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Chernobyl Accident Fatalities and Causes

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13 ABSTRACT *(Maximum 200 words)*

Based on available sources of information, an assessment is made of the Chernobyl accident fatalities and causes of death that resulted from acute injury effects. Accident victims grouped according to whole body radiation dose and biologic response were examined and reconciled based on comparing various sources of information. Fatalities are identified with the occurrence of acute radiation sickness (ARS) syndromes. A maximum likelihood regression analysis was performed on the available fatality and dose data based on five different statistical models to estimate the LD_{10}, LD_{50}, and LD_{90} values. The estimated LD_{50} is about a factor or two higher than previously published values which is attributed to post accident emergency medical and clinical care.

14 SUBJECT TERMS

Chernobyl Accident	Radiation Injury	Bone Marrow
Clinical Classification	Lethality Causes	Skin Damage
Radiation Pulmonitis	Radiation Doses	Fatalities

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14. SUBJECT TERMS (CONTINUED)

Intestinal Syndrome   Acute Effects

CONVERSION TABLE

Conversion factors for U.S. customary
to metric (SI) units of measurement

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E-10
atmosphere	kilo pascal (kPa)	1.013 25 X E+2
bar	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E-28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E-2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E-2
degree Fahrenheit	degree kelvin (K)	T_K=(t°f + 459.67)/1.8
electron volt	joule (J)	1.602 19 X E-19
erg	joule (J)	1.000 000 X E-7
erg/second	watt (W)	1.000 000 X E-7
foot	meter (m)	3.048 000 X E-1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E-3
inch	meter (m)	2.540 000 X E-2
jerk	joule (J)	1.000 000 X E+9
joule kilogram (J Kg) (radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E-6
mil	meter (m)	2.540 000 X E-5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E-2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force Inch	newton-Ometer (N.m)	1.129 848 X E-1
pound-force/inch	newton/meter (N/m)	1.751 268 X E+2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E-2
pound-force/inch^2 (PSI)	kilo pascal (kPa)	6.894 757
pound-mass (ibm avoirdupois)	kilogram (kg)	4.535 924 X E-1
pound-mass-foot^2 (moment of inertia)	kilogram-meter2 (kg.m^2)	4.214 011 X E-2
pound-mass/foot^3	kilogram/meter3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E-2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E-4
shake	second (s)	1.000 000 X E-8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg, 0°C)	kilo pascal (kPa)	1.333 22 X E-1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

This report reviews current available Soviet data sources on Chernobyl accident victims hospitalized for acute radiation sickness (ARS). Patients are grouped by the whole-body gamma radiation dose indicating the severity of bone marrow syndrome and biologic response criteria used to place patients in the different dose groups. We compare and reconcile the different data sources according to the fatalities reported as a result of the Chernobyl accident. Included is a brief review of information on additional unconfirmed casualties attributed to the nuclear accident.

We further review the Soviet data sources in terms of the reported causes of fatal outcomes and the occurrence of ARS syndromes identified as causes of fatalities. In many cases, fatal outcomes are ascribed to the effect of several severe ARS syndromes, each of which could have been an independent cause of a fatal outcome. All patient groups identified in the data sources are correlated in terms of the severity of bone marrow syndrome and ascribed causes of fatal outcome. Based on the available data, all but two of the Chernobyl fatalities can be accounted for according to patient category, dose level, and lethal cause considerations.

A maximum likelihood analysis of the available data on the Chernobyl accident survivors and fatalities was also performed. Five different statistical models were applied to develop estimates of the incidence of lethality with total body dose. The marked effect in survival owing to medical attention afforded the accident victims is demonstrated.

SECTION 2

DATA SOURCES ON CHERNOBYL VICTIMS

There are three sources of original data on Chernobyl patients with acute radiation sickness:

- USSR State Committee on the Utilization of Atomic Energy, (hereinafter referred to as State Committee). *The Accident at the Chernobyl Nuclear Power Plant And Its Consequences*, August 1986
- Guskova, *Early Acute Effects Among the Victims of the Accident at the Chernobyl Nuclear Power Plant*, April 1987
- Fry, *Foreign Trip Report*, October 1987

Dr. S. A. Fry reports on presentations by Dr. A. Barabanova, a Soviet physician associated with Dr. A. Guskova at the Moscow Hospital No. 6, and by Dr. D. P. Orsanov, an internationally known biophysicist who went to Chernobyl two to three days after the accident to supervise environmental monitoring activities.

The main clinical response and medical outcome data on ARS patients, as reported in the three references, are summarized in Tables 1, 2, and 3.

Table 1. Chernobyl victim follow-up reported by State Committee [1986].

Dose Group	Dose Range (Gy)	No. of Patients Moscow	No. of Patients Kiev	Onset Primary Reaction (h)	Latent Period (days)	Lymphocyte Count at 3–6 Days (per mm^3)	Time Platelets $\leq 40000/mm^3$ (days)	No. of Deaths Moscow	No. of Deaths Kiev	Fatal Radiation Damage To Skin
1st	0.8–2.1	(105)[a]		2	30+	600–1000	25–68	--	--	--
2d	2–4	53		1–2	15–25	300–500	17–24	--	--	--
3d	4.2–6.3	21	2	0.5–1.0	8–17	100–200	10–16	7[b]	--	6
4th	6–16	20	2	0.5	6–8	<100	8–10	17[b]	2[c]	14
Total		203						26[d]		20[e]

[a]Remainder not specifically reported.

[b]In days 10 to 50.

[c]On days 4 and 10.

[d]One additional victim died from severe burns at 6:00 a.m. on 26 April; another victim's body was not discovered, which puts the total at 28 deaths for the first 50 days following the accident.

[e]Given as 20 on p. 35 and as 19 on p. 34 of State Committee [1986].

Table 2. Chernobyl victim follow-up reported by Guskova [1987].

Dose Group	Dose Range (Gy)	No. of Patients Moscow	No. of Patients Kiev	No. of Patients with Radiation Burns[a] % of body surface damaged 50[b]	10–50	1–10	Total	No. of Deaths from ARS Moscow	No. of Deaths from ARS Kiev	Day of Death after Exposure
1st	0.8–2.1	31	109	--	1	2	3	--	--	
2d	2.0–4.0	43	12	1	9	2	12	1	--	96
3d	4.2–6.3	21	--	3	15	3	21	7	--	16, 18, 21, 23, 32, 34, 48,
4th	6–16	20	1	9	10	1	20	19	1[c]	14, 14, 14, 15, 17, 17, 18, 18, 18, 20, 21, 23, 24, 24, 25, 30, 48, 77, 91
	Total	115	122				56[d]	27	1[c]	
	Overall	237[e]						28[f]		

[a]Based on patients in Moscow.

[b]From text, this percentage should appear as 50–90 (or 50–100).

[c]Died on day 10 from combined heat and radiation injuries.

[d]The radiation burns were unquestionably fatal at least in 19 cases.

[e]A change from 203 to 237, announced on November 1986, occurred primarily as a result of persons with 1st degree ARS.

[f]With the first two (one at his work station, the other from heat burns in Pripyat in the first 5 h), the total is 30 deaths.

Table 3. Chernobyl victim follow-up reported by Fry [1987].

Chernobyl Fatalities	
Description	**No. of Victims**
Initial (on-site and in Pripyat)	2
Died as result of ARS	
In Moscow	27
In Kiev	1
Died as result of CVA	1
Total deaths	31

Radiation-induced Skin Injuries, Moscow Hospital No. 6	
Description	**No. of Victims**
Number of ARS patients	115
Radiation-induced skin injuries	56[a]
Skin injuries incompatible with life	19

Waves of Erythema

Wave	Onset	Remarks
1st	36 h	No obvious skin injury for 36 h. First wave lasted up to 24 h.
2d	5-10 days later	Erythema more widespread. Involved skin areas covered by clothing. Coincided with latent period of ARS.
3d	2-3 months	Included 28-30 patients. 8-10 had no previous manifestation of skin injury.

[a]Two of 56 patients also had thermal burns.

SECTION 3

CHERNOBYL FATALITIES

The number of fatalities from the Chernobyl accident totals 31. Table 4 shows the reported numbers of death and reconciles the different data sources. There were two initial fatalities: one victim died at his workplace, his body was never recovered; another victim died from severe burns at 6:00 a.m. in the morning of the accident in the Pripyat hospital. State Committee [1986] reports 28fatalities as occurring within the first 50 days (Table 1). Three people subsequently died from ARS on Days 77, 96, and 91 (Table 2), resulting in a total of 31 fatalities.

Dr. Barabanova reported that one transfer patient from Chernobyl, with signs and symptoms of acute radiation sickness, suffered a cerebrovascular accident (CVA) enroute and died from that cause shortly after admission to the hospital [Fry, 1987]. Hence, the Chernobyl fatalities include 2 initial fatalities, 28 ARS fatalities (27 died in Moscow, and 1 in Kiev), and 1CVA fatality (Table 3). In Table 4, notice that Guskova did not include the CVA fatality among the fatalities reported. Only one fatality is listed for Kiev in Table 2, whereas two fatalities are listed in Table 1.

Dr. Barabanova further reported that the CVA victim was among the fatalities at Hospital No. 6 in Moscow [Fry, 1987]. This piece of information appears to be in error. State Committee [1986] reports that two patients died in Kiev on days four and ten after the accident. Guskova [1987] shows only one death in Kiev, a patient who died on the 10th day from combined heat and radiation injuries. The transfer patient who died shortly after hospital admission from CVA must have been the Kiev fatality on day four. The early death in Kiev has been confirmed by Deputy USSR Minister of Health, Ye. Vorobyev, who told a press conference on 9May1986 that a third person, the first victim of radiation exposure, died three days after the accident in a Kiev hospital [Goure, 1987].

Table 4. Chernobyl fatalities.

Classification	State Committee (August 1986)	Guskova (April 1987)	Fry October 1987	Censensus
Initial Fatalities	2	2	2	2
Died as result of ARS				
In Moscow	24	27	27	27
In Kiev	2[a]	1[b]	1	1
Died as result of CVA	--	--	1	1[c]
Reported total	28[d]	30[c]	31	31
Other	3[d]	1[c]	--	--
	___	___	___	___
Total Fatalities	31	31	31	31

[a]On days four and ten.

[b]On day ten.

[c]One ARS patient suffered a CVA while being transferred from Chernobyl to Kiev and died shortly thereafter from that cause on day four.

[d]Reported fatalities refer to the first 50 days: three patients subsequently died from ARS [Guskova, 1987].

SECTION 4

UNCONFIRMED CHERNOBYL FATALITIES

According to Dr. Barabanova's presentation, Fry [October 1987] reports the following: "A journalist/photographer who spent some time at the accident site shortly after the accident is reported to have died about 9 months later; the cause of his death is controversial according to Dr. Barabanova who did not elaborate further."

The Moscow weekly *Nedelya* cited *Novoye Russkoye Slovo* of 31 May 1987 on the death of the motion picture director Vladimir Shevchenko two months earlier from radiation sickness [Goure, 1987a]. Shevchenko produced the documentary, "Chernobyl, Chronicle of Difficult Days," which was filmed in May 1986 at the Chernobyl power station. *Nedelya* also reported that two cameramen received large radiation doses and are [then] currently hospitalized.

The documentary film on the Chernobyl accident has been described in the *Moscow News* No. 11, 22-29 March 1987 [Goure, 1987a]. Readers are left with the impression that a camera and its crew are taken on a tour through the damaged reactor, often close to high levels of radiation by the plant's chief engineer, who says, "That pipe there (ten or so meters away) is roughly 1000 roentgens."[1] Later, in referring to Y. Velikhov, Vice President of the USSR Academy of Sciences, seen walking in front of the camera, the reporter adds: "A little bit earlier in the film, we were told why the famous scientists had to risk their lives. What about the invisible cameraman? The other members of the filming crew?"

Three Soviet sources appear to agree on at least one additional Chernobyl fatality. The *Moscow News* highlights the radiation risk to the camera crew. *Nedelya* reports the death of the movie director and the hospitalization of two cameramen. Dr. Barabanova mentions the reported but controversial death of a journalist/photographer.

Non-Soviet sources report additional fatalities and radiation injuries among the cleanup crews according to Radio Free Europe "Rad Background Report," 14 October 1986 [Goure, 1987b]. At the same time, official Soviet spokesmen deny that more people have died from radiation overdoses at the Chernobyl atomic power plant since the accident there last year killed 31 people [*Los Angeles Times*, 1987].

1. Probably refers to a dose rate of 1000 R/h.

SECTION 5

CAUSES OF FATAL OUTCOMES

All three Soviet data sources discuss the importance of radiation damage to skin and basically repeat the same message:

- "In 19 cases, the deaths of patients with third- and fourth degree acute radiation disease occurred only as a result of severe damage, which was incompatible with survival, to 50-90% of the surface of their bodies." [State Committee, 1986]

- "In the cases of at least 19 of the 56 patients with burns, the burns were unquestionably fatal." [Guskova, 1987]

- "Of the 27 patients who died of radiation injuries at Hospital No. 6, 19 had radiation induced skin injuries over 90-100% [*sic*] of their body surface. It was the Soviets's opinion that in these cases, the skin injuries were so severe as to be considered incompatible with life, even in the absence of bone marrow damage." [Fry, 1987]

All these statements appear to be true but incomplete. Guskova [1987] discusses the interrelationships between individual causes of lethal outcomes in somewhat more detail, summarized in Table 5. Although all patients with third- and fourth-degree bone-marrow syndrome had severe radiation burns (Table 2), only five lethal outcomes could be ascribed exclusively to radiation damage to vast areas of skin. These five cases did not involve radiation enteritis or irreversible myelodepression, and their whole-body doses did not exceed 6 Gy. In 14 other cases, radiation damage to skin was combined with other severe syndromes, each of which could have been an independent cause of a fatal outcome. These two groups total 19 fatalities, which is the number of cases with severe skin injury commonly cited as being incompatible with life. Apparently, the remaining eight fatalities were caused by combinations of various syndromes without radiation skin damage being an independent cause of the fatal outcomes.

Various ARS syndromes reported by Guskova [1987] as apparent independent causes of fatal outcomes (or being capable of producing a fatal outcome) are listed in Table 6. As mentioned before, radiation skin damage was the exclusive or contributing cause in 19 fatal outcomes. *Lethal* intestinal syndrome, indicated by the appearance of diarrhea from day four to day eight, was noted in 10 patients. These patients were exposed to 10 Gy or higher gamma radiation; they all died within the first three weeks after exposure.

Acute radiation pulmonitis was observed in seven patients with third- and fourth-degree ARS. It was typified by a rapidly intensifying difficulty in breathing, by ventilation failure, and by the onset of lethal outcomes from hypoxemic coma. "Autopsy revealed large blue lungs with marked interstitial edema." [Guskova, 1987]

Six cases with lethal outcomes were ascribed to radiation damage causing irreversible hematopoietic aplasia or to complications caused by bone marrow transplants. Hemophilia achieved thanatogenetic significance only in one case.

Table 5. ARS fatalities at Hospital No. 6 in Moscow.

Causes of Fatality	Number of Fatalities
Radiation skin damage exclusively	5
Skin damage combined with other ARS syndromes	14
Combinations of ARS syndromes other than skin damage	8
Total fatalities	27

Table 6. ARS syndromes identified as causes of fatalities.

ARS Syndrome	Fatalities with Syndrome
Radiation skin damage	19
Intestinal syndrome (10 Gy or more)	10
Acute radiation pulmonitis	7
Irreversible hematopoietic aplasia or bone-marrow transplant complications	6
Hemophilia	1
Thermal burns/internal contamination	2
Radiation induced vascular damage	1

In Moscow, 56 of the 115 ARS patients suffered from radiation induced skin injuries. Two of the 56 patients formed a unique subgroup: they also had severe thermal skin burns produced by steam and incurred a significant internal radionuclide dose estimated as 1.5 to 4 sieverts on the basis of postmortem radiometry. The radionuclide doses of all other patients did not exceed 1 to 3 percent of their external dose. The gamma dose of these two patients was on the order of 4 to 5 Gy. The patients died on days 23 and 18, respectively, from their combined injuries [Fry, 1987].

One patient in Moscow suffered a fatal CVA[2], probably associated with generalized radiation induced vascular damage [Fry, 1987]. The patient received an average bone marrow dose of 3 Gy and suffered severe radiation induced skin injuries, manifesting as three waves of erythema, with the third wave developing almost three months after the accident. Accordingly, this patient (case 3 presented by Dr. Barabanova) must be the one fatality in the second-degree ARS group who died on day 96 after the accident (Table 2).

Based on currently available Soviet data sources reviewed, Table 7 provides a summary of our effort to correlate the Chernobyl accident fatalities and causes grouped in terms of:

- Severity of the bone marrow syndrome (the whole-body gamma radiation doses).
- ARS syndrome identified as exclusive or contributing cause of fatal outcomes.
- Patient injury or medical treatment category.

Patient categories include one cerebrovascular accident, a patient in the medium gamma dose group who died from lethal radiation damage to the vascular system. Five fatal outcomes are ascribed solely to radiation damage to large skin areas. These patients fall in the severe gamma dose group: their estimated whole-body doses did not exceed 6 Gy.

Further, patient groups include bone marrow transplants and fetal liver cell transplants. These patients were selected on the basis of a whole-body dose of 6 Gy or greater, estimated from the lymphocyte count in peripheral blood and from cytogenetic analysis of chromosome aberrations. This dose level was understood to represent irreversible or extremely protracted and deep myelodepression.

The bone marrow transplants include 13 patients grouped in two subcategories:

a. Six patients had radiation damage to skin and intestines at a level that was deemed not incompatible with life. Four patients died between days 27 and 29 after the transplants. Two patients survived their bone marrow transplants; they had gamma exposures of 5.8 and 9.0 Gy. Gamma doses for the four patients who died ranged from 4.3 to 10.7 Gy, placing one fatality in the severe and three fatalities in the extremely severe bone marrow syndrome groups. They died from "mixed virus-bacterial infections," also called as "complications caused by bone marrow

2. Note that this CVA fatality occurred in Moscow; a different ARS patient suffered a CVA enroute to the hospital and died on day four in Kiev.

Table 7. Chernobyl accident fatalities and causes. Hospital No. 6 in Moscow.

Patient Category	Bone Marrow Syndrome Fatalities			Lethal Radiation Damage to				Lethal Infections/ GVH[a] Disease	Thermal Burns	Internal Contamination	Hemophilia
	Medium 2–4 Gy	Severe 4–6 Gy	Extremely Severe 6–16 Gy	Skin	Intestines	Lungs	Vascular System				
Cerebrovascular accident	1			--	--	--	Yes	--	--	--	--
Radiation skin damage alone		5		Yes	--	--	--	--	--	--	--
Bone marrow transplants											
Radiation damage "not incompatible with life"		1	3	--	--	--	--	Yes	--	--	?
Radiation damage "incompatible with life"			7	Yes	Yes	Yes	--	?	--	--	?
Fetal liver cell transplants			6	Yes	Yes	--	--	--	--	--	--
Thermal burns/internal contamination			2[b]	Yes	--	--	--	--	Yes	Yes	--
Unspecified		1	1	?	?	?	--	--	--	--	--
Total	1	7	19	19	10	7	1	6	2	2	1

[a]GVH = graft versus host.

[b]External gama dose 4 to 5 Gy. internal radionuclide dose 1.5 to 4 Gy.

transplants" [Guskova, 1987]. State Committee [1986] reports that all six bone marrow transplants in this group had similar disorders that may have been caused by graft-versus-host (GVH) disease. Two of the four fatalities in this group occurred prior to the publication of the State Committee [1986] report. It is stated that the GVH reactions may have been contributing causes of these two deaths.

b. Seven patients had radiation damage to their skin, intestines, and lungs at a level that was deemed incompatible with life. They died from acute radiation damage to the skin, gut, and lungs on days2 to 19 after the transplants (days 15 to 25 after exposure).

In the category of fetal liver cell transplants, all six patients died from radiation damage to the skin and intestines [Guskova, 1987]. Patients for the transplantation of human embryo liver cells were selected on the basis of extremely severe damage to the skin and intestines and extremely unfavorable prognosis [State Committee, 1986].

Two patients in the thermal burns and internal contamination category died from their combined injuries, including bone marrow damage and radiation damage to skin.

In Table 7 all but two of the 27 fatalities in Moscow can be traced through patient categories, thus leaving only two in the "unspecified" category. The totals of individual lethal causes have been taken from Table 6. Adding the numbers of patients in relevant patient categories, the corresponding totals are not always identical with those in Table 6, but are still in general agreement. For example, we would have 13 rather than 10 cases of lethal radiation damage to intestines. In cases where the fatal outcomes associated with a patient category are ascribed to multiple contributing ARS syndromes ("yes" in Table 7), all the syndromes may not necessarily be present for each and every fatality.

In other cases, the relevant patient categories identify fewer fatalities than the totals of Table 6. For example, only four rather than six total cases of lethal infections and GVH diseases are identified directly. In these cases, the question marks in Table 7 suggest other possible patient categories associated with a particular cause of death.

The individual gamma doses of the accident victims are generally unavailable. Exceptions are the cerebrovascular accident victim with an estimated dose of 3 Gy, the four bone marrow transplant fatalities who died from mixed virus and bacterial infections with estimated doses of 4.3, 5.0-7.9, 5.8-6.0, and 10.7 Gy, respectively, and the two thermal burn and internal contamination patients with their combined doses shown in Table 7. Guskova [1987] also states that the patients with lethal intestinal syndromes received a short-term whole-body gamma radiation dose on the order of 10 Gy or higher.

SECTION 6

FATALITY INCIDENCE VERSUS RADIATION DOSE

A total of 238 Chernobyl accident victims received estimated whole-body gamma radiation doses in excess of 0.8 Gy. They were diagnosed as suffering from acute radiation sickness (ARS). Based on the severity of ARS, the patients were grouped in four dose range categories. The radiation data published to date include the dose ranges and the number of patients and deaths in each dose range group.

Although individual case histories have not been published, individual dose estimates have been reported for some cases, including 11 survivors and 7 fatalities. Table 8 lists individual doses and reference followed by a number or letter of patient identification. The numbers associated with Guskova [1987] refer to the original patient identification system; the letter "x" refers to patients mentioned but not otherwise identified in reports. Some of the individual doses reported by Guskova [1987] have been updated in a later report (UNSCEAR, 1987); Table 8 contains the updated values.

Table 9 summarizes the available data on radiation doses for both individuals and groups of individuals. In most cases, the patients in a dose group divide into two subgroups: a few patients with individual dose estimates, and the remainder distributed over the given dose range. The lethalities of the fourth dose group have additional patient subgroups. Ten patients died as a result of lethal intestinal syndrome; they were exposed to a dose of 10 Gy or higher (Table 6). Two patients died from a combination of severe thermal skin burns, internal radionuclide contamination, and bone marrow syndrome. Their average combined dose was about 7.25 Gy (Table 7). Four individuals in the fourth dose group have specific dose estimates, but no specific values were available for the remaining five individuals.

Based on the method of analyzing binary data given by Cox (1983), a maximum likelihood analysis of the data given in Table 9 was performed to estimate the incidence of Chernobyl fatalities with dose. Along with the explicit dose estimates given in Table 9 for both survivors and fatalities, it was assumed that the remaining individual doses were uniformly distributed over the corresponding dose range. For example, there are five fatalities in the dose range of 4.2 to 6.3 Gy listed under the "3rd" dose group in Table 9; thus, for this analysis, doses of 4.41, 4.83, 5.25, 5.67, and 6.09 Gy each were assumed for the five fatalities.

For purposes of comparison, five different model forms were applied to analyze the survivor/fatality binary data: normal, log-normal, Weibull, logistic, and log-logistic. Table 10 gives the model forms along with parameter estimates obtained. Based upon the χ^2 goodness-of-fit statistic, a ranking would fall between the Weibull and log-normal models, with Weibull the best fit. However, all models fit the data well ($p<0.005$, υ =236 dgf).

Table 11 gives a summary of the 10-, 50-, and 90-percentiles obtained for each model. The 10-percentile dose estimates range from 391 to 423 cGy, the 50-percentile from 590 to 616 cGy, and the 90-percentile estimates from 789 to 895 cGy.

Plots of the incidence of fatalities are shown in Figs. 1 through 5 for each of the

Table 8. Radiation doses of individual patients.

Dose Group	Dose Range (Gy)	Number of Patients	Number of Deaths	Survivors Dose	Survivors Patient Reference	Fatalities Dose	Fatalities Patient Reference
1st	0.8–2.1	140	--	0.9	Guskova [1987] - 97		
				1.4	- 48		
				1.9	Geiger [1986] - 6		
2nd	2.0–4.0	55	1	3.3	Guskova [1987] - 39	3	Fry [1987] - 3
				3.9	- 21		
				3.3	State Committee [1986] - D		
				2.25	Fry [1987] - 2		
				3.0	Telyatnikov [1987]		
3rd	4.2–6.3	21	7	5.6	Guskova [1987] - x	5.2	Guskova [1987]- 6
				4.9	Geiger [1986] - 2	4.4	- 5
4th	6–16	22	21	8.7	Guskova [1987] - x	6.4	Guskova [1987]- 28
						10.2	- 16
						9	- 8
						7	Fry [1987] - x 7
Totals		238	29		11 patients		7 patients

Table 9. Radiation doses of individuals and groups.

Dose Group	Dose Range (Gy)	Number of Patients	Number of Deaths	Survivors Number	Survivors Dose or Dose Range (Gy)	Fatalities Number	Fatalities Dose or Dose Range (Gy)
1st	0.8–2.1	140	—	3[a]	0.9, 1.4, 1.9		
				137[b]	0.8–2.1		
2nd	2.0–4.0	55	1	5[a]	2.25, 3.0, 3.3, 3.3, 3.9	1[a]	3.0
				49[b]	2.0–4.0		
3rd	4.2–6.3	21	7	2[a]	4.9, 5.6	2[a]	4.4, 5.2
				12[b]	4.2–6.3	5[b]	4.2–6.3
4th	6–16	22	21	1[a]	8.7	4[a]	6.4, 7, 9, 10.2
						10[c]	10–16
						2[d]	7.25, 7.25
						5[b]	6–16
Total		238	29	209		29	

[a]From Table 8.
[b]Remainder of patients in dose group.
[c]Patients with lethal intestinal syndrome (Table 6).
[d]Patients with thermal burns and internal contamination (Table 7).

Table 10. Regression models.

Model		Parameters						
Type	Form	μ^{*} (cGy)	σ^{*} (cGy)	α	β	η	λ	χ^{2**}
Normal	$\Phi(\alpha+\beta D)$	616.4	161.1	1.737	0.00621	--	--	65.60
Log-normal	$\Phi(\alpha+\beta 1nD)$	623.3	206.5	1.9186	0.00484	--	--	76.28
Weibull	$1-\exp[-(D/\lambda)^{\eta}]$	--	--	--	--	4.149	689.75	57.58
Logistic	$\{1+\exp[-(\alpha+\beta D)]\}^{-1}$	--	--	0.9940	0.00661	--	--	67.95
Log-logistic	$\{1+\exp[-(\alpha+\beta 1nD)]\}^{-1}$	--	--	1.896	0.00501	--	--	72.05

*μ and σ are mean and standard deviation, respectively

**$p<.005$, $\nu = 236$ dgf.

Table 11. Fatality percentile doses.

Percentile Dose (cGy)				
Model	LD_{10}	LD_{50}	LD_{90}	slope* (percent/cGy)
Normal	409.9	616.4	822.9	0.194
Log-normal	391.4	592.0	895.3	0.159
Weibull	401.0	631.4	843.3	0.181
Logistic	422.8	606.0	789.3	0.218
Log-logistic	403.3	590.1	863.5	0.174

$$\text{*slope} \equiv \frac{(90 - 10)}{LD_{90} - LD_{10}} \text{ (percent/cGy)}$$

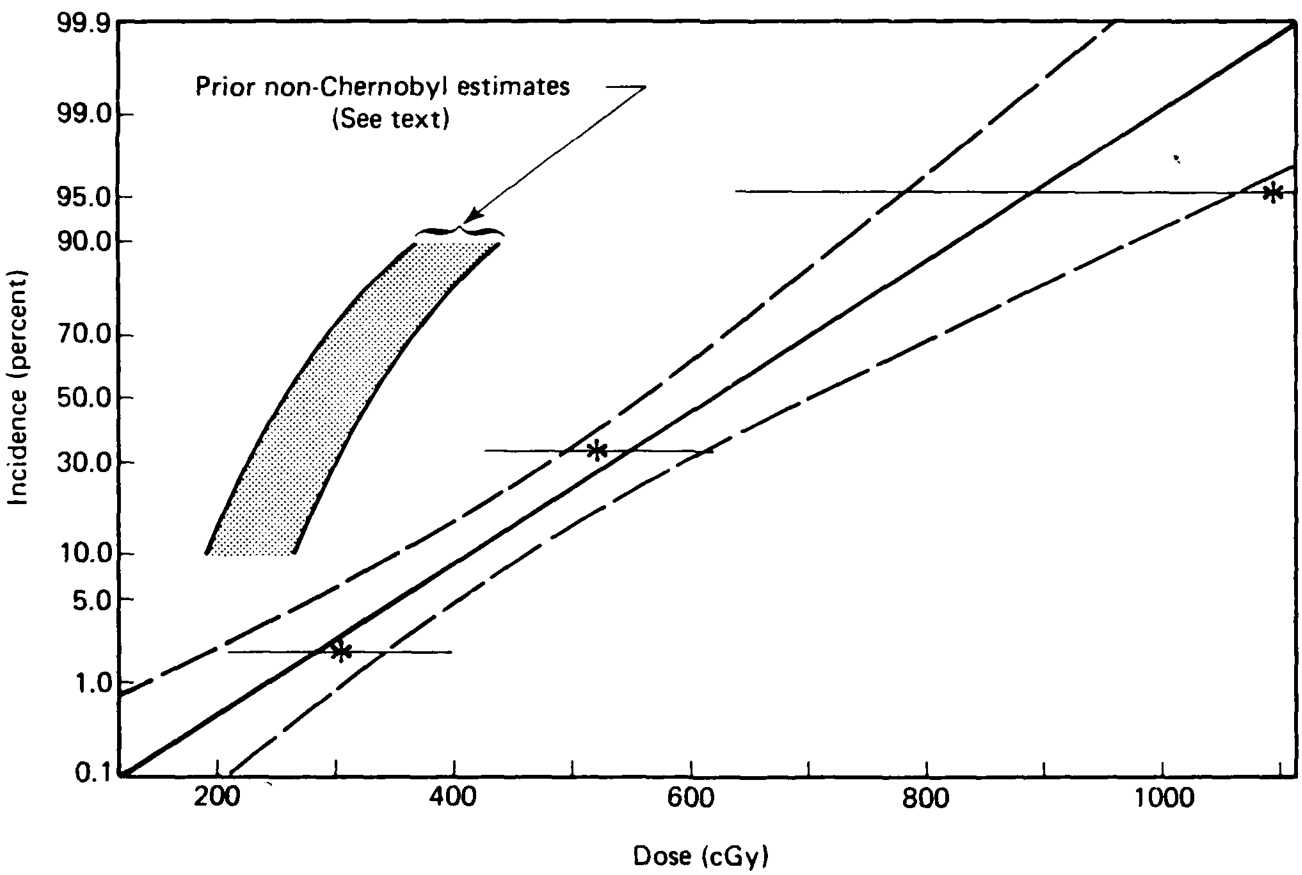

Figure 1. Chernobyl accident fatalities: normal distribution, 238 individuals, 90% confidence interval.

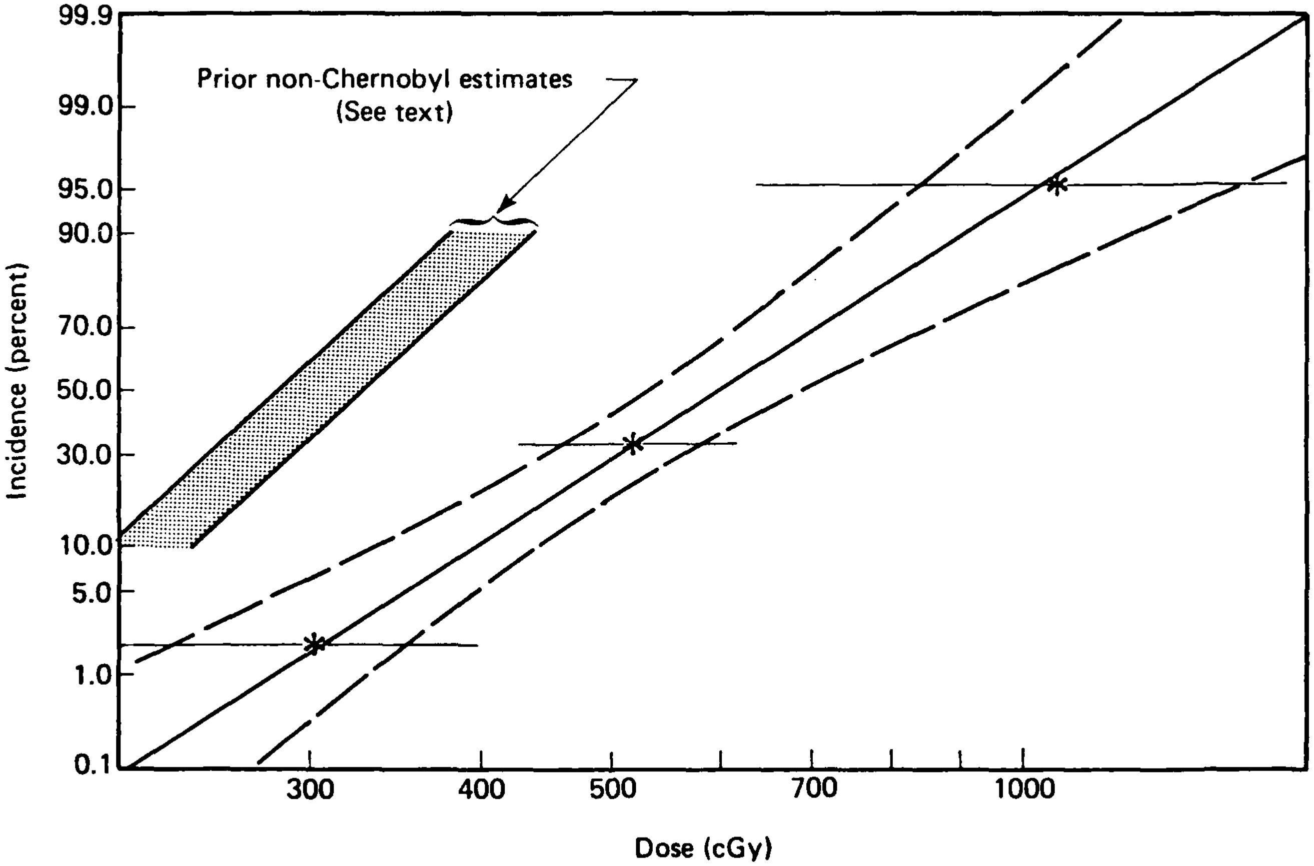

Figure 2. Chernobyl accident fatalities; log-normal distribution, 238 individuals, 90% confidence interval.

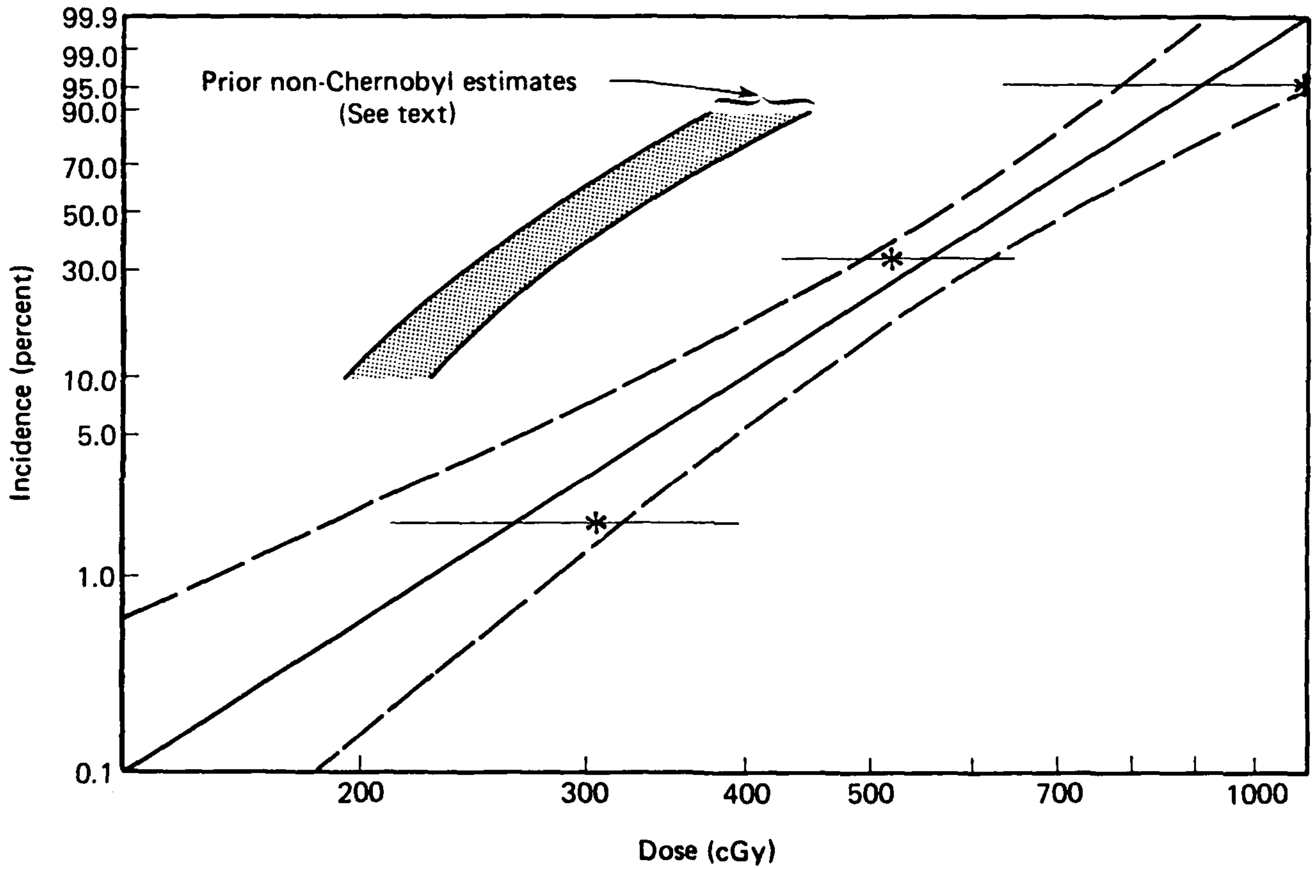

Figure 3. Chernobyl accident fatalities: Weibull distribution, 238 individuals, 90% confidence interval.

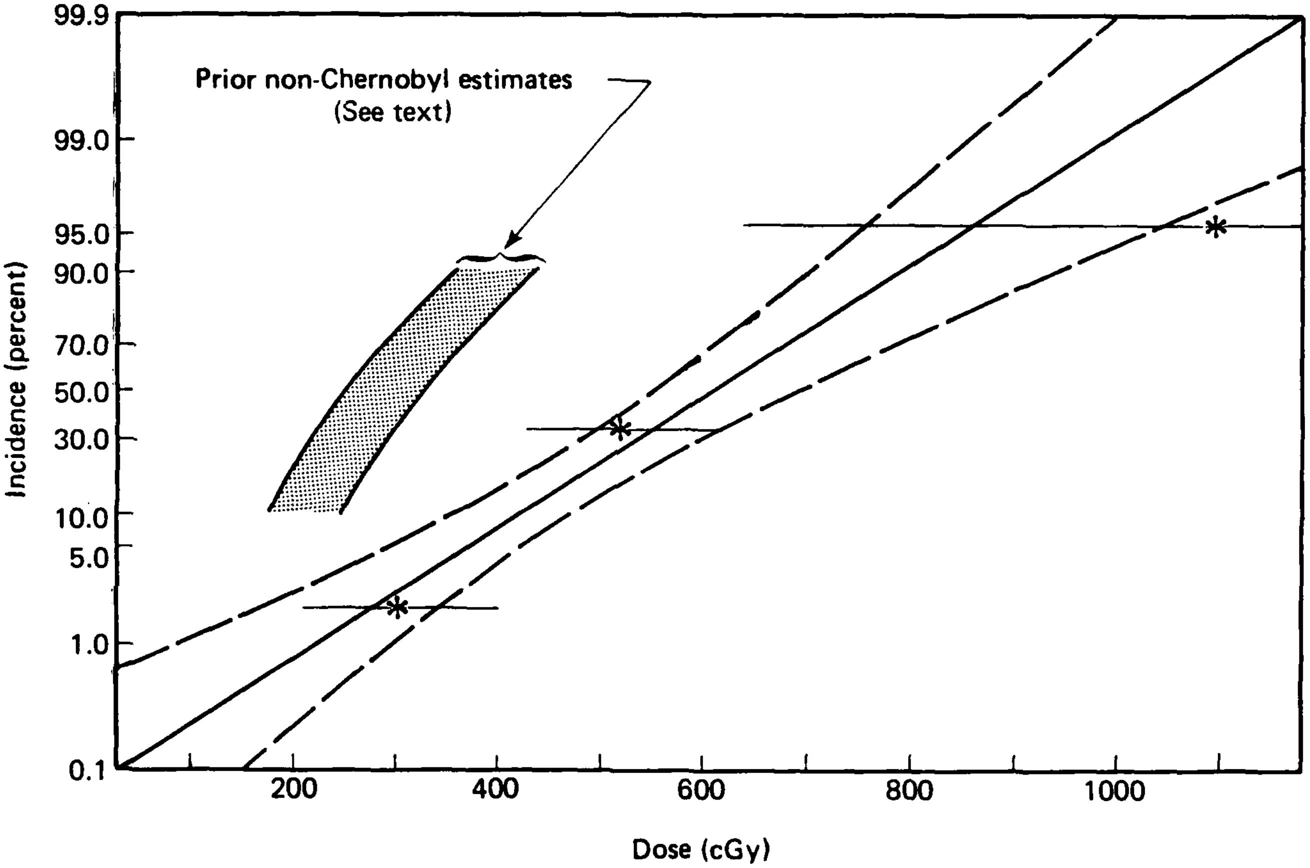

Figure 4. Chernobyl accident fatalities: logistic distribution, 238 individuals, 90% confidence interval.

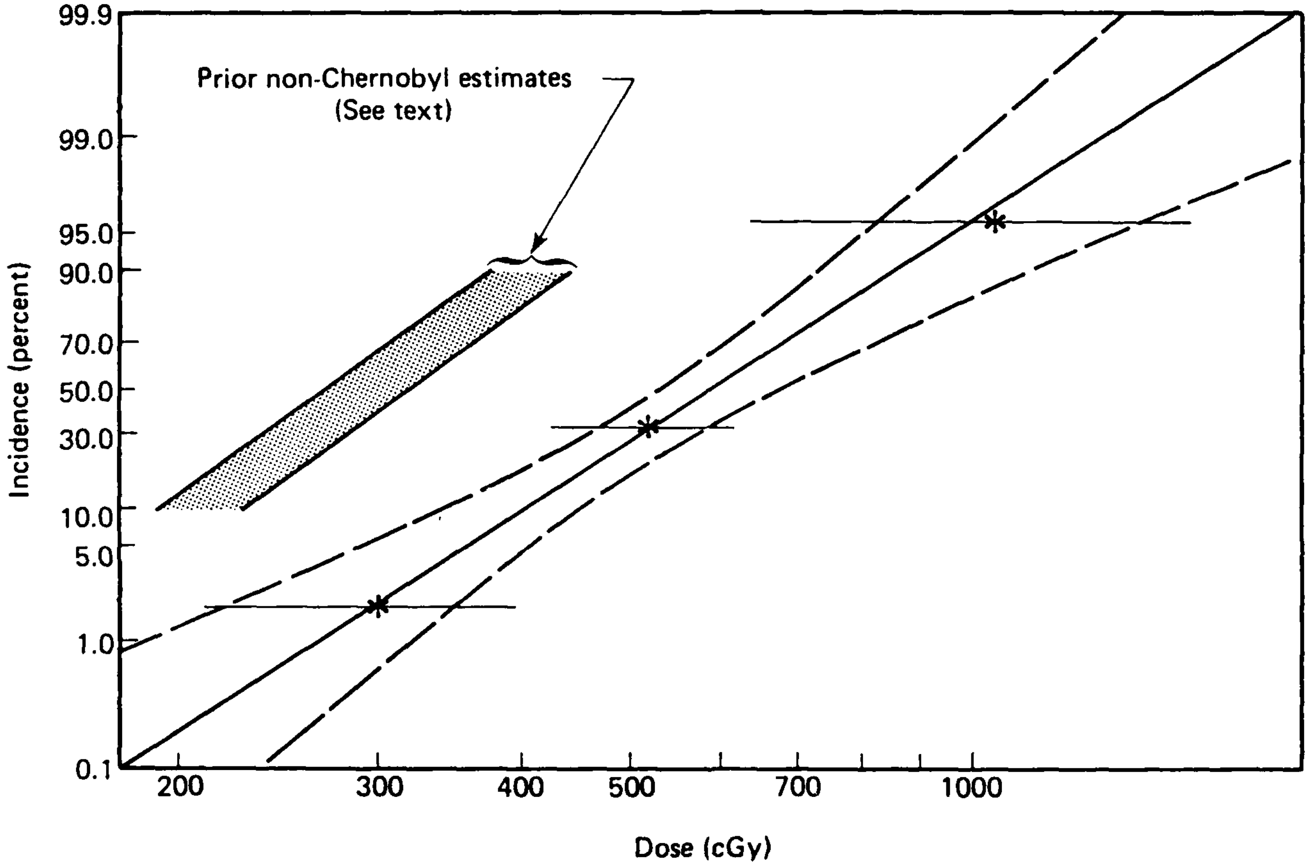

Figure 5. Chernobyl accident fatalities: log-logistic distribution, 238 individuals, 90% confidence interval.

five different models used to analyze the data; the 90% confidence bounds are given by the two dashed lines. In order to graphically illustrate the data from Table 9 used in fitting the various models, the data were grouped according to the horizontal lines shown in the plots. The data used in the maximum likelihood procedure is treated in binary form, and the asterisks on the horizontal line simply indicate the dose range midpoints of the data groups. Accordingly, while the log-normal (Fig. 2) and log-logistic (Fig. 5) models appear by inspection to fit the data better than the other models, they actually have the lowest χ^2 values (see Table 10); although as indicated above, all five of the models fit the data well.

A range of incidence for radiation lethality based on some prior estimates is also indicated in Figs. 1 through 5 by the broad shaded band. The left-most boundary is based on an LD_{50} midline tissue dose of 256 cGy and a slope estimated from dose response curves for large animals (swine, sheep, goats, and dogs) which tend to be parallel (Bond and Robertson 1957, Cronkite and Bond 1958, and Cronkite 1982). The right-most boundary is based on an LD_{50} value of 325 cGy, suggested by Lushbaugh (1969) for healthy young adults, with the slope also inferred from large animals.

One means of assessing the efficacy of medical care including the various treatment modalities of ARS afforded the Chernobyl accident victims is by comparing the LD_{50} based on prior estimates with that estimated here from the Chernobyl data. That is on average, prior estimates of the LD_{50} would be about 290 cGy whereas the value is about 607 cGy according to our analysis of the Chernobyl data; this amounts to about a factor of two reflected by medical care.

Also, as is apparent from the plots of fatality incidence versus dose, in general there is a significant difference in the slope magnitude between the Chernobyl dose response curves and that according to prior estimates of lethality. As indicated in Table 11, depending upon the model, slope estimates based on analysis of the Chernobyl data range from about 0.16 to 0.22 percent/cGy; the corresponding slope value from prior lethality estimates is about 0.44 percent/cGy. This difference in the steepness of the dose response curves could also be due in part to medical attention. Although more than likely, it is due to factors other than strictly ARS in combination with medical attention such as injuries to skin, which as mentioned above was a very significant factor. For example, in the absence of medical attention, a larger proportion of lethalities would be expected at lower doses, i.e., in the second and third dose groups. This certainly would tend to steepen the dose response curves. However, because of the imprecision of data regarding burn injuries and other non-ARS effects, we have not attempted to perform any isolated causal analysis with regard to fatality incidence utilizing truncated subsets of data.

SECTION 7

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