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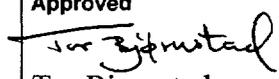
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The "Invisible" Radioactive Scale

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This article discusses transportation and deposition mechanisms, detection methods and provides some examples of measured results from the North Sea on equipment sent for maintenance. The article concludes that a regular measurement program for this type of contamination should be mandatory under all dismantling processes of transportation and fluid handling equipment for fluids and gases offshore and onshore. The intention is the need to classify equipment according to the Norwegian exempt level of 10 Bq/g: Is it radioactive or not radioactive?

1. INTRODUCTION

Radioactivity associated with scales in the petroleum production industry was realised for the first time as early as in 1904 in connection with oil and gas production in Canada [1]. This phenomenon did not catch much attention until the beginning of 1981 when central parts of the North Sea [2] also experienced the same phenomenon. Activity level in this scale was reported to vary between 0 and 15.000 Bq/ [3]. In the following years similar reports came from other parts of the world as well.

Radioactive contaminants of natural gas have been known since early in this century [4]. However, it was not until 1971 that this radioactivity, identified as ^{222}Ra , was found to concentrate in the lighter natural gas liquids during processing and could present a serious health hazard to industry personnel, particularly maintenance employees [5].

Due to frequently experienced high activity concentrations, radioactivity in scale started to become an environmental concern both with respect to the working environment for the oil and gas workers and with respect to treatment and storage. Radioactivity associated with the production of oil and gas has now been established as an important discussion subject in the oil and gas industry and a number of reports on its origin, occurrence, composition,

distribution, treatment, dissolution, monitoring, storage and even avoidance have been published. (A rather comprehensive bibliography is available from IFE upon request).

Radioactive scale is commonly termed LSA (Low Specific Activity) scale in Europe and NORM (Naturally Occurring Radioactive Material) scale in USA. One also finds some use of the term TENORM (Technologically Enhanced NORM). In the present text we will use the Norwegian acronym LRA (lav-radioaktive avleiringer).

2. ORIGIN OF RADIOACTIVE SCALE (LRA)

The earth crust contains small concentrations of the radioactive chemical elements uranium and thorium. The two nuclides of primary interest in this context are ²³⁸U ($T_{1/2}=4.5 \cdot 10^9$ y) and ²³²Th ($T_{1/2}=1.4 \cdot 10^{10}$ y). Both give rise to long series of radioactive decay. In these series the parent nuclides undergo up to 14 successive radioactive disintegrations, changing at each step into a daughter nuclide of a different chemical element during emission of either an alpha or a beta particle, often accompanied by gamma radiation. The consecutive radioactive transformations from one chemical element to another continue until the series end in stable lead isotopes (see Fig.1).

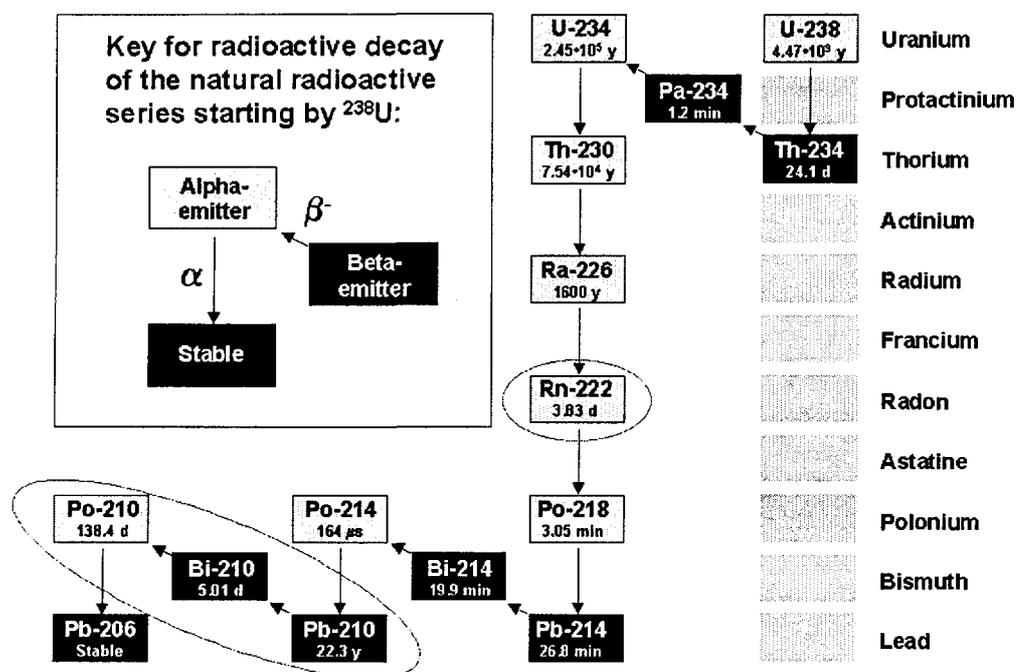


Fig.1. Decay sequence for the ²³⁸U natural series ending in stable ²⁰⁶Pb.

The concentration of uranium and thorium in sedimentary rock, or reservoir rock, is variable. Shales and clays have the highest contents: $C_U = 4.0 \cdot 10^{-4}$ μg/g, $C_{Th} = 11.0 \cdot 10^{-4}$ μg/g [6]. The concentrations in sandstones are somewhat lower: $C_U = 3.0 \cdot 10^{-4}$ μg/g, $C_{Th} = 10.0 \cdot 10^{-4}$ μg/g. Of the various reservoir materials, the uranium and thorium concentrations are lowest in calcite and limestone: $C_U = 1.4 \cdot 10^{-4}$ μg/g, $C_{Th} = 1.8 \cdot 10^{-4}$ μg/g.

Uranium and thorium in rocks are not easily dissolved and transported by the moving waters. However, more dissolvable are their decay products radium (^{226}Ra from the ^{238}U -series and ^{228}Ra and ^{224}Ra from the ^{232}Th -series) and radon (^{222}Rn from the ^{238}U -series and ^{220}Rn from the ^{232}Th -series). Common radioactive scale deposits are then composed of radium co-precipitated into host minerals like BaSO_4 , SrSO_4 , CaCO_3 and mixed crystals of these.

In brines with high chloride concentration also lead dissolve as chloride complexes. They are easily transported in the water systems [7,8]. The two most important lead isotopes are ^{214}Pb ($T_{1/2}=26.8$ min) and ^{210}Pb ($T_{1/2}=22.3$ y).

In this paper, we will concentrate exclusively on scales containing ^{210}Pb (and its decay products) which may partly occur as "invisible" radioactive deposits.

3. DEPOSITS CONTAINING ^{210}Pb AND PROGENY

3.1. ^{222}Rn -transportation

In the beginning of the petroleum production in a reservoir most of the ^{222}Rn is transported by the produced fluids from relatively deep into the reservoir. After some time of water production it is anticipated that the bulk part of the ^{222}Rn originates from the various scale deposits around in the production system starting from the near-well zone and all the way through the fluid handling system. ^{222}Rn -emanation has, however, been reported to be low from well pipe scale [9] as measured in laboratory experiments. However, scale may have different composition and porosity and is exposed to elevated temperatures in the near-well and the well promoting increased gaseous diffusion rate.

Radon may be transported and distributed around in the down-stream transportation and handling system for both the water, oil and gas phases. However, in commingled oil and water transportation radon dissolves preferentially in the oil phase (high partitioning into oil) and is transported along with the oil. Only a small fraction follows the water phase. Whenever all three phases coexist, radon is mainly transported in the gas (or condensate) phase while a fraction only is transported in the oil phase and an even smaller portion is left in the water phase. It has been reported that radon appears to concentrate preferentially in the ethane and propane streams in a gas treatment plant [5].

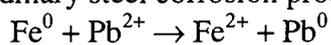
3.2. ^{210}Pb -transportation

When the inert gas ^{222}Rn decays, non-gaseous short-lived atoms are formed in consecutive decays changing from one chemical element to another. The atoms may, due to their high reactivity during rearrangement of their electron structure, enter into various chemical reactions. These reactions are dependent upon the chemical surroundings. When ^{222}Rn decays during transportation, the following scenarios are possible:

1. In water the decay products may stick to dispersed particles and colloids and be fixed there. The lead atoms formed may also be subject to chemical reactions, thus becoming eventually oxidised to $^{210}\text{Pb}^{2+}$. This ion may in turn be trapped along the flooding path by ion exchange reactions or electrostatic sorption reactions to surfaces. Even chemical reactions like the following have been suggested [10,11]:

a. $\text{Pb}^{2+} + \text{H}_2\text{S} \rightarrow \text{PbS} + 2\text{H}^+$ during decrease in temperature and pressure. It has been observed that some reservoirs/wells have produced a fair amount of stable lead (presumably from lead minerals in the formation rock) acting as a chemical carrier for ^{210}Pb [12,13]. Thus, ^{210}Pb may be found as the only primary (non-supported) radioactive contaminant in visible solid scale consisting mainly of PbS, various lead oxides and mixed lead carbonates/chlorides.

b. $\text{Fe}_{\text{metal}} + 2\text{H}_2\text{O} + \text{Pb}^{2+} \rightarrow \text{FeOOH} + \text{Pb} + 2\text{H}^+ + 1/2\text{H}_2$ as a co-reaction during the ordinary steel corrosion process, or simply [14]:



Here, ^{210}Pb is found in ultra-thin invisible layers of elementary lead or in thicker layers where produced inactive carrier lead is involved.

2. When ^{222}Rn decays in oil, the decay products may stick to particles dispersed in the oil. However, there is also a chance of forming organometallic compounds with lead (through hot-atom reactions), thus creating a fully oil-solvable ^{210}Pb -compound that follows the oil phase nearly as an ideal tracer. It may also be possible to form volatile organometallic ^{210}Pb -compounds that may partition somewhat into the gas phase.
3. When the decay takes place in the gas phase, the lead formed may stick to particles, which is transported along. A fraction of these particles may settle with their radioactive lead atoms to the inner surfaces of the transportation system. Due to the turbulent flow some of the lead atoms may also stick directly to this surface, thus forming a very thin and relatively stable deposit. This deposit may with time be converted to other lead compounds (elementary Pb, PbS) subject to gas humidity, content of CO_2 , H_2S etc.

3.3. Relative radioactivity levels

Supposing that the surface contamination is a result exclusively of ^{222}Rn decay, the contamination will in the beginning consist mainly of the longest-lived radionuclide in the chain, ^{210}Pb with a half-life of 21 years (all intermediate radionuclides following decay of ^{222}Rn are very short-lived). With time there is a build-up of its decay products ^{210}Bi and ^{210}Po . If ^{210}Pb is left in place for a sufficient length of time (3-4 y), these products may accumulate to reach an equilibrium state with the parent. This equilibrium is not necessarily the physical equilibrium but rather a practical equilibrium that varies for different conditions (temperature, pressure, and chemical environment). Differences in chemistry and volatility of lead, bismuth and polonium may be partly responsible for this practical equilibrium due to possible partial release into the fluid stream again with individual release yields for the three chemical elements. Polonium is the most volatile and most water-soluble.

It has been found experimentally that condensate (heavier fraction of the natural gas, composed mainly of propane and butane) may contain ^{210}Po far in excess of its grandparent ^{210}Pb [15]. There may be two sources for the polonium:

1. The "invisible" deposit on inner surfaces of handling equipment as a result of ^{222}Rn -transportation and subsequent decay.
2. Enhanced release of ^{210}Po from solid scale deposits in the near-well zone, the production tubing and the fluid handling and storage equipment topside.

Supposing a near-constant production of ²²²Rn for instance by emanation from solid ²²⁶Ra-containing deposits, the surface contamination of ²¹⁰Pb and its decay products will continue to increase for more than 100 years if undisturbed.

In gas and condensate transportation equipment the deposits are generally very thin. Therefore, it does not constitute an operational headache in normal operations. This is probably also the main reason why it has not attracted much attention. However, upon dismantle, abandonment or reuse of gas transportation and handling equipment, the described problem of surface contamination must be recognised and addressed [16,17]. Special measurement techniques must be used since the presence of long-lived ²²²Rn decay products cannot be measured on the outside of the contaminated equipment due to the low-energy radiation of the radionuclides.

4. NUCLEAR CHARACTERISTICS OF ²¹⁰Pb AND PROGENY

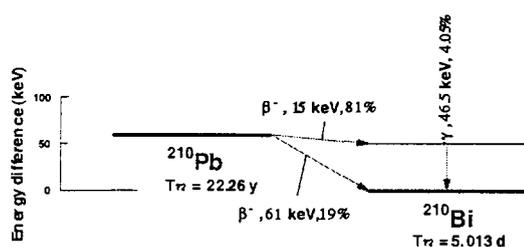
4.1. Decay schemes

Figs 2 a-c illustrate the desintegration schemes of ²¹⁰Pb, ²¹⁰Bi and ²¹⁰Po, respectively [18]. The main data are also summarized in Table 4 below:

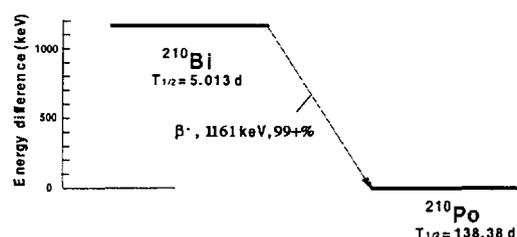
Table 4. Nuclear data for ²¹⁰Pb, ²¹⁰Bi and ²¹⁰Po actual for detection evaluations.

Radio-nuclide	Half-life	Radiation type, energy and absolute intensity (in brackets)
Lead-210	22.26 y	β^- : 15 keV (81%), 61 keV (19%). γ : 46.5 keV (4.05%)
Bismuth-210	5.013 d	β^- : 1161 keV (99+%)
Polonium-210	138.38 d	α : 5305 keV (99+%)

a Decay scheme for Lead-210



b Decay scheme for Bismuth-210



c. Decay scheme for Polonium-210

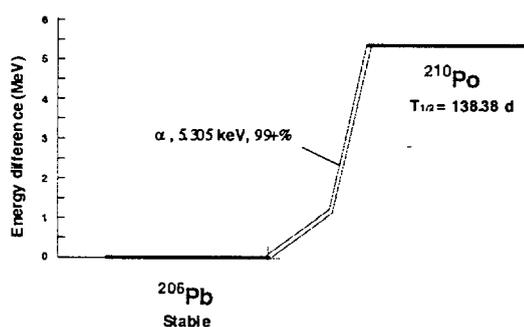
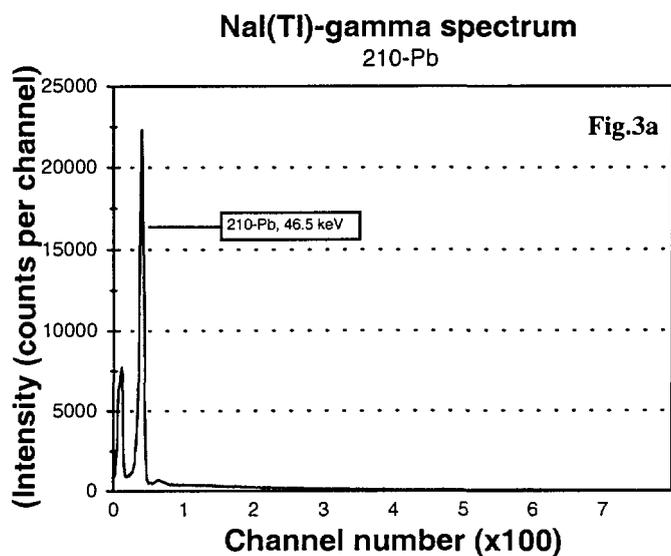


Fig.2. a. Decay scheme of ²¹⁰Pb showing low-energy beta and gamma emission. b. Decay scheme of ²¹⁰Bi which for practical purposes is a pure beta-emitter with relatively high beta energy. c. Decay scheme of ²¹⁰Po which for all practical purposes is a pure single-alpha emitter.

5. DETECTION METHODS FOR ²¹⁰Pb, ²¹⁰Bi and ²¹⁰Po

According to Norwegian legislation, equipment containing scale with activity concentration exceeding 10 Bq/g of one the radionuclides ²²⁶Ra, ²²⁸Ra and ²¹⁰Pb shall be classified as radioactive (exemption level). Accordingly, there are two steps in the monitoring process of radioactive scale:

1. A fast and reliable field monitoring process whereby the production equipment can be classified according to the exemption level. This measurement is used to direct the contaminated equipment to controlled decontamination processes.
2. For equipment exceeding the exemption level, a more detailed analysis may be needed on actual activity concentration and distribution of radionuclides. This detailed analysis can be carried out in the field or in the laboratory.



In the following, we will describe possible and ideal detection methods for the individual radionuclides under discussion here. Finally, a couple of practical field-applicable methods to address point 1 above will be briefly described.

5.1. Direct analysis of ²¹⁰Pb

5.1.1. Detection of γ -radiation

Although simple equipment like a *Geiger Muller (GM) tube* can be used to detect γ -radiation, it is not

recommended due to lack of energy resolution and low detection efficiency (<1%).

Solid scintillation detectors of different kind may be used for γ -detection. The most frequently

used solid scintillation detector is the *NaI(Tl)-detector*. Its energy resolution is sufficient to single out the photopeak of ²¹⁰Pb at 46.5 keV, even from relatively complex spectra of ²²⁶Ra and daughters, when connected to a multichannel analyser. This enables both qualitative (fingerprint) and quantitative analysis of ²¹⁰Pb in the sample. A NaI(Tl) γ -spectroscopy equipment may be made fairly rugged, and is possible to set up and use in an on-site situation.

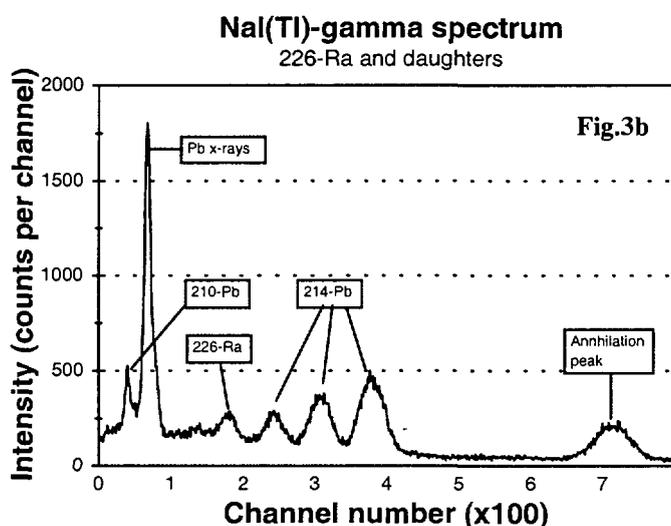
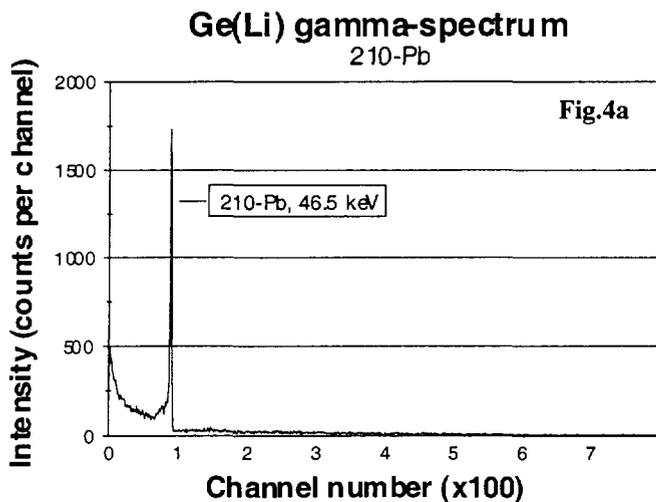


Fig.3a. NaI(Tl)-spectrum of ²¹⁰Pb in nuclear equilibrium with its daughters. b. Spectrum of ²²⁶Ra with daughter radionuclides.

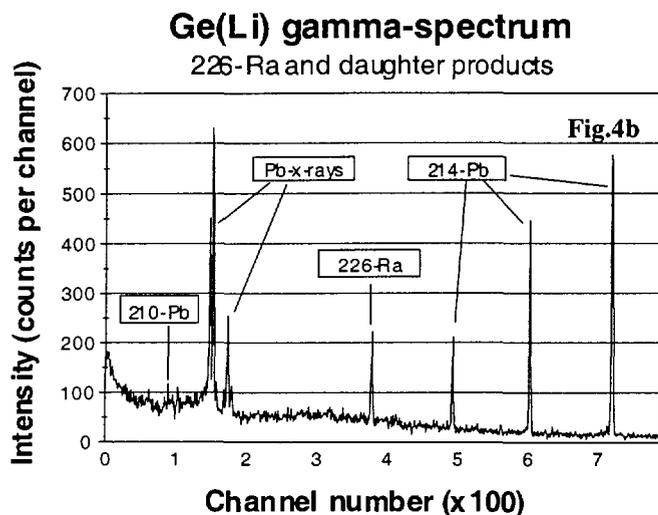
When exact and unambiguous determination of ²¹⁰Pb is required, the detector of choice in a laboratory

environment is the semiconductor detector based on Germanium, either the so-called high-purity Germanium (HpGe) or the Lithium-doped Germanium (Ge(Li)). These detectors have excellent energy resolution and may be designed to have good efficiency in the low-energy range. For the sake of demonstration, the same radioactive sources as monitored by NaI(Tl)-



detectors in Fig.3 are measured by a Ge(Li)-detector and shown in Fig.4 a and b below. It should be mentioned that the particular detector used here is a "general purpose" detector and not especially

*Fig.4a. Ge(Li) gamma-spectrum of a ²¹⁰Pb-source in nuclear equilibrium with its daughters ²¹⁰Bi and ²¹⁰Po.
 b. Ge(Li) gamma-spectrum of a ²²⁶Ra-source and daughter products inclusive ²¹⁰Pb.*



designed for low-energy detection. When compared to the NaI(Tl)- spectra in Fig. 3, the improved energy resolution is obvious. This high energy resolution facilitates non-destructive analysis even in rather complex radiation sources. Although transportable detector set-ups of this kind exists, it is not practical as a general on-site technique due to lack of detector roughness and to the fact that it requires to be cooled by liquid nitrogen during operation (the Ge(Li)-detectors even require such cool-down continuously during storage).

spectrometric analysis of ²¹⁰Pb [19-26].

A number of published articles describe the use of semiconductor detectors for γ -

7.1.2. Detection of β -radiation

Although very low β -energies, ²¹⁰Pb may be detected by *the liquid scintillation counting (LSC) method*. This method is mainly used for detection of charged particles like α - and β -particles, and Compton electrons resulting from interaction of the γ -rays with the scintillating medium. This method requires the sample dissolved in a liquid scintillator. Accordingly, sample preparation is required to some degree.

The LSC-method offers a certain energy resolution as well. However, due to the nature of the β -radiation (continuous distribution in the energy spectra from 0 to a maximum energy characteristic of each radionuclide), the possibility for undisturbed analysis is limited when the sample contains several radionuclides.

The big advantage with the LSC-method is, however, its very high counting efficiency, even for extreme low-energy particle radiation. Both the β -energies of 15 keV and 61 keV and the Compton electrons from the interactions of the 46.5 keV γ -radiation with the scintillator solution (and the conversion electrons from the same decay) will be detected with an

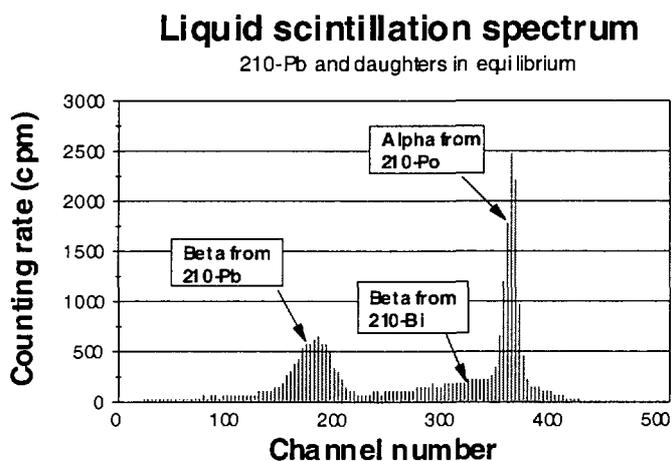


Fig.5. Unquenched liquid scintillation energy spectrum of ²¹⁰Pb in nuclear equilibrium with its daughters ²¹⁰Bi and ²¹⁰Po

efficiency of 30-50% dependant upon sample volume and degree of quenching in the sample. An LSC-spectrum of ²¹⁰Pb in nuclear equilibrium with ²¹⁰Bi and ²¹⁰Po is shown in Fig.5.

The LSC-method may be adapted to on-site analysis since transportable and rugged equipment exists. It might be the detection method of choice when very low activity levels are expected, for instance when free-classification decisions shall be taken.

Examples of published work that have utilised LSC for analysis of ²¹⁰Pb are given in the references [27-32].

5.2. Direct analysis of ²¹⁰Bi and indirect analysis of ²¹⁰Pb

The relatively high β -energy of 1161 keV makes possible detection with handheld gross-beta probes. However, reliable quantitative detection in complex sources can only be achieved by sampling followed by careful counting sample preparation.

One method of choice for ²¹⁰Bi-detection is, however, LSC after chemical purification of Bi. The counting efficiency of ²¹⁰Bi in LSC is close to 100%.

A detection method that is specific for ²¹⁰Bi in mixture with ²¹⁰Pb and ²¹⁰Po is the *Cerenkov counting*. In this method the sample must be dissolved in the same way as in ordinary LSC, but no scintillant is needed. Water only is sufficient. The theoretical requirement is that the beta particle must have energy > 265 keV when the sample is dissolved in pure water. It is simple and rugged, and the counting efficiency is around 20%. It has been described in the literature as a way of selectively measure ²¹⁰Bi in this particular radionuclide mixture [33].

Analytical methods have been developed where the measurement of ²¹⁰Bi is taken as an indirect measure of the ²¹⁰Pb-concentration. Separation of ²¹⁰Bi followed by LSC counting on the purified sample [28,34] or by gross β -counting on a solid source β -detector [35,36] has been reported. Likewise, separation of ²¹⁰Pb followed by a controlled decay time to allow the ²¹⁰Bi to grow in with subsequent counting of the grown-in activity either by a *gas proportional counter* [37] or by other types of solid-source β -detectors [38-41] have been described in published articles.

5.3. Direct analysis of ²¹⁰Po

Being a pure α -emitter, simple thin-window monitors may be used to detect the existence of ²¹⁰Po, but is of limited use for quantitative determination.

α -energies are specific for each α -emitter (fingerprints), and the α -particles have discrete narrow energies unlike the broad energy distribution for β -particles. Hence, an energy spectrum would ideally show narrow peaks corresponding to the α -energies. For ^{210}Po , one narrow peak at 5305 keV is expected when a detector with high-energy resolution is used. However, due to straggling (energy reduction and broadening due to particle collisions with material before detection), the α -peak may often appear somewhat broader and with a tail stretching downwards on the low-energy side.

α -spectra can be detected with selective α -detectors like *surface barrier detectors*. They are quite delicate instruments, and will have to be operated in a vacuum chamber together with the counting sample.

The energy straggling and the vacuum demands require the counting sample to be extremely thin ("mass-less") and in a solid form not prone to sublimation. This again requires radiochemical treatment of the sampled LRA. The surface barrier counting equipment is transportable, and can be applied in a stable environment on-site.

LSC is another possible detection method. However, when ^{210}Pb and daughters are present in mixtures, the simple and direct LSC method is not capable of resolving the contribution from ^{210}Po selectively, as shown in Fig.5. The α -peak from ^{210}Po sits on the shoulder of ^{210}Bi . However, more advanced LSC equipment has the possibility of electronic α/β -discrimination. This means that in a mixed α - and β -source it is possible to register both α - and β -counts separately [32,42]. Thus it is possible to measure ^{210}Po selectively in a source composed of ^{210}Pb and progeny.

5.4. Direct in-situ measurement

For in-field classification purposes, emphasis has to be put on rugged, simple and reliable monitoring methods. Two measurement strategies are recommended to cover different monitoring situations [43,44]:

1. Direct in-situ β -measurements on internal surfaces of components
2. Gross γ - or β -measurements of scale samples taken from the contaminated component.

Gross γ - or β -measurements will provide the most reliable results and should be preferred whenever possible. For sites where LRA-contaminated components are rare and the monitoring resources limited, it may be considered sufficient to rely on method 1 only.

5.4.1. Direct measurement of β -radiation

This method is based on β -measurements directly on contaminated inner surfaces of production equipment. Most β -detectors are, however, also sensitive to γ -radiation. Hence, the measurement probe should have as high as possible $\epsilon_{\beta}/\epsilon_{\gamma}$ -ratio where ϵ = detection efficiency.

The radiation detected by this method is mainly the β -particles from ^{210}Bi (energy 1.16 MeV). Accordingly, if the measurement shall represent the ^{210}Pb -contamination, one has to assume physical equilibrium between ^{210}Pb and ^{210}Bi . The range of these β -particles in ordinary scale is about 2 mm. This means that one always measures only from the top 2 mm of the scale layer. Accordingly, the method will give the activity concentration (Bq/g) for all scale thicknesses > 2 mm when a proper calibration of the instrument has been performed. Calibration may for instance be performed by use of 3 or 4 samples with thickness >2mm and

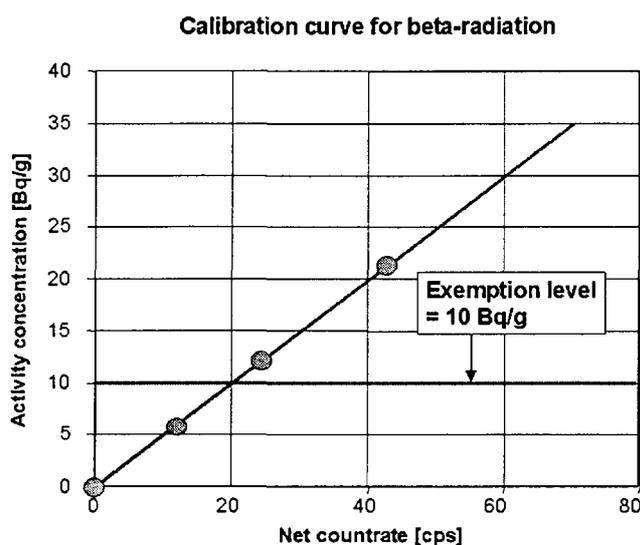


Fig.6. Calibration curve for measurement of ²¹⁰Pb with pure beta-detection.

different activity concentration. One will then establish a relationship between the measured countrate (in counts per second, cps) and activity concentration in Bq/g as sketched in Fig.6. There is no need to measure exactly the scale thickness. For scale thickness <2mm, the method will always measure a lower activity concentration than the real one if one uses the calibration for "thick" samples. It is, however, possible to calibrate for scale thickness <2mm too. In such cases the actual measurement is dependent on the scale thickness.

5.4.2. Gross β- and γ-measurements

This method utilises a γ-sensitive probe, which in some cases are also sensitive to β-radiation. In the latter case, β- and γ-radiation are detected together. The method is in principle similar to the previous one: One will need to calibrate the probe with calibration samples composed of scale material (or equivalent) with various concentrations of ²¹⁰Pb in physical equilibrium with ²¹⁰Bi and ²¹⁰Po and various sample thicknesses (in g/cm²). Since g-radiation is involved, the recording is not independent on scale thicknesses in excess of 2 mm.

The same two methods can be used in general for LRA-scale measurements as described in Ref.s [43,44].

6. ²¹⁰Pb AND PROGENY DEPOSITION SITES

Only a limited number of reports are published on field investigation of ²¹⁰Pb and progeny contamination in the petroleum production industry. Table 5 below summarises some of the data published:

From Table 1: Radon concentration in natural gas have been reported [17,47] to be rather high in areas in USA (up to 54 Bq/l) and Canada (up to 30 Bq/l). These elevated levels lead to considerable radioactive contamination by ²¹⁰Pb and daughters in gas transportation pipelines, condensate facilities (fractionators, condensers, pumps, storage tanks, waste pits etc.) and in filter assemblies for the dry-gas.

From the Netherlands it has been found that ²¹⁰Pb-contamination in the production equipment is associated with the normal well-known scale products (up to 1590 Bq/g) but are also found in corrosion films and products, along with macroamounts of elemental lead and as ultra-thin nearly invisible films on internal surfaces [11,14,45].

In gas treatment (fractionation) plants a surface contamination of up to 1660 Bq/cm² of ²¹⁰Pb has been reported [47].

Table 5. Literature reports on activity concentration (Bq/g and Bq/m³) and surface contamination (Bq/cm²) of ²¹⁰Pb and ²¹⁰Po as well as some corresponding data for ²²²Rn and ²²⁶Ra given along with contamination position and contaminated matrix type.

Position	Scale types	²²⁶ Ra (Bq/g)		²¹⁰ Pb (Bq/g)		Reference
Production manifold, gas-liquid separator	BaSO ₄ , PbS, Pb _{met} , ZnS, PbO _x , CaSO ₄ , Pb ₃ (CO ₃) ₂ Cl ₂	184 - 3016		57 - 1561		[11]
Tubings	PbS, Pb _{met} , ZnS, PbO _x	< detect. limit		204 - 1590		[11]
Pumps, valves, filters	Pb _{met} , PbS, PbO _x , Pb ₃ (CO ₃) ₂ Cl ₂	< detect. limit		271 - 950		[11]
NG-prod.:Tubings	Scale, thin layer, partly removable	Not detected		250 - 500		[45]
NG-prod: Inlet waterbath heater	BaSO ₄ , PbS, Pb _{met} , PbO _x , Pb ₃ (CO ₃) ₂ Cl ₂ Thin deposits	549		193		[14]
NG-prod: Flowlines	Ba _x Sr _y SO ₄ , FeOOH Fe ₃ O ₄ , CaCO ₃ / FeCO ₃ Thin deposits	125-2000		30-600		[14]
		²²² Rn (kBq/m ³)	²¹⁰ Pb (Bq/m ³)	²¹⁰ Po (Bq/m ³)		
NG-plants	Natural gas (NG)	0.005 - 200	0.005 - 0.002	0.002 - 0.008		[46]
NG/LNG-plants	Natural gas (NG)	2.3	-	-		[47]
NG-production	Canadian NG	5-20	-	-		[17]
NG-production	US NG Canadian NG	0-54 0-30	-	-		[47]
		²¹⁰ Pb (Bq/cm ²)	²¹⁰ Pb *) (Bq/g)	²¹⁰ Po (Bq/cm ²)		
LNG rail cars	Ferric dust from rail car interior	-	32	29 Bq/g		[17]
NG/NGL-plants: De-methaniser	Surface contamin.	-	-	0.17 - 0.47		[47]
NG/NGL-plants: De-ethaniser	Surface contamin.	0.04 - 5.5	8.2 - 31.3	-		[47]
NG/NGL-plants: De-propaniser	Surface contamin.	1.5 - 1660	76.4- 184.7	-		[47]
NG/NGL-plants: De-butaniser	Surface contamin.	0.024 - 4	0.3 - 234	-		[47]
NG/NGL-plants: Propene refig.	Surface contamin.	0.19 - 2.0	-	0.11 - 0.37		[47]
NG/NGL-plants: C ₃ transfer & stor.	Surface contamin.	5.3 - 596	-	-		[47]

To date, only scarce and scattered information is available about the level of ²¹⁰Pb-contamination in scale, topside handling equipment, gas transportation tubings and gas treatment plants in UK and Norway. A few results are however given in a relatively recent report which summarizes the LRA experiences in Norway and United Kingdom and some of the experiences in The Netherlands [49].

In United Kingdom ²¹⁰Pb has been detected as the predominant radionuclide in scales from an on-shore gas production facility in the South of England. No information is available on the content of ²¹⁰Pb in scales from off-shore petroleum production due to lack of regular analysis for this radionuclide.

Scale from the Netherlands show typical compositions that vary from high to low levels in ^{210}Pb , and no clear correlation to the content of ^{226}Ra can be derived.

In Norwegian samples of scale, sand and sludges, ^{210}Pb was not detected in most cases and only at very low levels wherever it was seen ($< 0.21 \text{ Bq/g}$). (These analyses were carried out by NRPA, Norwegian Radiation Protection Authority). In another report from NRPA [50], levels of up to 0.7 Bq/g are reported.

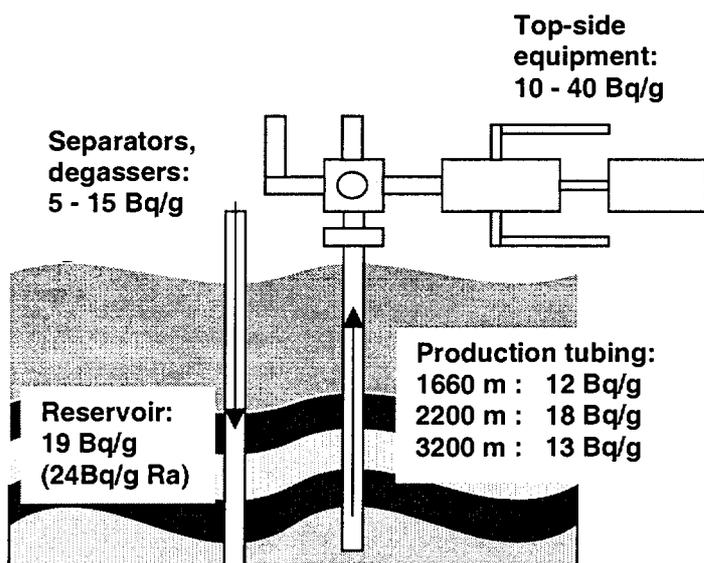


Fig 8. Measured activity concentration of Pb in scale from a Norwegian North Sea oil field.

Very recently, topside equipment acquired from BP in Norway showed unambiguous contamination by ^{210}Pb and progeny. Samples from production tubing, separators with attached equipment and from other topside equipment shows considerable activity of ^{210}Pb . The findings are sketched in Fig.8. We have not yet measured equipment further downstream in the NG or LNG transportation and treatment process.

The results of these surveys indicate that there certainly is a considerable potential for ^{210}Pb -contamination also in the Norwegian petroleum industry.

7. FINAL COMMENTS

The purpose of the present paper has been to remind the production engineers and HMS-personnel in the oil and gas industry of the problem of ^{210}Pb -contamination. The paper is based on work carried out for OLF during 1997 and 1998. Information on this problem in the inter-national oil and gas literature is limited. A few reports exist, mainly from USA, Canada and The Netherlands. They conclude that this type of radio-contamination should be handled seriously. From Norwegian operators there is even less information available on contamination levels, the main reason being lack of dedicated practical examinations. The data that are published [49] indicates, however, rather low levels, - in no case the activity concentration exceeded 0.21 Bq/g in scale. Not all types of equipment were surveyed, however. These measurements stand in contrast to results from a survey done on equipment from the Gyda-field (BP Exploration) which showed considerable contamination of ^{210}Pb [43,44] of more than 40 Bq/g in offshore topside equipment. The lack of consistency of measurements from the Norwegian petroleum industry suggests that more work should be done in the field of ^{210}Pb -contamination. This work could be carried out along the following lines:

1. Carry out a field study on equipment from the offshore industry and from the downstream gas and condensate treatment, storage and transportation activities.
2. Establish a competent service team (people and equipment) for reliable examination on a service basis.

The ^{210}Pb -contamination is foreseen to become an increasing practical problem as the industry grows older and decommissioning of installations becomes necessary.

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