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Managing Naturally Occurring Radioactive Material (NORM) in the oil and gas industry

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1. Introduction

This report provides guidance and general information on the management of process streams or equipment contaminated with minor concentrations of Naturally Occurring Radionuclides (NORs). Colloquially streams or installation parts contaminated with NORs are indicated as Naturally Occurring Radioactive Material (NORM) within the oil and gas industry.

NORs are present at varying concentrations in the Earth's crust and consequently also will be present in natural concentrations in gas and oil reservoirs. The NOR concentrations in well fluids may become enhanced due to extraction processes and subsequently form NOR enriched deposits within production facilities thereby forming NORM. Examples include produced water, scales, sludge and pigging debris.

Uncontrolled work activities involving NORM can lead to unwanted exposure and dispersal posing a risk to human health and the environment. These risks – or doses stemming from the exposure to ionizing radiation emerging from NORM – can be reduced by the adoption of appropriate controls to identify if and where NORM is present. The general principles of protection against the hazards of ionizing radiation are primarily implemented by utilizing best working practices at NORM work areas. In this respect exposure control and adequate dosimetry are the most critical components of a health and safety programme in the protection of workers. The protection of the environment, and subsequently the public at large, is achieved by controlled disposal of NORM-waste and the adoption of emission controls.

In this report, the term NORM will be used throughout, but alternative terminology can also be commonly encountered. The acronym TENORM – Technologically Enhanced NORM – is mainly used in the United States and is used to discriminate between 'natural' NORM and any NORM subject to human driven technological processing. Radioactive scale deposits were initially indicated as Low Specific Activity (LSA) scale. This acronym emerged from the International Atomic Energy Agency (IAEA) transport regulations. Similarly, installation parts that are contaminated at their inner surface with deposited NORs are sometimes termed Surface Contaminated Object (SCO).

Within the radiation protection discipline, there is a need for caution due to the myriad of different measurement units and prefixes in common usage. These can lead to potential errors of several orders of magnitudes and the risks incorrectly stated. Within this report, the International System of units (SI) will be used throughout, with alternatives and conversion factors shown in Appendix A.

Key units are:

Activity (becquerel or Bq) solely indicates the number of nuclear disintegrations per second but is also encountered as derived units such as activity per mass or volume (Bq/g[solid], Bq/L[liquid] and Bq/Nm^3[gas]).

Absorbed dose (gray or Gy) denotes the amount of energy (J) imparted per unit of mass (kg). This dose does not account for the biological harm done to the human body.

Effective dose (sievert or Sv) is a derived SI unit introduced by health physics and accounts for the type of radiation and the sensitivity of the tissue exposed.

As ionizing radiation cannot be detected by human senses, radiation monitoring instruments have to be used. The operating principles in these instruments are separately treated in section 5 (NORM monitoring).

This report acts as a road map and establishes uniform approaches on NORM management. It does not seek to obstruct or impede normal operations but to describe controls that are adapted to NORM working practices. This guidance is flexible and can accommodate regulatory variations under which individual IOGP member companies may be required to operate.

It must be stressed, however, that this guidance only provides a framework. Users should realise that management of NORM requires the consultation and engagement of a number of stakeholders, notably the approval of the competent regulatory authorities. Furthermore, only focussing to NORM might lead to overlooking other hazardous contaminants that are sometimes encountered alongside NORM. Examples include heavy metals such as mercury and pyroforic black dust (very finely dispersed iron sulfide).

This report is focused to unintentionally encountered natural radioactivity (NORM) and is not meant for the management of intentionally applied ionizing radiation (e.g. X-ray devices, neutron generators) and artificial radioactivity (e.g. sealed sources, radiotracers).

1.1 Origins of Naturally Occurring Radionuclides

All naturally encountered elements are present in the Earth's crust in varying concentrations[1]. However, only eight of these – oxygen (O), silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), sodium (Na), magnesium (Mg) and potassium (K) – make up 98.5%. In principle, all elements may be present in gas/oil reservoir rock and via (geo)chemical leaching processes in reservoir fluids, including connate water.

All elements are constituted from one or more naturally occurring nuclides. A set of nuclides with equal proton number are called isotopes. If a nuclide is not stable and decays, it is called a radioactive nuclide or radionuclide, and if naturally occurring they are indicated as Naturally Occurring Radionuclides (NORs). For instance, K (abundance in the Earth's crust 2.1%) consists of three isotopes; notably ^{39}K (natural abundance 93.2581%), ^{40}K (0.0117%) and ^{41}K (6.7302%). The elements thorium (Th) and uranium (U) are also present in the Earth's crust but at the parts per million (ppm) level, where Th consists of one (^{232}Th: 100%) and U mainly of two isotopes (^{235}U: 0.720%, ^{238}U: 99.275%).

Almost all elements are constituted from stable nuclides, but the elements Th and U are unstable or radioactive by nature, so that they will disappear in time by nuclear disintegration. As their half-life ($t_{½}$) times are extremely long (^{232}Th: $t_{½} = 1.405 \times 10^{10}$ years, ^{235}U: $t_{½} = 7.038 \times 10^{8}$ y and ^{238}U: $t_{½} = 4.468 \times 10^{9}$ years), these nuclides have been present ever since planet Earth was formed and are called primordial or terrestrial NORs.

K is widely distributed in nature in plants, animals, and rocks with the current isotopic distribution. If for instance K would leach from reservoir rock into connate water, the K isotope distribution in both phases (solid/rock, liquid/water) is identical. This implies that any object containing K will contain ^{40}K as well. Upon one nuclear disintegration of ^{40}K either a ß-particle (89%) or γ-photon (11%) is emitted. As one of the decay products is a stable (non-radioactive) isotope of argon (^{40}Ar) ^{40}K in rocks can be used to measure its age: the older the rock, the more ^{40}Ar is trapped and the less ^{40}K it contains.

In contrast to ^{40}K, ^{232}Th, ^{235}U and ^{238}U decay via a successive series of nuclear disintegrations (known as a decay chain), where their daughter nuclides are radioactive until at the end of the series a stable lead (Pb) isotope is formed. In secular equilibrium, the daughter nuclide activity concentrations are identical to that of their respective parent NOR.

Table 1 illustrates the mean and range of K, Th and U abundances in sedimentary (often reservoir) rocks[2].

Sedimentary Rock Class	potassium (K)			thorium (Th)			uranium (U)		
	%			(ppm)			(ppm)		
	mean	range	Bq(^{40}K)/g mean	mean	range	Bq(^{232}Th)/g mean	mean	range	Bq(^{238}U)/g mean
DETRITAL	2.1	0.01-9.7	7	12.4	0.2-362	0.05	4.8	0.1-80	0.06
Sandstone & Conglomerate Orthoquartzites Arkoses	1.2	0.1-8.5	0.4	9.7	0.7-227	0.04	4.1	0.1-62	0.05
	2		0.06	1.5		0.0006	0.5	0.5-3	0.005
				5		0.02	1.5		0.02
Shale grey/green back	3.5	0.9-8.5	1.1	16.3	5.3-39	0.07	5.9	0.9-80	0.07
	3		0.9	13		0.05	3	3-4	0.04
								8-20	
Clay	0.6	0.1-2.6	0.2	8.6	1.9-55	0.03	4	1.1-16	0.05
CHEMICAL	0.6	0.02-8.4	0.2	14.9	0.03-132	0.06	3.6	0.03-27	0.04
Carbonates Limestone	0.3	0.01-3.5	0.09	1.8	0-11	0.007	2	0.03-18	0.02
			0.2	3		0.01	13		0.16
Evaporites							<0.1		<0.001

Table 1: Mean and range of K, Th and U concentrations in sedimentary rocks

1.2 Thorium and uranium decay series

The NORs ^{232}Th, ^{235}U and ^{238}U form the starting point of three distinct radioactive decay series. However, due to its low natural abundance ^{235}U, including its decay chain products, is rarely encountered in practice. The ^{232}Th and ^{238}U chains are the most significant with regards to the origin of oilfield NOR[3]. These 'parents' undergo radioactive decay through a series of transformations (see 1.4): loss of an α-particle (element and mass change 4) or a β-particle (only element change, virtually no mass change). Some of these transitions are accompanied by the emission of γ-photons. Each transformation gives rise to a new radioactive 'daughter' – also a NOR that is both lighter and less energetic than its immediate 'parent' – until the last step when a stable Pb isotope is reached. The radioactive decay series ^{238}U and ^{232}Th are detailed in Figure 1 and show the NORs of concern, their decay mechanisms (α or β), their half-life and if any associated γ-photons are emitted[4]. See also Appendix E (Decay and radiation characteristics of ^{232}Th- and ^{238}U- decay series).

The amount of radioactivity, N, decreases at a rate proportional to its current value $dN/dt = \lambda N$, where λ is a positive rate called the exponential decay constant. λ is related to the half-life time, $t_{½}$, of a radionuclide: $\lambda = \ln(2)/t_{½}$. The half-life time is the time required for the disintegration of one-half of the radioactive atoms that were present when measurement starts. It does not represent a fixed number of atoms that disintegrate, but a fraction. The half-life of the members of the ^{232}Th and ^{238}U decay series decay varies by many orders of magnitude, from billions of years to less than a microsecond.

Secular equilibrium is a phenomenon that occurs when a long-lived parent decays via one (or more) shorter lived daughters. This is a situation in which the quantities of all daughter NORs remains constant (identical to that of ^{232}Th or ^{238}U) because their production rate due to decay of their immediate parent NOR equals their own decay rate. Assuming that the initial concentration of all member NORs is zero, full equilibrium is only established after several half-lives of the longest lived NOR involved: for the ^{232}Th series after about 30 years, but for the ^{238}U series only after about 10^6 years. The extreme long half-life of ^{232}Th and ^{238}U means that both series are in secular equilibrium on a geological time scale, so that the γ-emission intensities of their respective daughter NORs can be used for an indication of their parents concentration. This relationship is used in NORM surveys and γ-spectrometric measurement and analysis of samples.

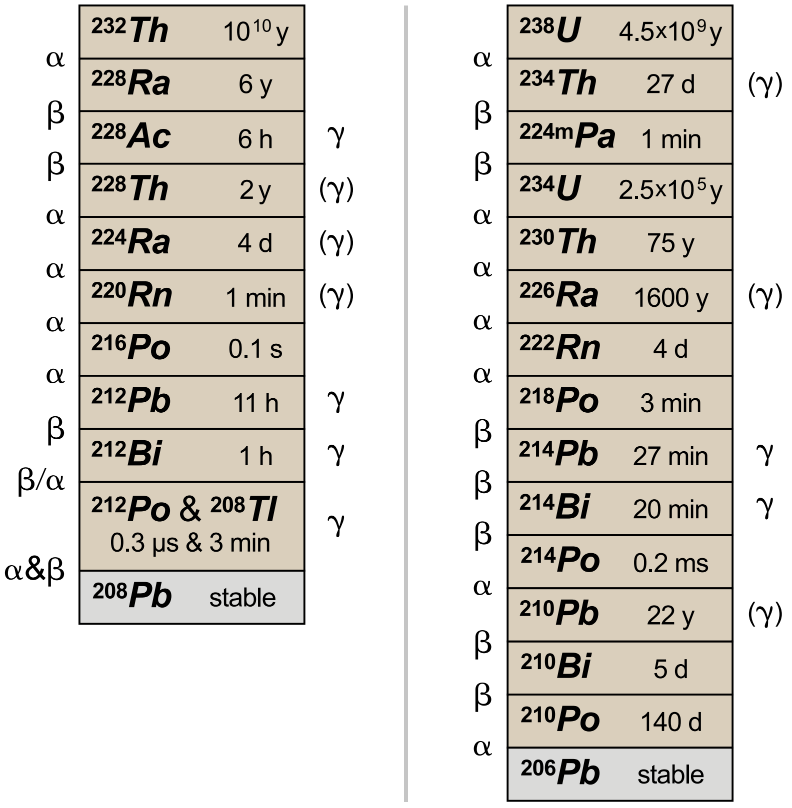


Figure 1: Full ^{232}Th and ^{238}U decay series including decay mechanism and half life

1.3 Radioactivity units

The international system of unit (SI) for the amount of radioactivity is the becquerel, or Bq for short.

One Bq is equal to one nuclear disintegration per second.

The Bq is only related to the amount of radioactivity and does not provide any information on the type of decay. As one disintegration is a very small quantity, values are frequently quoted with prefixes (Appendices A and B). In NORM measurements, these are typically kilo (k 10^3), mega (M 10^6), giga (G 10^9) and/or tera (T 10^{12}). The Bq will most commonly be encountered as an activity concentration in the gaseous phase (Bq/m^3), the liquid phase (Bq/L) or the solid phase (Bq/g), or as the amount of radioactivity per surface area: Bq/cm^2.

In some countries, older units of measurement are still commonly in use. For example, in the United States of America the Curie (Ci) is frequently encountered: originally defined as the rate of decay from 1 gram of radium (mainly ^{226}Ra) equalling 3.7×10^{10} Bq. As one Ci is a very large amount of radioactivity, the NORM activity or activity concentration is often accompanied by prefixes such as pico (p 10^{-12}), nano (n 10^{-9}), micro (μ 10^{-6}) and/or milli (m 10^{-3}). One Bq equals 27 pCi.

Care should be taken to ensure that the correct unit of measurement is used, especially when values are reproduced between reports, guidelines and instrument read-outs. This may be further confounded by the use of the SI units for dose (Gy, Sv) or their predecessors (rad, rem) (Appendix A). Activity cannot be directly calculated from dose rates and vice versa. This type of conversions requires additional contextual information (section 2).

1.4 Radiation characteristics

There are three types of radiation of interest that are emitted in various amounts by NOR[4]:

- Alpha (α) particles
- Beta (β) particles
- Gamma (γ) photons.

α-particles are a type of ionizing radiation ejected by the nuclei of some unstable atoms. They are large subatomic fragments consisting of two protons and two neutrons identical to a helium nucleus stripped from its electrons. They are a relatively heavy (mass 4), high energy (MeV) particles that are doubly (positively) charged and lose energy very quickly in matter. α-particles will only travel about 2 cm in air and only about 10 µm or less in solid material like human tissue.

They can easily be shielded with a piece of paper, gloves, disposable coverall or the dead outer layer of your skin. The primary health concern is inhalation and ingestion of α-particles into the body which places them in direct contact with essential layers of living tissue (e.g. oxygen or nutrients exchange layers in lung or intestine).

ß-particles are subatomic particles ejected from the nucleus of some radioactive atoms. They are equivalent to electrons. The difference is that ß-particles originate from the nucleus and electrons originate from electronic shells (orbitals) outside the nucleus. ß-particles have a negative charge of –1 and a mass which is about 1/2000 of the mass of a proton or neutron. The speed of individual ß-particles depends on how much energy they have, and varies over a wide range.

It is their excess energy, which causes harm to living cells. When transferred, this energy can break chemical bonds and form ions. ß-particles may travel up to about 1 m in air and the maximum range for 500 keV ß-particles in tissue is about 1 mm. They can be effectively shielded with a thin piece of aluminium, steel or plastic but unlike alpha particles will not be fully shielded by coveralls and gloves.

γ-photon emission often accompanies the emission of ß- and occasionally α-particles due to relaxation of the excited nuclear state, in which the newly formed NOR is created. γ-photons can travel an indefinite distance in air and needs to be shielded with material with a high electron density, like Pb.

Due to their long range in air γ-photons are considered as an external irradiation hazard to the human body. Only γ-photons that are stopped in living tissue may cause ionizations in the stopping tissue. Upon intake, irradiation from inside the body can occur.

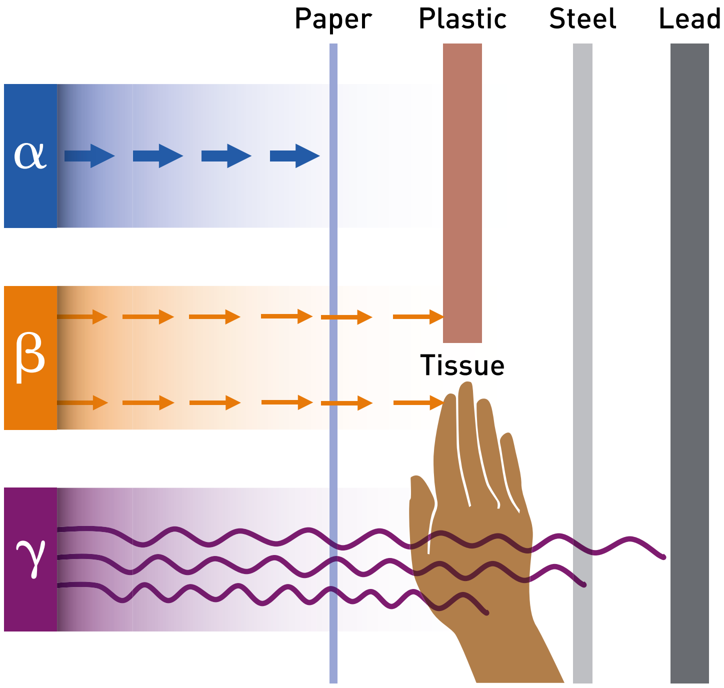


Figure 2: The penetration power of ionizing radiation. Redrafted from the NRPB 1999[5]

1.5 Accumulation of NOR in oil and gas production

In a gas/oil reservoir that has not been producing, both the ^{232}Th and ^{238}U decay series are in secular equilibrium. For reservoirs in production chemical partitioning equilibrium between NORs present in reservoir rock and reservoir fluids will be dependent on the elemental properties:

Th & U: as a gas/oil reservoir is a reducing environment both Th and U prefer the solid rock phase and do not dissolve in the aqueous or oily phase. Consequently the top of both series remains with reservoir rock and can only appear in natural concentrations (Table 1) at the surface during drilling operations.

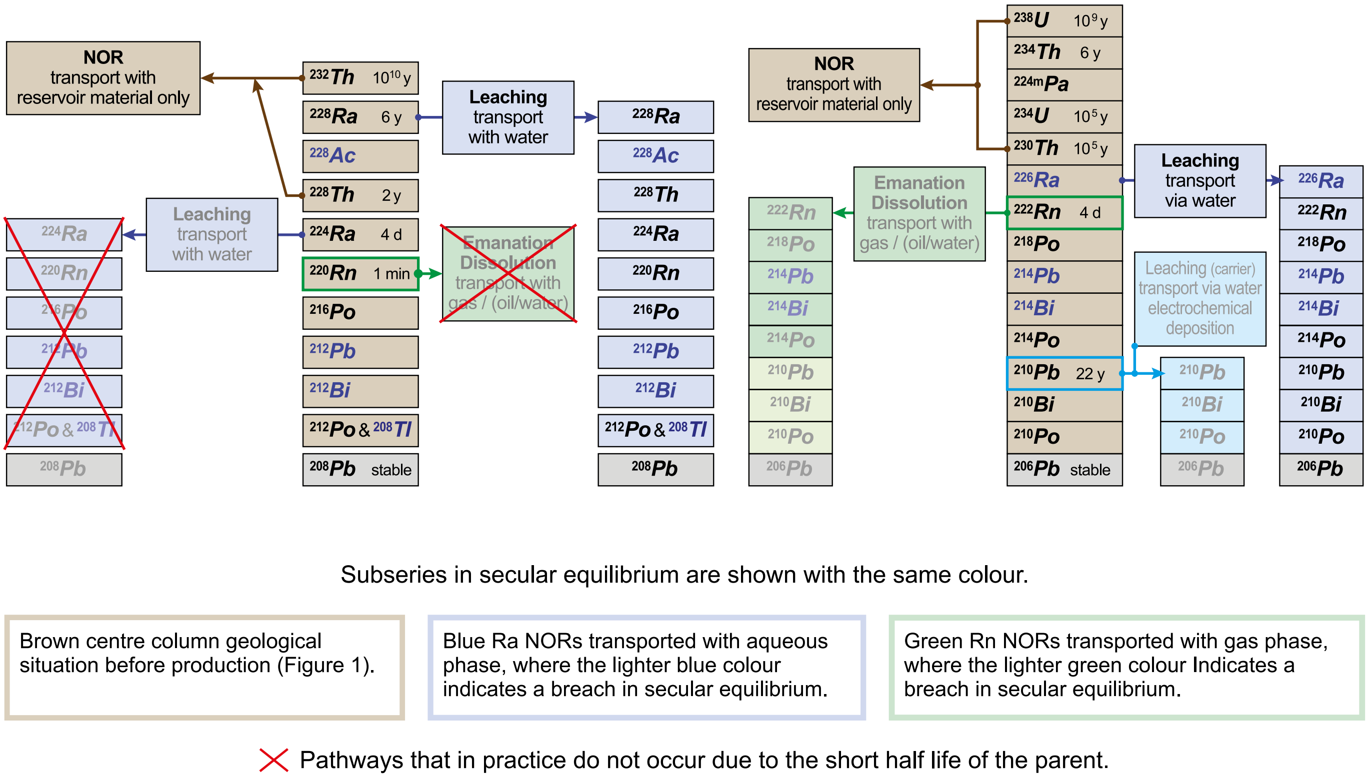
Ra: the partitioning of Ra (^{228}Ra, ^{226}Ra, ^{224}Ra) is special as they are formed by α-decay from their immediate parent (Figure 1) and may be injected from rock/fluid interface into well fluids by so-called α-recoil. In addition, Ra prefers the aqueous phase, leading to somewhat naturally enhanced concentrations. Therefore upon production the Ra will follow the aqueous produced water stream. Ra is chemically similar to barium (Ba), strontium (Sr), calcium (Ca) and magnesium (Mg) and becomes incorporated in group II sulfate or carbonate deposits and scale. Once deposited inside installations or produced at the surface due to their radiation characteristics all three Ra NORs show different behaviour[6]:

- ^{228}Ra is very quickly (within two days) in secular equilibrium with ^{228}Ac (denoted as $^{228}Ra_{eq}$), after which in a much slower process (about 10 years) ^{228}Th, that was absent in (deposits from) produced water, grows in (transient equilibrium). With the appearance of ^{228}Th all NORs until ^{208}Pb (Figure 1) appear as well in about two weeks (denoted as $^{228}Th_{eq}$).
- ^{226}Ra starts a secular equilibrium (within two weeks) of short-lived NORs (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) of its own denoted as $^{226}Ra_{eq}$. The ingrowth of ^{210}Pb occurs at a much slower rate (about 100 years).
- ^{224}Ra appears in produced water or its deposits without its immediate parent ^{228}Th, so it does not grow in anymore and quickly (within two weeks) dies out. This implies that only in freshly sampled fresh produced water ^{224}Ra may be detected. With the reappearance of ^{228}Th, ^{224}Ra will also reappear in more aged samples as member of the $^{228}Th_{eq}$ subseries.

Radon (Rn) isotopes are special as they, being a noble gas element, prefer the (natural) gas phase for transport from the subsurface to the surface. As ^{220}Rn (also known as thoron) only lives for minutes by the time that this NOR reaches the surface, it will have decayed. ^{222}Rn with a half-life of about four days may appear in Natural Gas Liquids (NGL) processing installations (particularly the C_3 process stream), in the gas cap of crude oil storage tanks (associated gas) or in Natural Gas (NG) transmission lines. Ultimately it will decay to ^{210}Pb, but as ^{222}Rn is short-lived with respect to ^{210}Pb, no equilibrium status will be reached. ^{210}Pb deposits originating from initial relative high ^{222}Rn concentrations may appear due to prolonged processing in deposits in NGL process installations, in tank bottom sludge of crude oil storage tanks and in sludge from booster stations in NG transmission lines.

Pb: In gas or oil fields, where stable Pb is present in produced waters, ^{210}Pb may be incorporated in any formed deposit as well[7]. In this kind of deposit ^{210}Pb activity concentrations will be substantially higher than ^{226}Ra activity concentrations, indicating that a separate and independent mechanism for Pb transport is present (unsupported ^{210}Pb).

The leaching and occurrence NORs always lead to chemical trace concentrations; e.g. 1 Bq[^{226}Ra] corresponds to about 30 pg[^{226}Ra]. The chemical separation occurring during gas and oil production as described above is shown in Figure 3. The level of NORM accumulation can vary substantially from one facility to another depending on geological formation and operational conditions and will also change over the lifetime of a single well. NORM cannot be readily differentiated from other oilfield materials and wastes except by specialist measurement. The quantity of material does not necessarily dictate the amount of NORM present or the radiological risk that it may represent. To determine whether or not a facility is accumulating NORM, a periodic NORM survey with likely subsequent sampling and analysis needs to be conducted.



Subseries in secular equilibrium are shown with the same colour.

Brown centre column geological situation before production (Figure 1).

Blue Ra NORs transported with aqueous phase, where the lighter blue colour indicates a breach in secular equilibrium.

Green Rn NORs transported with gas phase, where the lighter green colour Indicates a breach in secular equilibrium.

✕ Pathways that in practice do not occur due to the short half life of the parent.

Figure 3: ^{232}Th and ^{238}U decay series break up during gas/oil production

1.6 NOR in oil and gas industry products

The only NOR concentration that may be measured with the aid of a user-friendly measuring apparatus in (on-site) production laboratories[8] is ^{222}Rn in natural gas. The rest of the NOR activity concentrations in gas and oil industry products can only be measured by specialized contractor laboratories.

During the production process, NOR flows with the well fluid mixture in trace concentrations. Table 2 illustrates the range of NOR activity concentrations encountered in crude oil, natural gas liquids (NGL) and natural gas (NG). All concentrations are routinely many orders of magnitude lower than the activity concentrations later encountered at any point of accumulation. The heavier the crude oil, the higher Th and/or U concentrations may be, so that by deep processing/refining Th and/or U concentrations may become easily measurable in any residue material produced. Up until now, no heavy residues exceeding 1 Bq[NOR] per gram have been encountered.

^{222}Rn is a radioactive noble gas, which is present, to varying degrees in NG in oil and gas formations. In the absence of NG, ^{222}Rn partitions in the (light) hydrocarbon (NGL) and/or aqueous phase. When produced with the oil and gas, ^{222}Rn will usually follow the gas stream. If NG or NGL are fractionated, a disproportionately high percentage of ^{222}Rn can concentrate in propane and to a lesser degree in the ethane streams.

	NOR	Bq[NOR]/L[oil]	Bq[NOR]/L[NGL]	Bq[NOR]/m^3[NG]
^{232}Th series	**^{232}Th**	0.03 < > 2	n.r.	n.r.
	^{228}Ra$_{eq}$	n.r.	n.r.	n.r.
	^{228}Th$_{eq}$	n.r.	n.r.	n.r.
^{238}U series	**^{238}U$_{eq}$**	0.0001 < > 10	n.r.	n.r.
	^{226}Ra$_{eq}$	0.1 < > 40	n.r.	n.r.
	^{222}Rn$_{eq}$	n.r.	0.01 < > 1,500	5 < > 200,000
	^{210}Pb$_{eq}$	n.r.	0.3 < > 230	0.005 < > 0.02
n.r. = not reported.				

Table 2: NOR activity concentration range reported for crude oil, NGL and NG. eq denotes a decay series in secular equilibrium

^{222}Rn produces, through natural decay, several radioactive nuclides (radon progeny). Most ^{222}Rn progeny is short-lived, with the exception of ^{210}Pb$_{eq}$, which has a relatively long half-life of 22.6 years and occurs as solids at surface temperatures and pressures. Most of the ^{222}Rn short-lived progeny become attached to aerosols present in NG (or ambient air), airborne particulates or surfaces. Upon prolonged processing very thin ^{210}Pb$_{eq}$ can accumulate as thin radioactive films on the inner surfaces of gas processing equipment such as scrubbers, compressors, reflux pumps, control valves and product lines. Table 2 also provides NOR activity concentrations reported in NG and NGL (incl. hydrocarbon condensates).

Even for the highest ^{222}Rn concentrations in NG, no external radiation at the outside of transmission lines can be measured. Only in exceptional cases enhanced radiation levels have been measured in the (associated) gas cap/top of crude oil storage tanks. These radiation levels quickly disappeared upon venting. Upon uncontrolled release of NG, any hazards related to ^{222}Rn exposure will be superseded by suffocation or explosion hazards.

1.7 NOR oil and gas industry – liquid waste streams

NOR activity concentrations can vary substantially from one facility to another depending on geological formation and operational conditions and may also change over the lifetime of a single well. The activity concentrations in separated produced water streams are routinely many orders of magnitude lower than the concentrations later encountered at a point of accumulative deposition (Table 3 vs. Table 4).

	NOR	Bq[NOR]/L PW]
^{232}Th series	**^{232}Th**	0.0003 < > 0.001
	^{228}Ra$_{eq}$	0.3 < > 180
	^{228}Th$_{eq}$	0.5 < > 40
^{238}U series	**^{238}U$_{eq}$**	0.000 3 < > 0.1
	^{226}Ra$_{eq}$	0.002 < > 1,200
	^{210}Pb$_{eq}$	0.05 < > 190

Table 3: NOR activity concentration range reported for produced water

In recent years, there has been heightened interest in NOR activity concentrations in produced water from onshore oil and gas production associated with 'unconventional' reservoirs developed using hydraulic fracturing. As the conditions that will lead to their accumulation are fundamentally the same as for conventional wells, it is expected that NOR activity concentrations will follow Th and U activity concentration trends in the source rocks from which the connate water is extracted. So, on average NOR activity concentrations in unconventional produced water may be a factor of about 1.5 higher (ratio of Th and U contents in shale and sandstone) than in conventional produced water (Table 1). Up until now, the reported concentrations ranges [9,10,11,12,13,14] still are within the previously reported ranges for conventional wells.

In line with the scheme's presented in Figure 3, both ^{232}Th and ^{238}U$_{eq}$ concentrations are low. Any ^{228}Th generated in connate water will reabsorb onto reservoir material grains quickly. Consequently, ^{228}Th will not be present in produced water so that the analysed ^{228}Th$_{eq}$ contents very much depends on the time elapsed between sampling and sample measurement. Furthermore, analysis results of unconventional produced waters very much depends on the time elapsed from starting flowback operations. Initially (the first weeks) the hydraulic fracturing water will return (flow back water with low in NOR activity concentrations) and only after a while hydraulic fracturing water mixed with connate water will be produced. In the literature, often this distinction is not made and all water appearing at the surface is called produced water. If the concentration of dissolved ions rises[15], the main stream is returning hydraulic fracturing or flow back water, once the concentration starts to level off, a substantial contribution of connate water will be present. In line with the schemes presented in Figure 3, ^{228}Ra$_{eq}$, ^{226}Ra$_{eq}$ and ^{210}Pb$_{eq}$ concentrations may be quite substantial.

1.8 NOR in oil and gas industry – solid waste streams

Under certain conditions, NOR can become deposited or accumulated inside production or treatment installations as scale or sludge thereby making these otherwise routine oilfield by-products and waste materials radioactive (NORM). It is important to stress that NOR occur as impurities within bulk materials and mineral lattices. As Ra (^{226}Ra and ^{228}Ra) is chemically similar to Ba, Sr, Ca and Mg, the use of scale inhibitors plays a key role in the reduction of NORM.

Changes in operating conditions that can lead to NORM accumulation include:

- temperature and pressure variations
- varying flow (transition between laminar and turbulent)
- gas expansion due to a pipeline diameter change
- pH variation (increase in sulphate concentration due to injection of fluids rich in sulphates, or mixture of different produced waters)
- presence of seed crystals on the inner surface of the equipment and rough surfaces, (for example, in sour gas wells, the presence of NORM scale is enhanced by the presence of gypsum).

	NOR	Bq[NOR]/g[scale]	Bq[NOR]/g[deposit]
^{232}Th series	**^{232}Th**	0.001 < > 0.002	0.001 - 0.07
	^{228}Ra$_{eq}$	0.05 < > 2800	0.05 - 300
^{238}U series	**^{238}U$_{eq}$**	0.001 < > 0.5	0.001 - 0.05
	^{226}Ra$_{eq}$	0.1 < > 15,000	0.8 - 400
	^{210}Pb$_{eq}$	0.02 < > 75	0.05 < >2000

Table 4: NOR activity concentration range reported for scale and deposits

The main types of scale encountered in the oil and gas facilities are sulphate scale such as $BaSO_4$, and carbonate scale such as $CaCO_3$. Ra is chemically similar to Ba and Ca and co-precipitates forming incorporated trace impurities within the bulk mineral matrices[16].

There are a number ways in which normal oil field operations can induce scaling, some of which may contain NORM (Figure 4). For example, the mixing of seawater, which is rich in sulfate, with formation water, which is rich in brine, increases the scaling tendency. The sudden change in pressure and temperature or even acidity of the formation water, as it is brought to the surface, contributes to scale build-up.

The build-up of scale on the interior of a pipe is shown in Figure 3. This phenomenon has implications for the production of oil and gas; in this case, the capacity of the pipe to transfer oil and gas would be reduced significantly. Scales are rarely homogeneous and so the abundance of NOR contaminants will vary.

Figure 5 shows an autoradiograph of a scale sample, where the NORs activity occurs in variable bands.

Table 4 compares the NOR activity concentrations reported for hard sulphate/carbonate scales and softer deposits.

Very thin films of ^{210}Pb may be observed in the inner surfaces of gas transmission lines, linked to the presence of relative high ^{222}Rn concentrations in NG and prolonged exploitation of the lines.

Figure 4: Scale build up within a pipe (8 μSv/h dose rate at pipe exterior). Picture courtesy of ExxonMobil

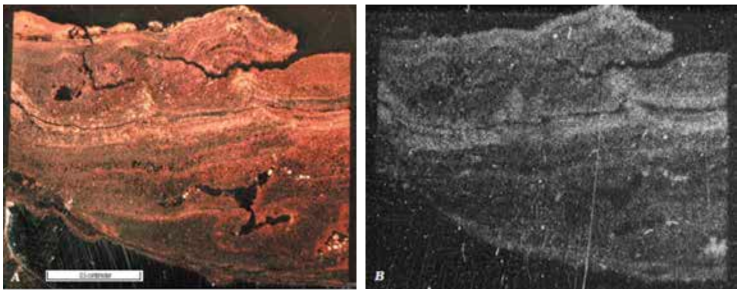


Figure 5: Radioactive scale deposits inside oil-field pipe (A) and the distribution of alpha-particle emitting radium and radium decay products in the same sample (B)[16]

1.9 NOR in oil and gas industry – sludge and scrapings

Sludge and scrapings may also contain NORs occurring within oil-wet fine mineral grains of sulfates and carbonates that have their origin in the same processes that lead to hard scales. Other NORs such as $^{210}Pb_{eq}$ may also be found in pipeline scrapings as well as sludge accumulating in tank bottoms, gas/oil separators, dehydration vessels, NGL storage tanks and in waste pits as well as in crude oil pipeline scrapings or pigging debris.

Some gas fields may produce Pb-compounds or even almost pure Pb contaminated with $^{210}Pb_{eq}$ (up to 1,000 Bq/g)[17,18,19,20]. The fingerprint of stable Pb-isotopes forming this kind of deposits is very typical for gas/oil fields.

Table 5 shows NOR activity concentration as reported for sludge and scrapings[6].

Alongside NORM contamination and the heavy hydrocarbons within which it is co-mingled, there are frequently elevated levels of other pollutants e.g. mercury (Hg), which has an associated environmental and health risks of its own. The issues related to NORM management should therefore not be considered in isolation, but take in to account all of the components present.

	NOR	Bq[NOR]/g[sludge]	Bq[NOR]/g[scrapings]
^{232}Th series	^{232}Th	0.002 < > 0.01	n.r.
	$^{228}Ra_{eq}$	0.5 < > 50	0.01 < > 10
	$^{228}Th_{eq}$	n.r.	n.r.
^{238}U series	$^{238}U_{eq}$	0.005 < > 0.01	n.r.
	$^{226}Ra_{eq}$	0.05 < > 800	0.01 < > 75
	$^{210}Pb_{eq}$	0.01 < > 1,300	0.05 < > 50
n.r. = not reported.			

Table 5: NOR activity concentration range reported for scale and deposits

Figure 6: Tank sludge

1.10 Discharge to the environment

As illustrated previously, NOR activity of produced water is typically very low. However, where large volumes of produced water are generated their potential cumulative impact requires consideration. For example, in the North Sea the oil industry accounts for around 7.6 TBq of α emissions and 5 TBq of β emissions (excluding tritium) annually[21]. To place this into context, the α emissions are forty times those reported by the nuclear energy sector and their overall impact remains a topic of ongoing discussion.

Produced water discharged to the sea will rapidly dilute substantially reducing the activity of the overall water body[22 23] and to date, research has found no evidence of increased accumulation of ^{226}Ra in marine organisms of the North Sea due to produced water inputs[24]. Attempts to measure the potential of radium in water and sediments to induce genetic effects in macro and meso fauna have proven inconclusive[25] [26]. With multiple sources of radionuclides entering the food chain via fish and seafood, the potential impacts to human-health also remain a topic of interest. Improvements in scale control and the greater use of water-flood technologies to improve oil recovery factors during tertiary reservoir development may further increase the relative total amount of NOR discharged. However, the increased risk to the environment that this potentially represents should be combined with a reduction in other probabilities such as the reduced exposure to oilfield workers cleaning NOR contaminated equipment[27].

In recent years, there has also been increased interest in the fate of NOR derived from onshore oil and gas operations and in particular from hydraulic fracturing for unconventional gas and oil. Here, the volumes of water may be orders of magnitude more than for conventional reservoirs and the hydrocarbon bearing rock types different. Shales, for example, frequently contain a higher abundance of both uranium and thorium. Flow back waters from unconventional wells can have very high levels of salinity and this is frequently correlated with elevated levels of NOR[28]. Here, there is some evidence to suggest that the abundance of radionuclides in the flow back water is not steady-state, with the early water showing the most elevated levels (Figure 7). Further studies based on the unconventional reservoirs of Pennsylvania (USA) have concluded that there is little or limited potential for radiation exposure to workers and the public from the development, completion, production, transmission, processing, storage, and end use of natural gas from these gas fields provided adequate controls are in place to manage fluids if spilled[29].

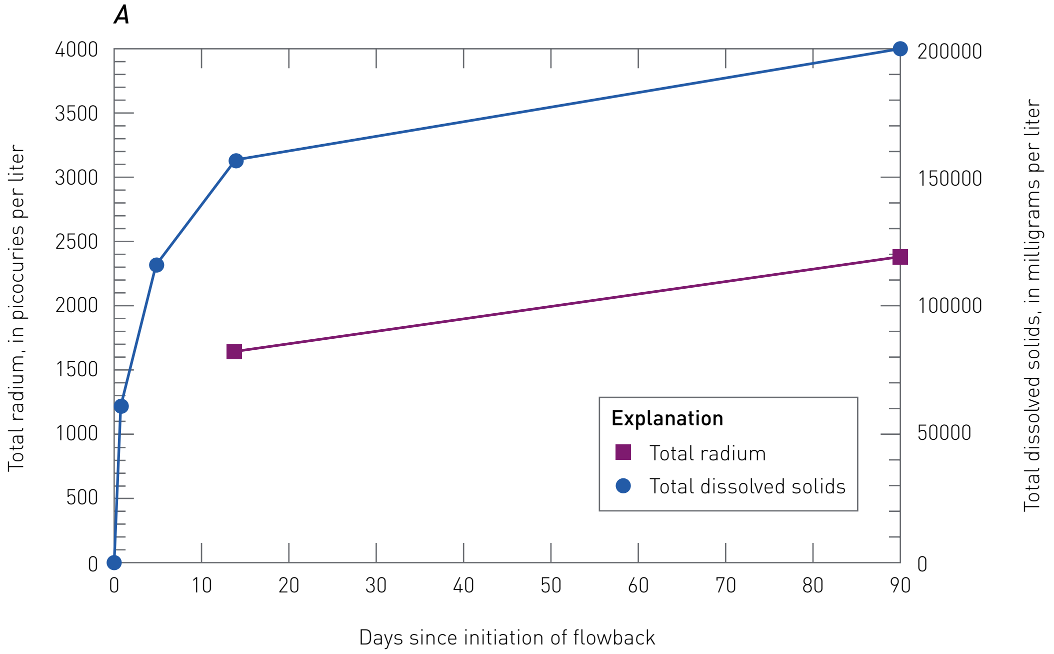


Figure 7: Time dependency of NOR in flowback waters from an unconventional gas well, Washington USA

2. Health hazards of NORM

The SI unit for absorbed (energy) dose is the Gray (Gy). One Gray equals 1 J/kg.

The health effects of NORM are a function of the energy transmitted to the body as the α, β or γ radiation dissipates excess energy into living cells, which may result in cellular damage and genetic mutation.

In the present framework of radiation protection[30] [31], effects originated by exposure of humans to radiation are grouped in:

- *deterministic effects* (harmful tissue reactions) due in large part to the killing/ malfunction of cells and in some instances large quantities resulting in organ damage following high doses
- *stochastic effects*, i.e. cancer and heritable effects involving either cancer development in exposed individuals owing to mutation of somatic cells or heritable disease in their offspring owing to mutation of reproductive (germ) cells. This is usually associated with long-term, low-level exposure.

Deterministic effects occur at doses exceeding 0.5 – 1 Gy. These thresholds vary with dose rate and with radiation quality. The severity of the effect increases with increasing dose and dose rate. Deterministic effects are mainly associated with incident scenarios in nuclear industry, industrial and medical use of high activity sources and X-ray generators and particle accelerators.

Even in worst case scenarios involving NORM in the oil industry, deterministic effects are never encountered. This is due to the relatively low abundances actually experienced and the tendency for many NORM to self-absorb, whereby the bulk mineral matrix and other surrounding material absorb the energy from underlying decays.

Radiation protection in the field of NORM concerns exclusively an adequate control of exposure to low doses, a situation where only stochastic effects may occur. Here, the absorbed energy alone is insufficient to determine the risk and this must take into consideration how much biological damage is expected from the absorbed dose. Different types of radiation have different damaging properties and different tissues have variable susceptibility to damage. Taking these factors into consideration provides us with the effective dose (section 2.2).

The present model of radiological protection is mainly based on the following evidence and assumptions:

- Exposure to ionizing radiation, even at low doses, can cause damage to the nuclear (genetic) material in cells that can result in the development of radiation induced cancer many years later (somatic effects), heritable disease in future generations and some developmental effects under certain conditions.

- Induction of cancer by low-linear energy transfer radiation has been firmly demonstrated in the dose range of about 100 mGy and higher, and it was concluded by UNSCEAR that "studies on DNA repair and the cellular/molecular processes of radiation tumorigenesis provide no good reason to assume that there will be a low-dose threshold for the induction of tumors in general"[32].
- Radiation-induced heritable disease has not been demonstrated in human populations but there is substantial evidence from animal studies of heritable damage to germ cells (ova and spermatozoa as well as their precursor cells)
- For both radiation-induced cancer and heritable disease it is the probability of the occurrence of the effect, not its severity, that depends upon the dose
- The general risk model for radiological protection is that the risk of these stochastic effects increases linearly with dose, without a threshold dose (a.k.a. linear no-threshold or LNT model).

2.1 Sources of exposure

There are two ways in which personnel can be exposed to radiation emitted by radioactive material, including NORM. Irradiation from external sources and contamination from inhaled and ingested sources (see Figure 8).

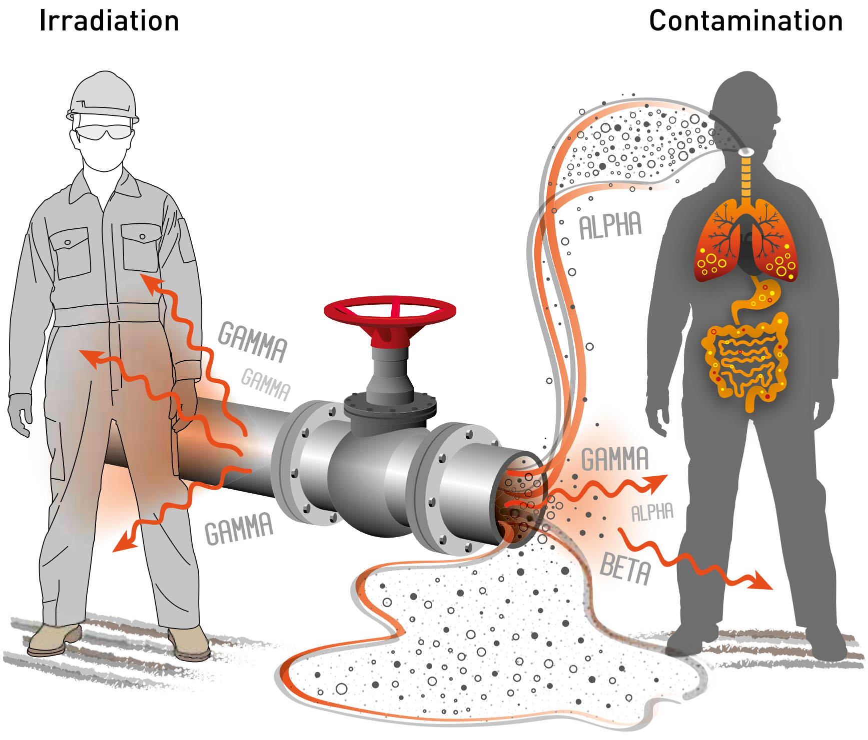


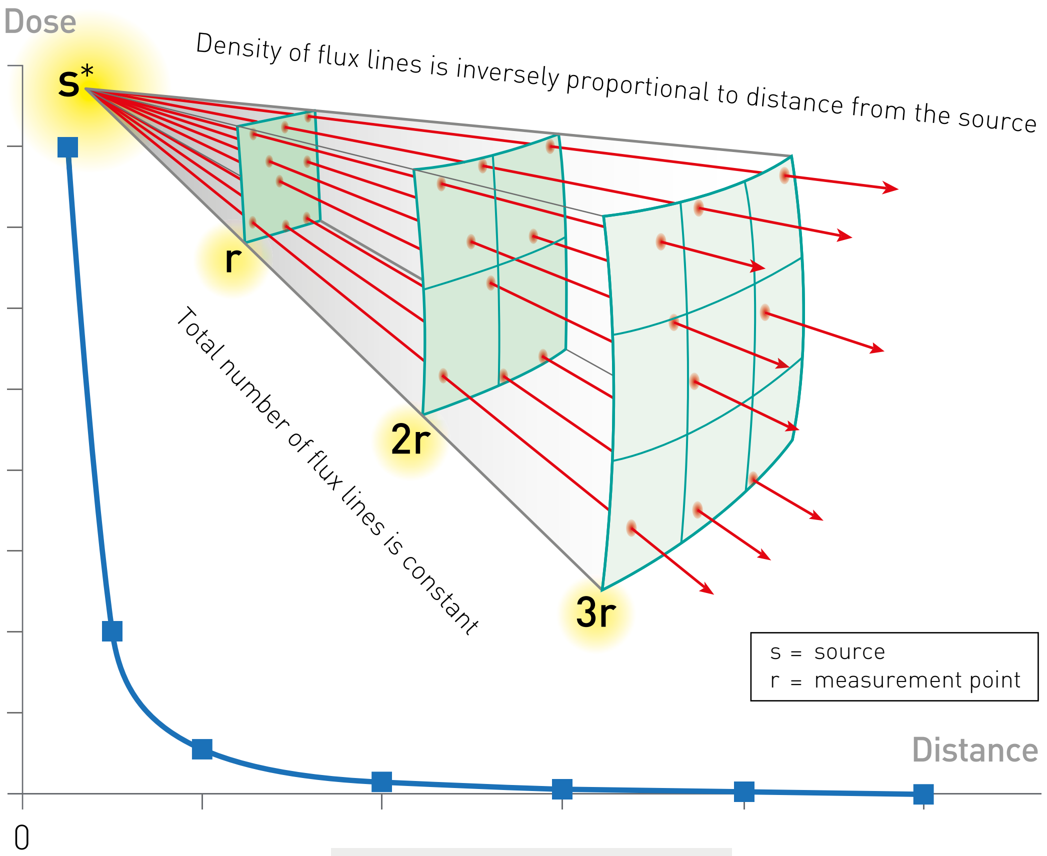
Figure 8: Exposure to NORM from internal and external sources

Irradiation from **external sources** occurs when the material emitting radiation is located outside the human body. Irradiation from **internal sources** occurs when the material emitting radiation is located inside the human body. Internal contamination can occur mainly due to inhalation or ingestion of material containing radionuclides such as dust particles.

Irradiation from external sources occur in the proximity of the source and decreases with distance, dropping to effectively 'zero' at a sufficient distance. In the case of NORM, this is usually a few metres from contaminated equipment and will follow the 'inverse square law' whereby intensity is inversely proportional to the square of the distance from the source (Figure 9). Absolute exposure at one metre will be four times greater than exposure at two metres. However, such models assume a single point-source for the radiation whereas, in real-life, NORM may be encountered over a large area. This has direct bearing upon the size of the controlled area around a NORM contaminated site (section 7).

Internal sources lead to irradiation of tissues and organs and persist after the introduction of radionuclides in the body. Reduction of irradiation depends mainly from the intrinsic propriety of the radionuclide (half life time) and excretion rate (depending of chemical composition of the contaminant). Control of dust and protection from inhalation during the handling of NORM is therefore one of the principal mechanisms by which exposure can be limited.

For a point source, absolute exposure at one metre will be four times greater than exposure at two metres. However, point sources are rarely encountered under operational conditions where NORM generally accumulates across an area.



$$\text{Intensity} \propto \frac{1}{\text{Distance}^2}$$

* This is a simplified model assuming a point-source of radiation. NORM contamination is usually found across a large area.

Figure 9: The effects of the inverse square law on exposure

2.2 Effective dose

The unit for the effective dose is the same as for absorbed dose, J/kg, and its special name is sievert (Sv). Sieverts are frequently expressed per unit time such as per hour (Sv/hr) or per year (Sv/a)

The quantity used to express radiological risk associated with stochastic effects is the 'effective dose'. Effective dose E is defined as:

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}}$$

where

w_{T} = tissue weighting factor - accounts for the susceptibility to damage different tissues

w_{R} = radiation weighting factor - accounts for damaging properties of different types of radiation

$D_{\mathrm{T,R}}$ = average adsorbed dose by the tissue T due to the radiation R and in expressed in terms of J/kg (or *gray* (Gy))

Effective dose is of particular importance in radiation protection since:

- it applies to all kind of radiation exposition (X-rays, γ-rays, electron, α, etc.)
- legal limits and 'attention levels' are usually expressed in terms of effective dose
- radiation protection for a generic exposure scenario or a specific task is essentially connected to the corresponding effective dose.

Clearly, both the type of radiation and type of exposure play a role in determining effective dose, with α particles representing a greater dose equivalent than β particles and γ-rays and where exposure to the colon or lungs resulting in a greater effective dose than exposure to the skin (where the dead cells of the outer skin absorb some of the radiation). For full details of weighting factors, refer to Appendix C (effective dose weighting levels).

However, the effective dose cannot be directly measured. It is necessary to use methods and quantities that enable an estimation of the effective dose conservatively. These methods differ primarily in relation doses resulting from external or internal sources.

As clinical symptoms have not been verified at doses lower than 100 mSv, there is no universal medical surveillance programme for expected low-level doses contracted by NORM work activities. Once NORM management practices are implemented, only in rare cases oil and gas industry workers may receive doses exceeding 1 mSv/year. For appropriate control generally a pre-defined action level is set in a NORM management system, so that dose can be kept as low as reasonably practical (ALARP) and the root cause for exceeding the action level may be investigated.

3. NORM management cycle

Where management of NORM is expected to form part of oil and gas production operations, a management plan is required to monitor and control the risk in an appropriate and proportional manner complying with relevant national and international legislation.

An indicative cycle is detailed in Figure 10. The flowchart is generic and requires many tasks, documents and support systems to enable it to function effectively. The remainder of this report works through this cycle.

The process begins with the need to routinely monitor and test for the presence of NORM. NORM cannot be directly observed, it has to be measured. This is not always easy and must therefore be factored in to operational cycles and maintenance schedules. NORM accumulation may occur in equipment that is frequently inaccessible. Surfaces may be irregular, making conventional instrumentation hard to use. Self-absorbance can mask the true abundance of NORM or it might be co-mingled with other wastes and hazardous materials. The selection of instrumentation will affect the ability to detect NORM of different types and in different circumstances. The monitoring plan must therefore be appropriate for the setting and refreshed regularly, especially when other changes are made to an operation (such as new drilling).

A strategy for NORM management is essential. Key areas to be considered are detailed in sections 4 to 12.

It is important that NORM management is planned and carried out with consideration of consultation and engagement of stakeholders. Specifically, the approval of the regulatory authorities may be required. Given the contentious nature of radioactivity and radioactive material, and the high degree of technical knowledge that is sometimes required, it may be necessary to engage independent specialized contractors within the monitoring plan.

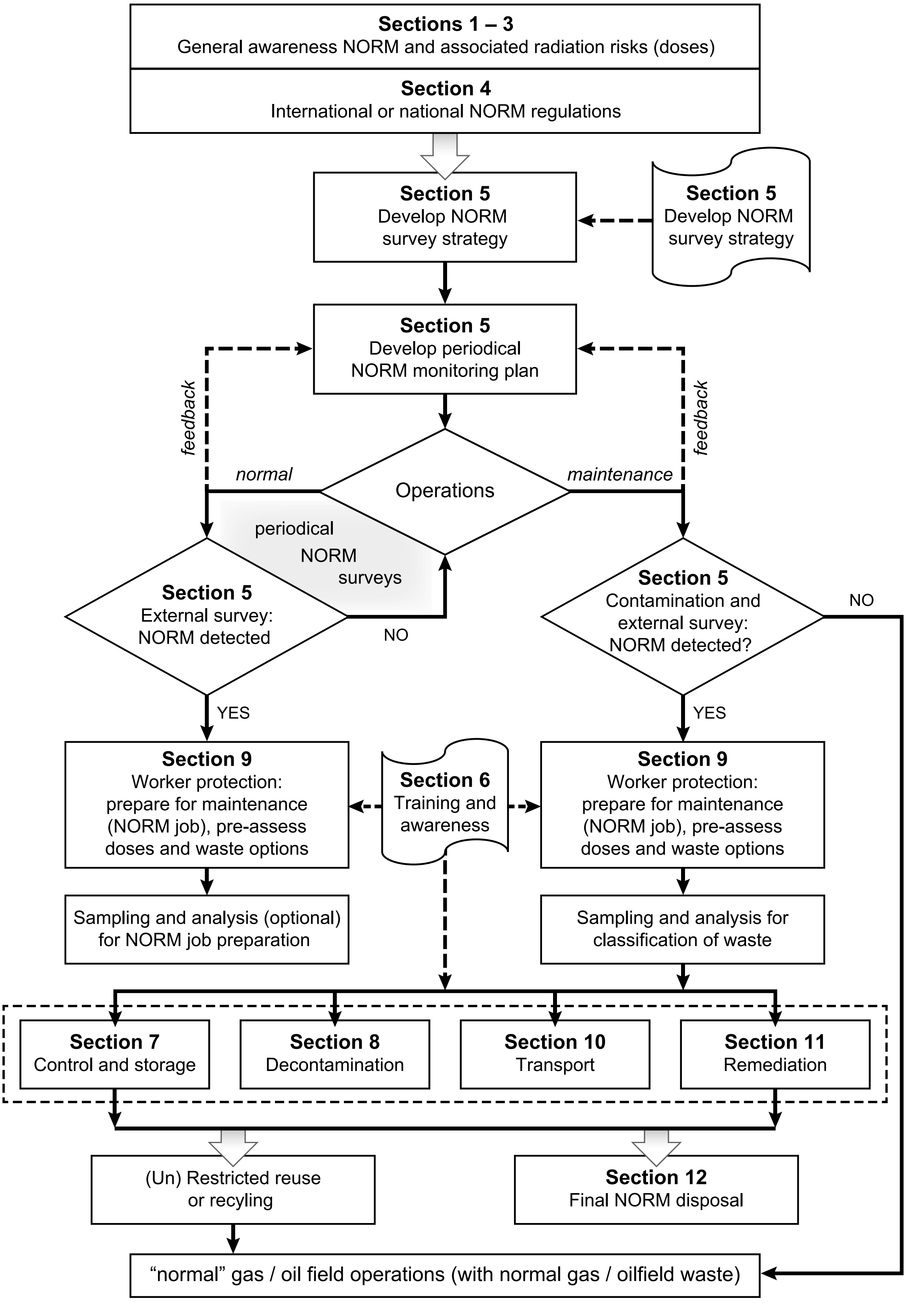


Figure 10: NORM management cycle

4. NORM Regulations

NORM regulations vary between countries. This section is intended as general guidance. It is important that any specific plans reflect the location of the NORM (e.g. spots in operational installations, where NORM may preferably deposit) and all applicable national and international regulations or laws.

In 2007, the International Commission on Radiological Protection (ICRP) recommended a public dose (risk) limit of 1 mSv/a additional to the natural background dose (~2.4 mSv/year). Ordinary gas and oil industry workers are treated as a member of the public with a limited exposure time (2,000 h/year). These recommendations have been implemented in the International Atomic Energy Agency (IAEA) Basic Safety Standards (BSS),[33] which in their turn have largely been harmonized with legislation issued by the European Union (EU).[34] The IAEA BSS treat "the mining and processing of raw materials that involve exposure due to radioactive material", including the oil and gas industry, as a practice in a planned exposure situation, the EU include the oil and gas industry in a "list of 16 distinct industrial sectors involving NORM."

In the latest draft for consultation, the ICRP stated that "sources of natural radiation (e.g. NORM) can legitimately be excluded completely from the scope of their recommendations once the activity concentration of each NOR is below 1 Bq[NOR]/g". This statement was implemented in the Basic Safety Standards of both the IAEA EU stating that "values for exemption or clearance for NORs in solid materials in secular equilibrium with their progeny" for members of the ^{232}Th- and ^{238}U-decay series will be 1 Bq[NOR]/g.

Consequently, a substance or material with a NOR-activity concentration exceeding 1 Bq/g, where the NOR should be a member of the ^{232}Th- or ^{238}U-decay series, may be defined as NORM .

Oil and gas production streams producing solid materials with lower activity concentrations than mentioned above will be out of scope. However, for somewhat higher activity concentrations the BSS provides a list of exempt activity concentrations (Table 6). These exempt activity concentrations have been computed on the basis of enveloping scenarios applying to practices involving small scale usage of the materials, where the quantities involved are at the most of the order of a tonne[35].

The BSS provides no general exempt concentrations for crude oil/water and natural gas. Where for production water in general its composition and salinity may be the determining factor, as a rule of thumb the values provided in Table 6 may be applied expressed in Bq/L for the aqueous phase. So, production waters with concentrations below 10 Bq[^{228}Ra]/L, 10 Bq[^{226}Ra]/L and/or 10 Bq[^{210}Pb]/L may be treated as exempt.

The IAEA and EU BSS stipulate a reference level of 1000 and 300 Bq[^{222}Rn]/Nm^3[air] respectively for potential exposure to radon in the workplace. These concentrations may possibly be reached when natural gas becomes mixed with ambient air, but in such a case explosion levels or suffocation will be the prevailing hazards.

It is advised always to check the NORM regulations with the competent authority, but in absence of such NORM regulations, the BSS activity concentrations for out of scope and exemption for moderate amounts may be applied as a best practice.

NOR in secular/transient equilibrium with (relevant NOR denoted as NOR$_{eq}$)		**Bq/g**
^{232}Th$_{nat}$	full natural decay series	
^{228}Ra$_{eq}$	^{228}Ac	10
^{228}Th$_{eq}$	^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po/^{208}Tl	1
^{238}U$_{nat}$	full natural decay series	
^{238}U$_{eq}$	^{234}Th, ^{234m}Pa, ^{234}U, ^{230}Th	10
^{226}Ra$_{eq}$	^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po	10
^{210}Pb$_{eq}$	^{210}Bi, ^{210}Po	10

Table 6: Exempt activity concentrations for moderate amounts of material without further consideration

5. NORM monitoring

The energy of ionizing radiation is measured in electronvolts (eV). One electronvolt is an extremely small amount of energy and so is most commonly encountered as multiple units kiloelectron (keV)

Various instruments are available for onsite monitoring of ionizing radiation or radioactive contamination including some developed specifically for use at oil and gas production and processing facilities. However, there is no single instrument capable of detecting all types of radiation (α, ß, γ) and energies of the particles (α, ß) or photons (γ) emitted by NORM. It is therefore important to carefully select and make instruments available that are appropriate and efficient for the NORM detection under operational and maintenance conditions.

The essential part of a radiation monitor is the detector, in which the ionization occurs due to the absorption stopping power of α/ß-particles or γ-photons. Detectors should be focusing on the characteristics of the radiation emitted by NORs encountered in the oil and gas industry. See Appendix D (Decay and radiation characteristics of ^{232}Th- and ^{238}U- decay series).

Under operational conditions, all α- and ß-particles will be absorbed by the wall of pipelines and other facilities, so that only γ-photons ("external radiation") may be detected. However, γ-photons until about 200 keV will also be mostly absorbed in a 1.5 cm thick steel wall. Only γ-photons with energies exceeding 200 keV may escape from an operational facility, so that deposits including the ^{228}Ra$_{eq}$ (via ^{228}Ac) and ^{226}Ra$_{eq}$ (via ^{214}Pb, ^{214}Bi) subseries (Appendix D) may be detected by dose rate meters (see 5.1.1 and 5.1.2) in an external NORM survey. If these deposits are aging, then radiation levels will increase not necessarily due to the build-up of more Ra-including deposits, but also due to the ingrowth of the ^{228}Th$_{eq}$ subseries (via ^{212}Pb, ^{212}Bi, ^{208}Tl;). It should be noted that ^{210}Pb deposits (excluding ^{226}Ra$_{eq}$) or internal contamination by ^{210}Pb cannot be detected by an external NORM survey as only low energy γ-photons are emitted.

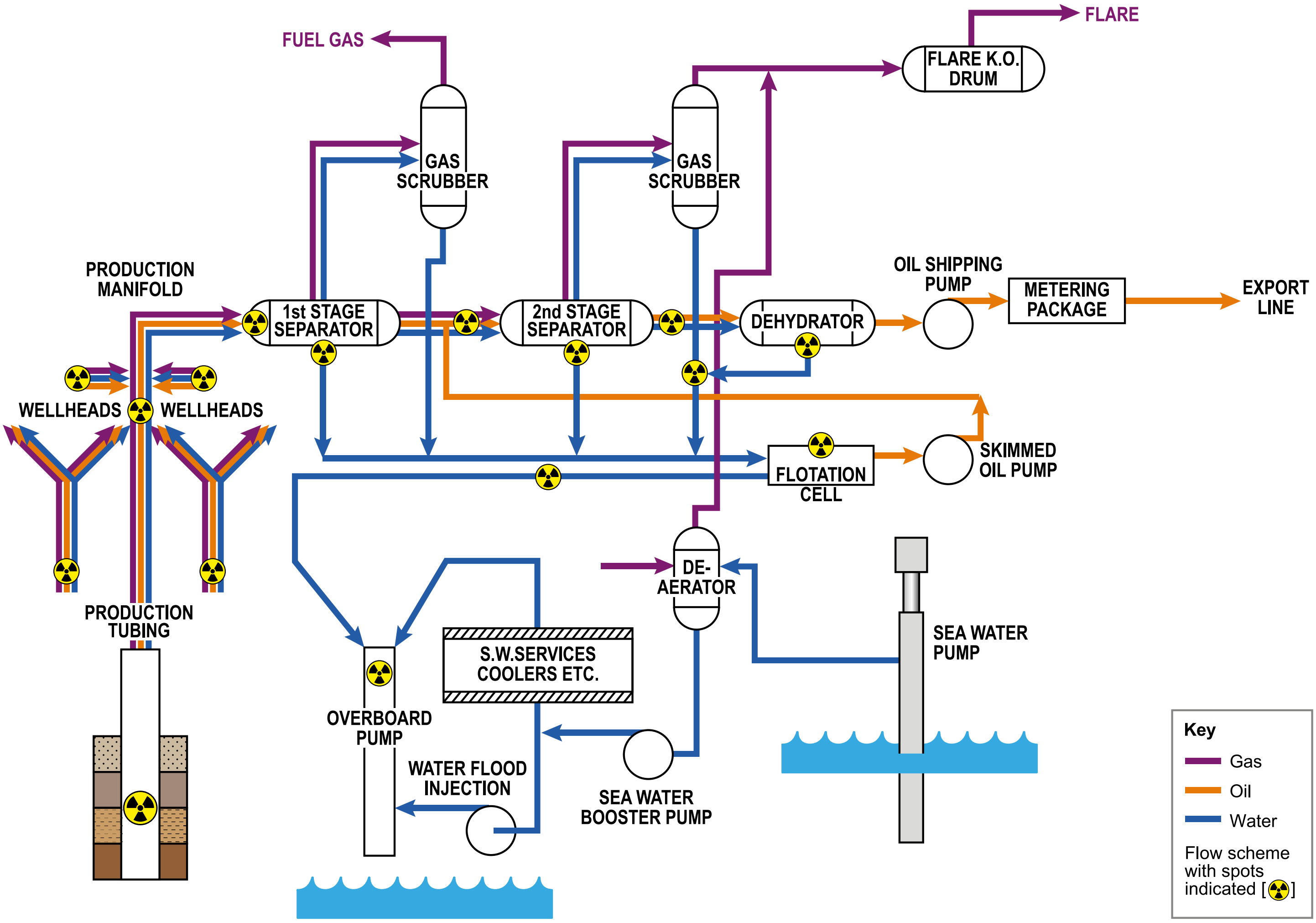


Figure 11: Schematic off-shore oil and gas production

To determine whether or not a facility is accumulating NORM, a NORM survey with likely subsequent sampling and analysis needs to be conducted. Figure 11 indicates a schematic offshore oil/gas production/treatment facility. Locations where NORM may potentially accumulate (e.g. near the perforation at wellheads as scale or inside gas/oil separators as sludge) are indicated by the radiation trefoil. This kind of knowledge in combination with any historical records of NORM build up should be exploited in any planned NORM survey.

The ultimate external radiation dose rate that may be detectable around the facility is dependent on many more variables additional to the ones already indicated. For instance, the amount and spatial distribution of NORM inside the installations. Consequently, it is impossible to convert a measured dose rate either into a real inner surface contamination or an activity concentration. Dose rates measured close to the circumference of the installations should be used to determine if there is NOR-contaminated scale or sludge present in the installations (in preparation of cleanout jobs), while dose rates measured at 1 m height and 1 m distance from the installation can be used for (operational) industry worker dose assessment purposes.

Under maintenance and/or sampling conditions, we may readily assume that all samples or surface contaminated objects stemming from the oil and gas industry are covered by a 50 µm (or thicker) oil/dirt film. Consequently, the detection of α-particles will not be possible as their range in oil is only 5 µm. ß-particles with energies below 200 keV will also mostly not be able to reach the detector probe as detectors probes may be close to, but should not be in contact with a sample. Higher energy ß-particles may be detected as their range in oil varies from about 1 mm (500 keV) to 5 mm (1 MeV). Virtually all γ-photons will be able to escape from such a sample. So, to determine if a sample or installation part is contaminated with NORs both ß- and γ-detectors may be used, where despite some absorption effects generally ß-detection is the more sensitive option.

In this case ,samples or installation parts including the $^{228}Ra_{eq}$ (via ^{228}Ac[ß/γ]) and $^{226}Ra_{eq}$ (via ^{214}Pb[ß/γ], ^{214}Bi[ß/γ]) subseries, but also the $^{210}Pb_{eq}$ (via ^{210}Bi[ß]) subseries may be detected by surface contamination monitors (Appendix D and 5.2.3). Aging sample or surface contamination will also be detectable via the $^{228}Th_{eq}$ subseries (via ^{212}Pb[γ], ^{212}Bi[ß/γ], ^{208}Tl[ß/γ]).

5.1 Radiation monitoring instruments

Four distinct types of radiation monitors may be distinguished:

1) **Dose rate meters** – measures potential external exposure, reads in µSv/h (or µGy/h). See 5.1.1.
2) **Dosimeters** – indicates cumulative external exposure, reads in µSv (or mSv) per exposure period. See 5.1.2.
3) **Surface contamination meters** – measures the amount of radioactive material distributed over a surface, reads in counts per second (c/s or cps) or per minute (c/min or cpm). See 5.1.3.
4) **Airborne contamination meters and gas monitors** – measures (indirectly) airborne particulate NORM or radon concentration in air; indicates potential internal exposure. See 5.1.4.

Several types of detectors are available: ionization chambers (gas filled, response proportional to ß/γ-energy absorbed), proportional counters (gas filled, response proportional to ß/γ-energy absorbed), Geiger-Müller (GM) counters (gas-filled count rate relates to radiation fluence, independent of energy absorbed), scintillation counters (extremely sensitive to γ-photons, though there are ß-scintillators on the market as well), solid state counters (high resolution γ-spectrometer).

5.1.1 Dose rate meters

The response of any dose rate meter is dependent on the characteristics of the detector it contains and in particular its detection efficiency at energies of the radiation to which it is exposed. An instrument may have good detection efficiency over a range of radiation energies, reducing to (nearly) zero efficiency at the detection range extremes. If the detection efficiency is poor, the instrument will indicate zero readings whatever actual dose rates those radiations may be producing. For example, an instrument that provides an accurate indication of dose rates due to ^{214}Bi γ-photons (E_γ = 609 keV) may be insensitive to dose rates due to ^{210}Pb γ-photons (E_γ = 47 keV).

A suitable and efficient dose rate meter is matched to the specific task and capable of measuring external exposure directly. Dose rates in the μSv/h range may be measured near NORM accumulations inside facilities (e.g. bottom of first stage separator). Instruments with sensitive probes capable of measuring low dose rate γ-radiation (*cf.* background dose rate at sea level are about 0.05 μSv/h) may be used to monitor the outside of operational installations to detect enhanced dose rates that would indicate that NOR-contaminated scale or sludge builds up inside.

Many dose rate meters are based on GM-detectors of the energy compensated type; where sensitivity/energy characteristic of the GM tube matches more or less the absorption/energy characteristics. Dose rate meters with a scintillation crystal are much more sensitive to γ-photon detection than the gas-filled GM-detector. Such dose rate meters are becoming increasingly available. Sensitive solid state detectors that combine both dose rate measuring capability and γ-spectrometry may be used by radiation protection experts. However, as these dose rate meters generally will be used in explosive or flammable atmospheres, it is essential that they are intrinsically safe, or explosion proof or that procedures be put in place to ensure that a flammable atmosphere is not present during the use of the instrument.

5.1.2 Dosimeters

There are different types of dosimeters for individual monitoring generally designed to be clipped to coveralls or be worn at the belt, that register the total dose accumulated over the period of exposure. Nowadays new models of dosimeter are also capable of measuring dose rates and data logging, where data logging in combination with the work carried out may be very useful for analysis of actual exposure situations. These direct reading electronic personal dosimeters (EPD's) also provide alarm setting indicating a high dose or dose rate in the event of unnoticed exposure.

EPDs are so-called 'active' detectors that should be intrinsically safe and are mainly equipped with GM-tube, though solid-state equipped detectors are now available. It should be realized that many competent authorities only accept the readings of a 'passive' thermo-luminescent dosimeter (TLD) as an official dose record, whereas those registered by EPD's may be used for in-company optimization.

5.1.3 Surface contamination monitors

Surface contamination monitors usually are designed to measure specific types of radiation and often have optimum detection efficiency over a limited range of radiation energies. For example the detector may respond only to γ-photons or β/γ radiation. It may also perform better in detecting high energy β- particles rather than those of low energy; or it may be designed to detect low energy γ-photons but not high energy. In this sense, currently instruments are being marketed that have been optimized to detect NOR-contamination. Most surface contamination monitors need to be calibrated for the type and energy of the radiation (e.g. a single radionuclide) to be detected, before the reading can be converted into meaningful units (Bq/cm^2). As NORM is always constituted from a suit of NORs appearing in different proportions, it is impossible to convert the acquire readings into accurate Bq/cm^2, so in general the reading will be in counts per time interval, where for a β/γ sensitive contamination monitor the count may be caused by β-particle or γ-photon absorption.

Surface contamination monitors generally incorporate a gas-filled β-detector with thin, vulnerable windows. There are monitors available with more sensitive plastic β-scintillators that dependent on the thickness of the scintillator and may be sensitive to γ-photons. β-contamination monitors only may be used for NORM detection after sampling or once access is provided to internal surfaces of the facility. At best, a β-contamination measurement provides a reliable indication of the need for radiation protection measures. Hereto often a two to three times the natural background counts per second (cps) criterion is applied as a discrimination level to indicate if the surface of an object is contaminated with NORs. A similar criterion may be used for 'representative' samples, but often the competent authority requires γ-spectrometric analysis by a certified laboratory to identify and quantify the NORs present in order to check against regulatory limits.

Occasionally, specially designed instruments are used in specific circumstances to monitor surface NOR-contamination; a cylindrically shaped β-detector may be drawn through flow lines. γ- radiation detectors (either sensitive dose rate meters or contamination meters) may also be used to detect NORM accumulations within facilities. As all surface contamination monitors are 'active' detectors, they should be intrinsically safe or procedures should be put in place to ensure that a flammable atmosphere is not present during the use of the instrument.

5.1.4 Contamination monitors for airborne radioactivity

Instruments for measuring airborne contamination need specialist assessment and consequently are rarely used in the oil and gas industry. These instruments normally draw potentially contaminated air (e.g. dusty scale removal treatments) at a constant rate through a filter mainly to monitor airborne α-emitters, including radon progeny. Personal air samplers based on the use of a filter may also serve as personal (inhalation) dosimeters, but the filter needs to be assessed by an external laboratory, where the results only provide a retrospective assessment of the working conditions.

Samples of natural gas may be taken and measured to determine the ^{222}Rn concentration in natural gas using the Lucas cell method. A Lucas cell is internally coated with an α-scintillator ($^{222}Rn_{eq}$ emits three α-particles, notably by ^{222}Rn, ^{218}Po and ^{214}Po decay, Appendix D) and is light tight connected to a photomultiplier tube. Once the cell/photomultiplier tube is well calibrated, such analyses can easily be performed by production laboratories.

5.1.5 Monitoring in practice

Under normal operational conditions

An explosion-proof or intrinsically safe dose rate meter (µSv/h; see 5.1.1) should be applied for monitoring the external dose rate around (potentially) contaminated installation parts. Nowadays, such dose rate meters can also be used as EPD (µSv/job; see 5.1.2). Applications and/or measurement conditions are, for example:

> **job preparedness:** measure dose rate at the outer circumference of operating installations. If measured dose rate exceeds twice the background dose rate due to the natural radiation environment, then the inside of the monitored installation part is contaminated with NORs and any job to be carried out inside this installation should be classified as NORM work. NOTE: $^{210}Pb_{eq}$ cannot be measured in this way and where PB is anticipated, measurements should be taken internally with a detector sensitive to beta emissions prior to conducting work.

worker dose assessment: measure dose rate at 1 m distance from circumference of installation parts with NORM and at 1 m height – in combination with assessed residence times potential external dose of industry workers can be pre-assessed ('radiation risk assessment'); judging the outcome of the pre-assessment, it may be decided if the worker should wear a TLD badge during his/her job.

worker dose monitoring: during his/her work the operator may wear a TLD or EPD during all his/her work related occupations – after about one month his/her occupational dose associated with the job carried out can be derived (by subtracting the natural background dose). As many EPDs are equipped with logging options, these are excellently suited to analyse what the actual exposure causing steps of a particular job are, so that doses can be kept ALARP.

An explosion-proof or intrinsically safe surface contamination monitor (cps; see 5.1.3) may be applied for screening substances sampled from operating installations for the presence of NORs. Applications are (dried out) produced water spills, surfaces around/of pig receiver stations, spills around sampling points, etc. Here it should be noted that close to concrete structures slightly enhanced (background) values may be noted due to the potassium (including ^{40}K) contents of concrete.

Under maintenance and/or cleaning conditions

An explosion-proof or intrinsically safe dose rate meter (μSv/h; see 5.1.1) and surface contamination monitor (cps; see 5.1.3) should be applied for monitoring the external dose rate and contamination level inside installation parts. Applications and/or measurement conditions are

job preparedness: measure dose rate and contamination levels at the inner surfaces of operating installations. If measured dose rate exceeds twice the background dose rate due to the natural radiation environment samples should be taken and submitted for γ-spectrometric analysis for transportation and disposal classification. Based on the analysis results a radiation risk assessment should be carried out taking all potential exposure pathways (external, inhalation, ingestion, skin contamination) into account and a strategy should be developed for any material removed from the installation. If only surface contamination readings exceed the natural background, the worker will not be at risk, but a strategy should be determined should be developed for any installation parts or material removed from the installation.

worker dose assessment: based on measured dose rate inside installations and taking into account potential formation of airborne contaminated material, the dose for the job should be assessed beforehand. If the assessment indicates that the potentially contracted dose will be well below 1 mSv/year, the job may be carried out. If the assessment indicates that the potentially contracted dose will exceed 1 mSv, it may be necessary to hire a specialist NORM decontamination contractor PPEs prescribed for jobs in confined spaces will also protect the worker against any inhalation, ingestion or skin contamination dose.

worker dose measurement: Where a worker dose assessment indicates the likelihood fo exposure, the only dose component that cannot be circumvented is the external dose, which may be monitored by an intrinsically safe EPD and of course the authority prescribed TLD. As many EPDs are equipped with logging options, these are excellently suited to analyse what the actual exposure causing steps of a particular job are, so that doses for the next similar job can be minimized. It is advised to keep dose records (even if no doses are recorded) for the various types of jobs to be carried out.

6. Training and awareness

Training and awareness are major components of a NORM management system. Workers need to be made aware of:

- the hazards associated with NORM
- procedures to identify NORM (and the challenges herein)
- controls that are required for their personal protection
- methods for preventing environmental contamination
- local documentation requirements and how to escalate actions over uncontrolled risks or non-conformant operations.

Training should focus on operational personnel who are potentially exposed to NORM and directly involved in maintenance operations. However, basic awareness should also be given to all the personnel involved in the facility, even though they are not involved directly or have low immediate risk of being involved.

Basic training should be refreshed at regular intervals and whenever a significant change is encountered – such as the introduction of new equipment.

Key personnel should be identified and provided with training that will permit them to ensure that the work they do pays due regard to the NORM hazards and prevent spreading. Training should be tailored to the specific potential hazard associated with NORM to which the personnel is exposed to.

NORM training is readily available both as classroom and virtual learning. Some training leads to specific qualifications, which may be specified in local guidelines or legislation. Examples include 'Radiological Protection Advisor', 'Radiological Protection Supervisor' and 'Suitably Qualified Person' but there is no universal standard as to the content of training or capability.

7. Control of NORM sites

The following are basic control procedures that should be practised when operating in or around potentially NORM sites:

- Identify an appropriately trained and qualified person responsible for managing the risk and ensure that they operate within a wider NORM management system and control of work.
- Establish a boundary around the work area and post radiation warning signs (Figure 12). This should be proportional to the level of contamination and re-evaluated whenever the level of information specific to the location changes. The boundary should be as small as reasonably practical, but large enough to allow for personnel and equipment access from the work area and to allow for all work to be accomplished in a safe manner. An effective barrier defines the extent of the contaminated area and controls exposure to the regulatory limits for members of the public.

Figure 12: Boundary warning signs with the internationally recognized radiation 'tri-foil' sign

- Consider whether:
  - a) the pre-existing controls, which are usually directed at controlling chemical contamination, are sufficient to address the NORM issue,
  - b) the pre-existing controls need some minor improvements, or
  - c) the pre-existing controls need considerable improvement to properly address the NORM issue.
- Containers or plastic bags should be provided for discarded protective clothing and contaminated trash at the exit of the work area.
- Only essential personnel should be allowed in the NORM work areas. They should have appropriate training in keeping with local laws and suitable measures and record keeping established to track exposure dosage relative to pre-determine limits within a given period.
- Prior to maintenance of contaminated equipment or opening inspection hatches, sludge traps or pig receivers, sufficient ground cover should be placed below the item in the work area. The ground cover should be made of a plastic, waterproof type material capable of withstanding the work activities involved without tearing or ripping. Alternatively, a suitable drip-tray or catch-pan may be used. The ground cover should be sized to provide for the containment of leakage and waste and to allow ample room for related peripheral work.
- Hold a safety meeting for all personnel performing work. Radiological items which should be addressed during the meeting are, but are not limited to, protective clothing and respiratory protection requirements, radiation and contamination levels, maintenance activities which can cause radioactive material to become airborne, requirements for waste generated and action to be taken in the case of emergencies.
- Commence maintenance activity; any dry material that is NOR-contaminated should whenever practical be wetted down to prevent the generation of airborne radioactive materials. Dry material should be wetted periodically throughout the maintenance work.
- Openings of equipment or pipes that have internal NOR contamination should be sealed or wrapped by plastic or other suitable materials.

- Obsolete NOR-contaminated pipes or equipment should be clearly labelled as "NORM Contaminated Material" and removed to a designated area. The area should be labelled as "Caution Naturally Occurring Radioactive Materials" and restricted for the general public.
- All NORM waste generated during maintenance should be drummed or put into containers and marked or labelled. Representative samples should be collected from the waste and analysed for radioactivity.
- Upon completion of maintenance, personnel should remove their protective clothing should be assessed for contamination, if necessary washed-down and removed before leaving the work area.
- All material, equipment and tools not placed in containers or drummed should be surveyed for both loose contamination and exposure rate levels upon exit from the work area (Figure 13).

Figure 13: Drums of NORM contaminated oilfield waste. Picture courtesy of ExxonMobil

A reading greater than twice background levels is positive indication of contamination, and should be handled as such.

Upon job completion, the accessible areas of the work area should be surveyed for loose contamination. Any loose surface contamination found should be promptly cleaned up and drummed.

Once the work area has been verified free of loose surface contamination, the boundary and postings may be taken down.

8. NOR contaminated equipment

The following section describes the basics of control and management applicable to NOR contaminated that are small enough to be isolated, cleaned or disposed of. Examples include tubulars, valves, vessels, pipes or machinery

8.1 Control

Beyond management of the equipment *in situ* (as detailed in section 7) NORM contaminated equipment must be handled, transported, stored, maintained or disposed in a controlled manner proportional to their activity and compliant with local or international guidelines. Protocols are needed to ensure that equipment is not released or handled without controls to protect the worker and prevent contamination of the environment. Therefore, it is critical to understand and control how and where NOR materials can be transported. For example, drilling pipe that contains low-level NOR contaminated scale can be unrecognized and transported to a variety of secondary pipe reprocessing facilities with subsequent, inadvertent exposure and spread of NORM.

The following should be considered the minimum requirements for the control of NOR-contaminated equipment with activity above exemption thresholds.

Equipment should:

- be decontaminated prior to release for unrestricted use
- be stored only in designated storage areas
- be tagged or clearly marked as NOR contaminated.
- be handled only by employees trained in NORM hazards and is using PPE
- not be sent for maintenance/repair to workshops without informing the workshop that the component is contaminated with NORM.
- be disposed of only in an approved NORM disposal facility.
- be decontaminated only in an approved NORM decontamination facility or according to an approved decontamination protocol.
- open sections of equipment, i.e., flange or pipe ends, etc., should wherever possible be adequately covered by heavy-gauge UV-stabilized plastic or other suitable materials to ensure that NORM material does not leak from the item.
- routine checks on all stored NOR-contaminated equipment should be undertaken to ensure that the integrity of the protective measures is adequate.
- detailed and verifiable records should be maintained of all stored NOR contaminated equipment

Once verified as free from NOR contamination, the equipment may be re-used sent for repair/servicing in the normal manner or sold or disposed of as scrap.

A typical process for the control of NOR contaminated equipment is detailed in Figure 14.

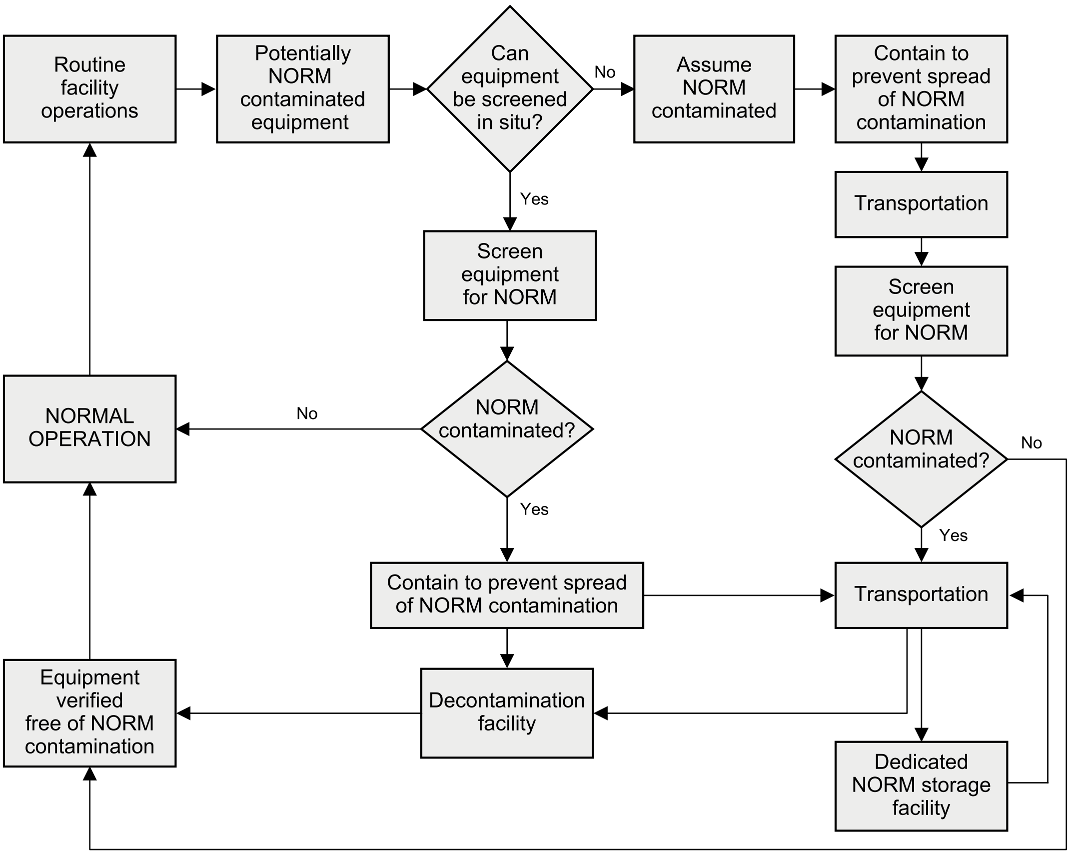


Figure 14: Control of NOR contaminated equipment

8.2 Local decontamination of equipment

Where regulations permit and other control measures have been established, it may be preferable to decontaminate equipment locally, either *in situ* or without transportation. This should be conducted only by adequately trained personnel.

Decontamination of equipment which is contaminated with NORM should be undertaken in a controlled manner to ensure worker protection, prevent the spread of NORM contamination, and to minimize the waste arising from the decontamination process. Simple mechanical/abrasive, i.e. high pressure water jetting (HPWJ) in conjunction with other mechanical/abrasive methods remain the most common techniques adopted but chemical cleaning solutions are increasingly available. All forms of decontamination have the potential to spread

NORM and in the case of abrasive cleaning increase the likelihood of NORM becoming airborne as dust. A full risk assessment is therefore required.

When such methods are used, considerations include:

- changing facilities for workers
- operating areas to carry out work
- handling/receiving areas
- strip down areas
- water jetting areas
- liquid re-circulation system
- ventilation system
- control of equipment (administration system)
- inspection of equipment
- monitoring of equipment
- safety related systems.

The decontamination plan should consider other hazards associated with the material including intrinsic hazards (shape, weight, etc.) and other forms of contaminant (hydrocarbons, heavy metals, etc.) Where possible, decontamination systems should be automated.

8.2.1 Operating areas

Main change room	This will allow access to the (supervised or controlled) NORM work areas where decontamination will take place.
Handling area	This will be for a) checking the inventory/material being sent for decontamination; b) carrying out radiation surveys of decontaminated equipment; c) providing a segregation system to keep incoming 'dirty' items separate for outgoing 'clean items'; d) a quarantine area for items that require further decontamination.
Strip down area	To allow the strip down of components such as valves, wellheads and other components.
Burning bay	For high levels of activity, to allow for oxy-propane cutting, grinding etc. of equipment this is an area where NORM may become airborne and therefore requires total containment with a ventilation system equipped with high efficiency particulate arrester (HEPA) or HEPA filter.

	Local extract ventilation (i.e. elephant trunks) will also be available in the area to control/remove airborne contaminated dust at source Workers will need to wear respiratory protective equipment (RPE) in this area; therefore the supply of breathing air for RPE is needed. The floor and surfaces should be of an impermeable non-flammable surface capable of withstanding heavy loads.
Water jetting area	This is a (supervised or controlled) NORM work area where NORM may become airborne and therefore requires total containment with a HEPA-filtered extract ventilation system. In this area, workers will be required to wear RPE in this area; therefore the supply of breathing air for RPE is required. The floor and surfaces should be of an impermeable non-flammable surface capable of withstanding heavy loads, and the impact of HPWJ
Liquid recirculation	All process liquid used in decontamination operations should be filtered and re-used. There should be no connection to any external drainage system. The following elements will be required in the system: The system needs to separate NORM-contaminated sediment and oily waste material from the process water. Water from the HPWJ area will be circulated back to the system by an enclosed and doubly contained drainage system. A leak detection system should be included in the water circulation system. The settling tank should be able to be readily accessible and able to have any sediment removed/decanted into waste containers. The system should have capacity to allow the transfer of water from the settling tank to another holding tank to allow sediment removal.

8.2.2 Control of works

- An administrative system is required to control and track the progress of all equipment and components entering the decontamination facility.
- Inspection of all equipment and components should be carried out on receipt. The status of the equipment should be logged and any damage not logged on the documentation should immediately be brought to the proponent's attention and the component should be quarantined pending further instruction from the proponent.
- Monitoring of equipment for clearance should only be carried out by trained operators.
- All monitoring equipment should be fully operational and within its calibration period. A check on the operational status of all radiological monitoring equipment should be maintained.
- An administrative system should be implemented to identify items which are NOR-contaminated from those that have been cleaned.

The acceptance criteria for successful decontamination should be:

a) All equipment must be visually clear of scale, sludge or other deposits (such as black powder).

b) All equipment must be free of detectable radioactive contamination, as per section 5 (i.e. less than double background).

9. Worker protection

The underlying principles of worker protection are derived from the properties of radiation which can be controlled through a combination of:

- ***shielding*: providing appropriate shielding (see 1.4)**
- ***distance*: increasing the separation of workers from the source (see 2.1)**
- ***time*: reducing the period of exposure reduces the dose (see 2.2).**

Under normal operating conditions, the greatest risk associated with NORM comes from workers operating in close proximity to NORM for extended periods such as during decontamination.

Workers entering confined spaces containing NORM (e.g. vessel tanks) or conducting intrusive work on NOR-contaminated equipment should adhere to the following guidance:

- Personnel required to work with NORM should be trained in the associated hazards and local procedures.
- An appropriate monitoring and cumulative dosage recording protocol should be established.
- All NORM operations should be covered by a safe system of work which should identify the hazards and highlight the precautions to be taken.
- Any item or area with detectable levels of loose NOR contamination should be subject to appropriate radiological controls.
- Appropriate PPE should be worn (which may include but not be restricted to):
    - 'Tyvek' style coveralls or chemical suits
    - Neoprene, PVC, nitrile or nitrile rubber (NBR) gloves
    - Respirators with HEPA cartridges
- Eating, drinking, smoking and chewing are not allowed in work areas where there is potential NORM.
- Only essential personnel should be allowed in the work areas where NORM is potentially present.
- Personnel should wash up thoroughly with copious quantities of soap and water, after working with contaminated equipment, and before eating, drinking, or smoking, and at the end of the workday.
- Use systems of work that minimize the generation of waste PPE.

9.1 Confined space entry

Personnel should adhere to applicable regulations and guidelines for confined space entry. In addition, before entering vessels/tanks or other confined spaces known or suspected to be NOR-contaminated, the workers' protection measures mentioned in the previous section should be implemented.

Furthermore, before entering tanks or vessels in gas plants, especially in propane and methane streams, vessels/tanks should be emptied and may need to be ventilated, through forced ventilation, for at least four hours prior to entry for cleaning or maintenance. Ventilation will force any trapped radon gas out of the vessel, while the delayed entry will allow adequate time for the decay of short-lived radon daughters (progeny). Radon is not the most significant hazard associated with confined space entry and all other loss prevention checks must also be completed. Radon does not present an acute hazard to health, and the requirement to vent the tank for four hours is a means of minimizing potential dose uptake and, as such, should be included as part of the full safety job risk assessment.

All personnel and equipment exiting a vessel should be subjected to a NORM contamination survey. Personnel or equipment found to be contaminated should be segregated and decontaminated.

10. Transport of NOR contaminated equipment (NORM)

Adequate precautions are needed for the safe and traceable transportation of NORM contaminated equipment and NORM wastes including scales, sludges and contaminated personal protection equipment (PPE) such as gloves and coveralls. This is to ensure that no NORM can contaminate either the transportation vehicle or route.

Transportation can include a wide variety of vehicles including shipping, road and rail and unlike many other hazardous materials trans-national shipping is possible either during the servicing of equipment and/or for disposal. Radioactive waste is not covered by the Basel convention which prohibits the international shipping of hazardous goods for the purpose of disposal.

The following guidance provides key principles of safe transportation, but are not a replacement for local laws and practises. Where regulations or codes are not in use by a country the IAEA Safety Standards Series 'Regulations for the Safe Transport of Radioactive Material' should be consulted.[36]

Depending on activity and quantity and local and international requirements, NORM under transportation may require labelling with an appropriate UN numbers. This is a four-digit numbers that identify hazardous substances, and articles (such as explosives, flammable liquids, toxic substances, etc.) in the framework of international transport. UN numbers are assigned by the United Nations Committee of Experts on the Transport of Dangerous Goods. They are published as part of their Recommendations on the Transport of Dangerous Goods, also known as the 'Orange Book'. These recommendations are adopted by the regulatory organization responsible for the different modes of transport. NOR materials fall predominately under 'class 7' e.g. UN 2912 (Low Specific Activity).

NORM must be packaged and prepared for shipping in order to comply with the latest transport regulations for the mode of transport being used, e.g. the International Maritime Dangerous Goods Code (IMDG Code) for sea freight. IMDG Code is intended to protect crew members and to prevent marine pollution in the safe transportation of hazardous materials by vessel. It is recommended to governments for adoption or for use as the basis for national regulations. The implementation of the Code is mandatory in conjunction with the obligations of the members of united nation government under the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL)

NOR contaminated equipment/items should first be wrapped/bagged to prevent the escape of NORM, labelled, then secured in a transport container. Where items are too large to be placed in a transport container, or it is impractical to do so such as a large oilfield 'Christmas tree', it may under certain circumstances be acceptable to ship these items as 'unpackaged' so long as there is no escape of material during transport.

NOR contaminated sand/scale/sludge must be packaged for transport in suitable drums or skips, with the end storage/disposal route often dictating which type are used. The specific activities present in the waste, along with the presence of any other hazards, will also influence the choice of container. The aim is always to ensure that there is no escape of material during transport, therefore checks should be made that seals are intact and lids fit correctly as shown in Figure 15.

Figure 15: NORM prepared for transportation.
Picture courtesy of ExxonMobil.

Before shipping NORM, consignors must ensure that staff are trained to understand the hazards, risks and requirements of the appropriate regulations/codes/safety standards. As a minimum, general awareness training should be provided to all personnel involved. However, this will also depend on the UN number and mode of transport being used. Training may also be needed for drivers, ship's Captains, etc. to ensure that contingency arrangements will be followed. A written contingency plan must be available, defining the actions to be taken in the event of an incident during the transport of NORM.

Labelling of NORM packages/equipment is the responsibility of the consignor and must take account of the latest IAEA standards and/or local Regulations. Where equipment is unpackaged shipping labels must still be attached to the item, its cradle, or its lifting device.

Some countries require vessels to be licensed to carry radioactive material, including NORM and consignors must always check to ensure they are complying with local requirements.

Transport documentation, e.g. dangerous goods transport documents, must be completed and signed by the consignor's representative, with the documents accompanying the shipment.

Notification/agreements to ship will be required by the receiving site, and consideration should also be given to other local requirements, e.g. 24 hour notification given to a harbour authority, shipping agent and/or crane company.

The following records must be kept by the consignor:

- description of items/waste being shipped
- no. of items/packages
- weight/volume
- identification of NORs, their activity concentrations and total activity
- transport route, destination and statement from the receiving site confirming that NORM will be accepted
- copy of all shipping paperwork
- any other relevant information, e.g. acceptance/disposal certificate

During transport, items/packages may require segregation from other types of cargo, e.g. photographic film, or other types of dangerous goods. Therefore, the relevant stowage and segregation tables must be consulted, this will usually be the responsibility of the carrier.

NORM waste is nearly always accumulated/shipped/disposed-of through a system of permits and licenses issued by the countries regulators. Exporting and importing of NORM may also be acceptable in some countries, but only with the approval of the regulators from both countries. It is therefore important that specialist advice is sought from a suitably qualified expert.

11. Remediation of NORM contaminated land

Land which is NORM contaminated as a result of oil and gas related operations, such as an evaporation pond or land farm, should be remediated prior to release for unrestricted use. Remediation is the systematic removal of NORM contamination from the area in a controlled manner, with the contaminated soil/ material becoming part of the NORM waste stream. It is crucial to establish clear release criteria with the regulator before starting land remediation.

Prior to any remediation operations, careful analysis of the overall risks should be completed to ensure that there is benefit to be gained by carrying out the operation.

A general schematic for land remediation is detailed in Figure 16. It is important to stress that a NORM management plan should also consider the context within which the material has been found. NORM contaminated sites may also be contaminated with other hazardous materials such as heavy metals and hydrocarbons, which will require separate risk assessments.

One of the greatest challenges in assessing NORM waste as part of a remediation plan lies in the selection of representative samples and appropriate survey techniques. As explained in section 3, the selection of instrumentation can have a significant bearing upon the levels and origins of NORM identified. NORM will not be found evenly across most sites, but will occur as 'hot spots' samples of elevated activity. Moreover, laboratory based assays in developing countries and remote locations can be hampered by the availability of in-country facilities with the capability to assess samples adequately. Such issues should form part of a remediation protocol.

The volume of material involved in remediating a site can be substantial. For example, remediation of the The Bay Marchand oil field in Lousiana required the disposal (via slurry injection) of 1 million barrels of contaminated soil[37].

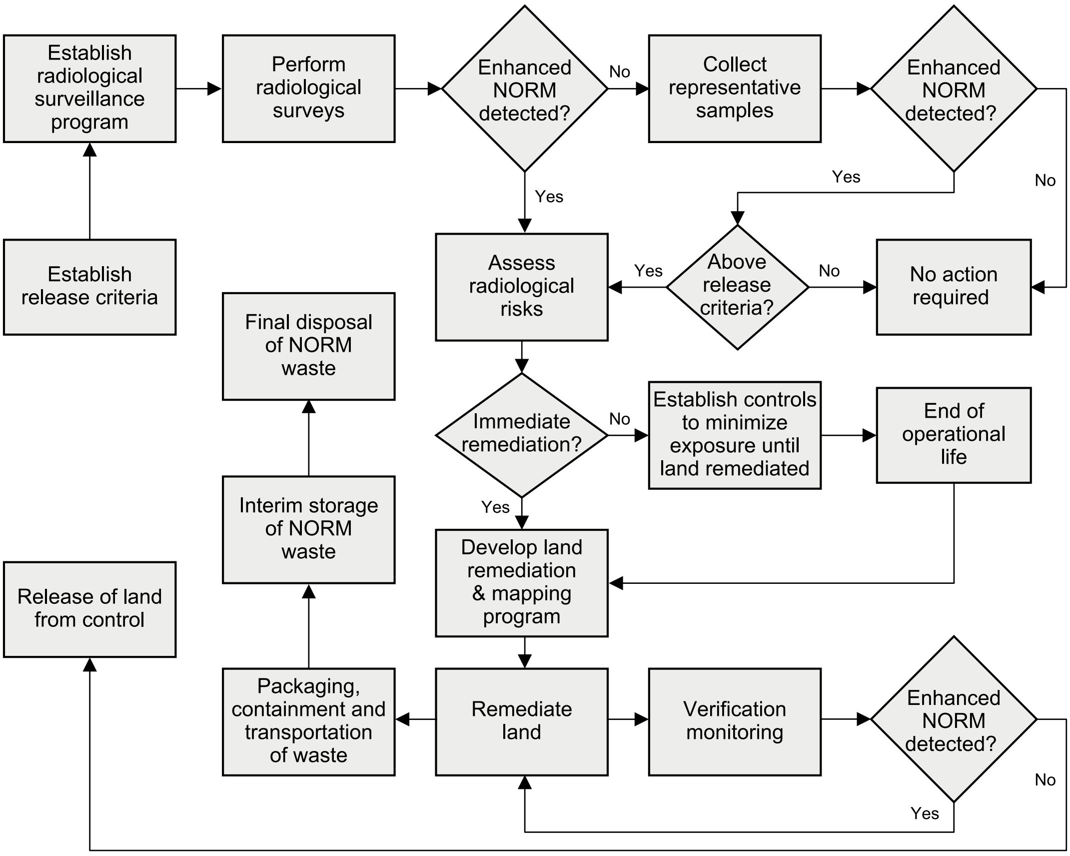


Figure 16: A generalized remediation management plan for NORM contaminated land

12. Permanent disposal options

Given the long half-lives of several NORs, (most notably ^{226}Ra $t_{½} = 1604$ y), the provision of long term disposal options that provide adequate protection to both human health and the environment over comparable timescales needs careful consideration. For example, a permanent disposal protocol should be designed to prevent contamination of natural resources such as underground water, or contamination of soil that could in future become residential or agricultural areas even although the area is currently remote or uninhabited.

It is essential to consult the national regulations when considering NORM disposal routes as these differ between countries. In some countries, it is acceptable that an oil company may propose disposal options (worked out internally) to the national competent authority whilst, in other countries, the approved options are more prescriptive. In addition, hazardous wastes of all kinds can be an emotive subject and consideration should also be taken of local opinion and public awareness of the issues and relative risks.

The preliminary selection for a disposal method may include:

- radiological risk during active use of a disposal site
- radiological risk over the effective lifespan of the waste
- technical feasibility, including geographical location
- general acceptance (regulatory and public)
- cost

Popular methods of NORM disposal currently used in the oil and gas industry include offshore disposal, landfill, underground injection and dedicated waste facilities such as subsurface salt cavern disposal. Figure 17 illustrates some of the most commonly encountered disposal methods.

Once potential disposal options are identified as a result of preliminary selection then a full assessment in terms of risk and cost can be undertaken. Risk assessment has shown that the lowest residual risk methods for NORM disposal may be underground injection and landfill.

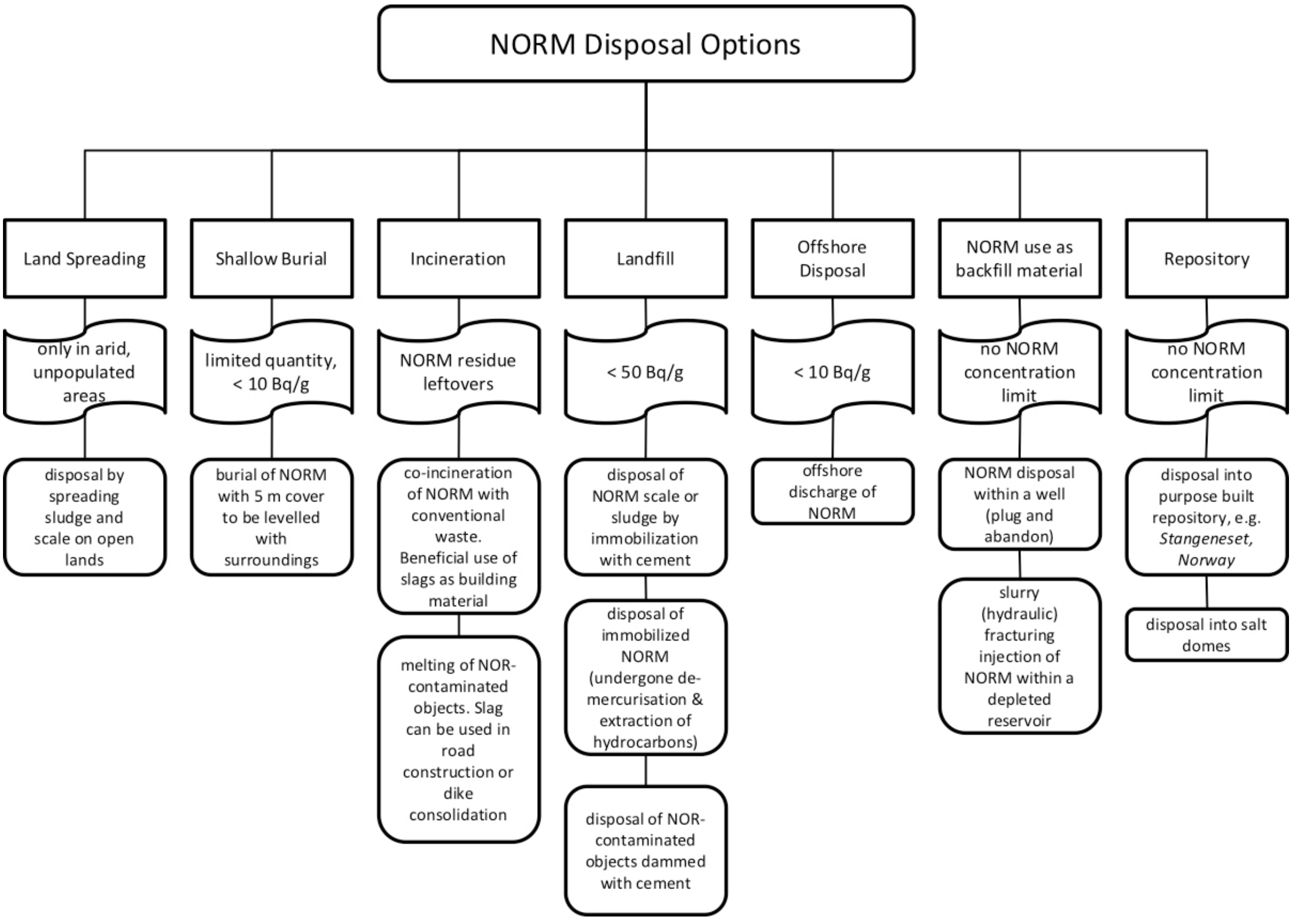


Figure 17: NORM disposal options

Appendix A
Radioactivity terminology and dose concepts

ACTIVITY				
Bq	Becquerel	SI unit of activity	one Bq equals one nuclear transformation per second	1 Bq = 2.7×10^{-11} Ci = 27 pCi
Ci	Curie	activity of 1 gram of radium (Ra)	one Ci equals 3.7×10^{10} transformations of radium nuclei per second	1 Ci = 3.7×10^{10} Bq = 37 GBq
activity concentrations (examples)		Bq[NOR]/g[solid] Bq[NOR]/L[liquid] Bq[NOR]/ Nm^3[gas]	Bq[^{210}Pb$_{eq}$]/g[deposit] Bq[^{228}Ra$_{eq}$]/L[PW] Bq[^{222}Rn]/Nm^3[NG]	^{210}Pb in secular eq with ^{210}Bi, ^{210}Po ^{228}Ra in transient eq with ^{228}Ac ^{222}Rn without short-lived progeny

DOSE				
X	exposure	old cgs unit: röntgen (R), only valid for X- and γ-radiation	number of charge carriers liberated in air per unit of mass by ionizing radiation	1 R = 2.58×10^{-4} C/kg[air]
D	absorbed dose	SI unit: **J**oule per **k**ilo**g**ram or Gray (Gy)	mean energy imparted to matter per unit mass by ionizing radiation	1 Gy = 1 J/kg
		old cgs unit: 100 erg per gram or rad	rad = **r**adiation **a**bsorbed **d**ose	1 rad = 0.01 Gy 1 Gy = 100 rad
D_T	absorbed dose in a tissue	SI unit: Joules per kilogram or Gray (Gy)	mean energy imparted to tissue T per unit mass by ionizing radiation	1 Gy = 1 J/kg[Tissue]
$D_{T,R}$			mean energy imparted to tissue T per unit mass by ionizing radiation type R	1 Gy = 1 J[type R]/kg[Tissue]
w_R	**R**adiation **w**eighting factor	unit introduced by health physics, no dimension	compensating for the relative biological effect caused by the type of radiation (α, β, γ, X)	$w_\alpha = 20$ $w_\beta = 1$ $w_{\gamma,x} = 1$

DOSE				
H_T	equivalent dose in a tissue	derived SI unit introduced by health physics: Sievert (Sv)	tissue absorbed dose multiplied by radiation weighting factor	$H_T \equiv \Sigma_R\ w_R \times D_{T,R}$ Sv[Tissue]
w_T	**T**issue **w**eighting factor	unit introduced by health physics, no dimension $\Sigma_T\ w_T \equiv 1$	compensating for the relative sensitivity of the various tissues to ionizing radiation always include w_T = 5% for average dose to adrenals, brain, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus	w_{gonads} = 20% w_{colon}, $w_{red\_bone\_marrow}$, w_{lung}, $w_{stomach}$ =12% $w_{bladder}$, w_{chest}, w_{liver}, $w_{thyroid}$, $w_{oesophagus}$ = 5% w_{skin}, $w_{bone\_surface}$ = 1%
E	**E**ffective dose (whole body dose)	derived SI unit introduced by health physics: Sievert (Sv)	world population averaged annual dose for Natural Radiation Environment ≈ 2.4 mSv/a or 2,400 µSv/a	$E \equiv \Sigma_T\ w_T\ \Sigma_R\ w_R \times D_{T,R}$ $E = \Sigma_T\ w_T \times H_T$
			rem = **r**öntgen **e**quivalent **m**an	1 rem = 0.01 Sv 1 Sv = 100 rem

Appendix B
Prefixes and examples

MULTIPLIER	PREFIX	SYMBOL	EXAMPLE	EXAMPLE VALUE
10^{-12}	pico	p	1 pCi	10^{-12} Ci = 0.037
10^{-9}	nano	n	1 nCi	10^{-9} Ci = 37
10^{-6}	micro	µ	1 µSv	10^{-6} Sv = 0.000001 Sv
10^{-3}	milli	m	1 mSv	10^{-3} Sv = 0.001
10^{3}	kilo	k	1 kBq	10^{3} Bq = 1,000
10^{6}	mega	M	1 MBq	10^{6} Bq = 1,000,000
10^{9}	giga	G	1 GBq	10^{9} Bq = 1,000,000,000
10^{12}	tera	T	1 TBq	10^{12} Bq = 1,000,000,000,000

Appendix C
Dose conversion factors

The Dose Conversion Coefficients (DCC) for ingestion (DCC_{ing}) and inhalation (DCC_{inh}) listed in table C-1 have been obtained by summing the relevant DCC's of the individual members of the secular or transient equilibrium listed in reference 38. As the NORs may appear in various unknown chemical compounds with distinct biochemical behaviour for a conservative approach the most restrictive inhalation class DCC_{inh} values have been used to generate table C-1. As very often the particle distribution of generated dust is unknown as well, it is recommended to apply the DCC_{inh} for an activity median aerodynamic diameter (AMAD) of 5 µm to compute the inhalation dose component (conservative approach).

Naturally Occurring Radionuclide	**secular/transient equilibrium members**	**DCC_{ing} Sv/Bq**	**DCC_{inh}**	
			1 µm AMAD Sv/Bq	**5 µm AMAD Sv/Bq**
$^{232}\mathrm{Th}$	$^{232}\mathrm{Th}$	2.2E-7	4.2E-5	2.9E-5
$^{228}\mathrm{Ra}_{eq}$	$^{228}\mathrm{Ra} > {}^{228}\mathrm{Ac}$	6.7E-7	2.6E-6	1.7E-6
$^{228}\mathrm{Th}_{eq}$	$^{228}\mathrm{Th} > {}^{224}\mathrm{Ra} > {}^{220}\mathrm{Rn} > {}^{216}\mathrm{Po} > {}^{212}\mathrm{Pb} > {}^{212}\mathrm{Bi} > {}^{212}\mathrm{Po}/{}^{208}\mathrm{Tl}$	7.0E-8	3.4E-5	2.5E-5
$^{238}\mathrm{U}_{eq}$	$^{238}\mathrm{U} > {}^{234}\mathrm{Th} > {}^{234m}\mathrm{Pa} > {}^{234}\mathrm{U} > {}^{230}\mathrm{Th}$	2.3E-7	4.6E-5	3.2E-5
$^{226}\mathrm{Ra}_{eq}$	$^{226}\mathrm{Ra} > {}^{222}\mathrm{Rn} > {}^{218}\mathrm{Po} > {}^{214}\mathrm{Pb} > {}^{214}\mathrm{Bi} > {}^{214}\mathrm{Po}$	2.8E-7	3.2E-6	2.2E-6
$^{210}\mathrm{Pb}_{eq}$	$^{210}\mathrm{Pb} > {}^{210}\mathrm{Bi} > {}^{210}\mathrm{Po}$	9.2E-7	3.0E-6	2.3E-6

Worker DCC (Sv/Bq) for ingestion and inhalation of particles with an AMAD of 1 and 5 µm

Appendix D
Decay and radiation characteristics of ^{232}Th- and ^{238}U- decay series

Isotope	α-decay	E_β average							
		Percentage β-decay per energy bin				Percentage β-decay per energy bin			
		<200 keV	<500 keV	<1000 keV	>1000 keV	<200 keV	<500 keV	<1000 keV	>1000 keV
^{232}Th	100%					0%			
^{228}Ra		100%				0%			
^{228}AC		19%	57%	22%		5%	32%	64%	26%
^{228}Th	99%					2%			
^{224}Ra	100%					4%	0%		
^{220}Rn	100%						0%		
^{216}Po	100%						0%		
^{212}Pb		100%				1%	48%		
^{212}Bi	36%	5%	3%	56%		1%	1%	15%	5%
^{212}Po	36%								
^{208}Tl			17%	47%			4%	77%	64%
^{208}Pb stable end member									
^{238}U	100%					0%			
^{234}Th		100%				9%			
^{234}Pa		100%					0%	0%	1%
^{234}U	100%					0%			
^{230}Th	100%					0%	0%		
^{226}Ra	100%					3%	0%		
^{222}Rn	100%						0%		
^{218}Po	100%							0%	
^{214}Pb		3%	96%			1%	66%	2%	
^{214}Bi		0%	31%	49%	19%		0%	59%	70%
^{214}Po	100%						0%	0%	
^{210}Pb		100%				4%			
^{210}Bi			100%						
^{210}Po	100%						0%		
^{206}Pb stable end member									

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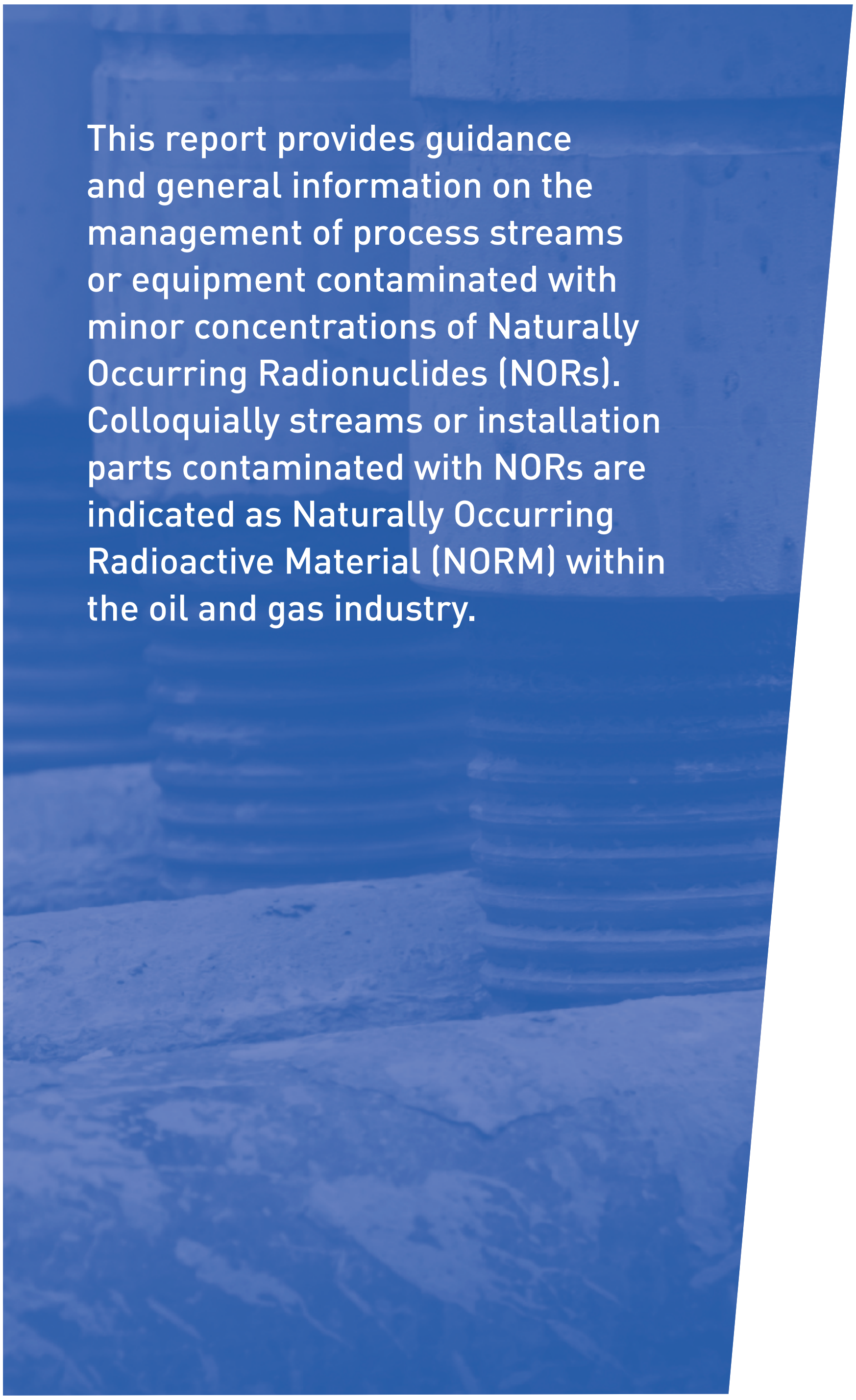

This report provides guidance and general information on the management of process streams or equipment contaminated with minor concentrations of Naturally Occurring Radionuclides (NORs). Colloquially streams or installation parts contaminated with NORs are indicated as Naturally Occurring Radioactive Material (NORM) within the oil and gas industry.