Ermittlung der Unsicherheiten der Strahlenexpositionsabschätzung in der Wismut-Kohorte- Teil I

Projektbericht

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Abstract

Part 1 of the research project "Determination of uncertainties of radiation exposure assessment in the Wismut cohort" included the following tasks: (1) Description of the working conditions at the Wismut company and procedures for estimating occupational exposure to radon and its progeny and (2) identification of potential sources of uncertainty and a preliminary evaluation of their possible relevance. The quantification of uncertainties and their impact on risk estimation are part of a follow-up research project and not the subject of this report.

During the operating period of the Wismut from 1946 to 1990, a large number of mining objects were in operation underground, in open pit mining, in processing facilities and at the surface. In the early years (1946-1955) the working and radiation protection conditions were very poor, as only artificial ventilation was available. At that time, radon concentrations were very high. With the introduction of measures to improve ventilation from 1955 onwards the working conditions improved and radon exposures dropped to average annual values below 4 Working Level Months (WLM) from the 1970s onwards. Around 1955, the first ambient air measurements of radon gas concentration started in the different mines. These were gradually extended. In 1966, regular measurements of radon decay products were introduced by the Wismut company in facilities in Saxony and in 1975 in Thuringia. Personal dosimeters were not introduced during the operating period of the Wismut and are therefore not available for the cohort.

The Wismut cohort was established in 1995. It includes about 59 000 former male employees of the Wismut company (follow-up period 1946 – 2013). The cohort members were randomly selected by stratified sampling (criteria: year of first employment, work place, area of mining). In addition, all employees of “Object 09” who started working between 1955 and 1970 and all workers employed after 1970 were included in the cohort. Thus, the cohort members are not representative of the Wismut workforce. For each worker a detailed working history was derived from the payrolls of the Wismut company. It includes information on begin and end of employment and on a daily basis on the work place (underground, open pit, processing, surface), mining object and shaft and type of job. In addition, times of absence were noted and specific underground shifts among surface workers were given. In the cohort, 76.1 % of the total work years were spent in underground mines.

In 1998, the Bergbau-Berufsgenossenschaft in Gera and the Hauptverband der gewerblichen Berufsgenossenschaften in St. Augustin developed a detailed job-exposure matrix (JEM) for estimating the exposure to radon progeny for employees of the Wismut. This was further developed for scientific purposes in 2004 and implemented in a software program in 2005. The JEM includes an estimation of the exposure to radon progeny in WLM for each work place (underground, open pit, processing or surface), mining facility, calendar year (1946-1989) and type of job.

For the time periods without measurements (underground 1946 to about 1954 and open pit mining 1946 to 1989), the exposure to radon was reconstructed by a group of experts based on the first available ambient air measurements of radon gas in 1955 in a reference mining object taking into account uranium deposit and delivery, ventilation and mine architecture over time. All these parameters had been evaluated based on extensive information on old mining and former mining activities. In processing companies, the exposure to radon was determined for each processing stage; the experts’ estimations in years without measurements were based on available measurements in reference processing companies as well as on the amount and quality of the processed ore, the working conditions and single measurements in the considered object. For years where only radon gas measurements were available, the mean annual concentrations of radon gas in the different shafts

were converted into WLM using equilibrium factors of 0.6 to 0.2, depending on the level of ventilation. These estimations were performed for the reference activity hewer (underground, open pit mining). For processing companies, exposure assessment was performed in a different way and estimates did neither refer to a reference activity nor a reference stage.

By means of the developed software, a linkage between the JEM and the job history was performed. The annual radon progeny values of the JEM were multiplied by a weighting factor for the number of exposed working days of each worker and an activity-specific weighting factor (0 to 1). This factor takes into account the proportion of time spent in contact with radiating ore and the ventilation rate compared to a hewer for underground or open pit miners. In total, about 700 different jobs have been evaluated by the expert group and were included in the JEM.

Sources and potential uncertainties in the exposure assessment are described and systematized in the report. The structure of uncertainties is complex because the multi-stage exposure assessment varies over time and depends on the working conditions and thus, generates different types and sizes of errors. Errors in the exposure assessment may arise from the generalization of exposure measurements to a JEM with object-, calendar-year- and activity-specific exposure (generalization error), from the assignment of the values in the JEM to the single workers (assignment error) and from estimation errors in all stages of the exposure estimation process. Generalization error and assignment error affect the exposure estimates of the whole cohort.

The size and relevance of estimation error depends on the estimation approach. Among the radon-exposed cohort members (underground, open pit mining, processing) the exposure estimates of about one third of the total work years were based on radon gas concentration measurements, for one third on radon progeny measurements and one third on experts' knowledge. The mining objects with the highest proportion of total work years underground were Aue ("Object 09", 33.61 %) in Saxony and Schmirchau (12.43 %) in Thuringia. In total, about 200 000 measurements were conducted in Saxonian objects and 195 000 in Thuringian objects, respectively.

Estimation error consists of several simultaneously acting errors: procedural measurement error, documentation error, parameter uncertainties, experts' evaluation error, transfer error and approximation error. In a preliminary evaluation, the generalization error (e.g. use of average values for objects or shafts) and the parameter uncertainties (e.g. evaluation parameter) are considered as particularly relevant.

Zusammenfassung

Teil 1 des Forschungsvorhabens „Ermittlung der Unsicherheiten der Strahlenexpositionsabschätzung in der Wismut-Kohorte“ umfasste folgende Aufgaben: (1) Beschreibung der Arbeitsbedingungen in der Wismut und der Vorgehensweise bei der Abschätzung der beruflichen Exposition gegenüber Radon und seinen Folgeprodukten und (2) Identifizierung möglicher Quellen von Unsicherheiten sowie eine vorläufige Bewertung von deren möglicher Relevanz. Die Quantifizierung der Unsicherheiten sowie ihres Einflusses auf die Risikoschätzung sind Teil eines Folgeforschungsvorhabens und nicht Gegenstand dieses Berichts.

In der Betriebszeit der Wismut von 1946 bis 1990 war eine Vielzahl von Bergbauobjekten unter Tage, im Tagebau, in der Aufbereitung und über Tage in Betrieb. In den Anfangsjahren (1946-1955) waren die Arbeits- und Strahlenschutzbedingungen sehr schlecht, da nur künstliche Bewetterung vorhanden war. Zu dieser Zeit waren die Radonkonzentrationen sehr hoch. Erst mit Einführung von Maßnahmen zur Verbesserung der Belüftung ab 1955 verbesserten sich die Arbeitsbedingungen zunehmend und die Radonexpositionen sanken ab den 1970er Jahren deutlich auf durchschnittliche Jahreswerte unter 4 Working Level Months (WLM). Um 1955 wurde bei der Wismut mit den ersten Messungen der Radongaskonzentration in der Atemluft an den Arbeitsplätzen begonnen. Diese wurden nach und nach ausgedehnt. 1966 führte die Wismut in Sachsen und 1975 in Thüringen regelmäßige Messungen der Radonfolgeproduktkonzentration ein. Messungen mit Personendosimetern wurden während der Betriebszeit der Wismut nicht durchgeführt und stehen daher für die Kohorte nicht zur Verfügung.

Die Wismut-Kohortenstudie wird seit 1995 durchgeführt. Sie umfasst rund 59 000 ehemalige männliche Mitarbeiter der Wismut (Beobachtungszeitraum 1946-2013). Die Kohortenmitglieder wurden zufällig mittels einer geschichteten Stichprobe ausgewählt (Kriterien: Jahr des Beschäftigungsbeginns, Arbeitsplatz, Bergbaugebiet). Darüber hinaus wurden alle Mitarbeiter von "Objekt 09", die zwischen 1955 und 1970 ihre Tätigkeit aufgenommen haben, sowie alle nach 1970 beschäftigten Mitarbeiter in die Kohorte aufgenommen. Damit sind die Kohortenmitglieder nicht repräsentativ für die gesamte Wismut-Belegschaft. Für jeden Mitarbeiter wurde aus den Lohn- und Gehaltsunterlagen der Wismut eine detaillierte Arbeitsanamnese abgeleitet. Sie enthält Informationen über Beginn und Ende der Beschäftigung und tagesgenaue Informationen über den Arbeitsplatz (unter Tage, Tagebau, Aufbereitung, Oberfläche), das Bergbauobjekt und den Schacht sowie über die Art der Tätigkeit. Darüber hinaus wurden Fehlzeiten und spezielle Untertageschichten von Übertagearbeitern erfasst. In der Kohorte wurden 76,1 % der gesamten Arbeitsjahre in untertägigen Bergwerken geleistet.

Die Bergbau-Berufsgenossenschaft in Gera und der Hauptverband der gewerblichen Berufsgenossenschaften in St. Augustin entwickelten 1998 eine detaillierte Job-Exposure-Matrix (JEM) zur Abschätzung der Strahlenexposition für Wismutbeschäftigte. Diese wurde 2004 für wissenschaftliche Zwecke weiterentwickelt und 2005 in einem Softwareprogramm umgesetzt. Die JEM enthält Abschätzungen der Radonfolgeproduktexposition in WLM für jeden Arbeitsplatz (unter Tage, Tagebau, Aufbereitung oder Oberfläche), jedes Bergbauobjekt, jedes Kalenderjahr (1946-1989) und jede Berufsgruppe.

Für die Zeiträume ohne Messungen (unter Tage 1946 bis etwa 1954, im Tagebau 1946 bis 1989) wurde die Radonexposition durch eine Expertengruppe auf der Grundlage der ersten verfügbaren Radongas-Messungen im Jahr 1955 in einem Referenzobjekt geschätzt, dabei wurden Urangehalt und -ausbringung, Belüftung und Grubenarchitektur über die Zeit berücksichtigt. Alle diese Parameter wurden anhand umfangreicher Informationen über den Altbergbau und frühere Bergbauaktivitäten

hergeleitet. In Aufbereitungsbetrieben wurde die Radonexposition für jede Prozessstufe ermittelt; Expertenschätzungen in Jahren ohne Messungen basierten auf verfügbaren Messungen in Referenz-Aufbereitungsbetrieben sowie auf der Menge und der Qualität des verarbeiteten Erzes, den Arbeitsbedingungen und Einzelmessungen im betrachteten Objekt. Für Jahre, in denen nur Radongasmessungen zur Verfügung standen, wurden die mittleren jährlichen Radongaskonzentrationen in den verschiedenen Schächten mit Gleichgewichtsfaktoren von 0,6 bis 0,2, je nach Belüftungssituation, in WLM umgerechnet. Die Expositionsabschätzungen für Betriebe unter Tage und im Tagebau wurden für die Referenztätigkeit Hauer durchgeführt. Für Aufbereitungsbetriebe wurden die Expositionen auf andere Art und Weise abgeschätzt, hier bezogen sich die Schätzungen weder auf eine Referenzaktivität noch auf eine Referenzstufe.

Die entwickelte Software ermöglicht die Verknüpfung zwischen der JEM und den Arbeitsanamnesen. Dabei werden die jährlichen Radonfolgeproduktwerte in der JEM mit einem tätigkeitsspezifischen Wichtungsfaktor (zwischen 0 und 1) multipliziert. Dieser Faktor für Beschäftigte unter Tage oder im Tagebau berücksichtigt den Anteil der Zeit mit Erzkontakt und die Belüftungsrate im Vergleich zu einem Hauer. Insgesamt wurden rund 700 verschiedene Tätigkeiten von einer Expertengruppe bewertet und in die JEM aufgenommen.

Quellen für potenzielle Unsicherheiten in der Expositionsabschätzung werden im Bericht beschrieben und systematisiert. Die Struktur der Unsicherheiten ist komplex, da die mehrstufige Bestimmung der Exposition zeitlich und in Abhängigkeit der Arbeitsbedingungen variiert und somit unterschiedliche Arten und Größen von Fehlern erzeugt. Fehler bei der Expositionsbestimmung können durch die Verallgemeinerung von Expositionsmessungen zu einer JEM mit objekt-, kalenderjahr- und tätigkeitsspezifischer Exposition (Generalisierungsfehler), durch die Zuordnung der Werte in der JEM zu einzelnen Beschäftigten (Zuordnungsfehler) und durch Schätzfehler in allen Stufen des Prozesses der Expositionsschätzung entstehen. Generalisierungsfehler und Zuordnungsfehler wirken sich auf die Expositionsschätzungen der gesamten Kohorte aus.

Die Größe und Relevanz des Schätzfehlers hängt vom Schätzverfahren ab. Bei den radonexponierten Kohortenmitgliedern (unter Tage, Tagebau, Aufbereitung) basierten die Expositionsschätzungen bei etwa einem Drittel der gesamten Arbeitsjahre auf Radongaskonzentrationsmessungen, bei einem Drittel auf Radonfolgeproduktmessungen und einem Drittel auf Expertenwissen. Die Bergbauobjekte mit dem höchsten Anteil an den Gesamtarbeitsjahren unter Tage waren Aue ("Objekt 09", 33,61 %) in Sachsen und Schmirchau (12,43 %) in Thüringen. Insgesamt wurden rund 200 000 Messungen in Objekten in Sachsen und 195 000 in Objekten in Thüringen durchgeführt.

Der Schätzfehler besteht aus mehreren gleichzeitig wirkenden Fehlern: prozeduraler Messfehler, Dokumentationsfehler, Parameterunsicherheiten, Expertenfehler, Übertragungsfehler und Approximationsfehler. In einer vorläufigen Bewertung werden der Generalisierungsfehler (z.B. Verwendung von Durchschnittswerten für Objekt oder Schacht) und die Parameterunsicherheiten (z.B. Bewertungskoeffizient) als möglicherweise besonders relevant erachtet.

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1. Background

1.1. History

Silver mining has been in existence since the 12th century in the Ore Mountains (Erzgebirge) located in the South of Eastern Germany in the Federal State of Saxony close to the border of the Czech Republic. In 1946, after World War II, the old silver mines were re-opened and the Soviet-Stock Corporation was founded with the code name WISMUT (i.e. the German name for bismuth). The aim of this corporation was to produce as much uranium as possible for the Soviet nuclear weapon program.

The working conditions at the Wismut company can be roughly categorized into three periods: 1946-1954, 1955-1970 and 1971-1989 (Bundesamt für Strahlenschutz 2016; Kreuzer et al. 2010c). In the early years, from 1946 to about 1954, a large number of workers had been employed (about 100 000) under extremely poor working conditions. No worker protection or radiation safety measures existed; consequently, exposures to radiation and dust were very high due to a lack of forced ventilation and the use of dry drilling. In 1954, the corporation was converted into the Soviet-German Stock Corporation. At that time mining was extended to the Federal State of Thuringia. In 1955, the first radon gas measurements were performed and from then onwards several worker protection measures such as forced ventilation and wet drilling were introduced. Thus, from 1955 to 1970, the working conditions steadily improved and the number of employees was reduced to between 30 000 and 40 000. After 1970, international radiation protection standards were introduced, with measures for individual radiation protection. The number of miners was stable at 20 000 and the working conditions had a high safety level. With the German reunification in 1990, mining was abandoned.

The Wismut company produced a total of 220 000 tons of uranium during its operation period from 1946 to 1990 and was the third-largest uranium producer worldwide. It is estimated that in total more than 400 000 persons worked at the company, most of whom underground or in uranium ore processing facilities. After the German reunification, the German Federal Ministry of Environment (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit/BMU) decided to preserve the health data that were stored at the Wismut Health Data Archives (Gesundheitsdatenarchiv Wismut/GDAW), which are now held by the Federal Office for Occupational Protection and Medicine (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin/BAuA). These archives include paper files and histological material. The German Statutory Accident Insurance (Deutsche Gesetzliche Unfallversicherung/DGUV) maintains records of all data relevant to the procedures for the compensation of occupational diseases. Payrolls are kept by the successor of the former Wismut company, the Wismut GmbH. Based on parts of the information held by these bodies, a cohort of former Wismut employees could be established, with financial support from the BMU and the European Commission. (Kreuzer et al. 2010a, 2010c)

Development of mining activities of the Wismut company

After the occupation of parts of East Germany by the Soviet army in the summer of 1945, uranium mineralization in the ore fields of Johanngeorgenstadt and Schneeberg were explored by Soviet experts. As a result, mining activity begun in 1946 in Saxonian diggings. In 1947, the “Staatliche Sowjetische Aktiengesellschaft (SSAG) Wismut“ (today: SAG Wismut), was founded and mining activities were conducted in Johanngeorgenstadt, Oberschlema, Schneeberg, Annaberg-Buchholz and Marienberg. (Lehmann et al. 1998 pp. 27–29)

Already between 1950 and 1954, some uranium reserves were exhausted. Further uranium reserves were discovered during exploration work in Thuringia, especially the diggings Ronneburg; these reserves included also near-surface uranium reserves, which were mined with open pit mining. The “Sowjetisch-Deutsche Aktiengesellschaft (SDAG) Wismut” was founded in 1954. (Lehmann et al. 1998 pp. 28–29, 109)

In a continuous process, ore mining was steadily spatially extended and relocated according to the availability of uranium reserves. Ores with high uranium content were directly shipped to the Soviet Union, whereas all other ores were sent to nearby milling facilities of the Wismut company with the two major facilities “Crossen” and “Seelingstädt”.

The further temporal development of the subdivisions of SAG/SDAG Wismut is described in Chapter 2.

The location of the diggings of SAG/SDAG Wismut are shown in the map in Figure 1.

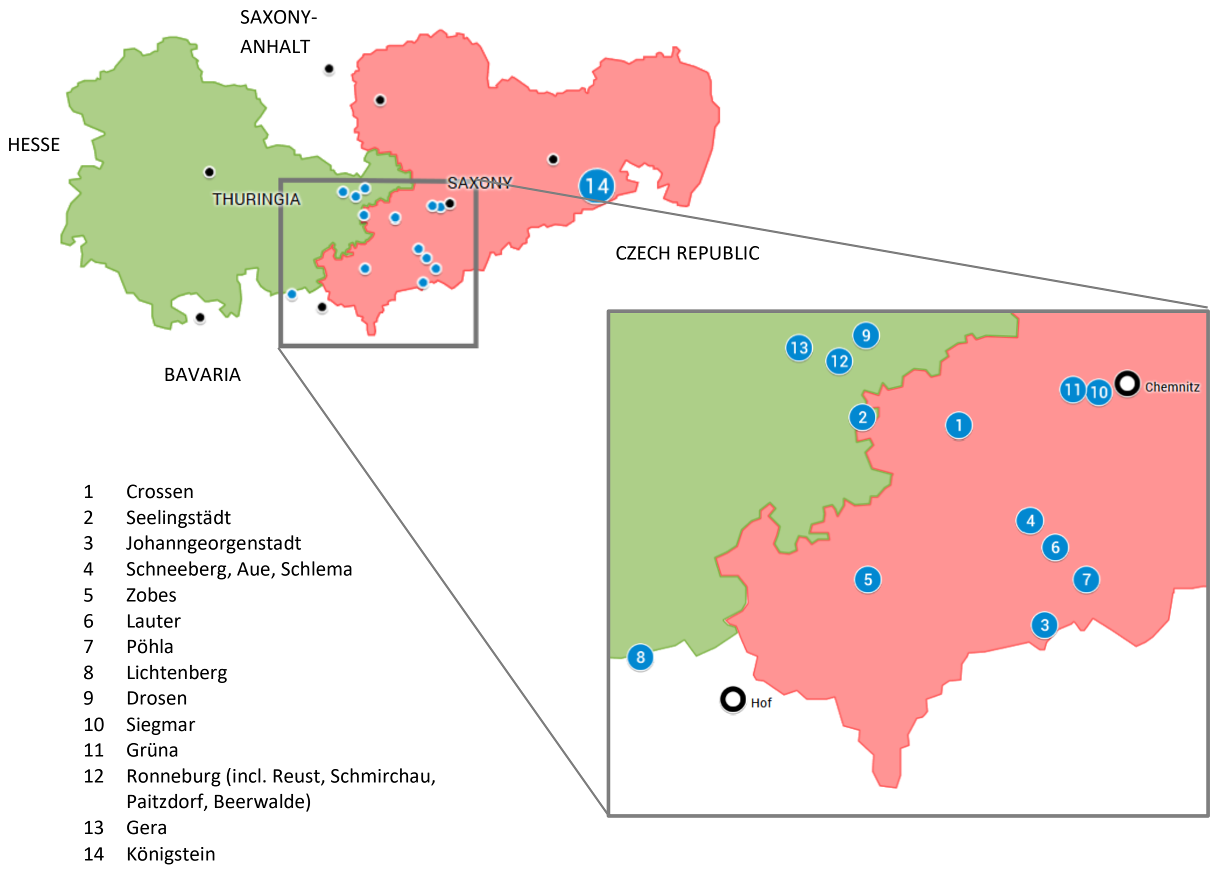

Figure 1: Uranium ore mining areas in Thuringia and Saxony and location of diggings of SAG/SDAG Wismut (diggings with proportion of total work years ≥ 1 %).

The diggings in Saxony can be categorized according to their geology (Lehmann et al. 1998 p. 46):

- Diggings in the Ore Mountains (except for diggings Freital) and the Vogtland
- Diggings Königstein
- Diggings Freital (not shown in Figure 1)

1.2. Wismut uranium miner cohort study

The Wismut cohort is one of the largest existing cohort studies of uranium miners who have been occupationally exposed to radon (Kreuzer et al. 2010c).

The study was initiated in the 1990ies. Due to financial reasons it was decided to limit the size of the cohort to about 64 000 workers taken from the files of about 130 000 workers with sufficient information on working history and personal data for follow-up as a stratified random sample. In order to represent the different mining conditions at the Wismut company, the sample was stratified by the date of first employment (1946–54, 1955–70 and 1971–89), work place (underground, milling/processing and surface) and area of mining (Saxony, Thuringia). Since it was assumed that during the first years of production women had also worked for at least some time underground, the sample was additionally stratified by gender. Moreover, all employees from one of the most important parts of the company (the so-called mining facility “Object 09”) who started working between 1955 and 1970 were included as well as any worker employed after 1970. Thus**, the cohort is not representative of the entire Wismut workforce**, but weighted towards those periods when exposures were medium to low in the selection of cohort members.

Inclusion criteria for this random sample were employment at the SAG/SDAG Wismut for at least 180 days in the period from 1946 to 1989, date of birth after the year 1899 and availability of basic information on personal data as well as on the occupational history (Kreuzer et al. 2010c).

The Wismut cohort includes 58 974 men accumulating over 2 million observed person years at risk in the most recent mortality follow-up period 1946-2013. About 14 % of the Wismut cohort members were never exposed to radiation during their employment, e.g. surface workers.

Figure 2 presents the number of radon-exposed cohort members per calendar year. The mean duration of follow-up is 40 years and the maximum is 67.5 years (Kreuzer et al. 2017). An overview on other uranium miners cohort studies is provided in Appendix A (Section A 1).

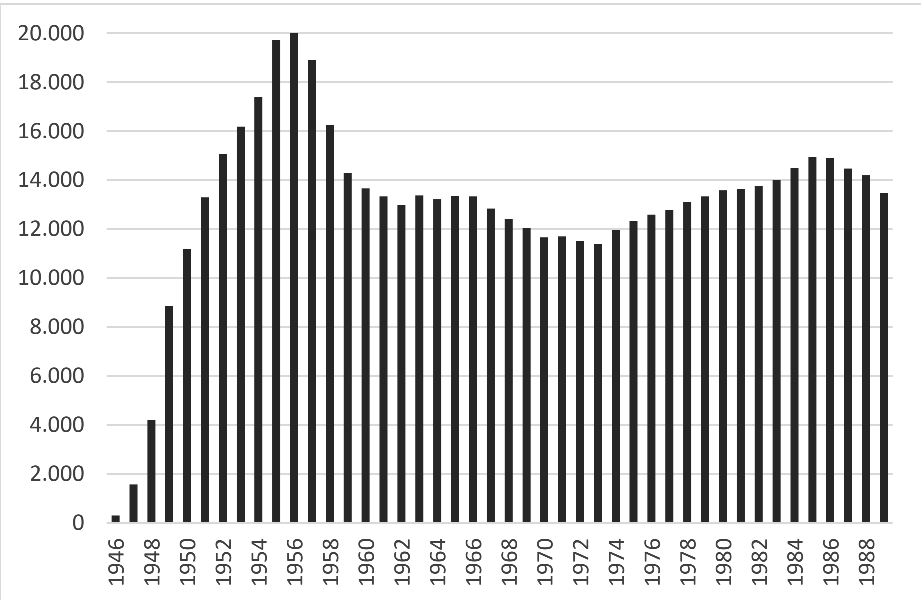

Figure 2: Number of radon-exposed cohort members per year (n=50,761, follow-up 1946-2013).

1.3. Exposure assessment

Occupational exposure to ionizing radiation of the workers in the SAG/SDAG Wismut was assessed within the research project "Belastung durch ionisierende Strahlung im Uranerzbergbau der ehemaligen DDR" by the "Bergbau-Berufsgenossenschaft" in Gera and the "Hauptverband der gewerblichen Berufsgenossenschaften" in St. Augustin and documented in the final report by Lehmann et al. (1998). The expert group developed a comprehensive job-exposure matrix (JEM) including information on exposure to radon progeny (RDP) in Working Level Months (WLM), exposure to gamma radiation in mSv and exposure to long-lived radionuclides in kBq h m^{-3}. The JEM was aimed as a basis for the declaratory and compensation procedures for occupational diseases. Scientific use for epidemiological studies was initially not intended and conservative exposure assessment for the miners was the target (Lehmann 2004 p. 7). The JEM included exposure estimates for each mining object/facility (see Chapter 2 for an overview of objects), calendar year (1946-1989), work place (underground, open pit, processing, surface) and job type/activity (Kreuzer et al. 2010c).

For scientific purposes, the JEM was further modified and documented in Lehmann et al. (2004). Shaft-specific exposure estimates were added, because exposure to radiation is known to be heterogeneous throughout an object (Lehmann 2004 p. 7). Additionally, the first version of the JEM did not cover the complete range of working times documented for the individuals in the Wismut cohort. For these two major reasons, the second version of the JEM was developed with shaft-specific exposure estimates for the occurring working times in the Wismut cohort.

Exposure assessment linking occupational histories with exposure estimates from the JEM was implemented in a software (HVBG and BBG 2005) (HVBG: Hauptverband der gewerblichen Berufsgenossenschaften; BBG: Bergbau-Berufsgenossenschaft).

A similar JEM was developed for occupational exposure to fine dust, silica dust and arsenic dust. In addition, data on smoking habits (for about 38 % of the cohort) and on vital status and causes of death were collected for the Wismut cohort (Kreuzer et al. 2010c). These data were used to examine radiation-related health risks, including risk of lung cancer mortality (Grosche et al. 2006; Kreuzer et al. 2015b; Schnelzer et al. 2010; Walsh et al. 2010), leukemia (Dufey et al. 2011; Kreuzer et al. 2017), cancers other than lung cancer (Kreuzer et al. 2008), cancers of the extra-thoracic airways (Kreuzer et al. 2014), kidney cancer (Drubay et al. 2014), liver cancer (Dufey et al. 2013), stomach cancer (Kreuzer et al. 2012) and prostate cancer (Walsh et al. 2012) as well as non-malignant respiratory diseases (Kreuzer et al. 2013b) and cardiovascular diseases (Kreuzer et al. 2006, 2010b, 2013a).

1.4. Aims of the research project

The aims of the research project are (1) to describe the working conditions at the Wismut company, (2) to describe the procedures for exposure assessment in the Wismut cohort, and (3) to identify potential sources of uncertainties and provide a preliminary evaluation of their possible relevance. The project did not include the quantification of the magnitude of uncertainty and the investigation of its influence on the risk estimates. This will be part of a separate project.

After an overview of the different work places of the Wismut cohort and the structure of mining/processing facilities of SAG/SDAG Wismut in Chapter 2 and the characterization of the working conditions in Chapter 3, a documentation of the methods and steps of exposure assessment over time is given in Chapter 4. The comprehensive presentation of exposure assessment in Chapter 4 is essential for the identification of potential sources and characteristics of uncertainties in the process of exposure assessment including the embedment in the statistical concept of measurement error in Chapter 5. A preliminary evaluation of the relevance of the uncertainties is given in Chapter 6 based on the frequency of occurrence as well as the potential impact on the exposure estimate and on risk estimates. Finally, recommendations regarding the question which uncertainties are particularly relevant for future consideration are given in Chapter 7.

2. Description of the different work places

The SAG/SDAG Wismut company was organized in so-called "objects". An object was a relatively autonomous facility within the SAG/SDAG Wismut (Lehmann et al. 1998 p. 28).

2.1. Work places

Four types of work places can be differentiated according their tasks: underground, open pit, processing, surface. The work places and corresponding number of objects as given in Lehmann et al. (1994, 1998), which occur in the Wismut cohort, are:

1. **Underground mining objects**: 36
    a. Saxony: 26
        - Mining objects: 14
        - Exploration objects: 8
        - Development objects: 5
    b. Thuringia: 11
        - Mining objects: 7
        - Exploration objects: 3
        - Development objects: 1
2. **Open pit mining objects**: 9
    a. Saxony: 0
    b. Thuringia: 9
3. **Processing companies**: 19
    a. Saxony: 17
        - Processing facilities: 8
        - RAS-/RAF-facilities: 4
        - Collieries: 5
    b. Thuringia: 2
        - Processing facilities: 1
        - RAS-/RAF-facilities: 1
        - Collieries: 0
4. **Surface objects**: 21

Underground mining objects were subdivided into mining ("Gewinnung"), exploration ("Erkundung") and development ("Ausrichtung") objects (Lehmann et al. 1998 p. 28). The task of underground mining objects was the underground mining of ore; underground mining objects were composed of several shafts. Potentially exploitable regions were explored before development and mining activities began.

Development objects had the task to prepare exploitable diggings for mining activity (Lehmann et al. 1998 p. 105). Note that object 010 was both, mining and exploration object and object 029 operated in Saxony and Thuringia.

Mining activities were also carried out in open pit mining objects, but in contrast to underground mining objects in near-surface diggings (Lehmann et al. 1998 p. 35).

Processing companies were subdivided into three types of facilities: processing facilities, RAS-/RAF-facilities and collieries (“Zechen”) (Lehmann et al. 1994, 1998; Lehmann 2004). Processing facilities had the task of ore enrichment through physical (radiometric and gravitational gradation) and chemical (acid and alkaline leaching) processing methods, which depended on the ore type (gangue or sedimentary ore). Besides the processing in the processing companies, ore was also directly processed in RAS-/RAF-facilities (RAS: radiometric automatic gradation; RAF: radiometric processing factory) of the mining companies through radiometric gradation. Sampling collieries mainly determined the amount, the moisture content and the uranium content of the processed ore, which required further processing stages like milling, classification, mixing, sampling, and analysis. Moreover, the sampling collieries had the task to temporally store and send the concentrate.

The distribution of working time in the four work places in the Wismut cohort is presented in Table 1. The majority of cohort members worked underground and very few in open pit mining.

Table 1: Proportion of person work years rendered in the different work places in the Wismut cohort. The total number of person work years relates to the person work years in all objects (except for object 000 000).

Work place	PPY (%)
Underground mining	76.1
Open pit mining	1.1
Processing	6.9
Surface	15.8
Sum	100.0

2.2. Labelling and operating times of objects

The objects were identified by numbers and names. Temporary renaming was used for reasons of secrecy. Adaptions of objects or object sections by another object (Lehmann et al. 1998 p. 28) or the change of the operation site occurred.

Object labelling in the JEM software (HVBG and BBG 2005) differs from the labelling which was originally documented in the occupational histories by ZeBWis (“Zentrale Betreuungsstelle Wismut”). For this purpose, a file was developed to link both labels (so-called “Umsteigerdatei” Lehmann 2004). In addition, a few further labels were changed during the implementation of the JEM.

In accordance with the labelling in HVBG and BBG (2005), we consistently use 3-digit numbers for objects and use three additional digits for denoting the shaft of an object. If the assignment of a shaft is ambiguous, 000 was used for the coding of the shaft; galleries and auxiliary and side shafts were summarized in shaft 999 (Lehmann 2004 pp. 103, 133). An overview of objects in the SAG/SDAG Wismut is given by Table 2. Note that only objects occurring in the Wismut cohort were included. Alternative object names are listed as well.

Table 2: Overview of objects of the SAG/SDAG Wismut occurring in the Wismut cohort. PPY: proportion of person work years in the Wismut cohort in %. BB: "Bergbaubetrieb" (mining operation). The total number of person work years relates to the person work years in all objects (except for object 000 000). A more detailed figure can be found in Appendix B (Figure B1).

Work place	Object no.[#]	Alternative object no.	Alternative object names [†]	Task	Location	PPY (in %)	Start of operation	End of operation
Underground mining object	001	01, 131	Johanngeorgenstadt	Mining	Saxony	2.49	1945	1959
	002	02, 129	Oberschlema	Mining	Saxony	4.07	1945	1958
	003	03	Schneeberg	Mining	Saxony	0.31	1947	1950
	004	04	Annaberg-Buchholz	Mining	Saxony	0.14	1947, 1948	1950
	005	05, 124	Marienberg	Mining	Saxony	0.13	1947	1952
	006	06, 118	Vogtland-Zobes	Mining	Saxony	0.96	1950	1964
	007	07, 111	Niederschlag-Bärenstein	Mining	Saxony	0.50	1948, 1949	1955
	008	08, 103	Breitenbrunn	Mining	Saxony	0.55	1948, 1949	1953
	009	09, 94	Aue, Niederschlema, Hartenstein, Alberoda	Mining	Saxony	33.61	1949	1990
	010	10	Bergrevier Johanngeorgenstadt (Westteil)	Development, mining	Saxony	<0.10	1949	1950, 1951
	011	11	Lauter	Development	Saxony	1.99	1946	1961
	012	12	Schwarzenberg	Development	Saxony	0.31	1947	1952
	013	13	Niederschlag	Development	Saxony	0.11	1949	1951
	014	14	Auerbach	Development	Saxony	0.13	1949	1950
	015	15, 52	Freiberg, Niederpöbel	Mining	Saxony	<0.10	1948, 1949	1953
	021	21	Niederschlema-Alberoda	Exploration	Saxony	<0.10	1947	1949
	022	22	Marienberg	Exploration	Saxony	<0.10	1947	1948
	023	23	Breitenbrunn	Exploration	Saxony	<0.10	1948	1949
	024	24	Oberwiesenthal	Exploration	Saxony	<0.10	1947	1948
	025	25	Vogtland	Exploration	Saxony	<0.10	1949	1950
	026	26	Freiberg-Osterzgebirge	Exploration	Saxony	<0.10	1947	1950
	027	27	Sachsen-Anhalt/Nordthüringen	Exploration	Thuringia	<0.10	1949	1951
	028	28	Lausitz	Exploration	Saxony	<0.10	1949	1950
	029	29, 47	Aue-Lauter- Schwarzenberg	Exploration	Saxony / Thuringia	0.20	1950	1952

Work place	Object no.#	Alternative object no.	Alternative object names †	Task	Location	PPY (in %)	Start of operation	End of operation
	030	30, 41, 90	Südthüringen-Dittrichshütte, Hirschbach	Mining	Thuringia	0.19	1950	1953
	047	47, 29	Thüringen / Sachsen-Anhalt (Expedition 2)	Exploration	Thuringia	0.13	1949	1951
	086	86	Saalfeld, Ronneburg, Dittrichshütte	Development	Thuringia	<0.10	1951	1955
	091	009 400	Bergbauabteilung Pöhla	Mining	Saxony	0.99	1968	1990
	096	6, 35, 49, 55, 96, 907	Steinkohlenlagerstätte Freital, BB Willi Agatz	Mining	Saxony	0.24	1948, 1968	1954, 1990
	901*	090 352	BB Lichtenberg	Mining	Thuringia	0.94	1954	1990
	902*	090 385, 379	BB Reust	Mining	Thuringia	4.30	1953	1990
	903*	090 356	BB Schmirchau	Mining	Thuringia	12.43	1952	1990
	904*	090 384	BB Paitzdorf	Mining	Thuringia	5.72	1962	1990
	905*	090 397	BB Beerwalde	Mining	Thuringia	2.59	1974	1990
	906*	090 403	BB Drosen	Mining	Thuringia	1.80	1980	1990
	908	000 390	BB Königstein	Mining	Saxony	1.18	1964	1990
Open pit mining object	300*	090 566	Lichtenberg	Mining	Thuringia	0.45	1958	1976
	301*	090 562	Stolzenberg	Mining	Thuringia	<0.10	1954	1957, 1960
	302*	090 557	Ronneburg/Raitzhain	Mining	Thuringia	<0.10	1950	1953, 1956
	303*	090 558	Sorge	Mining	Thuringia	0.21	1952	1957
	304*	090 560	Gauern	Mining	Thuringia	0.11	1953	1957
	306*	090 563, 564, 565	Culmitzsch, Culmitzsch (Mücke), Culmitzsch-Nord, Culmitzsch-Süd	Mining	Thuringia	0.27	1955	1967
	307*	090 561	Trünzig	Mining	Thuringia	<0.10	1953	1957
	308*	090 559	Steinach	Mining	Thuringia	<0.10	1953	1954
	309*	090 556	Erlau/Hirschbach, Tagebaue in der Region Schleusingen	Mining	Thuringia	<0.10	1950	1952, 1953
Processing company	031	31	Lengenfeld	Processing facility	Saxony	0.26	1947	1961
	032	32	Tannenbergsthal	Processing facility	Saxony	<0.10	1946	1957
	050	50	Aue	Colliery	Saxony	0.47	1950	1980
	051	51	Johanngeorgenstadt	Colliery	Saxony	<0.10	1948, 1949	1955

Work place	Object no.[#]	Alternative object no.	Alternative object names [†]	Task	Location	PPY (in %)	Start of operation	End of operation
	052	52	Oberschlema	Colliery	Saxony	<0.10	1948	1954, 1957
	054	54	Annaberg	Colliery	Saxony	<0.10	1947	1953
	058	58	Breitenbrunn	Colliery	Saxony	<0.10	1950	1958
	093	93	Freital	Processing facility	Saxony	<0.10	1949	1960
	095	95	Gittersee	Processing facility	Saxony	0.15	1952	1962
	098	98	Johanngeorgenstadt	Processing facility	Saxony	<0.10	1949	1956
	099	99	Oberschlema	Processing facility	Saxony	0.17	1948	1957
	100		Aue	Processing facility	Saxony	0.13	1947	1957
	101		Crossen	Processing facility	Saxony	2.58	1950	1989
	102		Seelingstädt	Processing facility	Thuringia	2.75	1960	1990, 1991
	200		Aue shaft 371	RAF-facility	Saxony	0.18	1959	1990
	202		Aue shaft 38	RAS-facility	Saxony	<0.10	1958	1972
	203		Pöhla	RAF-facility	Saxony	<0.10	1984	1988
	205		BB Schmirchau shaft 367/368	RAS-facility	Thuringia	<0.10	1960	1970
	206		BB Willi Agatz	RAF-facility	Saxony	<0.10	1986	1989
Surface object	016	16	Erzgebirge (Aue, Johanngeorgenstadt u.a.)	Building company ("Baubetrieb")	Saxony	<0.10	1947	1990
	017	17	Thüringen (Ronneburg u.a.)	Building company ("Baubetrieb")	Thuringia	3.57	1950	1990
	019		Wohnheime/ Betriebsschulen			2.41		
	033	33	Mechanischer Betrieb Lauter	Mechanical company ("Mechanischer Betrieb")	Saxony	<0.10		
	034	34	Bergbauausrüstung Cainsdorf	Mechanical company ("Mechanischer Betrieb")	Saxony	0.25		1990
	035	35	Mechanischer Betrieb Aue	Mechanical company ("Mechanischer Betrieb")	Saxony	<0.10		1990
	036	36	Wissenschaftliches-Technisches Zentrum Grüna	Scientific technical center	Saxony	<0.10		1990

Work place	Object no.[#]	Alternative object no.	Alternative object names [†]	Task	Location	PPY (in %)	Start of operation	End of operation
	037	37	Fahrzeug-Reparaturbetrieb Siegmar	Automobile workshop	Saxony	0.26		1990
	038		Generaldirektion Siegmar		Saxony	0.40		
	039		Organisations- u. Rechenzentrum Siegmar		Saxony	<0.10		
	080	80	Meßgerätebau Zwickau	Manufacturer of measuring device ("Messgerätebau")	Saxony	<0.10		
	103		Arbeitsförderungsgesellschaften (AFOG) Wismut			<0.10		
	105		Bergtechnikum Freiberg	Training	Saxony	<0.10		
	106		Zentraler Geologischer Betrieb Grüna		Saxony	1.98		
	107		Transportbetrieb Ronneburg / Aue	Transport service ("Transportbetrieb")	Thuringia	3.05		1990
	108		Bergbau-Ausrüstungswerk Cainsdorf	Mining equipment works ("Bergbau-Ausrüstungswerk")	Saxony	0.47		
	109		Bergbau-Ausrüstungswerk Aue	Mining equipment works ("Bergbau-Ausrüstungswerk")	Saxony	1.22		1990
	126		Projektierungsbetrieb Siegmar		Saxony	0.38		
	128		Arbeiterversorgungsbetrieb			0.12		
	177		Hochspannungsobjekt Schlema	Mechanical company ("Mechanischer Betrieb")	Saxony	<0.10		
	910		Hauptverwaltung Gera		Thuringia	1.37		

[#] HVBG and BBG (2005)

[†] Lehmann (1998 pp. 29–32)

[*] Underground mining and open pit mining companies in the regions Ronneburg, Saalfeld and Schleusingen (Thuringia) were assigned to object 090 until 1969 (Lehmann et al. 1998 p. 108); the object numbers for these objects during this period are given in column "Alternative object no.[*]".

Table 2 depicts the operating times of the objects as stated in the literature. In the first years of SAG/SDAG Wismut, the work was accomplished in many objects, whereas from the end of the 1960ies, only a few objects were operating:

- Underground mining objects 009 Aue, 096 Steinkohlenlagerstätte Freital, BB Willi Agatz, 908 Königstein, 091 Bergbauabteilung Pöhla and Thuringian objects (Lichtenberg, Reust, Schmirchau, Paitzdorf, Beerwalde, Drosen)
- Open pit mining object 300 Lichtenberg
- Processing companies 101 Crossen (processing facility), 102 Seelingstädt (processing facility) and 050 Aue (colliery)
- Surface objects

Operating times of the shafts of an object may differ from the operating times of the complete object and are only partially documented. Shaft-specific occupational histories for the individuals in the Wismut cohort deliver hints on the operating times of object sections and are depicted in Figure 9.

The proportion of person work years (PPY) was defined as follows:

$$\text{PPY} = \frac{\text{Number of person work years in specific subgroup}}{\text{Total number of person work years in the Wismut cohort}}$$

This measure can be used to assess the frequency of occurrence and thus indirectly the relevance of objects for the Wismut cohort. The total number of person work years is 788 thousand years and relates to the person work years in all objects (except for object 000 000).

A few peculiarities have to be kept in mind originating from the history of the objects:

- BB Dittrichshütte and BB Hirschbach, which were separately evaluated for the JEM (Lehmann 2004 p. 74; Lehmann et al. 1998 p. 248), were both denoted as object 030.
- Object numbers 091 000 and 009 400 both belong to the "Bergbauabteilung Pöhla". Unless otherwise noted, object number 091 000 is used for both objects.
- Object 096 Steinkohlenlagerstätte Freital, BB Willi Agatz is named from 1968 as object 907 BB Willi Agatz (Wismut GmbH 1999, 2.2.10, p. 3).

3. Working conditions

Ore mining in the SAG Wismut started with inadequate technical equipment and insufficient ventilation. Especially the mine ventilation conditions affect the radon progeny concentration (Lehmann et al. 1998 p. 198). The development of the working conditions in the objects of the SAG/SDAG Wismut was closely related to the technological progress and is described in detail in this chapter. The description of the working conditions is focused on conditions which are associated with the concentration of radon progeny but not of other occupational exposure such as dust. If the given information does not explicitly refer to an object or region, the information applies for all objects of the considered type whether located in Saxony or in Thuringia.

Table 3 provides an overview of the working conditions in the SAG/SDAG Wismut. The categories and characteristics are described in detail in the following subsections separately for each work place: underground (Section 3.1), open pit (Section 3.2) and processing (Section 3.3).

Table 3: Working conditions in the SAG/SDAG Wismut for the different work places subdivided into periods. Main sources: Lehmann et al. (1994, 1998), Wismut GmbH (1999). Working conditions in surface objects are not considered.

Underground mining			
Saxony			
Period	1946-1955	1956-ca. 1970	ca. 1971-1990
Mining method*	Firstenstoßbau	Firstenstoßbau	Firstenstoßbau
Drilling method⁺	Dry	Wet	Wet
Degree of mechanization	Mainly manual	Partly mechanized	Partly mechanized
Ventilation	Natural	Medium	Good
Thuringia			
Period	1952-1955/56	1956/1957-1964/1965	1965/1966-1990
Mining method*	Scheibenbruchbau	Kammerbau	Teilsohlenbau mit Versatz
Drilling method⁺	Dry	Wet	Wet
Degree of mechanization	Mainly manual	Partly mechanized	Mechanized
Ventilation	Natural	Medium	Good
Open pit mining			
Period	1950-ca. 1955	ca. 1956-1964/1965	1965/1966-1990
Mining method*	Drilling, blasting	Drilling, blasting	Drilling, blasting
Drilling method⁺	Dry	Dry	Dry
Degree of mechanization	Mainly manual	Partly mechanized	Mainly mechanized
Ventilation	Natural	Natural	Natural
Processing companies			
Period	1946-ca. 1955	ca. 1956-ca. 1973	1974-1990
Ore unloading	Manual	Mechanized	Mechanized
Pre-milling	Non-autogenous	Non-autogenous	Partly autogenous
Drying	Non-automatically	Partly mechanized	Partly mechanized
Ventilation	Natural	Medium	Good
Cleaning	Mainly dry	Mainly wet	Mainly wet

* Prevailing mining method

⁺ Drilling for baring the ore body

3.1. Underground mining

3.1.1. Operation methods

Mining method

The applied mining methods depended on the regionally varying type of ore mineralization and on the technological progress. The prevailing mining methods were (Wismut GmbH 1999, 1.4.6.1, pp. 1-4, 1.4.6.2, pp. 1-2, 1.4.6.3, pp. 1, 1.4.6.4, pp. 1, 5):

Ore Mountains (without Freital/Vogtland):	“Firstenstoßbau mit Versatz”
Thuringia (Ronneburg):	“Kammerbau“, “Scheibenbruchbau“, “Teilsohlenbau mit Versatz“
Freital/BB Willi Agatz:	“Strebbau”, “Kammerbau”
BB Königstein:	“Kammerpfeilerbau mit Versatz”, chemical mining

The amount of uranium mining was highest in the vein deposits (“Ganglagerstätten”) of the Ore Mountains/Vogtland, followed by the objects in Thuringia. Therefore, the mining methods in these regions are described in detail regarding ore mining, hoisting and ore transportation. Detailed information can be found in Lehmann et al. (1998) and Wismut GmbH (1999).

Mining method in the vein deposits of the Ore Mountains and the Vogtland

Selective ore mining was possible with the mining method “Firstenstoßbau mit Versatz“. Ore mining partially begun by the use of hammer (“Hammer”) and pick (“Hacke”). Until 1965, ore was mined with chipping hammers (“Pickhämmer”), a dry mining method. The mining technology was changed in 1966 (Lehmann et al. 1998 p. 195) towards drilling and blasts.

At the beginning, the waste rock was hoisted with chutes (“Rollen”). From the mid-1950ies, pneumatically driven scrapers (“Schrapper”) were introduced in the objects 002 Oberschlema, 006 Vogtland-Zobes and 009 Aue; electronic scrapers were rarely used. More effective hoisting technologies could not be applied due to the spatial conditions accompanied by this mining method.

Initially, the ore was transported with backpacks and tin buckets (“Blechkübeln”). Until 1960, ore gradation into boxes and transportation of the boxes were manually accomplished. From the early 1950ies, ore loading was mechanized with the overhead shovel loaders (“Wurfschaufellader”) and mine locomotives. From 1960, ore was directly loaded into the mine cars supported by transport containers, box holes (“Erzlutten”), scrapers and overhead shovel loaders.

Mining method in Thuringia

In object 903 Schmirchau, the Thuringian mining operation with the highest amount of uranium mining, “Scheibenbruchbau“ was the predominant mining method until 1956; between 1957 and 1965/66, “Kammerbau” was mainly used, before “Teilsohlenbau mit Versatz” became the prevailing mining method, as also in the other Thuringian mining operations (901 Lichtenberg, 902 Reust, 904 Paitzdorf, 905 Beerwalde, 906 Drosen) in the end of the 1960ies.

Initially and in low depth, ore mining was manually carried out with mechanical picks ("Abbau-hämmer"). Drilling and rock pile ("Haufwerk") blasts were used for ore mining in deeper depth with the "Kammerbau" and in areas with "Teilsohlenbau mit Versatz".

After extracting the ore with wheelbarrows ("Schubkarren"), mining buggies ("Abbauhunten") and later scrapers ("Schrapper") combined with chutes ("Rollen") in the "Kammerbau" were used. Collecting scraper drifts ("Sammelschrapperstrecken") were applied for "Scheibenbruchbau" and "Kammerbau". Ore was loaded and transported with overhead shovel loaders and mine locomotives. From 1969, pneumatically driven boggers ("Bunkerlader") and later diesel-driven and electric tractor shovels ("Fahrlader") came into operation.

Drilling method

In the first years, drill holes were partially pushed with drill rods ("Bohrstange") and sledge hammers ("Vorschlaghammer"). Until the end of the 1950ies, dry air drilling was carried out with hand-held light drill hammers (BH 16 type Flottmann, Herkules), afterwards with drill hammers in combination with telescopic jacklegs ("Teleskopstützen"). Between 1950 and 1954, wet drilling was introduced, which was generally established from 1955 onwards. In contrast to the baring of the ore body, ore was dryly mined until 1965. Due to the spatial conditions in the areas with "Firstenstoßbau mit Versatz", drill hammers with jacklegs ("Bohrstützen") remained prevailing in objects with this mining method. In contrast, the drilling technologies were further improved in the Thuringian objects with "Teilsohlenbau mit Versatz" (as from 1965/1966) by drill columns ("Bohrsäulen") and one/two-boom drilling vehicles ("ein-/zweiarmige Bohrwägen") as well as by large-diameter boreholes ("Großbohrloch").

Degree of mechanization

The predominant mining method "Firstenstoßbau mit Versatz" could be poorly mechanized due to spatial constriction. In contrast, the introduction of "Teilsohlenbau mit Versatz" in the Thuringian objects in 1964 enabled a high degree of mechanization.

3.1.2. Ventilation

The major task of mine ventilation was to ensure radiation protection for the miners. In 1949, the mine air service of the SAG Wismut was established. The following limit values for the minimum air quantity were claimed to be met during the operation time of SAG/SDAG Wismut (Wismut GmbH 1999, 1.4.8.1):

Statutory provision regarding the minimum air quantity:

- 30.12.1952: 2 m^3/min per person
- 25.01.1963: 3 m^3/min per person

Minimum air quantity determined by the SAG/SDAG Wismut:

- 1949: 3 m^3/min per person, 1.5 m^3/min during digging works ("Schürfarbeiten")
- 1965: 90 m^3/min per work place

Through mine ventilation measures, which are described in the subsequent paragraphs, the air quantity could be increased from 4.1 m^3/min per person in 1957 to 74.2 m^3/min per person in 1988 in object 009 Aue.

Until 1955, natural mine ventilation was prevailing using the difference in altitude of different surface exits; consecutive ventilation (“Hintereinanderbewetterung”) of the work places could not be prevented. Compressed air was used for air-cleaning after blasts. Already existing ventilators and air tubes (“Lutten”) from former mine operators were adopted; auxiliary ventilation systems were limited to horizontal drivages (“horizontale Auffahrungen”) and drift ventilators (“Streckenlüfter”) with low performance. A systematic and sufficient supply with fresh mine air could not be ensured in this period. (Lehmann et al. 1998; Wismut GmbH 1999, 1.4.8.1).

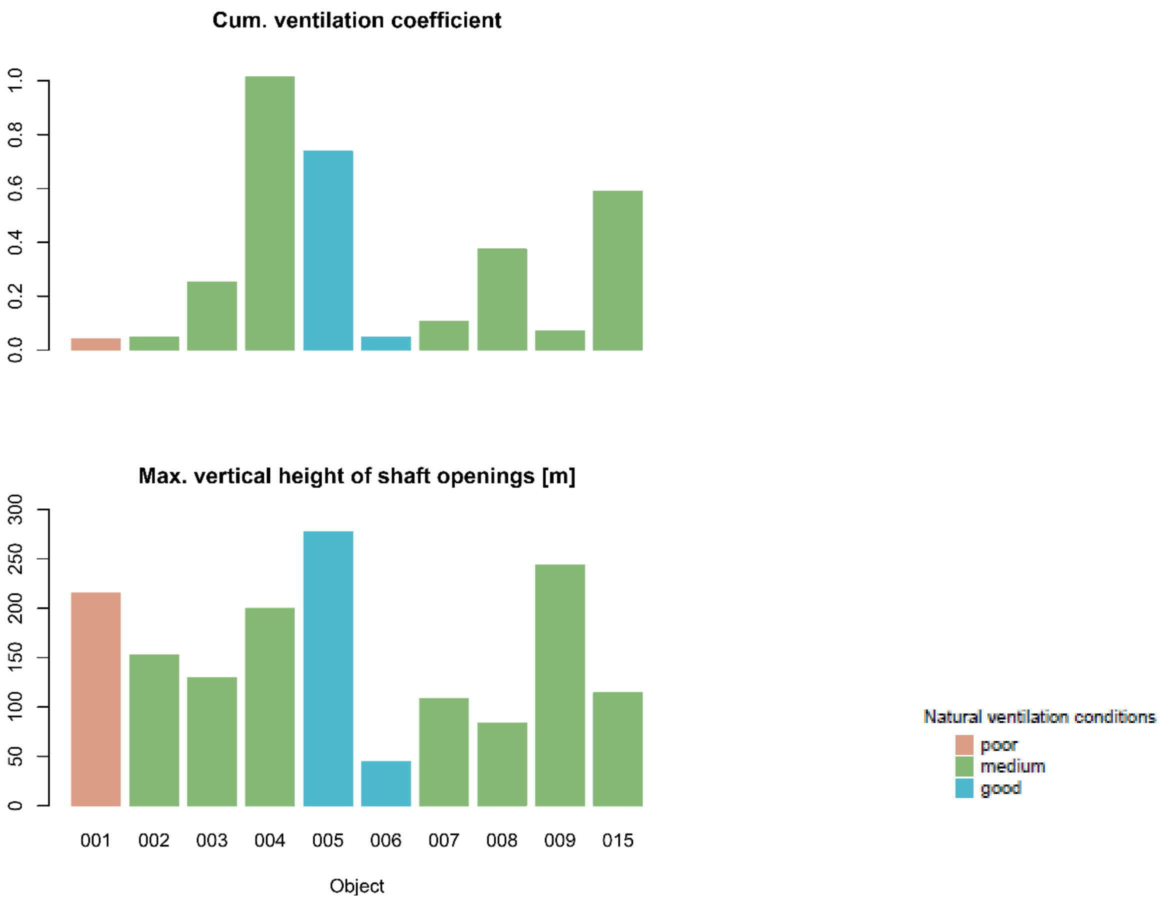

Figure 3: Cumulative ventilation coefficient and max. vertical height of the shaft openings in mining objects in the respective reference year according to Lehmann et al. (1998 pp. 70–71). The colors correspond to classification of the natural ventilation conditions according to Lehmann et al. (1998 p. 75).

The ventilation conditions in reference years (years which are used as reference for the characterization of the object for exposure assessment) were described in detail by Lehmann et al. (1998 pp. 62–65) and are depicted in Figure 3; this information was incorporated into exposure assessment for the period before 1955. A cumulative ventilation coefficient was deduced as the ratio between the profile area of the surface exits and the cumulative mined vein area in the reference year. Additionally, the maximum vertical height of the shaft openings of an object characterizes the efficiency of natural ventilation. The reference years were:

Table 4: Reference years for the evaluation of the ventilation conditions included in the experts' estimation of the radon progeny concentration according to Lehmann et al. (1998 pp. 61–65, 69–75), see also Section 4.3.3.

Object	Object name	Reference year	Object	Object name	Reference year
001	Johanngeorgenstadt	1953	006	Vogtland-Zobes	1955
002	Oberschlema	1955	007	Niederschlag-Bärenstein	1953
003	Schneeberg	1949	008	Breitenbrunn	1952
004	Annaberg-Buchholz	1951	009	Aue	1955
005	Marienberg	1951	015	Freiberg, Niederpöbel	1954

From 1955, the year of the mine fire in object section 009 208/250 of object 009 Aue (Wismut GmbH 1999, 1.4.8.1, p. 1, 1.9, pp. 10-11), ventilation conditions improved and can be rated as medium (Table 3). Artificial ventilation through main mine fans ("Hauptgrubenlüfter") was introduced to improve the mine ventilation as the most effective method for the reduction of radon gas and radon progeny concentrations, as described in Table 5.

Table 5: Number of main mine fans ("Hauptgrubenlüfter") and ventilators, the years of implementation and the type of ventilation in Saxonian and Thuringian objects (Lehmann et al. 1998 pp. 82, 85; Wismut GmbH 1999, 1.4.8.1, pp. 8-10, 15, 20, 1.8.2, p. 25, 2.2.1, p. 23, 2.2.5, p. 16, 2.2.6.1, p. 54-55, 2.2.8.3, p. 9, 2.2.8.4, p. 5, 2.2.8.10, p. 10, 2.2.9.4, pp. 7, 10). Exhaust ventilation: "saugende Bewetterung", blowing ventilation: "Überdruckbewetterung".

Object	Object name	no. of main mine fans/ventilators	years of implementation	type of ventilation
Saxony				
001	Johanngeorgenstadt	2	1949 (2)	not documented
005	Marienberg	3	not documented	not documented
006	Vogtland-Zobes	3	not documented	exhaust ventilation, from 1960 exhaust/blowing ventilation
008 248	Breitenbrunn	1	not documented	not documented
008 206/332	Breitenbrunn	3	not documented	exhaust ventilation
009	Aue	9	1958, 1959, 1960, 1961, 1964 (2), 1965 (2), 1987	exhaust ventilation, from 1974/75 exhaust/blowing ventilation
096 209/196	Steinkohlenlagerstätte Freital, BB Willi Agatz	3	not documented	exhaust ventilation
908	BB Königstein	> 0	not documented	blowing ventilation
Thuringia				
902	BB Reust	4	1961, 1964, 1967/1987, 1970	exhaust ventilation, partially blowing ventilation
903	BB Schmirchau	8	1956, 1960, 1964, 1966 (2), 1973, 1975, 1985	exhaust ventilation, partially blowing ventilation
904	BB Paitzdorf	6	1967, 1970, 1972, 1976, 1978, 1981	exhaust ventilation
905	BB Beerwalde	5	1975, 1979, 1983 (2), 1989	exhaust ventilation, later blowing ventilation
906	BB Drosen	1	1985	exhaust ventilation

Ventilation measures in other objects were either not documented or the object was already closed in the 1950ies. Already beginning with the first mining works in 1966, artificial ventilation control was accomplished in object 908 BB Königstein (Lehmann et al. 1998 p. 85).

Artificial ventilation was gradually improved through the installation of further main mine fans (“Hauptgrubenlüfter”) and ventilators. The efficiency of artificial ventilation does not only depend on the number of the installed facilities but also on the size of the object (see Chapter 2) and the effective operation of the facilities.

Between 1956 and 1964, pit shafts (“Schürfschächte”) were aerated by exhaust ventilation using radial ventilators; exhaust ventilation with surface main mine fans was the general aeration technique in this period. Furthermore, auxiliary ventilation systems were installed (cardboard air tube fans – “Papplutte”, pneumatic fans – “Druckluftlüfter”, electric fans – “Elektrolüfter”). Between 1965 and 1970, tube fans and iron sheet tube fans were applied for auxiliary ventilation (“Sonderbewetterung”). Weather cooling became necessary with deeper depths in objects 006 Vogtland-Zobes and 009 Aue; after the initial use of portable cooling aggregates in objects 006 Vogtland-Zobes (from 1961) and 009 Aue (from 1964), a cooling system (cooling of the main mine air, cooling of the air at the single work places, stationary cooling) was built in object 009 Aue. Effective methods of hermetic sealing (“Hermetisierung”) were applied in object 009 Aue from the mid-1960ies. (Lehmann et al. 1998; Wismut GmbH 1999, 1.4.8.1 and 2.2.6.1).

In 1974, exhaust ventilation was changed to exhaust/blowing ventilation in object 009 Aue using shafts 038, 066, 207, 366, 371, 382 and 383 as fresh air shafts and shafts 208 (including the shaft denoted by “208 W” in Wismut GmbH 1999, 1.4.8.1), 372 and 373 as exhaust air shafts.

Beside these measures, a set of further mine aeration measures (Table 6) were gradually applied to improve the ventilation conditions, among others to compensate the use of diesel-powered machines. Therefore, the overall ventilation conditions changed from “medium” to “good” (Table 3).

Table 6: Further mine aeration measures, besides main mine fans and ventilators, to improve the ventilation conditions.

Aeration measure (English)	Aeration measure (German)	Details, source
Exhaust air shafts	Abwetterschächte	
Large-diameter boreholes	Großbohrlöcher	
Ventilation raise drifts	Wetterüberhaue	
Air tubes	Lutten	
(Variable-speed) air tube fans	(Drehzahlveränderliche) Luttenlüfter	
Mine air control systems (steering, routing)	Grubenwetter-Kontrollsystem (Lenkung, Leitung)	
Mine doors	Wettertüren	Object 009 Aue, Lehmann (1998), p. 80
Ventilation dams	Wetterdämme	Object 009 Aue, Lehmann (1998), p. 80
Shut-off zones after blasts	Absperrbereiche nach Sprengungen	Thuringia, Wismut GmbH (1999), 1.4.8.1, p. 25
Ventilation stations	Lüfterstationen	Thuringia, Wismut GmbH, (1999), 1.4.8.1, p. 11

Aeration measure (English)	Aeration measure (German)	Details, source
(Temporary) hermetic sealing	(Temporäre) Hermetisierung	Lehmann (1998), p. 40, Object 009 Aue, Lehmann (1998), p. 82, Thuringia, Wismut GmbH (1999), 1.4.8.1, p. 22
Drainage ventilation	Drainagebewetterung	Thuringia, Wismut GmbH (1999), 1.4.8.1, p. 22
Insufflation of hot air	Einblasen von Heißluft	Thuringia, Wismut GmbH (1999), 1.4.8.1, p. 22
System of intake and return air levels	Frisch- und Abwettersohlensystem	Thuringia, Wismut GmbH (1999), 1.4.8.1, p. 23
Blowing ventilation	Überdruckbewetterung	From the mid-1970ies, objects 902 BB Reust, 903 BB Schmirchau, Wismut GmbH (1999), 1.4.8.1, p. 26
Weather flaps	Wetterjalousien	From the mid-1970ies, objects 902 BB Reust, 903 BB Schmirchau, Wismut GmbH (1999), 1.4.8.1, p. 26
Radon progeny filters (sporadically)	Radonfolgeproduktfilter (sporadisch)	From the end of the 1970, Wismut GmbH (1999), 1.4.8.1, p. 8
Separation of weather systems	Trennung des Wettersystems	Object 009, Wismut GmbH (1999), 1.4.8.1, p. 34
Separation of weather of development and mining work places	Wettertechnische Trennung der Abbau- und Aus- und Vorrichtungsbetriebspunkte	Lehmann (1998), p. 129

Dehumidification measures were not installed (Wismut GmbH 1999, 1.4.8.1).

In the starting years, mine fires occurred in the Thuringian objects due to the mineral composition of the rock. Mine firefighting and prevention was essential for the improvement of the mine ventilation. Therefore, warning systems, systematical supervision of fire gases (automatically in object 904 BB Paitzdorf) and sealing of fire areas were applied as protection measures (Lehmann et al. 1998; Wismut GmbH 1999, 1.4.8.1).

3.2. Open pit mining

3.2.1. Operation methods

Mining method

Drilling and blasting were used for ore mining in open pit mining. Initially, blast works were conducted during the shifts, later only on Saturdays. The blasted rock pile ("Haufwerk") was loosened with clay picks ("Kreuzhacken"). In the first years, the rock pile was loaded in tipping trucks ("Kipploren") or small mine cars with shovels. Beginning in 1953, Soviet diesel-driven or electric excavators ("Bagger") were used. Initially, the transport of rock pile was conducted with small mine cars and loading ramps. Later dumpers ("Kipper") and, from 1965, a belt conveyor ("Bandanlage") in the open pit mining object 300 Lichtenberg were used. (Lehmann et al. 1998 p. 35)

Drilling method

After drilling equipment from underground mining was used, rotating and rotary percussive ("drehschlagende") dry air drilling instruments were applied from the mid-1950ies, partially with suction cleaning ("Absaugung") (Lehmann et al. 1998 pp. 35, 155–156).

Degree of mechanization

Many manual tasks had to be accomplished in the first years. From the mid-1950ies, machines for drilling, mining, loading and transport were introduced resulting in less manual work.

3.2.2. Ventilation

Air velocity decreases with increasing depth, which was particularly relevant for the open pit mining object 300 Lichtenberg; all other open pit mining objects reached only a low depth. In general, ventilation measures were not in operation in open pit mining objects. (Lehmann et al. 1998 pp. 150–153; Wismut GmbH 1999, 1.4.8.1)

The great depth and the kettle-shaped ground opening hindered natural ventilation in object 300 Lichtenberg. Catalytic converters were installed in dumpers and the air condition monitoring was improved in 1965/66 (Wismut GmbH 1999, 1.4.8.1). A portable ventilator was tentatively applied in 1972.

The mineral composition of the rock in object 300 Lichtenberg involved endogenous fires at the slopes ("Böschung") of the open pit mine resulting in increasing radon gas concentrations; moreover, old seats of fire in the underground mines were reactivated through the work in the corresponding underground mines (Lehmann et al. 1998 pp. 147–148). Fires did not occur in any other open pit mining object (Lehmann et al. 1998 p. 152).

From 1975, blowing ventilation ("Überdruckbewetterung") was applied in the object 903 BB Schmirchau, adjacent to the open pit mining object 300 Lichtenberg, to prevent the entering of fire gases through the open connection between the objects (Wismut GmbH 1999, 1.4.8.1, p. 26). Thus, exhaust air from underground mining infiltrated the open pit mining object resulting in an increased radon gas concentration of about 10 % (Lehmann et al. 1998 p. 150).

3.3. Processing companies

The Wismut Company, in its operation period from 1946 to 1990, produced a total of 230 400 t uranium, which was delivered in different products to the former Soviet Union. Ores with high uranium content were directly shipped to the Soviet Union, whereas all other ores were sent to nearby milling facilities of the Wismut company. In general, ore processing was mechanically performed in the processing companies of SAG/SDAG Wismut with temporally decreasing manual working steps. After crushing and grinding, uranium was further processed either physically (via radiometric or gravimetric sorting) or chemically (via alkaline or acid leaching resulting in so-called Yellow-cake) (Lehmann et al. 1998). Uranium milling was performed in nine processing facilities, among them the two major facilities "Crossen" (1950–1989) and "Seelingstädt" (1960–1990) and a few smaller ones had been in operation at some time between 1946 and 1962. In addition, there were facilities, where primary radiometric or gravimetric sorting of the ore was performed (RAS-/RAF-facilities), and sampling collieries, where the amount, humidity and uranium content of the delivered product were determined (Lehmann et al. 1998). Working conditions in the mills had been very poor in the early years, due to old technologies, lack of wet cleaning, no fresh air supply and "dry" processing of the ore with high dust, radiation and aerosol exposures. Moreover, frequently occurring technological disturbances of the processing facilities caused large-scale contaminations (Lehmann 2004 pp. 9, 62). Disturbances occurred less often, conditions improved and uranium recovery increased by the end of the 1950ies through implementation of new technologies, improved ventilation and dust reducing measures (Lehmann 2004 pp. 6, 10; Lehmann et al. 1998).

The working conditions in the processing companies depended on (1) the processing method which was applied, especially in processing stages with high exposure to radiation and close uranium contact (unloading, milling, drying), (2) the ventilation conditions and (3) the cleaning method (Lehmann 2004 p. 9).

3.3.1. Operation methods

According to the descriptions in Lehmann et al. (1994), unloading, milling and drying were processing stages with high exposure to radiation due to manual tasks ; the working conditions in these processing stages improved with the technological progress. The different types of processing companies accomplish different tasks in ore processing, as described in Section 2.1.

Ore unloading

Ore was delivered in open wagons and dumpers ("Kipper") to the processing facilities and the sampling collieries. In the early years, the wagons were manually unloaded with pick and shovel. In the early 1950ies, facilities for mechanical ore unloading were installed, but still a large amount of manual work was necessary. From 1980, ore unloading in the chemical colliery of object 101 Crossen was carried out with wagons of type OOT. In object 102 Seelingstädt, ore was delivered in closed wagons and unloaded through opening of the wagons over unloading hoppers ("Entladebunker"). Note that from 1981 only the processing facilities 101 Crossen and 102 Seelingstädt were operating. (Lehmann et al. 1994)

Pre-milling

The first processing stages of ore processing performed the milling of the ore in several stages in the processing facilities and the RAS-/RAF-facilities. The first milling stages for coarse milling of the ore were dry processing stages with high dust exposure (Lehmann et al. 1998 pp. 169, 177, 182); the introduction of autogenous milling, i.e. self-gringing without the addition of grinding elements (1971 in object 101 Crossen, 1974 in object 102 Seelingstädt), improved the situation (Lehmann et al. 1994 pp. 6, 9, 16, 23, 1998 p. 168).

Drying

Heated plates, heated drying cupboards and ovens were used under high radiation exposure for ore drying in collieries with a high amount of manual work. Dust and aerosol exposure was improved through the introduction of mechanical and process-controlled drying, more precisely through the initiation of rotary furnaces ("Drehrohröfen") in 1964 in object 101 Crossen and through the use of a tower-shaped spray dryer ("turmförmiger Sprühtrockner") from 1960 to 1983 and the initiation of rotation thin-film evaporators ("Rotationsdünnschichtverdampfer") in 1984 in object 102 Seelingstädt (Lehmann et al. 1994). With improving technology, less manual work was necessary for the preparation of the ore for drying and for the operation of the drying machines.

3.3.2. Work hygiene

Since work hygiene was relevant for the occupational exposure to radiation in all three types of processing companies, work hygiene in processing facilities, RAS-/RAF-facilities and collieries is jointly considered in this section addressing the aspects "ventilation", "cleaning" and "radon progeny and radioactive aerosols".

Ventilation

High radon gas/radon progeny concentrations were measured in working rooms with bad ventilation conditions (especially ore bunkers, milling and classification facilities, pump rooms). The improvements of ventilation are depicted in (Lehmann et al. 1994).

In the first years, only natural ventilation via building apertures (windows, doors, gates, apertures in the roof) was possible; the use and the effect depended on the season and the window area of the room, which was closely related to the location of the room in the building (basement/ first floor/ upper floor). Not before the end of the 1950ies measures for the hermetic sealing and suction cleaning ("Absaugung") of dust sources were initiated. During the 1960ies, ventilation systems and dedusting facilities ("Entstaubungsanlagen") were installed in the majority of the processing companies. (Lehmann et al. 1994)

For some objects, the start of the initiation of the ventilation system was not reported (processing facilities 093 Freital, 099 Oberschlema, 100 Aue, RAS 205 BB Schmirchau shaft 367/368, colliery 050 Aue). In processing facility 099 Oberschlema the ventilators/dedusting facilities and in processing facility 101 Crossen the ventilation system was indifferent or inefficient. In other objects, the ventilators/dedusting facilities (processing facilities 095 Gittersee, 099 Oberschlema) or the ventilation system (processing facilities 031 Lengenfeld, 093 Freital, 100 Aue, colliery 052 Oberschlema) was not installed in all buildings. Later, ventilation systems were installed and gradually improved in the objects with available information on ventilation conditions.

Cleaning

Since the processing companies were partially situated in already existing, dissimilar buildings or in timber constructions, many rooms were inadequate in terms of radiation protection and industrial health, in particular they were not designed for wet cleaning. Therefore, dust extensively accumulated in the buildings of the processing companies. The situation gradually improved through the assignment of special cleaning stuff and renovation and reconstruction of buildings and work places enabling wet cleaning. The development of the cleaning of the work places in the processing companies of SAG/SDAG Wismut is summarized in Figure 4. (Lehmann et al. 1994 pp. 9–10)

In the processing facilities 032 Tannenbergsthal and 101 Crossen and the collieries 050 Aue, 054 Annaberg and 058 Breitenbrunn, only dry cleaning was possible or the buildings of the facilities were in parts timber constructions, where effective wet cleaning was not practicable. Timber constructions were partially renovated in processing facility 101 Crossen and colliery 050 Aue. In processing facility 093 Freital and colliery 050 Aue (start unknown), wet cleaning was possible in some but not all buildings, whereas wet cleaning was established in the processing facilities 031 Lengenfeld, 095 Gittersee, 098 Johanngeorgenstadt, 099 Oberschlema, 100 Aue and 102 Seelingstädt and the RAS-/RAF-facilities 200 RAF Aue shaft 371, 203 RAF Pöhla and 206 RAF Willi Agatz.

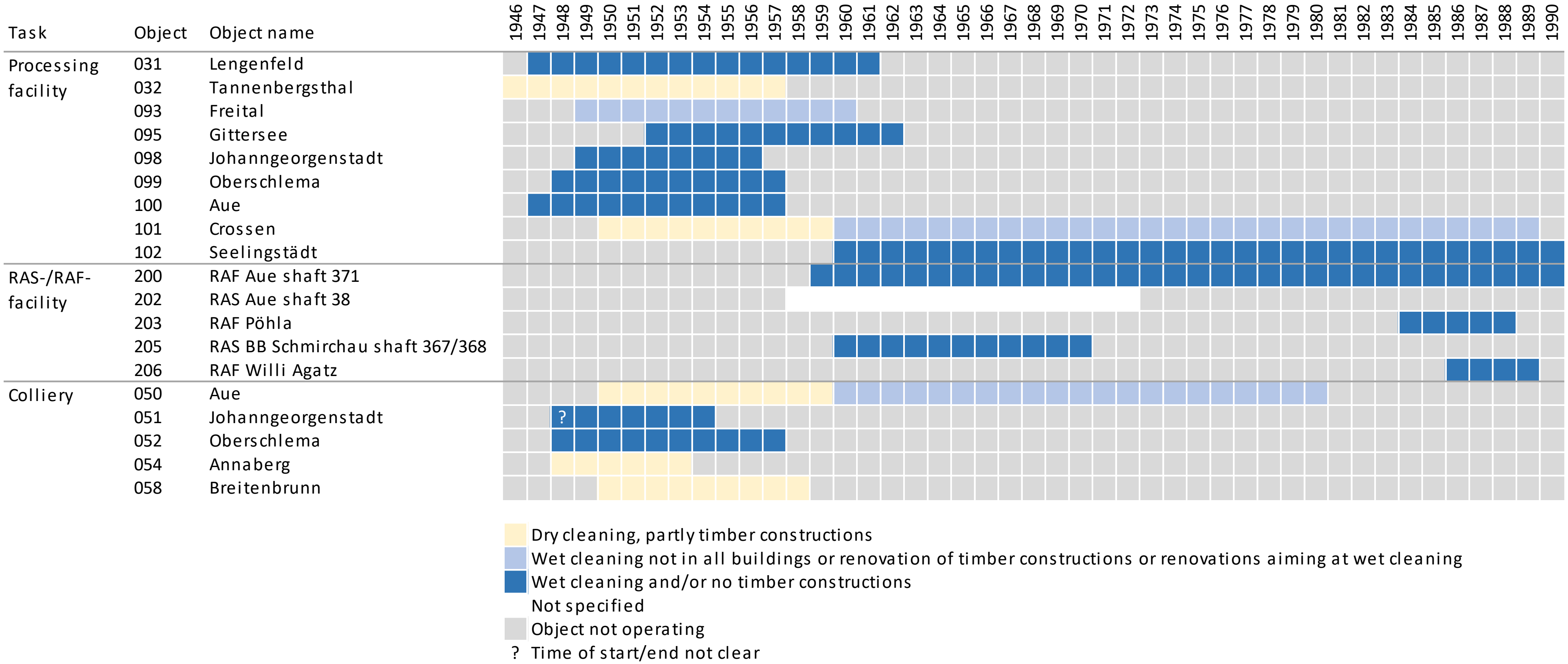

Figure 4: Cleaning methods in processing companies of the SAG/SDAG Wismut over time. Source: Lehmann et al. (1994).

Exposure to radon progeny and radioactive aerosols

Activities and buildings with high exposure to radon progeny and radioactive aerosols (Lehmann et al. 1994) are listed in the following and had been considered in exposure assessment (JEM).

Activities

- Auskleiden von Aufbereitungsausrüstungen mit Verschleißteilen
- Entladen und Bandtransport von Erz im Bandkeller (Aufbereitungsbetrieb 101 Crossen)
- Erzentladung (Zeche 058 Breitenbrunn, „Mühlengebäude“ in Aufbereitungsbetrieb 100 Aue)
- Erztransport in den unterflurigen Bandanalgen bis zur Zerkleinerung (bis 1957 in Aufbereitungsbetrieb 031 Lengenfeld)
- Setz- und Herdarbeiten (Aufbereitungsbetrieb 101 Crossen)
- Chemische Aufbereitung (Agitation, Laugung, Filtration) (Aufbereitungsbetriebe 093 Freital, 095 Gittersee, 099 Oberschlema, 100 Aue, 101 Crossen)
- Filtrationsprozess (mit „Filterpressen“ in Aufbereitungsbetrieb 101 Crossen, bis 1957 in Aufbereitungsbetrieb 031 Lengenfeld)
- Manuelle Entleerung der Filtratbehälter (Aufbereitungsbetrieb 093 Freital)
- Beseitigung von Havarien und Störungen (Aufbereitungsbetriebe 098 Johanngeorgenstadt, 101 Crossen)
- Bandbedienung und Wartung von Pumpen in Kellerräumen (Aufbereitungsbetrieb 101 Crossen)
- Fäll- und Regenerationsprozess (Aufbereitungsbetrieb 101 Crossen)
- Bandkeller des Erzreservelagers (Aufbereitungsbetrieb 102 Seelingstädt)
- Bereich der Kaskadenmühle bis zum Zeitpunkt der Kapselung der Siebe (Aufbereitungsbetrieb 102 Seelingstädt)
- Zerkleinerung (Backen- und Symonsbrecher) und trockener Klassierung (Aufbereitungsbetriebe 095 Gittersee, 100 Aue)
- Brecher- und Siebanlagen (Zeche 050 Aue)
- Mahlung und nassmechanische Aufbereitung (Aufbereitungsbetrieb 098 Johanngeorgenstadt)
- Parabelbunker bis 1974 (Aufbereitungsbetrieb 102 Seelingstädt)
- Bunkeranlagen (Zeche 050 Aue)
- Kugelmühlenzeche bis 1975 (Aufbereitungsbetrieb 102 Seelingstädt)
- Mischzeche bis 1963 (Aufbereitungsbetrieb 102 Seelingstädt)
- An den Holzsieben auf der + 27 m – Sohle in der Zeche 5 (Aufbereitungsbetrieb 102 Seelingstädt)
- Kellerräume (Aufbereitungsbetriebe 032 Tannenbergsthal („Gravitationszeche“), 099 Oberschlema), Pumpensümpfe (Aufbereitungsbetrieb 099 Oberschlema) und Aufmahlung (Aufbereitungsbetrieb 032 Tannenbergsthal)
- Konzentrattrocknung, Beprobung, Verpackung (Aufbereitungsbetrieb 098 Johanngeorgenstadt)
- Waschanlage (RAF-Anlage 200 Aue Schacht 371)
- Sortiergebäude unmittelbar im Sortierraum (RAS-/RAF-Anlagen 200 RAF Aue Schacht 371, 203 RAF Pöhla)
- Anlagen im Hochhaus (Zeche 050 Aue)
- Erzabfüllung (Zeche 050 Aue)

Exposure to radon progeny was high in processing facility 102 Seelingstädt due to bad working hygienic conditions in the initial phase of the processing facility (Lehmann et al. 1994 p. 97). An explicit statement regarding the relation between working conditions and exposure to radiation for other processing companies was not reported in Lehmann et al. (1994). In colliery 052 Oberschlema and processing facility 098 Johanngeorgenstadt, exposure to radon progeny was high due to the contact of the buildings to underground mine openings and larger geological fault systems ("geologische Störungs-systeme") (Lehmann et al. 1998 p. 164).

The working conditions in the collieries developed almost parallel to the conditions in the processing and RAS-/RAF-facilities. The exposure to dust and radiation was partly remarkably higher due to processing of products with higher uranium contents, exclusively dry processing and pulverulent milling. (Lehmann et al. 1994 p. 10)

4. Exposure assessment

After some information on the radiation measurements of SAG/SDAG Wismut and a schematic overview of exposure assessment in Sections 4.1 and 4.2, the exposure estimation approaches developed in Lehmann et al. (1998) will be described in Sections 4.3-4.5. Retrospective modifications of the resulting exposures developed in Lehmann (2004) are explained in Section 4.6. In Section 4.7, the estimation approaches for individual exposure to radon progeny are presented. The software implementation of exposure assessment for the Wismut cohort is overviewed in Appendix A (Section A 3).

Since exposure estimation methods for Saxonian and Thuringian objects were largely equal, the presented methods generally apply for both federal states and only the differences are described.

4.1. Radiation measurements

History

For purposes of radiation protection of uranium miners, activity measurements of both radon gas and radon progeny have been performed. Quantitative radiation protection in the SAG/SDAG Wismut started in 1954 with measurements of radon gas concentration. Radon gas concentration measurements at the work places were conducted from the end of 1954 by the central dosimetric service and from 1957 by operational dosimetric services using presumably the same measuring procedure in Saxony and in Thuringia. The measurements aimed at systematic and regular monitoring of the work places. See Figure 5 and the corresponding explanations for further details. (Lehmann et al. 1994 pp. 4, 10, 1998 p. 164; Wismut GmbH 1999, 1.4.8.1, 1.8.2)

Documentations of radiation measurements were found for the following objects according to Lehmann et al. (1994) and Lehmann et al. (1998):

Saxonian objects:	001, 002, 006, 009, 031, 032, 050, 052, 054, 058, 093, 095, 096/907,098, 099, 100, 101, 908
Thuringian objects:	102, 300, 901, 902, 903, 904, 905, 906

Radiation measurements were not documented in the available literature for the following objects:

Saxonian mining objects:	003, 004, 005, 007, 008, 010, 015, 091
Thuringian mining object:	030
Exploration/development objects:	021, 022, 023, 024, 025, 026, 027, 028, 029, 047, 010, 011, 012, 013 014, 086
Open pit mining objects:	All but object 300 Lichtenberg
Processing companies:	Some

In the first years of the SAG/SDAG Wismut, the radiation concentrations were irregularly measured, e.g., between 1955-1957, measurements were conducted once a year at about 50 % of the work places. Later, the measurements were regularly carried out once a month. If an exceedance of 66 % of the annual limit value was expected, it was measured twice a month in the last years (Dokument der

BBG Gera 1991). The maximum permitted concentration of radon progeny in the SAG/SDAG Wismut were (Wismut GmbH 1999, 1.8.2, p. 4):

Underground:

- 1955-1960: 37 kBq/m³
- 1961-1966: 3.7 kBq/m³

Surface:

- 1955-1964: 3.7 kBq/m³

In the first two to three years of measurements, the radon gas concentration in the air was measured at selected sites. Afterwards, the measurements (for radon gas and from 1965 for radon progeny (Wismut GmbH 1999, 1.4.8.1, p. 6)) were conducted at all underground work places in Saxony and Thuringia.

The radon gas concentration measurements were carried out with the following devices (Lehmann et al. 1994 p. 10; Wismut GmbH 1999, 1.8.2, pp. 8-12):

- 1955 – ca. 1972: Ionization chamber electrometers ("Ionisationskammer-Elektrometer") SG-1 M and SG-11 (Soviet production)
- 1972 – ca. 1980: Alphadoppelzähler (produced by SDAG Wismut, scintillation chambers)

In order to get the exposure to radon progeny, radon gas exposure needs to be converted by taking into account assumptions on equilibrium factors. If radioactive decay is the unique source of radon progeny, after a short time an equilibrium of decay appears. For radon gas, it is defined by a potential alpha energy concentration of 5.5 nJ per Bq/m^3. A so-called equilibrium factor of 1 is assumed. By ventilation or filtering of air this equilibrium is often disturbed in underground mines so that an equilibrium factor < 1 must be estimated which is an additional source of exposure uncertainty. (Tirmarche et al. 2010)

Since 1964 direct measurements of the radon progeny concentration have been performed using various measurement gear of Soviet and German production. From 1971, radon progeny concentrations were determined using the alpha energy concentration of short-lived Radon-222 progeny in the air (Eigenwillig and Ettenhuber 2000 p. 11). The measurements were documented in measurement reports and were carried out regularly every month with mine radiometers developed and produced in the Soviet Union or by SDAG Wismut and VEB Meßelektronik Dresden (Lehmann et al. 1994 p. 10; Sardisong and Ullmann n.d. pp. 30–31):

- 1964 – ca. 1972: Ranag (Soviet production)
- 1972 – ca. 1982: Alphadoppelzähler (produced by SDAG Wismut)
- From ca. 1982: Alphazähler (produced by SDAG Wismut)

The potential alpha energy concentration was measured according to the method of Markov by an air sample of five minutes.

Between 1972 and 1984, both types of measurements, radon gas and radon progeny concentration measurements exist (Sardisong and Ullmann n.d. p. 31). Measurements in objects 001 and 002 and for 1957 in a subdivision of object 006 (diggings "Gottesberg") were appraised as implausible and were not used for exposure estimation (Lehmann et al. 1998 pp. 54–55, 72, 83).

From 1970/1971, estimation of individual radiation exposure based on the alpha energy concentration of short-lived radon progeny at work places ("Ortsdosimetrie") has been performed including the consideration of residence times at the work place (Wismut GmbH 1999, 1.4.8.1, p. 8, 1.8.2, p. 10 "Individuelle Belastungskartei"). Personal dosimeters have not been in use in the Wismut company until 1991. Comparison of individual measurements of selected persons with results from "Ortsdosimetrie" revealed remarkable agreement for occupational groups with little variation in the working environment (Eigenwillig and Ettenhuber 2000 p. 13).

Figure 5 depicts the number of radon gas/radon progeny concentration measurements for each calendar year and object as given in Lehmann et al. (1998). Numbers for the regular measurements in the processing companies were not found in the available literature and are therefore not shown. To obtain annual exposure values in the JEM, arithmetic means of radon concentration measurements, $\bar{\bar{\bar{C}}}_{Rn}$, and of radon progeny measurements, $\bar{\bar{\bar{C}}}_{RDP}$, were calculated and converted to Working Level Months (WLM). Afterwards, these values were evaluated and, if reasonable, slightly adapted by experts (e.g. Lehmann et al. 1998, p. 133).

Exposure to radon and its progeny was generally expressed in Working Level Months (WLM) which is a cumulative historical unit related to uranium mining and nowadays only rarely used. A working level (WL) is defined as 1.3×10^5 MeV of alpha energy/l air which will be emitted by short-lived radon progeny. One working level month equals exposure to 1 WL for 170 hours.

Operational disruption of ventilation

Breakdown of the ventilation system was a frequently reported failure in underground mines (Richter 1994). On these occasions warnings had to be issued and closures of shafts had to be ordered. The warning level for the radon progeny concentration was 80 MeV/cm^3 and the closure level was 160 MeV/cm^3. In general, disruption of ventilation led to higher radon exposures but was not always correctly accounted for in the reported exposure values. Examples for the inclusion of higher exposure levels during ventilation disruption led to elevated exposure values by factors of 1.3 to 1.7 (Richter 1994).

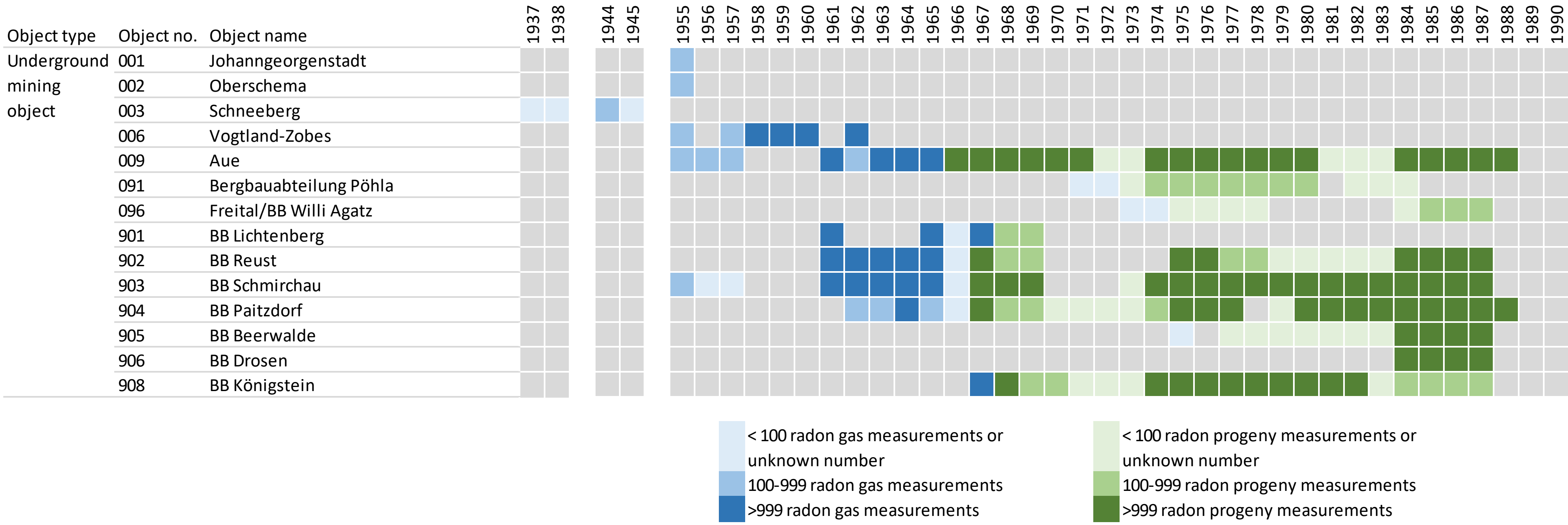

Figure 5: Number of radon gas/radon progeny concentration measurements in underground mining objects over time according to Lehmann et al. (1998). Numbers for measurements in processing companies are not shown. If radon gas and radon progeny measurements are available, only the number of radon progeny measurements is depicted. A more detailed figure can be found in Appendix B (Figure B2).

4.2. Overview

The procedure to assess radon exposure for the workers in underground mining objects of SAG/SDAG Wismut is schematically presented in Appendix B (Figure B3); a less detailed diagram is depicted in Figure 6.

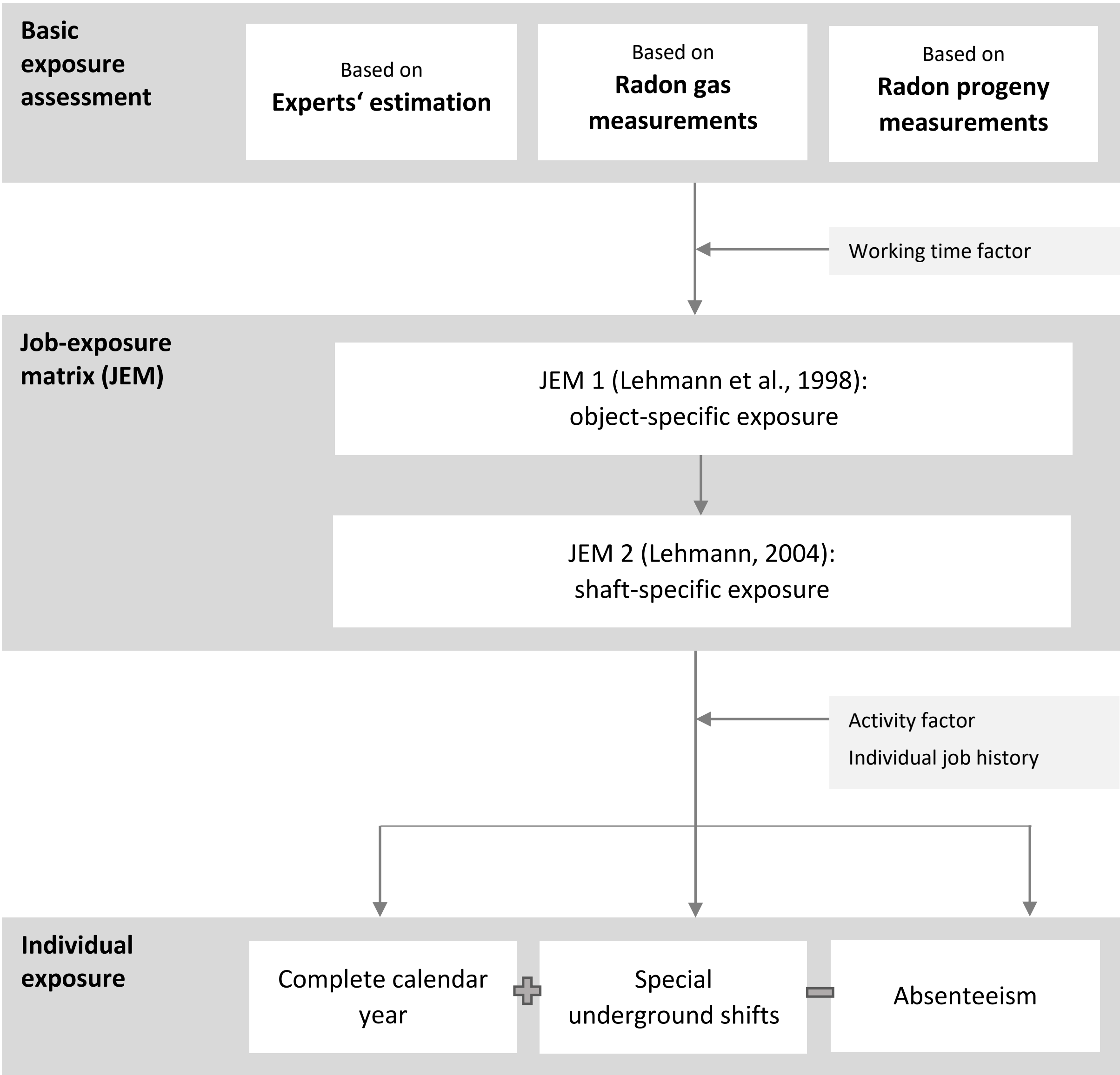

Figure 6: Schematic overview (less detailed than in Appendix B, Figure B3) of the exposure assessment procedure for work places in underground mining in the Wismut cohort.

The figure gives an overview of the basic principle and the parameters which will be explained in detail in Sections 4.3-4.7. The overview is restricted to workers in underground mining objects because they represent the majority of the workers in SAG/SDAG Wismut. The differences of the exposure assessment for workers in open pit mining objects and processing companies will be explained in Sections 4.4 and 4.5.

To describe the general procedure of exposure assessment, the scheme is structured in three main parts:

(I) Exposure assessment for workers in a reference activity with 2000 working hours per year

Being a hewer was considered as the reference activity in underground mining. The way to determine the annual exposure to radon progeny for a hewer with 2000 working hours per year depended on the availability of radon measurements.

Firstly, if neither radon gas nor radon progeny measurements were available (mainly in the early years), exposure assessment was based on experts' estimation. In this case, annual exposure to radon progeny was determined based on radon gas measurements in (later) reference years and reference objects taking into account other parameters (separately for objects in Saxony and Thuringia).

Secondly, if radon gas measurements at hewer work places were available, the annual exposure to radon progeny was calculated based on these measurements and an equilibrium factor. Thirdly, if radon progeny measurements were available, the annual exposure to radon progeny was calculated based on these measurements.

(II) JEM: Job-exposure matrix

The job-exposure matrix contains annual exposure values to radon progeny for a hewer with 2000 working hours. Therefore, the annual exposures to radon progeny described in part (I) had to be adapted for temporally varying working times. The annual object-specific exposures to radon progeny (JEM 1, Lehmann et al. 1998) were retrospectively improved to obtain shaft-specific exposure estimates (JEM 2, Lemann 2004, see Section 4.6).

(III) Individual exposure

The individual annual exposure to radon progeny is finally assessed using the values from the JEM by applying weighting factors for individual activities and the individual occupational history (Section 4.7). For each complete calendar year individual exposure during special underground shifts was added and individual exposure during absenteeism was subtracted from the individual exposure.

Table 7 provides an overview of the methods for radon progeny exposure assessment in the SAG/SDAG Wismut. The single issues are described in detail in the following sections separately for each work place: underground mining objects (Section 4.3), open pit mining objects (Section 4.4) and processing companies (Section 4.5). Figure 5 contains a more detailed presentation of the number of measurements.

Table 7: Methods for radon progeny exposure assessment in the Wismut cohort.

Underground mining objects			
Saxony			
Period	1946-1954/55	1955/56-1965	1966-1990
Method	Experts' estimation	Based on radon gas measurements	Based on radon progeny measurements
Number of measurements	0	ca. 57 000	ca. 140 000
Thuringia			
Period	1946-1954/55	1955/56-1974	1975-1990
Method	Experts' estimation	Based on radon gas measurements	Based on radon progeny measurements
Number of measurements	0	ca. 39 000	ca. 160 000
Open pit mining objects			
Period		1950-1990	
Method		Experts' estimation	
Number of measurements		0	
Processing companies			
Period	1946-1962	1963-1990	
Method	Experts' estimation	Based on radon gas measurements	
Number of measurements	ca. 1 600	Unknown (>0)	

The main sources for the overview in Table 7 are: Lehmann et al. (1994, 1998).

4.3. Exposure of a hewer in underground mining objects (JEM 1)

The reference activity for underground workers in the JEM was the activity of a hewer.

4.3.1. Estimation methods

The estimation method for the individual exposure to radon progeny of a hewer in underground mining objects was chosen according to the availability and plausibility of radon gas concentration measurements and radon progeny concentration measurements depending on the considered calendar year. Three approaches have to be differentiated (Lehmann et al. 1998 pp. 50, 188):

- Retrospective exposure estimation based on expert models (about 1946-1954/55)
- Exposure estimation based on radon gas concentration measurements (Saxony: about 1955/56-1965; Thuringia: about 1955/56-1974)
- Exposure estimation based on radon progeny concentration measurements (Saxony: about 1966-1990; Thuringia: about 1975-1990)

Figure 7 gives a more detailed overview about the applied estimation methods for each calendar year and each mining object. The three dark colors indicate the three estimation methods. In objects and calendar years marked with a one stage lighter color, radon gas or radon progeny measurements were not available, i.e. there exists a gap in the data. The fields colored with the lightest green shade indicate cases for which the available measurements or the resulting exposure estimates were appraised to be implausible. Exposure in both cases was evaluated by an expert based on temporally adjacent concentration measurements and on the conditions in the diggings.

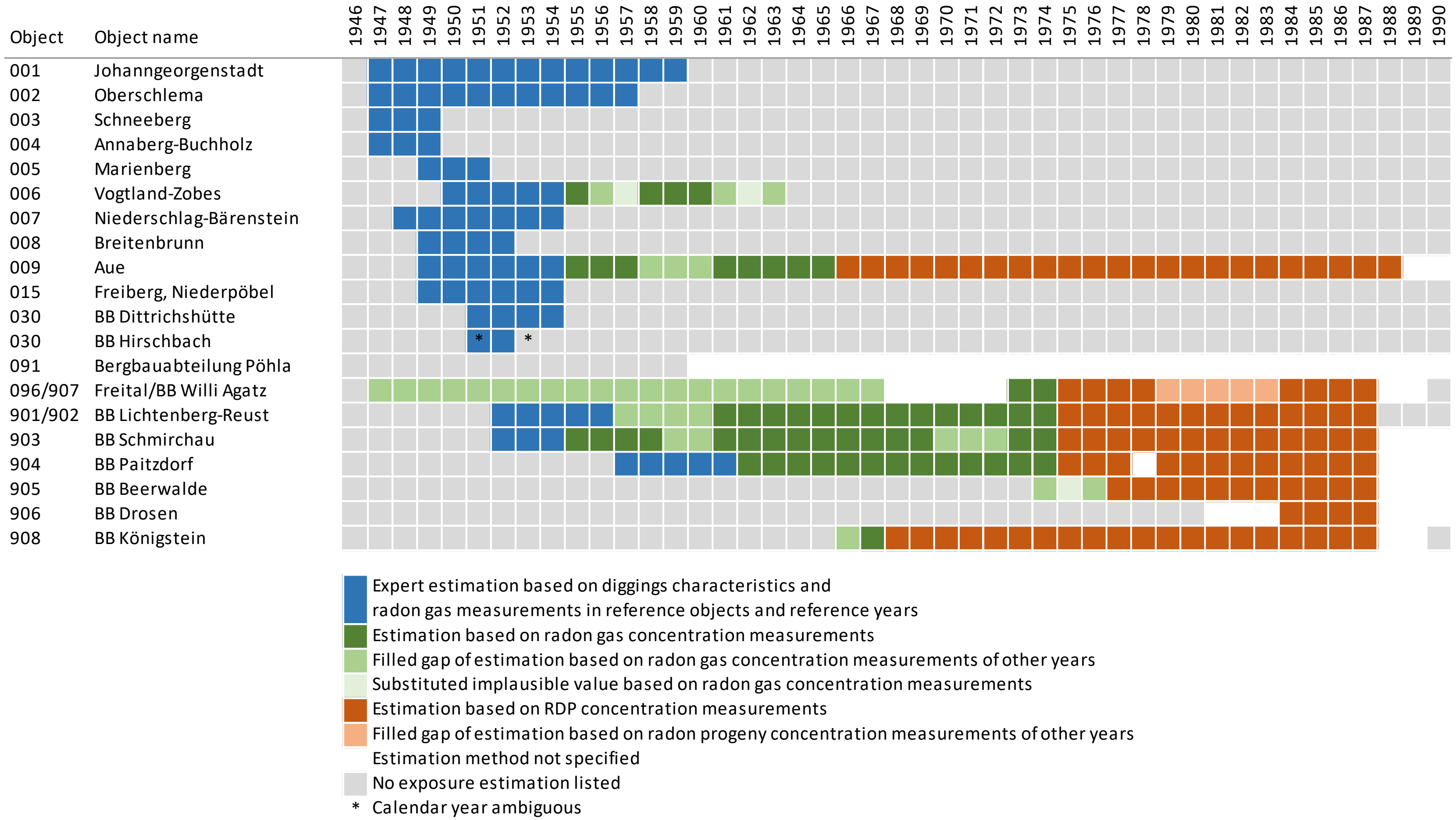

Figure 7: Methods for exposure assessment for a hewer in underground mining objects of the SAG/SDAG Wismut according to Lehmann et al. (1998). Objects for which exposure assessment was not based on any measurements, but was deduced from exposure estimations of other objects, are not depicted.

4.3.2. General approach

The exposure to radon progeny (in WLM) of a hewer in mining in calendar year t, object o and activity j (here: reference activity $j_0(o)$, hewer for underground mining) was calculated through

$$E(t,o,j_0(o)) = \begin{cases} E^*(t,o,j_0(o)) \cdot g(t,o) \cdot w(t,o), & \text{based on radon gas concentration measurements or experts' estimations} \\ E^{2000}(t,o,j_0(o)) \cdot w(t,o), & \text{based on radon progeny concentration measurements} \end{cases}$$

$E^{2000}(t,o,j_0(o))$ and $E^*(t,o,j_0(o))$ denote the annual exposure to radon progeny and to radon gas, respectively, of a hewer in underground mining with 2000 working hours per year. The annual exposure to radon gas of a hewer in underground mining with 2000 working hours per year, $E^*(t,o,j_0(o))$ has to be multiplied with an equilibrium factor $g(t,o)$ to obtain the annual exposure to radon progeny (Lehmann et al. 1998 pp. 50, 76) and with the working time factor $w(t,o)$.

Annual exposure to radon gas

The annual exposure to radon gas of a hewer in underground mining with 2000 working hours per year $E^*(t,o,j_0(o))$ for the mining objects is determined as the basic exposure from old mining $E^B(o)$ and from mining activity $E^M(t,o,j_0(o))$ (Lehmann et al. 1998 pp. 69, 77–78, 189):

$$E^*(t,o,j_0(o)) = E^B(o) + E^M(t,o,j_0(o))$$

The estimation approach of $E^M(t,o,j_0(o))$ varies depending on the calendar year and is therefore separately presented in Section 4.3.3. In general, the exposure to radon in objects and calendar years without measurements were derived from comparable reference objects (regarding diggings characteristics, the production and the mine ventilation) with available measurements (Lehmann et al. 1998 pp. 50–51).

Basic exposure from old mining ("Altbergbau-Grundbelastung")

Basic exposure from old mining $E^B(o)$ is defined as the exposure without any mining activities occurring in old mining objects or in objects affected by mine air of old mining objects (Lehmann et al. 1998 pp. 69, 76, 189). The level of basic exposure from old mining depends on the diggings and on mine ventilation conditions (Lehmann et al. 1998 p. 69). The basic exposure from old mining was estimated for object 003 Schneeberg (without the shaft "Siebenschlehen") through measurements in 1937/38 by Rajewski with 22.5 WL (originally: 22.5 Eman; Eman corresponds to WL for an equilibrium factor of 1, Lehmann et al. 1998 pp. 66, 119) which were assumed to reflect the basic exposure from old mining due to a low mine output volume (Lehmann et al. 1998 p. 77).

Since further suitable measurements in other objects were not available, basic exposure from old mining for other objects is determined in relation to object 003:

$$E^B(o) = \begin{cases} b(o) \cdot E^B(003), & o \text{ old mining object} \\ 0, & o \text{ new ground-opening object} \end{cases}$$

Proportion $b(o)$ was determined by comparing diggings-specific criteria, see Table 8.

Table 8: Proportion of exposure from old mining in comparison to object 003 Schneeberg as assumed in Lehmann et al. (1998 p. 78).

Object	*b(o)*
003	1
002, 007	0.6
004	0.33
001, 005	0.25
008, 015	0.17

Objects 006 and 009 as well as all objects in Thuringia were new ground-opening objects (Lehmann et al. 1998 pp. 77, 112), where exposure from old mining did not occur, i.e. $E^B(o) = 0$.

Working time factor

The working time factor $w(t, o)$ is necessary to adjust for the actual working time of a hewer, which was temporally varying, as shown in Table 9.

Table 9: Working time factors for mining objects in the SAG/SDAG Wismut as assumed in Lehmann et al. (1998 pp. 45, 130, 132).

Period	*w*	Number of annual working hours	Source
1946-1958	1.2	2400	interviews
1959-1965	1.1	2200	interviews
1966-1980	0.9	1800	literature
1981-1990	0.88	1760	literature

The values of the working time factor were determined by interviews, which were not further described, and by details in the literature (Lehmann et al. 1998 p. 45).

Equilibrium factor

The equilibrium factor $g(t, o)$ for the diggings was deduced according to the ventilation engineering, the degree of ground opening of the diggings and their contact to old mining (Table 10).

Table 10: Equilibrium factors for underground mining objects in the SAG/SDAG Wismut as reported in Lehmann et al. (1998 pp. 68, 76, 82, 84–85, 120, 123–126, 130–132). The colors were chosen according to the equilibrium factor.

		Calendar year(s)													
Object	Object name(s)	-1951*	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964 - *
001-005, 007, 015	Johanngeorgenstadt, Oberschlema, Schneeberg, Annaberg-Buchholz, Marienberg, Niederschlag-Bärenstein, Freiberg, Niederpöbel	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6					
006	Vogtland-Zobes	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	
008	Breitenbrunn	0.5	0.5												
009	Aue	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.2
030	BB Dittrichshütte	0.4	0.4	0.5	0.5										
030	BB Hirschbach		0.4	0.4											
096/907	Freital/BB Willi Agatz	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
901/902	BB Lichtenberg/Reust		0.4	0.4	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
903	BB Schmirchau		0.4	0.4	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
904	BB Paitzdorf							0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3
905	BB Beerwalde														0.3
908	BB Königstein														0.3

* Period from/until start/end of exposure assessment in Lehmann et al. (1998)

4.3.3. Experts' estimation (1946 – 1954/55)

Initial situation

In the early years, the assessment of the exposure to radon gas predominantly could not be based on radon concentration measurements, because of lacking measurements. Therefore, the radon concentration for the reference activity "hewer" had to be estimated. Exposure estimations for the early years were primarily based on radon gas concentration measurements in reference objects in a reference year (Lehmann et al. 1998 p. 51). The radon concentration in the mining plant mainly depends on the mine void ("Grubenhohlraum") or the boundary surface of the mine void ("Grubenhohlraum-Umgrenzungsfläche"), the amount of radon exhalation (measurable through the radon gas or respectively, the uranium content) and the ventilation conditions (Lehmann et al. 1998 pp. 54, 60–61). These quantities were, except for mine void and radon exhalation rate in the reference objects, not available for this period and had to be estimated. For this purpose, indicators, which describe conditions of the diggings ("Lagerstättenverhältnisse"), the production and the mine ventilation conditions ("Produktionskennziffern und Bewetterungsbedingungen"), are the second prerequisite for the exposure estimations (Lehmann et al. 1998 p. 51), in addition to radon concentration measurements in reference objects. The experts' estimation is schematically overviewed in Figure 8 from Lehmann et al. (1998 p. 52).

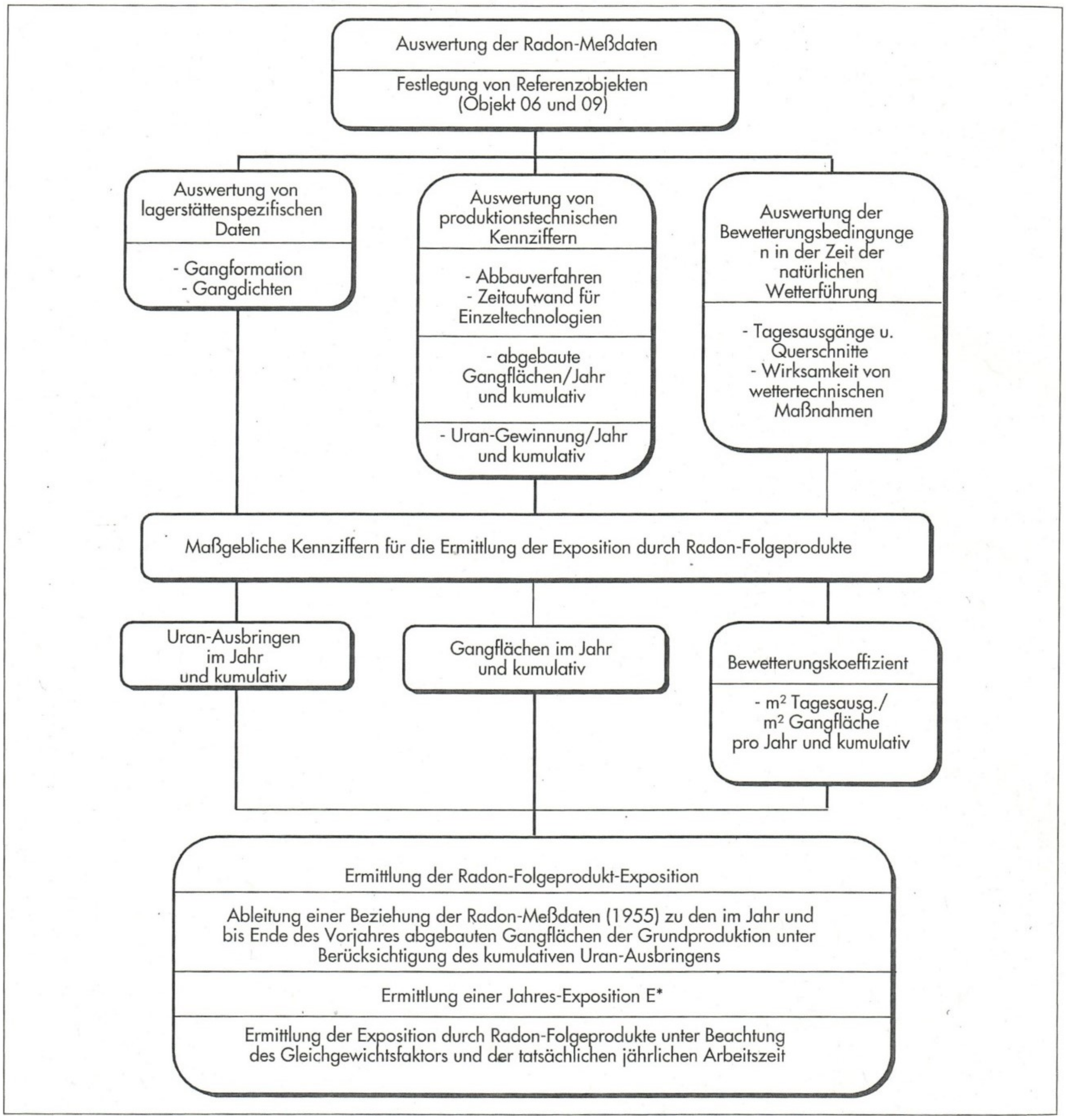

Figure 8: Model to deduce evaluation coefficients for the determination of radon progeny exposure from diggings-specific, production- and ventilation-related quantities in hydrothermal vein deposits (“Ganglagerstätte”) in Saxony. (Lehmann et al. 1998 p. 52)

Exposure from mining activity

The annual exposure to radon gas from mining activity $E^M(t,o,j_0(o))$ was assessed with the evaluation area $A(t,o)$ (“Bewertungsfläche”) as a measure for the size of the radon exit field, and the evaluation factor $e(t,o)$ (“Bewertungsfaktor”) as a measure of the exposure to radon per unit of the mined area for 2000 working hours a year (Lehmann et al. 1998 pp. 76, 120–121):

$$E^M(t,o,j_0(o)) = \begin{cases} r(t,o) \cdot A(t,o) \cdot e(t,o), & o \text{ in Saxony} \\ A(t,o) \cdot e(t,o), & o \text{ in Thuringia} \end{cases}$$

For objects in Saxony, the relative uranium recovering rate $r(t,o)$ was additionally considered which is a measure of the radon exhalation of object o in relation to the reference object $o_0(o)$. This term was not needed for objects in Thuringia because the evaluation area $A(t,o)$ for Thuringian objects implicitly allows for uranium recovery.

Evaluation area

Whereas the uranium mineralization in Saxony was bounded to vein structures ("Gangstrukturen"), this was not the case for uranium mineralization in Thuringia (Lehmann et al. 1998 p. 119). Therefore, the evaluation area was approximated through the mined vein area ("Gangflächen", Lehmann et al. 1998 p. 61) for objects in Saxony and through the void volume ("Hohlraumvolumen", Lehmann et al. 1998 p. 118) for objects in Thuringia:

$$A(t,o) = \begin{cases} C(t,o) + 0.2 \sum_{s=1946}^{t-1} C(s,o), & o \text{ in Saxony} \\ \sum_{s=1946}^{t} V(s,o), & o \text{ in Thuringia} \end{cases}$$

For Saxonian objects, the evaluation area $A(t,o)$ is composed of the mined vein area $C(t,o)$ in year t, and a proportion of 20 % of the mined vein area $C(t,o)$ in the previous years. Since the vein areas mined in previous years have not been hermetically sealed, they still emit radon due to mining losses. The proportion 0.2 was chosen according to the approximate mining losses in the early years (Lehmann et al. 1998 pp. 66–67).

The vein areas serve as approximation for the void volume and the boundary area of the mine void ("Grubenhohlraum-Umgrenzungsfläche") which are proportionally related to the radon concentration. It was assumed that the proportion of exploration ("Erkundung"), development ("Ausrichtung"), lateral development ("Vorrichtung") and mining ("Abbau") work as well as the geometric proportions ("Abbauquerschnitte") of different diggings were equal. (Lehmann et al. 1998 p. 61)

For Thuringian objects, the evaluation area $A(t,o)$ in year t was determined as the cumulative void volume $V(t,o)$ until year t (Lehmann et al. 1998 pp. 120, 123–126). Since uranium mineralization was not bound to vein structures, the void volume in previous years has to be totally considered (Lehmann et al. 1998 p. 119). The void volume of year t was approximated through the ratio between the total shaft output in year t, $F(t,o) \cdot q(t,o)$, and the density of the bedrock $h(o)$ (Lehmann et al. 1998 p. 118):

$$V(t,o) = \frac{F(t_0(o),o)}{h(o)} q(t,o)$$

The total shaft output in year t, $F(t,o)$, is calculated by the total shaft output in the reference year $t_0(o)$, $F(t_0(o),o)$, and the percentage of total uranium recovery of year t, $q(t,o)$, which is defined as

$$q(t,o) = \frac{R(t,o)}{\sum_t R(t,o)}$$

$R(t,o)$ denotes the amount of uranium recovery of object o in calendar year t. The sum in the denominator ranges over the years with expert estimation.

Evaluation factor

The evaluation factor $e(t, o)$ of mining object o quantifies the annual exposure to radon gas from mining activity $E^M(t, o, j_0(o))$ per unit of the mined area in year t for 2000 working hours. It accounts for the aeration conditions in the considered evaluation area. The evaluation factor of object o was estimated with the evaluation factor of the corresponding reference object $o_0(o)$ (see Table 11) in the reference year $t_0(o_0(o))$ (see Table 12). The evaluation factors for the reference objects o_0 were estimated based on the arithmetic mean of *N* radon gas concentration measurements (at mining and development locations) in the reference year t_0, denoted by $\overline{\overline{\overline{C}}}_{Rn}$, multiplied by 12 to obtain annual exposure, in comparison to the evaluation area (Lehmann et al. 1998 pp. 66–67, 121, 126):

$$e(t, o) = e(t_0(o_0(o)), o_0(o)) = \frac{E^M(t_0(o_0(o)), o_0(o), j_0(o))}{A(t_0(o_0(o)), o_0(o))} = \frac{\overline{\overline{\overline{C}}}_{Rn}(t_0(o_0(o)), o_0(o)) \cdot 12}{A(t_0(o_0(o)), o_0(o))}$$

The reference year t_0 was defined as a year with a relatively unique definition of production and mine ventilation conditions (Lehmann et al. 1998 p. 72).

The mean radon concentration $\overline{\overline{\overline{C}}}_{Rn}(t, o)$ at mining work places in the reference objects and in the reference years build the starting point for the experts' estimation of $E^M(t, o, j_0(o))$. Table 11 shows the results of the measurements and the calculation of the evaluation factors for the reference objects.

Table 11: Evaluation factors for evaluating the ventilation conditions in the reference underground mining objects and measured values of the parameters used for the calculation of the evaluation factors.

Object	Object name	t_0	N	$\overline{\overline{\overline{C}}}_{Rn}$ in WL	E^M	A[9]	e
006	Vogtland-Zobes	1955	919[1]	40.88[3]	491[3]	800.9[6]	0.613[8]
009	Aue	1955	655[1]	27.30[3]	328[3]	1505.16[6]	0.218[8]
903	BB Schmirchau	1955	299[1]	34.51[4]	414.1[4]	493.96[7]	0.8384[7]
904	BB Paitzdorf	1962	123[2]	6.44[5]	77.3[5]	65.54[5]	1.18[5]

[1] Lehmann et al. (1998), p. 51; [2] Lehmann et al. (1998), p. 460; [3] Lehmann et al. (1998), p. 66;

[4] Lehmann et al. (1998), p. 119; [5] Lehmann et al. (1998), p. 126; [6] Lehmann et al. (1998), p. 68;

[7] Lehmann et al. (1998), p. 120; [8] Lehmann et al. (1998), p. 67

[9] A: cumulative mined vein area (Saxony); cumulative void volume (Thuringia)

Radon concentration was also measured in the objects 001 Johanngeorgenstadt and 002 Oberschlema, but the measurements were appraised to be implausible after the comparison with former measurements in similar objects in Germany and the Czech Republic and the comparison of production-related indicators (Lehmann et al. 1998 pp. 54–55). Therefore, the results for the objects 001 Johanngeorgenstadt and 002 Oberschlema are not shown, because they were not used for exposure assessment.

Since plausible measurement results for the exposure from mining in the reference year are only available for the mining objects 006 Vogtland-Zobes, 009 Aue 903 BB Schmirchau and 904 BB Paitzdorf, the experts crudely estimated the evaluation factors for the other mining objects considering the mine aeration conditions and the uranium mineralization. The values for the evaluation factor were assigned as given in Table 12.

Table 12: Assumed values of the evaluation factors for experts' estimation in underground mining objects.

Object(s)	Object name(s)	*e*	Rationale
001-003, 007-009, 015	Johanngeorgenstadt, Oberschlema, Schneeberg, Niederschlag-Bärenstein, Breitenbrunn, Aue, Freiberg, Niederpöbel	0.2[1]	Medium aeration conditions, better than in object 006 Vogtland-Zobes
004-005	Annaberg-Buchholz, Marienberg	0.1[1]	Good aeration conditions, substantially better than in object 006 Vogtland-Zobes
006	Vogtland-Zobes	0.618[2]	Bad aeration conditions
030	BB Dittrichshütte/ Hirschbach	0.4192[3]	Half of object 903 BB Schmirchau due to minor uranium mineralization
901/902	BB Lichtenberg/Reust	0.8384[4]	Comparable uranium mineralization and similar aeration conditions as object 903 BB Schmirchau
903	BB Schmirchau	0.8384[4]	
904	BB Paitzdorf	1.18[5]	

[1] Lehmann et al. (1998), p. 75; [2] Lehmann et al. (1998), p. 69; [3] Lehmann et al. (1998), p. 124;

[4] Lehmann et al. (1998), p. 123; [5] Lehmann et al. (1998), p. 126

Relative uranium recovering rate

Besides the size of the evaluation area $A(t,o)$ and the evaluation factor $e(t,o)$, the annual exposure to radon gas from mining activity $E^M(t,o,j_0(o))$ also depends on the uranium content of the bedrock in comparison to the reference object, measured with the relative uranium recovering rate $r(t,o)$ (Lehmann et al. 1998 p. 76):

$$r(t,o) = \begin{cases} \dfrac{R^R(t_0(o),o)}{R^R(t_0(o_0),o_0)}, & t \le t_0(o) \\ \dfrac{R^R(t,o)}{R^R(t_0(o_0),o_0)}, & t > t_0(o) \end{cases}$$

with the relative cumulative uranium recovery rate $R^R(t,o)$

$$R^R(t,o) = \frac{\sum_{s=1946}^{t} R(s,o)}{\sum_{s=1946}^{t} C(s,o)}$$

$R(t,o)$ denotes the amount of uranium recovery of object o in calendar year t and $C(t,o)$ the mined vein area. The uranium recovery rate describes the radium and, respectively, the uranium concentration of the bedrock which is directly related to the radon exhalation and thus, to the radon concentration in the mine opening (Lehmann et al. 1998 p. 56). The cumulative annual uranium recovery rate was used for the calculation of the exposure to radon gas instead of the annual recovery rate to avoid to overemphasize single years (Lehmann et al. 1998 p. 57). The values for the reference years are given in the Table 13 (Lehmann et al. 1998 p. 70).

Table 13: Relative uranium recovery rates *r* for Saxonian underground mining objects in the reference years and measured values of the parameters used for their calculation. Last column *r* is based on own calculation.

Object	Object name	Reference year	ΣR	ΣC	R^R	r
001	Johanngeorgenstadt	1953	2182.27	4804.7	0.454 *	0.442
001	Johanngeorgenstadt	1955	3585.57	7547.9	0.475	0.463
002	Oberschlema	1955	4800.58	7395.6	0.649	0.632
003	Schneeberg	1949	73.25	415.1	0.176	0.171
004	Annaberg-Buchholz	1949	57.01	285.5	0.2	0.195
005	Marienberg	1951	70.42	356.5	0.198 *	0.193
006	Vogtland-Zobes	1955	831.7	1904.5	0.437 *	0.426
007	Niederschlag-Bärenstein	1953	266.38	1303.9	0.204	0.199
007	Niederschlag-Bärenstein	1954	378.12	1539.3	0.246	0.24
008	Breitenbrunn	1952	334.17	1444.4	0.231	0.225
009	Aue	1955	3784.21	3685.4	1.027	1
015	Freiberg, Niederpöbel	1954	78.17	251.05	0.311	0.303

* Values resulting from a recalculation differ from Lehmann et al. (1998), p. 70

4.3.4. Exposure assessment based on radon gas concentration measurements (1955/56 – 1965 in Saxony, 1955/56 – 1974 in Thuringia)

An overview of the availability of radon gas concentration measurements is given in Figure 5 and the periods for which exposure assessment was based on radon gas concentration measurements are presented in Figure 7. Due to deficient measurements of the radon progeny concentration, exposure assessment was based on radon gas measurements until 1974 in Thuringian objects (Lehmann et al. 1998 p. 133).

The annual exposure to radon gas of a hewer with 2000 working hours per year, $E^{*}(t, o, j_0(o))$, was directly approximated by the mean radon gas concentration $\bar{\bar{\bar{C}}}_{Rn}(t, o) \cdot 12$ for both, Saxonian and Thuringian objects, because all active objects in that period were new ground-opening objects:

$$E^{*}(t, o, j_0(o)) = E^{B}(o) + E^{M}(t, o, j_0(o)) = E^{M}(t, o, j_0(o)) = \bar{\bar{\bar{C}}}_{Rn}(t, o) \cdot 12$$

The radon gas concentration measurements of all hewer work places (development and mining) were averaged for the estimation of $\bar{\bar{\bar{C}}}_{Rn}$ due to insufficient hermetic sealing as follows:

Always:	Objects 006 Vogtland-Zobes (not specified in Lehmann et al. 1998), 009 Aue (Lehmann et al. 1998 p. 82), 905 BB Beerwalde (Lehmann et al. 1998 p. 132)
Until 1960:	Objects 901/902 BB Lichtenberg/Reust (Lehmann et al. 1998 pp. 130–131), 903 BB Schmirchau (Lehmann et al. 1998 pp. 128–129)
Until 1963:	Object 904 BB Paitzdorf (Lehmann et al. 1998 p. 132)

Because better hermetic sealing was assumed for objects 901/902 BB Lichtenberg/Reust, 903 BB Schmirchau and 904 BB Paitzdorf, radon gas concentration measurements measured only at mining work places of hewers were used from 1961 and from 1964, respectively (Lehmann et al. 1998 pp. 129, 132, 193).

The mean annual radon concentration for calendar years with missing values in the objects 006 Vogtland-Zobes, 009 Aue, 096/907 Steinkohlenlagerstätte Freital, BB Willi Agatz, 901/902 BB Lichtenberg/Reust, 903 BB Schmirchau, 905 BB Beerwalde and 908 BB Königstein were determined to fixed values in consideration of the introduced ventilation measures (Lehmann et al. 1998 pp. 82–85, 128–132). A few exposure values were changed according to experts' evaluation due to implausible values considering the working conditions in the objects 006 Vogtland-Zobes and 905 BB Beerwalde (Lehmann et al. 1998 pp. 83–84, 132).

4.3.5. Exposure assessment based on radon progeny concentration measurements (1966 – 1990 in Saxony, 1975 – 1990 in Thuringia)

For periods and objects with radon progeny concentration measurements, the annual exposure to radon progeny of a hewer with 2000 working hours per year in underground mining, $E^{2000}(t,o,j_0(o))$, was based on the radon progeny concentration measurements $\bar{\bar{\bar{C}}}_{RDP}(t,o)$ in MeV/cm³ ($1\text{MeV/cm}^3 = 130\text{ WLM}$) at mining work places (Lehmann et al. 1998 pp. 86–87, 133, 193):

$$E(t,o,j_0(o)) = E^{2000}(t,o,j_0(o)) \cdot w(t,o) = \bar{\bar{\bar{C}}}_{RDP}(t,o) \cdot 12 \cdot c(o) \cdot w(t,o)$$

with $c(o)$ as a correction factor since deficits and disruptions of the ventilation systems are only partially represented in these measurements (Lehmann et al. 1998 pp. 86–87, 133, 193). Table 14 gives an overview of the applied correction factors for ventilation disruption.

Table 14: Correction factors for underground mining objects in order to account for deficits and disruptions of the ventilation systems in the exposure assessment based on radon progeny concentration measurements (Lehmann et al. 1998 pp. 86–87, 133).

Object	Object name	*c*
009	Aue	1.45
096/907	Steinkohlenlagerstätte Freital, BB Willi Agatz	1.3
901/902	BB Lichtenberg/Reust	1.3
903	BB Schmirchau	1.2
904	BB Paitzdorf	1.4
905	BB Beerwalde	1.3
906	BB Drosen	1.3
908	BB Königstein	1.3

Note the varying operation times of the objects (Table 2).

4.3.6. Deviating assessment of annual exposure to radon

Exposure assessment differs for some objects from the exposure assessment approach presented in the Sections 4.3.2-4.3.5 due to lacking or only partially available exposure measurements.

Object 096/907 Steinkohlenlagerstätte Freital, BB Willi Agatz

Object 096/907 Steinkohlenlagerstätte Freital, BB Willi Agatz was operating in a stone coal diggings (Lehmann et al. 1998 p. 78) for which stable diggings and ventilation conditions were assumed (Lehmann et al. 1998 p. 79). Exposure to radon progeny

- for 1947-1967 was determined related to the exposure calculated for the years 1973 and 1974 on the basis of radon gas concentration measurements (Lehmann et al. 1998 p. 84),
- for 1973-1974 was assessed based on radon gas concentration measurements,

- for 1975-1978 and for 1984-1987 was assessed based on radon progeny concentration measurements and
- for 1979-1983 was determined related to the value of the previous years due to radon absorption of coal (Lehmann et al. 1998 p. 87).

It was not specified how the exposure to radon progeny was assessed in the period 1968-1972 (Lehmann et al. 1998 p. 84).

Object 091 Bergbauabteilung Pöhla

From 1969, mining activities in the diggings Pöhla as a part of object 009 Aue were conducted (Lehmann et al. 1998 p. 58). Separate exposure estimates for object 091 Bergbauabteilung Pöhla are given in Lehmann et al. (1998), but the exposure estimation approach is not described.

Exploration objects

Table 2 includes a list of exploration objects. The ore contact during exploration works was lower than during development and mining works. The exposure in exploration objects was assumed to be related to the adjacent mining object (Lehmann et al. 1998 p. 105).

For Saxonian exploration objects, 10 % or 20 % of the mean radon progeny exposure of the corresponding reference mining objects $o_0(o)$ were determined as the exposure to radon progeny in exploration object o, depending on the degree of ground opening of the reference object (Lehmann et al. 1998 p. 105):

$$E(t, o, j_0(o)) = \begin{cases} 0.1 \cdot E(t, o_0(o), j_0(o)), & o_0(o) \text{ is a new ground-opening object} \\ 0.2 \cdot E(t, o_0(o), j_0(o)), & o_0(o) \text{ is an old mining object} \end{cases}$$

For Thuringian exploration objects, exposure was determined to the fixed value of 1 WLM, because exploitable uranium mineralization was not found (Lehmann et al. 1998 p. 140).

Development objects

Table 2 includes a list of development objects. Following radon gas measurements in mine areas of Czech mines, which were comparable to development objects, 30 % of the mean radon progeny exposure for a hewer in the corresponding reference mining objects $o_0(o)$ (see Table 15) was determined as radon progeny exposure for a hewer in the development object (Lehmann et al. 1998 pp. 105–106, 140):

$$E(t, o, j_0(o)) = 0.3 \cdot E(t, o_0(o), j_0(o))$$

The corresponding mining objects of the development objects are shown in Table 15.

Table 15: Development objects and corresponding underground mining objects (Lehmann et al. 1998 pp. 106, 140).

Development object *o*		Corresponding reference mining objects $o_0(o)$	
Object	Object name	Object(s)	Object name(s)
010	Bergrevier Johanngeorgenstadt	001	Johanngeorgenstadt
011	Lauter	002, 009	Oberschlema, Aue
012	Schwarzenberg	001, 008	Johanngeorgenstadt, Breitenbrunn
013	Marienberg	001-009, 015, 096	Several Saxonian objects
014	Auerbach	006	Vogtland-Zobes
086	Saalfeld, Ronneburg, Dittrichshütte	030	BB Dittrichshütte/Hirschbach

Surface areas affiliated to mining objects

Surface areas were affiliated to the exploration and mining objects of the SAG/SDAG Wismut. The workers in these surface areas worked at facilities for the handling of waste rock and ore. (Lehmann et al. 1998 pp. 106–107)

The reference activity for the exposure assessment for workers in surface areas which were affiliated to mining objects was not the hewer in mining, but a worker in ore milling. Radon progeny exposure was determined in consideration of the exposure during the uranium ore loading in the processing companies, the mined uranium concentrations and (from 1967) the concentration measurements of long-lived radionuclides and the gamma dose. (Lehmann et al. 1998 p. 107)

4.4. Exposure of a hewer in open pit mining objects (JEM 1)

Exposure assessment for a hewer in the reference open pit mining object was documented in Lehmann et al. (1998 pp. 141–153). The estimation method for the annual exposure to radon progeny of a hewer in open pit objects was a retrospective experts' estimation. The estimation was based on radon gas concentration measurements in 1994/1995 in object 300 Lichtenberg.

4.4.1. General approach

The annual exposure to radon progeny of a hewer in open pit mining (reference activity $j_0(o)$) in calendar year t and object o was retrospectively calculated through

$$E(t,o,j_0(o)) = E^*(t,o,j_0(o)) \cdot g(t,o) \cdot w(t,o)$$

with the working time factor $w(t,o)$, the equilibrium factor $g(t,o) = 0.4$ for open pit mining objects and the annual exposure to radon gas for 2000 working hours per year $E^*(t,o,j_0(o))$. $E^*(t,o,j_0(o))$ was estimated by the sum of the annual basic exposure at ground level ("Grundbelastung in bodennaher Atmosphäre") without mining activity $E^B(o)$ and the additional annual exposure in the depth ("zusätzliche Belastung in der Teufe") without mining $E^D(t_0,o,j_0(o))$ scaled by the evaluation factor $e(t,o)$ ("Bewertungskoeffizient"):

$$E^*(t,o,j_0(o)) = \frac{1}{3700} \cdot 12 \cdot \left(E^B(o) + E^D\big(t,o,j_0(o)\big) \cdot e(t,o)\right)$$

By applying the correction factors of $\frac{1}{3700}$ and 12 the resulting exposure in Bq/m^3 is converted to WLM.

4.4.2. Reference object

The reference object for open pit mining objects, o_0, is object 300 Lichtenberg. $E^B(o_0)$ was determined to 30 Bq/m^3:

$$E^B(o_0) = 30 \ \mathrm{Bq/m^3}$$

The mean radon gas concentration (in Bq/m^3), $\bar{\bar{\bar{C}}}_{Rn}(t_0,o_0)$, was measured in the reference object in the reference years $t_0 = 1994/1995$ in a depth of $d_m(t_0,o_0) = 130 \ \mathrm{m}$ (depth of radon gas concentration measurements): $\bar{\bar{\bar{C}}}_{Rn}(t_0,o_0) = 80 \ \mathrm{Bq/m^3}$. This value was used to estimate the exposure in a depth of $d_m(t_0,o_0) = 130 \ \mathrm{m}$ without mining activity:

$$E^D(t_0,o_0,j_0(o_0)) = \bar{\bar{\bar{C}}}_{Rn}(t_0,o_0) - E^B(o_0) = 50 \ \mathrm{Bq/m^3}$$

Exposure without mining activity in a non-reference year t was assumed to be linearly related to the exposure without mining activity in the reference year depending on the depth in year t, $d(t,o_0)$:

$$E^D(t,o_0,j_0(o_0)) = E^D(t_0,o_0,j_0(o_0)) \cdot \frac{d(t,o_0)}{d_m(t_0,o_0)} = \left(\bar{\bar{\bar{C}}}_{Rn}(t_0,o_0) - E^B(o_0)\right) \cdot \frac{d(t,o_0)}{d_m(t_0,o_0)}$$
$$= 50 \cdot \frac{d(t,o_0)}{130}$$

The evaluation factor $e(t, o_0)$ accounted for deviating conditions in the object in the years of interest compared to the reference years and was composed of six sub-factors, which evaluate certain aspects of mining conditions (diggings, production, weather exchange, fire events, underground blowing ventilation, uranium mineralization):

$$e(t, o_0) = e_1(t, o_0) \cdot e_2(t, o_0) \cdot e_3(t, o_0) \cdot e_4(t, o_0) \cdot e_5(t, o_0) \cdot e_6(t, o_0)$$

The sub-factors for the reference object are presented in Table 16 (Lehmann et al. 1998 p. 151); empty entries were taken as one.

Table 16: Evaluation sub-factors for evaluating the conditions in the reference open pit mining object 300 Lichtenberg over time.

Year	Diggings (e_1)	Production (e_2)	Weather exchange (e_3)	Fire events (e_4)	Underground blowing ventilation (e_5)	Uranium mineralization (e_6)
1959	1.2	20	1.0	1.25		
1960	1.2	25	1.0	1.25		
1964	1.2	25	1.0	1.25		
1968	1.2	25	1.3	1.25		
1975	1.2	25	1.3	1.25	1.1	
1977	1.2	5	1.3		1.1	

Thus, the general formula for exposure assessment is given by:

$$\begin{aligned} E(t, o_0, j_0(o)) &= E^*(t, o_0, j_0(o_0)) \cdot g(t, o_0) \cdot w(t, o_0) \\ &= \tfrac{1}{3700} \cdot 12 \cdot \left(30 + 50 \cdot \frac{d(t, o_0)}{130} \cdot e(t, o_0)\right) \cdot 0.4 \cdot w(t, o_0) \end{aligned}$$

4.4.3. Non-reference objects

The exposure of a hewer to radon progeny in a non-reference object was determined along the lines of the method for the reference objects in the previous section, but with object-specific depths, $d(t, o)$, and evaluation factors, $e(t, o)$:

$$E(t, o, j_0(o)) = \tfrac{1}{3700} \cdot 12 \cdot \left(30 + 50 \cdot \frac{d(t, o)}{130} \cdot e(t, o)\right) \cdot 0.4 \cdot w(t, o)$$

The fixed value for the basic exposure $E^B(o) = 30\ \mathrm{Bq/m^3}$ was also assumed for non-reference objects and the exposure in a depth of 130 m, $E^D(t, o, j_0(o))$, was estimated by the exposure in a depth of 130 m in the reference object to the reference years. The evaluation factor consisted again of the six sub-factors, which were independent from time:

$$e(t, o) = e_1(t, o) \cdot e_2(t, o) \cdot e_3(t, o) \cdot e_4(t, o) \cdot e_5(t, o) \cdot e_6(t, o)$$

The sub-factors for the non-reference objects are presented in Table 17 (Lehmann et al. 1998 p. 153).

Table 17: Evaluation sub-factors for evaluating the conditions in the non-reference open pit mining objects.

Object	Object name	Diggings (e_1)	Production (e_2)	Weather exchange (e_3)	Fire events (e_4)	Underground blowing ventilation (e_5)	Uranium mineralization (e_6)
301	Stolzenberg	1.2	20	1.0			
302	Ronneburg/Raitzhain	1.2	15	1.0			
303	Sorge	1.2	20	1.0			
304	Gauern	1.2	15	1.0			
306	Culmitzsch	1.2	25	1.0			1.2
307	Trünzig	1.2	15	1.0			
308	Steinach	1.2	15	1.0			
309	Erlau/Hirschbach	1.2	15	1.0			

4.5. Exposure in the processing stages of processing companies (JEM 1)

4.5.1. Initial situation

Radon gas measurements in processing companies were conducted between 1955 and 1957 during a maximum of three measurement campaigns, one per year and each lasting one week (Lehmann et al. 1994 p. 108). The seasons of the campaigns are unknown. The number of measurements and mean radon gas concentrations are shown in Table 18.

Table 18: Number of measurements and mean radon gas concentrations in processing companies between 1955 and 1957 (according to Lehmann et al. 1998 p. 164).

Object	Object name	No. of measurements	Mean radon gas conc. in Bq/m³ (1955-1957)
031	Processing facility Lengenfeld	446	1 100
032	Processing facility Tannenbergsthal	193	700
050	Colliery Aue	16	4 070
052*	Colliery Oberschlema	82	16 600
054	Colliery Annaberg	28	8 900
058	Colliery Breitenbrunn	72	2 800
093	Processing facility Freital	238	590
095	Processing facility Gittersee	67	2 600
098*	Processing facility Johanngeorgenstadt	45	19 000
099	Processing facility Oberschlema	30	1 800
100	Processing facility Aue	180	3 600
101	Processing facility Crossen	171	1 370

* Reason for higher values: contact to underground mine openings and larger geological fault systems ("geologische Störungssysteme")

The starting point for exposure assessment were ambient radon gas concentration measurements for different processing stages (e.g., ore unloading, belt transport, grinding, crushing, classification, leaching, filtration, precipitation, concentrate drying)

- from 1963 for processing facility 101 Crossen
- from 1963 for processing facility 102 Seelingstädt
- from 1959 for RAF facility 200 Aue (shaft 371) and
- from 1963 for sampling colliery 050 Aue

at fixed measurement sites (Kreuzer et al. 2015a; Lehmann et al. 1998 pp. 165, 178, 180). For example, 28 processing stages were differentiated for processing facility 101 Crossen. Short term exposure variations were not collected.

4.5.2. General approach

In contrast to exposure assessment for mining activities, the exposure for each job in the processing companies was estimated depending on processing stages (Lehmann et al. 1998 pp. 170–173, 178, 183–184):

Step 1: Assessment of annual exposure to radon progeny for 2000 working hours per year during processing stage $s(j)$ of activity j and period $p(t, o_0)$ of calendar year t in reference object o_0:

$$E^{2000}(p(t, o_0), o_0, s(j))$$

Step 2: Deduction of annual exposure in other objects o than the reference object:

$$E^{2000}(p(t, o), o, s(j))$$

Step 3: Assessment of annual exposure for each calendar year t:

$$E(t, o, s(j))$$

The processing facilities 101 Crossen and 102 Seelingstädt, RAF facility 200 Aue (shaft 371) and colliery 050 Aue were chosen as reference objects due to the availability of frequent radon gas concentration measurements, the long and parallel operation time in comparison to other objects and the existence of the essential processing stages and detailed information about the objects (Lehmann et al. 1998 pp. 165, 171, 176, 184). An equilibrium factor $g(t, o)$ of 0.4 was assumed for processing companies (Lehmann et al. 1994 pp. 91–106).

4.5.3. Step 1: Exposure during the single periods in the reference object

The annual exposure to radon progeny for 2000 working hours per year $E^{2000}\big(p(t, o_0), o_0, s(j)\big)$ of a worker in a reference processing company was assessed depending on the processing stage $s(j)$ of activity j for which the person has been working and the period $p(t, o_0)$:

$$E^{2000}(p(t, o_0), o_0, s(j)) = \begin{cases} E^*(p(t, o_0), o_0, s(j)) \cdot g(t, o), & \text{if } E^* \text{ is available} \\ \text{retrospective experts' estimation}, & \text{if } E^* \text{ is not available} \end{cases}$$

with $E^*(p(t, o_0), o_0, s(j))$ denoting the annual exposure to radon gas of a worker with 2000 working hours and the equilibrium factor $g(t, o)$. The periods $p(t, o_0)$ were chosen in order to reflect approximately equal conditions in terms of production-related and procedural conditions, spatial design of the processing companies and work hygiene conditions (Lehmann et al. 1994 pp. 90–106, 1998 p. 171):

Processing facility 101 Crossen:	1950-1962,	1963-1970,	1971-1980,	1981-1989
Processing facility 102 Seelingstädt:	1960-1962,	1963-1970,	1971-1980,	1981-1990
RAF-facility 200 Aue shaft 371:		1959-1970,	1971-1980,	1981-1990
Colliery 050 Aue:	1950-1960,	1961-1970,	1971-1980	

Processing stages in processing facilities and RAF-/RAS-facilities were determined to allow for comparability of equivalent activities (Lehmann et al. 1998 p. 178).

The annual exposure to radon gas for 2000 working hours per year $E^*(p(t,o_0),o_0,s(j))$ in the different processing stages $s(j)$ in the reference objects were obtained through measurements; for the periods without detailed measurements (101 Crossen: 1950-1962, 102 Seelingstädt: 1960-1962, 050 Aue: 1950-1960), annual exposures to radon progeny were estimated retrospectively by experts based on the first routine measurements (Kreuzer et al. 2015a; Lehmann et al. 1994 pp. 88–90, 1998 pp. 170–171). The retrospective estimates took into account parameters related to production, milling techniques, spatial arrangement and available measurements (Lehmann et al. 1994).

The material used for the determination of E^* was according to Lehmann et al. (1994 pp. 90, 97, 103, 1998 p. 482) as follows:

Table 19: Material used for the estimation of the annual exposure to radon gas in the processing companies based on regular radon gas concentration measurements.

	Applied for object(s)	
Material	Object no.	Object names
Measurements and dosimetric reports for processing facility 101 Crossen	101	Processing facility Crossen
Measurements and dosimetric reports for processing facility 102 Seelingstädt	102	Processing facility Seelingstädt
Dosimetric reports of mining object 009 Aue from 1962 to 1980	050, 200	Colliery 050 Aue, RAF-facility shaft 371
Report of the dosimetric service of the SDAG Wismut 1957	050, 101	Colliery 050 Aue, processing facility Crossen
Mean values of the radon concentration in the objects of the SDAG Wismut of 1965	101, 102	Processing facilities Crossen and Seelingstädt
Descriptions of the work hygiene situation by interview partners	101	Processing facility Crossen
Assumption of increased RDP concentrations in cellars and pump rooms by the factor 2-3 in comparison to the 1980ies	101	Processing facility Crossen
Large-scale contaminations of the production rooms through frequently occurring technological disturbances	101	Processing facility Crossen
Usage of waste rock pile material as building-material additive and for landfill	101	Processing facility Crossen
File note of the radiation protection commissioner of the SDAG Wismut regarding the job of the concentrate presser	102	Processing facility Seelingstädt

Material	Applied for object(s)	
	Object no.	Object names
Information of the environment protection department of the SB Aue	050, 200	Colliery 050 Aue, RAF-facility shaft 371
Evaluation of the radiation protection of colliery 50 at 08.03.1982	050	Colliery 050 Aue

Measurements in processing facility 102 Seelingstädt were used for years without measurements in processing facility 101 Crossen (Lehmann et al. 1998 p. 165).

4.5.4. Step 2: Exposure during single periods in non-reference objects

Annual exposure to radon progeny of workers with 2000 working hours per year in other objects than the reference objects $E^{2000}(p(t,o),o,s(j))$ are obtained through weighting the respective exposure values of the reference objects $E^{2000}(p(t,o),o_0(o),s(j))$ with the object weighting factor $z(o,s(j))$ depending on the processing stage $s(j)$ (Lehmann et al. 1998 pp. 173, 179, 184):

$$E^{2000}(p(t,o),o,s(j)) = E^{2000}(p(t,o),o_0(o),s(j)) \cdot z(o,s(j))$$

Criteria for the comparison and evaluation of different objects regarding the exposure to radiation are the following (Lehmann et al. 1994 pp. 107, 112, 1998 pp. 171–173):

- Annual throughput (“Jahresdurchsatz”) and mean uranium contents of the processed ore
- Condition and suitability of the facilities and the applied technologies
- Single measurements of the exposure to radiation
- Evaluations of experts

Table 20 shows the evaluations of the objects regarding the exposure to radiation. In Appendix B (Table B1), the weighting factors for the single processing stages are listed.

Table 20: Evaluations of the processing companies regarding the exposure to radiation in comparison to the reference object of each type of processing company (Lehmann et al. 1998 pp. 173, 179, 184). Reference objects: processing facilities: 101 Crossen, RAS-/RAF-facilities: 200 Aue shaft 371, collieries: 050 Aue.

	Processing facilities								RAS-/RAF-facilities					Collieries				
	101	031	032	093	095	098	099	100	200	202	203	205	206	050	051	052	054	058
Comparetive measure	Crossen	Lengen-feld	Tannen-bergsthal	Freital	Gittersee	Johann-georgen-stadt	Ober-schlema	Aue	Aue shaft 371	Aue shaft 38	Pöhla	BB Schmir-chau shaft 367/368	BB Willi Agatz	Aue	Johann-georgen-stadt	Ober-schlema	Anna-berg	Breiten-brunn
Suitability of buildings	0	+	0	+	+	+	0	0	0	-	0	0	0	0	-	-	-	-
Technological density / constriction	0	+	0	0	+	-	-	0	0	-	+	-	+	0	-	-	-	-
Cellar rooms	0	+	+	+	+	+	+	+										
Ventilation / exhaustion	0	+	0	0	+	-	0	0	0	-	+	0	0	0	-	-	-	-
Manual activity	0	0	-	-	0	0	0	-	0	0	0	0	0	0	0	0	0	0
Technological disruptions	0	+	-	0	0	0	-	+										
Loading / unloading / transportation									0	-	0	+	0					
Milling / classification									0	-	0	-	0					
Radiometric gradation									0	-	0	0	0					
Exposure to dust									0	-	+	-	0	0			-	-
Exposure to radon									0	+	+	+	+	0		-	-	0
Exposure to external radiation									0	+	+	+	+	0		0		-

0	Level of reference object
-	Worse/more inconvenient than in the reference object
+	Better/more convenient than in the reference object

4.5.5. Step 3: Exposure for each calendar year

Since exposure was assessed for time periods in the previous steps, the adjustment for the actual working time of an individual was accomplished in step 3 through a working time factor $w(t,o)$:

$$E(t,o,s(j)) = E^{2000}(p(t,o),o,s(j)) \cdot w(t,o)$$

The working time varied depending on the calendar year and the type of processing object (Lehmann et al. 1994 p. 89):

Table 21: Working time factors for processing companies in the SAG/SDAG Wismut as assumed in Lehmann et al. (1994 p. 89).

	w(t,o)	
Type	1946-1965	1966-1990
Processing facilities, RAS-/RAF-facilities	1.2	1.0
Collieries, sampling and packaging of concentrates in processing facilities 101 Crossen and 102 Seelingstädt	0.9	0.88

4.6. Retrospective modifications of exposure estimations (JEM 2)

The previously described exposure estimations, which were published in Lehmann et al. (1998) and used in a first version of the JEM, were retrospectively adapted for scientific purposes as documented in Lehmann (2004) resulting in the second version of the JEM. Only exposure estimations for underground mining and open pit mining objects were retrospectively adapted, but not the exposure estimations for processing companies. The majority of the retrospective changes relied on expert knowledge and were not based on additional radon measurements. These modifications were necessary due to the following reasons (Lehmann 2004 pp. 5, 7–8, 225):

1. Heterogeneous exposure throughout a diggings and different shafts
2. Occupational histories of the workers in an object might cover longer periods than the operating time of the object, because of
    a. lead and follow-up times (“Vor- und Nachlaufzeiten”) of the object
    b. unconsidered changes in the assignment of shafts/diggings to objects and
    c. continued employment (“Weiterbeschäftigung”) in other objects.
3. Shafts of the same diggings might be assigned to different objects, e.g. for securing the raw materials base (“Absicherung der Rohstoffbasis”) (Lehmann 2004 p. 142).
4. Erroneous assignment of single shafts to objects (double naming)

More details to the retrospective modifications of exposure estimations can be found in Appendix A (Section A 2).

After a discussion of the reasons for the discrepancy between the occupational histories and the operating time of the objects with the ZeBWis (Lehmann 2004 p. 8), the experts agreed on the further procedure for the individual exposure estimation.

Exposure estimations relating to diggings, sections of diggings or, if possible, shafts were developed in Lehmann (2004) based on criteria which will be summarized in the following sections and which are visualized with different colors in Figure 9. The modifications were based on the production-related development of the mining areas (Lehmann 2004 p. 101).

Figure 9 gives an overview of the changes of the second version of the JEM (Lehmann 2004) compared to the first version (Lehmann et al. 1998). It visualizes the type of adaptation for each calendar year and each shaft group. The figure was developed for the objects and sections described in Lehmann (2004). The changes of JEM 2 in comparison to JEM 1 (Lehmann et al. 1998) were already marked with two colors in the table section of Lehmann (2004):

- Yellow: added values
- Green: changed values

We extended the categorization for the development of Figure 9 according the detailed explanations of the changes in JEM 2 given in Lehmann (2004 pp. 100–225). The first two columns of Figure 9 identify the shaft group; in the following the shaft groups which consist of several shafts will be abbreviated by the number of the firstly specified shaft with an additional “s”. Object labelling of Lehmann (2004) is retained for clarity, which concerns the objects listed in Table 22.

Table 22: Overview of objects of the SAG/SDAG Wismut occurring in the Wismut cohort with deviating object labelling in Lehmann (2004) in comparison to Table 2.

Work place	Table 2	Lehmann (2004)	Alternative object names
Underground mining object	091	009 400	Bergbauabteilung Pöhla
	901	090 352	BB Lichtenberg
	902	090 385, 379	BB Reust
	903	090 356	BB Schmirchau
	904	090 384	BB Paitzdorf
	905	090 397	BB Beerwalde
	906	090 403	BB Drosen
	908	000 390	BB Königstein
Open pit mining object	300	090 566	Lichtenberg
	301	090 562	Stolzenberg
	302	090 557	Ronneburg/Raitzhain
	303	090 558	Sorge
	304	090 560	Gauern
	306	090 563, 564, 565	Culmitzsch, Culmitzsch (Mücke), Culmitzsch-Nord, Culmitzsch-Süd
	307	090 561	Trünzig
	308	090 559	Steinach
	309	090 556	Erlau/Hirschbach, Tagebaue in der Region Schleusingen
		090 555	Tagebaue allgemein

The column “Cat.” of Figure 9 summarizes main reasons for changes, as listed in Table 23 and relationships between different objects.

Table 23: Legend for column "Cat." in Figure 9. Further details to the reasons for adaptations can be found in Appendix A (Section A 2.2).

Letter	Reason for adaptation
A	Adoption
I	Temporary independence
G	Geologic assignment
F	Further amendments

Object	Shafts	Abbreviation	Cat.
000	390	000 390	
001	000	001 000	
001	001, 002, 018, 022, 030, 031, 032, 039, 051, 053, 054, 055, 056, 058, 060, 061, 120, 121, 122, 145, 147, 999	001 001s	I 010
001	021, 078	001 021s	A 004, 007
001	023, 087, 098, 126, 164, 253, 336	001 023s	A, G 008
001	235	001 235	A 008, 009
002	000, 004, 005, 006, 007, 008, 014, 015, 016, 999	002 000s	
002	064	002 064	G 009
002	065	002 065	
002	063, 067	002 063s	
002	012, 027, 127	002 012s	A 009
002	309, 310, 311, 312	002 309s	A 009
002	172, 275	002 172s	
002	013	002 013	A 009
003	000, 003, 009, 010, 011, 026, 083, 130, 173	003 000s	A 009
003	999	003 999	A 009
004	000, 019, 020, 021, 028, 029, 033, 049, 078, 079, 080, 116, 117, 132, 182, 231, 999	004 000s	A 001, 007
004	034	004 034	G 007
005	000, 044, 045, 046, 048, 068, 084, 085, 106, 137, 138, 139, 152, 238, 262, 302, 999	005 000s	A 007
005	251, 283, 303, 322	005 251s	
005	292	005 292	G 007
006	000, 277, 294, 320, 362, 999	006 000s	A 009
006	254	006 254	
006	241, 244, 252, 343, 344, 347	006 241s	
006	181, 295	006 181s	
006	381	006 381	
006	092, 095, 269	006 092s	A 015, 096
007	000, 034, 111, 169, 245, 281, 999	007 000s	G 004
007	097, 191, 249, 292, 327	007 097s	G 005
007	206, 257, 278	007 206s	A 008
007	021, 049, 078, 132, 182	007 021s	A 001, 004
007	045, 238	007 045s	A 005
008	206, 257, 278	008 206s	A 007
008	240, 247, 306	008 240s	
008	023, 087, 098, 126, 164, 204, 253, 332, 336, 337	008 023s	A, G 001
008	000, 203, 235, 248, 333, 999	008 000s	A 001, 009

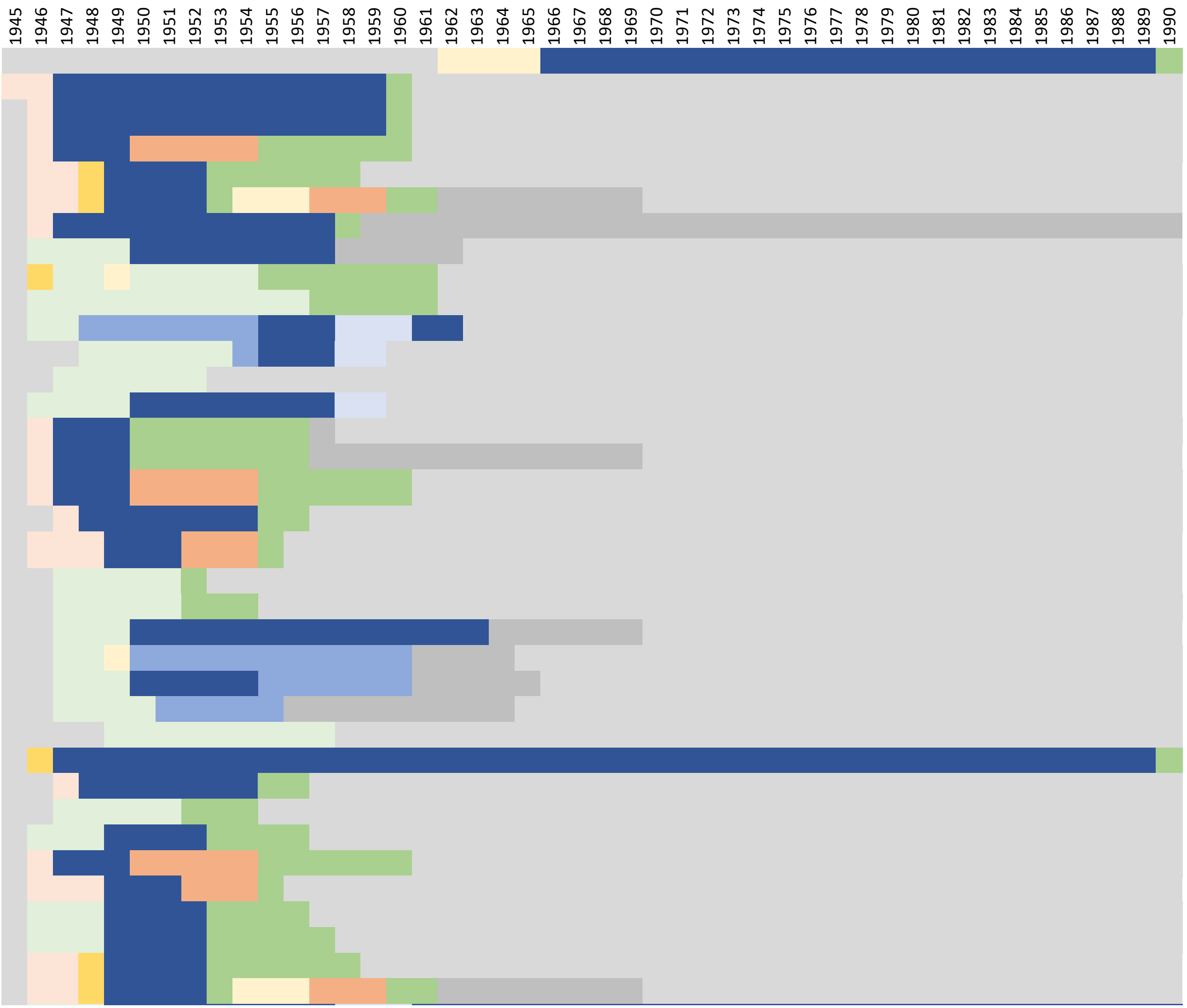

Figure 9a: Modifications of the first version of the JEM to obtain shaft-specific radon exposure for a worker in a reference activity in objects of the SAG/SDAG Wismut according to Lehmann et al. (1998) and Lehmann et al. (2004) (part 1). Objects are labeled according to Lehmann (2004). A more detailed figure can be found in Appendix B (Figure B4).

Object	Shafts	Abbre-viation	Cat.
009	000, 072, 170, 186, 207, 208, 250, 296, 366, 371, 999	009 000s	G 002
009	012	009 012	A 002
009	013, 038, 066	009 013s	A 002
009	003, 010	009 003s	A 003
009	041, 082, 129, 246	009 041s	
009	310, 312	009 310s	A 002
009	235	009 235	A 001, 008
009	277	009 277	A 006
009	400	009 400	
010	000, 018, 039, 053, 054, 055, 056, 058, 060, 061, 120, 999	010 000s	I 001
011	000	011 000	A 009
012	000	012 000	
013	000	013 000	
014	000	014 000	
015	000, 101, 104, 118, 196, 209, 293, 999	015 000s	G 096
015	113, 115	015 113s	
015	092, 093, 094, 095, 096, 269	015 092s	A 006, 096
021	000, 999	021 000s	
022	000, 999	022 000s	
023	000	023 000	
024	000	024 000	
025	000	025 000	G 096
026	000	026 000	
027	000	027 000	
028	000	028 000	
029	000, 297, 299, 313, 330	029 000s	G 047
030	000, 345, 353, 999	030 000s	
047	000	047 000	G 029
086	000, 353	086 000s	

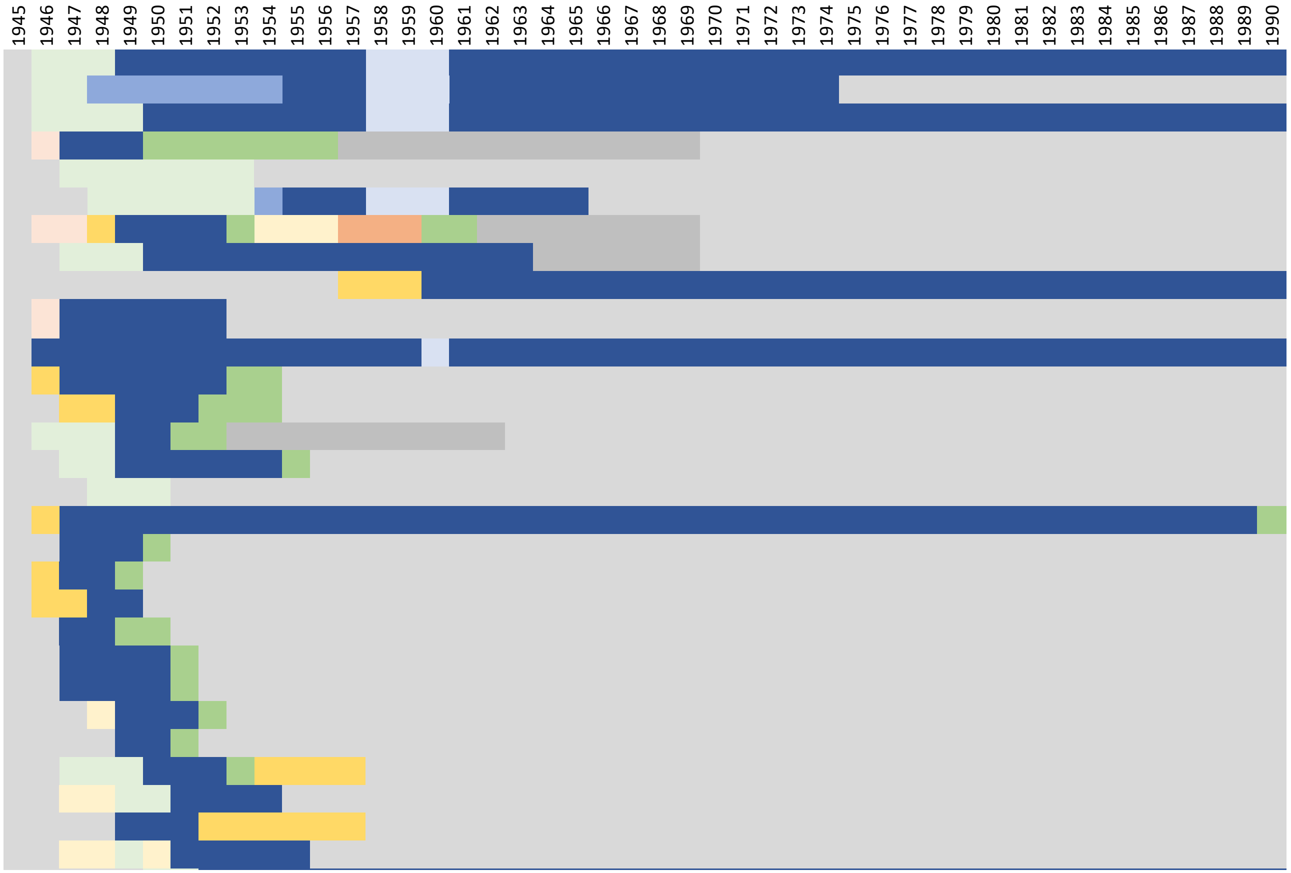

Figure 9b: Modifications of the first version of the JEM to obtain shaft-specific radon exposure for a worker in a reference activity in objects of the SAG/SDAG Wismut according to Lehmann et al. (1998) and Lehmann et al. (2004) (part 2). Objects are labeled according to Lehmann (2004). A more detailed figure can be found in Appendix B (Figure B4).

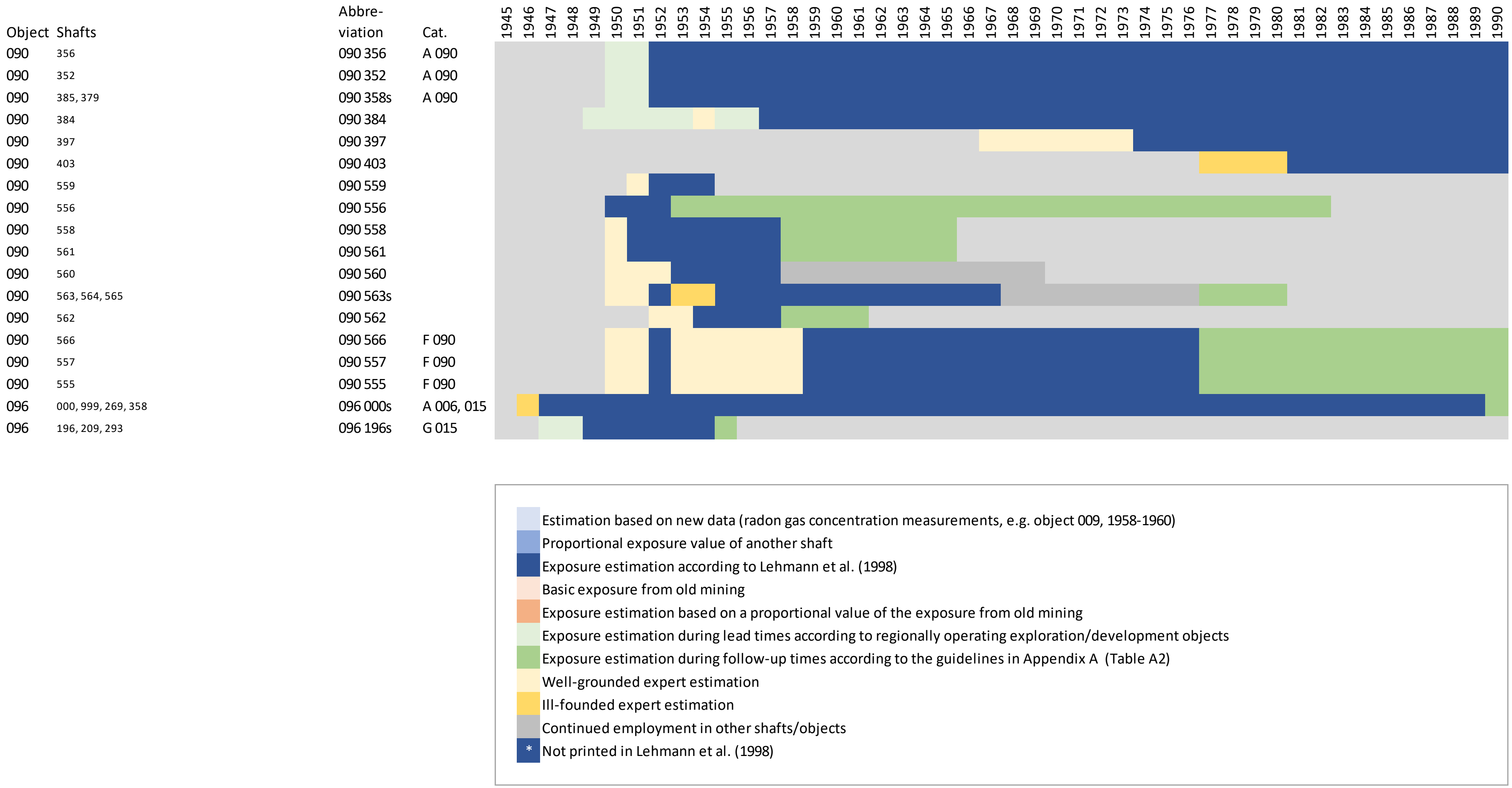

Figure 9c: Modifications of the first version of the JEM to obtain shaft-specific radon exposure for a worker in a reference activity in objects of the SAG/SDAG Wismut according to Lehmann et al. (1998) and Lehmann et al. (2004) (part 3). Objects are labeled according to Lehmann (2004). A more detailed figure can be found in Appendix B (Figure B4).

4.7. Estimation of individual exposure

4.7.1. Activity-specific exposure

In HVBG and BBG (2005), activity-specific exposure estimations $E(t,o,j)$ are assessed on the basis of exposure estimations for year t, object o and reference activity $j_0(o)$ or processing stage $s(j)$, respectively, by weighting with activity weighting factors $f(t,o,j)$ for jobs in mining or open pit mining objects or by assigning the activities to the processing stages $f(p(t,o),o,j)$ for jobs in processing companies.

Underground mining objects

The exposure to radon progeny $E(t,o,j)$ of a worker conducting activity j is assessed on the basis of the exposure to radon progeny of a reference activity $j_0(o)$:

$$E(t,o,j) = E(t,o,j_0(o)) \cdot f(t,o,j)$$

The reference activity for workers in underground mining objects is the activity of a hewer and the activity weighting factor for the reference activity is one; only for surface areas that are affiliated to underground mining, the reference activity is worker in ore milling (Lehmann et al. 1998 p. 107). The categorization of the activities was based on a list of activities which was developed by the ZeBWis (Lehmann et al. 1998 p. 108). It included more than 700 different jobs and activities underground, in open pit mining, processing or surface. Experts of a committee of specialists (radiation safety officers, technologists of the former mining companies of SDAG Wismut and staff of BBG BV Gera) determined the values of the activity weighting factors $f(t,o,j)$ based on the following criteria which were deviated from the “Katalog der physischen Belastung und der Herz-Kreislauf-Beanspruchung im Arbeitsprozeß” (Arbeitshygienisches Zentrum Niederdorf des Gesundheitswesens Wismut) (Lehmann et al. 1998 p. 108):

- degree of ore contact
- respiratory volume per hour
- energy expenditure per shift
- exposure time per shift
- task and behavior of the activity group

Activity weighting factors vary between zero and one; only the activity weighting factor of a “Meister Förderung” in the object 908 BB Königstein is larger than one (Lehmann et al. 1998 p. 262), maybe due to a typing error. The main list of activity weighting factors for exposure to radon progeny of underground miners can be found in Lehmann et al. (1998 pp. 256–266). The factors for a few activities vary between the Ore Mountains/Vogtland, the Thuringian region and object 908 BB Königstein. For workers in surface areas affiliated to underground mining, separate activity weighting factors were defined (Lehmann et al. 1998 pp. 107, 141, 289–290).

Open pit mining objects

The exposure to radon progeny of a worker conducting activity j is assessed on the basis of the exposure to radon progeny of a reference activity $j_0(o)$:

$$E(t,o,j) = E(t,o,j_0(o)) \cdot f(p(t),o,j)$$

with $p(t)$ referring to the four periods: 1946-1962, 1963-1967, 1968-1976, 1977-1990. The reference activity for workers in open pit mining objects is the activity of a hewer in open pit mining and the activity weighting factor for the reference activity is one. The activity weighting factors for open pit mining objects, $f(p(t),o,j)$, were determined to be different for the four periods $p(t)$. Similar to mining objects, experts of a committee of specialists determined the values of the activity weighting factors $f(p(t),o,j)$ based on the following criteria which were deviated from the "Katalog der physischen Belastung und der Herz-Kreislauf-Beanspruchung im Arbeitsprozeß" (Lehmann et al. 1998 p. 160):

- degree of ore contact
- respiratory volume per hour
- energy expenditure per shift
- exposure time per shift
- task and behavior of the activity group

The activity weighting factors vary between zero and one. The main list of activity weighting factors for exposure to radon progeny of open pit miners can be found in Lehmann et al. (1998 pp. 300–301).

Processing companies

The estimation of radiation exposure $E(t,o,s(j))$ in the processing stage $s(j)$ was described in Section 4.5. The assessment of the exposure $E(t,o,j)$ of a worker conducting activity j was based on the radiation exposure $E(t,o,s(j))$ in the corresponding processing stage $s(j)$:

$$E(t,o,j) = E(t,o,s(j))$$

The resulting exposure values can be found in Lehmann et al. (1998 pp. 322–333, 358–369, 394–405). The categorization of the activities was carried out by means of a list of activities which was developed by the ZeBWis (Lehmann et al. 1994 p. 115, 1998 p. 186). If an activity could be assigned to several processing stages, the time-weighted mean exposure of these processing stages was calculated. The average time spent in the pre-defined processing stages in each facility was determined by expert rating (Lehmann et al. 1994). The exposure to radon progeny for the job colliery worker ("Zechenarbeiter") was determined as the mean exposure of all processing stages in the core process ("Grundprozess"); final processing ("Endverarbeitung") was only partially considered (Lehmann et al. 1994 p. 115, 1998 p. 186). The exposure to radon progeny for workers in the auxiliaries ("Hilfsabteilungen"), for managing staff and other personnel with frequently changing work places was determined by the weighted exposure of a colliery worker. The weights can be found in Lehmann et al. (1994 p. 131, 1998 pp. 483–484).

4.7.2. Individual exposure for the documented occupational history

To obtain individual annual exposure to radon progeny the values from the JEM are multiplied by weighting factors for individual activities according to the individual occupational history.

Data on the occupational histories had been extracted from the payrolls on a daily basis, including information on the type of job, type of mining facility, area of work place, number of special underground shifts and periods of absence. In a feasibility study, a lot of effort had been spent to retrieve complete information from the payrolls. For about 200 cohort members data had been extracted from Wismut files a second time. Some discrepancies led to an improved standardized data collection procedure for the main cohort study. During the whole data collection period detailed double plausibility checks had been performed at the German Social Accident Insurance (DGUV) and the Federal Office for Radiation Protection. Implausible, incomplete or unclear data were returned to DGUV, where the data were re-examined and corrected. Thus, a high validity of these data can be assured. (Kreuzer et al. 2010c)

Individual exposure for the complete calendar year

Individual exposure to radon progeny $E(i,t)$ was estimated with the individual exposure for the complete calendar year $E^A(i,t)$ corrected by the exposure during special underground shifts $E^{UT}(i,t)$ and absenteeism $E^F(i,t)$:

$$E(i,t) = E^A(i,t) + E^{UT}(i,t) - E^F(i,t)$$

Individual exposure for the complete calendar year $E^A(i,t)$ was estimated as the time-weighted sum of the radon progeny concentrations of potentially different objects o and activities j of individual i in calendar year t:

$$E^A(i,t) = \sum_{o,j} l(i,t,o,j) \cdot E(t,o(i,t),j(i,t))$$

$l(i,t,o,j)$ denotes the proportion of days per year t of individual i working in object o conducting job j.

Individual exposure during special underground shifts

Single underground shifts with the potential of conducting more than one activity were registered for employees of objects without any exposure to radiation. The exposure during these special underground shifts of individual i in calendar year t, $E^{UT}(i,t)$, was estimated using mean exposure values for the reference activity $\bar{E}(t,o,j_0(o))$ and mean activity weighting factors $\bar{f}(t,o,j)$ of the affiliated mining object(s) o:

$$E^{UT}(i,t) = l^{UT}(i,t) \cdot \bar{E}(t,o(i,t),j_0(o(i,t))) \cdot \bar{f}(t,o(i,t),j(o(i,t)))$$

$l^{UT}(i,t)$ denotes the proportion of days in year t in special underground shifts of individual i. The calculation of mean exposure values and mean activity weighting factors for worker i and calendar year t is only necessary if more than one entry with underground shifts was registered in the occupational history of worker i and calendar year t. This may for example occur, if the individual conducted different activities or worked in several objects within calendar year t.

Individual exposure during absenteeism

Individual exposure during longer absenteeism was calculated in order to correct the individual exposure during a calendar year for days absent from work (i.e. days without exposure). The exposure during absenteeism of individual i in calendar year t, $E^F(i,t)$, was estimated using mean exposure values $\bar{E}(t,o,j)$ and mean activity weighting factors $\bar{f}(t,o,j)$ for the scheduled activities as follows:

$$E^F(i,t) = l^F(i,t) \cdot \bar{E}(t,o(i,t),j(i,t)) \cdot \bar{f}(t,o(i,t),j(o(i,t)))$$

where $l^F(i,t)$ denotes the proportion of months in calendar year t of absenteeism of individual i. The calculation of mean exposure values and mean activity weighting factors for worker i and calendar year t is again only necessary if more than one entry with absenteeism was registered in the occupational history of worker i and calendar year t. This is for example the case, if the individual was absent in different activities or objects within calendar year t.

5. Potential sources and characteristics of uncertainties in exposure assessment

The elaborated exposure assessment procedure provides well-grounded exposure estimates, but may involve a large number of potential uncertainties. The detailed formalized presentation of the exposure assessment procedure permits the identification of potential sources of uncertainties. A comprehensive view of the type, distribution and structure of the uncertainties in exposure assessment is given in this chapter as an essential step towards the evaluation of the potential relevance of the uncertainties for the statistical analysis and the implementation of methods accounting for measurement error.

5.1. Statistical concept of measurement error

The characteristics of the measurement errors are closely related to their sources. The different relevant types of measurement errors are outlined in this section providing the groundwork for the characterization of the potential sources and types of uncertainties in the following sections. Differentiation of the error types is essential for the evaluation of their epidemiological relevance (Heid et al. 2004).

The exact radon progeny concentration, X, could not be observed. Instead, an error-prone radon progeny concentration, X^*, was estimated. As a consequence of the various steps and approaches of exposure assessment, various types of measurement errors, U, occur. Measurement errors are either systematic or random (see for example Allodji et al. 2012a).

Systematic measurement error is not stochastic, results in a systematic bias of the exposure estimation and is constant for all observations or for subgroups of observations (e.g. within certain time periods):

$$U = \text{const.} \quad \text{or} \quad U_k = \text{const.}$$

with $k = 1, \dots, K$ indicating the subgroups of observations.

Two types of random measurement errors are differentiated in the statistical concept of measurement error: classical measurement error and Berkson error. In the case of classical measurement error, the observed error-prone values X^* represent the unobserved true values X overlaid with measurement error U:

$$X^* = X + U$$

In contrast, the observed Berkson error-prone values X^* represent an aggregate of the unobserved true values X, e.g. ambient pollutant concentrations as surrogate for individual pollutant concentrations (Tosteson et al. 1989):

$$X = X^* + U$$

Usually, random errors of both types are assumed to be independent and identically distributed and to follow a normal distribution:

$$U \sim \mathrm{N}(0, \sigma_U^2)$$

Moreover, two additional sub-types of random measurement errors are considered: specific (or heteroscedastic) error and temporally autocorrelated error. Specific error or shared error called, e.g. object-specific error, ν_k, is assumed to be identically distributed for subgroups of observations which are defined by a categorical variable (e.g. object, shaft) with values $k = 1, \dots, K$:

$$\nu_k \sim \mathrm{N}(0, \sigma_\nu^2)$$

Temporally autocorrelated error may occur in time series data through temporal dependencies between the errors; these temporal dependencies may be restricted to single subgroups, $k = 1, \dots, K$, of observations, as e.g. to the observations of the single individuals in longitudinal data:

$$\boldsymbol{U}_k \sim \mathrm{N}(0, \sigma_U^2 \boldsymbol{W}_k)\ ,\ \ \boldsymbol{W}_k \text{ correlation matrix}$$

5.2. Uncertainties in exposure assessment in other cohort studies

Uncertainties in exposure assessment have already been extensively investigated for the French uranium miners cohort (Allodji et al. 2012a, 2012b, 2012c; Hoffmann et al. 2017); an overview on the French uranium miners cohort is given in Appendix A (Section A 1). Six primary sources of uncertainty in the exposure assessment are identified: natural variations of exposure, precision of the measurement device, approximation of the equilibrium factor, human error, estimation of the working time, and record keeping/data transcription (Allodji et al. 2012a). The complex exposure assessment procedure for the Wismut cohort requires a more general framework for the evaluation of exposure uncertainties. This framework comprises the uncertainties identified for the French uranium miners cohort.

Lubin et al. (1995) and Heid et al. (2004) study measurement error in residential radon exposure assessment. One important source, which both of the studies mention in conjunction with the study from Allodji et al. (2012a), is the potential error in the equilibrium factor for the conversion of measured radon gas concentrations to radon progeny concentrations. Both articles identify errors as results of the following problems, which bear resemblance to difficulties occurring for the measurement of occupational radon exposure:

1. Devices which are installed at a fixed place in a room ignore the variability inside this room
   → Corresponds to the problem of measurements at a fixed site in the mines
2. Measurements are often taken in one or two rooms only, so the variability between rooms is not taken into account
   → Corresponds to the problem of assigning the measurements taken in one object to another, similar object
3. Concerning the occupancy of the homes by the study subjects, imprecisions in the measurement of occupancy time as well as its temporal variation lead to uncertainties
   → Corresponds to the uncertainties occurring during the estimation/documentation of the working time in general and additionally to the working time spent underground or on the surface

5.3. Overview

Error components of the exposure estimations for the Wismut cohort are overviewed, described in detail and classified in the following. Therefore, we distinguish between two main steps in the exposure assessment procedure (Figure 10):

(I) Generalization: Assessment of shaft-specific exposure, i.e. the annual exposure to radon progeny for the reference activity separately for each shaft/object, based on averaged radiation concentration measurements and expert evaluations

(II) Assignment: Assessment of individual radon progeny exposure based on shaft-specific exposure

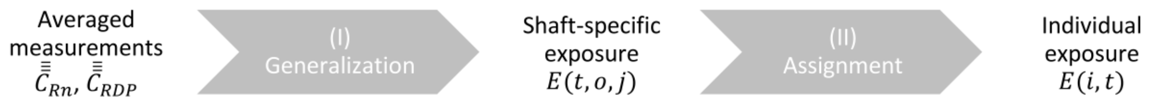

Figure 10: The two main steps in exposure assessment for the Wismut cohort.

Estimation errors occur in both steps of exposure assessment and depend on the estimation approach (experts' estimation, estimation based on concentration measurements, etc.). The uncertainty which can occur in the first step of the estimation procedure by using averaged radiation concentration measurements from measurements at single measurement sites and few time points to assess shaft-specific exposure, we denote as generalization error ("Generalisierungsfehler"). In the second step, assignment error ("Zuordnungsfehler") may arise through the use of shaft-specific exposure to assess individual exposure.

The measurement error of the exposure estimates is a mixture of three major error types: generalization error, assignment error and estimation error. In general, these three major error types are implicitly attended by the usage of a JEM for individual exposure assessment. Each of the three major error types is composed of uncertainties from various sources, which are structured in Figure 11a and 11b and explicated in detail in the subsequent subsections.

The various measurement errors in the exposure estimates of the Wismut cohort can be summarized with a few categories with potentially multiple effects on a single exposure estimate:

- Generalization error
- Assignment error
- Estimation error
    - Procedural measurement error
    - Documentation error
    - Parameter uncertainties
    - Experts' evaluation error
    - Transfer error
    - Approximation error

The exposure estimates are simultaneously affected by several categories of measurement error.

In general, generalization error is of classical error type, assignment error is of Berkson error type and estimation error may be of classical or Berkson error type.

Error in the annual, shaft-specific exposure (JEM, reference activity)

- Generalization error
  - Spatial: object, shaft, work place, measurement site
  - Temporal: season, day, shift, time point
  - Activity
- Estimation error
  - Estimation based on radon progeny measurements
    - $E(t,o,j_0(o)) = E^{2000}(t,o,j_0(o)) \cdot w(t,o) = \bar{\bar{\bar{C}}}_{RDP}(t,o) \cdot 12 \cdot c(o) \cdot w(t,o)$
    - Procedural measurement error: $\bar{\bar{\bar{C}}}_{RDP}(t,o)$ (radon progeny)
    - Documentation error
    - Parameter uncertainties: working time factor $w(t,o)$, ventilation disruption correction factor $c(o)$
    - Approximation error: rounding, estimation equation
  - Estimation based on radon gas measurements
    - $E\big(t,o,j_0(o)\big) = E^*\big(t,o,j_0(o)\big) \cdot g(t,o) \cdot w(t,o)$
      $= \bar{\bar{\bar{C}}}_{Rn}(t,o) \cdot 12 \cdot g(t,o) \cdot w(t,o)$
    - Procedural measurement error: $\bar{\bar{\bar{C}}}_{Rn}(t,o)$ (radon gas)
    - Documentation error
    - Parameter uncertainties: equilibrium factor $g(t,o)$, working time factor $w(t,o)$
    - Approximation error: rounding, estimation equation
  - Experts' estimation
    - Object-specific experts' estimation (Lehmann et al. 1998)
      - Procedural measurement error: $\bar{\bar{\bar{C}}}_{Rn}(t,o)$ (radon gas)
      - Documentation error
      - Parameter uncertainties: many, depending on object and time
      - Approximation error: rounding, estimation equation (incl. specification)
      - Transfer error: transfer of conditions in reference objects/years
    - Retrospective adaptions, experts' evaluations (Lehmann et al. 1998; Lehmann 2004)
      - Transfer error: transfer of exposure values from other objects/years, depending on the underlying evidence
      - Experts' evaluation error regarding exposure

Figure 11a: Overview of uncertainties in exposure assessment for the Wismut cohort (part 1).

Error in the individual exposure

- Assignment error
  - Spatial: shaft-specific average
  - Temporal: annual average
  - Activity
  - Working time
- Estimation error
  - $E(i,t) = E^{A}(i,t) + E^{UT}(i,t) - E^{F}(i,t)$
  - Documentation error: times of special underground shifts and absenteeism
  - Approximation error: rounding, estimation equation
  - Parameter uncertainties: activity factor $f(t,o,j)$

$$E(t,o,j) = E(t,o,j_0(o)) \cdot f(t,o,j)$$

Figure 11b: Overview of uncertainties in exposure assessment for the Wismut cohort (part 2).

5.4. Detailed description

The error components of the exposure estimations for the Wismut cohort, which are overviewed in the previous section, will be described in detail in this section. Therefore, subtypes of the error components will be specified and will be related to the statistical context of measurement error. The results are summarized for each error component using a figure with a structure as shown in the schematic Figure 12.

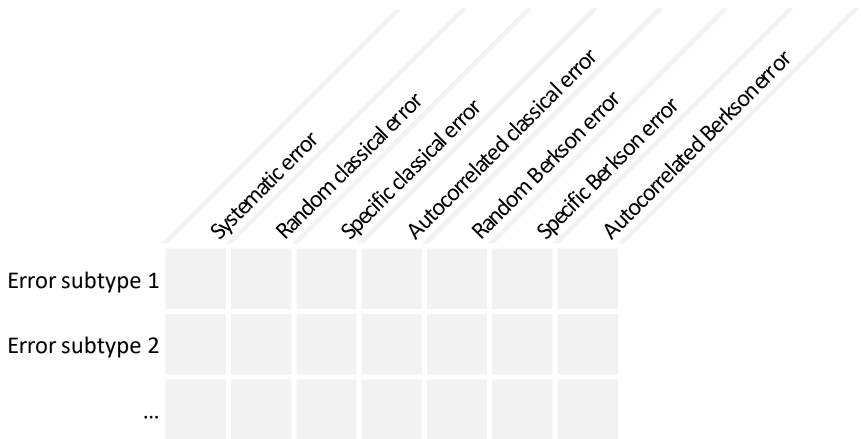

Figure 12: Graphical structure of figures for the summarized description of error components.

The subtypes of the error components are listed in the rows of Figure 12 and the statistical types of measurement error in the columns of Figure 12. The following statistical types of measurement error are considered:

- Systematic error
- Classical error: random, specific, autocorrelated
- Berkson error: random, specific, autocorrelated

Crosses mark the statistical error types of the corresponding error subtype regarding the exposure estimations for the Wismut cohort.

5.4.1. Generalization error

Generalization error arises through the usage of averages of single exposure measurements for shaft-specific exposure assessment. The generalization error in the Wismut cohort consists of three aspects: spatial, temporal and activity generalization error. Generalization errors are of classical type (Heid et al. 2004) and are classified in detail as shown in Figure 13.

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Spatial generalization error		X	X				
Temporal generalization error	X	X	X				
Activity generalization error	X	X	X				

Figure 13: Types of measurement errors: generalization errors.

Spatial generalization error

Single radiation concentration measurements at certain sites serve as basis for assessing work-place-specific, shaft-specific and object-specific exposure (cf. Heid et al. 2004; Lubin et al. 1995). The generalization of measurements at single sites results in random classical measurement error (Heid et al. 2004; Lubin et al. 1995), which may potentially depend on spatial units (specific classical error). Since the selection procedure of measurement sites was not documented in the available literature, the appropriateness of the selected sites cannot be verified. Furthermore, the objects 007 Niederschlag-Bärenstein, 008 Breitenbrunn and 015 Freiberg, Niederpöbel were operating in several diggings, but exposure values averaged over the diggings were determined for these objects (Lehmann et al. 1998 p. 78). There is no evidence that the selection of the measuring points leads to systematically biased measurements.

Temporal generalization error

For concentration measurements, air samples were collected over 5 minutes on an arbitrary time of day (predominantly during the morning shift) and on arbitrary days of the year (initially only twice a year (Eigenwillig 2011 pp. 43–45) and later once a month (see also Section 4.1)). Since these measurements were used to calculate annual exposure, diurnally and seasonally selective exposure samples and thus, random and specific temporal generalization error (extrapolation error in Dokument der BBG Gera 1991) of classical error type may result. Disruptions, disturbances, insufficient ventilation and blastings were only globally covered in the exposure assessment procedure (Dokument der BBG Gera 1991; Eigenwillig 2011 pp. 44, 46, 48–49, 54, 66), these proceedings may involve systematic errors.

Activity generalization error

Generalization error may also occur by using exposure measurements as the exposure during a certain activity (Dokument der BBG Gera 1991). Since exposure measurements reflect the true mean exposure of the reference activity with varying appropriateness, the error may vary randomly or between subgroups (random and specific error). Partially, measurements at mining and development work places were averaged and used for exposure assessment of a hewer; further, auxiliary processes were insufficiently monitored (Eigenwillig 2011 p. 45), e.g. a hewer only worked between 6 hours 45 minutes and 7 hours in the mining area (Lehmann et al. 1998 p. 60). Both can lead to systematic error.

5.4.2. Assignment error

Potential uncertainties in the assignment of exposure values to an individual worker may occur in a spatial and temporal respect as well as through the assignment of activities and average working time to individual workers. The classification of the assignment errors regarding statistical measurement error types is shown in Figure 14. Since the JEM comprises annual mean exposure values for each activity for several shafts or subdivisions instead of individual exposure values, the exposure values in the JEM exhibit Berkson error (Heid et al. 2004; Küchenhoff et al. 2007).

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Spatial assignment error					X	X	X
Temporal assignment error	X				X	X	
Activity assignment error					X	X	X
Working time assignment error					X	X	X

Figure 14: Types of measurement errors: assignment errors.

Spatial assignment error

Spatial assignment error arises because shaft-specific exposure values were used as aggregated exposure values of the individual employees working in a shaft neglecting the spatial variation of individual radon progeny concentrations (Heid et al. 2004; Reeves et al. 1998); Allodji et al. (2012a) refer to this source of uncertainty as “Natural variations of air-borne radon gas concentration”. Individual exposure may differ from the estimated annual exposure due to local radiation sources (random and autocorrelated Berkson error) and possibly due to some variability within the subdivisions (specific Berkson error) according to which the average values were determined.

Temporal assignment error

Temporal assignment error occurs because individual exposure, which varies seasonally and diurnally around the annual mean exposure of the shaft, is neglected with the use of annual exposure values $E(t,o,j)$ (Heid et al. 2004; Lubin et al. 1995). At first glance, temporal assignment error does not seem to be relevant because annual individual exposure is determined. However, this error may become particularly relevant for workers who change the shaft or object within a calendar year (random and subgroup-specific error). Since the JEM contains the exposure during normal operation, high exposure events are not covered by the temporally aggregated values. Thus, annual individual exposure based on the JEM tends to be underestimated and systematic error may occur.

Activity assignment error

An activity may be conducted differently between the workers; thus, exposure may be heterogeneous between the workers in the same job. The Berkson error in this case is not only random, but may be also specific (e.g. activity-specific) and autocorrelated.

Working time assignment error

Since individual working times were not documented, average working times were used for exposure assessment neglecting the individual variation of the working times (cf. Lubin et al. 1995). Random, subgroup-specific and autocorrelated working time assignment errors may occur.

5.4.3. Procedural measurement error

Device measurement errors and errors in the measurement procedure are called procedural measurement errors and are typically of classical type (Figure 15). Richter (1991) mentions three types of device measurement errors: methodical, calibration and statistical errors, which affect the following quantities:

$\bar{\bar{\bar{C}}}_{RDP}(t,o)$ Mean radon progeny concentration

$\bar{\bar{\bar{C}}}_{Rn}(t,o)$ Mean radon gas concentration

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Methodical error		X	X				
Calibration error			X				
Statistical error/precision		X	X	X			
Human error	X	X	X	X			

Figure 15: Types of measurement errors: procedural measurement error.

Methodical error

The methodical error denotes the error originating from the measuring approach itself. The methodical error of the MARKOV method substantially depends on the radioactive equilibrium between the short-lived Radon-222 progenies (Wismut GmbH 1999, 1.8.2, p. 12). We assume that the equilibrium conditions vary randomly between measuring locations or between shafts (random or specific classical error).

Calibration error

Calibration and maintenance of the devices was accomplished with high diligence (Wismut GmbH 1999, 1.8.2, p. 11). Nevertheless, calibration error may represent a further potential source of period- and device-specific uncertainty of classical error type (Heid et al. 2004); the periods were defined by the time points of recalibration.

Statistical error

Since measurements usually vary around the true value, the usage of measurement instruments is a potential source for exposure uncertainty which is quantified by the precision of the measurement device (cf. Allodji et al. 2012a; Heid et al. 2004; Lubin et al. 1995; Eigenwillig and Ettenhuber 2000 p. 11; Wismut GmbH 1999, 1.8.2, p. 12). The precision may be device-specific or temporally varying resulting in random, specific and autocorrelated statistical classical measurement error.

Human error

Errors of the dosimetrists during the measurement process is another procedural measurement error (Allodji et al. 2012a). Systematic as well as random (including specific, e.g. dosimetrist-specific, and autocorrelated) human errors are possible.

5.4.4. Documentation error

Documentation error, which may be intentional or unintended (Figure 16), occurs in the documentation of measurements (radiation measurements and measurements of other parameters included in exposure assessment) and the documentation of the individual occupational histories (location and time) (Dokument der BBG Gera 1991). Intentional documentation error results in systematically biased individual exposure estimates. Unintended documentation error may occur at several points of the documentation process and is of random or subgroup-specific classical error type.

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Intentional documentation error	X						
Unintended documentation error		X	X				

Figure 16: Types of measurement errors: documentation error.

The occupational history is essential for individual exposure assessment. The payrolls, which built the basis for the occupational histories, may contain erroneous entries. The following parameters characterizing the individual working times documented in the occupational histories were included in individual exposure assessment:

$l(i,t,o,j)$	Proportion of days per year t of individual i working in object o conducting job j
$l^F(i,t)$	Proportion of months per year t of individual i with absenteeism
$l^{UT}(i,t)$	Proportion of days per year t of individual i in special underground shifts

Moreover, assignment of the wrong activity to a worker may be possible either through an erroneous entry in the occupational history or through the retrospective changes of the activity labels.

Error may originate from the deficient assignment of an individual to an object or shaft. This aspect may be potentially relevant for only a few workers which were not assigned to the shaft/object documented in the occupational history, but to another shaft/object for which continued employment was assumed by the experts. Furthermore, the retrospective changes of the object/shaft labels may result in the assignment of the wrong shaft/object to a worker.

5.4.5. Parameter uncertainties

Uncertainties of the parameters used for exposure estimation represent a further potential source of uncertainty for exposure assessment (cf. the approximation of the equilibrium factor or the working time in Allodji et al. 2012a). The exposure estimation approaches for the Wismut cohort varied for different objects/shafts and calendar years. Many parameters were involved in the estimation procedure. The parameters can be categorized in three groups:

- Unbiased parameters based on measurements
- Unbiased parameters based on an aggregated evaluation of experts
- Biased parameters

“Aggregated evaluation” means that the expert determines the same value of a parameter for temporally and spatially comparable observations. The three parameter groups differ in the types of measurement error of the parameters (Figure 17).

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Unbiased parameters based on measurements		X	X				
Unbiased parameters based on an aggregated evaluation of experts					X	X	X
Biased parameters	X						

Figure 17: Types of measurement errors: parameter uncertainties.

Unbiased parameters based on measurements

The values of the following parameters were calculated from measurements:

$A(t, o)$	Evaluation area
$C(t, o)$	Mined vein area
$d(t, o)$	Depth
$F(t, o)$	Total shaft output
$h(o)$	Density of bedrock
$q(t, o)$	Percentage of total uranium recovery
$r(t, o)$	Relative uranium recovery rate
$R(t, o)$	Amount of uranium recovery
$R^R(t, o)$	Relative cumulative uranium recovery rate
$V(t, o)$	Void volume

Parameters based on measurements are supposed to exhibit a random and potentially specific classical device measurement error.

Unbiased parameters based on an aggregated evaluation of experts

The values of the following parameters were determined by experts without the help of measurements:

$b(o)$	Proportion of basic exposure from old mining in relation to object 003
$c(o)$	Correction factor for deficits and disruptions of the ventilation systems
$e(t, o)$	Evaluation factor
$f(t, o, j)$	Activity weighting factor

$g(t, o)$ Equilibrium factor (Lubin et al. 1995)
$w(t, o)$ Working time factor
$z(o, s(j))$ Processing stage-specific object weighting factor

The derivation of the correction factors $c(o)$ is documented in Lehmann (1998 pp. 85–87, 133; Richter 1994). The evaluation factor $e(t, o)$ denotes a measure of the exposure to radon per unit of the mined area for 2000 working hours per year in underground mining objects and a weighting factor for exposure without mining activity in open pit mining objects.

The activity weighting factors $f(t, o, j)$ were determined by experts considering the degree of ore contact, the respiratory volume per hour, the energy expenditure during shifts, the exposure time per shift and the task and behavior of the activity group as described in Section 4.7.1. These experts' evaluations are potentially erroneous, which may be of particular relevance for occupational groups with non-stationary activities.

Heid et al. (2004) characterize the uncertainty regarding the equilibrium factor $g(t, o)$ to be of Berkson type.

The working time factor $w(t, o)$ was evaluated based on interviews and information in the literature (see Section 4.3.2). However, individual working times differ from the average value (Eigenwillig 2011 p. 45).

In general, parameter error of parameters based on an aggregated evaluation of experts is supposed to exhibit Berkson error (Heid et al. 2004), which may depend on the evaluation subgroup and may show temporal autocorrelation.

Biased parameters

Exposure assessment for the Wismut cohort was developed with consolidated expert knowledge, also in order prevent systematical bias. However, Eigenwillig (2011 pp. 40, 60) refers to a potential source of systematical bias in the expert estimation of the basic exposure from old mining for object 009 (Aue). If this potential source of error proves to be valid, this misjudgment will not result in a stochastic measurement error but a systematic error.

5.4.6. Experts' evaluation error

For some entries of the JEM, exposure estimation was based on or supplemented by potentially deficient evaluations of an expert. These experts' evaluations are classified into three groups (Figure 18):

- Experts' adaptions
- Proportional exposure value of another shaft
- Experts' exposure estimation

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Experts' adaptions					X	X	X
Proportional exposure value of another shaft					X	X	X
Experts' exposure estimation					X	X	X

Figure 18: Types of measurement errors: experts' evaluation error.

Radiation measurements were not directly taken but were evaluated considering the ventilation conditions (Lehmann et al. 1998 p. 50). This proceeding might be the reason for slight deviations of the exposure estimations in the JEM and the manually retraced exposure estimations, as also mentioned in Eigenwillig (2011 pp. 56–58). These adaptions may introduce an experts' evaluation error of Berkson type.

Moreover, experts' estimations were derived as proportional exposure value from the exposure of another shaft or object (see Appendix A, Section A 2.2); this approach involves potentially subgroup-specific and autocorrelated Berkson error regarding the evaluation of the experts.

A further aspect of experts' evaluation error is the uncertainty in exposure estimates which are completely based on expert knowledge. The size of this Berkson type error varies depending on the reliability of the expert knowledge, which may range from a vague magnitude for the exposure estimate to a well-grounded derivation of the exposure estimate considering qualitatively relevant quantities (e.g. the ventilation conditions). Moreover, the error may depend on the evaluation subgroup and may exhibit temporal dependencies.

5.4.7. Transfer error

Transferring and imputing data collected in a certain calendar year and in a certain object to another calendar year or to another object in the regional vicinity in order to retrospectively estimate the radon progeny exposure may involve potential errors (Heid et al. 2004; Lubin et al. 1995).

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Transfer error		X	X				

Figure 19: Types of measurement errors: transfer error.

This error occurred, for example, for a few cases in which exposure estimates were transferred to lead or follow up times of the objects or to similar shafts and objects during the development of the second version of the JEM. Transfer error is of classical error type because the estimated, error-prone exposure depends on the measurement error; further, transfer error may depend on subgroups, e.g. shafts (Figure 19).

5.4.8. Approximation error

The individual exposure values are prone to approximation error due to the usage of estimation equations and due to rounding within the estimation process (Figure 20). In particular annual radon progeny exposure of the JEM is not solely based on concentration measurements but is assessed with a multi-stage procedure which includes various approximations. Moreover, the estimation of individual working time potentially leads to approximation error.

	Systematic error	Random classical error	Specific classical error	Autocorrelated classical error	Random Berkson error	Specific Berkson error	Autocorrelated Berkson error
Errors due to the usage of estimation equations		X	X		X	X	X
Rounding		X					

Figure 20: Types of measurement errors: approximation error.

Error due to the usage of estimation equations

Individual exposure estimation for the Wismut cohort is based on estimation equations, i.e. on calculation rules to calculate individual exposure based on the available measurements. The usage of estimation equations for exposure assessment involve uncertainties, because they provide an approximation of the actual exposure. The Berkson error resulting from the uncertainty by using an estimation equation depends on the method of exposure assessment and occurs for the estimation of shaft-specific exposure as well as the estimation of individual exposure (Lubin et al. 1995). This includes also the usage of mean activity weighting factors and mean exposure for individual exposure assessment during special underground shifts and absenteeism and the conversion error, which originates from the conversion of different units for the exposure to radiation (Lubin et al. 1995). Moreover, individual working times are used for individual exposure assessment, which are estimated based on occupational histories. The Berkson error may be random, systematic or autocorrelated error as well. Furthermore, the estimation equations may also be misspecified, which results in classical measurement error. For example, the basic exposure from old mining was estimated by a percentage of the basic exposure in object 003; relevant factors might have been neglected with this estimation. Eigenwillig (2011 pp. 47–48) supposes that rock permeability might be such a neglected factor for the experts' estimation of the exposure to radon progeny. The effect of the misspecification on individual exposure estimates varies between subgroups (specific classical error).

Rounding

Exposure estimates calculated in Lehmann et al. (1998) were rounded (e.g. Lehmann et al. 1998 p. 87). Moreover, times of absenteeism were rounded to months.

5.5. Structure of measurement error in the Wismut cohort

We differentiate two types of mixture measurement errors, i.e. mixtures of Berkson and classical errors, which are both relevant for the Wismut cohort:

(I) Mixture error through the simultaneous impact of several errors of different error types on a single observation

(II) Mixture error through varying type and size of measurement error between subgroups of the cohort.

For clarity, we superscribe random variables which are related to classical measurement error with "C" and random variables which are related to Berkson error with "B".

Mixture error through the simultaneous impact of several error types on a single observation

The first type of mixture error results from the simultaneous impact of several errors of different types on a single observation (e.g. Pierce et al. 2008). In the Wismut cohort, individual exposure to radiation X was calculated using shaft-specific radiation concentrations X^{*B} which exhibit prevailingly Berkson error (assignment and estimation error), denoted by Υ^{B}:

$$X = X^{*B} + \Upsilon^{B}$$

However, the calculated shaft-specific concentration X^{*BC} is uncertain due to prevailingly classical measurement errors (generalization and estimation error) in the estimation procedure (cf. Reeves et al. 1998; Schafer et al. 2001), denoted by Υ^{BC}:

$$X^{*BC} = X^{*B} + \Upsilon^{BC}$$

Mixture error through varying type and size of measurement error between subgroups of the cohort

The type of measurement error of the exposure estimations for the individuals varies with the approach for exposure assessment depending on the calendar year and the object/shaft of the considered observation:

$$X^*(i,t) = \begin{cases} X^*(o_1,t_1), & \text{if } o(i,t) = o_1 \text{ and } t = t_1 \\ X^*(o_2,t_2), & \text{if } o(i,t) = o_2 \text{ and } t = t_2 \\ & \vdots \end{cases}$$

X^* denotes an error-prone random variable of arbitrary error type. Thus, we assume that the quality of exposure estimates differs spatially as well as temporally.

Further characteristics of the measurement errors

Besides the types and subtypes of the measurement errors mentioned in Section 5.1 and the mixture structure of the error, the measurement errors in the exposure estimates of the Wismut cohort exhibit two further characteristics. For simplicity, measurement errors originating from different sources can be assumed to be independent (as e.g. in Allodji et al. 2012a). Due to the complex structure of the measurement error, the measurement error model is a complex function of the estimated exposure and the measurement errors, which originate from different sources with additive and multiplicative as well as nested structures. Furthermore, non-differential measurement error can be assumed, i.e. the error-prone covariate does not provide any information on the outcome beyond the true covariate can be assumed (as e.g. in Heid et al. 2004).

6. Evaluation of the potential relevance of uncertainties for the statistical analysis

The potential relevance of uncertainties for the statistical analysis is evaluated regarding three aspects. First, the frequency of the occurrence of the uncertainties is determined and investigated. Second, the impact of measurement errors on the exposure estimates for the Wismut cohort is discussed. Third, the impact of uncertainties on the health risk estimates of statistical analyses is examined.

6.1. Frequency of occurrence of selected features

6.1.1. Relevance of calendar years, objects and activities

Since the type and size of the uncertainties vary depending on years, objects and activities, the relevance of years, objects and activities is evaluated in this subsection using the proportion of person work years (PPY) as defined in Chapter 2:

$$\text{PPY} = \frac{\text{Number of person work years in specific subgroup}}{\text{Total number of person work years in the Wismut cohort}}$$

Calendar years

As depicted in Figure 2, the work performance steadily increased until the number of cohort members decreased from the late 1950ies.

Objects

The relevance of the work places is shown in Table 24; the total number of person work years relates to the person work years in all objects (except for object 000 000). The majority of the working time in the Wismut cohort (82.78 %) was rendered in 15 objects.

Table 24: Distribution of PPY of objects and shafts of the most relevant object sections (highest values of PPY) in SAG/SDAG Wismut, which occur in the Wismut cohort. PPY: proportion of person work years in the Wismut cohort in %. The total number of person work years relates to the person work years in all objects (except for object 000 000).

Object	Object name	Shafts	PPY (%)
009	Aue	000, 072, 170, 186, 207, 208, 250, 296, 366, 371, 999	28.63
903	BB Schmirchau	000, 356	12.43
904	BB Paitzdorf	000, 384	5.72
009	Aue	013, 038, 066	4.58
902	BB Reust	000, 379	4.30
017	Thüringen (Ronneburg u.a.)	000	3.57
107	Transportbetrieb Ronneburg / Aue	000	3.05
002	Oberschlema	000, 004, 005, 006, 007, 008, 014, 015, 016, 999	2.78
102	Seelingstädt	000	2.75
905	BB Beerwalde	000	2.59
101	Crossen	000	2.58
019	Wohnheime/ Betriebsschulen	000	2.41
011	Lauter	000	1.99
106	Zentraler Geologischer Betrieb Grüna	000	1.98
906	BB Drosen	000	1.80
001	Johanngeorgenstadt	001, 002, 018, 022, 030, 031, 032, 039, 051, 053, 054, 055, 056, 058, 060, 061, 120, 121, 122, 145, 147, 999	1.63
			82.78

By far, the largest proportion of person days was worked in the various shafts of underground mining object 009 Aue shafts 000, 072, 170 ,186, 207, 208, 250, 296, 366, 371 and 999 (28.63 %), followed by underground mining object 903 BB Schmirchau (12.43 %) and underground mining object 904 BB Paitzdorf (5.72 %). Object 300 Lichtenberg was the open pit mining object with the highest working activity in the Wismut cohort (0.45 %).

Activities

The most frequently conducted activity in the Wismut cohort was the hewer in mining (16.43 % PPY). Further relevant activities are listed in Table 25; the total number of person work years relates to the person work years in all activities (except for activity 00000).

Table 25: Distribution of PPY of the most relevant activities (highest values of PPY) in SAG/SDAG Wismut, which occur in the Wismut cohort. PPY: proportion of person work years in the Wismut cohort in %. The total number of person work years relates to the person work years in all activities (except for activity 00000).

Activity code	Activity	PPY (%)	Activity code	Activity	PPY (%)
10000	Hauer - Abbau	16.43	14000	Anschläger (untertage)	0.98
24061	Dienstschlosser (untertage)	3.47	53400	Schweißer / Brennschneider	0.98
62000	Kraftfahrer (übertage)	2.86	20001	Geophysiker (untertage)	0.94
10211	Berglehrling (übertage)	2.57	54001	Elektriker (übertage)	0.92
21150	Zimmerling	2.46	24500	Schweißer (mechanisch-elektrischer Dienst)	0.9
24800	Elektriker - Werkstatt (untertage)	2.23	62100	Fahrer von Kraftomnibussen	0.83
15000	Lokfahrer (untertage)	1.98	57100	Maurer (übertage)	0.82
53000	Schlosser (übertage)	1.91	69230	Raumpflegerin	0.78
62250	Fahrer von Spezialfahrzeugen	1.48	15050	E-Lokmaschinist	0.73
11000	Fördermann (untertage)	1.41	71050	Sachgebietsbeauftragter (Leitung / Verwaltung)	0.73
60000	Transportarbeiter (übertage)	1.29	12000	Bohrarbeiter (untertage)	0.71
40000	Zechenarbeiter	1.24	16100	Lokbegleiter	0.59
13050	Schießmeister	1.21	53200	Kfz - Schlosser	0.59
24064	Dienstschlosser; Dienstschlosser Aufbereitung	1.2	16800	Gleisleger	0.58
34500	Steiger für verschiedene Aufgaben	1.12	21050	Grubenzimmerer	0.53
24202	Schlosser Spezialarbeiten / Invest	1.1	21252	Maurer (Grubenunterhaltung)	0.51
57150	Zimmerer (übertage)	1.09	14500	Fördermaschinist (untertage)	0.51
99970	Arbeiter	1.01	69270	Wachmann / Wächter / Pförtner	0.5

6.1.2. Potential relevance of uncertainties

To get a rough overview we examine the relevance of uncertainties through the relevance of the different exposure estimation approaches, because error size and structure are largely homogeneous within the different exposure estimation approaches and we assume that data quality strongly varies with the method of exposure assessment. We focus on the uncertainties regarding the shaft-specific exposure estimates of the JEM since uncertainties arising by the calculation of individual exposure based on the JEM affect all individual exposure estimates.

Figure 7 on page 42 and Figure 9 on the pages 67-69 visualize the various exposure estimation methods depending on the calendar year and the shaft group. Exposure estimates by each of the estimation methods are affected by particular uncertainties. Thus, these figures build the groundwork to evaluate the potential relevance of uncertainties.

Relevance of uncertainties in exposure assessment according to Lehmann et al. (1998) (JEM 1)

Figure 7 was extended with the proportion of person work years for each cell (Appendix B, Figure B5). Exposure assessment for exploration, development, surface and open pit mining objects was solely based on experts' estimation and is therefore not depicted in Figure 7. Furthermore, processing companies are not included in Figure 7 because exposure estimation in processing companies is only distinguished between experts' estimation and estimation based on radon gas concentration measurements (see Section 4.5). The frequencies of occurrence of the categories shown in Figure 7, which refers only to underground mining, are summarized in Table 26.

Table 26: Frequency of occurrence of methods for exposure assessment in the Wismut cohort according to Lehmann et al. (1998). Category labels and colors are in accordance with Figure 7. PPY: proportion of person work years in the Wismut cohort in %. The total number of person work years relates to the person work years in all objects (except for object 000 000).

	Method of exposure assessment	PPY (%)
	Expert estimation based on diggings characteristics and radon gas measurements in reference objects and reference years of underground mining objects	11.0
	Estimation based on radon gas concentration measurements	20.1
	Filled gap of estimation based on radon gas concentration measurements of other years	6.5
	Substituted implausible value resulting from the estimation based on radon gas concentration measurements	0.2
	Estimation based on radon progeny concentration measurements	29.0
	Filled gap of estimation based on radon progeny concentration measurements of other years	0.0
	Estimation method not specified	5.3
	No exposure estimation approach listed	1.0
-	Estimation based on radon gas concentration measurements for processing companies	4.6
-	Estimation for surface objects	15.8
-	Expert estimation for exploration/development objects, processing companies and open pit mining objects	6.3
		100

The majority (64.8 % PPY) of the exposure estimates in the first version of the JEM were derived from the three main estimation approaches: experts' estimation for underground mining objects (11.0 % PPY), estimation based on radon gas concentration measurements for underground mining objects (20.1 % PPY) and processing companies (4.6 %) and estimation based on radon progeny concentration measurements (29.0 %). A further large part of the exposure data of 15.8 % PPY are estimations for surface objects, which were determined to 0 WLM and which only exhibit a minor error. Exposure values for 6.3 % PPY were assessed by experts' estimation, which concern exploration/development objects, processing companies and open pit mining objects. Presumably, the experts' estimation in these cases (see Chapter 4) is of less quality than the experts' estimation for underground mining objects because the estimation was not or only to a minor extent based on objective, measurable criteria. Some exposure estimates are determined by filling the gaps between exposure estimates based on radon gas concentration measurements of other years (6.5 % PPY); the relevance of this estimation approach is reduced by the availability of additional data for the calculation of the second version of the JEM (see Appendix A, Section A 2.2). For 5.3 % PPY, the estimation method was not specified in Lehmann et al. (1998).

Relevance of uncertainties in exposure assessment according to Lehmann (2004) (JEM 2)

Figure 9 was extended with the proportion of person years for each cell (Appendix B, Figure B6). For the second version of the JEM, exposure assessment for surface objects was determined to a fixed value of 0 WLM and is therefore not depicted in Figure 9. Processing companies are not included in Figure 9, because exposure estimation in processing companies was not adapted for the second version of the JEM. The frequencies of occurrence of the categories shown in Figure 9 are summarized in Table 27.

Table 27: Frequency of occurrence of methods for exposure assessment in the Wismut cohort according to Lehmann (2004). Category labels and colors are in accordance with Figure 9. PPY: proportion of person work years in the Wismut cohort in %. The total number of person work years relates to the person work years in all objects (except for object 000 000).

	Method of exposure assessment	PPY (%)
	Estimation based on new data (radon gas concentration measurements)	4.3
	Proportional exposure value of another shaft	0.4
	Exposure estimation according to Lehmann et al. (1998) (underground, open pit)	70.4
	Basic exposure from old mining	0.0
	Exposure estimation based on a proportional value of the exposure from old mining	0.3
	Exposure estimation during lead times according to regionally operating exploration/development objects	0.4
	Exposure estimation during follow-up times according to the guidelines in Appendix A (Table A2)	0.8
	Well-grounded expert estimation	0.2
	Ill-founded expert estimation	0.3
	Continued employment in other shafts/objects	0.1
	No method of exposure assessment documented	0.0
-	Exposure estimation according to Lehmann et al. (1998) (processing companies)	6.9
-	Estimation for surface objects	15.8
		100.0

The majority of shaft-specific exposure in the second version of the JEM is composed of exposure estimates of the first version of the JEM according to Lehmann et al. (1998) (77.3 % PPY: 70.4 % underground and open pit mining objects, 6.9 % processing companies). This proportion covers also reassignment of existing exposure estimates to shafts and shaft groups. Beyond that, the most relevant extensions of the second version of the JEM are exposure estimates based on newly available data on radon gas concentrations (4.3 % PPY).

Concluding evaluation

29.0 % PPY of the exposure estimates in the Wismut cohort were based on radon progeny concentration measurements. Also 29.0 % PPY of the exposure estimates in the Wismut cohort were based on radon gas concentration measurements. The remaining exposure estimates covering 42.0 % PPY were based on experts' estimation. These experts' estimations consist of three groups: experts' estimations for surface objects (15.8 % PPY), experts' estimations based on estimation equations (11.0 % PPY) and experts' evaluation, for which the experts determine the exposure (15.2 % PPY). Experts' evaluation comprises the following estimation approaches:

JEM 1:

- Filled gap of estimation based on radon gas concentration measurements of other years
- Substituted implausible value resulting from the estimation based on radon gas concentration measurements
- Filled gap of estimation based on radon progeny concentration measurements of other years
- Estimation method not specified
- Experts' estimation for exploration/development objects, some processing companies and open pit mining objects

JEM 2:

- Proportional exposure value of another shaft
- Exposure estimation based on a proportional value of the exposure from old mining
- Exposure estimation during lead times according to regionally operating exploration/ development objects
- Exposure estimation during follow-up times
- Well-grounded expert estimation
- Ill-founded expert estimation
- Continued employment in other shafts/objects
- No method of exposure assessment documented

6.2. Impact of measurement errors on the exposure estimate

A quantification of the uncertainties in the French uranium miners cohort was performed by Allodji et al. (2012a, 2012b), where natural variation and approximation of the equilibrium factor were considered to be the largest sources of uncertainty. The resulting estimated uncertainties for the French cohort in the different periods are depicted in Table 28 (Allodji et al. 2012a, 2012b).

Table 28: Magnitude of relative uncertainty of the exposure to radon progeny in the French uranium miners cohort (Allodji et al. 2012a, 2012b).

Period	1946 - 1955	1956 - 1974	1975 - 1977	1978 - 1982	1983 - 1999
Estimated size of uncertainty in exposure estimations	93.6 %	46.8 %	41.7 %	32.6 %	10.1 %

The overall estimated uncertainty decreases moderately by time from 1956 to 1982, which is mainly driven by a decreasing assumed natural variation (justified by an increasing number of measurements) as well as by a decreasing uncertainty in the approximation of the equilibrium factor. The large reduction in estimated uncertainty after 1983 can be attributed to fact that individual dosimetry was introduced at this time.

The quantification of the size of measurement errors is not the target of this research project. Therefore, in this section the rough size dimensions of the major sources for uncertainties are discussed with data examples and literature in order to support the evaluation of the relevance of the uncertainties. The detailed quantification of the size of measurement errors for all steps and components of exposure assessment will be the subject of future research.

6.2.1. Generalization error

Generalization error develops through the generalization of single averaged exposure values in a certain situation to annual (temporal generalization error) and shaft-specific (spatial generalization error) exposure of a worker in a reference category (activity generalization error).

Averaged concentration measurements of several shafts and levels were used for exposure assessment based on radon gas and radon progeny concentration measurements, but also for experts' estimation (e.g. Unternehmensarchiv Wismut 1962) as depicted in Figure 21. In the following, we show exemplarily how the available shaft-, level- and work-place-type-specific averages of radiation measurements in object 009 Aue for the year 1961 can be used for the quantification of the generalization error of exposure values for object 009 Aue in 1961.

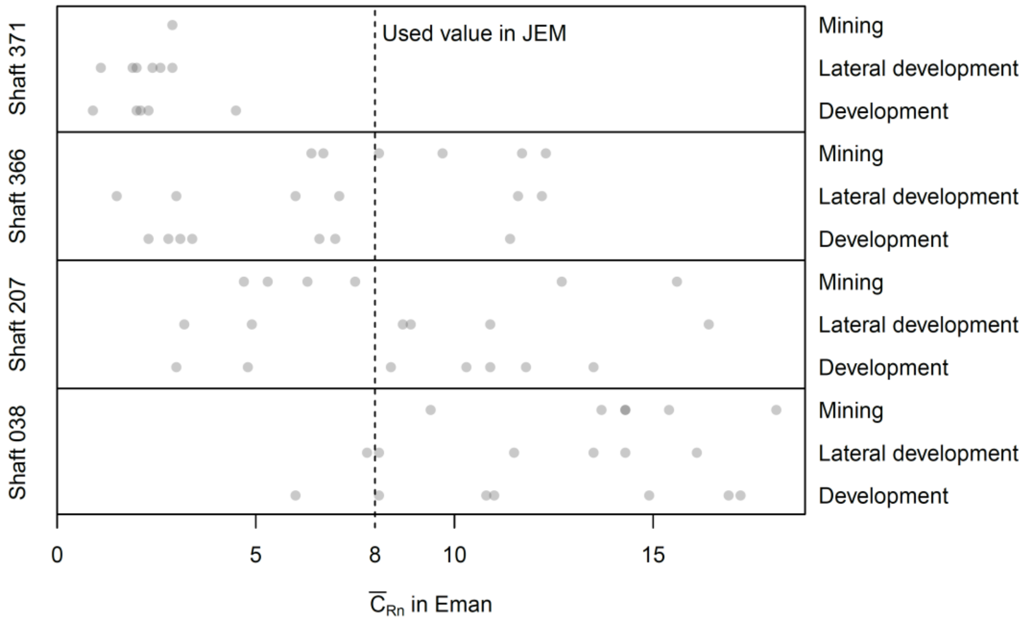

***Figure 21**: Example for the variability of radon gas concentrations within an object: site-specific radon gas concentrations in shafts of object 009 Aue in 1961 for different work places (mining, lateral development, development) and different levels (-420, -450, -480, -510, -540, -585, -630, -675, -720, -765, -810, -855, -990) (Unternehmensarchiv Wismut 1962).*

Mean concentration measurements $\bar{\bar{\bar{C}}}_{Rn/RDP}$ were assessed using n single concentration measurements $C_{Rn/RDP,ijkl}$ at site i ($i = 1, \dots, I_{jkl}$) in work place type (mining/development) l ($l = 1, 2$) of shaft k ($k = 1, \dots, K_l$) at level j ($j = 1, \dots, J_{kl}$). Development and lateral development are jointly considered in the work place type "development". The following averaging steps were conducted:

1. Averaging of single measurements to site-specific exposure:

$$\bar{C}_{Rn/RDP,jkl} = \frac{1}{I_{jkl}} \sum_{i=1}^{I_{jkl}} C_{Rn/RDP,ijkl}$$

   These values are depicted as dots in Figure 21.

2. Averaging of site-specific exposure to work-place-type-specific exposure:

$$\bar{\bar{C}}_{Rn/RDP,l} = \frac{1}{n_l} \sum_{k=1}^{K_l} \sum_{j=1}^{J_{kl}} I_{jkl} \cdot \bar{C}_{Rn/RDP,jkl}$$

   with I_{jkl} denoting the number of measurements in shaft k, at level j and at work place type l and n_l denoting the number of measurements at work place type l. The resulting values are the exposure values which were listed in the appendix of Lehmann et al. (1998).

3. Determination of mean concentration measurements:

$$\bar{\bar{\bar{C}}}_{Rn} = \begin{cases} \bar{\bar{C}}_{Rn,mining}\ , & \text{from 1961 in objects 901/902 BB Lichtenberg/Reust and} \\ & \text{903 BB Schmirchau and from 1964 in object 904 BB Paitzdorf} \\ \frac{1}{n} \sum_{l=1}^{2} n_l \cdot \bar{\bar{C}}_{Rn,l}, & \text{else} \end{cases}$$

$$\bar{\bar{\bar{C}}}_{RDP} = \bar{\bar{C}}_{RDP,mining}$$

with n_l denoting the number of measurements at work place type l. This value is depicted as vertical dashed line in Figure 21 annotated by "Used value in the JEM" and was used for shaft-specific exposure assessment.

Shaft-specific exposure based on mean concentration measurements was assessed by

$$E(t,o,j_0(o)) = \begin{cases} \bar{\bar{\bar{C}}}_{Rn} \cdot 12 \cdot g(t,o) \cdot w(t,o), & \text{based on radon gas concentration measurements} \\ \bar{\bar{\bar{C}}}_{RDP} \cdot 12 \cdot c(o) \cdot w(t,o), & \text{based on radon progeny concentration measurements} \end{cases}$$

The generalization error U^G results from the deviation between the annual exposure estimation $E(t,o,j_0(o))$ based on $\bar{\bar{\bar{C}}}_{Rn/RDP}$ and the actual annual shaft-specific exposure. Therefore, the variability of $E(t,o,j_0(o))$ provides information about the size of the generalization error:

$$\widehat{Var}(U^G) \approx \widehat{Var}(E(t,o,j_0(o))) = \begin{cases} \widehat{Var}\left(\bar{\bar{\bar{C}}}_{Rn} \cdot 12 \cdot g(t,o) \cdot w(t,o)\right), & \text{based on radon gas concentration measurements} \\ \widehat{Var}\left(\bar{\bar{\bar{C}}}_{RDP} \cdot 12 \cdot c(o) \cdot w(t,o)\right), & \text{based on radon progeny concentration measurements} \end{cases} = \begin{cases} 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \widehat{Var}\left(\bar{\bar{\bar{C}}}_{Rn}\right), & \text{based on radon gas concentration measurements} \\ 12^2 \cdot c(o)^2 \cdot w(t,o)^2 \cdot \widehat{Var}\left(\bar{\bar{\bar{C}}}_{RDP}\right), & \text{based on radon progeny concentration measurements} \end{cases}$$

The variability of the mean radon gas concentration measurements, $\widehat{Var}\left(\bar{\bar{\bar{C}}}_{Rn}\right)$, for underground mining objects in Saxony (and in the first years of operation of some underground mining objects in Thuringia) can be quantified by the weighted sum of the variability of the mean concentration measurements at mining work places and at development work places, i.e.

$$\widehat{Var}\left(\bar{\bar{\bar{C}}}_{Rn}\right) = \widehat{Var}\left(\frac{1}{n}\sum_{l=1}^{2} n_l \cdot \bar{\bar{C}}_{Rn,l}\right) = \frac{1}{n^2}\sum_{l=1}^{2} n_l^2 \widehat{Var}\left(\bar{\bar{C}}_{Rn,l}\right) \ ,$$

assuming independence between the mean concentration measurements at mining work places and at development work places. Further, the variability of the mean concentration measurements at work place type l, $\widehat{Var}\left(\bar{\bar{C}}_{Rn,l}\right)$, is approximated using the variance of the mean concentration measurements in different shafts and at different levels at work place type l, because the number of measurements at work place type l of shaft k at level j, I_{jkl}, is unknown:

$$\begin{aligned} \widehat{Var}\left(\bar{\bar{C}}_{Rn,l}\right) &= \widehat{Var}\left(\frac{1}{n_l}\sum_{k=1}^{K_l}\sum_{j=1}^{J_{kl}} I_{jkl} \cdot \bar{C}_{Rn,jkl}\right) \\ &\approx \widehat{Var}\left(\frac{1}{n_l}\sum_{k=1}^{K_l}\sum_{j=1}^{J_{kl}} \frac{n_l}{m_l} \cdot \bar{C}_{Rn,jkl}\right) \\ &= \frac{1}{m_l}\widehat{Var}\left(\bar{C}_{Rn,jkl}\right) \ , \end{aligned}$$

with $m_l = \sum_{k=1}^{K_l}\sum_{j=1}^{J_{kl}} 1$ denoting the number of site-specific exposure values $\bar{C}_{Rn,jkl}$ at work place type l (in contrast to n_l which denotes the number of measurements $C_{Rn,jkl}$ at work place type l).

With this approximation, the variability of the single measurements at a certain level and work place type of a certain shaft are neglected. Moreover, it is assumed that the number of measurements at each measurement site at work place type l was approximately equal, i.e.

$$I_{jkl} \approx \frac{n_l}{m_l} \quad .$$

The approximate size of the generalization error is

$$\widehat{Var}(E(t,o,j_0(o))) \approx 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \frac{1}{n^2}\sum_{l=1}^{2}\frac{n_l^2}{m_l}\widehat{Var}(\bar{C}_{Rn,jkl})$$

Thus, the size of generalization error strongly depends on the number of measurements and the variability of the averaged measurements.

Exemplarily, the impact of generalization error on the exposure estimates are demonstrated in three situations in the following.

Exposure estimation based on radon gas concentration measurements: object 009 Aue, 1961

The size of the generalization error in 1961 of object 009 Aue is calculated by

$$\widehat{Var}(E(t,o,j_0(o))) \approx 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \frac{1}{n^2}\sum_{l=1}^{2}\frac{n_l^2}{m_l}\widehat{Var}(\bar{C}_{Rn,jkl})$$

The values for this example (object 009 Aue, 1961) are taken from the literature:

Parameter	Value	Meaning	Source
$g(t,o)$	0.3	Equilibrium factor	Lehmann et al. (1998)
$w(t,o)$	1.1	Working time factor	Lehmann et al. (1998)
n	1091	Number of measurements	Unternehmensarchiv Wismut (1962)
n_{mining}	228	Number of measurements at mining work places	Unternehmensarchiv Wismut (1962)
$n_{development}$	863	Number of measurements at development work places	Unternehmensarchiv Wismut (1962)
m_{mining}	19	Number of site-specific exposure values at mining work places	Derived from Unternehmensarchiv Wismut (1962)
$m_{development}$	50	Number of site-specific exposure values at development work places	Derived from Unternehmensarchiv Wismut (1962)
$\widehat{Var}(\bar{C}_{Rn,jk,mining})$	18.85	Variance of site-specific exposure at mining work places of shaft k at level j	Calculated based on Unternehmensarchiv Wismut (1962)
$\widehat{Var}(\bar{C}_{Rn,jk,development})$	23.86	Variance of site-specific exposure at development work places of shaft k at level j	Calculated based on Unternehmensarchiv Wismut (1962)

Thus, the size of the generalization error in 1961 of object 009 Aue is

$$\widehat{Var}(E(t,o,j_0(o))) \approx 12^2 \cdot 0.3^2 \cdot 1.1^2 \cdot \frac{1}{1091^2} \cdot \left(\frac{228^2}{19} \cdot 18.85 + \frac{863^2}{50} \cdot 23.86\right) = 5.36$$

The variance of the estimated shaft-specific exposure (31.85 WLM, value in the JEM: 35 WLM) due to generalization error results in 5.36 in this example. Assuming normality of the generalization error, the density of the shaft-specific exposure in 1961 in object 009 Aue is depicted in Figure 22; the 95 % confidence interval for the shaft-specific exposure is [27.31; 36.39].

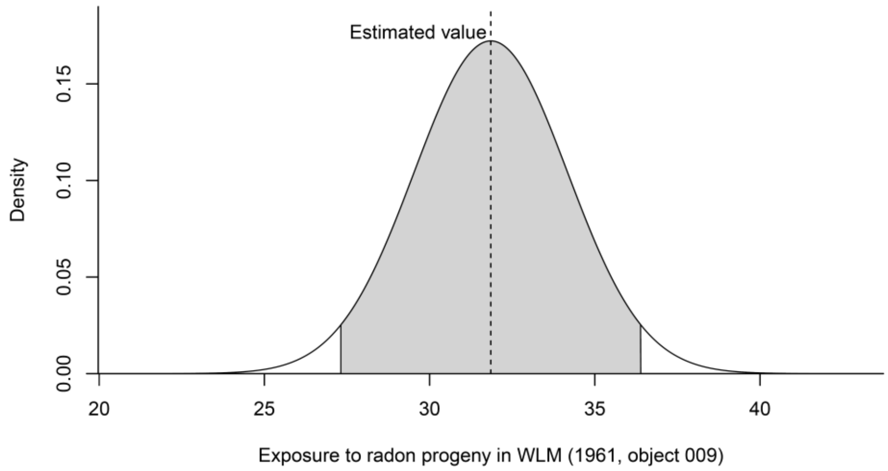

Figure 22: Approximative density of the estimated shaft-specific exposure to radon progeny in 1961 for object 009 Aue resulting from the estimation of the generalization error; gray: confidence interval; vertical line: estimated value.

$$\widehat{Var}(C_{Rn}) = \widehat{Var}\left(\overline{\overline{\overline{C}}}_{Rn} \cdot 12 \cdot g(t,o) \cdot w(t,o)\right) \cdot \frac{n}{12^2 \cdot g(t,o)^2 \cdot w(t,o)^2}$$
$$\approx 5.36 \cdot \frac{1091}{12^2 \cdot 0.3^2 \cdot 1.1^2} = 373.04$$

represents the estimated variance of a single exposure measurement in 1961 in object 009 Aue for an equilibrium factor and a working time factor of 1, which can be used for similar considerations in other objects.

Experts' estimation: object 903 BB Schmirchau, 1955

Experts' estimations are also prone to generalization error because single measurements were averaged and used for assessing the evaluation factor. The size of the generalization error in 1955 of object 903 BB Schmirchau, where $n = 299$ measurements were conducted, is approximately

$$\widehat{Var}(E(t,o,j_0(o))) \approx \frac{12^2 \cdot g(t,o)^2 \cdot w(t,o)^2}{n} \cdot \widehat{Var}(C_{Rn}) \quad .$$

The values are taken from the literature:

Parameter	Value	Meaning	Source
$g(t,o)$	0.5	Equilibrium factor	Lehmann et al. (1998)
$w(t,o)$	1.2	Working time factor	Lehmann et al. (1998)
n	299	Number of measurements	Lehmann et al. (1998)

The estimated shaft-specific exposure is 248.47 (value in the JEM: 250 WLM). The size of the generalization error is

$$\widehat{Var}(E(t,o,j_0(o))) \approx \frac{12^2 \cdot 0.5^2 \cdot 1.2^2}{299} \cdot 373.04 = 64.68 \quad ,$$

resulting in a 95 % confidence interval of [232.71; 264.23] for the shaft-specific exposure and the density in Figure 23 under the normality assumption.

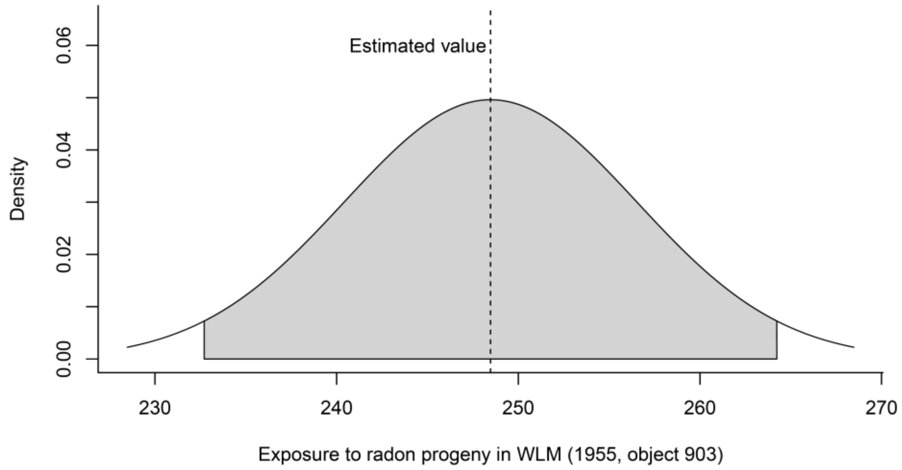

Figure 23: Approximative density of the estimated shaft-specific exposure to radon progeny in 1955 for object 903 BB Schmirchau resulting from the estimation of the generalization error; gray: confidence interval; vertical line: estimated value.

Estimation of the basic exposure from old mining: object 003 Schneeberg, 1937/38

Basic exposure from old mining was not relevant for objects 009 Aue and 903 BB Schmirchau as both objects were new ground-opening objects. However, basic exposure from old mining is especially affected by generalization error because the estimation was based on few ($n = 70$) radon gas concentration measurements in object 003 Schneeberg (without shaft "Siebenschlehen") in 1937/38. The size of the generalization error in 1937/38 of object 003 Schneeberg is approximately

$$\widehat{Var}(E(t,o,j_0(o))) \approx \frac{12^2 \cdot g(t,o)^2 \cdot w(t,o)^2}{n} \cdot \widehat{Var}(C_{Rn}) \quad .$$

The values are taken from the literature:

Parameter	Value	Meaning	Source
$g(t,o)$	0.6	Equilibrium factor	Lehmann et al. (1998)
$w(t,o)$	1.2	Working time factor	Lehmann et al. (1998)
n	70	Number of measurements	Lehmann et al. (1998)

The estimated shaft-specific exposure is 194.4 (value in the JEM: 194 WLM). The size of the generalization error is

$$\widehat{Var}\left(E\big(t,o,j_0(o)\big)\right) \approx \frac{12^2 \cdot 0.6^2 \cdot 1.2^2}{70} \cdot 373.04 = 397.82 \quad .$$

The 95 % confidence interval is comparably wide: [155.31; 233.49]. The density of the estimated basic exposure from old mining under the normality assumption of the corresponding generalization error is depicted in Figure 24.

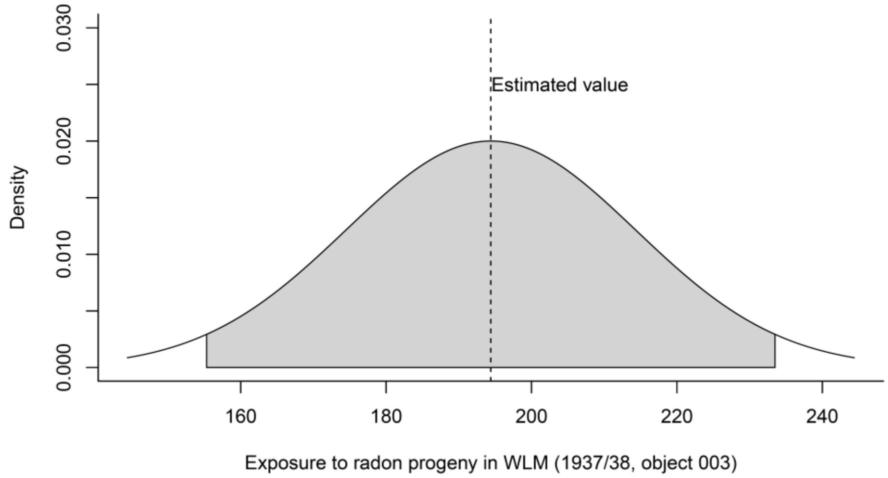

Figure 24: Approximative density of the estimated basic exposure to radon progeny from old mining in 1937/38 for object 003 Schneeberg resulting from the estimation of the generalization error; gray: confidence interval; vertical line: estimated value.

6.2.2. Assignment error

Spatial assignment error, which is supposed to be the most relevant type of assignment error, emerges from the use of shaft/object-specific exposure estimates instead of individual exposure measurements. Küchenhoff et al. (2007) mention that the variance of the Berkson error in radiation epidemiology, which is mainly involved through spatial assignment error, can be up to 400 % of the observed variance. The magnitude of spatial assignment error becomes particularly evident in Figure 21: exposure values collected at different locations in a shaft strongly vary around the shaft-specific exposure of e.g. 8 WL (originally: 8.0 Eman; Eman corresponds to WL for an equilibrium factor of 1, Lehmann et al. 1998 pp. 66, 119) in 1961 in object 009 Aue.

Exemplarily, we consider the assignment error of a worker who worked the complete calendar year t as a hewer in object o without absenteeism and special underground shifts in calendar year t. The exposure of this worker i is assessed by the respective value in the JEM:

$$E(i,t) = E(t, o(i,t), j_0)$$

Thus, an assignment error U^A occurs; in contrast to the generalization error where the variability of annual shaft-specific exposure is considered, the rough size of the assignment error can be evaluated by the variability of the single measurements in calendar year t in object o:

$$\widehat{Var}\left(U^A(t,o)\right) \approx \begin{cases} 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \widehat{Var}\left(C_{Rn,ijkl}\right), & \text{based on radon gas conc. measurements} \\ 12^2 \cdot c(o)^2 \cdot w(t,o)^2 \cdot \widehat{Var}\left(C_{RDP,ijkl}\right), & \text{based on radon progeny conc. measurements} \end{cases}$$

However, single measurements $C_{Rn/RDP,ijkl}$ are not available. Therefore, the variability of single measurements at site i of a certain work place type l of a certain shaft k at a certain level j is approximated by averaging the within-group variability of the site-specific exposure values $\widehat{Var}_{kl}(\bar{C}_{Rn/RDP,jkl})$ (groups are defined by a certain shaft and work place type) and by assuming equal numbers of measurements within each group. Thus, the assignment error for exposure estimates based on site-specific radon gas concentration values at mining and development working places (certain calendar years of underground mining objects in Saxony and of some underground mining objects in Thuringia) can be approximated by

$$\widehat{Var}\big(U^A(t,o)\big) \approx 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \overline{\widehat{Var}_{kl}\big(\bar{C}_{Rn,jkl}\big)}$$
$$\approx 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \sum_{l=1}^{2}\sum_{k=1}^{K_l}\frac{J_{kl}}{n}\cdot \widehat{Var}_{kl}\big(\bar{C}_{Rn,jkl}\big)$$

Since the number of measurements at work place type l of shaft k J_{kl} is unknown, we again assume that the number of measurements at each measurement site at work place type l was approximately equal:

$$J_{kl} \approx n_l \cdot \frac{m_{kl}}{m_l}$$

with $m_{kl} = \sum_{j=1}^{J_{kl}} 1$. Thus,

$$\widehat{Var}\big(U^A(t,o)\big) \approx 12^2 \cdot g(t,o)^2 \cdot w(t,o)^2 \cdot \sum_{l=1}^{2}\frac{n_l}{n}\sum_{k=1}^{K_l}\frac{m_{kl}}{m_l}\widehat{Var}_{kl}\big(\bar{C}_{Rn,jkl}\big)$$

For example, the assignment error of a hewer in year t in object 009 Aue without absenteeism in year 1961 can be approximated with this formula. The values are taken from the literature:

Parameter	Value(s)	Meaning	Source
$g(t,o)$	0.3	Equilibrium factor	Lehmann et al. (1998)
$w(t,o)$	1.1	Working time factor	Lehmann et al. (1998)
n	1091	Number of measurements	Unternehmensarchiv Wismut (1962)
n_{mining}	228	Number of measurements at mining work places	Unternehmensarchiv Wismut (1962)
$n_{development}$	863	Number of measurements at development work places	Unternehmensarchiv Wismut (1962)
m_{mining}	18*	Number of site-specific exposure values at mining work places	Derived from Unternehmensarchiv Wismut (1962)
$m_{development}$	50	Number of site-specific exposure values at development work places	Derived from Unternehmensarchiv Wismut (1962)
$m_{k,mining}$	6, 6, 6	Number of site-specific exposure values at mining work places of shaft k	Derived from Unternehmensarchiv Wismut (1962)
$m_{k,development}$	7, 6, 7, 6 7, 6, 5, 6	Number of site-specific exposure values at development work places of shaft k	Derived from Unternehmensarchiv Wismut (1962)
$\widehat{Var}_{jl}\big(\bar{C}_{Rn,jkl}\big)$		Variance of site-specific exposure at work place type l of shaft k at level j	Calculated based on Unternehmensarchiv Wismut (1962)

*One site-specific measurement was excluded as the only one at this work place type and shaft.

Thus, the size of the assignment error is

$$\widehat{Var}\left(U^A(t,o)\right) \approx 12^2 \cdot 0.3^2 \cdot 1.1^2 \cdot \frac{1}{1091} \cdot (228 \cdot 11.31 + 863 \cdot 12.34) = 190.18$$

From this result it can be calculated that the approximative 95 % confidence interval for the individual exposure of a hewer in object 009 Aue in 1961 with an estimated individual exposure value of 100 WLM would be [72.97, 127.03].

6.2.3. Estimation error

Parameter uncertainties: equilibrium factor

The approximation of radon progeny concentrations on the basis of radon gas concentrations requires the estimation of the equilibrium factor. The equilibrium factor g was an important parameter for the estimation of shaft-specific exposure to radon progeny based on experts' evaluation and radon gas concentration measurements. Since the equilibrium factor depends on the air exchange rate, it varies between shafts and objects and changes with the ventilation conditions. For the objects of SAG/SDAG Wismut, the equilibrium factor was determined separately for periods and objects by experts (Lehmann et al. 1998); the available literature does not contain any indications that measurements were adduced for the experts' decision.

Simultaneous radon gas and radon progeny concentration measurements were conducted in the objects of SAG/SDAG Wismut beginning with the implementation of radon progeny concentration measurements. However, these measurements cannot be used to determine the equilibrium factor for years where only radon gas concentration measurements are available, but they support to deduce the evaluation of its variability. Estimated equilibrium factors are exemplary depicted in Figure 25 for the years 1966-1981 in object 009 Aue.

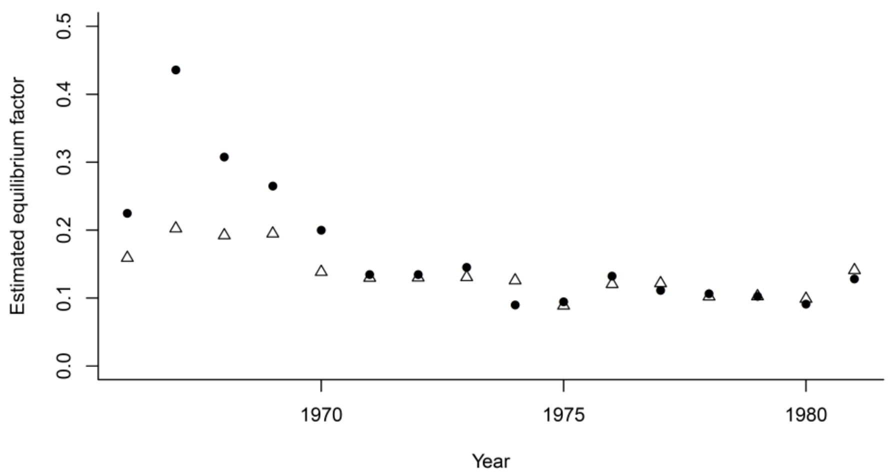

Figure 25: Estimated equilibrium factor (calculated from Lehmann et al. (1998 pp. 436–439)) for the years 1966-1981 in object 009 Aue; circles: work places in the development, triangles: mining work places.

The mean relative uncertainty in this example is 33.1 % The variability estimate can reflect the temporal variability of the equilibrium factor, but only insufficiently its spatial variability within the object. Moreover, the variability estimate represents only an approximation for the actual variability, because the variability of the equilibrium factor may differ between the years before and the years with radon progeny concentrations measurements due to different ventilation conditions.

Uncertainty of the equilibrium factor was identified as a major source of uncertainty in exposure assessment for the French uranium miners cohort with relative uncertainties of 29.4 % (1956-1977) and 11.8 % (1978-1982) (Allodji et al. 2012a). With a relative uncertainty of 30 %, the actual annual exposure to radon progeny may amount to a value between 70 and 130 WLM when the assessed exposure is 100 WLM.

Many parameters affect the experts' evaluation of exposure to radon besides the equilibrium factor. Especially parameters whose values were not based on adequately measured quantities, e.g. basic exposure from old mining and the evaluation factor, may be heavily charged with uncertainty.

Parameter uncertainties: proportion of basic exposure from old mining in relation to object 003 $b(o)$

Basic exposure from old mining is an important factor for the assessment of individual exposure with experts' estimation. Basic exposure from old mining was assessed in relation to the basic exposure in object 003 Schneeberg. The experts' evaluation of the proportion of basic exposure from old mining $b(o)$ in relation to object 003 Schneeberg is uncertain in addition to the uncertainty of the basic exposure from old mining in object 003 Schneeberg itself.

The impact of uncertainties in the determination of $b(o)$ on the exposure estimate is exemplary depicted for object 002 Oberschlema in Figure 26. In this figure, the basic exposure from old mining (gray horizontal line) is compared with estimated annual exposures to radon gas, i.e. the sum of the basic exposure from old mining and of the exposure from mining activity, under the consideration of uncertainty of $b(o)$ (yellow, orange and red lines).

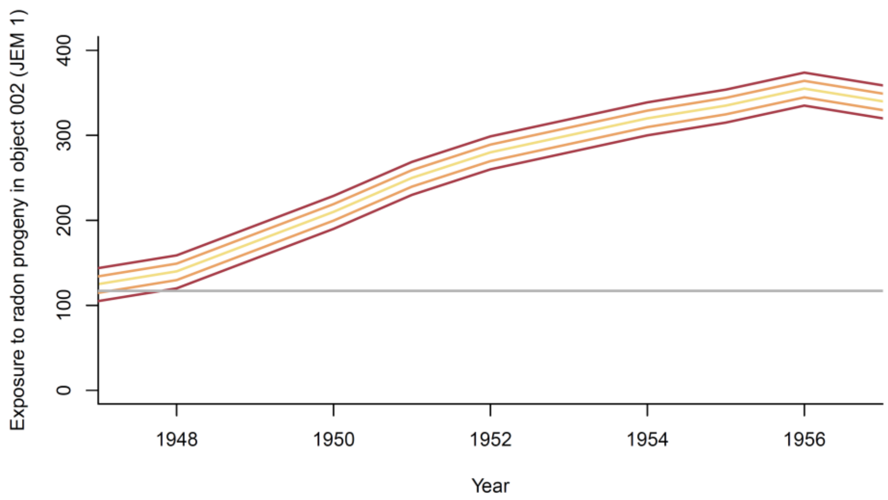

Figure 26: Exposure to radon progeny in object 002 Oberschlema according to JEM 1 (yellow line: $\boldsymbol{b(o) = 0.6}$); orange lines: $\boldsymbol{b(o) = 0.6 \pm 0.05}$; red lines: $\boldsymbol{b(o) = 0.6 \pm 0.1}$; gray horizontal line: basic exposure from old mining.

The majority of exposure in the first years of object 002 Oberschlema originated from basic exposure from old mining; with proceeding operating time of the object, exposure from mining activities preponderated. In general, a deviation of 0.05 in $b(002)$, i.e. $b(002) = 0.55$ or $b(002)$ =0.65, results in a deviation of -10.3 and 9.1 WLM in object-specific exposure; a deviation of 0.1 in $b(002)$ results in deviations of -20 WLM and 18.8 WLM.

Parameter uncertainties: evaluation factor

The evaluation factor quantifies for underground mining the exposure to radon per unit of the mined area for 2000 working hours per year and is determined by experts as constant for a certain period of an object. The uncertainty of exposure estimates based on experts' estimation originating from the evaluation factor plays an important role due to its potentially large size.

We consider experts' exposure estimation in the year 1951 for object 009 Aue as an example. Using an evaluation factor of 0.218 (Lehmann et al. 1998 p. 67) resulted in an estimated exposure to radon progeny of 56 WLM. If the evaluation factor is varied between the minimum and maximum applied value, the resulting estimated exposure would vary between 26 and 305 WLM (Figure 27). Even a small change of the evaluation factor to 0.3 would result in an exposure of 78 WLM (corresponds to an increase of 39.3 % compared to 56 WLM).

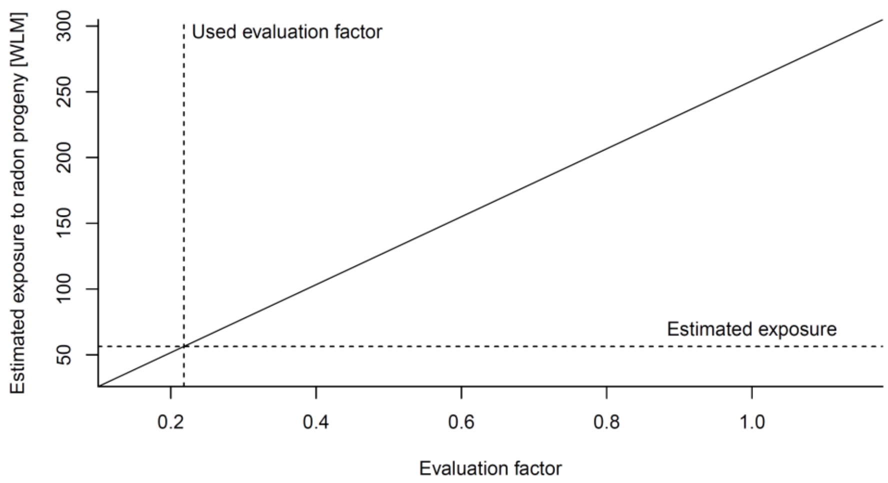

***Figure 27**:* Estimated exposure to radon progeny in object 009 Aue in 1951 for evaluation factors between 0.1 and 1.18.

Assuming a constant evaluation factor for each object neglects the spatial and temporal variability of this quantity. Additional information on the magnitude of the evaluation area, the relative uranium recovery rate and shaft-specific exposure measurements may support the quantification of the variability of the evaluation factor and thus, the size of the measurement error.

Parameter uncertainties: activity weighting factor

Exposure to radiation for the members of the Wismut cohort was assessed based on weighting the exposure of a reference activity with an activity weighting factor. Since 16.43 % of the working time in the Wismut cohort was rendered by hewers (the reference activity for underground mining objects), the majority of the exposure estimates are affected by the uncertainty of the activity weighting factor.

The uncertainty regarding the activity weighting factor affects the individual exposure estimates. For example, if an underground worker with activity "Dienstschlosser (untertage)" (the second most frequent activity in the Wismut cohort) and an annual shaft-specific exposure of 100 WLM is considered, the individual exposure for this person is 60 WLM, based on the activity weighting factor of 0.6. Activity weighting factors for other locksmith works ("Schlosserarbeiten") are (Lehmann et al. 1998 pp. 256–266, 289–290):

Activity	**Activity weighting factor**
Baggerschlosser (untertage)	0.2-0.4
Bohrhammerschlosser	0.4
Demontage(hilfs)schlosser	1
Dienstschlosser (übertage)	0.5
E-Lokschlosser	0.2
Gangschlosser	0.8
Hilfsschlosser (übertage)	0.5
Hilfsschlosser (untertage)	0.6
Hunteschlosser (übertage)	0.5
Hunteschlosser (untertage)	0.2-0.4
Kompressorschlosser (untertage)	0.2
Lampenschlosser (übertage)	0.3-0.5
Lampenschlosser (untertage) Beleuchtungsanlagen	0.2
Lokschlosser (untertage)	0.2
Luttenschlosser	0.2
Magazinschlosser (untertage)	0.2
Montageschlosser	0.2
Revierschlosser	0.6
Schachtschlosser	0.1
Schlosser/Schweißer – Werkstatt (untertage)	0.2
Schlosser Großkühlanlagen	0-0.1
Schlosser Spezialarbeiten	0.2
Staubschlosser (untertage)	1
Streckenschlosser	0.6

Note that the comparison of activity weighting factors for activities in underground and open pit mining cannot be compared, because the reference activity differs for underground and open pit mining. This list illustrates the variability of the activity weighting factors for locksmith works and thus, the precise decoding of the exposure of similar activities depending on the individual work locations and tasks with a presumably low error.

Transfer error

Exposure evaluation by experts is thoroughly justified in Lehmann et al. (1998) and Lehmann (2004) and is summarized in Chapter 4. These works allow to determine the uncertainties due to data transfer involved by the experts' estimation because the detailed documentation suggests an objective evaluation based on comprehensible criteria.

For example, exposure estimation was based on transferred values for the development object 011 Lauter and was calculated by 30 % of the average exposure of the mining objects 002 Oberschlema and 009 Aue. As depicted in Figure 28, changes of this proportion to 20 % or to 40 % strongly affects the objects-specific exposure estimates.

Figure 28*:* Estimated exposure to radon progeny in object 011 Lauter according to JEM 1 (yellow line: proportion of 30 % of the average exposure of objects 002 Oberschlema and 009 Aue). Red lines: exposure to radon progeny based on a proportion of 20 % and 40 % of the average exposures.

6.3. Impact of uncertainties on risk estimates

One of the main research questions regarding exposure uncertainties in the Wismut cohort is the question whether and how health risk estimates are affected by those uncertainties, in particular regarding the relationship between lung cancer and radon. The uncertainties in the exposure assessment for the Wismut cohort are particularly high for the period from 1946 to 1954 (Kreuzer et al. 2010c, 2014). As described in Kreuzer et al. (2010b), stratified analyses with data from the second follow-up period 1946-2003 in Kreuzer et al. (2008) and Walsh et al. (2010) yielded similar effect estimates and might indicate that the uncertainties in the exposure assessment only lead to small or even no bias in the effect estimates. Slightly increased effect estimates were detected during the stratified analyses for data from the third follow-up period 1946-2008 (Kreuzer et al. 2014). However, these sensitivity analyses provide only first hints on the impact of uncertainties on risk estimates in the Wismut cohort.

A short overview on statistical regression methods to account for uncertainties is given in the following, with special focus on stat-of-the-art methods to account for measurement error in radiation related health risk analyses. Many explanations in this section base on the assumption of additive measurement error due to general as well as specialized scientific literature on the impact of measurement error in project-related research questions. The impact of multiplicative measurement error can be easily evaluated by considering additive measurement error of a logarithmically transformed error-prone covariate (Carroll et al. 1996; Heid et al. 2004). Moreover, we do not consider systematic error because this error usually only affects the intercept and not the risk estimates.

6.3.1. Classical and Berkson error in general linear regression models

In the following paragraphs the impact of measurement error on regression models is introduced with the simple linear regression model for the outcome Y_i and the true exposure X_i:

$$Y_i = \beta_0 + \beta_X X_i + \varepsilon_i \ , \qquad i = 1, \dots, n$$

β_0 is the intercept and β_X the regression coefficient for the impact of the exposure on the outcome. ε_i are independent model errors with $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$.

Classical measurement error

Classical covariate measurement error U_i^C, which results in the classical error-prone covariate X_i^{*C}, of the form

$$X_i^{*C} = X_i + U_i^C \ , \qquad U_i^C \sim N\left(0, \sigma_{U^C}^2\right)$$

causes in the simple linear regression model a biased effect estimate. Thus, the usage of a classical error-prone covariate X_i^{*C} yields an estimate for a naïve slope coefficient β_X^{*C}, which is attenuated in comparison to the slope coefficient β_X:

$$\beta_X^{*C} = \lambda^C \beta_X$$

with $\lambda^C \in [0,1]$ denoting the attenuation factor. The attenuation of the effect estimate in a simple linear regression with classical covariate measurement error is depicted in Figure 29 for simulated data.

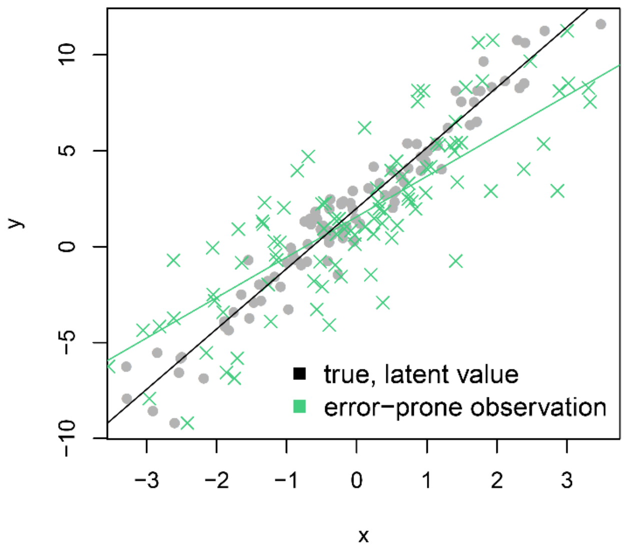

Figure 29: Impact of classical covariate measurement error in a simple linear regression with simulated data.

For the simple linear regression model, the attenuation factor λ^C can be easily estimated if the measurement error variance $Var(U^C)$ is known or can be estimated, e.g. through experts' knowledge or a validation study:

$$\lambda^C = \frac{Var(X)}{Var(X^{*C})} = \frac{Var(X^{*C}) - Var(U^C)}{Var(X^{*C})}.$$

The formula for the attenuation factor was derived for many other, more complex settings, in particular for classical measurement error with specific as well as autocorrelated components in the general linear model (Deffner et al. accepted), which represents an extended version of the above formula.

A simple approach to account for classical covariate measurement error is to correct the bias of the naïve effect estimate $\widehat{\beta_X^{*C}}$ using the estimated attenuation factor $\widehat{\lambda^C}$:

$$\hat{\beta} = \frac{\widehat{\beta_X^{*C}}}{\widehat{\lambda^C}}$$

This approach is called the method of moments and is applicable also for more complex models if the attenuation factor can be estimated.

Moreover, classical covariate measurement error affects the variability of the effect estimate, but the impact is only low.

Berkson error

A Berkson error-prone covariate X_i^{*B} of the form

$$X_i = X_i^{*B} + U_i^B$$

with the Berkson error denoted by U^B is known to preserve an unbiased effect estimate in a simple linear model, but to enhance the variability of the estimate (Carroll et al. 2006). Thus, the usage of a Berkson error-prone covariate X_i^{*B} yields an estimate for a naïve slope coefficient β_X^{*B}, which equals the slope coefficient β_X:

$$\beta_X^{*B} = \beta_X \,.$$

The unbiasedness of the effect estimate in a simple linear regression with Berkson covariate measurement error is depicted in Figure 30 for simulated data.

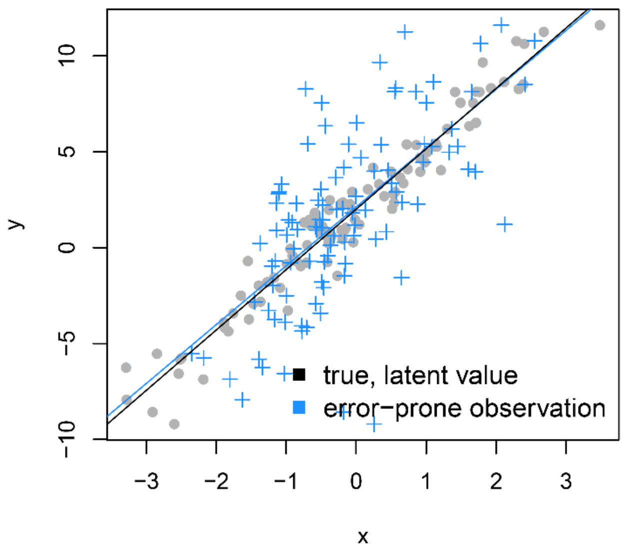

Figure 30: Impact of Berkson covariate measurement error in a simple linear regression with simulated data.

Thus, unbiased effect estimates are obtained without accounting for Berkson error in the covariate of a simple linear regression model.

6.3.2. Mixture measurement errors in general linear regression models

Exposure estimates for the Wismut cohort can be assumed to exhibit a mixture of Berkson and classical measurement error, as described in Section 5.5. In order to calculate individual exposure to radiation X_i shaft-specific radiation concentrations X_i^{*B} are used, which exhibit prevailingly Berkson error Υ^B:

$$X_i = X_i^{*B} + \Upsilon_i^B \ , \quad \Upsilon_i^B \sim N(0, \sigma_{\Upsilon^B}^2).$$

However, the shaft-specific exposure X_i^{*B} cannot be observed or calculated and can only be determined with a classical measurement error Υ_i^{BC}:

$$X_i^{*BC} = X_i^{*B} + \Upsilon_i^{BC} \ , \quad \Upsilon_i^{BC} \sim N\left(0, \sigma_{\Upsilon^{BC}}^2\right).$$

Additive mixture measurement error of type I yields an estimate of the naïve regression coefficient β_X^{*BC}, which is attenuated in comparison to the slope coefficient β_X, unless $\sigma_{\Upsilon^{BC}}^2 = 0$ (Reeves et al. 1998):

$$\beta_X^{*BC} = \frac{Var(X^{*B})}{Var(X^{*B}) + Var(\Upsilon^{BC})} \beta_X$$

An extended version for general linear models can be found in Deffner (2016).

Multiplicative mixture measurement error of type I in a simple linear regression model results in a non-linear regression model (Reeves et al. 1998).

Mixture measurement error of type II also attenuates the slope coefficient in general linear regression models as extensively studied in Deffner et al. (accepted) and Deffner (2016). Both, subgroup-specific and autocorrelated Berkson and classical error influence the degree of attenuation.

6.3.3. Measurement error in risk models for radiation exposure

Two model classes were commonly used to model the association between health risks and radiation exposure. The Poisson regression model is an established, very popular approach using grouped data. An alternative approach is the analysis of individual data with the Cox regression model.

Poisson regression models

In the basic model of this approach, the disease or mortality rate $r(a, y, w)$ of subgroups defined by age a, calendar year y and cumulative exposure w, is modelled using the baseline disease/mortality rate $r_0(a, y)$ and the excess relative risk $ERR(w) = \beta w$ (see e.g. Kreuzer et al. 2008):

$$r(a, y, w) = r_0(a, y) \times \{1 + ERR(w)\} \ .$$

The baseline disease/mortality rate, which represents an offset, is internally estimated as the disease/mortality rate of the unexposed cohort members and is scaled depending on the cumulative exposure w.

The impact of measurement error on Poisson regression models was examined in the literature theoretically as well as via simulations. In a Poisson regression model with a single covariate, classical covariate measurement error yields an attenuated effect (e.g. Armstrong 1985; Fung and Krewski 1999; Lundevaller 2006; Wang 2012; Zidek et al. 1996) with the same attenuation factor as in the simple linear regression model (Kukush et al. 2004):

$$\beta_X^{*C} = \frac{Var(X)}{Var(X^{*C})} \cdot \beta_X$$

Berkson error-prone covariates result in slightly biased effect estimates (Lundevaller 2006). Fung and Krewski (1999) investigated a mixture of classical and Berkson error (mixture type II, see Section 5.5) and found an attenuating effect of this error type.

So far, only few studies deal with the impact of measurement error on internal non-linear Poisson regression models as used for the Wismut cohort. To our knowledge, only Allodji et al. (2012b) examined the impact of exposure measurement in such models with a simulation study for the settings in the French uranium miners cohort. They simulated classical, Berkson and a mixture of Berkson and classical measurement error (mixture type II, see Section 5.5). The naïve estimates showed a strong negative bias, especially in the case of Berkson and mixture error and became more severe with increasing size and increasing heterogeneity of the measurement error.

Using a different model for the calculation of the excess relative risk in the a-bomb survivor study, Pierce et al. (2008) argued that a size of classical measurement error in the range of 35.0–50.0 % results in a downward bias of approximately 10.0–15.0 % in radiation risk estimates.

Measurement error in Cox regression models

The second model class for modelling health risks of radiation exposure are Cox regression models. Some approaches to account for uncertainties already exist for this model class. The Cox regression model for the hazard rate $\lambda_i(t|\boldsymbol{X}_i, \boldsymbol{Z}_i)$ is defined as

$$\lambda_i(t|\boldsymbol{X}_i, \boldsymbol{Z}_i) = \lambda_0(t) \cdot \exp(\beta_X^{\mathrm{T}} \boldsymbol{X}_i + \beta_Z^{\mathrm{T}} \boldsymbol{Z}_i)$$

The baseline hazard function $\lambda_0(t)$ is independent of the covariates. Prentice (1982) shows that the model for the hazard rate is no longer a Cox regression model in case of error-prone covariates $\boldsymbol{X}^*$:

$$\lambda_i(t|\boldsymbol{X}_i^*, \boldsymbol{Z}_i) = \lambda_0(t) \cdot \exp\left(\beta_X^{\mathrm{T}} \boldsymbol{Z}_i\right) \cdot \mathbb{E}(\exp(\beta_X^{\mathrm{T}} \boldsymbol{X}_i | T \geq t, \boldsymbol{X}^*, \boldsymbol{Z}))$$

The proportional hazard assumption is violated because the relative risk function, $\mathbb{E}(\exp(\beta_X^{\mathrm{T}} \boldsymbol{X}_i | T \geq t, \boldsymbol{X}^*, \boldsymbol{Z}))$, depends on $\lambda_0(\cdot)$ (Carroll et al. 2006 p. 321; Prentice 1982). Indeed the relative risk function could be simplified under the assumption of rare events (Carroll et al. 2006 p. 321), but this assumption is unsustainable for the Wismut cohort.

For a simple Cox regression model, classical measurement error causes again an attenuation of the effect estimate and Berkson error delivers an unbiased effect estimate, provided that the dependence of the distribution of $X|T \geq t, X^*$ on the regression parameters, $\lambda_0(\cdot), \beta_0$ and β_X, is negligible (Prentice 1982).

Classical covariate measurement error was found to attenuate the corresponding estimate in a Cox regression model (e.g. Bender et al. 2005; Nakamura 1992).

Additive (see also Bender et al. 2005) and multiplicative Berkson errors of the exposure was found to cause an attenuation of the relationship between hazard rates for non-rare diseases, which is less severe than for classical measurement error. Additive Berkson error even affects the effect estimations of precisely measured covariates. Moreover, the model assumptions, i.e. the log-linear relationship between linear predictor and hazard rate and the proportional hazard assumption, do not hold for predictors with additive or multiplicative Berkson error. (Küchenhoff et al. 2007)

Schafer et al. (2001) accounted for type I mixture error by means of an adapted regression calibration approach: dose-response model and calibration model were simultaneously estimated; measurement error correction hardly changed the results.

7. Recommendations

Finally, recommendations for the consideration of the sources of uncertainties in the follow-up project are given. These recommendations rely on the preliminary evaluation of the potential uncertainties in Chapter 6. The concluding evaluation of the relevance of uncertainties is overviewed in Table 29.

Table 29: Preliminary evaluation of the potential sources of uncertainties in the exposure assessment for the Wismut cohort.

Type of uncertainty	**Details**	**Potential relevance**	**Reasons**
Generalization error	Usage of averages of single values for shaft-specific exposure assessment	major	Classical measurement error, medium error size, concerns all exposure estimates
Parameter uncertainties	Uncertainties in the determination of parameters, e.g. evaluation factor	major	Major effect on some exposure estimates, concerns all exposure estimates
Assignment error	Assignment of group-specific values to an individual	medium	Berkson error, large error size, concerns all exposure estimates
Transfer error	Data transfer to another calendar year or object	medium	Classical measurement error, high degree of uncertainty, concerns some exposure estimates
Documentation error	Documentation of measurements and occupational histories	medium-minor	Concerns an unknown number of exposure estimates, error type unclear
Experts' evaluation error	Determination of exposure values by experts	minor	Berkson error, possibly high degree of uncertainty, concerns few exposure estimates
Procedural measurement error	Human and technical errors in the measurement procedure	minor	Aggregation of several measurements
Approximation error	Approximation through estimation equations and rounding	minor	Experts' decision, minor effect on exposure estimates

Generalization error occurs through the usage of averages of single measured values for the calculation of shaft-specific exposure in the JEM. Generalization error is estimated to be of potential major relevance, because the measurement error is of classical type and of medium size (depending on the number of measurements). Further, this error type concerns all exposure estimates.

Parameter uncertainties embrace all uncertainties in the determination of parameters. A possibly very important parameter are is the evaluation factor. Many parameters were particularly used for experts' estimation. Parameter uncertainties are of major relevance because they strongly affect all exposure estimates. The type of error is ambiguous and depends on the considered parameter.

Assignment error occurs through the assignment of shaft-specific exposure values from the JEM to an individual. Indeed, this error concerns all exposure estimates and is large, but assignment error is of medium relevance, because it is of Berkson type, which is known to have a minor impact on risk estimates in comparison to classical measurement error.

Transfer error originates from the data transfer of exposure estimates to another calendar year or object. Transfer error is relevant because it is a classical measurement error and bears a high degree of uncertainty. This error affects some exposure estimations that were based on data from reference objects or reference years as well as exposure estimations that were determined by the direct transfer of exposure values.

Documentation error refers to uncertainties in the documentation of measurements and occupational histories. This error concerns an unknown number of exposure estimates. Additionally, the intentionality by the generation of the error and thus the error type (classical or systematic) is unclear. Therefore, the documentation error was evaluated as a medium to minor relevant error.

Experts' evaluation error results from the error-prone determination or adaption of exposure values by experts. Due to the Berkson error type and the impact on few exposure estimates, we rate this error as minor relevant.

Procedural measurement error occurs through human and technical errors in the measurement procedure of radon gas and radon progeny concentrations. Since the measurements are integrated in exposure assessment in an aggregated form, we believe that procedural measurement error is of minor relevance.

Approximation error results through the usage of estimation equations and through rounding. This error is of minor relevance, because the approximations were performed by specialists and only slightly affect the exposure estimates.

The impact of covariate measurement errors on risk estimates strongly depends on the size of the measurement error. We recommend the re-evaluation of the relevance of uncertainties for the statistical analyses after the quantification of the size of the uncertainties.

Regarding Table 29, the number of types of uncertainties seems manageable, but each error type may consist of several subtypes. Furthermore, the measurement error size of each type of uncertainty temporally and spatially varies and the uncertainties exhibit a complex structure due to the elaborate exposure assessment. For these reasons, several uncertainties occur simultaneously and the size and type of measurement error differs between the single observations in the Wismut cohort. Overall measurement error sizes for the French uranium miners cohort study were obtained by applying the RSS (root sum square) method in order to combine the single uncertainties from the different sources (Allodji et al. 2012a). This method was conducted separately for every period, due to the assumed changes in the sources of uncertainty. We believe that stratified consideration of measurement errors by time periods as in Allodji et al. (2012a) does not come up with the complex and highly heterogeneous structure of the measurement error in the Wismut cohort.

The impact of uncertainties on risk estimates was only roughly evaluated in Section 6.3 on the basis of the available scientific literature. The structure of the measurement errors of exposure estimates in the Wismut cohort is more complex in comparison to the examined situations in the literature. A simulation study, as conducted by Allodji et al. (2012b), is a commonly used approach to gain useful information on the impact of uncertainties with a possibly complex structure on risk estimates. In such a simulation study, the data situation of the Wismut cohort would be reproduced based on fixed, hypothetical knowledge about the parameters, which are unknown or estimated for the Wismut cohort. Thus, the data generating mechanism would be fully known, in particular the risk estimates and the precise exposure values of the mechanism. This enables the investigation of the impact of measurement errors of different structures and compositions on exposure estimates for the artificial data. A further benefit of a simulation study is the support of and comparison with theoretical considerations regarding the development of a method taking measurement error into account. For example, Küchenhoff et al. (2007) examined the impact of Berkson and classical measurement error on risk estimates resulting from a Cox regression model with theoretical considerations as well as with a simulation study; the simulation study enabled also to investigate this issue in a multiple regression model for which theoretical consideration would be complex or even impossible.

8. Conclusion

Exposure assessment for the Wismut cohort and the associated uncertainties were investigated within the scope of the research project “Ermittlung der Unsicherheiten der Strahlenexpositionsabschätzung in der Wismut-Kohorte - Teil I”. The project is overviewed in Figure 31.

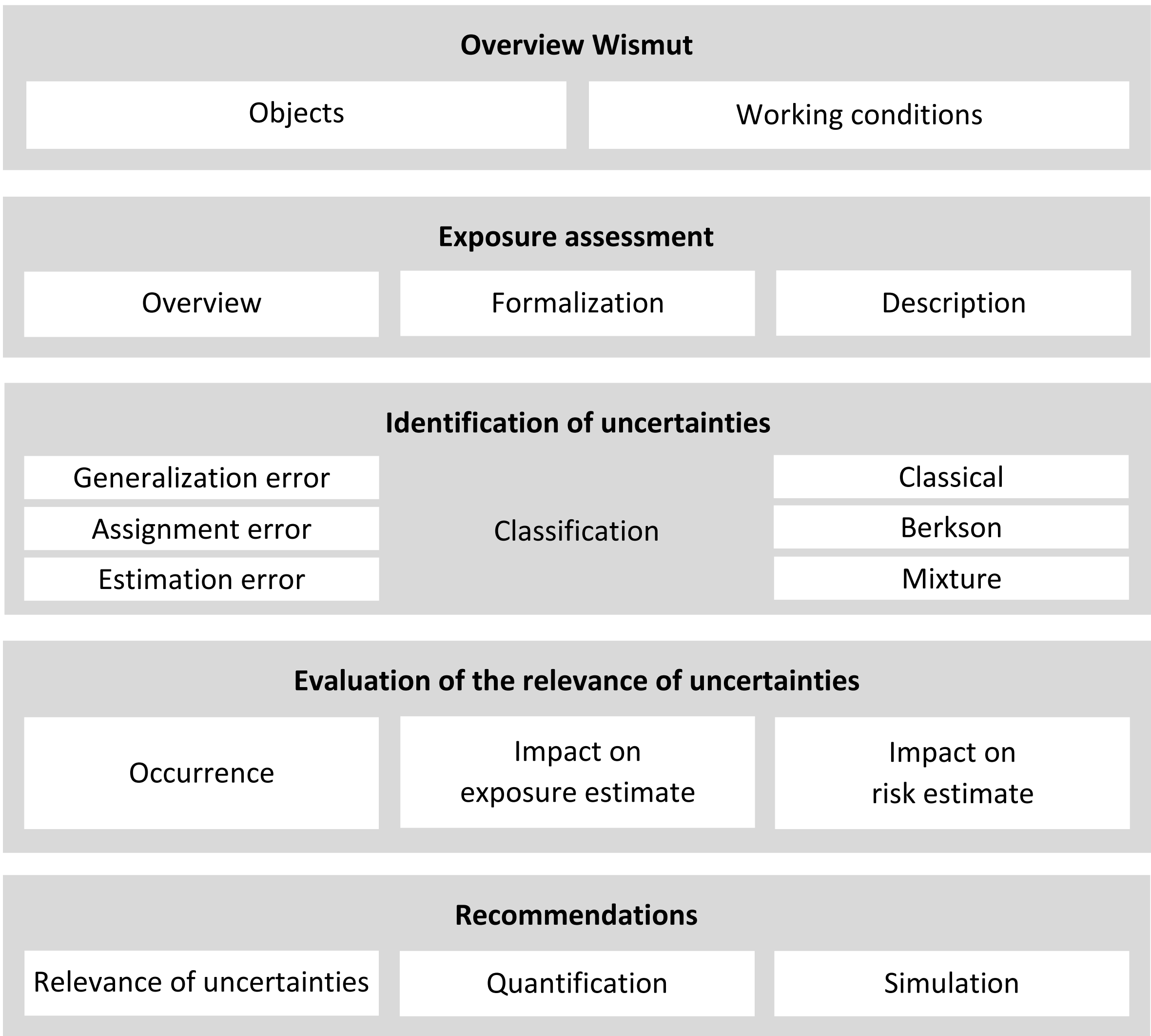

Figure 31: Overview of the research project “Ermittlung der Unsicherheiten der Strahlenexpositionsabschätzung in der Wismut-Kohorte - Teil I“.

A detailed overview of the SAG/SDAG Wismut and the Wismut cohort was obtained regarding the structure of the company and the prevailing working conditions. A schematic summary as well as a consistent formalization and detailed description of the retrospective exposure assessment were developed. A key result is the elaborate and detailed collation of the exposure assessment approach for JEM 1 as well as for JEM 2 for each shaft/object and for each calendar year, which was the ground-work for the consideration of uncertainties. The different uncertainties in exposure assessment, which are implicitly attended by the usage of a JEM and which originated from diverse approaches of exposure assessment, were identified, described in detail depending on different error types (generalization error, assignment error and estimation error) and classified into statistical error categories. Different types of uncertainties, which are temporally and spatially varying and dependent, were simultaneously operating in a complex way. The relevance of the uncertainties in exposure assessment was preliminarily evaluated regarding the frequency of occurrence, the potential impact on the estimated exposure and on the risk estimate. Generalization error and parameter uncertainties were rated as the most relevant errors; assignment, transfer and documentation error were considered as less relevant error types which should, however, not be ignored. Error quantification and a simulation study may reveal further important and useful information on the measurement error in the exposure estimates of the Wismut cohort including their relevance.

Our work essentially contributes towards the calculation of lung risk estimates depending on radon exposure taking measurement error into account, as depicted in Figure 32.

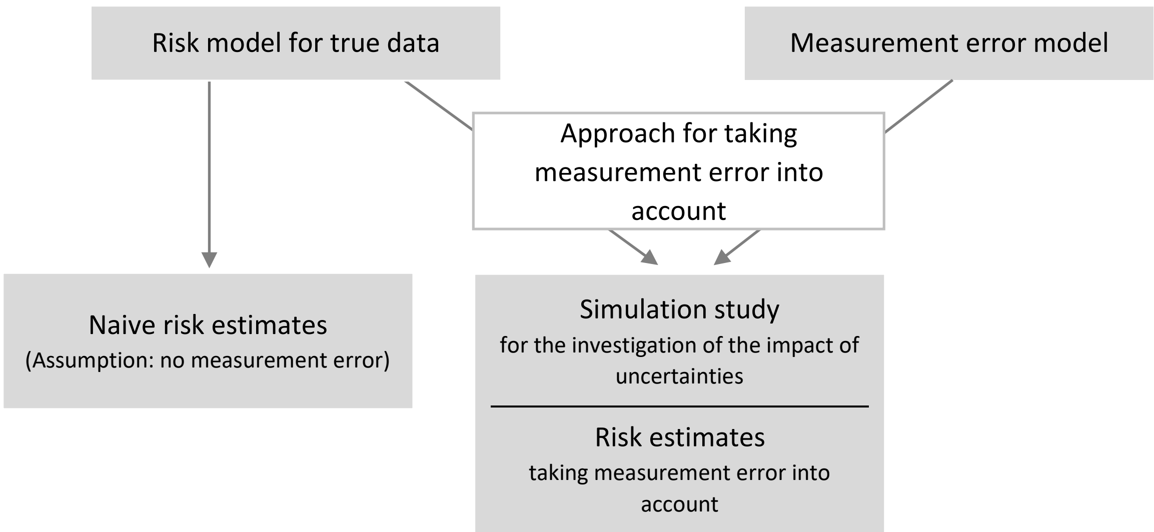

Figure 32: Steps toward risk estimates taking measurement error into account.

Firstly, a risk model for the true data is needed. This risk model already exists for the Wismut cohort and is used to calculate “naïve” risk estimates under the assumption that the size of the measurement error is zero.

Secondly, a measurement error model has to be developed. The work presented in this report is essential to define the measurement error model for the Wismut cohort because the two components of the measurement error model, the observed exposures and the measurement errors, are extensively described. The quantification of the measurement error and the definition of the measurement error model were not part of this research project and would complete this second requirement.

Thirdly, an approach has to be developed, which enables the calculation of risk estimates taking measurement error into account on the basis of the risk model for the true data and the measurement error model. A simulation study helps to evaluate the quality of this approach as well as to examine the impact of the measurement error on risk estimates.

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Appendix A

A 1. Exposure assessment in other cohorts

The French uranium miners cohort

The assessment of radon and its decay products within the French uranium miners cohort is well described in Allodji et al. (2012a). The whole study spans over a period of 54 years (from 1946 to 1999) which can be divided into different periods according to the method of exposure estimation. For the first period (1946 to 1955), the individual exposure was retrospectively estimated by a group of experts in 1981. These estimations were based on historical environmental measurements in the mines (obtained by scintillation flasks), as well as on information on the place and the period of employment for each miner.

In the ensuing period (1956 to 1982), potential alpha energy concentration (PAEC) was estimated by multiplying ambient measurements of radon gas concentration with an equilibrium factor. The equilibrium factor was obtained by dividing the PAEC for the actual mixture of radon progeny by that which would apply at the radioactive equilibrium. In the first approximately two decades of this period (1956 to 1974) at least one measurement per week was taken, whereas from 1975 to 1982 several measurements per week were conducted. The measurements were again obtained by using scintillation flasks for the whole period.

From 1983 onwards, personal measurements were introduced, by using a dosimeter device called ISID (Integrated system of individual dosimetry). Each miner was from now on equipped with a personal device which directly measured the PAEC as well as the individual radon exposure monthly. This allowed for continuous exposure measurements in the period from 1983 to 1999.

The Czech uranium miners cohort

Information on the exposure assessment in the Czech uranium miners cohort can be found in Tomasek et al. (1994) and Tomasek et al. (2008). The first of these two papers reports about 39 000 total measurements of radon gas in the period from 1949 to 1963 in 19 mine shafts. These measurements were converted into working levels (WL) by using equilibrium factors based on radon progeny measurements taken after 1960. Individual WLM-estimates were eventually obtained as the product of the time spent in the mine shaft with the year- and shaft-specific WL-estimates.

Working time was assumed to be 6 days a week with 1 month of holiday per year and for most of the men, 8 hours of underground work per day was assumed. For some job groups it was estimated less of the time was spent underground: Geologists, safety and ventilation technicians and emergency workers approximately spent only 70 % of their working time underground while for managers it was only 50 %.

Tomasek et al. (2008) deliver more detailed information: In the period from 1946 to 1960 there were 200 measurements per year and shaft, whereas afterwards the number of measurements rose to more than 900 per year and shaft. Concerning the measuring method, duplicate air samples were measured in ionization chambers from 1949 to 1967. From 1968 onwards, there were personal measurements of radon progeny in the ambient air. In those shafts, where no measurements were available for the first years, exposure data were extrapolated from later data.

The Colorado Plateau uranium miners cohort (USA)

The exposure estimates for this cohort are based on radon progeny measurements from the mines beginning in 1951. Unfortunately, the mines were not continuously monitored, so that extrapolation and interpolation was done to obtain individual exposure estimates (Stram et al. 1999).

Studies regarding measurement error within the biologically-based two-stage clonal expansion model are based on data from the Colorado Plateau uranium miners cohort (Heidenreich et al. 2004) and the European uranium miners cohorts (Heidenreich et al. 2012). Both papers report more complex effects of the dose uncertainties, as several parameters of this specific model are allowed to depend on the exposure. Heidenreich et al. (2004) apply likelihood-based techniques to error-prone data (multiplicative classical and Berkson error) and report them to work reliably, if the distribution of the true exposures as well as the distribution of the recorded exposures conditional on the true exposures is known. Heidenreich et al. (2012), despite finding the overall consequences for the model parameters not to be of great magnitude, report a strong effect of the measurement error on the initiation part of the model.

The Port Hope cohort (Canada)

This description of the exposure assessment in the Port Hope cohort is based on Zablotska et al. (2013). For almost two decades, in the 1930ies to the 1950ies, the estimates were based on the "quantities of radium present in the plant in ore and at various stages of refinement, measured radon emanation rates from various radium-bearing materials, building air volumes and estimates of air exchange rates". Individual annual exposures (in WLM) were estimated dependent on the type of work place, the proportion of employees in each activity and the proportion of time in a work place by an employee of a certain activity.

In the 1970ies, radon progeny was measured in the Yellow-cake warehouses, but no exposure estimates were made due to the low occupancy.

Cohort of Chinese tin miners (Qiao et al. 1989)

The exposure assessment in the Chinese tin miners cohort can be roughly divided into three different periods: For the period before 1953, the exposure estimates are based on 117 samples from 13 small pits which already operated before 1949 and were still available for testing. In the subsequent period (1953 – 1972), the exposure values were estimated based 413 samples of radon daughters from 1972. Ultimately, in 1972, the radon problem was recognized and since then systematic monitoring has been carried out. Qiao et al. (1989) reported over 26 000 collected and analyzed samples. On this basis, mine-, job- and era-specific estimates (in WLM) were calculated.

A 2. Details to retrospective modifications of exposure estimations

A 2.1. Exposure estimation during lead and follow-up times of an object

The original exposure estimations could not be directly used for the calculation of individual exposure because the occupational histories of some workers cover longer periods than the operating time of the object, for which they have been employed (Lehmann 2004 p. 8). Lead and follow-up times ("Vor- und Nachlaufzeiten") of the objects were a main reason. Exposure estimations for these periods were closely related to the operational development of the objects and shafts. The guidelines for the estimations are summarized in the following.

Exposure during lead times ("Vorlaufzeiten")

The determination of the exposure during lead times was conducted according to differentiated guidelines documented in Lehmann (2004). Table A1 summarizes these guidelines.

A reading example for Table A1 is: If preliminary exploration activities like emanation measurements were conducted in an object, e.g. in object 000 390 (908 BB Königstein), the exposure to radon progeny was evaluated by an expert as 0.1 WLM.

Table A1: Guidelines in Lehmann (2004) for experts' evaluation of exposure during lead times of objects.

Object development status	Activities	Objects/shafts	Exposure estimation method
Preliminary exploration			
Preliminary exploration	Emanation measurements, radio-hydrological recordings, beginning geologic exploration, surface search and exploration works	000 390, 027, 030, 086, 090 555, 090 557, 090 558, 090 559, 090 560, 090 561, 090 562, 090 563s, 090 566	Expert estimation (0.1 WLM)
Search and exploration work			
In old mining		001 000, 001 001s, 001 021s, 001 023s, 001 235, 002 000s, 003, 004 000s, 004 034, 005 000s, 007 000s, 007 021s, 007 045s, 008 000s, 008 023s, 009 003s, 009 235, 010 000s,	Basic exposure from old mining

Object development status	Activities	Objects/shafts	Exposure estimation method
Low extent of basic exposure from old mining		**021**: 002 012s, 002 013, 002 063s, 002 064, 002 065, 002 172s, 009 000s, 009 012, 009 013s, 009 041s, 029 **023**: 005 251s, 007 206s, 008 206s ,008 240s **024**: 005 292, 007 097s **025**: 006 000s, 006 254, 006 381, 009 277 **026**: 015 000s, 015 113s, 096 196s **027**: 030, 086, 090 352, 090 356, 090 385s, 090 384 **029**: 002 172s, 009 041s	Regionally and approximately contemporaneously operating exploration object
Development work			
In old mining		001 000, 001 001s, 001 021s, 001 023s, 001 235, 002 000s, 003, 004 000s, 004 034, 005 000s, 007 000s, 007 021s, 007 045s, 008 000s, 008 023s, 009 003s, 009 235, 010 000s,	Basic exposure from old mining
Low extent of basic exposure from old mining	Progressing/systematic exploration and miner's activities, further ground opening, sinking work, search and exploration work with small extent of basic exposure from old mining	**011**: 002 012s, 002 013, 002 063s, 002 064, 002 065, 002 309s, 009 012, 009 013s, 009 310s, 014 **012**: 007 206s, 008 206s, 008 240s **013**: 005 251s, 005 292, 007 097s, 015 000s, 096 196s **014**: 006 000s, 006 241s, 006 181s, 006 381, 009 277 **086**: 030, 090 352, 090 356, 090 384, 090 385s	Regionally and approximately contemporaneously operating development object
	Sinking work	000 390, 090 397	Expert estimation (1 or 2 WLM)
	Development work	000 390, 006 254	Expert estimation (4 or 6 WLM)

The duration of the lead times depends on the object and can be extracted from Figure 9. Exceptions from the guidelines in Table A1 were the object sections 096 000s and 090 403, for which exposure values of the first year with exposure estimations were carried backward to the lead times of the object sections (Lehmann 2004 pp. 193, 212).

Exposure during follow-up times ("Nachlaufzeiten")

After the phase-out of the production in a shaft/object, the workers usually continued working in other shafts/objects. Frequently, the shaft/object change was not documented in the occupational histories of these workers and thus, their occupational histories exceeded the follow-up times of the object. It was generally assumed that the workers of an abandoned shaft were further employed in other shafts of the same diggings (Lehmann 2004 p. 105). The exposure for a shaft/object in periods with continued employment in another shaft/object was determined related to the exposure in the object which was most likely the object of continued employment (occurred in the objects 001 235, 002 000s, 002 064, 003, 006 000s, 006 181s, 006 254, 006 241s, 008 000s, 014, 090 560, 090 563s). If other shafts of the original object were still operating, workers were assumed to continue their work in the same object but in a different shaft (Lehmann 2004 p. 105) (occurred in the objects 006 181s, 006 241s, 006 254, 009 003s, 009 235, 009 277).

The determination of the exposure during follow-up times was conducted according to differentiated guidelines documented in Lehmann (2004). Table A2 summarizes these guidelines.

A reading example for Table A2 is: During the phase-out of exploration or mining works, like e.g. in the exploration object 029 Aue Lauter-Schwarzenberg, the last available exposure value was continued for the following years.

Table A2: Guidelines in Lehmann (2004) for experts' evaluation of exposure during follow-up times of objects.

Object development status	Activities	Objects/shafts	Exposure estimation method
Continuing development/mining works			
Continuing exploration/mining works (short period: 1-3 years)	Continuing development/mining assumed (partially not mentioned)	000 390, 001 023s, 001 235, 002 000s, 006 092s, 007 206s, 008 000s, 008 023s, 008 206s, 008 240s, 009 235, 012, 014, 015 092s, 022, 025, 027, 028, 096 000s	Continuation of values
Continuing exploration/mining works (longer period: >3 years)	Continuing development/mining assumed (partially not mentioned)	001 021s, 004 000s, 007 021s, 003, 009 003s	Adapted continuation of values (depending on uranium mining)
Phase-out of mining works			
Phase-out of exploration/mining works	Execution of finishing works, surface works in open pit mining objects	029, 090 556, 090 562	Continuation of values
Custodial works			
Custodial works		001 000, 001 001s, 001 235, 005 251s, 005 292, 007 097s, 008 000s, 008 240s, 009 235, 015 000s, 096 196s	Continuation of values

Object development status	Activities	Objects/shafts	Exposure estimation method
Custodial works with reduced mine void		001 023s, 004 034, 005 000s, 007 000s, 007 045s, 008 023s	Adapted continuation of values
Indefinite information about custodial activities		001 023s, 007 206s, 008 023s, 008 206s, 008 240s	Continuation of values
Remedial actions			
Remedial actions	E.g. filling of the excavation pit with mine waste	090 555, 090 557, 090 558, 090 561, 090 562, 090 566, 090 563s	Expert estimation (0.1/0.3 WLM)
Dismantling works	Dismantling works (partially only indirectly mentioned)	002 063s, 002 065	Regionally operating development object

A 2.2. Exposure during the main operating period

Exposure before and after shaft/object adoption

Several objects or sections of objects of the SAG/SDAG Wismut were adopted by other objects during the operating time of the company. The updated exposure estimations in Lehmann (2004) accounted for these adoptions. For the time before the adoption, the original exposure estimations of the adopted objects/sections of objects were retained and used for corresponding shafts in the new (adopting) object (001 021s, 001 023s, 001 235, 002 012s, 002 013, 002 309s, 003, 004 000s, 005 000s, 006 000s, 007 021s, 007 045s, 007 206s, 008 000s, 008 023s, 008 206s, 008 240s, 009 003s, 009 012, 009 013s, 009 235, 009 277s, 009 310s, 011, 090 352, 090 385s). The exposure estimation procedure for the years after the adoption can be classified into three categories (Lehmann 2004):

1. *No/marginal basic exposure from old mining, execution of finishing works and phase-out of production*:

   Exposure estimations of the new (adopting) object were used for the adopted shafts (002 012s, 002 013, 002 309s, 003, 009 013s, 009 310s, 011, 090 352, 090 385s).

2. *Important effect of the adopted shafts on the total production volume of the new object and substantial basic exposure from old mining*:

   The important effect shaft adoption on the total production volume of the new object involves also an impact on the exposure to radon. Therefore, exposure estimations of the new object were used, but with consideration of the different basic exposure from old mining in the adopted shafts (001 021s, 001 235, 004 000s, 005 000s, 007 021s, 007 045s, 008 000s, 009 235):

   $$E^*(t, o_1, j) = E^*(t, o_2, j) - \left(E^B(o_1) - E^B(o_2)\right)$$

   with o_1 denoting the adopted object and o_2 denoting the adopting object. The exposure to radiation originating from mining activities was assumed to be equal in objects o_1 and o_2.

3. *Negligible effect of the adapted shafts on the total production volume of the object:*

Use of the exposure values of the adapted shafts (001 023s, 007 206s, 008 023s, 008 206s)

As a result of the update of the original exposure estimations, shafts which were assigned to different objects received the same exposure values, independent of their object assignment, e.g. shaft 021 in the diggings Annaberg-Buchholz received the same exposure values under the various labels 004 021, 007 021, 001 021 (Lehmann 2004 p. 101).

Exposure during temporary independent operation of shafts

A part of object 001 Johanngeorgenstadt was temporarily independently operating as object 010 Bergrevier Johanngeorgenstadt (Westteil). Exposure estimations for the main object in the diggings 001 Aue were assumed for object 010 (Lehmann 2004 p. 122).

Shaft-specific exposure

Heterogeneous exposure throughout a diggings requires shaft-specific amendments of the original exposure estimations. The exposure for exploration or development shafts of an object, which never go beyond the exploration or development status, was changed to the exposure in regionally operating exploration or development objects (002 063s, 002 065, 002 172s, 005 251s, 006 381, 007 097s, 009 041s, 015 113s) (Lehmann 2004); e.g. object section 002 063s received the same exposure as the exploration object 021 for the years 1946-1947 (Lehmann 2004 p. 150). Proportional exposure values were used for areas of an object with less uranium mining than the main part of the object (002 012s, 002 309s, 006 181s, 006 241s, 006 254, 009 012, 009 310s) (Lehmann 2004); e.g. the exposure for object section 002 012s was determined to 40 % of the exposure of the main part of the object, 002 000s, in the period 1948-1954 (Lehmann 2004 p. 151). Shaft-specific exposure estimations existed already in the first version of the JEM (Lehmann et al. 1998 pp. 222–223), but only for object 091, i.e. shaft 400 of object 009 Aue (Bergbauabteilung Pöhla), but the reason as well as the exposure assessment approach were not specified.

In some cases, the organizational units (objects) are not consistent with the geological units, i.e. parts of a diggings or single shafts were assigned to other objects and not to the object of the remaining part of the diggings (shaft 004 034 was assigned to object 007 (Lehmann 2004 p. 104); shaft 005 292 was assigned to object 007 (Lehmann 2004 p. 108), object section 096 196s was assigned to object 015 (Lehmann 2004 p. 189)) or objects accomplish works in other diggings (object 001 023s accomplished works in object 008 (Lehmann 2004 p. 126)). Similar circumstances comprise the following:

- The exposure estimated for object 002 was not adequate for shaft 064 due to a lower basic exposure from old mining; exposure estimations from a neighboring object were used (Lehmann 2004 p. 147).
- Double named objects existed (006: 006 092s, 015 092s, 096 000s; Lehmann 2004 p. 171).
- The objects 014, 025, 029, 047 changed their site of operation (Lehmann 2004 pp. 196–197, 199, 203; Lehmann et al. 1998 p. 105), which was not considered in the exposure estimation of Lehmann et al. (1998).

The exposure vales for these shafts ware changed according to their geologic affiliation.

Filling of gaps

Gaps in the time series of exposure estimations arose, if, for a certain period, original exposure estimations were not available or if exposure estimations of other objects were not appropriate to be applied. The procedure for filling these gaps with expert estimations in Lehmann et al. (2004) was:

1. Reasonable filling of gaps, i.e. proportional exposure values of an adequate shaft/object of an adequate calendar year on the basis of other shafts/objects or expert estimation due to e.g. mining of ore with higher quality, mining in deeper levels, development of inventories ("Vorratsentwicklung"), mining of explored inventories, giving up of mine sites or expiring extraction (001 235, 002 065, 006 254, 008 000s, 009 235, 086, 090 384, 090 555, 090 566, 090 557)
2. Filling of gaps without mentioning the reasons (000 390, 001 023s, 001 235, 002 000s, 006 092s, 008 000s, 008 023s, 009 235, 009 400, 012, 013, 015 092s, 022, 023, 029, 047, 090 403, 090 563s, 096 000s)

Further amendments of original exposure estimations

The exposure estimation for some special cases differed from the previously defined guidelines. These further amendments of the original estimations are listed in the following:

- In comparison to Lehmann et al. (1998), additional data were found for the update of the exposure estimations in Lehmann (2004) for object 009 Aue in the calendar years 1958-1960 (Lehmann 2004 pp. 161–162). These newly available data affected the exposure estimations of the shafts/objects 002 012s, 002 013, 002 309s, 009 000s, 009 012, 009 013s and 009 310s.
- The exposure in the open pit mining objects 090 566 Lichtenberg and 090 557 Ronneburg/ Raitzhain was evaluated to be equal due to ambiguous assignment of the workers to the objects (Lehmann 2004 p. 222).
- The newly introduced object 090 555 comprises workers in open pit mining objects in general. The exposure for object 090 555 was determined related to the values of the open pit mining objects 090 566 Lichtenberg and 090 557 Ronneburg/Raitzhain (Lehmann 2004 p. 225).

A 3. Software for individual exposure assessment in the Wismut cohort

A 3.1. Overview

The individual annual exposures to radon progeny in the Wismut cohort are calculated based on a specific software for exposure assessment (HVBG and BBG 2005). This software was developed on the basis of the second version of the JEM (Lehmann 2004). Appendix B (Figure B7) visualizes the functionality of the software for exposure assessment as well as relevant input and output datasets and variables. The descriptions in Tschense (2014) serve as major source for the subsequent information.

In short, individual occupational histories of the cohort members, special underground shifts and absenteeism is linked to underlying JEM tables as printed in Lehmann (2004). The resulting output data contains for each cohort member and considered working period the associated exposure to radon progeny and the activity weighting factor (based on input data on object and shaft, type of object and activity). Individual annual exposure is finally calculated by weighting the resulting exposure by the activity weighting factor, as described in Appendix B (Figure B7).

The input data consists of the three databases “BERUF.DBF”, “ANDERSPI.DBF”, and “PERKURZ.DBF”:

BERUF.DBF	Occupational histories of the cohort members
ANDERSPI.DBF	Durations of special underground shifts and absenteeism
PERKURZ.DBF	Personal information about the Wismut cohort members

In a first step, the input data is prepared by calculating new and modified variables. Labelling of objects and activities was originally not consistent. Therefore, the original labels of the ZeBWis are converted and unified to obtain the labels of the Bergbau-Berufsgenossenschaft (BBG); the unified object labels are depicted in Table 2. According to the category of the work place (variable “ARBEITSORT” in “BERUF.DBF”) a classification in underground (“U”) and surface (“O” for “Oberfläche”) is conducted. The output data contains a new variable “O_U”:

U	Working more than 50 % underground in underground mining objects or in processing companies
O	Working in objects without exposure, open pit mining objects or less than 50 % underground in underground mining objects

This variable roughly indicates whether a cohort member was not or less exposed (“O”) or exposed (“U”). The variable “O_U” determines which exposure values and activity weighting factors are used for exposure assessment if separate values for the two categories “U” and “O” exist.

Moreover, the duration of each entry of the occupational histories is assessed, i.e. the duration of work in each activity, of special underground shifts and of absenteeism. The resulting output data is separated into three tables:

WLM_Zeit	Individual exposure for the complete duration of the considered work period in a given object and activity

WLM_Zeit can be regarded as the main table, it contains for each worker the objects he worked in, the activity and the time spent there. Further, it gives the exposure related to the objects, the activity weighting factor and the resulting individual exposure.

WLM_Fehl — Individual exposure during absenteeism

WLM_Fehl contains for each worker and each year the number of months of absenteeism converted into days, the exposure related to the associated objects, the activity weighting factor and the resulting exposure during absenteeism.

WLM_Schi — Individual exposure during special underground shifts

WLM_Schi gives for each worker and each year the number of days worked underground, the exposure related to the associated object, the activity weighting factor and the resulting exposure for the special underground shifts.

In the second step, database queries are conducted based on the prepared data to obtain the exposures to radiation and the activity weighting factor for each working period of each individual, as given in the JEM. These information are determined for WLM_Zeit, WLM_Fehl and WLM_Schi. Since WLM_Fehl and WLM_Schi contain annual data, exposures and activity weighting factors are averaged if necessary.

In the third step, individual exposure is calculated separately for WLM_Zeit, WLM_Fehl and WLM_Schi. Therefore, the exposure to radiation (second step), the activity weighting factor (second step) and the duration percentage (first step) are multiplied (see Section 4.7).

Individual annual exposure is finally assessed as the individual exposure for the complete duration of the work in a considered object and activity (WLM_Zeit) without the individual exposure during absenteeism (WLM_Fehl) and with the individual exposure during special underground shifts (WLM_Schi) (see Section 4.7). The results are transferred into the dataset fu2013. This dataset stores the individual annual exposure to radon progeny calculated from the aforementioned tables.

A 3.2. Background on example cases for exposure assessment

In the following, illustrative examples are presented to understand the software and calculations for exposure assessment. The example cases were chosen for the illustration of the following aspects in individual exposure assessment:

- Underground workers in underground mining objects:
  - Hewer
  - Worker other than hewer
- Changes of objects and activities
- Surface workers:
  - Worker on the surface of a mining object with exposure
  - Worker on the surface of a mining object without exposure
  - Worker in a surface object
  - Surface worker with special underground shift
    (constant activity/object within a calendar year)
  - Surface worker with special underground shifts
    (varying activities/objects within a calendar year)
- Absenteeism (varying activities/objects within a calendar year)

Based on the tables “WLM_Zeit”, “WLM_Schi” and “WLM_Fehl”, the database queries and the preparing calculations are reproduced. Afterwards the procedure for the final calculations of the individual exposure to radon progeny is revised.

Only relevant excerpts of the datasets are shown.

A 3.3. Underground mining objects

Hewer in underground mining: ID 53023, 1947-1950

Looking at “WLM_Zeit” (Table A3) for the worker with ID 53023 (“ORDBG”) we can see that he worked from 1947 until 1950 as a hewer (“Taetigkeit=10000”) in shaft 004 of object 002 (“Objekt=002004”). The columns “Berechnung_vom” and “Berechnung_bis” give the starting and end date for the respective working period. “Tag” gives the number of days in this period. Column “O_U” indicates the working location with underground (“U”).

Table A3: Excerpt from WLM_Zeit: ID 53023, 1947-1950.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung _vom	Berechnung _bis	Taetigkeitsfaktor _WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
53023	10000	002004	19-Sep-47	31-Dez-47	1.00	125.00	104	U	35.42
53023	10000	002004	01-Jan-48	31-Dez-48	1.00	140.00	366	U	140
53023	10000	002004	01-Jan-49	31-Dez-49	1.00	175.00	365	U	175
53023	10000	002004	01-Jan-50	31-Dez-50	1.00	210.00	365	U	210
					↓	↓			↓
					$f(t,o,j)$ L., 1998, p. 259	$E(t,o,j_0)$ L., 2004, p. 25			$l(i,t,o,j) \cdot E(t,o,j)$

$E(t,o,j_0)$, the annual exposure to radon progeny for the reference activity in object 002 004 is listed in the column “WLM_Jahr”, which is given in Lehmann (2004 p. 25). In 1947, for example, the annual exposure to radon progeny was 125 WLM. The activity weighting factor $f(t,o,j)$ is listed in column “Taetigkeitsfaktor_WLM”, which can be found in Lehmann et al. (1998 p. 259).

The exposure for the worker during the respective working period is given in “Ergeb_WLM”. It is obtained through

$$\begin{aligned} \text{Ergeb\_WLM} &= \text{Taetigkeitsfaktor\_WLM} \cdot \text{WLM\_Jahr} \cdot \frac{\text{Tag}}{365\ (366 \text{ in leap years})} \\ &= f(t,o,j) \cdot E(t,o,j_0) \cdot l(i,t,o,j) \\ &\overset{\text{here}}{=} 1.00 \cdot 125.00 \cdot \frac{104}{365} = 35.42 \end{aligned}$$

During the years 1947 to 1950, the worker worked only in object 002 004 and had neither special underground shifts nor times of absenteeism. Hence, the column “Ergeb_WLM” in “WLM_Zeit” (Table A3) already equates to his annual exposure to radon progeny, i.e. $E(i,t) = E^A(i,t)$, which is listed in column “w” of table “fu_2013” (Table A4).

Table A4: Excerpt from fu_2013: ID 53023, 1947-1950.

fu_2013

id	year	Objekt	O_U	Taet_code	w
53023	1947	2004	U	10000	35.42
53023	1948	2004	U	10000	140
53023	1949	2004	U	10000	175
53023	1950	2004	U	10000	210
					↓ $E(i,t)$

Worker other than hewer in underground mining: ID 125411, 1984-1987

Worker with ID 125411 worked underground from 1984 until 1987 in object 906 as a pit foreman ("Steiger") for different tasks ("Taetigkeit"=34500). The annual exposure to radon progeny for the reference activity in object 906 ("WLM_Jahr") $E(t,o,j_0)$ can be found in Lehmann (2004 p. 85) and the activity weighting factor ("Taetigkeitsfaktor_WLM") $f(t,o,j)$) is given in Lehmann et al. (1998 p. 265).

Table A5: Excerpt from WLM_Zeit: ID 125411, 1984-1987.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung _vom	Berechnung _bis	Taetigkeitsfaktor _WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
125411	34500	906000	01-Jan-84	31-Dez-84	0.40	2.00	366	U	0.8
125411	34500	906000	01-Jan-85	31-Dez-85	0.40	2.00	365	U	0.8
125411	34500	906000	01-Jan-86	31-Dez-86	0.40	2.00	365	U	0.8
125411	34500	906000	01-Jan-87	31-Dez-87	0.40	3.00	365	U	1.2
					↓ $f(t,o,j)$ L., 1998, p. 265	↓ $E(t,o,j_0)$ L., 2004, p. 85			↓ $l(i,t,o,j) \cdot E(t,o,j)$

Again, during the respective period, the worker was employed in the same object and had neither special underground shifts nor times of absenteeism. As a consequence, $E(i,t) = E^A(i,t) = f(t,o,j) \cdot E(t,o,j_0) \cdot l(i,t,o,j)$ and "Ergeb_WLM" is equal to column "w" in "fu_2013" (Table A6).

Table A6: Excerpt from fu_2013: ID 125411, 1984-1987.

fu_2013

id	year	Objekt	O_U	Taet_code	w
125411	1984	906000	U	34500	0.80
125411	1985	906000	U	34500	0.80
125411	1986	906000	U	34500	0.80
125411	1987	906000	U	34500	1.20
					↓ $E(i,t)$

A 3.4. Change of objects and activities

Change of objects: ID 125411, 1983

The following example illustrates the calculation of the annual exposure to radon progeny for a change of objects during a single calendar year. In 1983, the worker with ID 125411 was employed in two different objects as a pit foreman for different tasks (“Taetigkeit”=34500). From January 1st until June 2nd he worked in object 903. Then, from June 3rd until the end of the year he worked in object 906. Therefore, two separate rows for this year occur in table “WLM_Zeit” (Table A7). Column “Ergeb_WLM” lists the exposure for the worker during the respective working period.

Table A7: Excerpt from WLM_Zeit: ID 125411, 1983.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung_vom	Berechnung_bis	Taetigkeitsfaktor_WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
125411	34500	903000	01-Jan-83	02-Jun-83	0.40	3.00	153	U	0.51
125411	34500	906000	03-Jun-83	31-Dez-83	0.40	2.00	212	U	0.46
					↓	↓			↓
					$f(t,o,j)$ L., 1998, p. 265	$E(t,o,j_0)$ L., 2004, pp. 80, 85			$l(i,t,o,j) \cdot E(t,o,j)$

The annual exposure to radon progeny for the worker ($E(i,t) = E^A(i,t)$), is obtained by summing up the exposure values of the two periods:

$$\text{w}=E(i,t) = E^A(i,t) = \sum_o f(t,o,j) \cdot E(t,o,j_o) \cdot l(i,t,o,j)$$

$$\overset{\text{here}}{=} 0.4 \cdot 3 \cdot \frac{153}{365} + 0.4 \cdot 2 \cdot \frac{212}{365} = 0.97$$

The result is given in table “fu_2013”, column “w” (Table A8).

Table A8: Excerpt from fu_2013: ID 125411, 1983.

fu_2013

id	year	Objekt	O_U	Taet_code	w
125411	1983	906000	U	34500	0.97
					↓
					$E(i,t)$

Change of activity: ID 125502, 1988-1989

This example illustrates the calculation of the annual exposure to radon progeny for changing activities during one year. In 1988 and 1989 the worker with ID 125502 worked in object 906 as a hewer (“Taetigkeit”=10000) and as a pit foreman for different tasks (“Taetigkeit”=34500). As the object did not change, the annual exposure to radon progeny for the reference activity stays the same and only the activity weighting factor, changes for the respective working periods.

Table A9: Excerpt from WLM_Zeit: ID 125502, 1988-1989.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung _vom	Berechnung _bis	Taetigkeitsfaktor _WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
125502	10000	906000	01-Jan-88	31-Jan-88	1.00	3.00	31	U	0.25
125502	34500	906000	01-Feb-88	31-Dez-88	0.40	3.00	335	U	1.1
125502	34500	906000	01-Jan-89	30-Jun-89	0.40	3.00	181	U	0.6
125502	10000	906000	01-Jul-89	31-Dez-89	1.00	3.00	184	U	1.5
					↓ $f(t,o,j)$ L., 1998, pp. 259, 265	↓ $E(t,o,j_0)$ L., 2004, p. 85			↓ $l(i,t,o,j) \cdot E(t,o,j)$

The annual exposure to radon progeny for the worker ($E(i,t) = E^A(i,t)$) is obtained by summing up the exposure of the two periods for the same year:

$$w{=}E(i,t) = E^A(i,t) = \sum_j f(t,o,j) \cdot E(t,o,j_o) \cdot l(i,t,o,j)$$

The result is given in table “fu_2013”, column “w” (Table A10).

Table A10: Excerpt from fu_2013: ID 125502, 1988-1989.

fu_2013

id	year	Objekt	O_U	Taet_code	w
125502	1988	906000	U	34500	1.35
125502	1989	906000	U	10000	2.10
					↓ $E(i,t)$

A 3.5. Surface workers

Worker on the surface of a mining object with exposure (at the surface): ID 100052, 01-Sep-81 – 23-Sep-81

From September 1st 1981 until September 23rd 1981 this worker was employed as heap keeper (“Haldenarbeiter – Bergbaubetrieb”, “Taetigkeit”=60602) at the surface (“O_U”=O) of object 902. Both, the annual exposure to radon progeny for the reference activity on the surface in this object and the activity weighting factor can be found in Lehmann et al. (1998). Note that Lehmann et al. (1998) developed exposure estimates for workers on the surface of mining objects, which differ from the corresponding exposure estimates for the underground working areas of mining objects. The resulting exposure of the worker during the working period is very small (0.02 WLM) due to the shortness of the period.

Table A11: Excerpt from WLM_Zeit: ID 100052, 01-Sep-81 – 23-Sep-81.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung_vom	Berechnung_bis	Taetigkeitsfaktor_WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
100052	60602	902000	01-Sep-81	23-Sep-81	0.50	0.50	23	O	0.02
					↓ $f(t,o,j)$ L., 1998, p. 289	↓ $E(t,o,j_0)$ L., 1998, p. 253			↓ $l(i,t,o,j) \cdot E(t,o,j)$

Worker on the surface of a mining object without exposure: ID 53023, 1952

The worker considered in this example worked in two different activities on the surface of object 002 in 1952, as a carpenter (“Zimmerer”, “Taetigkeit”=57150) and a transport worker (“Transportarbeiter”, “Taetigkeit”=60000). The activity weighting factors are listed as zero in “WLM_Zeit” (Table A12); the resulting exposure during these time periods is zero as well.

Table A12: Excerpt from WLM_Zeit: ID 53023, 1952.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung_vom	Berechnung_bis	Taetigkeitsfaktor_WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
53023	57150	002000	01-Jan-52	14-Jun-52	0.00	1.00	166	O	0
53023	60000	002000	15-Jun-52	31-Dez-52	0.00	1.00	200	O	0
					↓ $f(t,o,j)$	↓ $E(t,o,j_0)$ L., 1998, p. 235			↓ $l(i,t,o,j) \cdot E(t,o,j)$

Worker in a surface object: ID 49924, 1970-1972

From 1970 to 1972 the worker with ID 49924 worked in the surface object 019 as a teacher (“Lehrmeister”, “Taetigkeit”=74110). For this object, both the annual exposure to radon progeny for the reference activity and the activity weighting factor are zero in “WLM_Zeit” (Table A13).

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung_vom	Berechnung_bis	Taetigkeitsfaktor_WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
49924	74110	019000	01-Jan-70	31-Dez-70	0.00	0.00	365	O	0
49924	74110	019000	01-Jan-71	31-Dez-71	0.00	0.00	365	O	0
49924	74110	019000	01-Jan-72	31-Dez-72	0.00	0.00	366	O	0
					↓ $f(t,o,j)$	↓ $E(t,o,j_0)$			↓ $l(i,t,o,j) \cdot E(t,o,j)$

Table A13: Excerpt from WLM_Zeit: ID 49924, 1970-1972.

Surface worker with special underground shifts (same activity/object within a calendar year): ID 100052, 1980

In 1980, the worker with ID 100052 worked as mining apprentice ("Berglehrling", "Taetigkeit"=10211) in the surface object 019. As in the previous example, the annual exposure to radon progeny for the reference activity in this object and the activity weighting factor are listed with zero in "WLM_Zeit" (Table A14). Therefore,

$$E^A(i,t) = \text{Ergeb\_WLM} = \text{Taetigkeitsfaktor\_WLM} \cdot \text{WLM\_Jahr} \cdot \frac{\text{Tag}}{365\ (366\ \text{in leap years})}$$
$$= f(t,o,j) \cdot E(t,o,j_o) \cdot l(i,t,o,j) \overset{\text{here}}{=} 0$$

Table A14: Excerpt from WLM_Zeit: ID 100052, 1980.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung_vom	Berechnung_bis	Taetigkeitsfaktor_WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
100052	10211	019000	01-Jan-80	31-Dez-80	0.00	0.00	366	O	0
					↓	↓			↓
					$f(t,o,j)$	$E(t,o,j_0)$			$l(i,t,o,j) \cdot E(t,o,j)$

According to the table "WLM_Schi" (Table A15), the worker had 122 days with special underground shifts in 1980.

Table A15: Excerpt from WLM_Schi: ID 100052, 1980.

WLM_Schi

ORDBG	Jahr	Tage	WLM_Faktor	WLM_Wert	WLM_Ergeb
100052	1980	122	0.4	3	0.4
			↓	↓	↓
			$\bar{f}(t,o,j)$ L., 1998, p. 259	$\bar{E}(t,o,j_0)$ L., 2004, p. 80	$l^{UT}(i,t) \cdot \bar{E}(t,o,j)$

The activity weighting factor and the annual exposure to radon progeny in the underground object are listed in "WLM_Schi". Information about the object name and the activity can only be viewed in the input data "BERUF.DBF", but not in the output data.

The exposure during special underground shifts $E^{UT}(i,t)$ is calculated as follows:

$$E^{UT}(i,t) = \text{WLM\_Ergeb} = \text{WLM\_Faktor} \cdot \text{WLM\_Wert} \cdot \frac{\text{Tage}}{365\ (366\ \text{in leap years})}$$
$$= \bar{f}(t,o,j) \cdot \bar{E}(t,o,j_o) \cdot l^{UT}(i,t)$$

In the next step, the exposure to radon progeny in 1980 for the worker is calculated by adding the exposure during special underground shifts in 1980 to the exposure for the complete calendar year:

$$E(i,t) = E^A(i,t) + E^{UT}(i,t)$$

Table A16: Excerpt from fu_2013: ID 100052, 1980.

fu_2013

id	year	Objekt	O_U	Taet_code	w
100052	1980	19000	O	10211	0.40
					↓
					$E(i,t)$

Surface worker with special underground shifts (varying activities/objects within a calendar year): ID 37276, 1965

In this example, the worker with ID 37276 was a mining apprentice (“Berglehrling”, “Taetigkeit”= 10211) on the surface of underground mining object 009 in 1965. Apparently, there were different activities and/or locations during this year of apprenticeship, as there are different entries for this year in “WLM_Zeit” (Table A17).

Table A17: Excerpt from WLM_Zeit: ID 37276, 1965.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung _vom	Berechnung _bis	Taetigkeitsfaktor _WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
37276	10211	009000	01-Jan-65	28-Feb-65	0.00	2.00	59	O	0
37276	10211	009000	01-Mrz-65	30-Sep-65	0.00	2.00	214	O	0
37276	10211	009000	01-Okt-65	31-Okt-65	0.00	2.00	31	O	0
37276	10211	009000	01-Nov-65	31-Dez-65	0.00	2.00	61	O	0
					↓	↓			↓
					$f(t,o,j)$	$E(t,o,j_0)$ L., 1998, p. 236			$l(i,t,o,j) \cdot E(t,o,j)$

The annual exposure to radon progeny for the reference activity on the surface of object 009 in 1965 is listed in Lehmann et al. (1998 p. 236). The activity weighting factor is zero in “WLM_Zeit” (Table A17).

The worker spent 16 days in special underground shifts in 1965.

Table A18: Excerpt from WLM_Schi: ID 37276, 1965.

WLM_Schi

ORDBG	Jahr	Tage	WLM_Faktor	WLM_Wert	WLM_Ergeb
37276	1965	16	9.9	999.9	0.16
					↓
					$E^{UT}(i,t)$

As the worker conducted varying activities/objects within 1965, “WLM_Faktor” is coded with 9.9 and “WLM_Wert” with 999.9. Thus, the resulting value in “WLM_Ergeb” cannot be calculated from Table A18 only. The values of the parameters used to calculate the exposure during the special underground shifts $E^{UT}(i,t)$ in 1965 are listed in Lehmann et al. (1998). The mean exposure value of the affiliated mining object, $\bar{E}(t,o,j_0)$, amounts to 9 WLM (Lehmann et al. 1998 p. 220) and the mean activity weighting factor, $\bar{f}(t,o,j)$, amounts to 0.4 (Lehmann et al. 1998 p. 257). Again, the exposure to radon progeny in 1965 for the worker is assessed by

$$E(i,t) = E^A(i,t) + E^{UT}(i,t)$$
$$E^A(i,t) = \sum_{o,j} f(t,o,j) \cdot E(t,o,j_o) \cdot l(i,t,o,j)$$
$$E^{UT}(i,t) = \bar{f}(t,o,j) \cdot \bar{E}(t,o,j_o) \cdot l^{UT}(i,t)$$
$$\overset{\text{here}}{=} 0.4 \cdot 9 \cdot \frac{16}{365}$$

Table A19: Excerpt from fu_2013: ID 37276, 1965.

fu_2013

id	year	Objekt	O_U	Taet_code	w
37276	1965	9000	O	10211	0.16
					↓ $E(i,t)$

A 3.6. Absenteeism

Worker with absenteeism (varying activities/objects within a calendar year) and special underground shifts: ID 100102, 1979

In 1979, the worker with ID 100102 had times of absenteeism and special underground shifts. The exposure to radon progeny for the complete calendar year, $E^A(i,t)$, and the exposure during special underground shifts are analogously calculated as described in the previous examples.

Table A20: Excerpt from WLM_Zeit: ID 100102, 1979.

WLM_Zeit

ORDBG	Taetig-keit	Objekt	Berechnung _vom	Berechnung _bis	Taetigkeitsfaktor _WLM	WLM_Jahr	Tag	O_U	Ergeb_WLM
100102	10211	019000	01-Jan-79	31-Jan-79	0.00	0.00	31	O	0.00
100102	10210	903000	01-Feb-79	15-Jul-79	0.40	3.00	165	U	0.55
100102	10000	902000	16-Jul-79	31-Dez-79	1.00	3.00	169	U	1.38
					↓ $f(t,o,j)$ L., 1998, pp. 257, 259	↓ $E(t,o,j_0)$ L., 2004, pp. 80, 82			↓ $l(i,t,o,j) \cdot E(t,o,j)$

Table A21: Excerpt from WLM_Schi: ID 100102, 1979.

WLM_Schi

ORDBG	Jahr	Tage	WLM_Faktor	WLM_Wert	WLM_Ergeb
100102	1979	8	0.4	3	0.03
			↓ $\bar{f}(t,o,j)$ L., 1998, p. 259	↓ $\bar{E}(t,o,j_0)$ L., 2004, p. 80	↓ $E^{UT}(i,t)$

"WLM_Fehl" (Table A22) shows that the worker was absent for 120 days or four months in 1979.

Table A22: Excerpt from WLM_Fehl: ID 100102, 1979.

WLM_Fehl

ORDBG	Jahr	Tage	WLM_Faktor	WLM_Wert	WLM_Ergeb
100102	1979	120	9.9	999.9	0.64
					↓
					$E^F(i,t)$

The columns "WLM_Faktor" and "WLM_Wert" indicate that the worker was employed in varying activities and objects during this time. The mean exposure value, $\bar{E}(t,o,j_0)$, is obtained by calculating the mean of the non-zero "WLM_Jahr" of "WLM_Zeit" (Table A20) entries, weighted by the number of days worked in the object. Here, $\bar{E}(t,o,j_0)$ is 3. Similarly, the mean activity weighting factor, $\bar{f}(t,o,j)$, is calculated as weighted mean, $\bar{f}(t,o,j) = \frac{165}{365} \cdot 0.4 + \frac{169}{365} \cdot 1 = 0.64$. These quantities are then used to calculate the exposure during absenteeism of the worker in 1979:

$$E^F(i,t) = \bar{f}(t,o,j) \cdot \bar{E}(t,o,j_o) \cdot l^F(i,t)$$
$$\overset{\text{here}}{=} 0.64 \cdot 3 \cdot \frac{120}{365} = 0.64$$

Subsequently, individual exposure to radon progeny for the worker in 1979, which is listed in "fu_2013", is obtained through:

$$E(i,t) = E^A(i,t) + E^{UT}(i,t) - E^F(i,t)$$
$$\overset{\text{here}}{=} 0.55 + 1.38 + 0.03 - 0.64 = 1.32$$

Table A23: Excerpt from fu_2013: ID 100102, 1979.

fu_2013

id	year	Objekt	O_U	Taet_code	w
100102	1979	902000	U	10000	1.32
					↓
					$E(i,t)$

A 4. Dictionary

English	German
(variable-speed) air tube fan	(drehzahlveränderlicher) Luttenlüfter
additional annual exposure in the depth	zusätzliche Belastung in der Teufe
aeration conditions	wettertechnische Bedingungen
air	Wetterstrom
air quantity	Wettermenge
air tube	Lutte
air velocity	Wettergeschwindigkeit
alpha energy concentration	Alphaenergiekonzentration
annual throughput	Jahresdurchsatz
artificial ventilation control	künstliche Wetterführung
auxiliary	Hilfsabteilung
auxiliary processes	Nebenprozesse
auxiliary ventilation	Sonderbewetterung
basic exposure at ground level	Grundbelastung in bodennaher Atmosphäre
basic exposure from old mining	Altbergbau-Grundbelastung
bedrock	anstehendes Gestein
belt conveyors	Bandanlagen
belt transport	Bandtransport
blowing ventilation	Überdruckbewetterung
bogger	Bunkerlader
boundary surface of the mine void	Grubenhohlraum-Umgrenzungsfläche
box hole	Erzlutte
building company	Baubetrieb
building-material additive	Bauzuschlagstoff
bunkering	Bunkerung
cardboard air tube	Papplutte
carpenter	Zimmerer
chipping hammer	Pickhammer
chute	Rolle
classification	Klassierung
clay pick	Kreuzhacke
collecting scraper drift	Sammelschrapperstrecke
colliery	Zeche
concentrate	Konzentrat
concentrate presser	Konzentratpresser
concentration	Gehalt
conditions of the diggings	Lagerstättenverhältnisse
consecutive ventilation	Hintereinanderbewetterung
continued employment	Weiterbeschäftigung

English	German
cooling aggregate	Kühlaggregat
core process	Grundprozess
custodial works	Verwahrungsarbeiten
dedusting facility	Entstaubungsanlage
degree of ground opening	Aufschlussgrad
development object	Ausrichtungsobjekt
development of inventories	Vorratsentwicklung
digging works	Schürfarbeiten
diggings	Lagerstätte
dismantling works	Demontagearbeiten
drainage ventilation	Drainagebewetterung
drift ventilator	Streckenlüfter
drill column	Bohrsäule
drill hammer	Bohrhammer
drill rod	Bohrstange
drilling instrument	Bohrgerät
drilling vehicle	Bohrwagen
drivage	Auffahrung
dry drilling	Trockenbohren
drying	Trocknung
dumpers	Kipper
electric fan	Elektrolüfter
emanation measurements	Emanationsmessungen
energy expenditure per shift	Arbeitsenergieumsatz
equilibrium factor	Gleichgewichtsfaktor
evaluation area	Bewertungsfläche
evaluation factor	Bewertungsfaktor
excavation pit	Restloch
excavator	Bagger
exhaust air	Abwetter
exhaust air shaft	Abwetterschacht
exhaust ventilation	saugende Bewetterung
exit field	Austrittsfläche
exploration	Erkundung
exploration work	Erkundungsarbeiten
filling	Abfüllung
filtration	Filtration
final processing	Endverarbeitung
follow-up time	Nachlaufzeit
fresh (mine) air	Frischwetter
gallery	Stollen

English	German
gamma dose	Gamma-Dosis
gangue	Gangerz
geological fault system	geologisches Störungssystem
gravitative gradation	gravitative Sortierung
grinding elements	Mahlkörper
grinding	Mahlen
hammer	Hammer
heap keeper	Haldenarbeiter
hermetic sealing	Hermetisierung
hewer	Hauer
hoisting of waste rock	Bergeförderung
in mining	auf dem Abbau
insufflation	Einblasen
intake air level	Frischwettersohle
ionization chamber electrometer	Ionisationskammer-Elektrometer
ionizing radiation	Ionisierende Strahlung
jackleg	Bohrstütze
laboratory	Labor
large-diameter borehole	Großbohrloch
lateral development	Vorrichtung
leaching	Laugung
lead time	Vorlaufzeit
level	Sohle
loading	Verladung
loading ramp	Verladerampe
locksmith works	Schlosserarbeiten
long-lived radionuclides	langlebige Radionuklide
main mine fan	Hauptgrubenlüfter
manufacturer of measuring device	Messgerätebau
mechanical company	mechanischer Betrieb
mechanical pick	Abbauhammer
milling / classification	Mahlung/Klassierung
mine air control system	Wetterleitsystem
mine car	Förderwagen
mine door	Wettertüre
mine opening	Grubenbau, Grubenraum
mine output volume	Gewinnungsumfang
mine ventilation conditions	Bewetterungsbedingungen
mine void	Grubenhohlraum
mine waste	Berge
mining	Bergbau

English	German
mining activity	Gewinnungstätigkeit
mining apprentice	Berglehrling
mining buggy	Abbauhunt
mining company	Bergbaubetrieb
mining equipment works	Bergbau-Ausrüstungswerk
mining plant	Grubengebäude
new ground-opening objects	Neuaufschlüsse
occupational history	Arbeitsanamnese
old mining	Altbergbau
one-boom	einarmig
ore milling	Erzzerkleinerung
ore unloading	Erzentladung
overhead shovel loader	Wurfschaufellader
packaging	Verpackung
pick and shovel	Hacke und Schaufel
pit foreman	Steiger
pit mining company	Tagebau
pit shaft	Schürfschacht
pneumatic fan	Druckluftlüfter
precipitation	Fällung
pre-milling	Vorzerkleinerung
processing company	Aufbereitungsbetrieb
processing stage	Prozessstufe
pump room	Pumpenraum
radial ventilator	Radialventilator
radiation protection commissioner	Strahlenschutzbeauftragter
radio-hydrological recording	radiohydrologische Aufnahmen
radiometric gradation	Radiometrische Sortierung
radon progeny	Radon-Zerfallsprodukte
raise drift	Überhau
remedial actions	Sanierungstätigkeiten
return air level	Abwettersohle
rock pile	Haufwerk
rotary furnace	Drehrohrofen
rotary percussive	drehschlagend
rotation thin-film evaporators	Rotationsdünnschichtverdampfer
routing	Leitung
sample division	Probeteilung
sampling	Beprobung, Probenahme
scraper	Schrapper
securing the raw materials base	Absicherung der Rohstoffbasis

English	German
semi-technical facility	halbtechnische Anlage
shaft opening	Schachtansatzpunkte
shut-off zone	Absperrbereich
sinking work	Teufarbeiten
sledge hammer	Vorschlaghammer
slope	Böschung
steering	Lenkung
stone coal	Steinkohle
suction cleaning	Absaugung
surface exit	Tagesausgang
teacher	Lehrmeister
telescopic jackleg	Teleskopstütze
thickening	Eindickung
tin bucket	Blechkübel
tipping truck	Kipplore
tower-shaped spray dryer	turmförmiger Sprühtrockner
tractor shovel	Fahrlader
transport service	Transportbetrieb
transport worker	Transportarbeiter
tube fan	Luttenlüfter
two-boom	zweiarmig
underground mining	Grubenbetrieb
unloading hoppers	Entladebunker
uranium mineralization	Vererzung
uranium mining	Urangewinnung
uranium ore	Uranerz
uranium ore loading	Uranerzverladung
uranium recovery	Uranausbringen
vein area	Gangfläche
vein deposit	Ganglagerstätte
vein structure	Gangstruktur
ventilation dam	Wetterdamm
ventilation engineering	Bewetterungstechnik
ventilation station	Lüfterstation
vertical height	Höhendifferenz
void volume	Hohlraumvolumen
waste management	Abraumwirtschaft
waste rock pile material	Haldenmaterial
water purification	Wasserklärung
weather flap	Wetterjalousie
wet drilling	Nassbohren

English	German
wheelbarrow	Schubkarre
working time	Arbeitszeit
workshop	Werkstätte

A 5. Index and parameter declarations

A 5.1. Indices

i	Individual
j	Job, activity
j_0	Reference activity
o	Object
o_0	Reference object
t	Calendar year
t_0	Reference year

A 5.2. Parameters

$A(t,o)$	Evaluation area ("Bewertungsfläche", measure for the size of the radon exit field)
$b(o)$	Proportion of basic exposure from old mining in relation to object 003
$c(o)$	Correction factor for deficits and disruptions of the ventilation systems
$C(t,o)$	Mined vein area ("Gangfläche")
$\bar{\bar{\bar{C}}}_{RDP}(t,o)$	Mean radon progeny concentration
$\bar{\bar{\bar{C}}}_{Rn}(t,o)$	Mean radon gas concentration
$d(t,o)$	Depth (in open pit mining objects)
$e(t,o)$	Evaluation factor ("Bewertungsfaktor", underground mining objects: measure of the exposure to radon per unit of the mined area for 2000 working hours per year; open pit mining objects: weighting factor for exposure in depth without mining activity)
$e_1(t,o), \dots, e_6(t,o)$	Weighting factors for exposure without mining activity according to different mining conditions in open pit mining
$E(i,t)$	Individual exposure to radon progeny in calendar year t
$E(t,o,j)$	Annual exposure to radon progeny for calendar year t, object o and activity j
$E^{2000}(t,o,j)$	Annual exposure to radon progeny for 2000 working hours per year
$E^{*}(t,o,j)$	Annual exposure to radon gas for 2000 working hours per year
$\bar{E}(t,o,j)$	Mean annual exposure to radon progeny for calendar year t
$E^{A}(i,t)$	Individual exposure to radon progeny for the complete calendar year t

$E^{B}(o)$	Underground mining objects: annual basic exposure to radon gas from old mining ("Altbergbau-Grundbelastung") Open pit mining objects: annual basic exposure at ground level without mining activity ("Radon-Konzentration in bodennaher Atmosphäre")
$E^{D}(t,o,j)$	Additional annual exposure in the depth without mining activity ("zusätzliche Belastung in der Teufe")
$E^{F}(i,t)$	Individual exposure to radon progeny during absenteeism
$E^{M}(t,o,j)$	Annual exposure to radon gas from mining activity
$E^{UT}(i,t)$	Individual exposure to radon progeny during underground work
$f(t,o,j)$	Activity weighting factor
$\bar{f}(t,o)$	Mean activity weighting factor
$F(t,o)$	Total shaft output
$g(t,o)$	Equilibrium factor
$h(o)$	Density of bedrock
$j_0(o)$	Reference activity of object o
$l(i,t,o,j)$	Proportion of days per year t of individual i working in object o conducting job j
$l^{F}(i,t)$	Proportion of months per year t of individual i with absenteeism
$l^{UT}(i,t)$	Proportion of days per year t of individual i in special underground shifts
N	Number of concentration measurements
$o_0(o)$	Reference object of object o
$p(t,o)$, $p(t)$	Period of calendar year t (in processing companies and open pit mining objects)
$q(t,o)$	Percentage of total uranium recovery ("Uranausbringen")
$r(t,o)$	Relative uranium recovery rate (in relation to the reference object, as measure of radon exhalation)
$R(t,o)$	Amount of uranium recovery ("Uranausbringen")
$R^{R}(t,o)$	Relative cumulative uranium recovery rate
$s(j)$	Processing stage (in processing companies)
$t_0(o)$	Reference year of object o
$V(t,o)$	Void volume ("Hohlraumvolumen")
$w(t,o)$	Working time factor
$z(o,s(j))$	Processing stage-specific object weighting factor (in processing companies)