Learning More from Fukushima Dai-ichi

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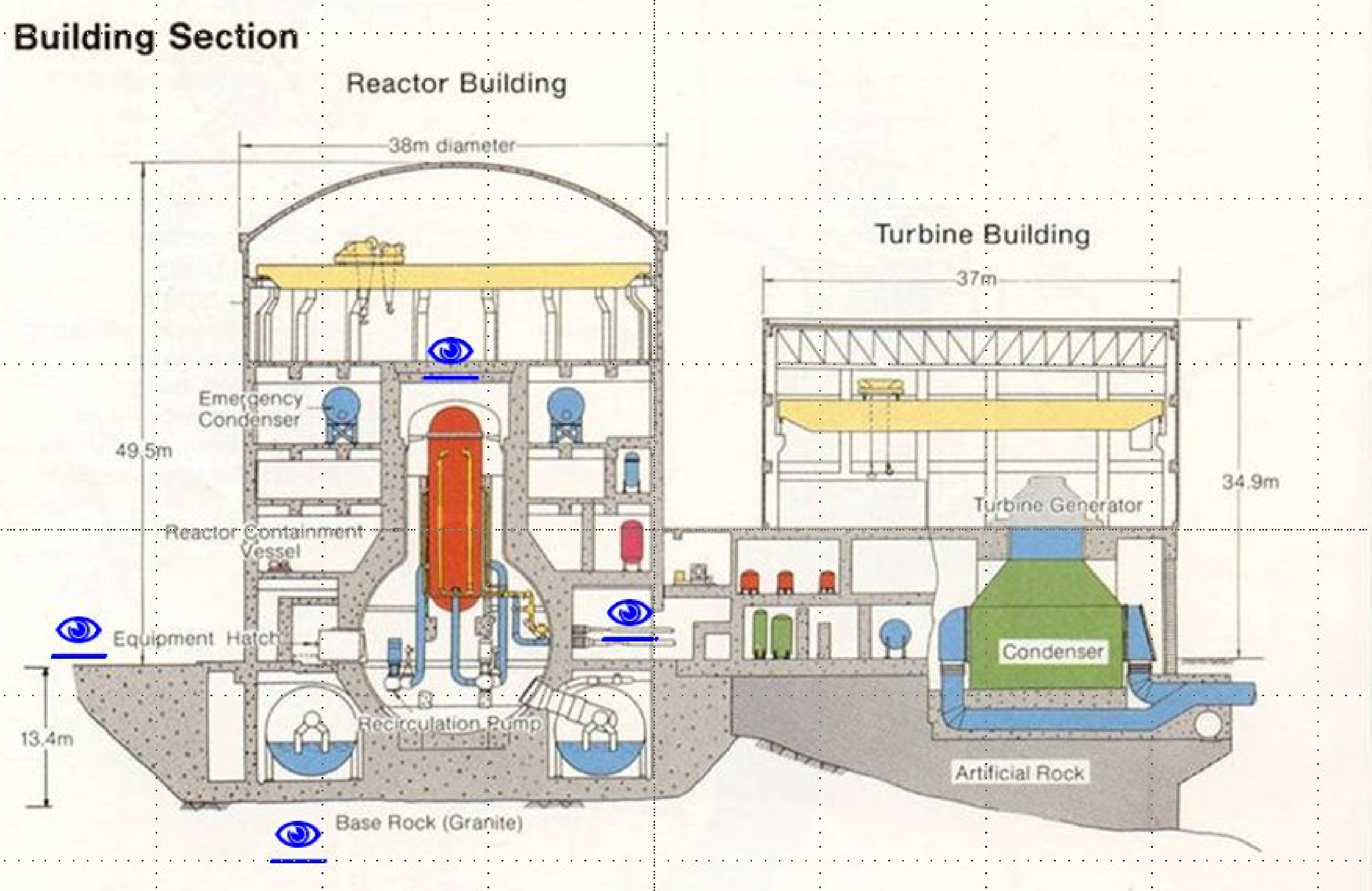
Abstract

A tsunami caused by the magnitude 9.0 Tohoku Earthquake of 11 March 2011 of the northeast coast of Japan drowned the emergency diesel generators of three boiling-water reactors at Fukushima Dai-ich, resulting in station blackout and the meltdown of the three reactor cores. Although emergency injection of seawater was improvised to remove the decay heat from the reactors, it was too late to avoid boiling off of much of the water in the reactor pressure vessels and the reaction with steam of the zirconium alloy "clad" of the fuel rods in the reactor with the evolution of hydrogen, which in turn overpressurized the massive concrete containment of the reactor and compelled venting of the hydrogen and some of the radioactive material from the reactor. This paper reports the course of events, the resulting contamination of the environment and the evacuation of 180,000 inhabitants, the efforts to prevent further damage to the reactors and spent fuel pools, and how the world can learn to prevent such accidents and to better alert and inform the public of the hazards and how they can protect themselves.

On March 11, 2011 an intense earthquake off the northeast coast of Japan, ranked as magnitude 9.0, severely tested Japan's earthquake code and discipline. The country and its buildings passed with flying colors. Some 16 nuclear reactors shut down instantly, as planned, as the earthquake strong motion exceeded on the order of 0.5 g, as measured by strong-motion seismometers within the buildings themselves. The reactors, including three operating reactors at Fukushima Dai-ichi (1F), Units 1,2, and 3, automatically inserted their control rods into the reactor core, terminating the neutron chain reaction, and reducing the thermal power output to that of the "decay heat" of the fission products themselves. With so much power generation suddenly off line, transmission line power to the 1F site was lost, and emergency diesel generators (EDG) took over[1].

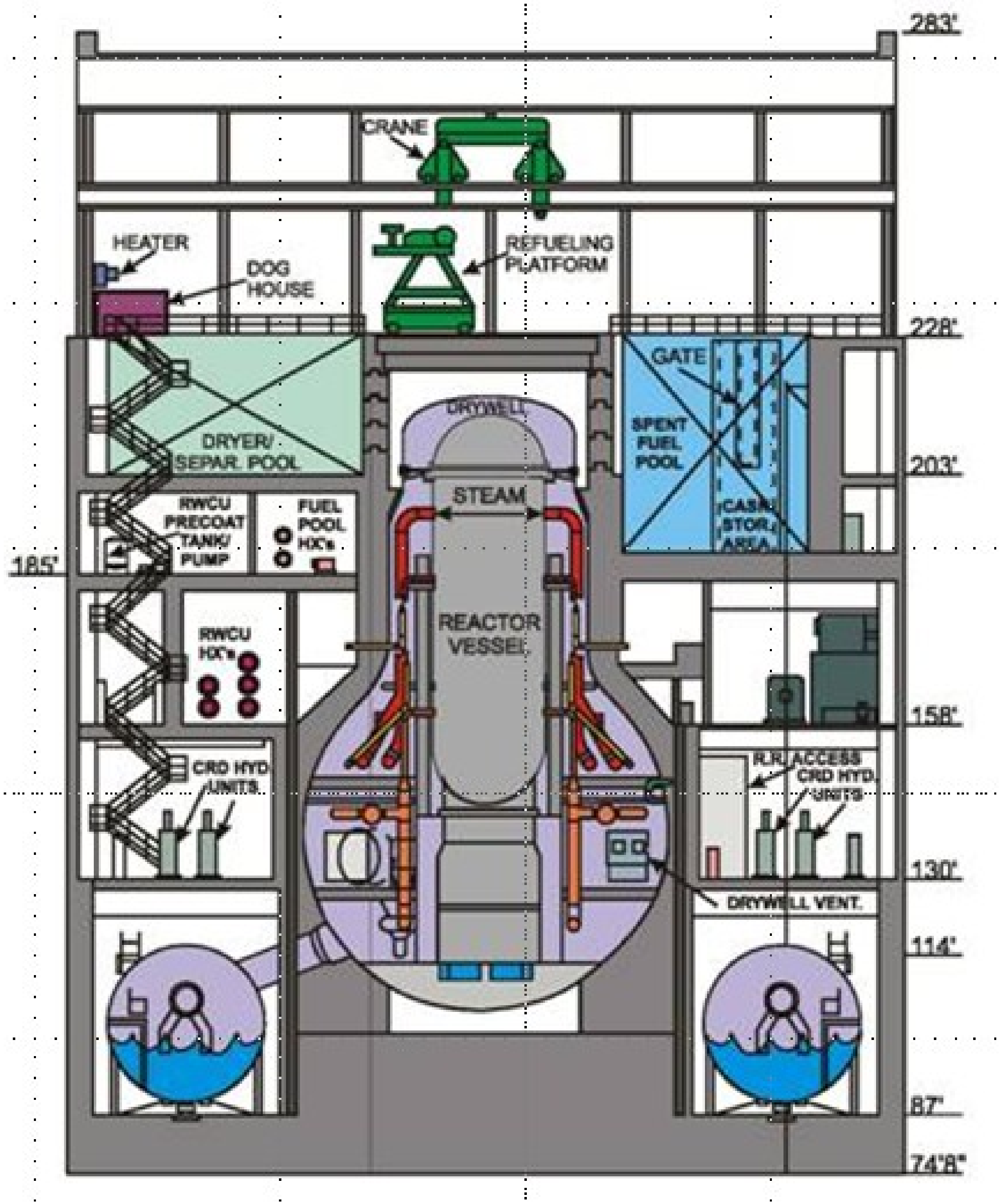
[1] E.g., http://allthingsnuclear.org/post/4609790167/what-happened-at-fukushima-dai-ichi

Unit 1, 2, and 3 Operating Reactors



The Mark I primary containment features a drywell (the inverted lightbulb) and a torus (the donut) connected by eight vent pipes. The reactor building surrounds the primary containment. Steam and feedwater piping passes through the containment walls and reactor building to the turbine building.

For the early boiling water reactors (BWR) of 1F with power outputs on the order of 500 MWe (hence thermal power on the order of 1600 MWt), electrically powered circulating pumps continued to cool the reactor pressure vessels and to reject the heat through heat exchangers to seawater. About an hour later an enormous tsunami swept west into Japan, striking Fukushima Dai-ichi with an inundation about 15 m above mean sea level. This was about a "500-yr" tsunami, but the seawall at 1F had been built to repel a 100-yr tsunami and it did nothing to retard the enormous flow of water that flooded far inland. In particular, the water almost instantly stopped the EDG which were supplying Units 1-4 with power in the absence of grid power. With the grid and EDG power both gone, these reactors were dependent on their sets of lead-acid batteries, like those in automobiles, which were specified to power the instrumentation (valves and lights and meters) of the site for at least 4 hrs. After that, there was no light or instrumentation power, and under these conditions of "station blackout" (SBO) the circulation of water and the cooling of the reactor pressure vessel (RPV) ceased. But fission-product decay heat continued to boil water in the RPVs.


283'
CRANE
HEATER
DOG HOUSE
REFUELING PLATFORM
228'
GATE
DRYWELL
SPENT FUEL POOL
DRYER/ SEPAR. POOL
203'
STEAM
RWCU PRECOAT TANK/ PUMP
FUEL POOL HX's
CASK STOR. AREA
185'
REACTOR VESSEL
RWCU HX's
158'
R.R. ACCESS
CRD HYD. UNITS
CRD HYD. UNITS
130'
DRYWELL VENT.
114'
87'
74'8"

Although steam from the RPV in reactors 1-3 no longer went to the main turbine and alternator, it did flow either to an emergency condenser (Unit 1) or, in Units 2 and 3, to drive a small auxiliary turbine that itself directly powered a recirculating pump to cool the reactor core. With the batteries exhausted, the valves to the emergency turbine could no longer be opened and with continued decay heat accumulating, the pressure in the RPVs rose until steam began to emerge from the overpressure safety valve near the top of each RPV.

The decay heat, initially at the level of about 10 MWt, sufficed to evaporate water at its latent heat on the order of 2 gigajoule per ton, or 18 tons per hour.

There was no control from the control room, because there was no electrical power.

Working under the greatest difficulty, Tokyo Electric Power Company (TEPCO) staff rigged high-pressure injection of water from external pumps into the RPV, using a "feed and bleed" approach in order to replace water lost to steam and thus, they hoped, to maintain the water level above the top of the heating zone in the 5-m-long fuel rods.

Unfortunately, the only water quickly available in these amounts was seawater, which is highly corrosive to the reactors, and contains about 1.3% sodium chloride (NaCl). Thus, at a rate that would stabilize at about 7 tons per hour or 168 tons per day into each of reactors 1-3, each RPV accumulated 2 tons of salt per day, initially in the form of brine and ultimately in the form of salt cake encrusting hot portions of the reactor and the bottom regions of the RPV, or so it is thought.

Before seawater cooling could be established, the water level in the RPVs fell low enough that the zirconium alloy (zircaloy) tubes cladding the uranium oxide pellets in the fuel overheated and burst, reacting with the water to form hydrogen, which escaped with the vented steam but, unlike the steam, did not condense in the large water-filled torus shown in the figure. The hydrogen pressure increased in the "drywell," which, in turn, needed to be vented to prevent its bursting. Unfortunately, although there are valves installed to conduct the vented gas to the tall stack, the valves seem not to have retained their position after the power failure, and hydrogen invaded the reactor buildings, including Building 4. There was no fuel at all in Unit 4's RPV because it had been shut down for refueling, with its fuel all transferred to the elevated spent fuel pool in Unit 4, where it was residing deep underwater, as was the case with the old spent fuel in Units 1-3.

There was much concern and uncertainty in Japan and in the world technical nuclear community that water had leaked or was leaking from the spent fuel pools, which were without circulating water cooling. If they had not leaked, there would have been several days of safety before the cooling by evaporation to the atmosphere would uncover the top of active fuel in the stored fuel elements. Major concern was warranted because the spent fuel pool every year receives 25% of a full core-load of spent fuel, so that there is about 6 (ck) times as much long-lived fission product content (e.g., 30-yr half-live Cs-137) as in an operating reactor core.

In the attempt to cool the spent-fuel pools, futile efforts were made to provide water by helicopter, until finally a low-tech solution was implemented in the form of ordinary “giraffes” used on high-rise building sites to deliver concrete to higher floors of the buildings under construction. Of course, the giraffes delivered water and not concrete, but there was continuing uncertainty about the temperature and the water level in the spent fuel pools. Unfortunately, initially only seawater was available and was used to prevent further disaster, but at the cost of an as yet unassessed corrosion problem of the fuel rods and assemblies.

THE PROBLEM OF WATER ACCUMULATION

For weeks some 20 tons per hour (480 tons per day) of water was pumped to the reactor pressure vessels to remove the decay heat and to prevent further evolution of hydrogen and fission products. Additional water was pumped to the spent fuel pools until circulation could be restored. This water input (including much of the condensed steam from the RPVs) accumulated in the reactor buildings and the turbine buildings and in trenches among the buildings. It was apparent that this highly radioactive water would spill into the sea unless it was pumped into holding tanks. It is no small matter to dispose of 120,000 tons of such intensely radioactive water. Its radiation destroys seals and limits the technology that can be used. Some tanks at 1F have been emptied to accommodate some of this water. Large barge-tank reservoirs have been brought in, and TEPCO contracted with AREVA for ion-exchange decontamination of the water, with a stage of reverse osmosis (not usually required in the spent-fuel reprocessing facilities) in order to remove most of the salt from the water that is then decontaminated by a factor 100,000 or so. Much of the fission product radioactivity is taken out as highly radioactive resin, but the salt has been left as concentrated brine.

More recently, TEPCO has planned to introduce an evaporator to convert the brines to solid waste for eventual burial as high-level waste, but that will take much research to provide a suitable containment system. It seems also that TEPCO may plan to skip the reverse osmosis process and move directly to evaporation of the water; the problem will be to ensure that the content of radioactivity is low enough to release the steam to the atmosphere.

The damage done by the hydrogen explosion is evident in the figures, with massive destruction of Buildings 1, 3, and 4. Building 2 was spared, perhaps because staff preemptively cut a large ventilation panel in the exterior paneling..

With the venting of the hydrogen, fission products escaped into the environment as well, and the government of Japan (GOJ) on March 12 called for mandatory evacuation of a 10-km radius, and later that day a 20-

km radius—a region home to 78,000 people (including those within 10 km of an undamaged set of TEPCO reactors at Fukushima Dai-ini). A “stay-in-house” order was issued to those living within between 20 and 30 km of 1F, many of which residents evacuated voluntarily. Under the conditions of severe tsunami damage in the region and disruption of normal local government services, there was little attention as to living conditions of those who were ordered to stay-in-house. Regions where aerial survey jointly performed by GOJ and the U.S. government (USG) showed contamination above the Protective Action Guide (PAG) have also been subject to evacuation.

The EPA Protective Action Guide, cited in the box in the Figure reads, “If a person is in danger of receiving an external radiation dose greater than R Rem over Y years, the EPA recommends relocation until radiation levels decrease.” It should be noted that this is not an urgent action because the dose is received over Y years. Note also, that the figure charts the dose received from ground contamination after May 9, 2011. Because each sievert (Sv) of adult exposure corresponds to an added probability of death from cancer of about 5%,[2] the 2-Rem (0.02 Sv) exposure over the first year for a person saying within the edge of the red boundary would connote about 0.1% lifetime additional probability of death by cancer for that one year of exposure. Per 100,000 people exposed, this would be about 100 additional deaths. Normal background radiation from rocks, cosmic rays, radon, and medical diagnostics contribute about 0.4 Rem per year to each person's exposure.

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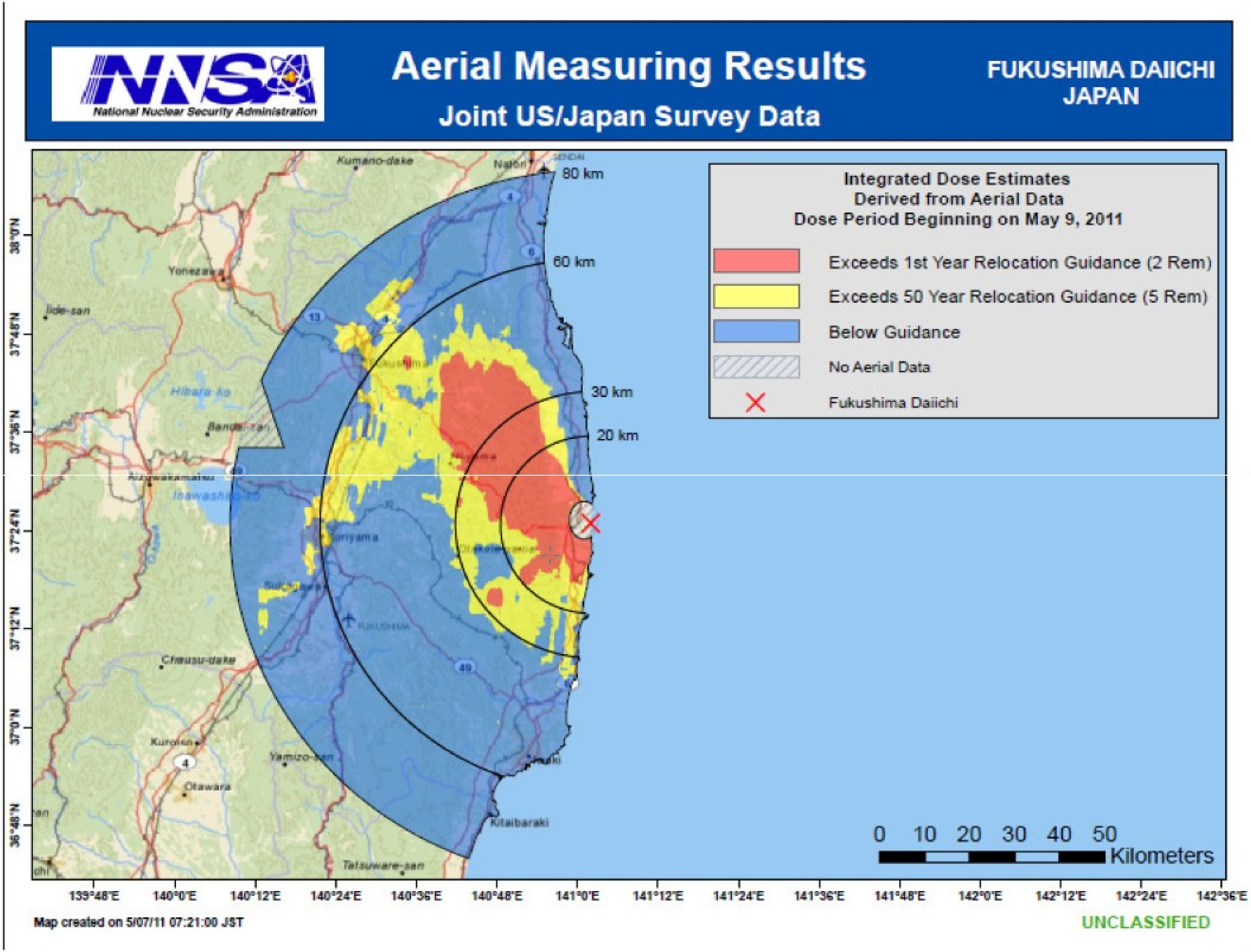
[2] Board on Effects of Ionizing Radiation, BEIR-7, National Academies Press, 2006.



NNSA
National Nuclear Security Administration
Aerial Measuring Results
Joint US/Japan Survey Data
FUKUSHIMA DAIICHI
JAPAN
Integrated Dose Estimates
Derived from Aerial Data
Dose Period Beginning on May 9, 2011
Exceeds 1st Year Relocation Guidance (2 Rem)
Exceeds 50 Year Relocation Guidance (5 Rem)
Below Guidance
No Aerial Data
Fukushima Daiichi
80 km
60 km
30 km
20 km
0 10 20 30 40 50
Kilometers
Kumano-dake
Yonezawa
Iide-san
Hibara-ko
Aizuwakamatsu
Inawashiro-ko
Koriyama
Chausu-dake
Kuroiso
Yamizo-san
Otawara
Iwaki
Kitaibaraki
Tatsuware-san
38°0'N
37°48'N
37°36'N
37°24'N
37°12'N
37°0'N
36°48'N
139°48'E
140°0'E
140°12'E
140°24'E
140°36'E
140°48'E
141°0'E
141°12'E
141°24'E
141°36'E
141°48'E
142°0'E
142°12'E
142°24'E
142°36'E
Map created on 5/07/11 07:21:00 JST
UNCLASSIFIED

But a larger and broader tragedy had already occurred. Some 22,000 souls had been killed by the tsunami, many of them drowned on land or swept to sea. This is totally unlike the earlier reactor accidents at Windscale in England (1957), at Three-Mile Island in the United States (1979), or at Chernobyl in the Ukraine (1986), which had occurred without any external disruption. The details of the 1979 and 1986 accidents are detailed for instance in my 2005 book with Georges Charpak and Venance Journé[3].

At Three-Mile Island, the reactor core of Unit 2 (Unit 1 was unaffected) melted, and much of its load of radioactivity escaped from the reactor pressure vessel into the reactor building housing the pressurized water reactor (PWR) and into an auxiliary building. But only radioactive xenon and some iodine escaped from the reactor stack, and almost none was deposited on the ground. It is estimated that exposure from the passing cloud to the population at large totaled 20-40 person-sieverts (p-Sv) which

[3] "De Tchernobyl en tchernobyls," by G. Charpak, R.L. Garwin, and V. Journé, (Odile Jacob, 2005)

at the rate of 0.05 lethal cancer deaths per p-Sv corresponds to an expected cancer death toll of one or two, among the millions of natural cancer deaths expected within the lifetime of those exposed to the small amount of radioactivity in the passing cloud. At Chernobyl, the world exposure has been documented as some 600,000 p-Sv, corresponding to a lethal cancer death toll of some 30,000 people. I provide here for reference a figure from a 2005 paper on comparative risks of various energy technologies[4].

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[4] "**Accident Risks in the Energy Sector: Comparison of Damage Indicators and External Costs" by S. Hirschberg, P. Burgherr, A. Hunt,**

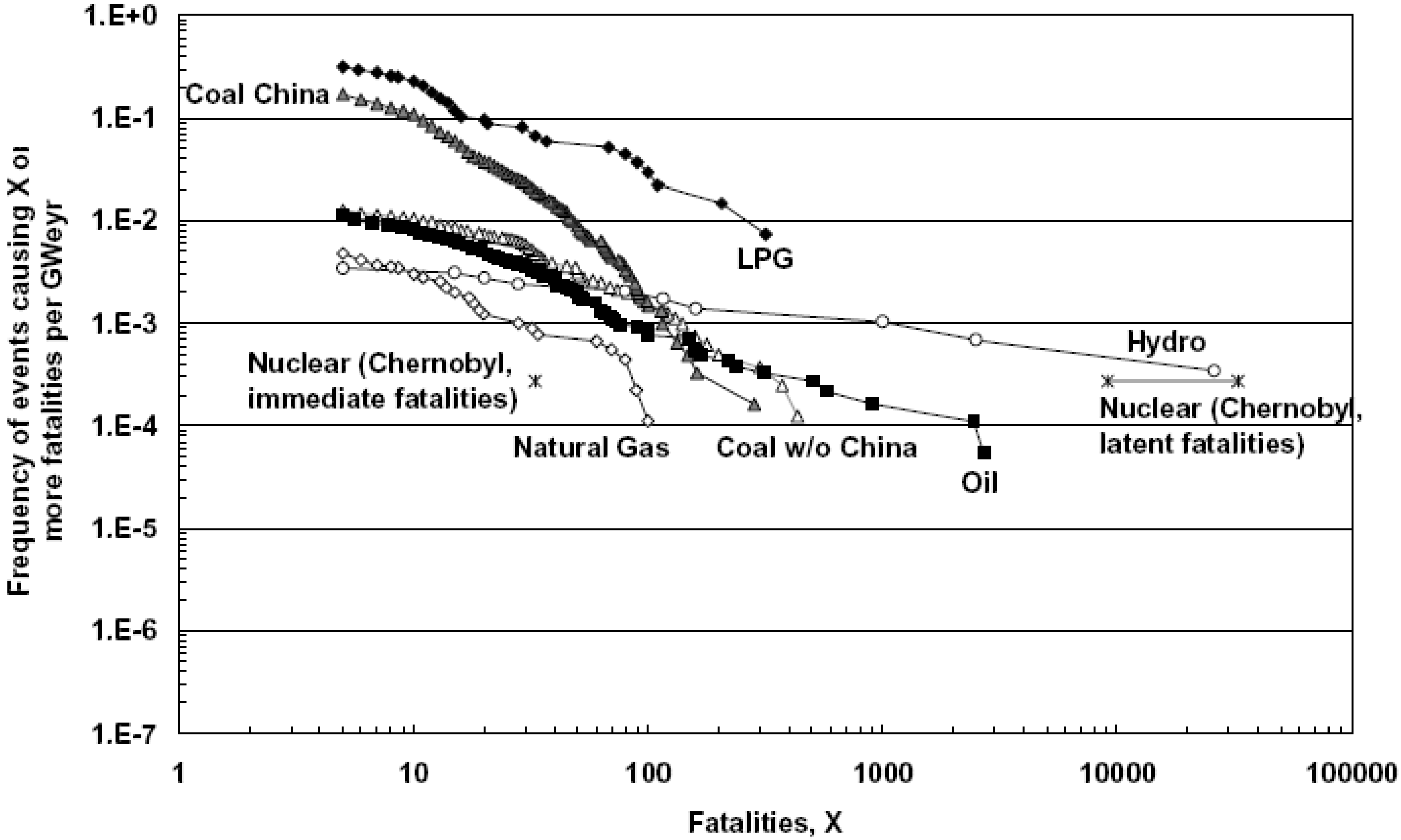

Figure 4: Comparison of frequency-consequence curves for full energy chains in non-OECD countries with partial reallocation for the period 1969-2000. The curves for coal w/o China, coal China, oil, natural gas, LPG and hydro are based on historical accidents and show immediate fatalities. For the nuclear chain, the immediate fatalities are represented by one point (Chernobyl); for the estimated Chernobyl-specific latent fatalities lower and upper bounds are given.

At every level, the earthquake and tsunami must have impaired the response to the accident at 1F. For instance, the workers must have been concerned not only about their own safety but especially about the fate of their families. Almost all of the personal dosimeters were lost to the tsunami. And government at the local level was largely nonfunctional. At the national level, the concerns were understandably dominated by the earthquake and tsunami, and not by some possible damage to reactors.

In this brief talk, I can only touch on another urgent need, as mentioned in my June 2010 article.[5] This is the analog of a Geographic Information System (GIS) in wide use for multiple layers of information about urban utilities ranging from the location of gas pipes, to electricity nets, to telephone numbers and street addresses. Another layer should be added, which would be the local radiation exposure rate, in mSv per year (normal

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[5] R.L. Garwin, "A Nuclear Explosion in a City or an Attack on a Nuclear Reactor," *The Bridge*, Vol. 40, No. 2, pp 20-27, Summer 2010, http://www.nae.edu/File.aspx?id=19815.

background is 3 mSv per year), and also the level of ground contamination, closely related to the radiation level.

In addition, without waiting for an accident, approximate shielding factors against local radiation should be calculated and recorded for easy retrieval in case of need. Access would be by the ubiquitous Web browser available not only on PCs but on smartphones and other handheld computer systems.

Feeding such an information system following a disaster (and practiced often before!) should be an automated Airborne Monitoring System (AMS) which could consist of a substantial number of 10-kg drone aircraft carrying crude radiation detectors such as NaI crystals viewed by a detector, that from an altitude of 500 m in open terrain (1000 m in high-rise cities) could readily map the averaged contamination on the ground and the derived average dose. See[6]

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[6] http://www.spyplanes.com/pages_new/products.htm

BAT 3 UAV

Bat 3 is a complete man-portable UAV system that operates autonomously from unimproved areas and delivers high quality video imagery. A ready-to-fly aircraft with launch catapult, standard sensor payload, and complete ground station is available starting at US $52,000. The Bat 3 UAV has a wingspan of 6 feet, weighs only 19 to 25 pounds, and can fly for up to 5 hours (8 with optional wing tanks). Download PDF File.

Features

Georeferenced imagery
Fully autonomous missions
Small system footprint
Operations from unimproved areas
Low cost - Starts at $52,000

The Bat 3 is a 20-lb class UAV that seems to fit the description. These could be used for routine patrol of the Fukushima area at a non-interfering altitude of 1 km or 2 km, or at considerably lower altitude in order to resolve individual reactor sources.

Ultimately, they could be used to patrol populated areas such as Tokyo in order to provide a contamination map that would in large part reassure the public and guide any precautionary measures. The aircraft provide "georeferenced imagery" or (presumably) georeferenced counts of nuclear radiation. How this would actually be used depends on the database to which it is supplied and the access of authorities to that database.

Similar detectors carried on buses or taxi cabs or street-cleaning machines could supplement this over days or weeks (except in the case of nuclear explosion) with information on each and every street to provide refined data to guide decisions by individuals and by the authorities.
From the beginning of the Fukushima Dai-ichi crisis, U.S. government entities asked the National Atmospheric Release Advisory Center (NARAC) at LLNL for projections of the radiation exposure from assumed releases at 1F. Because the radiation measurements at 1F were unavailable because of lack of electrical power, absolute estimates were not available, but relative projections could be made.

The GOJ had a tool for this purpose as well, SPEEDI (System for Prediction of Environmental Emergency Dose Information), but it was not initially used because there was no agreement on the source term—the amount and type of radioactive material released from 1F. It wasn't until May 3 that the SPEEDI results were publicly available.

Finally, we may hope to bring some rationality into such blunt tools as mandatory evacuation, which itself is said to be as traumatic as a divorce or the death of a loved one, which costs should be quantified and balanced against the reduction of damage due to radiation in case one remains in the contaminated area. Taking the "50-yr" committed dose of 5 Rem at the outer edge of the yellow, which corresponds to 0.25% additional probability of death by radiation-induced lethal cancer, one needs to compare with the 20% probability of death by cancer in the same population not exposed to radiation. With the exception of the Nuclear Regulatory Commission, the U.S. government for planning purposes values a premature death at $5 million, so that an exposure to 5 Rem would indicate a cost of 0.25% x $5,000,000 = $12,500. Surely the population should have the opportunity to judge whether they would prefer to remain in the contaminated area and receive compensation in this amount, or be relocated, which would cost the state far more.

On the other hand, the government of Japan for a short time relaxed the environmental exposure limit for children from 1 to 20 mSv/yr (2 Rem/yr), in order that they should be able to continue to receive schooling at sites that would otherwise require evacuation. This edict was soon reversed after public protest and the resignation of Prof. Toshio Kosako, a radiation expert and an appointee of Prime Minister Naoto Kan. The government also stated that it would pay for the cleanup of the soil on school grounds.

COMMENT ON THE EVENTS OF FUKUSHIMA DAI-ICHI

In describing the course of the accident at Fukushima Dai-ichi, and some of its consequences thus far, it is apparent that the situation was much exacerbated by the general disaster in that area of the earthquake and tsunami.

The GOJ did provide much information on the Internet, although not in readily accessible form, either by public safety specialists or by the general public. The job was complicated by power failures and by the fact that many residents did not have their computers. In Chapter 9 of a major document[7] published by the Office of the Prime Minister, "kantei," the GOJ expresses itself on communications and messaging:

"While monitoring data has been quickly publicized, we need to come up with some ways to promptly communicate necessary information to the sufferers who want to obtain information but do not have access to the

[7] http://www.kantei.go.jp/foreign/kan/topics/201106/pdf/chapter_ix.pdf Also, http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html

Internet due to power failure in such a case as combined emergency with natural disaster."

and,

"The main channel of information provision has been through the mass media, which has transmitted press conferences and press releases to residents in the surrounding area, general public in Japan and international community. Hence, it is important to identify the needs of the mass media in addition to adequately communicate what people want to know. For example, when a hydrogen explosion occurred at reactor building of Units 1 and 3, television broadcast it almost real-time. The mass media strongly requested the ERC right after the explosion for an explanation of the accident by someone with appropriate knowledge in front of the camera about what really happened there and how the explosions would affect the reactors and so on. However, because it took time to verify the related facts, their needs were not always satisfied. As

this issue is liable to be involved with trade-off between swiftness and accuracy, it would have been appropriate to develop a manual to respond to such situations in advance."

I have quoted only two paragraphs, one concerned with the mechanical problem of reception of information, and the other with both substance and presentation.

In addition to the Internet, urgent messages such as the demand for evacuation were pushed by telephone, but much of the telephone service was disrupted, both to residents and to public officials. And, recall, the public was faced with clear and present disaster from the tsunami, with an uncertain number of tens of thousands of people lost at the time—not whether there might be tens of thousands of deaths eventually, but how many had actually occurred.

In previous documents, the PMP-MTA has discussed in great detail the formulation of messages in regard to pandemics ("Personal Protective Measures" in particular), the testing of those messages for understandability and effectiveness, and also for the degree to which they can be adopted.

As for format and presentation, for the most part the mechanisms envisaged by the PMP were Web based, in order to have the information available when needed, without having it lost or outdated in homes or offices.

As technology has advanced, it is now feasible to guard against loss of communications (but not necessarily of power); or the latest version of the emergency communications could be routinely downloaded into the home and office PCs, so that it would be available if communication lines were down or overloaded. To guard against temporary loss of power, the same capability should be and is available via smartphones and tablets.

Major questions are whether families will indeed have emergency kits and whether they will practice access to the emergency communication sites.

IMPACT OF FUKUSHIMA DAI-ICHI ON THE WORLD NUCLEAR POWER PROGAM

An example of potential response is a "90-day study" by the staff of the U.S. Nuclear Regulatory Commission which draws lessons for improving the safety of U.S. nuclear reactors[8]. The Chairman of the NRC has called for rapid implementation of most of the recommendations, but the other four NRC commissioners in testimony to the U.S. Congress seem to advocate extended delay.

Non-governmental organizations in the U.S. had also provided their views, and now their response to the 90-day NRC study. In particular, the Union

[8] http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf

of Concerned Scientists (UCS) which provided timely and substantive information as the 1F crisis evolved, takes issue technically with some of the detailed recommendations[9] and calls attention to its own broader set of issues[10], including that the NRC set similar priorities on its own performance in regard to safety as it does in regard to timely action on management and contract issues.

[9] http://www.ucsusa.org/assets/documents/nuclear_power/UCS-Response-to-NRC-90-day-recs-8-1-11.pdf
[10] http://www.ucsusa.org/assets/documents/nuclear_power/ucs-rpt-nuclear-safety-recs.pdf

APPENDIX

CONTINUING GROUND RADIATION SURVEY by a fleet of GPS-guided aircraft with data telemetered to populate a Geographic Information Service (GIS) database:

In more detail, within the Permanent Monitoring Panel on Mitigation of Terrorist Acts (PMP-MTA) we have long discussed a capability to use small UAVs to monitor from the air radioactive contamination of the ground, to guide public health measures such as evacuation, "remove your shoes when entering the house", and the like. This would have been very useful in case of an incident involving a radiological dispersal device (RDD), and it will surely be valuable in the aftermath of Fukushima. The attenuation length in air[11] for a typical gamma ray of 1-MeV energy is 15.7 grams per sq cm, and at sea level density of 1.3 mg/cc, an aircraft patrolling 1 km above ground level is shielded by 130 g/sq cm, or 8.3

[11] http://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html

mean free paths (MFP). So a signal from a 2-inch cube of NaI radiation detector might appear to be attenuated by a factor 3900 from what it would be at ground level. A contamination level of 1 R/yr at ground level[12] is 100 erg/g-yr and for a 1-MeV gamma ray ($1.6x10^{-6}$ erg/MeV) this corresponds to 66 x 10^6 MeV/g-yr. Per second this is 2.20 MeV/s-g and for a 2-inch NaI cube, we need to multiply by about 250 to find that we have about 550/s counting rate from the contamination at ground level. At flight altitudes, this is much suppressed.

For instance, at 1000-m above ground level (AGL) the suppression would appear to be by a factor 3900, to about 0.14 c/s; at 500-m altitude, the attenuation could be only $e^{-4.15}$ or 62, so the count rate would be about 8.7c/s. At a mapping altitude of 500 m, the UAV would need to be warned about the location of radio transmitting towers.

[12] For comparison, "First Year DRL (Derived Response Level): If a person is in danger of receiving an external radiation dose greater than 2 Rem during the first year, the EPA recommends relocation until radiation levels decrease. This is not an urgent action because the dose is received over a full year. "

In reality, for a non-collimated detector with poor energy resolution, we should use the energy-absorption coefficient, for 1-MeV photons given by NIST [6] as only 28 g/sq-cm, so that the count rates would be much higher at altitude-- specifically, about 5.5 c/s at 1000-m and 55 c/s at 500-m AGL (above ground level).

Because the detector is essentially nondirectional, there is an averaging over an area of linear size comparable with the patrol altitude. And the extrapolation to ground level depends on not only the altitude of the aircraft but the altitude of the terrain below, which, is readily available from Google Earth,