Electro-Thermal Phosphorus Production Radioactivity in the Workplace: The Consequences for the Operators Concerned

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Summary

The phosphate ore processed by Thermphos International in Vlissingen to produce elemental phosphorus contains approximately 1 Bq per g uranium 238 with daughter nuclides in near equilibrium ($^{238}U+$).

During the production process, radionuclides are emitted into the environment.

Slag is formed as a by-product. This is used as a construction material in road and hydraulic engineering, and causes a slight increase in external radiation. The process produces calcined precipitator dust, which has to be disposed of as radioactive waste. Operators involved in the production of phosphorus receive a dose due to inhalation of radionuclides. This paper deals with the dose operators receive due to inhalation of the radionuclides, the way the dose is determined, the measures taken to reduce the dose and the ALARA considerations applied to some measures.

General background and history

Hoechst Holland N.V. (referred to below as HHNV) began to produce elemental phosphorus from phosphate ore in April 1968. Since December 1971 three phosphorus furnaces have been in operation. Elemental phosphorus is used to produce a high-grade (thermal) phosphoric acid. As well as the phosphorus division, installations have been built at the Vlissingen site for the production of DMT, TAED and alkane sulphonate and for supplying energy. In July 1997 HHNV was divided into several independent companies. Thermphos International BV (referred to below as TIBV) is continuing the phosphorus production. For readability reasons, in this paper the name HHNV is replaced by TIBV as the legal successor carrying on the phosphorus production of HHNV.

In March 1983 the monitoring network, situated in the Sloe area to watch over the nearby nuclear power plant, detected radionuclides that appeared to come from TIBV. This was discussed for the first time with government representatives in May 1983. This meeting resulted in a request, which was submitted on 5 July 1985, for a licence under the Dutch Nuclear Power Act. The first such licence was granted on 30 December 1985. In 1984 the RIVM carried out emission/dose calculations. A recalculation took place in 1988.

In 1993 KEMA carried out another recalculation, based on the latest policy principles propagated by VROM (the Dutch Ministry of Public Housing, Planning and the Environment). After publication of the risk management policy, as applied by VROM to radiation, TIBV applied for an updated licence in 1994. The licence was granted on 28 December 1994.

The problem of radioactivity covers both the environment and the workplace. For the environmental aspects see the paper (no. 17) presented on the 2nd ALARA network workshop.

The production process

Introduction

The phosphorus production process consists of various stages, which are described below in sequence.

Sintering plant

The phosphate ore is milled to a fine powder in this plant. The powder is brought onto a rotating granulator disk, together with a binder (clay suspension). Due to the rotation of the disk, granules (pellets) are formed. The unsintered pellets are transported onto the front end of the slowly rotating sintering grid roaster. They pass through a drying zone (temperature up to 300 °C) and are then sintered to hard spheres under two large burners at temperatures around 800°C. The pellets then pass through a cooling zone. The heat released is re-used in the drying zone.

The pellets are then conveyed to an intermediate storage facility, where they are stored in large silos before being fed into the electric furnaces.

There are three sintering lines.

Slurry station

In the slurry station clay is suspended in water to produce the clay suspension used for granulation. Furthermore, precipitator dust, a return flow from the electric furnaces, is also added to the binding suspension.

There are two slurry lines.

Purging unit

The slurry station also houses the purging unit. This is the discharge from the precipitator dust cycle that is formed in the production process (see 3.2). By discharging more or less of the precipitator dust, the concentration of volatile inorganic matter, metals and radionuclides in the precipitator dust cycle can be controlled. The purging unit consists of a high-pressure filter and a rotating calcining kiln where the pressed, lumped precipitator dust is calcined at temperatures of up to 750 °C.

Phosphorus plant

There are three electrothermal phosphorus furnaces in the phosphorus plant. The pellets are fed into the furnaces together with gravel and coke. In each furnace there are three electrodes, which draw electrical energy from a triangular arrangement of transformers and channel it into the furnace for heating the burden. At temperatures higher than 1500°C a reaction takes place, in which phosphate ore is reduced to elemental phosphorus (P_4). The chemical reaction is shown in Figure 1.

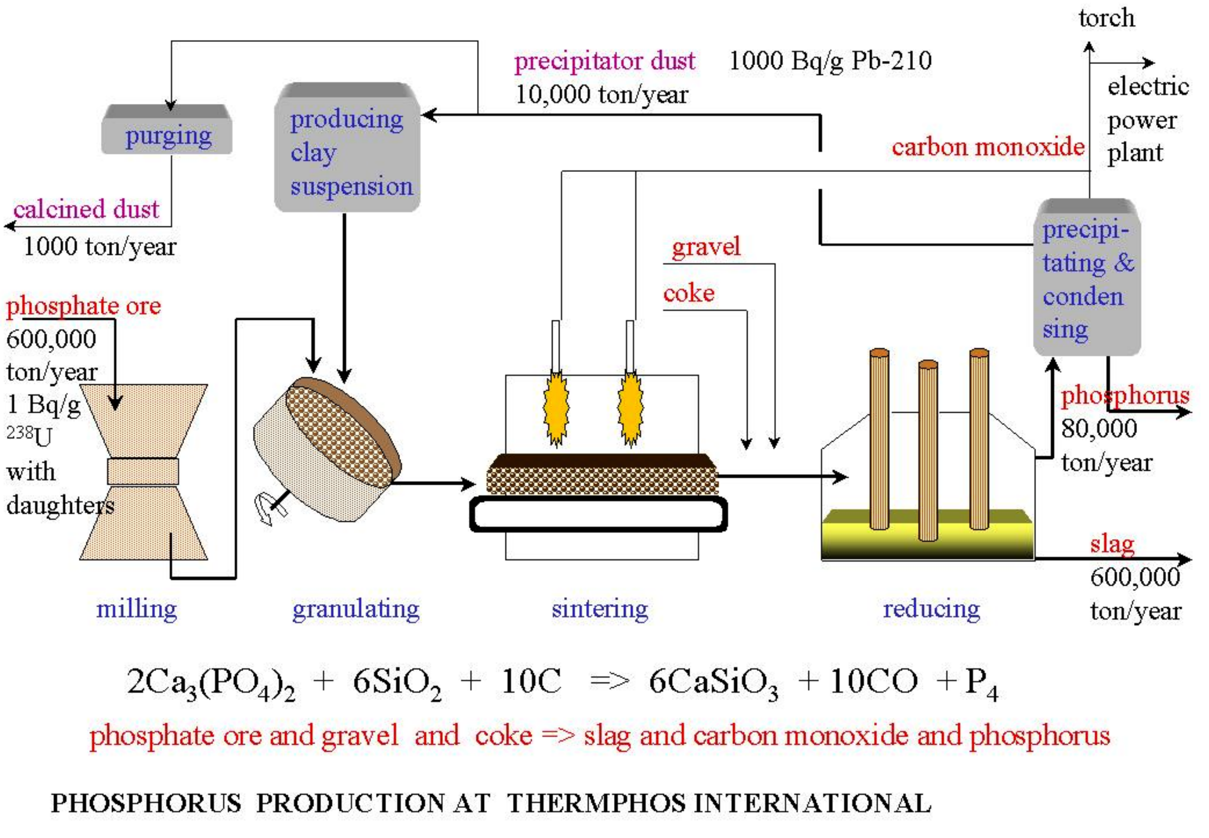

Figure 1.

A calcium silicate slag is formed, which flows continuously out of the furnace. The elemental phosphorus leaves the furnace as a gas, together with the carbon monoxide formed during the reaction. Entrained dust is separated from the gases in an electrostatic precipitator. This dust is collected in the slurry tanks, where it is mixed with water. The resulting precipitator slurry is pumped to the slurry station, where it is re-used in the granulator binder. The now dust-free gases are subsequently cooled, causing the phosphorus to condense to a stream of liquid phosphorus. The carbon monoxide (CO) is used as fuel in the sintering plant. The excess gas is compressed and piped to a nearby electric power plant as a fuel.

Radioactivity problem

Introduction

The mix of sedimentary and magmatic phosphate ore used contains approximately 1 Bq per g of uranium with atomic number 238 (^{238}U). This nuclide has a half-life of $4.4*10^9$ years. All daughters of the ^{238}U decay chain are in a state of (approximate) equilibrium with the parent nuclide. This means that all daughter nuclides (see Figure 2) are also present with an activity of 1 Bq per g.

Enrichment mechanism

During the electro-thermal phosphorus production process, the radionuclides are unintentionally enriched.

At the high temperatures prevailing in the furnace, volatile inorganic substances, metals and radionuclides evaporate and condense on dust particles. The dust is trapped in the electrostatic precipitators and is recycled via the clay suspension into the pellets. When they reach the furnace for the second time, the volatile inorganic substances, metals and radionuclides evaporate again. In this way these substances are enriched in the so-called precipitator dust cycle. High concentrations of volatile inorganic matter and metals cause instability in the operation of the furnaces. To control the concentration the system is purged. The purge unit produces calcined dust with radionuclides, which is regarded as radioactive waste under existing legislation (see 2.4).

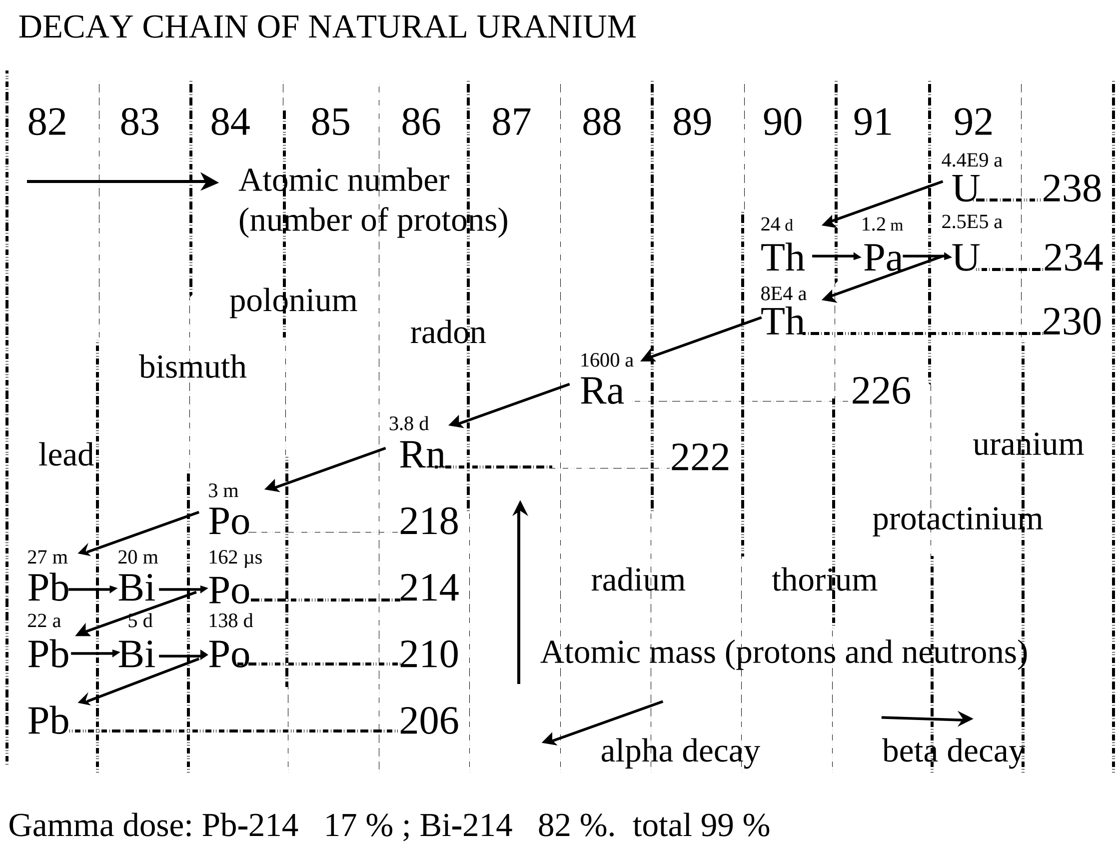

Figure 2.
The uranium 238 chain (see Figure 2)

The radionuclides with an atomic number greater than that of radon remain in the furnace and therefore become part of the slag. Approximately one ton of slag is formed per ton of phosphate ore. Due to this the natural radionuclides in the ore are not enriched in the slag. Radon is an inert gas and therefore escapes along with carbon monoxide. The nuclides with an atomic number less than that of radon escape from the melt and therefore end up in the precipitator dust cycle. The short-lived nuclides with atomic numbers 214 and 218 decay within a few hours. The problem nuclide is ^{210}Pb (lead), which has a half-life of 22 years and is therefore relatively long-lived. Moreover, most of the ^{210}Pb remains in the pellets in the sintering roaster. ^{210}Po, with a half-life of 138 days, is more volatile than ^{210}Pb and therefore leaves the pellets during the sintering process, passes both scrubbers (see 4.1), where the sinter gases are washed, and is emitted into the environment. Consequently the activity of ^{210}Po in the precipitator dust is lower than the activity of ^{210}Pb.

The daughter nuclides formed from ^{210}Pb, {^{210}Bi (bismuth) and ^{210}Po (polonium)} have half-life times of 5 and 138 days. This means that, after about 4 half-life periods, these daughter nuclides exhibit nearly the same activity as the parent nuclide ^{210}Pb.

The activity of ^{210}Pb in the precipitator dust and in the calcined dust is approximately 1000 Bq per g. This nuclide has therefore been enriched by a factor of 1000.

Recognition of the problem

From the very start of TIBV in Vlissingen it was known that the phosphate ore contained enhanced concentrations of radionuclides. The problem of enrichment of radioactivity and the associated emission was not recognised until 1983, when the monitoring network of the nearby nuclear power station detected activity emitted by TIBV.

Measurement effort

TIBV’s own environmental sampling team takes 200 samples of the air and water discharges each year.

TIBV has set up a C-laboratory to enable the emissions of radionuclides to be determined. The measurements needed to check for compliance with the environmental and workplace regulations, imposed by the Nuclear Power Act licence, are carried out here.

See Table 1 for the emissions during the period from 1987 to 1997.

Table 1. Emissions to air and water

Year	α to air ^{210}Po GBq/y	β to air ^{210}Pb GBq/y	α to water ^{210}Po GBq/y	β to water ^{210}Pb GBq/y
1987	538	50	73	69
1988	843	98	95	40
1989	634	50	99	34
1990	381	34	107	24
1991	687	32	91	21
1992	490	66	166	24
1993	616	52	96	24
1994	506	33	82	29
1995	503	48	76	23
1996	390	95	58	36
1997	306	106	29	21
Average	536	60	88	31

These emissions comply with the conditions of the license.

Workplace problems

Introduction

Operators who are involved in the production of phosphorus are exposed to radionuclides (^{210}Pb and ^{210}Po) predominantly from the precipitator dust cycle. These nuclides are practically only alpha- and beta-emitters. To cause a dose, there must be an intake of these radionuclides into the human body. In workplaces an intake occurs predominantly by inhaling the dust enriched in the precipitator dust cycle.

Dust characteristics

The inhaled dust was examined by leaching tests in simulated lung moisture. The results of these tests showed that the relevant radionuclides (^{210}Pb and ^{210}Po) are leached out of the inhaled dust very poorly and as a consequence the lung retention class was set to class Y. This means that the radionuclides are retained in the lungs for periods of up to several years. Consequently the caused dose is received predominantly by the lungs.

Measurements

To determine the dose received by the operators concerned, Personal Air Sample measurements were carried out.

The personal air sampler consists of an air pump and a filter in a filter holder, connected by a tube. It is carried by the operator in such a way that a continuous sample of the air surrounding the operator passes through the filter in the filter holder. The dust containing the radionuclides is separated from the air and collects on the filter. The operator carries the personal air sampler for the working period of 8 hours. The filter is measured for alpha- and beta-counts on a proportional counter tube. The intake of radionuclides can be calculated from the count rate obtained, the amount of air that flowed through the filter and a worker's assumed breathing rate. Given the intake, together with a Dose Conversion Coefficient (Sv per Bq), it is possible to make a dose assessment. The measurements are carried out after a period of three weeks. After this time ^{210}Bi is in equilibrium with ^{210}Pb and therefore ^{210}Pb is measured by the ^{210}Bi beta particle with a maximum energy of 1.16 MeV. ^{210}Pb is a very weak beta emitter, which cannot be determined directly. ^{210}Po is measured by the alpha particle of 5.3 MeV. The measurements are carried out on a proportional counting tube, which can discriminate between alpha and beta particles. The dust in the workplace is a mixture of phosphate ore and precipitator dust. Because of the high enrichment factor in the precipitated dust cycle for the ^{210} series nuclides, all the alpha particles are regarded as ^{210}Po and all the beta particles as ^{210}Pb. This made it possible to measure the radionuclides with a relative simple measurement method. If all the nuclides of the ^{238}U, or the chain below ^{226}Ra, are present in an unknown ratio the dose assessment becomes more complicated.

Measurement effort, dose assessment and dose reduction measures

In the period 1984 to 1993 approximately 30 PAS-measurements per year were taken on the operators in working conditions in which inhalation of dust is most likely to occur. To learn more about specific working circumstances, if the dose assessment for a certain job exceeded a threshold value, more specific measurements were taken. By taking more measurements at the same time at different places in a working area and comparing them with earlier measurements, taking the working and process conditions into account, it was possible to determine the pathways by which the radionuclides from the process reach the operators involved. As a result, a number of measures were taken to prevent the inhalation of radionuclides in order to obtain dose reductions.

In general it can be said that operators concerned with the production of phosphorus at the TIBV site are exposed to an average dose of 1 mSv per year based on the measurement until 1997. This dose is not given in the same dose rate every day. There are days when the dose, extrapolated from one workday (the measuring period) to a year dose, yields an annual dose of 5 mSv per year with normal working conditions. On the other hand, there are also days that yield an extrapolated dose of 0 mSv per year. The variations depend on the (determined) process and working conditions (pathways).

Some examples of the pathways that were found in 1994:

The way the work is carried out

Two operators did the same cleaning work on the same floor. After the work was finished the first person was covered with dust while the other was clean. The first person used a broom for certain cleaning activities whereas the other only used the prescribed vacuum cleaner. Both operators inhaled the same „background“ air. The dose assessment for the first operator was 5 mSv per year while the assessment for the other person was almost 0. This proved that there were no nuclides in the „background“ air and that the dose was caused by the working activities and especially the way they were carried out.

The air in the room is contaminated with radionuclides

Some employees, such as electrode welders, work in an environment (surrounding surfaces) which is not contaminated with radionuclides and consequently they cannot receive a dose due to re-suspension. It was proved that the air in this workplace was contaminated by the activities necessary to remove slag (into slag beds situated directly next to the furnace building) and iron from the furnaces.

Surface contamination in the workplace

Large areas of the surface of some workplaces were contaminated by dry dust that contained 1000 Bq per gram $^{210}Pb+$. This contamination does not necessarily lead to a dose. Extrapolation of the daily dose measurements from operators working in these circumstances often gives 0 mSv per year. If an operator walks through these contaminated areas the re-suspended radionuclides are not necessarily inhaled because of the distance between the inhalation point (nose and mouth) and the re-suspension point (feet). However, if the work is carried out in one place then the re-suspended radionuclides can cause a dose up to 10 mSv per year. 30 mSv per year were measured when a compressed air hose broke loose from its connection and blow dust from the floor. This incident lasted for a period of several minutes during the total measuring time of approximately 8 hours.

Surface contamination inside the process equipment

Measurements proved that it is possible to obtain dose rates up to 1 mSv per hour if parts of the installation, covered with high concentrations of radionuclides, are polished, jagged or subjected to other operations that remove radionuclides from the contaminated surface with a risk of bringing them into the air.

Contamination up to several hundred Bq per cm^2 has been determined on surfaces on the inside of the process equipment. Operators are consequently, under normal circumstances, not exposed to these high levels of contamination. However, during plant stops or repair work, when the installation is opened, preventive measures (see 4.7) are prescribed to avoid a high inhalation dose.

The measures taken to reduce the dose included:

Large-scale cleaning operations.

Floor surfaces were renewed and coated with the aim of decontaminating them more easily.

Contamination was prevented by installing new measuring instruments, which monitor and control the process.

Ventilation was improved at the iron outlet of the furnaces.

The slag beds were moved from their position next to the furnace building to a greater distance from the building.

Central vacuum cleaning installations were built to avoid the opening and emptying of mobile vacuum cleaners.

Improving measurements and use of new lung model

Due to the expected stricter legislation, in combination with the implementation of the new „Human Respiratory Tract Model for Radiological Protection“ by the ICRP, TIBV improved the measurement methods for determining the dose operators are exposed to.

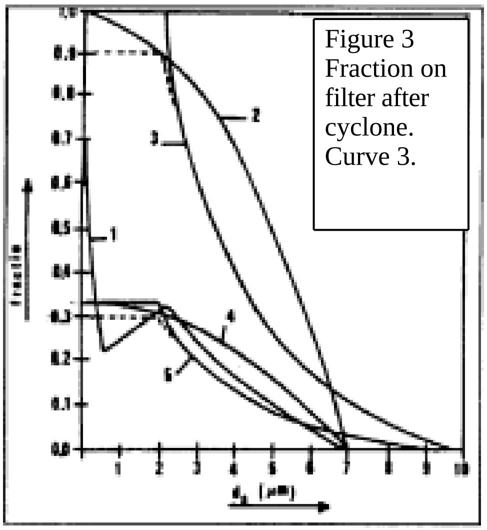

Figure 3
Fraction on filter after cyclone.
Curve 3.

Measuring time.

Instead of the carousel 1 channel proportional counter, TIBV purchased a 10-channel proportional counter analyser to measure the used filters. As a consequence it was possible to increase the measuring time from 3 hours to 5 days to obtain the necessary statistical accuracy.

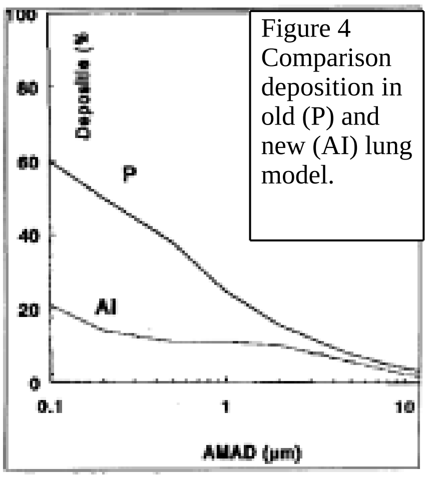

Figure 4
Comparison deposition in old (P) and new (AI) lung model.

DCC dependency of particle size, filter holder and cyclone efficiency.

The lung retention class is Y, so the dose after inhalation is predominantly received in the deepest parts of the lung. The deposition in these parts therefore determines the dose. In the old lung model the DCC (ALI) was very dependent on the particle size. This is shown in figure 4 curve P (pulmonary) which gives the deposition percentage in the old lung model (ICRP-30) in the deeper parts of the lung as a function of the particle size. Curve AI (alveolar interstitium) gives this relation for the new lung model (ICRP-66). It was agreed that, for the former lung model, TIBV could use a cyclone to distinguish between respirable and non respirable dust. This cyclone has a 50% performance for particles between 3 and 4 _m. See figure 3 curve 3 for the cyclone's performance. In the new lung model the deposition in the deeper parts of the lung and consequently the DCC is less dependent on particle size, as shown in figure 4 curve AI. NRG determined the DCCs for ^{210}Po and ^{210}Pb as a function of the particle size (AMAD), the distribution of activity (Geometrical Standard Deviation) and the lung retention class S. This relation is given in figures 5 and 6. The DCC does not significantly change over a range from approximately 0.5 to 5 _m.

Therefore TIBV now uses a simple filter IOM cassette for the dust collection instead of a filter cassette with a cyclone, which corrected for the particles size.

TIBV uses the values of 4.2 _Sv per Bq and 5.8 _Sv per Bq for all the dust collected on the filter. Consequently, if the measured activity is from particles bigger then 5 to 10 _m, the dose is an overestimation because of the lower DCC for those particles. Especially with operators producing the dust themselves during cleaning work, it is not unlikely that a considerable part of the activity is from particles bigge nd consequently the dose would be overestimated.

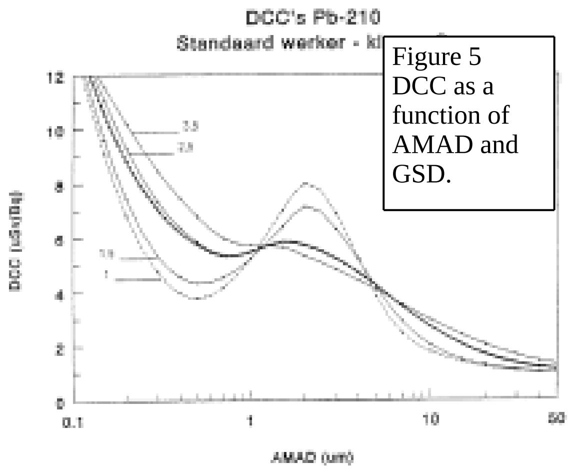

Figure 5 DCC as a function of AMAD and GSD.

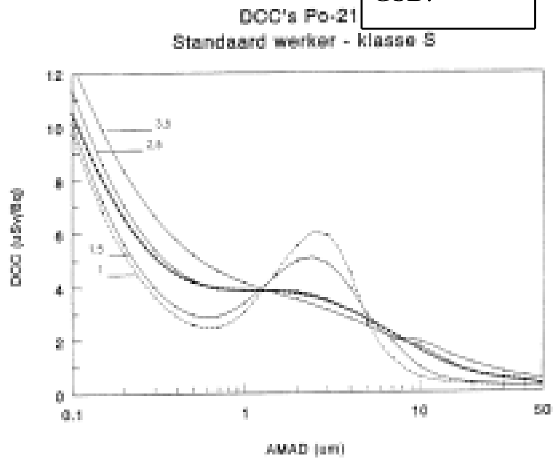

Figure 6 DCC as a function of AMAD and GSD.

Photos 2 and 3. Filter holders and (open) cascade impactor

Cascade impactor measurement

TIBV carried out a measurement with a cascade impactor to determine the activity distribution as a function of the particle size. The results indicated that there is more activity on bigger particles than had been assumed on the basis of the results obtained from the measurements with the cyclone in the past. It appeared that the dose had been overestimated with a factor of 2 in a work situation (cleaning) with freshly produced airborne dust. At this moment measurements are being carried out to compare the influence of the IOM filter holder with the PAS-6 holder. The IOM filter holder appears to be very effective for the bigger dust particles. The PAS 6 is less effective for the bigger particles. The 50% effectiveness level lies at 40 _m. What really is needed is a device with a separation characteristic in accordance with the DCC/AMAD curves of figures 5 and 6 with 50% effectiveness on particles with a size of approximately 10 _m. TIBV is currently looking at the market for the availability of such a device.

The cascade impactor operating with only the 10 _m plate is one option. Another possibility is a cyclone with 50% efficiency performance for particles with a size of 10 _m.

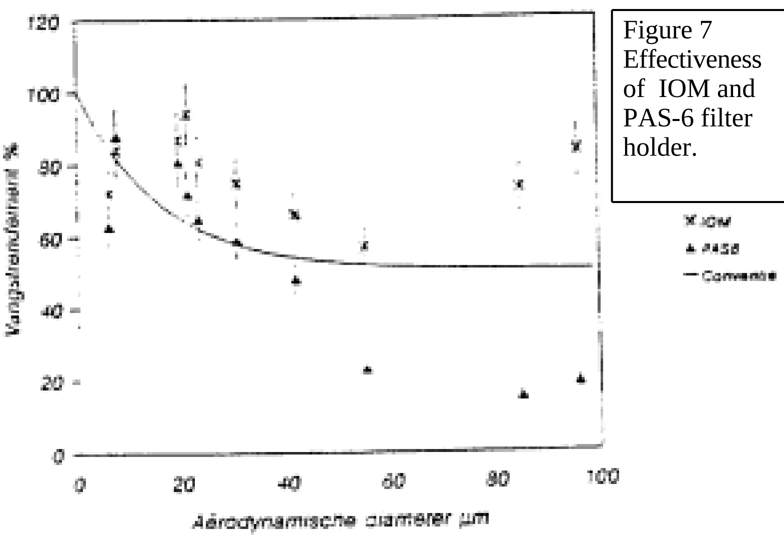

Figure 7 Effectiveness of IOM and PAS-6 filter holder.

Measurement results (improved measuring system with new DCCs and overestimation of, especially, cleaning work)

Table 1. The mean yearly dose ($\bar{X}$) (in mSv), the standard deviation (_), the 90%-confidence interval (C.I.), the number of measurements (n) and the percentage of the contribution of ^{210}Po respectively ^{210}Pb in the dose.

Plant	Function	$\bar{X}$ (mSv)	σ	CI (90%) +/-	% Po	% Pb	n (1998)	n (1999)
Phosphorus and Sinter		1,33	1,36	0,21	48	52	71	60
Phosphorus		1,25	1,48	0,34	34	66	32	32
	Control room	0,15	0,07	0,16	44	56	2	1
	Filtration	0,67	0,10	0,21	51	49	2	1
	Condensation	0,67	0,05	0,12	49	51	2	1
	Electrode welder	0,82	0,48	0,53	33	67	3	2
	Daytime operator	1,26	1,55	1,27	28	72	4	3
	Furnace feed	0,72	0,21	0,45	43	57	2	1
	Slag operator	0,872	0,467	0,28	42	58	6	2
	Slurry operator	0,44	0,14	0,15	39	61	3	2
	Shift supervisor	0,76			59	41	1	3
	Assistant supervisor	2,15	1,87	1,28	33	67	5	8
	Cleaning operator	4,98	2,23	4,85	25	75	2	8
Sinter		1,39	1,28	0,27	59	41	39	28
	Control room	0,28	0,06	0,06	62	38	3	1
	Indoor operator	0,35			62	38	1	1
	Granulating operator	1,16	0,67	0,29	52	48	10	4
	Slurry operator	0,78	0,40	0,19	48	52	9	2
	Shift supervisor	1,45	1,00	0,47	65	35	9	4
	Assistant supervisor	2,55	1,42	1,16	55	45	4	8
	Cleaning operator	3,77	2,42	2,64	67	33	3	8

From the results it is clear that the outcome of the measurements varies significantly. This is because the work activities can differ on several days and the concentration of radionuclides in the air fluctuates widely. This is studied with an aerosol monitor which gives 3 hour average alpha and beta concentrations of the air. With this device it is possible to determine sources which enhance the air concentration.

The operator functions with the highest mean dose and a wide Confidence Interval will be measured with the highest frequency to obtain a smaller Confidence Interval and consequently a better dose estimation. The figures show that a prohibitively high number of measurements would have to be made to achieve small confidence intervals for every operator function. For all the functions together within one plant the Confidence Interval is within an acceptable value. In earlier measurement programs it was found that the dose assessment for an operator function can differ from year to year, due to the large variation in the daily process and working conditions. The new measurement method gives a higher result (1.5 mSv per year) compared to results with the old model (1 mSv per year). However, if the correction for the particles above 5 to 10 _m is implemented, it is expected that the measurements results are in the same range. It is also possible that an obtained dose reduction, due to the measures already carried out, cannot be proved because of the improvements in the measurement system.

The above list with dose results is presented to all operators working in the phosphorus production plants. The risk caused by the received dose is compared with „accepted risks“ attributable to activities such as:

Going to work every day, which gives a comparable risk as a dose of 1.5 mSv,
Smoking 20 cigarettes every day, which is a far higher risk.

This comparison is carried out to put the risk into perspective in comparison with other „risks“ connected to accepted activities.

The policy of TIBV is aimed at dose reduction. The measures taken to reach that aim go further than ALARA considerations based on a CBA value would suggest (see 4.8).

Safety procedures and protection

TIBV has safety procedures to avoid an excessive dose rate.

If an installation vessel, sintering ovens, furnaces, etc, have to be opened and operators have to go inside, the surface contamination has to be measured first. If the concentration is below 0.25 Bq per cm^2 then operators can enter without protective equipment. From 0.25 Bq per cm^2 to 10 Bq per cm^2 a FFP3 half mask with an assigned (by BS 4275 BS EN 149) protection factor of 20 is prescribed. Above 10 Bq per cm^2 a full face mask with overpressure breathing air is prescribed. These values are conservatively derived from the results of the measurement programs. However, they should only be used for inspection work or activities which do not produce excessive dust. In the latter case a full face mask with overpressure breathing air is prescribed.

Photos 4 and 5: FFP3 half mask.

Photos 6 and 7. Full face mask with remote air supply

Optimisation and ALARA considerations in the workplace

About 200 operators and technical staff work in the factories where the production of phosphorus takes place. Consequently the collective dose that this population receives in 25 years is 5 man Sv.

Assuming that an investment in improving working conditions would avert that collective dose, reasonable investment costs are about NLG 750,000, based on the CBA value of £50,000 per saved man Sv used for occupational situations.

Some measures:

- New floors in the phosphorus plant that can be cleaned easily.
  (The costs involved were NLG 600,000)

- Central vacuum cleaning system without the need to empty the filter system.

- Process automation to avoid work during which a dose is received.

- Breathing air protection measures in situations where the creation of concentrations of radionuclides in the surrounding air is unavoidable.

- Continuous cleaning operations carried out by several workers.

- Measurement and monitoring programs.

The dose reduction due to these improvements is not the complete 5 man Sv mentioned above but only a fraction of it. Therefore it is evident that the improvements carried out are based on „good housekeeping“, „best available techniques“ and „responsible care for the operators concerned“ considerations, rather then on strict ALARA considerations based on a CBA value.

Legislation

If workers can be exposed to a dose of more then 5 mSv per year, under existing law they should be regarded as classified workers.

It is expected that this value in the Netherlands will be decreased to 1 mSv per year by the year 2000. TIBV is in discussion with the competent authorities concerning whether it is necessary and appropriate to give the operators involved the status of classified worker.

Conclusion

The measurements in the workplaces of the Thermal Phosphorus production show that operators receive a dose of approximately 1 mSv per year. The daily measurement results show large variations. It is possible to receive a dose rate of 1 mSv per hour if work is carried out on surfaces with contamination of up to several hundred Bq per cm^2. The policy of TIBV is aimed at further dose reduction. Measures are taken. Procedures are prescribed. The costs involved with the measures already taken are higher than would be suggested by ALARA-considerations with a CBA-value. TIBV is in discussion with the competent authorities concerning the status of classified worker after the implementation of new legislation.

Abbreviations

^{238}U	Uranium with mass number 238
$^{238}U+$	Uranium with mass number 238 and daughters in equilibrium
ALARA	As Low As Reasonably Achievable; social and economic facts taken into account.
ALI	Annual limit of intake
AMAD	Activity Median Aerodynamic Diameter
Bq	Becquerel (the number of disintegration’s per sec. due to RA-decay)
BS	British Standard
CBA value	Cost Benefit Analyse value. (NRPB)
C-laboratory	A laboratory licensed to handle with radionuclides
DCC	Dose Conversion coefficient
dose	Effective dose: the sum of the equivalent doses, weighted by the appropriate tissue weighting factors, in all tissues and organs of the body
ECN	A Dutch research institute
GSD	Geometrical Standard Deviation (default 2)
HHNV	Hoechst Holland NV
ICRP	International Commission on Radiological Protection
IOM	Institute of Occupational Medicine (Edinburgh)
KEMA	A Dutch research institute
Man Sv	Collective dose Man-Sievert
NLG	Dutch guilders
NRG	A Dutch research institute
PAS	Personal Air Sampling
Practice	Utilisation of radionuclides for their radioactive properties (functional)
RIVM	A Dutch governmental research institute
Sv	Sievert. The SI unit of equivalent dose. 1Sv=1 J/kg
TIBV	Thermphos International BV
Work activity	Activity with enhanced levels radionuclides not processed for their radioactive properties (non-functional)

Literature

The relevant ICRP publications.

NRG. (KEMA) C.W.M. Timmermans. Inhalation DCCs for ^{210}Pb and ^{210}Po calculated with the new lung model of the ICRP as a function of the particle size. (Report in Dutch). 4138 NUC 96-9095.