Available online at www.worldnewsnaturalsciences.com

World News of Natural Sciences

WNOFNS 4 (2016) 44-60 EISSN 2543-5426

Chernobyl Liquidators - the people and the doses

Luis K. Gan-Jose[1,*], Virginia Gonzalez-Kimena[2]

[1]Department of Ecology and Evolution, Faculty of Biology and Medicine, University of Lausanne, Biophore - 1015 Lausanne, Switzerland

[2]Instituto Pirenaico de Ecología (IPE-CSIC), Nuestra Señora de la Victoria s/n, 20700 Jaca, Spain

*E-mail address: luis.ganjose@unil.ch

ABSTRACT

The clean-up operations following the Chernobyl accident were arguably the greatest in the history of mankind. This paper is not intended to give a comprehensive review of the Chernobyl related research, we present only a review of the scientific literature available till now about the “liquidators”, i.e. people who performed the task of decontamination work near the damaged Chernobyl nuclear power plant. Most of the approximately 300,000 liquidators who took part in the mitigation of the local consequences of the Chernobyl accident between 1986 and 1989 received only low radiation doses which are comparable or lower than those documented in nuclear worker registries. The health consequences from these radiation doses are too small to be identifiable in any epidemiological study that does not target specific sub-groups with potentially higher exposure. From our review of the published literature, several criteria are derived which could be used to identify potentially suitable sub-populations; in particular, among those being the liquidators who participated in the clean-up work during in 1986, including CNPP staff, special groups such as the “sarcophagus workers” (39), helicopter crews (3, 48), liquidators from the Institute of Biophysics who had participated in clean-up work in Chernobyl (12, 20), the Samoilenko group (12), sarcophagus builders (12) and groups other that the aforementioned.

Keywords: Chernobyl liquidators, the people, the doses

1. TERMINOLOGY AND DEFINITIONS OF LIQUIDATORS

The explosion which occurred on 26 April 1986 at unit 4 of the Chernobyl Nuclear Power Plant (CNPP) was initially classified by Soviet authorities as an incident (12). Officials believed that the situation was manageable and the consequences of the Chernobyl accident could be eliminated in a short time. This was the reason why people who were engaged in the clean-up operations were called “liquidators” (10). The word "liquidator" is derived from the Russian verb, which means "to eliminate” or “to eliminate consequences of an accident". It became clear very soon after the explosion that the consequences of the accident would not be “eliminated” but only “reduced”. Nevertheless the word “liquidator” was in common use already (10).

Fot. 1. Location of Chernobyl Nuclear Power Plant in northern Ukraine, near the border of Belarus. Also labeled are the cities of Chernobyl and Pripyat. The white dashed circle shows the original 30 km-radius Exclusion Zone. The yellow line delineates the current Exclusion Zone. Within the Exclusion Zone there are highly radioactive areas, as well as areas with little or no radiation.

There are a few synonyms for the word “likvidator”, such as: “emergency workers (32, 44, 47), “Chernobyl emergency accident workers” (44), “clean-up workers” (8, 11, 21, 22, 42, 51), “accident recovery workers” (43), “salvage personnel” (5, 6) or “salvage workers” (7), “rescuers of consequences” of the Chernobyl accident (29), “decontamination participant” (41) and “ameliorators” of the Chernobyl accident (18, 37, 38).

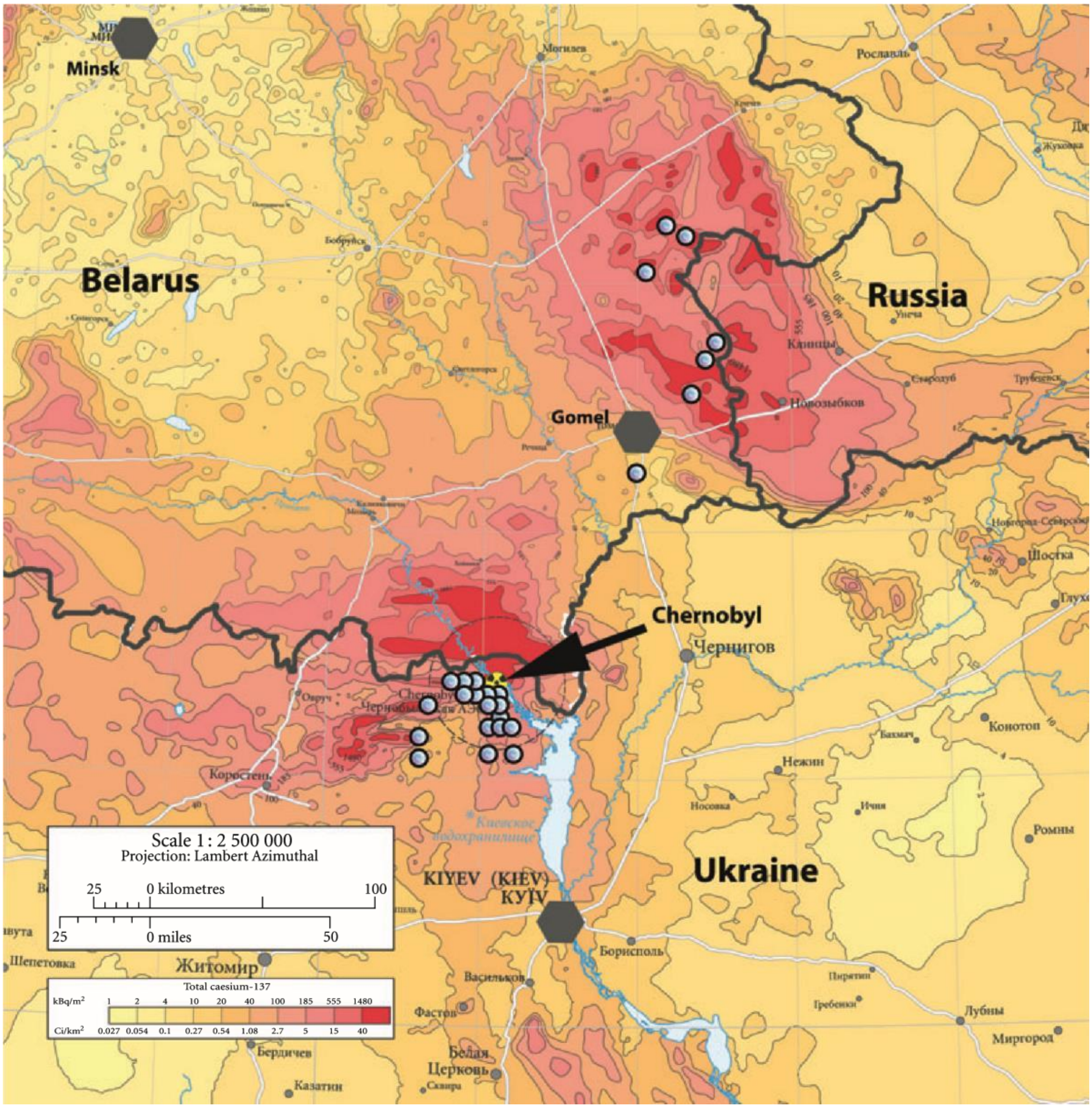

Fig. 1. Location of breeding bird census areas and levels of background radiation around Chernobyl. Partly developed from European Union (1998).

The OECD Nuclear Energy Agency Committee on Radiation Protection and Public Health (28) defined as liquidators people who “took part in mitigation activities at the reactor and within the 30-km zone surrounding the reactor”. The International Conference "One Decade After Chernobyl: Summing up the consequences of the accident", arranged by IAEA, EC and WHO in co-operation with UNDHA, UNESCO, UNEP, UNSCEAR, FAO, and NEA described liquidators in very general terms as "a large number of ad hoc workers, including operators of the plant, emergency volunteers such as fire-fighters, and military personnel, as well as many non-professional personnel. All these people became known by the Russian term "likvidator", also liquidators, as "persons who were registered as involved in activities relating to alleviating the consequences of the accident. This includes persons who participated in the cleanup after the accident (including cleaning up around the reactor, construction of the sarcophagus, decontamination, road building, and destruction and burial of contaminated buildings, forests and equipment), as well as many other general personnel who worked in the territories designated as "contaminated"" (9).

Papers in scientific journals usually do not give a definition for liquidators but describe groups of examined people in various ways (8, 21, 36). Sometime authors state that examined subjects were "liquidators" assuming that this term would be well defined (19). Most papers obviously assumed tacitly that liquidators were people who dealt with consequences of the accident within a 30 km zone around the destroyed reactor in 19861989 or later.

The books about the Chernobyl accident provide a better description of liquidator cohorts (20, 25, 27). Probably the most comprehensive is the book by Ilyin (12) which describes liquidator as: "decontamination workers who were in the 30 km zone in 1986-1989".

2. THE NUMBER OF LIQUIDATORS

The number of liquidators quoted in the literature ranges from several hundred thousand to nearly a million people. Ilyin gives the most realistic estimate as 300,000 - 320,000 persons (12), yet the report by the OECD Nuclear Energy Agency quotes a figure "up to 800,000". The International Conference in Vienna refers to "about 200,000 'liquidators' who worked in the region of Chernobyl during the period 1986-1987 whereas the total number would be some 600,000 to 800,000 persons who were registered as involved in activities relating to alleviating the consequences of the accident" (9). According to the main, parental All-Union (later State) Distribution Register (USSR, 1986-1989) the number of liquidators is 293,100 (12). The report from the Russian National Medical Dosimetric Registry quotes 168,000 liquidators in Russia. With 123,536 liquidators from Ukraine (23) and 63,500 liquidators from Belarus (12), this gives a total number of around 355,000. The Conference which was jointly organised by the European Commission, Belarus, the Russian Federation and Ukraine on the Consequences of the Chernobyl Accident in Minsk uses a figure of about 600,000 people (4). Papers from scientific journals cover a wide range between 200,000 - 600.000 liquidators of the period 1988 to 1997 (17, 50).

The main reasons of such differences in figures are:

- Erroneous mistakes in estimation. This can be attributed to "a manifest error" due to "reporters' negligence, terminological inaccuracies and incorrect translation" (12). It is suggested that the common figure of 600,000 liquidators could originate from incorrect summing of liquidators who were working in the *permanent eviction zone*[1] with people evacuated from the *permanent eviction zone.*

[1] Formerly the "30 kilometre zone" (in 1986-1987)

- Low attention to the study design and using different definitions of liquidators for the cohort forming
- Politics concerning the Chernobyl liquidators which varies between different states of the former Soviet Union
- The attractive social status of the Chernobyl liquidators might also affect numbers.

Because of uncertainties stated above it appears prudent (12) to assume “for the purpose of subsequent analysis that the total number of decontamination workers who were in the 30 km zone in 1986-89 constituted approximately 300,000”.

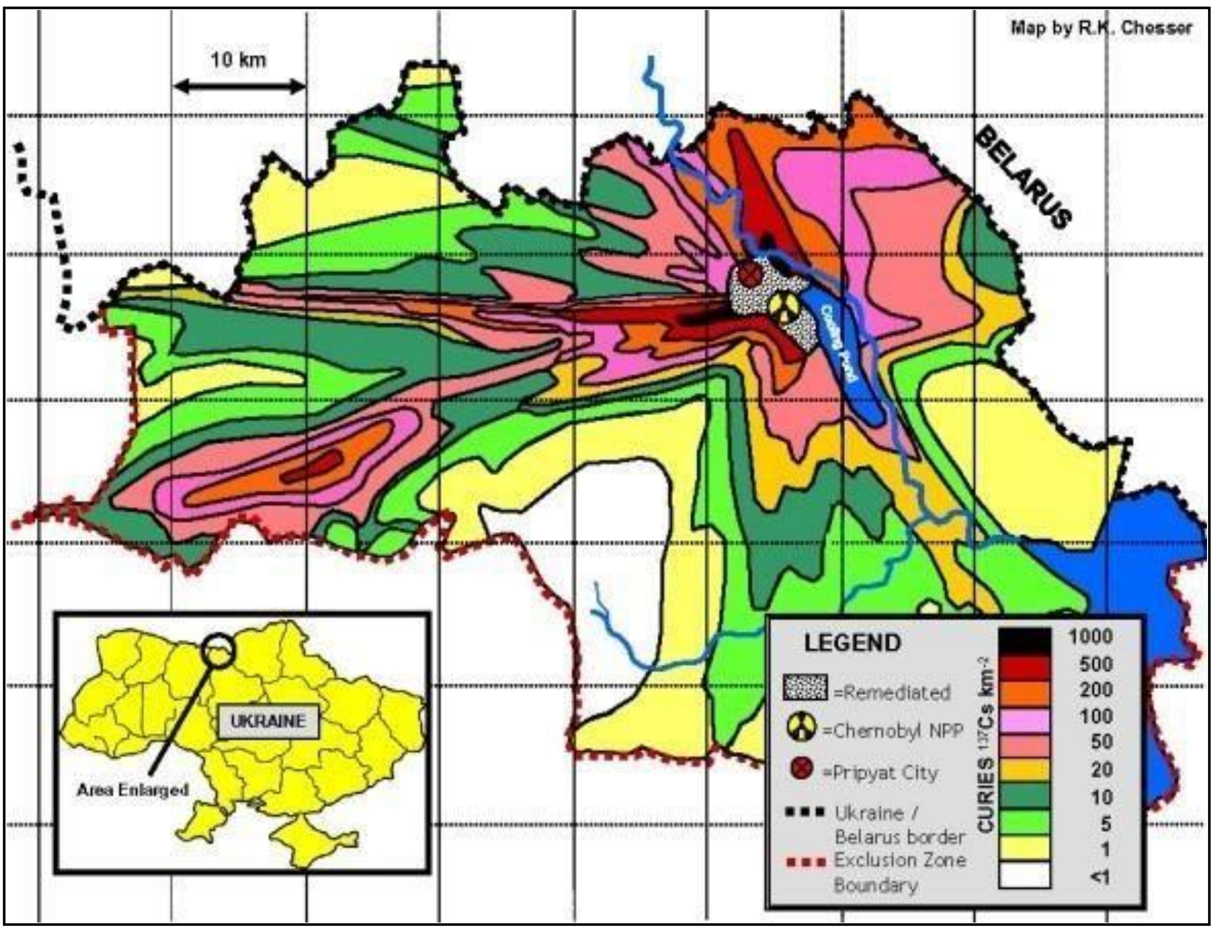

Fig. 2. This figure illustrates the dispersion of ^{137}Cesium in the regions around Chernobyl. Black and red areas indicate the areas of highest radiation fallout. The isotope ^{137}Cesium is used as the model for the distribution of radiation in the environment, because it is the most long-lived of the 100+ radioactive elements that were released from the Chernobyl reactor. Most of the radioactive elements released were short-lived and decayed rapidly, and thus less than 3% of the initial radioactivity in the area remains today. Because of their long half-lives, however, ^{137}Cesium and ^{90}Strontium are still present in the environment and will persist for many more decades.

3. GROUPING OF LIQUIDATORS

The time-oriented classification might divide liquidators into three subtypes:

1. During the *initial phase*, people called the "early liquidators" were on site during the explosion or came in during the initial phase of the accident (0-1 days, before the evacuation of Pripyat), including fire fighters.

2. The *early phase* ranges from the end of the evacuation of Pripyat to the end of the construction of the sarcophagus (November 1986). Within this group the most interesting subgroup of liquidators are people who participated in clean-up works during 1986. Among these are subgroups with considerable doses (0.20-0.25 Gy). The "high dose" subgroups may be about 7% of all liquidators (10)

3. The *late phase* liquidators worked between the end of the Sarcophagus construction until the dissolution of the USSR in 1991, when central management of clean-up work was split between Russia, Belarus and Ukraine. The All-Union Distribution Register was divided between the Newly Independent States.

The number of liquidators active in the different years as recorded in the All-Union Distribution register is given in Table 1. Table 2 gives the age distributions at the time of work according to the Russian register (16). Fewer than 1% of the liquidators were women (31, 32).

Table 1. The numbers of liquidators active in different years as derived from the AllUnion Distribution Register (12)

Year	Number of Liquidators
1986	138,390
1987	85,556
1988	26,134
1989	43,020
1986-1989	293,100

Table 2. Distribution of liquidators by age at the time of arrival to the Chernobyl area (30 km zone). Cohort consisted of 114,504 selected cases, average age is 34.3 years (16).

Age Group	Number of Liquidators	Percent of Liquidators
15-19	2,180	1.9

20-24	8,905	7.78
25-29	4,097	12.31
30-34	36,323	31.72
35-39	37,116	32.41
40-44	11,587	10.12
45-49	3,294	2.88
50-54	664	0.58
55-59	263	0.23
≥60	75	0.00

4. LIQUIDATOR REGISTRIES

The main source of "documented" data of the Chernobyl liquidators' physical dosimetry is the Russian National Medical and Dosimetric Registry (RNMDR). This registry originated from the All-Union (later State) Distribution Register which was formed soon after the accident (46). The All-Union Distribution Register was in turn formed by different ministries' and organisation registries. After the dissolution of the Soviet Union, the All Union Registry of persons exposed to radiation was terminated as common register in 1992 and continued as Russian National Radiation and Epidemiological Registry by decree of the Russian Council of Ministers (22.9.1993). RNMDR (named as Chernobyl Registry before 1992) is the part of Russian National Radiation and Epidemiological Registry.

It covers only people who have Russian citizenship. At present it has more than 160,000 entries, 155,680 of which have been validated in terms of radiation doses (15). According to Pitkevitch (32) the RNMDR has 152,325 liquidators' entries and 119,416 (78.4%) of them have dosimetry data. The official report by RNMDR with the most comprehensive data about liquidators' dosimetry quotes a figure of 159,027 liquidators and 125,771 (79.1%) liquidators with dosimetry (47). All dosimetric data entered in the registry originated from the official documents issued in the "zone of Chernobyl accident clean-up works".

Although liquidator registries exist also in Ukraine and Belarus, little factual information has been published about them. On the other hand, the liquidator registries of Estonia, Latvia and Lithuania, comprising approximately 17,500 liquidators, are well managed and publicised (2, 21, 45, 49-52). In particular the Estonian registry formed the basis of several excellent studies (8, 13, 22, 24, 33).

5. RADIATION DOSES OF LIQUIDATORS

Physical Dosimetry and "Documented" Doses

"Documented" doses mean doses stated for the individual liquidator in various documents and references. These doses have different origins but are commonly based on physical dosimetry data. Pitkevitch (32) distinguish three main sources of these "documented" doses:

- Dose recorded by an individual dosimeter (the maximum error is about 50%). Only 2-3% of liquidators had a dosimeter during all time of their work (12, 34, 35)

- "Group" dose values assigned to the members of a group performing an operation in the zone, based on the readings of an individual dosimeter held by one member of the group. The dose uncertainty in the group can be as high as 300%. The majority of liquidators' dosimetric data is derived from this source.

- "Marching route" dose values estimated from a dose rate in the zone and the duration of stay of the group in this area: the dose uncertainty in the group can be as high as 500%.

Another source of uncertainty comes from differences in recording of dosimetric information in military and civil divisions serving in the Chernobyl area. According to Tsyb (47) dosimetric control was assigned to three USSR ministries: Ministry of Defence, Ministry of Middle Machine Building and Ministry of Energy by order of the Chernobyl Government Committee from 28 May 1986. However, dosimetric control were also performed by the USSR Ministry of Internal Affairs, the USSR Committee of State Safety (KGB) (before September 1987) and by the Ukraine Academy of Science. In total, dosimetric measurements were performed by more than 600 organisation from 49 Ministries and other USSR government departments. The majority of dosimetrists were from the USSR Ministry of Energy. Because of difference in measurement facilities and standards the military and paramilitary organisations used exposure units for dosimetry while civil organisations usually expressed results of dosimetry in units of absorbed dose. It is impossible now to distinguish which dosimetric data originated from which source (31, 47). All dosimetric data in the RNMDR are taken as absorbed dose and expressed in Gy. The error in this approximation would not be more than 30%.

All dosimetric equipment measured only gamma-irradiation. However, the betaradiation dose was a very considerable component of total external dose for the early liquidators (30). There are even fewer data available concerning the internal irradiation of the liquidators.

Figure 1 gives a sources of collective dose for a highly exposed group of 1986 liquidators from staff of CNPP and scientists from the Institute of Biophysics, Russian Ministry of Public Health obtained by analysis of the marching routs (20). This group consisted of 670 persons. Total collective dose is 980 men Gy, mean individual dose is 1.46 Gy. Most of the collective dose (60%) was accumulated during the first five days after the accident (20). Two thirds of this dose (40%) received solely by CNPP staff at the first day (excluding dose of fire fighters and CNPP staff who died soon after the accident). A large portion of the collective dose (19%) accumulated from non-professional activity (see Fig. 1).

This occurred e.g. when liquidators stayed waiting for orders in contaminated areas. Moreover, more collective dose was accumulated during transportation to and from work (43%) than during work (17%). This particular pattern of exposure cannot be extrapolated to the total group of 138,390 liquidators who received a mean dose of 0.159 Gy in 1986 according to the RNMDR (14).

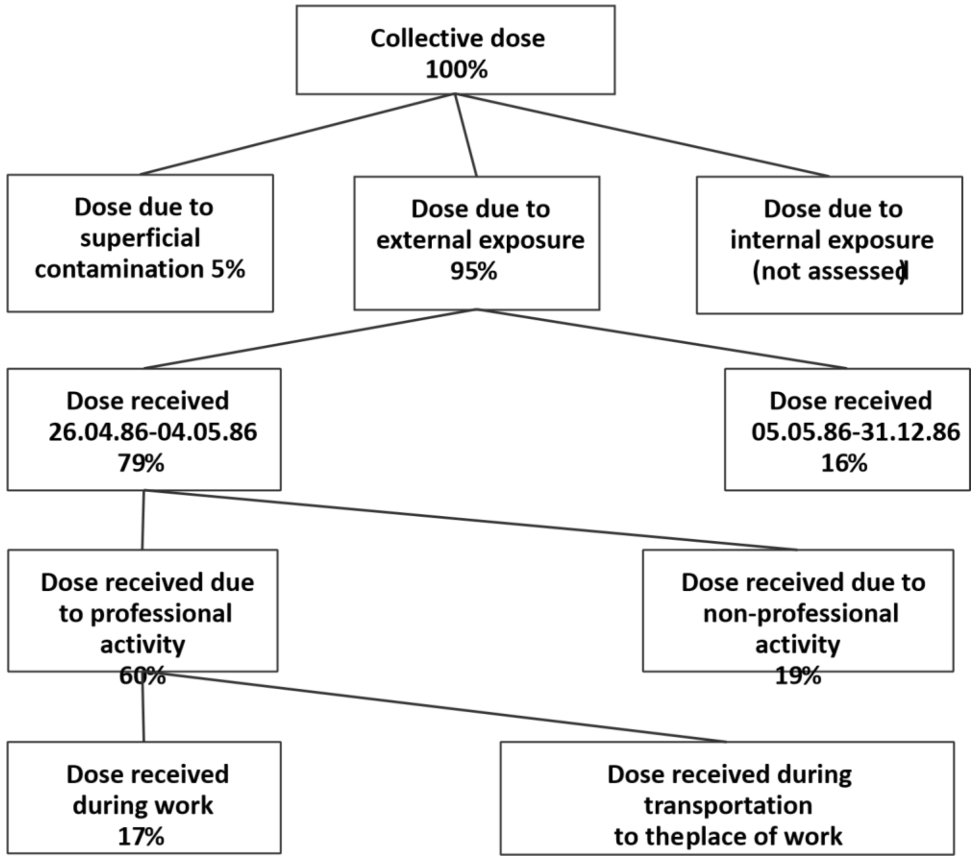

Figure 1. Sources of collective dose of 670 highly exposed liquidators from CNPP staff and the Institute of Biophysics. Total collective dose was 980 man Gy (20)

6. BIOLOGICAL DOSIMETRY IN LIQUIDATORS

Documented physical dosimetry data have been compared with biodosimetry data. Although a large number of chromosome studies have been published, only a few compare on a group basis the mean results of physical dosimetry with the mean results of biological dosimetry of the study group.

Table 3 describes in details the working sites, time spent in these places and the estimated dose of 16 early liquidators. These doses were verified by unstable chromosome aberration biodosimetry (20).

Another group consisted of 15 highly exposed liquidators, who monitored the status of the sarcophagus from 1986 to 1995 (39). Some received very high doses according to their personal dosimeters. In six of them physical dosimetry data were verified with unstable chromosome aberration biodosimetry (Table 4). Overall the agreement between physical and biological dosimetry was better than a factor of two. The high dose values observed in some small groups of highly selected liquidators (e.g. Tables 3 and 4) are exceptional.

The vast majority of liquidators, even those who worked in the closed zone in 1986, received much lower doses as shown in Table 5. The mean doses as documented in the RMDR are 0.159 Gy for 1986 liquidators and 0.105 Gy for 1986-1989 liquidators. The value of 0.04-0.08 Gy for Glycophorin A somatic cell mutation assay (GPA) (Table 5) appears to be preliminary but the later publication (2) reported that exposure was too low to be determined with GPA.

Table 3. A comparison of the results of dose estimation by the “imitation modelling” method with chromosome aberration biodosimetry in early liquidators (20).

Subgroup of Liquidators		Exposure Time	Exposure Rate, C kg^{-1} s^{-1}	“Imitation Modelling” Dose, Gy	Biodosimetry Dose, Gy[2]
Reactor workers	hall	19 min	$7.74x10^{-3}$	3-6	2.6
Turbine hall		2 h 32 min	$1.72x10^{-3}$-2.58 $x10^{-3}$	5-15	10.9
workers		1 h 42 min	1.72x10	3.5-10.5	10.1
		2 h 47 min	4.30x10 $x10^{-4}$	1.4-5.6	8.7
		2 h 57 min	$1.72x10^{-3}$	5.9-12	8.2
		1 h 27 min	$1.72x10^{-3}$	3.0-6.0	7.5
		45 min – 1 h 20min	$1.72x10^{-3}$	1.5-5.3	3.6
		2 h 00 min	2.58 $x10^{-3}$	6.0-12.0	7.1
Fire fighters		1 h 30 min	$2.15x10^{-3}$ and $4.30x10^{-3}$	5.6-11.3	12.5
		3 h 25 min	$15x10^{-4}$	0.85-1.7	0.8
		40 min	45 $x10^{-3}$	5-10	10
		1 h 50 min	29 $x10^{-3}$	2.8-5.5	2.8
Construction		1 h 40 min	6.45x10	1.3-3.4	3.4
workers on 5		2 h 00 min	6.45x10 $x10^{-4}$	1.5-4.0	2.2

[2] Results of unstable chromosome aberration test

and 6 block		**1 h 00 min**	**7.74x10^{-4}-1.03^{-3}**	**0.9-2.4**	**2.1**
		3 h 00 min	**7.74x10^{-4}-1.03^{-3}**	**2.7-7.2**	**4.0**
Collective dose		**-**	**-**	**50-139**	**97**

Table 4. Dose estimates of "sarcophagus workers" (39)

No.	Year of Birth Starting	Work Total Physical	Sampling	Results of at Chernobyl	Dose, Gy[3]	**Biodosimetry (Gy)**
					Qdr[4]	**ESR[5]**
1.	**1958**	**Sept. 1988**	**11.6**	**1992**	**13.1**	**-**
				1993	**12.2**	**-**
				1994	**12.6**	**-**
2.	**1947**	**May 1986**	**17.1**	**1992**	**8.4**	**9.3**
				1994	**8.0**	**-**
3.	**1933**	**Sept. 1986**	**3.6**	**1991**	**4.1**	**3.7**
				Sept. 1992	**3.3**	**-**
				Oct. 1992	**6.0**	**-**
				1993	**4.7**	**-**
4.	**1955**	**Aug. 1986**	**2.0**	**1991**	**2.7**	**-**
				1992	**5.5**	**-**
5.	**1956**	**Sept. 1989**	**1.5**	**1991**	**1.0**	**-**
6.	**1946**	**Aug. 1989**	**0.9**	**1991**	**0.5**	**-**

Various studies were performed in addition to those described above which compared physical doses and biodosimetry results, showing even lover doses.

126 liquidators were examined by FISH within a collaboration study between Lawrence Livermore National Laboratory, University of California, Moscow and St.Petersburg scientists (26). They found that the shape of biodosimetry distribution is significantly different from that obtained using estimated doses from the liquidators dosimetry cards. The mean population exposure based on cytogenetic analysis is 0.09 Gy, while the mean based on

the estimated doses is 0.25 Gy, ranging from 0.02 Gy to 2.7 Gy. Since detailed information on the source of the estimated doses is not available, the authors are inclined to consider the results of the biodosimetry as more reliable.

Another paper (24) is about the Estonian liquidator cohort. This group used fluorescence in situ hybridisation (FISH) for retrospective biodosimetry of 100 blood samples out of the well defined cohort of 4,833 cleanup workers from Estonia. They observed lower translocation frequencies than has been reported in previous studies using FISH among Chernobyl cleanup workers. A clear association with increased levels of translocations was seen with increasing age at the time of blood sampling. No correlation between aberration frequency and recorded measurements of physical dose or any category of potential high-dose and high-dose-rate exposure could be found. Based on these results, it was estimated that the Estonian liquidator group of 118 men received an average whole-body dose of 0.10-0.11 Gy. The main conclusion of the paper is that recorded doses for these cleanup workers overestimate their average bone marrow doses, perhaps substantially.

7. CONCLUSIONS

Most of the approximately 300,000 liquidators who took part in the mitigation of the local consequences of the Chernobyl accident between 1986 and 1989 received only low radiation doses which are comparable or lower than those documented in nuclear workers registries. The health consequences from these radiation doses are too small to be identifiable in any epidemiological study, which does not target specific sub-groups with potentially higher exposure. From our review of the published literature, several criteria may be derived which could be used to identify potentially suitable sub-populations; in particular among those are liquidators who participated in the clean-up work during in 1986 including staff of CNPP, special groups such as “sarcophagus workers” (39), helicopter crews (3, 48), liquidators from the Institute of Biophysics participating in clean-up work in Chernobyl (12, 20), the Samoilenko group (12), sarcophagus builders (12) and some other groups from those mentioned in Table 3.

Although fewer than 10% of all liquidators (10) may be suitable for epidemiological follow-up, their number is high enough to make a study on long-term health consequences feasible. The national liquidator registries in Russia, but also in Ukraine and Belarus, should permit research, which could add valuable information on radiation risks at low doses and low dose rates. Yet there is little justification for epidemiological research into radiation effects on the entire liquidator population. They are much too heterogeneous with regard to the work performed, the organisational affiliation, nationality, exposure to additional risk factors, and in particular to radiation doses and the possibility of their validation as liquidators.

References

[1] Bigbee, W., Jensen, R., Veidebaum, T., Tekkel, M., Rahu, M., Stengrevics, A., Auvinen, A., Hakulinen, T., Servomaa, K., Rytomaa, T., Obrams, G., Boice JD, J., *Biodosimetry of Chernobyl cleanup workers from Estonia and Latvia using the glycophorin A in vivo somatic cell mutation assay*. Radiat Res. 147:215-224, 1997.

[2] Emerit, I., Arutyunyan, R., Oganesian, N., Levy, A., Cernjavsky, L., Sarkisian, T., Pogossian, A., Asrian, K., *Radiation-induced clastogenic factors: anticlastogenic effect of Ginkgo biloba extract*. Free Radic Biol Med. 18: 985-991, 1995

[3] Emerit, I., Levy, A., Cernjavski, L., Arutyunyan, R., Oganesyan, N., Pogosian, A., Mejlumian, H., Sarkisian, T., Gulkandanian, M., Quastel, M., *Transferable clastogenic activity in plasma from persons exposed as salvage personnel of the Chernobyl reactor*. J Cancer Res Clin Oncol. 120: 558-561, 1994

[4] Fischbein, A., Zabludovsky, N., Eltes, F., Grischenko, V., Bartoov, B., *Ultramorphological sperm characteristics in the risk assessment of health effects after radiation exposure among salvage workers in Chernobyl.* Environ Health Perspect. 105: Suppl 6, 1445-1449, 1997

[5] Granath, F., Darroudi, F., Auvinen, A., Ehrenberg, L., Hakulinen, T., Natarajan, A., Rahu, M., Rytomaa, T., Tekkel, M., Veidebaum, T. *Retrospective dose estimates in Estonian Chernobyl clean-up workers by means of FISH*. Mutat Res. 369: 7-12, 1996

[6] Inskip, P., Hartshorne, M., Tekkel, M., Rahu, M., Veidebaum, T., Auvinen, A., Crooks, L., Littlefield, L., McFee, A., Salomaa, S., Makinen, S., Tucker, J., Sorensen, K., Bigbee, W., Boice JD, J., *Thyroid nodularity and cancer among Chernobyl cleanup workers from Estonia.* Radiat Res. 147: 225-235, 1997

[7] Ivanov, V., Tsyb, A., Konogorov, A., Rastopchin, E., Khait, SE, K., *Case-control analysis of leukaemia among Chernobyl accident emergency workers residing in the Russian Federation, 1986-1993.* J Radiol Prot. 17: 137-157, 1997

[8] Ivanov, V. K., Rastopchin, E. M., Gorsky, A. I., Ryvkin, V. B., *Cancer incidence among liquidators of the Chernobyl accident: solid tumors, 1986-1995.* Health Phys. 74: 309-315, 1998

[9] Jensen, R., Langlois, R., Bigbee, W., Grant, S., Moore D, n., Pilinskaya, M., Vorobtsova, I., Pleshanov, P., *Elevated frequency of glycophorin A mutations in erythrocytes from Chernobyl accident victims*. Radiat Res. 141: 129-135, 1995

[10] Koliubaeva, S. N., Raketskaia, V. V., Borisova, E. A., Komar, V. E., *Radiation damages in human lymphocytes studied by micronucleus and chromosomal analysis.* Radiats Biol Radioecol. 35: 150-156, 1995

[11] Kordysh, E., Goldsmith, J., Quastel, M., Poljak, S., Merkin, L., Cohen, R., Gorodischer, R., *Health effects in a casual sample of immigrants to Israel from areas contaminated by the Chernobyl explosion*. Environ Health Perspect. 103: 936-941, 1995

[12] Kruchkov, V. P., Nosovsky, A. B., *Retrospective Dosimetry*. Kiev:1996 (in Russian).

[13] Lazutka, J., *Chromosome aberrations and rogue cells in lymphocytes of Chernobyl clean-up workers*. Mutat Res. 350: 315-329, 1996

[14] Lazutka, J., Dedonyte, V., *Increased frequency of sister chromatid exchanges in lymphocytes of Chernobyl clean-up workers.* Int J Radiat Biol. 67: 671-676, 1995

[15] Littlefield, L. G., McFee, A. F., Salomaa, S. I., Tucker, J. D., Inskip, P. D., Sayer, A. M., Lindholm, C., Makinen, S., Mustonen, R., Sorensen, K., Tekkel, M., Veidebaum, T., Auvinen, A., Boice, J. D., Jr., *Do recorded doses overestimate true doses received*

by Chernobyl cleanup workers? Results of cytogenetic analyses of Estonian workers by fluorescence in situ hybridization. Radiat Res. 150: 237-249, 1998

[16] Moore, D. H., Tucker, J. D., Jones, I. M., Langlois, R. G., Pleshanov, P., Vorobtsova, I., Jensen, R., *A study of the effects of exposure on cleanup workers at the Chernobyl nuclear reactor accident using multiple end points*. Radiat Res. 148: 463-475, 1997

[17] Novikov, V., Nikiforov, A., Cheprasov, V., *The psychological sequelae of the accident*. Voen Med Zh. 317: 6 57-62, 80, 1996

[18] Pitkevich, V., Ivanov, V., Chekin, S., Tsyb, A., *Exposure levels of persons involved in cleaning-up after the Chernobyl AES accident and included in the Russian State Medical and Dosimetric Registry (letter).* Radiats Biol Radioecol. 36: 5, 747-757, 1996

[19] Pitkevitch, V. A., Ivanov, V. K., Tsyb, A. F., Maksyoutov, M. A., Matiash, V. A., Shchukina, N. V., *Exposure levels for persons involved in recovery operations after the Chernobyl accident. Statistical analysis based on the data of the Russian National Medical and Dosimetric Registry (RNMDR).* Radiat Environ Biophys. 36: 149-160, 1997

[20] Rahu, M., Tekkel, M., Veidebaum, T., Pukkala, E., Hakulinen, T., Auvinen, A., Rytomaa, T., Inskip, P., Boice JD, J., *The Estonian study of Chernobyl cleanup workers: II. Incidence of cancer and mortality*. Radiat Res. 147: 653-657, 1997

[21] Salassidis, K., Georgiadou-Schumacher, V., Braselmann, H., Muller, P., Peter, R., Bauchinger, M., *Chromosome painting in highly irradiated Chernobyl victims: a follow-up study to evaluate the stability of symmetrical translocations and the influence of clonal aberrations for retrospective dose estimation*. Int J Radiat Biol. 68: 257-262, 1995

[22] Salassidis, K., Schmid, E., Peter, R., Braselmann, H., Bauchinger, M., *Dicentric and translocation analysis for retrospective dose estimation in humans exposed to ionising radiation during the Chernobyl nuclear power plant accident*. Mutat Res. 311: 39-48, 1994

[23] Schevchenko, V., Akayeva, E., Yeliseyeva, I., Yelisova, T., Yofa, E., Nilova, I., Syomov, A., Burkart, W., *Human cytogenetic consequences of the Chernobyl accident*. Mutat Res. 361: 29-34, 1996

[24] Semov, A., Iofa, E., Akaeva, E., Shevchenko, V., *The dose dependence of the induction of chromosome aberrations in those who worked in the cleanup of the Chernobyl accident*. Radiats Biol Radioecol. 34: 6, 865-871, 1994

[25] Sevan'kaev, A., Moiseenko, V., Tsyb, A., *The possibilities of using biological dosimetry methods for the retrospective assessment of dosages in relation to the sequelae of the accident at the Chernobyl Atomic Electric Power Station. An assessment of the dosages based on an analysis of unstable chromosome aberrations.* Radiats Biol Radioecol. 34: 6, 782-792, 1994

[26] Sevan'kaev, A., Lloyd, D., Edwards, A., Moiseenko, V., *High exposures to radiation received by workers inside the Chernobyl sarcophagus*. Radiation Protection Dosimetry. 59: 2, 85-91, 1995.

[27] Sevan'kaev, A., Lloyd, D., Braselmann, H., Edwards, A., Moiseenko, V., Zhloba, A., *A survey of chromosomal aberrations in lymphocytes of chernobyl liquidators.* Radiation Protection Dosimetry. 59: 2, 85-91, 1995

[28] Snigireva, G., Liubchenko, P., Shevchenko, V., Novitskaia, N., Borisova, N., Dubinina, E., Maslennikova, V., *Results of cytogenetic examination of participants in the decontamination after the accident at the Chernobyl nuclear power station, 5 years later*. Gematol Transfuziol. 39: 3, 19-21, 1994

[29] Snigiryova, G., Braselmann, H., Salassidis, K., Shevchenko, V., Bauchinger, M., *Retrospective biodosimetry of Chernobyl clean-up workers using chromosome painting and conventional chromosome analysis*. Int J Radiat Biol. 71: 119-127, 1997

[30] Souchkevitch, G., *Main scientific results of the WHO International Programme on the Health Effects of the Chernobyl Accident (IPHECA).* World Health Stat Q. 49: 209-212, 1996

[31] Svirnovski, A., Ivanov, E., Danilov, I., Bakkun, A., Ageichick, V., Ivanov, V., *Frequencies of unstable chromosome aberrations in peripheral blood lymphocytes of Chernobyl emergency accident workers*. Bull Soc Sci Med Grand Duche Luxemb. 131: 35-39, 1994

[32] Tekkel, M., Rahu, M., Veidebaum, T., Hakulinen, T., Auvinen, A., Rytomaa, T., Inskip, P., Boice JD, J., *The Estonian study of Chernobyl cleanup workers: I. Design and questionnaire data*. Radiat Res. 147: 641-652, 1997

[33] Tsyb, A., Dedenkov, A., Ivanov, V., Stepanenko, V., Pozhidaev, V., *The development of an all-Union registry of persons exposed to radiation resulting from the accident at the Chernobyl atomic power station*. Med Radiol (Mosk). 34: 7 3-6, 1989 (in Russian).

[34] Tsyb, A., *Radiation Doses for Emergency Workers*. Bulletin of the National Radiation and Epidemiological Registry. Special Issue 2: 44, 1995

[35] Ushakov, I., Soldatov, S., *An analysis of the health status of helicopter pilots who participated in the cleanup of the consequences of the accident at the Chernobyl Atomic Electric Power Station*. Voen Med Zh. 4, 77-79, 1993

[36] Viel, J. F., Curbakova, E., Dzerve, B., Eglite, M., Zvagule, T., Vincent, C., *Risk factors for long-term mental and psychosomatic distress in Latvian Chernobyl liquidators*. Environ Health Perspect. 105: Suppl 6, 1539-1544, 1997

[37] Vorobtsova, I., Mikhel'son, V., Vorob'eva, M., Pleskach, N., Bogomazova, A., Prokof'eva, V., Piukkenen, A., *The results of a cytogenetic examination performed in different years on those who worked in the cleanup of the aftermath of the accident at the Chernobyl Atomic Electric Power Station*. Radiats Biol Radioecol. 34: 6, 798804, 1994

[38] Wishkerman, V. Y., Quastel, M. R., Douvdevani, A., Goldsmith, J. R., *Somatic mutations at the glycophorin A (GPA) locus measured in red cells of Chernobyl liquidators who immigrated to Israel*. Environ Health Perspect. 105: Suppl 6, 14511454, 1997

[39] Valko, M., Izakovic, M., Mazur, M., Rhodes, C.J. & Telser, J. 2004. Role of oxygen radicals in DNA damage and cancer incidence. Mol. Cell. Biochem. 266: 37-56.

[40] Williams ED. Thyroid cancer in United Kingdom children and in children exposed to fall-out from Chernobyl: Nagasaki Symposium on Chernobyl: update and future. In: Nagasaki S, editor. Excerpta Medica. International Congress Series 1074: Amsterdam: Elsevier, 1994: 89–94.

[41] Harach HR, Williams ED. Childhood thyroid cancer in England and Wales. Br J Cancer 1994; 72: 777–83.

[42] Bogdanova T, Bragarnik MM, Tronko ND, Harach HR, Thomas GA, Williams ED. Childhood thyroid cancer after Chernobyl. J Endocrinol 1995; 144(Suppl OC): 25.

[43] Peters SB, Chatten J, LiVolsi VA. Pediatric papillary thyroid carcinoma. Abstracts of the annual meeting of the United States and Canadian Academy of Pathology. San Francisco, 1994: 55A.

[44] Tronko N, Bogdanova T, Oliynyk V, Epstein E, Boshova E, Zak K, et al. Priorities in scientific research of thyroid pathology in children of Ukraine affected by the Chernobyl accident. In: Nagasaki S, editor. Nagasaki Symposium, Series 1074. Amsterdam: Elsevier North-Holland, 1994: 217–26.

[45] Wachholz B. United States cooperation with Belarus and Ukraine in the development and implementation of scientific protocols of thyroid cancer and other thyroid disease following the Chernobyl accident. In: Nagasaki S, editor. Nagasaki Symposium on Chernobyl: update and future. Excerpta Medica, International Congress Series 1074. Amsterdam: Elsevier North-Holland, 1994: 145–58.

[46] Dubrova, Yuri E; Nesterov, Valeri N; Krouchinsky, Nicolay G; Ostapenko, Vladislav A; et al., Human minisatellite mutation rate after the Chernobyl accident. Nature, Apr 25, 1996, 380, 6576

[47] M Santoro, G A Thomas, G Vecchio, G H Williams, A Fusco, G Chiappetta, V Pozcharskaya, T I Bogdanova, E P Demidchik, E D Cherstvoy, L Voscoboinik, N D Tronko, A Carss, H Bunnell, M Tonnachera, J Parma, J E Dumont, G Keller, H Höfler and E D Williams. Gene rearrangement and Chernobyl related thyroid cancers. *British Journal of Cancer* (2000) 82, 315–322. doi:10.1054/bjoc.1999.0921

[48] Likhtarev IA, Sobolev BG, Kairo IA, Tronko ND, Bogdanova T, Oliynyk V, et al. Thyroid cancer in the Ukraine. Nature 1995; 375: 365.

[49] Kazakov V, Demidchik E, Astakhova L. Thyroid cancer after Chernobyl. Nature 1992; 359: 21–3

[50] Baverstock K, Egloff B, Pinchero A, Ruchti C, Williams D. Thyroid cancer after Chernobyl. Nature 1992; 359: 21–2.

[51] Furmanchuk AW, Averkin JI, Egloff B, Ruchti C, Abelin T, Schappi W, et al. Pathomorphological findings in thyroid cancer of children from the Republic of Belarus. Histopatology 1992; 21: 401–8

[52] Nikiforov Y, Gnepp DR. Pediatric thyroid cancer after the Chernobyl disaster. Pathomorphologic study of 84 cases (1991–1992) from the Republic of Belarus. Cancer 1994; 74: 748–66.

(Received 06 July 2016; accepted 15 August 2016)