原子能科技應用面探討
特輯報導 2017/5/31

報告摘要(KEY INFORMATION)

核子科技的應用

1. 全球 70 億居民中至少有 8 億人長期營養不良，每天有數以萬計的人因飢餓或與飢餓有關的原因死亡。聯合國糧食及農業組織（糧農組織）與國際原子能總署合作，透過原子能和相關生物技術，協助改善糧食的永續性。
2. 昆蟲造成的農作物損失可能超過全世界總收成的 10%以上。無菌昆蟲技術（SIT）在孵化前用γ輻射照射其卵，對其進行滅菌，然後在受侵襲的地區大量釋放無菌雄蟲，當與雌性交配時，不會產生後代。隨著受滅菌雄蟲的多次釋放，受侵襲區域的蟲害種群將會大大減少。
3. 許多國家的農作收穫與食品約有 25-30%由於微生物和害蟲的腐敗而喪失。使用輻射技術能延長食物的保存期限，而不會影響食物本身的營養價值或留下任何殘留物並延長食物的保存。
4. 同位素水文學技術可以準確追踪和測量地下水資源，這些技術提供了重要的分析數據，這些數據分析提供關於地下水的起源、年齡和分佈，能促進現有水資源的保護和永續管理。

放射性同位素在工業中的角色

1. 中子科技之分析應用：熱中子捕獲與中子非彈性散射
2. 伽瑪射線與 X 光之分析應用：在礦物濃縮過程中測定元素含量
3. 伽瑪放射攝影：不需電力且較 X 光機輕便，只需一粒鈦膠囊屏蔽包覆，可用於管路焊接之探勘
4. 量測：用放射源搭配偵測器，可在不接觸帶測材料的條件下測得放射強度衰減，以得到總量、密度等數據
5. 科學運用—示蹤劑：追查環境中污染物的來源
6. 科學運用—定年：為地理學、人類學、考古學定年之重要工具；也可藉測定地下水中自然放射性核種含量，知地下水耗用與補充之情形
7. 放射性同位素熱電發電系統：其電力可於太空船、衛星、航海照明以及其他無法應用太陽能的極端環境使用
8. 放射性廢棄物：處理含有天然放射性材料的工業製程累積更高濃度的放射性核種，可致工安問題與環境污染，如磷肥的製造
9. 石油與天然氣之開採與提煉：北歐現今放射性污水之主要來源
10. 燃煤：大部分煤礦都含鈾及釷，燃燒後於飛灰中存在
11. 污水處理：離子交換樹脂等過濾裝置中累積鈾、釷等放射性核種
12. 金屬工業：廢五金工業與金屬提煉產生之污泥

核子科技的應用

食物與農業

At least 800 million of the world's seven billion inhabitants are chronically malnourished, and tens of thousands die daily from hunger and hunger-related causes. Radioisotopes and radiation used in food and agriculture are helping to reduce these tragic figures.

As well as directly improving food production, agriculture needs to be sustainable over the longer term. The UN's Food and Agriculture Organisation (FAO) works with the IAEA on programs to improve food sustainability assisted by nuclear and related biotechnologies.

1.肥料

Fertilisers are expensive and if not properly used can damage the environment. Efficient use of fertilisers is therefore of concern to both developing and developed countries. It is important that as much of the fertiliser as possible finds its way into plants and that a minimum is lost to the environment.

Fertilisers 'labelled' with a particular isotope, such as nitrogen-15 and phosphorus-32 provide a means of finding out how much is taken up by the plant and how much is lost, allowing better management of fertiliser application. Using N-15 also enables assessment of how much nitrogen is fixed from the air by soil and by root bacteria in legumes.

2.增加遺傳變異性

Ionising radiation to induce mutations in plant breeding has been used for several decades, and some 1800 crop varieties have been developed in this way. Gamma or neutron irradiation is often used in conjunction with other techniques, to produce new genetic lines of root and tuber crops, cereals and oil seed crops.

New kinds of sorghum, garlic, wheat, bananas, beans and peppers are more resistant to pests and more adaptable to harsh climatic conditions. In Mali, irradiation of sorghum and rice seeds has produced more productive and marketable varieties.

Crop losses caused by insects may amount to more than 10% of the total harvest worldwide, - in developing countries the estimate is 25-35%. Stock losses due to tsetse in Africa and screwworm in Mexico have also been sizeable. Chemical insecticides have for many years been the main weapon in trying to reduce these losses, but they have not always been effective. Some insects have become resistant to the chemicals used, and some insecticides leave poisonous residues on the crops. One solution has been the use of sterile insects.

The Sterile Insect Technique (SIT) involves rearing large numbers of insects then irradiating their eggs with gamma radiation before hatching, to sterilise them. The sterile males are then released in large numbers in the infested areas. When they mate with females, no offspring are produced. With repeated releases of sterilised males, the population of the insect pest in the project area is drastically reduced.

Major SIT operations have been conducted in Mexico, Argentina and northern Chile against the Medfly (Mediterranean fruit fly) and in 1981 this was declared a complete success in Mexico. In 1994-95 eradication was achieved in two fruit-growing areas of Argentina and 95% success in another, as well as in Chile. The program has been extended to all of southern South America and to Africa. Meanwhile the EU is financing a 'fly factory' on Portugal's Madeira island to produce up to 100 million sterile male Medflies per week.

A very successful SIT campaign was screwworm eradication in southern USA, Mexico and nearby. By 1991 the screwworm eradication had yielded some US$ 3 billion in economic benefits due to healthier livestock, not to mention humans. The Mexican plants and equipment were then applied to infestations in Libya, Jamaica and Central America, providing 20 million sterile pupae per week.

SIT has been effective on the Medfly in southern Africa and is now being applied to Codling Moths which damage citrus crops. The IAEA and FAO are assessing the potential of using SIT against Sugarcane Borers on sugarcane, as well as consolidating Codling Moth management to support the apple and pear export industries.

A number of the most fertile parts of Africa cannot be farmed because of the tsetse fly which carries the parasite trypanosome that causes the African sleeping sickness disease and the cattle disease Nagana. Economic losses due to this are estimated by FAO at US$ 4 billion per year. However, SIT in conjunction with conventional pest controls is starting to change all this. Zanzibar was declared tsetse-free in 1997 and Nigeria has also benefited. In southern Ethiopia a major tsetse SIT program is under way, with a million sterile males per month being produced in a 'fly factory' at Addis Ababa and then released.

Screwworm flies are major pests in some parts of the world. Females lay eggs into animal wounds and on soft tissues, the larvae then burrow through the flesh creating serious bacterial infections that attract more egg-laying females and are often fatal. Using SIT, screwworm has been eradicated from North and Central America, and also Libya. South America, most of Africa, and south Asia through to Melanesia remain a challenge.

Three UN organizations - the IAEA, the FAO, the World Health Organisation (WHO), with the governments concerned, are promoting new SIT programs in many countries.

食品保鮮

In all parts of the world there is growing use of irradiation technology to preserve food. In over 40 countries health and safety authorities have approved irradiation of more than 60 kinds of food, ranging from spices, grains and grain products to fruit, vegetables and meat. It can replace potentially harmful chemical fumigants to eliminate insects from dried fruit and grain, legumes, and spices.

Some 25-30% of the food harvested in many countries is lost as a result of spoilage by microbes and pests. In a hungry world we cannot afford this. The reduction of spoilage due to infestation and contamination is of the utmost importance. This is especially so in countries which have hot and humid climates and where an extension of the storage life of certain foods, even by a few days, is often enough to save them from spoiling before they can be consumed. Some countries lose a high proportion of harvested grain due to moulds and insects.

Following three decades of testing, a worldwide standard was adopted in 1983 by a joint committee of WHO, FAO and IAEA. In 1997 another such joint committee said there was no need for the earlier recommended upper limit on radiation dose to foods.

As well as reducing spoilage after harvesting, increased use of food irradiation is driven by concerns about food-borne diseases as well as growing international trade in foodstuffs which must meet stringent standards of quality. On their trips into space, astronauts eat foods preserved by irradiation.

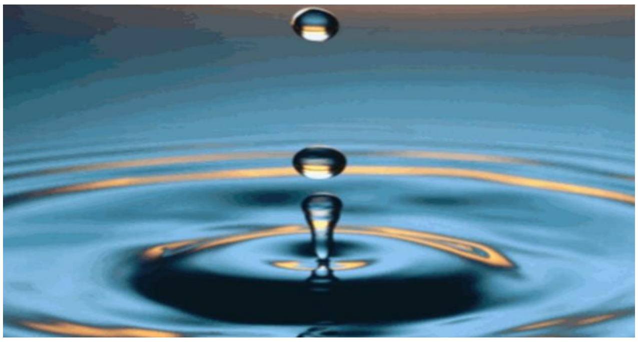
Food irradiation means that raw foods are exposed to high levels of gamma radiation which kills bacteria and other harmful organisms without affecting the nutritional value of food itself or leaving any residue. It is the only means of killing bacterial pathogens in raw and frozen food. Of course, irradiation of food does not make it radioactive!

食品輻射應用

Low dose (up to 1 kGy)	Inhibition of sprouting	Potatoes, onions, garlic, ginger, yam
	Insect and parasite disinfestation	Cereals, fresh fruit, dried foods
	Delay ripening	Fresh fruit, vegetables
Medium dose (1-10 kGy)	Extend shelf life	Fish, strawberries, mushrooms
	Halt spoilage, kill pathogens	Seafood, poultry, meat
High dose (10-50 Gy)	Industrial sterilisation	Meat, poultry, seafood, prepared foods
	Decontamination	Spices, etc

Radiation is also used to sterilise food packaging. In the Netherlands, for example, milk cartons are freed from bacteria by irradiation.

水資源



Adequate potable water is essential for life. Yet in many parts of the world fresh water has always been scarce and in others it is becoming scarcer. Yet for any new development, whether agricultural, industrial or human settlement, a sustainable supply of good water is vital.

Isotope hydrology techniques enable accurate tracing and measurement of the extent of underground water resources. Such techniques provide important analytical tools in the management and conservation of existing supplies of water and in the identification of new, renewable sources of water. They provide answers to questions about origin, age and distribution of groundwater, as well as the interconnections between ground and surface water and aquifer recharge systems. The results permit planning and sustainable management of these water resources.

For surface waters they can give information about leakages through dams and irrigation channels, the dynamics of lakes and reservoirs, flow rates, river discharges and sedimentation rates. From Afghanistan to Zaire there are some 60 countries, developed and developing, that have used isotope techniques to investigate their water resources in collaboration with IAEA.

Neutron probes can measure soil moisture very accurately, enabling better management of land affected by salinity, particularly in respect to irrigation.

工業運用

1.環境追蹤器

Radioisotopes also play an important role in detecting and analysing pollutants, since even very small amounts of a radioisotope can easily be detected, and the decay of short-lived isotopes means that no residues remain in the environment.

Nuclear techniques have been applied to a range of pollution problems including smog formation, sulphur dioxide contamination of the atmosphere, sewage dispersal from ocean outfalls and oil spills.

2.工業追蹤器

The ability to measure radioactivity in minute amounts has given radioisotopes a wide range of applications in industry as 'tracers'. By adding small amounts of radioactive substances to materials used in various processes it is possible to study the mixing and flow rates of a wide range of materials, including liquids, powders and gases and to locate leaks.

Tracers added to lubricating oils can help measure the rate of wear of engines and plant and equipment. Tracer techniques have been used in plant operations to check the performance of equipment and improve its efficiency, resulting in savings in energy and the better use of raw materials.

3.儀器

Gauges containing radioactive (usually gamma) sources are in wide use in all industries where levels of gases, liquids and solids must be checked. They measure the amount of radiation from a source which has been absorbed in materials. These gauges are most useful where heat, pressure or corrosive substances, such as molten glass or molten metal, make it impossible or difficult to use direct contact gauges.

Radioisotope thickness gauges are used in the making of continuous sheets of material including paper, plastic film, metal, glass, etc, when it is desirable to avoid contact between the gauge and the material.

Density gauges are used where automatic control of a liquid, powder or solid is important, for example, in detergent manufacture.

Radioisotope instruments have three great advantages:

・measurements can be made without physical contact with the material or product being measured.

・Very little maintenance of the isotope source is necessary.

・The cost/benefit ratio is excellent - many instruments pay for themselves within a few months through the savings they allow.

4.造影

Radioisotopes which emit gamma rays are more portable than x-ray machines, and may give higher-energy radiation, so can be used to check welds of new gas and oil pipeline systems, with the radioactive source being placed inside the pipe and the film outside the welds.

Other forms of radiography (neutron radiography/ autoradiography), based on different principles, can be used to gauge the thickness and density of materials or locate components that are not visible by other means.

5.放射性同位素電源

Some radioisotopes emit a lot of energy as they decay. Such energy can be harnessed for heart pacemakers and to power navigation beacons and satellites. The decay heat of plutonium-238 has powered many US space vehicles. It enabled the Cassini space probe to investigate Saturn, and it powers the Mars Science Laboratory, the rover Curiosity.

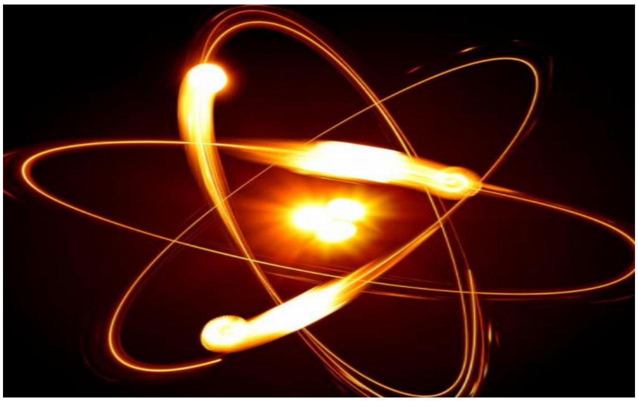
6.分析

Analysing the relative abundance of particular naturally-occurring radioisotopes is of vital importance in determining the age of rocks and other materials that are of interest to geologists, anthropologists and archaeologist.

放射性同位素在工業中的角色

Nuclear techniques are increasingly used in science, industry and environmental management. The continuous analysis and rapid response of nuclear techniques, many involving radioisotopes, mean that reliable flow and analytic data can be constantly available. This results in reduced costs with increased product quality.

中子科技之分析應用



Neutrons from a research reactor can interact with atoms in a sample causing the emission of gamma rays which, when analysed for characteristic energies and intensity, will identify the types and quantities of elements present. The two main techniques are Thermal Neutron Capture (TNC) and Neutron Inelastic Scattering (NIS). TNC occurs immediately after a low-energy neutron is absorbed by a nucleus, NIS takes place instantly when a fast neutron collides with a nucleus.

Most commercial analysers use californium-252 neutron sources together with sodium iodide detectors and are mainly sensitive to TNC reactions. Other use Am-Be-241 sources and bismuth germanate detectors, which register both TNC and NIS. NIS reactions are particularly useful for elements such as C, O, Al & Si which have a low neutron capture cross section. Such equipment is used for a variety on on-line and on-belt analysis in the cement, mineral and coal industries.

A particular application of NIS is where a probe containing a neutron source can be lowered into a bore hole where the radiation is scattered by collisions with surrounding soil. Since hydrogen (the major component of water) is by far the best scattering atom, the number of neutrons returning to a detector in the probe is a function of the density of the water in the soil.

To measure soil density and water content, a portable device with an americium-241-beryllium combination generates gamma rays and neutrons which pass through a sample of soil to a detector. (The neutrons arise from alpha particles interacting with Be-9.) A more sophisticated application of this is in borehole logging.

伽瑪射線與 X 光之分析應用

Gamma ray transmission or scattering can be used to determine the ash content of coal on line on a conveyor belt. The gamma ray interactions are atomic number dependant, and the ash is higher in atomic number than the coal combustible matter. Also the energy spectrum of gamma rays which have been inelastically scattered from the coal can be measured (Compton profile analysis) to indicate the ash content.

X-rays from a radioactive element can induce fluorescent X-rays from other non-radioactive materials. The energies of the fluorescent X-rays emitted can identify the elements present in the material, and their intensity can indicate the quantity of each element present.

This technique is used to determine element concentrations in process streams of mineral concentrators. Probes containing radioisotopes and a detector are immersed directly into slurry streams. Signals from the probe are processed to give the concentration of the elements being monitored, and can give a measure of the slurry density. Elements detected this way include iron, nickel, copper, zinc, tin and lead.

X-ray diffraction (XRD) is a further technique for on-line analysis but does not use radioisotopes.

伽瑪放射攝影

Gamma radiography works in much the same way as X-rays screen luggage at airports. Instead of the bulky machine needed to produce X-rays, all that is needed to produce effective gamma rays is a small pellet of radioactive material in a sealed titanium capsule.

The capsule is placed on one side of the object being screened, and some photographic film is placed on the other side. The gamma rays, like X-rays, pass through the object and create an image on the film. Just as X-rays show a break in a bone, gamma rays show flaws in metal castings or welded joints. The technique allows critical components to be inspected for internal defects without damage.

Gamma sources are normally more portable than x-ray equipment so have a clear advantage in certain applications, such as in remote areas. Also while X-ray sources emit a broad band of radiation, gamma sources emit at most a few discrete wavelengths. Gamma sources may also be much higher energy than all but the most expensive X-ray equipment, and hence have an advantage for much radiography. Where a weld has been made in an oil or gas pipeline, special film is taped over the weld around the outside of the pipe. A machine called a 'pipe crawler' carries a shielded radioactive source down the inside of the pipe to the position of the weld. There, the radioactive source is remotely exposed and a radiographic image of the weld is produced on the film. This film is later developed and examined for signs of flaws in the weld.

X-ray sets can be used when electric power is available and the object to be X-rayed can be taken to the X-ray source and radiographed. Radioisotopes have the supreme advantage in that they can be taken to the site when an examination is required – and no power is needed. However, they cannot be simply turned off, and so must be properly shielded both when in use and at other times.

Non-destructive testing is an extension of gamma radiography, used on a variety of products and materials. For instance, ytterbium-169 tests steel up to 15 mm thick and light alloys to 45 mm, while iridium-192 is used on steel 12 to 60 mm thick and light alloys to 190 mm.

量測

The radiation that comes from a radioisotope has its intensity reduced by matter between the radioactive source and a detector. Detectors are used to measure this reduction. This principle can be used to gauge the presence or the absence, or even to measure the quantity or density, of material between the source and the detector. The advantage in using this form of gauging or measurement is that there is no contact with the material being gauged.

Many process industries utilise fixed gauges to monitor and control the flow of materials in pipes, distillation columns, etc., usually with gamma rays.

The height of the coal in a hopper can be determined by placing high energy gamma sources at various heights along one side with focusing collimators directing beams across the load. Detectors placed opposite the sources register the breaking of the beam and hence the level of coal in the hopper. Such level gauges are among the most common industrial uses of radioisotopes.

Some machines which manufacture plastic film use radioisotope gauging with beta particles to measure the thickness of the plastic film. The film runs at high speed between a radioactive source and a detector. The detector signal strength is used to control the plastic film thickness.

In paper manufacturing, beta gauges are used to monitor the thickness of the paper at speeds of up to 400 m/s.

When the intensity of radiation from a radioisotope is being reduced by matter in the beam, some radiation is scattered back towards the radiation source. The amount of 'backscattered' radiation is related to the amount of material in the beam, and this can be used to measure characteristics of the material. This principle is used to measure different types of coating thicknesses.

伽瑪滅菌

Gamma irradiation is widely used for sterilising medical products, for other products such as wool, and for food. It kills bacteria and does not damage packaging. Cobalt-60 is the main isotope used, since it is an energetic gamma emitter. It is produced in nuclear reactors, sometimes as a by-product of power generation.

Large-scale irradiation facilities for gamma sterilisation are used for disposable medical supplies such as syringes, gloves, clothing and instruments, many of which would be damaged by heat sterilisation. Such facilities also process bulk products such as raw wool for export from Australia, archival documents and even wood, to kill parasites. Currently ANSTO in Australia sterilises up to 25 million Queensland fruit fly pupae per week for NSW Agriculture by gamma irradiation. See also The Peaceful Atom.

Smaller gamma irradiators are used for treating blood for transfusions and for other medical applications. They often use caesium-137, with gamma rays about half as energetic as cobalt's.

Food preservation is an increasingly important application, and has been used since the 1960s. In 1997 the irradiation of red meat was approved in USA. Some 41 countries have approved irradiation of more than 220 different foods, to extend shelf life and to reduce the risk of food-borne diseases.

Radioisotopes are used as tracers in many research areas. Most physical, chemical and biological systems treat radioactive and non-radioactive forms of an element in exactly the same way, so a system can be investigated with the assurance that the method used for investigation does not itself affect the system. An extensive range of organic chemicals can be produced with a particular atom or atoms in their structure replaced with an appropriate radioactive equivalent.

Using tracing techniques, research is also conducted with various radioisotopes which occur naturally in the environment, to examine the impact of human activities.

Even very small quantities of radioactive material can be detected easily. This property can be used to trace the progress of some radioactive material through a complex path, or through events which greatly dilute the original material. In all these tracing investigations, the half-life of the tracer radioisotope is chosen to be just long enough to obtain the information required. No long-term residual radioactivity remains after the process.

Sewage from ocean outfalls can be traced in order to study its dispersion. Small leaks can be detected in complex systems such as power station heat exchangers. Flow rates of liquids and gasses in pipelines can be measured accurately, as can the flow rates of large rivers.

Mixing efficiency of industrial blenders can be measured and the internal flow of materials in a blast furnace examined. The extent of termite infestation in a structure can be found by feeding the insects radioactive wood substitute, then measuring the extent of the radioactivity spread by the insects. This measurement can be made without damaging any structure as the radiation is easily detected through building materials.

Measuring trace levels of radioactive fallout from nuclear weapons testing in the 1950s and 60s is now being used to study soil movement and degradation. This is assuming greater importance in environmental studies of the impact of agriculture.

科學運用—定年

Analysing the relative abundance of particular naturally-occurring radioisotopes is of vital importance in determining the age of rocks and other materials that are of interest to geologists, anthropologists and archaeologists. Dating techniques include: K-Ar (potassium-argon and its more recent variant Ar-40/Ar-39), Rb-Sr (rubidium-strontium), Sm-Nd (samarium-neodymium), Lu-Hf (lutetium-hafnium), and U-Pb (uranium-lead and its variant Pb-Pb).

One common application is in determining the age of carbon-containing materials up to about 20,000 years by measuring the abundance of carbon-14, or its beta signature. This is a naturally-occurring radioisotope formed in the upper atmosphere by cosmic rays converting nitrogen into C-14, also known as radiocarbon. Living organisms are constantly incorporating CO2 with this C-14 into their bodies along with other carbon isotopes (mostly C-12). When the organisms die, they stop incorporating new C-14, and the constituent C-14 starts to turn back into N-14 by beta decay. Carbon dating of groundwater works similarly, the decay timer starting when the water with dissolved CO2 leaves the atmosphere. The half-life of C-14 is 5730 years.

The age of water obtained from underground bores can be estimated from the level of naturally occurring radioisotopes in the water. This information can indicate if groundwater is being used faster than the rate of replenishment.

放射性同位素熱電發電系統

Radioisotope thermoelectric generators (RTGs) have been the main power source for US and much other space work for over 50 years, since 1961. The high decay heat of plutonium-238 (0.56 W/g) in particular enables its use as an electricity source in the RTGs of spacecraft, satellites, navigation beacons, etc., and its intense alpha decay process with negligible gamma radiation calls for minimal shielding. Heat from the oxide fuel is converted to electricity through static thermoelectric elements (solid-state thermocouples), with no moving parts. RTGs are safe, reliable and maintenance-free and can provide heat or electricity for decades under very harsh conditions, particularly where solar power is not feasible.

See also information paper on Nuclear Reactors and Radioisotopes for Space

低耗電電池

Tritium and nickel-63 can be used for beta-voltaic cells, which have low power but long life. They can be used in heart pacemakers or as power supply for satellites. Russia is implementing a project to develop nickel-63 power sources. The project involves several companies under the supervision of the Mining and Chemical Combine at Zheleznogorsk.

放射性廢棄物

Industries and scientific establishments utilize radioactive sources for a wide range of applications. When the radioactive sources used by industry no longer emit enough penetrating radiation for them to be of use, they are treated as radioactive waste. Sources used in industry are generally short-lived and any waste generated can be disposed of in near-surface facilities.

Some industrial activities involve the handling of raw materials such as rocks, soils and minerals that contain naturally occurring radioactive materials. These materials are known by the acronym "NORM". Industrial activity can sometimes concentrate these materials and therefore enhance their natural radioactivity (hence the further acronym: TENORM - technically-enhanced NORM). This may result in:

- A risk of radiation exposure to workers or the public
- Unacceptable radioactive contamination of the environment

• The need to comply with regulatory waste disposal requirements

See also NORM information paper.

The main industries that result in NORM contamination are:

石油與天然氣之開採與提煉

Oil and gas exploration and production generates large volumes of water containing dissolved minerals. These minerals may be deposited as scale in piping and oil field equipment or left as residues in evaporation lagoons. Occasionally the radiation dose from equipment contaminated with mineral deposits may present a hazard. More significantly contaminated equipment and the scale removed from it may be classified as radioactive waste. Oil and gas operations are the main sources of radioactive releases to waters north of Europe for instance.

燃煤

Most coal contains uranium and thorium, as well as other radionuclides. The total radiation levels are generally about the same as in other rocks of the Earth's crust. Most emerge from a power station in the light flyash. Some 99% of flyash is typically retained in a modern power station (90% in some older ones) and this is buried in an ash dam. Many hundred million tonnes of coal ash is produced globally each year.

磷肥

The processing of phosphate rock to produce phosphate fertilizers (one end product of the phosphate industry) results in enhanced levels of uranium, thorium and potassium.

污水處理

Radionuclides are leached into water when it comes into contact with uranium and thorium bearing rocks and sediments. Water treatment often uses filters to remove impurities. Hence, radioactive wastes from filter sludges, ion-exchange resins, granulated activated carbon and water from filter backwash are part of NORM.

廢五金工業

Scrap metal from various process industries can also contain scales with enhanced levels of natural radionuclides. The exact nature and concentration of these radionuclides is dependent on the process from which the scrap originated.

金屬提煉產生之污泥

Metal smelting slags, especially from tin smelting, may contain enhanced levels of uranium and thorium series radionuclides.