FILE ATTACHMENT #100

Dose Reconstruction for Caesium-137, Chornobyl Source Term: Summary for Full Sample, N=702

DRU: Modeling Nuclear Disaster Risk: The Effects of Perceived Risk and Radiation Exposure on Post-Chornobyl Psychosocial and Health Behavior Outcomes in Ukrainian Residents **NSF Grant #082 6983**

Dose Reconstruction

^{137}Cs Source Term

The European Commission and the IAEA has published the *Comprehensive Atlas of Caesium Deposition on Europe after the Chernobyl Accident* (1998) [D1]. The *Atlas* contains detailed projection maps of deposition contours that are color coded based on ^{137}Cs concentrations. The maps were available as vector graphics with multiple layers of information, including contour lines representing intervals of Cs deposition.

The *Atlas* includes overlapping maps at several different levels of resolution. One plate shows the entire continent of Europe, while other plates show regional detail, and some plates show details of hotspots. Plates with a larger geographical extent contain less detailed ^{137}Cs concentration information; whereas hotspot plates show more geographical detail and display more refined ^{137}Cs concentrations than regional plates, which are in turn more detailed than the continental plate. To accommodate this, a hierarchy is established such that ^{137}Cs concentration data from hotspot plates supersedes regional plates, which in turn supersede the European plate. For the final data set, only the following map plates were loaded to the geo-database (listed in order of precedence):

i. Plate 60 – Chernobyl Hotspot
ii. Plate 19 – Ukraine
iii. Plate 17 – Belarus
iv. Plate 23 – Western Russia
v. Plate 1 – Europe

These maps are presented in the *Atlas* as equal-area Lambert oblique azimuthal projections. The maps also contain a labeled grid corresponding to intersections of latitude and longitude (properly referred to as the *conjugate graticule*). The conjugate graticule provides a coordinate system which was used to develop an inverse transform of the original Lambert projection that effectively stretches the oblique azimuthal projection into an equirectangular projection corresponding to the surface of the earth. This process was used to transform the isolines defining contours of ^{137}Cs deposition in each respective plate. Software was then developed to recover the contour color and determine the ^{137}Cs concentration at a specified latitude and longitude for each residence identified for a person in the survey.

To accommodate locations outside the extent of the *Atlas*, the source term was approximated from the nearest available location available in the *Atlas*. ^{137}Cs deposition for Asia was approximated using the deposition of easternmost Russia. ^{137}Cs deposition for points south and west of the available maps was approximated using the deposition of southwestern most Europe.

Dose Assessment

A model was created to determine the dose rate at an arbitrary time t for any individual in the study. This model was generated by combining previously published algorithms for estimating soil mixing of ^{137}Cs in the Ukraine, kerma in air from radionuclides in soil, absorbed dose to a person, and reduced exposure due to typical behavior. The result is a piecewise function $\mathrm{H}(t)$ which takes in the time t and outputs an absorbed dose rate in units of pGy/s.

The dose rate model can be expressed in its most general form as the following equation:

$$\dot{\mathrm{H}}(t) = \mathrm{K}(\mathrm{A}(t),\mathrm{O}(t)) \cdot \mathrm{X}(t) \cdot \mathrm{E}(t) \cdot \mathrm{R}(t) \cdot \mathrm{C}(\mathrm{L}(t))$$

This equation represents the following process for determining the absorbed dose rate for an individual at some time t, where the units for t are days, and t=0 on the date of the accident at Chernobyl. This model is obtained through the following process:

Step 1: Determine demographic data

Define **L(*t*), A(*t*),** and **O(*t*)** as the location, age, and occupation (respectively) of the individual in question at time t and determine these values from the survey dataset.

Step 2: Find an initial source term (kBq/m^2)

Let $\mathbf{C_0(L(}\boldsymbol{t}\mathbf{))}$ be defined as the concentration of 137Cs in soil at location *L(t)*, <u>normalized to the time of the accident</u>. We will refer to this as the *initial indicator source term:* The concentration of Cs ^{137}will be used as a normalized indicator for the presence of other radionuclides which contribute to dose. This value is extracted from published 137Cs concentration maps in the Atlas [1] as described later in this document. $\mathrm{C_0}(\mathrm{L}(t))$ has units of kBq/m^2.

Step 3: Account for decay and soil mixing

Let $\mathbf{C_E(}\boldsymbol{t}\mathbf{, L(}\boldsymbol{t}\mathbf{)) := R(t) \cdot C_0(L(}\boldsymbol{t}\mathbf{))}$, where $\mathrm{C_E}(t,\mathrm{L}(t))$ is the effective concentration of 137Cs in soil at location L(t), <u>at time t</u>. We will refer to this as the *effective indicator source term*. This is found by multiplying $\mathrm{C_0}(\mathrm{L}(t))$ by a normalized function $\mathrm{R}(t)$ which accounts for both soil mixing [and associated attenuation] and radiological decay of ^{137}Cs between the time of the accident and the time t. The soil mixing/decay function $\mathrm{R}(t)$ is based on a soil mixing and attenuation model from [D2] which has been adjusted to include radiological decay. The function $\mathrm{R}(t)$ has been normalized to the units of $\mathrm{C_0}(\mathrm{L}(t))$ and is unitless; thus, $\mathrm{C_E}(t,\mathrm{L}(t))$ has units of kBq/m^2.

Step 4: Determine kerma rate in air

Let $\dot{\Gamma}(t)\mathbf{:= E(t) \cdot C_E(t)}$, where $\dot{\Gamma}(t)$ is the *kerma rate in air (at 1m elevation) from all gamma emitters*. This is found by multiplying $\mathrm{C_E}(t)$ by a normalized, piecewise function E(t), producing a kerma rate in air from all gamma-emitting radionuclides released by the accident. E(t) is a function with three pieces: The first piece captures the change in kerma rate during the 30 days immediately following the accident (including the effect of the contaminant cloud, short-lived radionuclides, and ongoing radionuclide deposition); the second piece captures the effect of short-lived radionuclides during the next 11 months; the third piece captures the effect of long-lived radionuclides through the present. The motivation for the function E(t) is presented in [D3] and has units of (pGy/s)/(kBq/m^2); thus, $\dot{\Gamma}(t)$ has units of pGy/s.

Step 5: Convert to absorbed dose

Let $\dot{\mathrm{h}}(t)$ **:= X(*t*)·Γ(*t*)**, where $\dot{\mathrm{h}}(t)$ is the *absorbed dose rate in tissue*. This is found by multiplying $\dot{\Gamma}(t)$ by a normalized function X(*t*), producing an absorbed dose rate in tissue based on an approximation of the individual's body mass at time *t*. The function X(t) is described in [3] and is based on models from [D4-D6]. X(*t*) here is unitless; thus, $\dot{\mathrm{h}}(t)$ has units of pGy/s.

Step 6: Accommodate behavior factors

Let $\dot{\mathrm{H}}(t)$ **:= K(A(*t*),O(*t*))·h(*t*)**, where $\dot{\mathrm{H}}(t)$ is the *absorbed dose rate*. This is found by multiplying $\dot{\mathrm{h}}(t)$ by a coefficient K(A(*t*),O(*t*)) which estimates the portion of time the individual spent indoors [and shielded] and outdoors [and unshielded] based on their age A(*t*) and occupation O(*t*). The values for K(A(*t*),O(*t*)) represent typical Ukrainian behavior and are extracted from tables published in [D3]. These behavior factors are unitless; thus, $\dot{\mathrm{H}}(t)$ has units of pGy/s.

Consider an interval of time T within the study period, where T is comprised of a set of days $t \in T$. Cumulative dose H(T) from this interval of time can be found by summing $\dot{\mathrm{H}}(t)$ over T:

$$\mathrm{H}(T) = \sum_{t \in T} \dot{\mathrm{H}}(t)\Delta t$$

Because measurements in the survey data set recorded time with no granularity finer than days, we set Δ*t* to one day (86,400 seconds), and can then rewrite our equation for H(*t*) as:

$$\begin{aligned}\mathrm{H}(T) &= \sum_{t \in T} \dot{\mathrm{H}}(t)\Delta t \\ &= \sum_{t \in T} 86400 \cdot \dot{\mathrm{H}}(t) \\ &= \sum_{t \in T} 86400 \cdot \mathrm{K}(\mathrm{A}(t),\mathrm{O}(t)) \cdot \mathrm{X}(t) \cdot \mathrm{E}(t) \cdot \mathrm{R}(t) \cdot \mathrm{C}(\mathrm{L}(t))\end{aligned}$$

Results

The data are presented as the cumulative dose for each individual expressed at the end of three time waves ending in: 31 December 1986, 31 December 1996 and 31 December 2009. The solid lines in Fig. 1 show the estimated cumulative distribution of external dose (mGy) received by the sample of individuals at the end of each of the three waves (solid lines)

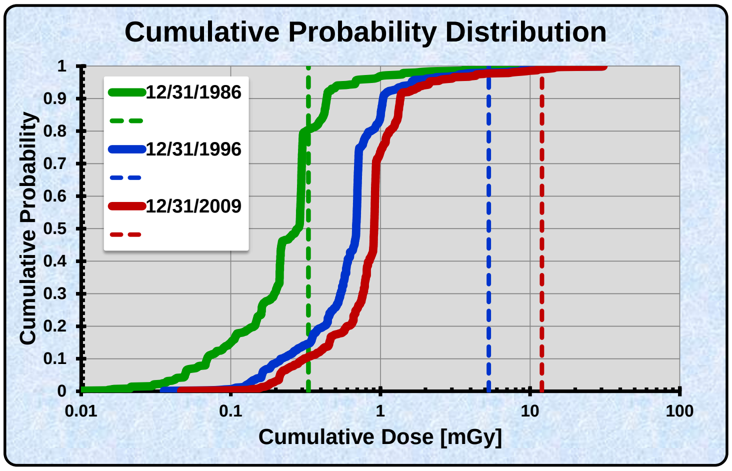

Fig.1 Cumulative doses computed for the sample population using the dose reconstruction methods (Solid Lines) and the average cumulative doses received from Natural Background Radiation (Dashed Lines)

Figure 2 shows a log normal probability plot of the distribution of cumulative doses received by the population of persons at the end of the third wave.

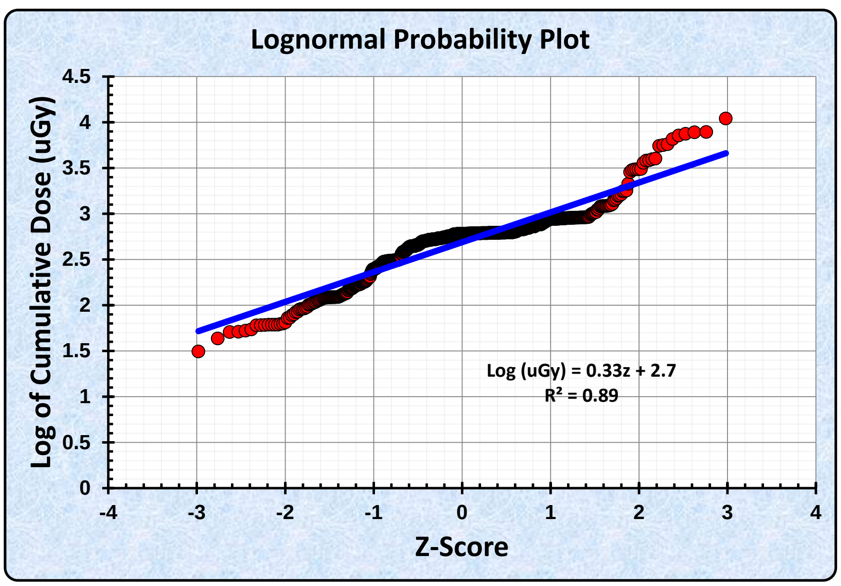

Fig. 2. Log-Normal Probability plot of the distribution of Cumulative doses received by the sample population at the end of the third wave.

As a point of reference, Fig. 3 shows the distribution of the annual average exposure from sources of ionizing radiation received by the population of the United States (D7).

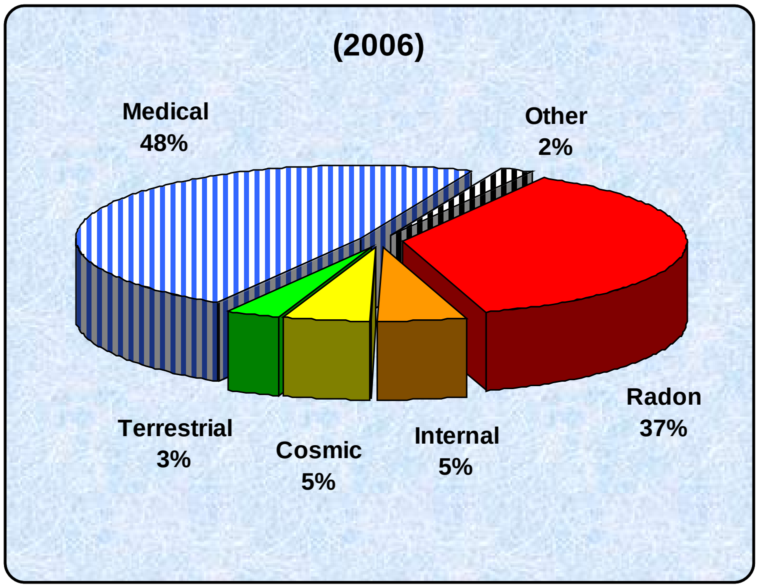

Fig. 3. Contributions to the annual averaged exposure received by the population of the United States. The Solid portions represent ubiquitous sources (i.e. natural background) and the lined portions represent man-made sources.

The total contribution from all sources is 6 mSv/year. The sections in solid colors represent the contributions from ubiquitous sources of ionizing radiation (i.e., natural radiation background) and the lined sections represent man-made sources. External exposures from the ubiquitous sources come from gamma rays originating in primordial terrestrial radioactivity (^{238}U, ^{232}Th and ^{40}K) and penetrating cosmic rays (muons) originating as secondary particles from primary cosmic rays incident on the atmosphere. These two sources of external exposure result in an annual average dose 0.48 mGy/year. Sources of natural background in Ukraine are not considered to be significantly different from the US. The dashed lines in Fig.1 illustrate the average cumulative dose that would be attributable to natural sources during the three time waves following the Chernobyl accident.

Table 1 is a summary of these results.

Table 1
Summary statistics of external dose reconstruction based on ^{137}Cs deposition following the accident in Chernobyl

	Ending Date		
	12/31/1986	12/31/1996	12/31/2009
Lowest value of External Dose received by an individual (mGy)	0.0074	0.036	0.047
Largest value of External Dose received by an individual (mGy)	28.0	30.0	31.0
Average value of External Dose received by an individual (mGy)	0.38	0.93	1.2
Median value of External Dose received by an individual (mGy)	0.28	0.69	0.91
Geometric Mean value of External Dose received by an individual (mGy)	0.23	0.61	0.84
Estimated Average value of External Dose from Natural Background (mGy)	0.33	5.3	12.0

Discussion

The US National Academies of Sciences has compiled reports that advise the US government on the relationship between exposure to ionizing radiation and human health. The latest report, *Biological Effects of Ionizing Radiation (BEIR VII)*, summarized the latest information from epidemiological and experimental research to low levels of radiation. They defined low level as doses less than 100mGy for external sources of low LET radiation such as gamma rays from ^{137}Cs and other terrestrial radionuclides as well as and high energy muons that are the primary component of cosmic rays reaching the earth. (D8).

The most thoroughly studied individuals for determination of health effects following exposure to ionizing radiation are the survivors of the atomic detonations in Hiroshima and Nagasaki. Sixty-five percent of these survivors received a low dose of radiation. Excess cancers above the number expected in the population have been observed for doses exceeding 100 mGy. There has been no evidence of increased risk of non-cancer diseases including hereditary effects at low doses, and the data are inadequate to quantify the risk if it does exist (D8).

Statistical limitations make it difficult to estimate cancer risks from external exposures of low LET radiation (photons, muons) below 100mGy. This is because radiation induced cancers are indistinguishable from those due to other causes, and during their lifetime, approximately 42 percent of the population will be diagnosed with cancer in developed countries. Thus, it is necessary to use models to estimate risks at low doses. These models are in effect extrapolations from the higher dose regions where excess cancers have been statistically identified.

The Linear-No-Threshold model estimates that the lifetime-attributable-risk (LAR) to a population receiving 100 mGy would be about 1% for males and 1.4% for females. This is about 40 times lower that the spontaneous risk. The median accumulated dose received by the population in this study is about 10 times less that the external dose from natural background sources and the estimated risk for excesses cancers would be 400 times less than the spontaneous rate.

Some of these conclusions for the general public in the Ukraine following the Chernobyl accident have been supported by epidemiological investigations over the past 20 years (D9, D10, D11). Apart from a large increase in thyroid cancer in young people, there is has been no clearly demonstrated radiation related increase in cancer risk. Given that radiation induced cancers continue to appear for decades following exposure, and because only twenty five years have passed since the accident, it may be too early to evaluate the full radiological impact of the accident.

The increase in childhood thyroid cancers was a unique circumstance relating to the demography and lifestyle in rural Ukraine near the site of the accident. Large amounts of radioactive ^{131}I were released and deposited on the fields used for grazing livestock. Dairy cows consumed the contaminated grass and bovine ingested iodine accumulates metabolically in the milk. If fresh milk is consumed by humans, most of the iodine is excreted, but the remainder accumulates metabolically in the thyroid. This resulted in a large dose to the thyroid that was highest in young persons both because of the quantity of milk consumed and the smaller volume of their thyroids. The thyroid is one of the most sensitive organs for radiation induced cancer induction in the body. Had the grass-cow-milk pathway been interrupted, the epidemic could have been dramatically reduced. This has been realized following the nuclear accident in Fukushima where ingestion of contaminated milk was eliminated and measurements of childhood thyroid doses have been extremely low (D12).

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