases from a reactor, we worry most about the ^{131}Iodine (^{131}I). Our thyroids continually take up iodine and if radioactive iodine is available it will be taken up along with the stable iodine we get from food (eg. iodized salt). Radiation to the thyroid can cause thyroid cancer, particularly in children (as we saw after the Chernobyl accident). Fortunately, ^{131}I has a half-life of only 8 days and the combination of radioactive decay and dispersal by wind etc. means that it will not be around for a long time.

^{137}Caesium (^{137}Cs), on the other hand, has a half-life of 30 years. It too represents both an internal and an external hazard. Chemically, it behaves like potassium which is found in all of our cells, so our bodies readily take it up and use it if available. Like iodine, it will settle out as

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[2] Betas particles travel typically only a few mm in tissue and so do not tend to be an external hazard except to surface tissues (skin); gamma rays are quite penetrating and can be a hazard when inside the body or when irradiating the body from outside.

the radioactive cloud passes by, onto fields and crops. Given its 30-year half-life, it is ^{137}Cs that presents the most significant long-term hazard of a contaminated environment[3].

Examining the time course of the dose-rates shown in Figure 1, we see a rapid reduction in dose-rate during the first week after the major release on March 15. This reduction in dose-rate slows during the second week. After 16 days, only ¼ of the original ^{131}I remains, the rest having decayed away to stable daughter atoms. Soon the environment will be left contaminated with essentially only ^{137}Cs. With its 30 year half-life the drop in residual gamma background will be much slower than is seen in Figure 1. Currently the levels measured in Iitate village are approximately 6 microSievert/hr; we can expect these levels to drop but remain elevated for many years. For the sake of discussion below I will assume a level of 3-5 microSievert/hr.

The impact of radiation on health is a function of both the dose-rate and the total accumulated dose. In Table 1, the dose-rate information for Iitate Village has been separated into 7 different time periods over the past 2 ½ weeks. The additional gamma dose-rate resulting from the damaged reactors ranges from 48 down to 6 microSievert/hr. Since average background dose-rates from all natural sources is approximately 0.27 microSievert/hr, the ^{131}I and ^{137}Cs in the environment has resulted in dose-rates that were 175 times background levels for 12 hours on the 15th of March (46 microSievert/hr), falling to 22 times background by early April. Residual gamma dose rates for the future could be 10-18 times normal background levels (3-5 microSievert/hr). Summing the doses received from 15th March through 4th April shows a total accumulated dose of ~7600 microSievert (7.6 milliSievert) at the Iitate Village measurement point.

(ii) Health Implications for the Japanese public:

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[3] Plutonium (Pu) has been measured on the ground in several locations in Japan. The presence of ^{131}I and ^{137}Cs indicates that fuel elements have been compromised and thus we might expect to see smaller levels of other, less volatile, radionuclides as well. Levels of Pu are similar to those detected elsewhere in the Northern Hemisphere as a result of nuclear weapons testing in the 1950s and early 1960s. The ratio of different plutonium isotopes from partially used reactor fuel differs from that seen in weapons fallout; thus it is certain that the plutonium is, in fact, from the damaged nuclear power plants. Levels are far too small to present a human hazard.

It is worth noting that we have the ability to detect and quantify most radionuclides in almost any material with extreme accuracy and precision.

Dose-Rate (µSv/hr)	Duration (hrs) and Date	Accumulated Dose (µSv)
Part A: Dose-rates in Iitate Village since 15 March		
40	12 [3/15]	480
30	24 [3/16]	720
25	48 [3/17-3/18]	1200
23	48 [3/19/3/20]	1104
16	72 [3/21-3/23]	1152
10	216 [3/27-3/31]	2160
8	96 [4/1-4/4]	768
Total accumulated dose:		7584 ~ 7.6 mSv
Part B: General dose-rate information		
3-5	Long term residual gamma dose-rate in Iitate Village	
0.055	Natural external gamma dose-rate	
0.27	Total natural background dose-rate	
3 – 6.6	Dose-rate during airline travel	
9.7	Dose-rate during supersonic flight	
Part C: Dose-rates used in estimating the magnitude of the dose-rate effect		
	Shown are the 'high' and 'low' dose-rates (expressed in µSv/hr), used to compare the effectiveness of a given radiation dose in generating tumors. These studies were cited in NCRP Report 64 [1980]. The first five dose-rate comparisons were used in examining shorter term irradiations; the final four studies examined long term irradiations.	
4,200,000 vs 2,400-42,000		
48,000,000 vs 2,400-36,000		
27,000,000 vs 3458		
6,000,000 vs 180,000		
90,000,000 vs 600,000		
48,000,000 vs 3,600-36,000		
4,020,000 vs 0.17		
1,200,000-12,000,000 vs 6000-36,000		
23,333 vs 125		

Table 1. Information concerning radiation dose-rates including those measured at Iitate Village, those encountered in other aspects of life, and those used in the evaluation of the dose-rate effect by NCRP 64.

Does an additional 7,600 microSievert result in harm to an individual? Does living for short periods of time (hours or days) at elevated dose-rates result in harm? Does living for long periods of time (years) at dose-rates 10-18 times background cause harm? Although we do not have a lot of data regarding health impact at these very low radiation levels, the data we do have suggest that these radiation levels are not a cause for concern or fear. Here are the reasons why:

Point 1: Even using the world's largest and most comprehensive dataset examining the health impact of radiation (the long term follow-up of the survivors of the A-bomb attacks on Hiroshima and Nagasaki in 1945; more on this in (iv) below), we can detect no increase in cancer risk at 7.6 milliSievert (7600 microSievert). This may be because cancer is not increased or it may be because cancer really is increased but there aren't enough survivors in the low dose groups to show it. It is encouraging to note, however, that if increased cancer risk really does exist at these very low doses, the risk must be very small because it isn't large enough to be detectable, even with many thousands of A-bomb survivors exposed to these doses.

Before proceeding further an important point must be made here. It is standard practice when dealing with radiation in the workplace to make use of a *hypothetical* model that states that any dose of radiation carries with it some measure of harm (this is called the linear, no-threshold risk model). It is important to realize that this is only a hypothesis. There are other hypotheses that propose different ways of estimating the effects of small doses of radiation. One theory says the body is able to effectively deal with small doses and increased cancer would only occur after a sufficiently large radiation dose has been received (the threshold model). Another suggests that low levels of radiation have a stimulatory effect causing our immune system to respond better to any negative stimulus so that overall, low level radiation might provide a benefit (the hormesis model). All of these models remain scientific hypotheses; none of them has been shown to be accurate. For various reasons, the conservative approach (assuming all radiation is harmful) has been adopted in the workplace. The reasons that make this model appropriate for radiation workers do not apply in the situation of a contaminated environment.

Point 2. The radiation levels experienced by residents in Japan are lower than those encountered from many diagnostic medical scans that people willingly and sometimes repeatedly undergo. A computed tomography scan of the chest delivers a radiation dose of about 7.0 milliSievert to a lean individual, and an abdominal CT scan delivers about 10 milliSievert[4]. We have no indication that CT doses of this magnitude have any negative effects on our health. Of course CT scans are quick deliveries of radiation (< 1 minute) whereas living in a contaminated environment represents a prolonged delivery of radiation, a situation that is much gentler on our bodies, as described below. A better comparison might be with background radiation. At 7.6

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[4] The patient dose from CT procedures is always determined assuming the patient is lean (ie Reference Man, 170 cm tall, 70 kg). However, body fat leads to increased doses for CT and other radiographic imaging procedures since the automatic shutoff of the x-ray beam occurs only once a sufficient number of x-rays has exited the patient. Thicker patients absorb more x-rays and therefore require longer irradiation times and receive correspondingly larger doses; the thicker the patient the larger the dose. Thus, 7 and 10 milliSievert for chest and abdominal CT exams *underestimates* the doses to an overweight individual.

milliSievert this represents an additional ~3 years of background dose, received in a period of only 2.5 weeks. The chest CT exam represents ~3 years of background radiation dose but delivered in less than 1 minute.

Point 3. Our best information about radiation and its impact on health comes, as mentioned above, from a close study of the survivors of the A-bomb attacks in 1945. However, A-bomb survivors received their entire dose in less than 1 minute. Everything we know about radiation and health tells us that it matters to our bodies how quickly the dose is received. Rapid delivery of radiation has a much greater impact than a similar dose delivered slowly, spread out in time. Spreading the dose out gives our bodies a chance to detect and try to correct any damage that has occurred. Thus, a certain dose accumulated from environmental contamination is much less hazardous than the same dose delivered quickly.

So how do we move from what the A-bomb survivor study tells us about the risks of radiation to similar doses received but at a much lower dose-rate and spread out in time? In 1980, the US National Council on Radiation Protection and Measurement (NCRP) published a report[5] examining and quantifying the "dose-rate effect". This report remains the most comprehensive examination of the impact that delivery time has on biological outcome. The NCRP reviewed all laboratory data regarding tumor induction published at that time. [The dose-rates compared by studies cited in their review are summarized in part C of Table 1.] Lengthening the time over which a fairly large radiation dose (>250 milliSievert) is delivered substantially lessens the biological effect (ie. reduces the number of fatal tumors induced). If irradiation times are on the order of hours or days, the reduction in tumor incidence was seen to decrease by an average factor of 4. When the irradiations were much longer term irradiations, comprising "a significant or sizeable fraction of the life span" an even larger reduction in effect was observed, an average of a factor of 10.

Looking at Part C of Table 1 we see that, with few exceptions, the dose-rates used in all of the laboratory studies cited in NCRP 64 used 'low dose rates' that are still many hundreds of times greater than normal background dose-rates. Some of these 'low dose-rates' are thousands of times higher than the dose-rates some Japanese in Fukushima prefecture were exposed to and can expect to face in the coming decades. It is also the case that none of the studies cited examined

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[5] "Influence of Dose and its Distribution in Time on Dose-Response Relationships for Low-LET Radiations" NCRP Report No. 64, April 1, 1980, National Council on Radiation Protection and Measurement, Bethesda, MD.

total cumulative doses less than 250 milliSievert. What do the data tell us about doses of ~7.6 milliSievert or about dose-rates that are 10, 20, or 50 times background?

The problem noted by the NCRP was that **deleterious effects of these very low dose-rates could not be observed**. In fact, low doses and low dose-rates led to *increased* longevity rather than the decreased lifespan seen at higher doses and dose-rates. In addressing the apparent life lengthening at low dose-rates, the NCRP interpreted this effect as reflecting "a favorable response to low grade injury leading to some degree of systemic stimulation." They go on to state that "…there appears to be little doubt that mean life span in some animal populations exposed to low level radiation throughout their lifetimes is longer than that of the unirradiated control population."

Thus, our available data points to no negative health impact of living for long periods of time with elevated background doses. Around the world there exists a large variation in natural background dose-rates. In some places people live with natural radiation dose-rates that are 30 times the background most of us experience in the US or Japan. People living in high background radiation areas do not seem to suffer from any ill effects and, in fact, some studies show a decrease in cancer rate and an increase in lifespan with increasing background dose[6].

In summary, the dose-rates measured since problems with the Daiichi reactor began do not represent a cause for alarm or concern, even in Iitate Village where measured dose-rates have been the highest outside the 20 km evacuation zone. Not only has no increase in cancer rate ever been demonstrated at the estimated cumulative doses received, but the fact that the dose was spread-out in time would substantially reduce any biological impact.

(iii) Radiation Doses to the workers inside the Fukushima nuclear power plants:

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[6] [6] (i) "High Levels of Natural Radiation and Radon Areas: Radiation Dose and Health Effects" Proceedings of the 6th International Conference on High levels of Natural Radiation and Radon Areas, Osaka, Japan, Sept. 6-10, 2004, Elsevier 2005. (ii) C. Dissanayake "Of Stones and Health: Medical Geology in Sri Lanka" *Science*, 309(5736), 883-885, 2005. (iii) M. Durante and L. Manti "Human response to high-background radiation environments on Earth and in space" *Advances in Space Research*, 42, 999-1007, 2008. (iv) Hickey RJ, Bowers EJ, Spence DE, *et al*. Low level ionizing radiation and human mortality: multi-regional epidemiological studies. A preliminary report *Health*. *Phys 1981*;*40*:*625-41*. (v) Thompson RE, Nelson DF, Popkin JH, Popkin Z Case-control study of lung cancer risk from residential radon exposure in Worcester county, Massachusetts. *Health Physics.* Mar;94(3):228-41,2008. (vi) Wei LX, Zha YR, Tao ZF, He WH, Chen DQ, Yuan YL. Epidemiological investigation of radiological effects in high background radiation areas of Yangjiang, China. *J Radiat Res (Tokyo).* 1990 Mar;31(1):119-36.

The reactors in Fukushima shut down in response to the large earthquake on 11 March, as expected. However heat continues to build up in reactor fuel elements even after the fission chain reaction has been terminated due to radioactive decay of the fission fragments in the fuel. Following the earthquake, a 7-11 meter high tsunami wave hit the plant, knocking out the ability to continue cooling the reactor vessels. The existing water level in the reactor vessels fell, exposing the top of the fuel. The temperature of the fuel gradually increased as fission fragments continued to decay, causing water to vaporize and causing the fuel cladding (coating) to burn. This resulted in the release of some radioactive fission products from the fuel. Eventually it was decided to release pressure buildup by venting some of the steam to the atmosphere. Some volatile fission fragments were released to the environment resulting in a spike of radiation levels measured at the site and beyond. Water supply was eventually restored but a fire in Unit 2 on 15 March resulted in uncontrolled release of aerosols and high local radiation doses, as seen in Figure 1.

Local peak dose rate values at the facility were as high as 12,000 microSievert/hr for short periods of time and led to a temporary evacuation of the plant. Much of the released fission products were deposited in close proximity to the facility, however some elevated radiation levels were measured in other prefectures. Dose rates within the 20 km evacuation zone were as high as 300 microSievert/hr (more than1000 times background) for short periods of time. Currently the maximum dose rate at the site is roughly 5 microSievert/hr (18 times normal background rates) but is lower in most locations. Inside the reactor buildings the dose rates are much higher. In order to limit the total accumulated doses to individual workers the time spent in the building and exposed to high dose rates is minimized as much as possible. It has been reported that 17 workers have received doses exceeding 100 milliSievert.

Three employees working in contaminated water were hospitalized for evaluation on March 24 and released on March 28. They were not injured as reported widely in the media beyond a mild and transient skin reddening, like sunburn. From the timing and extent of the skin reddening the dose they must have received to the skin in that area is 2000-3000 milliSievert[7]. The water contained ^{140}Ba, ^{131}I, and ^{137}Cs, all beta and gamma emitters. The beta particles have an effective

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[7] Since one in every three people is diagnosed with cancer at some point in their lives, and half of all cancer patients receive radiation as part of their treatment, the skin's response to radiation as a function of dose is known fairly precisely.

penetration distance of only a few millimeters but are capable of delivering a high dose when adjacent to the skin. The gamma rays would contribute to the whole body dose of the workers.

While there was little to no acute injury to these workers, the radiation dose delivered to the whole body from gamma-rays emitted by radionuclides in the water was significant. The dosimeters worn by the three workers (likely somewhere on their torso) showed total radiation dose equivalence readings of 173, 179 and 180 milliSievert. 180 milliSievert represents ~75 years of natural background radiation which, in this case, was likely received over a period of several hours. It is possible that this radiation exposure has increased the likelihood of being diagnosed with cancer, later in life.

(iv) Health Implications for the Workers:

How dangerous is 180 milliSievert?

Throughout the world our estimates of the risks of radiation are based, almost exclusively, on close examination of the survivors of the A-bomb attacks on Hiroshima and Nagasaki in 1945. A-bomb survivors are followed until death, and the cause(s) of death recorded. Cancer fatality rates in the exposed and control groups are compared and the relative excess is plotted versus the dose received[8]. Figure 2 is taken from a recent update of the estimated risk of fatal cancers due to radiation for the A-bomb survivor population. The dose axis spans a very large range (for instance, 2.0 Sievert is the equivalent of ~830 years of average natural background dose but delivered within one minute). At large doses (>0.5 Sievert) it is clear that survivors are at an increased risk of dying of cancer in later life. [Radiation-induced cancers have a latent-period of 20-30 years.] At the lowest doses (below ~ 100 milliSievert), the large natural cancer death rate in both the exposed and the unexposed populations makes it impossible to declare, with any certainty, what effect small radiation doses have on the cancer fatality rate in acutely exposed

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[8] Health effects other than cancer have been examined at high doses; however at low doses non-cancer risks are especially uncertain and are not typically incorporated into risk estimates. According to BEIR VII, radiation-induced mutations in sperm or egg cells resulting in heritable disease (ie. genetic effects of radiation) have such a low risk they have not been detected in humans, even in the A-bomb survivors.
[BEIR VII: "Health Risks from Exposure to Low Levels of Ionizing Radiation, BEIR VII Phase 2" Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, Board on Radiation Effects Research, Div. on Earth and Life Studies, National Research Council of the National Academies, National Academies Press, Washington, DC, 2006.]

persons. Remembering that ionizing radiation is not like a chemical contaminant in the environment – that some level of ionizing radiation is not only natural but representative of the conditions in which life evolved and continues, makes fixing the zero dose point on this graph and hence quantifying the ‘increase above normal’ very difficult.

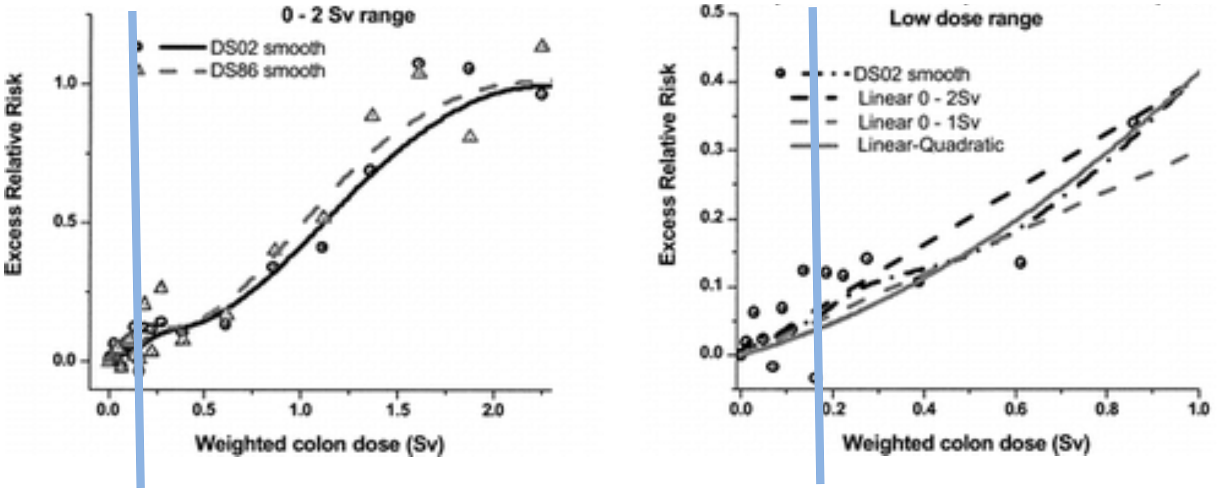

Figure 2. Excess cancer risk versus dose as observed with the A-bomb survivor population. [From D.L. Preston et al, “*Effect of Recent Changes in Atomic Bomb Survivor Dosimetry on Cancer Mortality Risk Estimates*,” **Radiation Research** (162) 377-89, 2004 [27].]

Plot on the left shows data for a large dose range up to 2.5 Sievert (~1000 years of background, all-at-once). Data are shown based on two dosimery systems (DS02 and DS86) but that doesn’t concern us here.

An enlargement of just the lower dose data is shown on the right. Data points are connected with linear fits to the data (leading to risk estimates of 0.43/Sievert) and by a linear-quadratic fit (giving a risk estimate of 0.19/Sievert). Superimposed on both plots is a vertical line representing 180 milliSievert, the whole body doses received by 3 employees at the Daiichi plants working in contaminated water. Keep in mind that their dose was spread out in time whereas the dose to the A-bomb population was received in less than 1 minute.]

Drawing a straight line (a linear extrapolation) from high dose data through the zero point generates a risk estimate of 0.43 per Sievert. That means a 1 Sievert dose, received in less than a minute, is seen to increase risk of fatal cancer by 43%. Since there already is a 22% cancer death rate in Japan (similar to most countries), the chance of dying from cancer goes from 22% to 31.5% following an acute dose of 1 Sievert. If the data are instead fit with a linear-quadratic model (adopted by some agencies and regulatory bodies), the risk estimate is only 0.19 per

Sievert. This estimate leads to an increase in cancer risk following a 1 Sievert dose, rapidly delivered, from 22 % to 26%.

Now examine the risk for the three radiation workers laying cable in contaminated water with dosimeter readings (representative of the 'whole body' dose) of approximately 180 milliSievert. If their exposure to radiation had been acute, their risk would have increased from 22% to 23.7% using the linear risk model and from 22% to 22.8% using the linear-quadratic risk model. However their radiation exposure was not received all at once, it was spread out over a period of time. Since the dose is spread out in time, the body is able to repair much of the DNA damage that may have been caused by the radiation (DNA repair halftimes are on the order of 15-30 minutes). The risk is therefore reduced by a factor of at least 2 and maybe more. Thus, for doses of 180 milliSievert, the risk models used in occupational radiation protection suggest the three workers have increased their risk of dying of cancer, many years from now, from 22 to 22.85 % (linear model) or from 22 to 22.38 % (linear-quadratic model)[9].

Summary:

- There is no evidence demonstrating that the dose-rates measured in Iitate Village or the cumulated dose (to date) of 7600 microSievert results in harm. [Doses to other areas of Japan are substantially lower than those measured in Iitate Village in Fukushima prefecture.]
- The cumulative dose of 7600 microSievert is similar to that received from a CT scan of the chest and substantially less than that received from a CT scan of the abdomen.
- Doses have been spread out in time, a situation that results in substantially less biological impact than the same dose delivered acutely.
- Doses to a small number of radiation workers at the damaged nuclear power plant are substantially higher than doses to the public. Applying standard risk models used in radiation protection predicts increased fatal cancer risk of 1.7-3.9% for these radiation workers.

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[9] If we perform the same analysis for people exposed to 7.6 milliSievert (my estimate of the cumulative dose at the detector position in Iitate Village) then this model predicts an increased risk of dying of cancer, many years from now, from 22.0 % to 22.035% (linear model) or from 22.0% to 22.016 % (linear-quadratic).