Mayak worker dosimetry system: History and Perspectives

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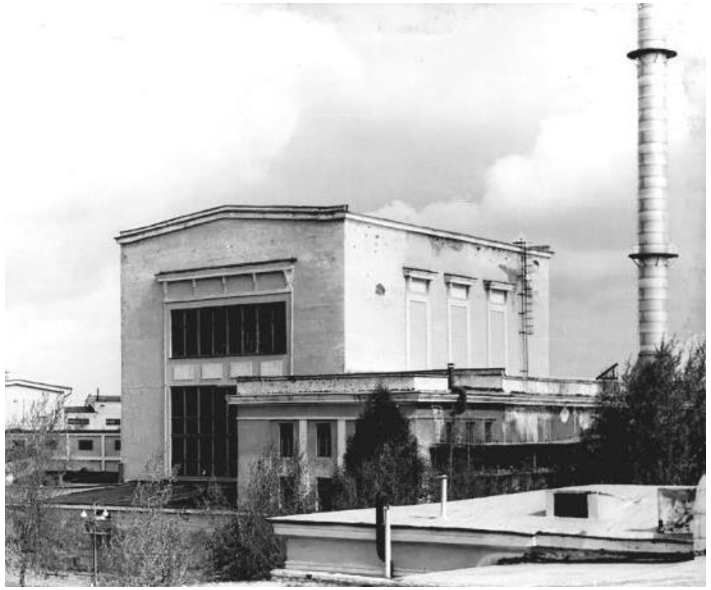
The first Russian facility for production of weapons-grade plutonium – Mayak PA



Reactor A-1 “Annushka”

In June 1948, the first Pu-producing industrial reactor was launched.

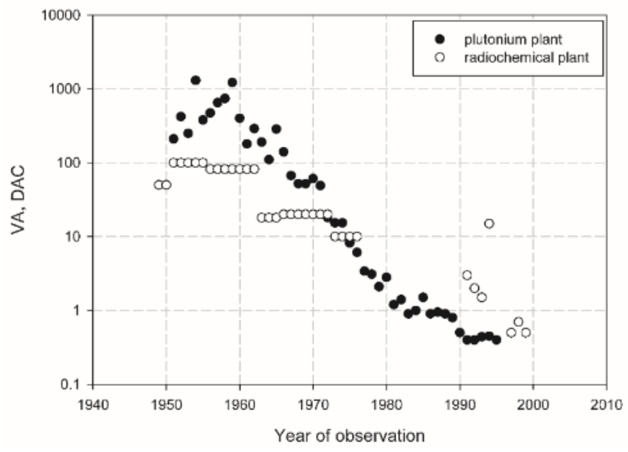
In December 1948, a transfer of the product to the radiochemical plant was initiated to extract weapons-grade plutonium.

Detailed history: First Industrial-scale Reactor “A” For Plutonium Production
https://www.bochvar.ru/en/company_en/first-industrial-scale-reactor-a-for-plutonium-production/

The first Russian facility for production of weapons-grade plutonium – Mayak PA

Laboratory No. 9 of Mayak PA

In the early years of operation, the content of alpha-active aerosols in the air of plutonium plant workshops was thousands of times higher than the permissible levels, and at the work sites of radiochemical plant it was hundreds of times higher.



Only in 1970 the radiation environment at Mayak PA came to a satisfactory state.

Quoted by: Sokolova, A.B.; Birchall, A.; Efimov, A.V.; Vostrotin, V.V.; Dorrian, M.D. The Mayak Worker Dosimetry System (MWDS-2013): Determination of the individual scenario of inhaled plutonium intake in the Mayak workers. Radiat. Prot. Dosimetry, 2017 Nov 1;176(1-2):83-89. DOI:10.1093/rpd/ncw190

The first Russian facility for production of weapons-grade plutonium – Mayak PA

First radiochemists of Mayak PA

The Mayak worker cohort (MWC) under study has the largest number of individuals and the highest chronic radiation exposures of any known population on Earth.

Approximately one-fourth of the exposed workers were women.

Detailed health and exposure records are available, thereby facilitating radiation health effects research.

For more information on MWC: Koshurnikova NA, Shilnikova NS, Okatenko PV, Kreslov VV, Bolotnikova MG, Sokolnikov ME, Khokhriakov VF, Suslova KG, Vasilenko EK, Romanov SA (1999) Characteristics of the cohort of workers at the Mayak nuclear complex. Radiat Res 152(4):352–363.

Project 2.4. Mayak Worker Dosimetry. Project Goals

This dose reconstruction project is to develop a computerized database of individual internal and external radiation doses and uncertainty about those doses for each member of the 25,757 Mayak worker cohort under study in Project 2.2, Mayak Worker Cancer Mortality.

The work product is an electronic database containing updated individual annual dose estimates called Mayak Worker Dosimetry System (MWDS)-2019.

Information on the project: https://www.energy.gov/ehss/russian-health-studies-program-active-projects

Project 2.4. Mayak Worker Dosimetry. Design basis

The basic assumptions:

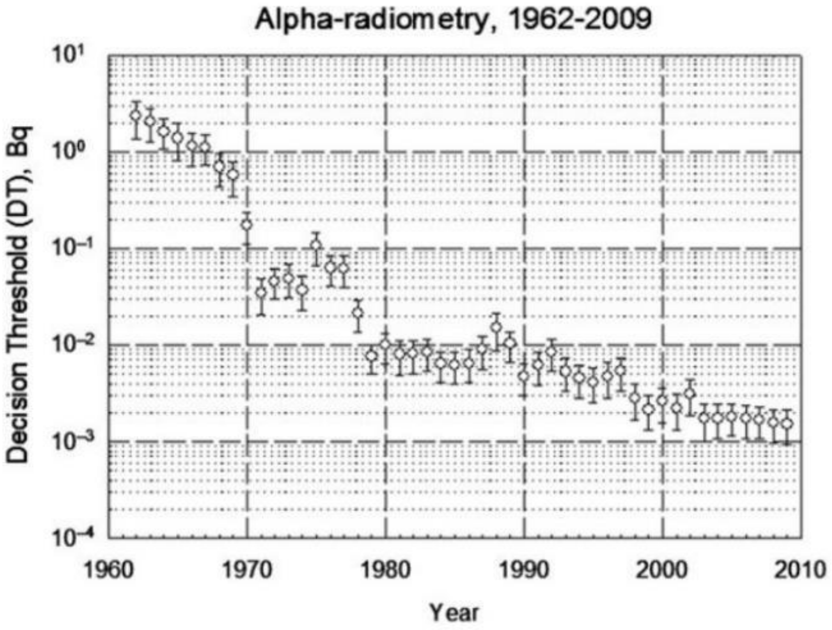
The main dose-forming radionuclide in the internal exposure is ^{239}Pu.

The radionuclide chronic intake is under consideration. Acute intakes are not included.

Dose estimates are based on bioassays of ^{239}Pu in urine samples and workers' exposure histories and conditions. The calculations use a biokinetic model with parameters relevant to the conditions of exposure.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Analysis of retrospective data on the results and methods of monitoring the plutonium content in urine and autopsy samples



Source data was verified; the limits of the nuclide detection were determined for different techniques used in different periods of time; the method of alpha spectrometry was implemented (the work was carried out primarily as part of Project 2.1).

Illustration from: Vostrotin, V.; Birchall, A.; Zhdanov, A.; Gregoratto, D.; Suslova, K.; Marsh, J.; Efimov, A. The Mayak Worker Dosimetry System (MWDS-2013): Uncertainty in the measurement of Pu activity in a 24-hour urine sample of a typical Mayak PA worker. Radiat. Prot. Dosimetry published online September 21, 2016. DOI:10.1093/rpd/ncw247

Project 2.4. Mayak Worker Dosimetry.
Project Tasks

Analysis of retrospective data on the results and methods of monitoring the plutonium content in urine and autopsy samples

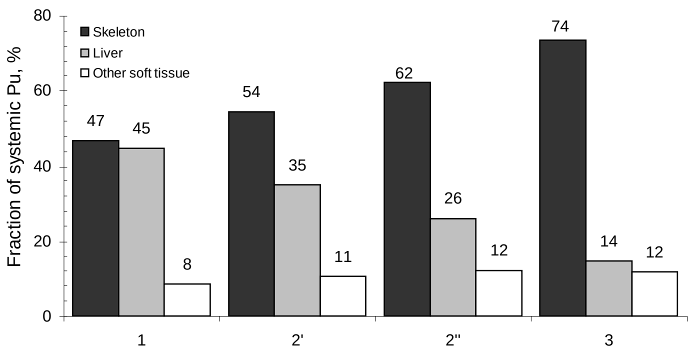
Characteristics of methods for measuring ^{239}Pu content in urine used in obtaining bioassay results in SUBI

Characteristics	Alpha-radiometry (1962–2009)	Alpha-spectrometry (1998–2013)
Measuring instrument	Alpha-radiometer RIA-05	Ortec spectrometer
Type of detector	Scintillation, FEU-5, ZnS (Ag)	Silicic surface-barrier
Equipment background, s^{-1}	9×10^{-4}	2×10^{-5}
Efficiency, %	95 ± 3	20–25
Resolution, keV	—	25
Radiochemical method	Coprecipitation: coprecipitation with carrier-agent-precipitation $BiPO_4$	Anion-exchange separation: trace ^{242}Pu, anionite AG 1-X4, electrolytic deposition
Volume of analyzed sample	1962–76: 200 ml 1977–98: 500 ml	24-hour urine sample
Background α-activity, mBq	0.83 ± 0.50	^{238}Pu: 0.20 ± 0.23 $^{239+240}Pu$: 0.28 ± 0.17 ^{241}Am: 0.22 ± 0.16
MDA, mBq·sample^{-1}	4.0	1.0
Error, $P = 0.95$	Not more than 60%	Not more than 60%

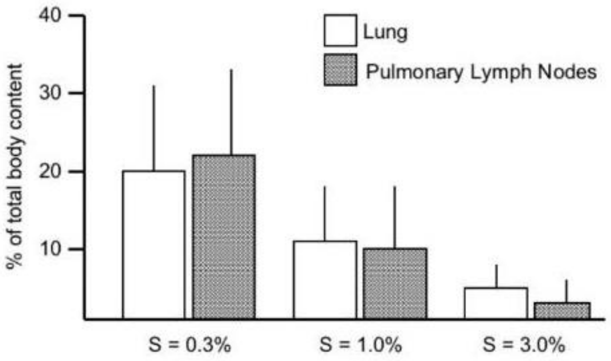
Illustration from: Vostrotin, V.; Birchall, A.; Zhdanov, A.; Gregoratto, D.; Suslova, K.; Marsh, J.; Efimov, A. The Mayak Worker Dosimetry System (MWDS-2013): Uncertainty in the measurement of Pu activity in a 24-hour urine sample of a typical Mayak PA worker. Radiat. Prot. Dosimetry published online September 21, 2016. DOI:10.1093/rpd/ncw247)

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Postmortem measurements of ^{239}Pu content in tissues and organs as an initial dataset to find out the model parameters



Distribution of Pu as a function of health status: 1- healthy, 2' - cancer (excluding liver), 2'' – cardiovascular and other diseases, 3- liver diseases



Relative content of plutonium in lungs and lung lymph nodes of workers (males) who have no chronic lung diseases, as a function of the type of transportability of plutonium aerosols (S) detected in the production workshops

More information in:

Suslova, K.G.; Khokhryakov, V.F.; Tokarskaya, Z.B.; Nifatov, A. P.; Sokolova, A.B; Miller, S.C. and Krahenbuhl, M.P. Modifying effects of health status, physiological, and dosimetric factors on extrapulmonary organ distribution and excretion of inhaled plutonium in workers at the Mayak Production Association. Health Phys. 90:299–311; 2006

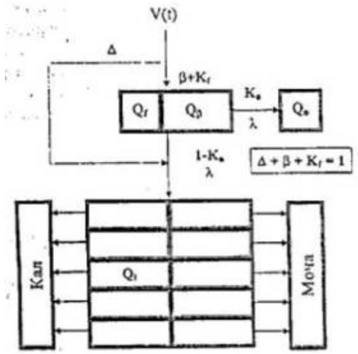
More information in:

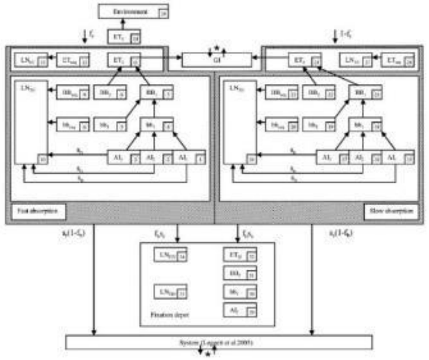
Khokhryakov, V.V.; Khokhryakov, V.F.; Suslova, K.G.; Vostrotin, V.V.; Vvedensky, V.E.; Sokolova, A.B.; Krahenbuhl, M.P.; Birchall, A.; Miller, S.C.; Schadilov, A.E.; Ephimov, A.V. Mayak worker dosimetry system 2008 (MWDS-2008): assessment of internal dose from measurement results of plutonium activity in urine. Health Phys. 104: 366–378; 2013

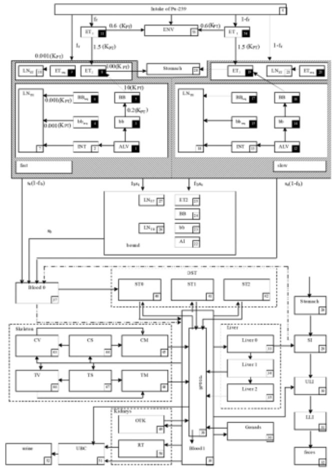
Project 2.4. Mayak Worker Dosimetry.
Project Tasks

Development of a biokinetic model specific for the Mayak personnel

Evolution from “Doses-1999” model to “MWDS-2019” model







Doses-1999 | MWDS-2008 | MWDS-2013

Doses-1999 | Doses-2000 | Doses-2005 | MWDS-2008 | MWDS-2013 | MWDS-2016 | MWDS-2019 | MWDS-2023

More information in:

- Leggett, R. W., K. F. Eckerman, V. F. Khokhryakov, K. G. Suslova, M. P. Krahenbuhl, and S. C. Miller. “Mayak Worker Study: An Improved Biokinetic Model for Reconstructing Doses from Internally Deposited Plutonium.” Radiation Research 164, no. 2 (2005): 111–22.
- Khokhryakov VV, Khokhryakov VF, Suslova KG, Vostrotin VV, Vvedensky VE, Sokolova AB, Krahenbuhl MP, Birchall A, Miller SC, Schadilov AE, Ephimov AV. Mayak Worker Dosimetry System 2008 (MWDS-2008): assessment of internal dose from measurement results of plutonium activity in urine. Health Phys. 2013 Apr;104(4):366-78. doi: 10.1097/HP.0b013e31827dbf60. PMID: 23439140.
- Napier BA. THE MAYAK WORKER DOSIMETRY SYSTEM (MWDS-2013): AN INTRODUCTION TO THE DOCUMENTATION. Radiat Prot Dosimetry. 2017 Nov 1;176(1-2):6-9. doi: 10.1093/rpd/ncx020. PMID: 28338990; PMCID: PMC5927475.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Development of a biokinetic model specific for the Mayak personnel

Evolution from “Doses-1999” model to “MWDS-2019” model

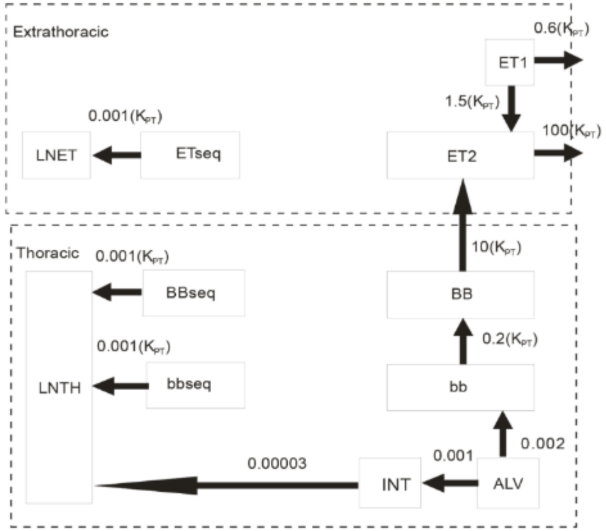
Characteristics	Doses-1999	MWDS-2008	MWDS-2013/2016/2019
Respiratory tract model	Reduced model ICRP Publication 30	Modified model ICRP-66	Modified model ICRP-66
GIT model	Not considered	ICRP Publication 30, resorption depends on transportability	ICRP Publication 30
Systemic model	10-chamber model FIB-1	Modified ICRP-67	Leggett model (2005)
Inhalation intake regime	Chronic, uniform in time	Chronic, descending exponentially in time	Three-step function

More information in:

- Leggett, R. W., K. F. Eckerman, V. F. Khokhryakov, K. G. Suslova, M. P. Krahenbuhl, and S. C. Miller. “Mayak Worker Study: An Improved Biokinetic Model for Reconstructing Doses from Internally Deposited Plutonium.” Radiation Research 164, no. 2 (2005): 111–22.
- Vasilenko EK, Khokhryakov VF, Miller SC, Fix JJ, Eckerman K, Choe DO, Gorelov M, Khokhryakov VV, Knyasev V, Krahenbuhl MP, Scherpelz RI, Smetanin M, Suslova K, Vostrotin V. Mayak worker dosimetry study: an overview. Health Phys. 2007 Sep;93(3):190-206. doi: 10.1097/01.HP.0000266071.43137.0e. PMID: 17693770.
- Khokhryakov VV, Khokhryakov VF, Suslova KG, Vostrotin VV, Vvedensky VE, Sokolova AB, Krahenbuhl MP, Birchall A, Miller SC, Schadilov AE, Ephimov AV. Mayak Worker Dosimetry System 2008 (MWDS-2008): assessment of internal dose from measurement results of plutonium activity in urine. Health Phys. 2013 Apr;104(4):366-78. doi: 10.1097/HP.0b013e31827dbf60. PMID: 23439140.
- Napier BA. THE MAYAK WORKER DOSIMETRY SYSTEM (MWDS-2013): AN INTRODUCTION TO THE DOCUMENTATION. Radiat Prot Dosimetry. 2017 Nov 1;176(1-2):6-9. doi: 10.1093/rpd/ncx020. PMID: 28338990; PMCID: PMC5927475.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Development of a biokinetic model specific for the Mayak personnel



MWDS-2013/2016/2019 suggests a significant modification for the description of transport of particulate compounds:

1) In extrathoracic region, the part of activity from ET1 travels into ET2 region where it may either be absorbed into the blood, or excreted into gastro-intestinal tract;

2) Slow clearance of particles in bronchiolar compartment (bb) is applied only to a small part of material deposited there, and this fact, together with the desire to simplify the model, has led to complete elimination of fraction of slow clearance from upper airways. Any possible slow clearance of some deposited activity is compensated by reduced clearance rate in this region;

3) Alveolar-interstitial region is presented by two physiologically justified chambers, ALV and INT.

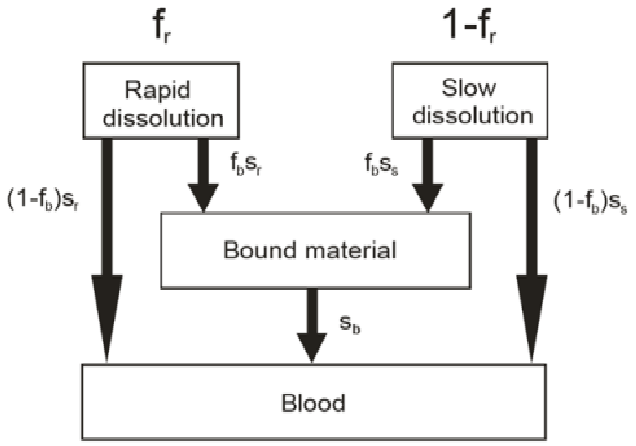
For the purposes of MWDS-2013, to provide uncertainty fro each separate worker, each rate constant in extrathoracic region and upper airways is multiplied by a random variable K_{PT} sampled from lognormal distribution with median 1 and geometrical standard deviation 1.73.

More information in:

Birchall A, Vostrotin V, Puncher M, Efimov A, Dorrian MD, Sokolova A, Napier B, Suslova K, Miller S, Zhdanov A, Strom DJ, Scherpelz R, Schadilov A. THE MAYAK WORKER DOSIMETRY SYSTEM (MWDS-2013) FOR INTERNALLY DEPOSITED PLUTONIUM: AN OVERVIEW. Radiat Prot Dosimetry. 2017 Nov 1;176(1-2):10-31. doi: 10.1093/rpd/ncx014. PMID: 31945164.

Project 2.4. Mayak Worker Dosimetry.
Project Tasks

Development of a biokinetic model specific for the Mayak personnel



Absorption from the respiratory tract. Fraction f_r, containing the initially accumulated activity dissolves quickly, s_r, while the additional fraction dissolves slower, s_s. Fraction f_b binds with lung tissue where it is absorbed into blood much more slowly, s_b.

It is assumed that all absorption parameters depend on physical-chemical properties of a material inhaled and are therefore 100% common for all workers. Records on the Mayak workers have no information on fast phase of dissolution (f_r and s_r), so the values are derived from literature and they were published earlier (Puncher et al, 2011). Values s_s for nitrates and oxides were derived separately.

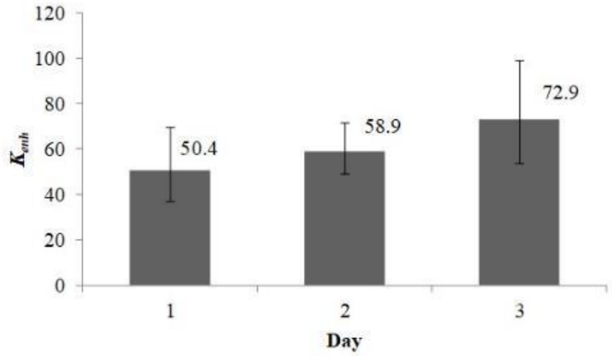
More information in:

Birchall A, Vostrotin V, Puncher M, Efimov A, Dorrian MD, Sokolova A, Napier B, Suslova K, Miller S, Zhdanov A, Strom DJ, Scherpelz R, Schadilov A. THE MAYAK WORKER DOSIMETRY SYSTEM (MWDS-2013) FOR INTERNALLY DEPOSITED PLUTONIUM: AN OVERVIEW. Radiat Prot Dosimetry. 2017 Nov 1;176(1-2):10-31. doi: 10.1093/rpd/ncx014. PMID: 31945164.

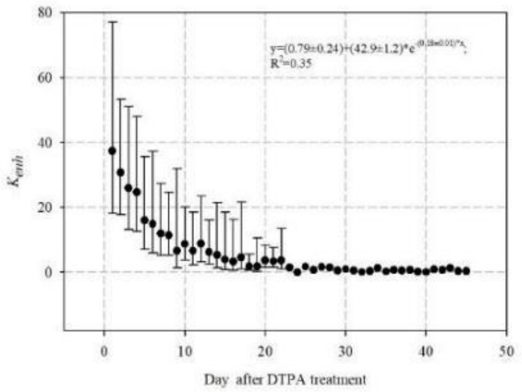
Project 2.4. Mayak Worker Dosimetry. Project Tasks

Effects of chelation therapy on ^{239}Pu urinary excretion

For the workers who were in contact with ^{239}Pu, Ca DTPA administered on a daily basis for 3 days was being used until the middle of 70s to enhance the urinary excretion of plutonium and increase the sensitivity of bioassay measurements. In the Mayak worker cohort under study, the enhancement coefficient values are used in the biokitetic models to estimate doses to different organs and organ systems.



Factors enhancing the plutonium excretion during the period of Ca DTPA effect



Factors enhancing the plutonium excretion during the period of Ca DTPA after-effect

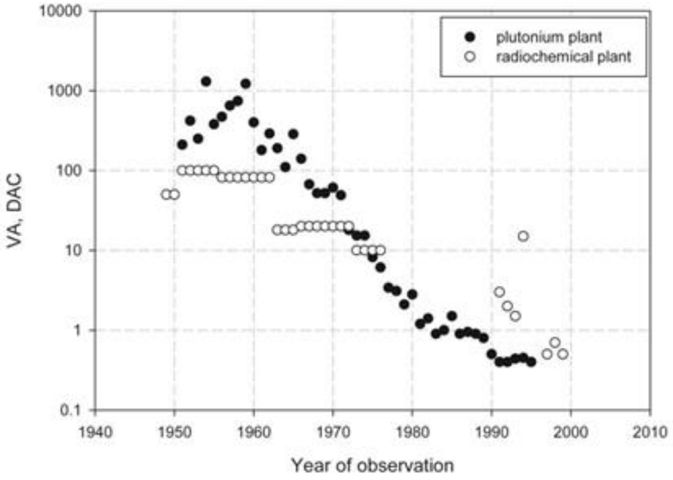
More information in:

Sokolova A.B., Suslova K.G., Miller S.C. Urinary excretion of plutonium in Mayak workers during and after Ca-DTPA administration // Radiation Protection Dosimetry. 2021. 197 (2). PP.154-162. DOI 10.1093/rpd/ncab176.

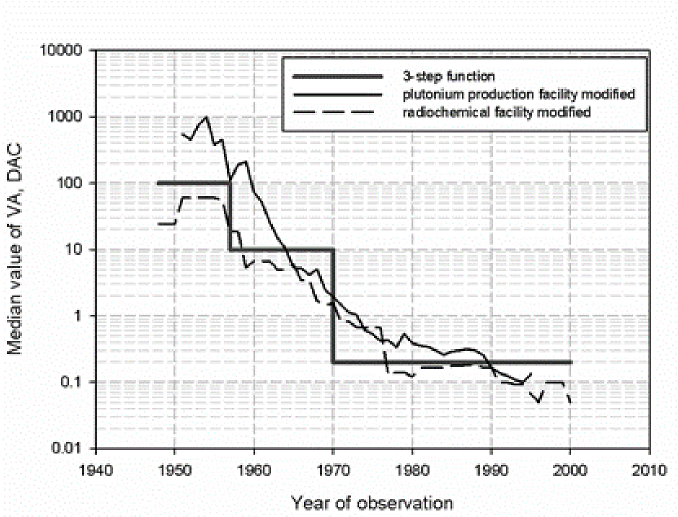
Project 2.4. Mayak Worker Dosimetry.
Project Tasks

Function of intake (Typical scenario of exposure)

Based on aerosol activities in the air of workshops, a three-step function of intake was developed. Also, the respirator use from 1957 was considered.



Dynamics of alpha-emitting aerosol content in the air of two typical workplaces of plutonium and radiochemical plants



The annual VA measurements can be nicely represented by a three-step function with heights H1, H2 and H3 given by: H1(≤1957)=100; H2(1958-1970)=10; H3(>1970)=0.2

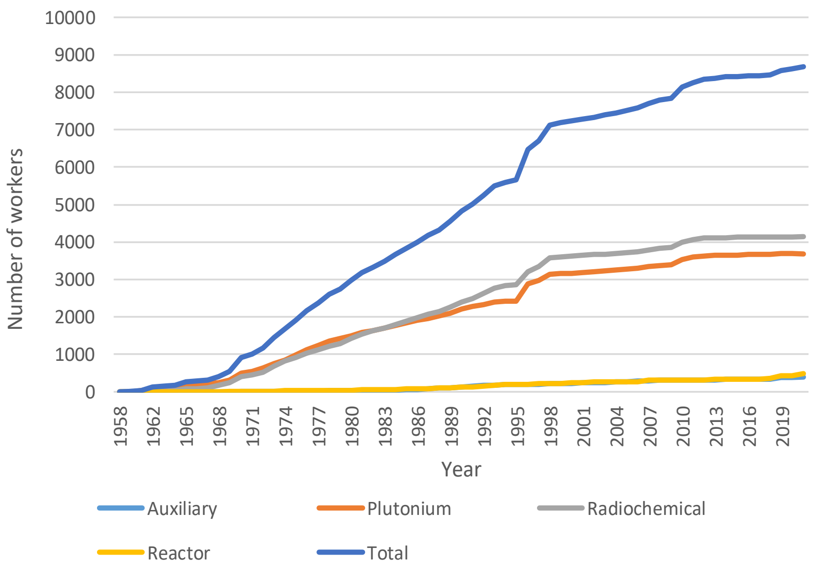
More information in:

Sokolova A.B., Birchall A., Efimov A.V., Vostrotin V.V., Dorrian M-D. The Mayak Worker Dosimetry System (MWDS-2013): Determination of the individual scenario of inhaled plutonium intake in the Mayak workers // Radiation Protection Dosimetry. 2017. 176 (1-2). PP. 83–89. DOI 10.1093/rpd/ncw190.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Individual biophysical examinations

Program of individual biophysical examinations had two goals: to examine and provide with dose data the previously unexamined MWC representatives; and to examine those MWC representatives who at one time were provided with inadequate number of measurements and were examined using insufficiently sensitive techniques.



Number of examined representatives of MWC in dynamics

In total, from 1998 to 2022, 8,400 bioassays were performed for 4,900 workers. Among them, 2,000 people were examined for the first time.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

PANDORA Calculation Complex

To perform test calculations, quality control calculations and final calculations, a program code named PANDORA was developed.

The output hyper-realizations of PANDORA incorporate the overall uncertainty of the doses, but result in essentially one million results per individual. In order to make preliminary epidemiological analyses tractable, and also for consistency with the external doses, it was required to convert the hyper-realizations to realizations using a method described by A.Birchall and M.Puncher.

The calculation of internal doses with PANDORA for MWDS-2013 involved extensive computational resources due to the complexity and sheer number of calculations required. A single run of the code for the entire cohort took about 47 days.

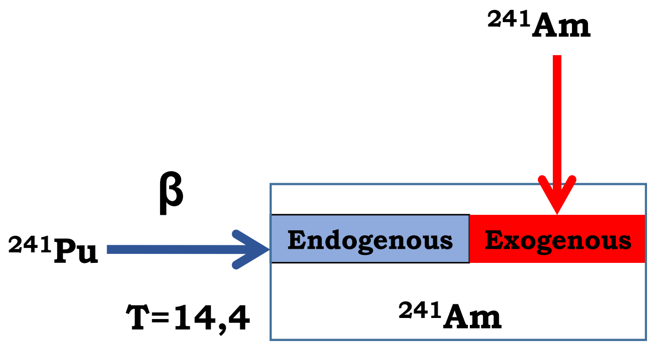
More information in:

- Birchall A. and Puncher M.. The Mayak Worker Dosimetry System (MWDS-2013): how to reduce hyper-realizations to realizations. Radiat. Prot. Dosim. 176(1-2), 154–162 (2017)
- Zhdanov A., Vostrotin V. V., Efimov A., Birchall A. and Puncher M.. Mayak Worker Dosimetry System-2013 (MWDS-2013): implementation of the dose calculations. Radiat. Prot. Dosim. 176(1-2), 163–165 (2017)

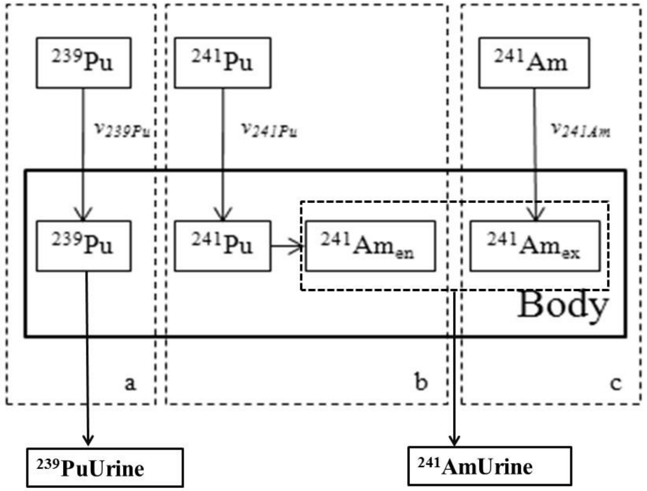
Project 2.4. Mayak Worker Dosimetry. Project Tasks

Development of ^{241}Am model

The contribution of ^{241}Am to a total dose increased in later years. This nuclide was more and more often detected in urine samples and by WBC. A model was developed to consider the ^{241}Am contribution. The model has been verified but not implemented yet in the dataset to be submitted to epidemiologists.



Development of MWDS_Am system that will provide the correct Am doses and their uncertainties



Structure scheme of Am model (the number of compartments is 210!)

Project 2.4. Mayak Worker Dosimetry. Project Tasks

Job Exposure Matrix (JEM)

The Mayak cohort is provided with annual estimated plutonium doses to different organs and tissues only for approximately 45% of the main production personnel.

A method of extrapolation of working conditions of certain workers provided with estimates of harmful exposure onto the rest of workers is called Job Exposure Matrix (JEM).

To estimate internal exposure doses using the JEM method based only on occupational histories of workers with no bioassays, it was necessary to build new prior distributions of intake at each workplace using the available data on workers from same workplaces but those who were provided with bioassay measurements of plutonium, i.e. from MWDS-2016 Dosimetry System.

The total number of workers with internal exposure doses estimated by JEM is 25,485.

Project 2.4. Mayak Worker Dosimetry. Project Tasks

External Exposure

Most of the work on the external dose database was performed by Mayak PA. The results are detailed in the September 2007 special issue of the Health Physics journal and electronic annexes to it.

Spot estimates and their uncertainties are obtained for gamma and neutron related occupational exposure, along with the doses from medical diagnostic exposure.

After 2010 the works were performed without the Mayak data and participation, mostly by the method of reverse engineering. A hyper model was developed for external dosimetry. The dataset obtained is consistent with the structure of internal dosimetry data including the doses from medical diagnostic exposure.

More information in:

- Vasilenko, E K. Khokhryakov, V F. Miller, S C. Fix, J J. Eckerman, K. Choe, D O.; Gorelov. M; Khokhryakov, V V. Knyasev, V. Krahenbuhl, M P. Scherpelz, R I. Smetanin, M; Suslova, K; Vostrotin, V. MAYAK WORKER DOSIMETRY STUDY: AN OVERVIEW. Health Physics 93(3):p 190-206, September 2007. DOI: 10.1097/01.HP.0000266071.43137.0e
- Napier B. A., Efimov A. and Baker S. C. The Mayak worker dosimetry system (MWDS-2013) for external irradiation. Radiat. Prot. Dosim. (2016) (submitted)

Project 2.4. Mayak Worker Dosimetry. Amount of data submitted to epidemiologists

Information on the number of dose estimates using the MWDS-2019 method

In accordance with the project goals, one of the key indicators is the number of MWC representatives provided with dosimetry data

Facility	Subcohort					Total
	I	II	III	IV	V	
Auxiliary	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Plutonium	865 (35%)	549 (44 %)	692 (43%)	805 (61%)	709 (63%)	3,620 (47%)
Radiochemical	1,492 (40%)	863 (43%)	672 (46%)	490 (62%)	804 (70%)	4,321 (47%)
Reactor	221 (9%)	63 (8%)	50 (7%)	36 (6%)	84 (9%)	454 (8%)
Total	2,578 (30%)	1,475 (37%)	1,414 (38%)	1,331 (50%)	1,597 (50%)	8,395 (33%)

% of workers with individual doses of total number in the cohort is indicated in brackets

Project 2.4. Mayak Worker Dosimetry. Amount of data submitted to epidemiologists

Main characteristics of MWDS-2016 and MWDS-2019 datasets

Parameter	MWDS-2016	MWDS-2019
Number of examined workers	8,340	8,395
Date of the first examination	26.10.1958	26.10.1958
Date of the last examination	30.06.2016	04.06.2019
Number of cases with urine data only	7,305	7,345
Number of cases with urine+autopsy data	578	586
Number of cases with autopsy data only	457	464
Number of urine examinations (total)	18,541	19,663
Average number of biophysical measurements per worker	2.35	2.48
Average number of urine samples per worker	7.59	7.61
Number of newly added monitored workers	-	81
Number of newly added analyses	-	530

Project 2.4. Mayak Worker Dosimetry.
Amount of data submitted to epidemiologists

Information on the number of doses estimated by JEM

Facility	Subcohort					Total
	I	II	III	IV	V	
Auxiliary						3,439 (99,2%)
Plutonium	2,423 (99.2%)	1,204 (97.3%)	1,566 (96.9%)	1,257 (96.0%)	1,085 (96.6%)	7,535 (97.5%)
Radiochemical	3,740 (99.9%)	2,004 (99.7%)	1,458 (99.3%)	784 (99.6%)	1,144 (99.0%)	9,130 (99.6%)
Reactor	2,467 (99.8%)	793 (99.9%)	672 (99.9%)	551 (99.3%)	898 (99.4%)	5,381 (99.7%)
Total	8,630 (99.7%)	4,001 (99.0%)	3,696 (98.4%)	2,592 (97.7%)	3,127 (98.3%)	25,485 (98.9%)

% of workers with individual doses of total number in the cohort is indicated in brackets

Project 2.4. Mayak Worker Dosimetry. Amount of data submitted to epidemiologists

The number of workers provided with MWDS-2013 occupational dose estimates due to external exposure

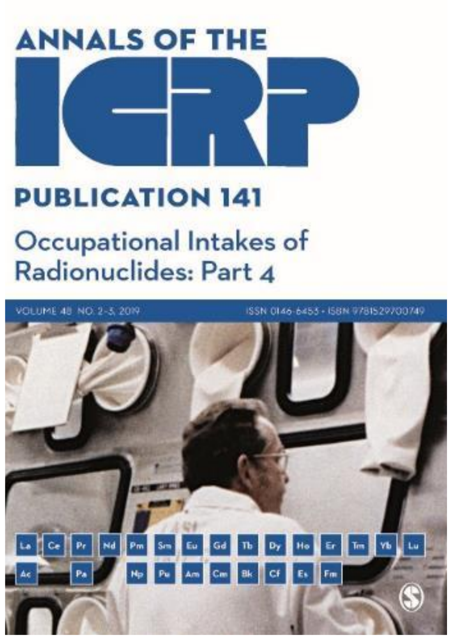
Facility	Gamma exposure		Neutron exposure	
	Number of workers	Number of annual doses	Number of workers	Number of annual doses
Plutonium	6,909	82,736	1,149	12,136
Reactor	5,196	81,663	2,485	28,087
Radiochemical	9,120	147,434	449	3,325
Auxiliary	2,625	29,098	9	49
Total	23,850	340,931	4,092	43,597

500 realizations of each annual organ and tissue doses were calculated for all the considered exposures. Doses distributions and their central values with uncertainty are provided in tables for external gamma, external high energy neutron, external low-energy neutron, and medical exposures for the period from 1948 through 2007. The occupational dose tables include all of the subjects previously analyzed in MWDS-2008.

The doses due to medical examinations were calculated based on the available medical records. This data is available for about 58% of workers only.

Project 2.4. Mayak Worker Dosimetry.

An important key indicator is recognition of the research results at the level of the global scientific community



The researches performed to reconstruct doses for the Mayak workers are particularly noted, including:

- classification of industrial aerosols of plutonium in accordance with their transportability,
- study of the biokitetics of ^{241}Am entered as a part of industrial aerosols and formed as a result of ^{241}Pu decay based on autopsy data, bioassay results and WBC measurements,
- determination of parameter values of the lung model – bound fraction f_b, parameter s_s based on autopsy data of the Mayak workers.

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Key researches from the Russian Federation

Alexander Efimov
Principal Investigator. Individual biophysical examinations. External and medical exposure.

Vadim Vostrotin
Mathematical modeling. Biokitetic model development. Programming. Quality control.

Alexandra Sokolova
Modifying factors of plutonium metabolism. Bioassay quality control. Typical intake scenario. ^{241}Am model

Vladimir Vvedensky
Development of JEM method. Programming. Quality control.

Klara Suslova
Autopsy program.

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Project Members

Project Team (as of 2014)

RF: Mikhail Gorelov (Leader of External Dosimetry until 2009, Mayak PA) and Alexander Efimov (Leader of Internal Dosimetry, Southern Urals Biophysics Institute).

USA: Bruce Napier (Leader of External Dosimetry, Pacific Northwest National Laboratory)

GB: Richard Bull (Leader of Internal Dosimetry, Nuvia, Ltd).

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