



Norwegian University of  
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# Radioactive Sources in Industrial Radiography

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Eline Kjørsvik  
Tone Marie Åsen Bastiansen

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Supervisors: Marte Sørteit Mørkve and Kristian Nelvik

## Preface

The present work has been written in the course TMAK3001 as a part of the Bachelor's degree programme at the Department of Materials Science and Engineering at the Norwegian University of Science and Technology. Marte Sørteit Mørkve and Kristian Nelvik have supervised the work together with Anita Auseh and Ståle Andre Ustad. The experimental work has been performed at Axess AS in Orkanger in April 2019.

We would like to thank both of our supervisors, Marte Sørteit Mørkve and Kristian Nelvik, for guidance and help during this project. A special thanks goes to Kristian Nelvik for being available for questions whenever needed. Our gratitude also goes to Ståle Andre Ustad for helping us with the experimental work.

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Finally, we would like thank our families for support, guidance and proofreading.

Tone Marie Åsen Bastiansen:

Tone Bastiansen

Eline Kjørvik:

Eline Kjørvik

## Abstract

The objective of this work was to assess the use of radioactive sources in industrial radiography. A big part of the work consisted of conducting interviews with several companies in the industry. An experimental work was also carried out. The purpose of the experimental work was to visualize one of the problems regarding the thesis question, which is to assess the possibility of eliminating radioactive sources in industrial radiography.

The isotopes are demanding to handle and expensive to produce, store, transport and use. This is mainly due to the fact that they cannot be turned on and off, and therefore require a lot of shielding and security. They also have a relatively short half-life, depending on the isotope, which means that after a while the radiation drops below the limit for practical application. It is therefore desirable to eliminate or reduce the use of radioactive sources in industrial radiography.

Several companies in the industry were interviewed to participate in finding possible solutions to the thesis question. Three different interview guides were made for customers, manufacturers and suppliers. In addition to the interviews, an experimental part was performed. This was done in the radiography strong room facilities at Axess AS in Orkanger. In the experimental work, an Ir-192 isotope and a 300 kV X-ray tube were used. The two sources of radiation were used on three different test objects. The results from this experiment confirmed that the Ir-192 isotopes' penetration capacity was needed to get images with high enough quality to detect a wall thickness.

Through the interviews, it was revealed that a complete elimination of radioactive sources in industrial radiography would be difficult with current technology, but it is possible to reduce the use of these sources. The elimination will be difficult to implement, partly due to the benefits of the isotopes, such as mobility and penetration capacity. Finding a replacement that also includes these benefits is not possible today. A technological development and a bigger desire or need to replace the radioactive sources will therefore be necessary in order to implement the elimination. Despite this, a combination of X-ray tubes, such as battery-powered X-ray tubes and mobile X-ray systems, and advanced ultrasonic testing, could be used during some inspections where radioactive sources are used today.

## Sammendrag

Problemstillingen i denne rapporten var å vurdere muligheten for å avvikle gamma-isotoper i industriell radiografi. Store deler av arbeidet bestod av å utføre intervjuer med ulike bedrifter i bransjen. Det ble også utført et eksperimentelt arbeid for å vise ett av problemene ved å erstatte isotopene.

Isotopene er krevende og kostbare i framstilling, lagring, transport og bruk. Det er flere årsaker til dette, men det skyldes hovedsakelig at isotopene sender ut stråling hele tiden. De krever derfor mye skjerming og sikring. De har også en relativt kort halveringstid, avhengig av isotopen, noe som betyr at de fort blir ubrukelige. Det er derfor ønskelig å eliminere eller redusere bruken av radioaktive kilder i industriell radiografi.

For å finne mulige løsninger på problemstillingen ble ulike bedrifter i bransjen intervjuet. Det ble laget tre forskjellige intervjuguider tilpasset kunder, leverandører og produsenter. I tillegg til intervjuene ble det utført en eksperimentell del, på radiografirommet til Axess AS på Orkanger, for å illustrere et av problemene tilknyttet problemstillingen. Det ble her brukt en Ir-192 isotop og et røntgenrør på 300 kV. De ulike strålingskildene ble benyttet på tre ulike testobjekter. Resultatene fra det eksperimentelle arbeidet bekreftet at gjennomtrengingsevnen til Ir-192 isotopen var nødvendig for å få bilder med høy nok kvalitet til å fastslå vegtykkelsen.

Fra intervjuene kom det frem at en fullstendig avvikling av gamma-isotoper vil være vanskelig med nåværende teknologi, men det vil være mulig å redusere bruken. Avviklingen vil være vanskelig å gjennomføre blant annet på grunn av mobiliteten og gjennomtrengningsevnen til gamma-isotopene. Å finne en erstatning som også har disse fordelene er ikke mulig i dag. Det vil derfor være nødvendig med en teknologisk utvikling og et større ønske eller behov om å erstatte isotopene for å kunne gjennomføre en avvikling. Til tross for dette, vil en kombinasjon batteridrevne røntgenrør, CP-anlegg og avansert ultralydteknologi kunne benyttes ved noen av inspeksjonene hvor gamma-isotoper benyttes i dag.

## Abbreviations and symbols

Unit		Explanation
Becquerel	Bq	Disintegrations per second
c	m/s	Speed of light
CP	–	Constant potential
CR	–	Computed radiography
Curie	Ci	Disintegrations per second
D	–	Density
DSA	–	Norwegian Radiation and Nuclear Safety Authority
E	J	Energy of the photon
EX	–	Explosion
DR	–	Digital radiography
ET	–	Electromagnetic testing
f	$s^{-1}$	Frequency of the photon
h	Js	Planck's constant
HSE	–	Health, safety and environment
ICRU	–	International Commission of Radiation Units and Measurements
ICRP	–	International Commission on Radiological Protection
$I_i$	Candela	Light in
$I_o$	Candela	Light out
MT	–	Magnetic particle testing
Megaelectron volt	MeV	Energy
Microsievert per hour	$\mu\text{Sv}/\text{h}$	Health effect of ionizing radiation
NDT	–	Non destructive testing
l	nm	Length
PAUT	–	Phased array ultrasonic testing
PT	–	Penetrant testing
RT	–	Radiographic testing
SI	–	International system of units
UT	–	Ultrasonic testing
VT	–	Visual testing
$\lambda$	m	Photon's wavelength

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# **1 Introduction**

## **1.1 Background**

Industrial radiography is a method for non destructive testing. It is used to inspect the volumetric defects in materials and welds by using X- or gamma radiation. X-ray tubes and isotopes are used as radiation sources.

The isotopes are demanding to handle and expensive to produce, store, transport and use. This is mainly due to the fact that they cannot be turned on and off, and therefore require a lot of shielding and security. They also have a relatively short half-life, depending on the isotope, which means that after a while the radiation drops below the limit for practical application. There is also a demanding environmental aspect regarding the disposal of the isotopes.

Companies in the industry want to eliminate the use of isotopes in industrial radiography, mainly due to technical reasons, and economic and environmental challenges, but also due to health, safety and environment (HSE).

## **1.2 Aim of work**

In this work, the use of isotopes in industrial radiography will be investigated based on available literature, interviews with companies and our own results from experimental work. We have chosen to focus on metal pipes and welds in the offshore industry, because this is a common area of interest.

The main object of this project is to study the possibility of eliminating the use of isotopes in industrial radiography, and to recommend other alternative sources or methods.

## 2 Theoretical background

This chapter consists of theory needed in order to discuss the thesis question of this project. The first part contains an introduction to radioactivity and isotopes, followed by electromagnetic radiation. The second part presents imperfections in solids, and describes different defects. The last part of this chapter describes theory about non-destructive testing, including both ultrasonic testing and industrial radiography. Radiography is the main focus, and radiation sources, radiographic films, cost and radiation hazards are described.

### 2.1 Elements

#### 2.1.1 The structure of the atom

Electrons are located in orbitals that surround the nucleus of an atom. An orbital is defined as areas where electrons are likely to be found in an atom. Figure 1 shows a simplified model of the atom, called the nuclear shell model. In an atom there are an equal number of electrons in the orbitals as protons in the nucleus. The total electric charge of an atom is therefore zero, also said to be neutral [1].

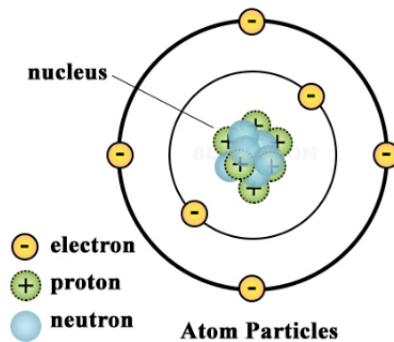


Figure 1: The atomic model with protons and neutrons in the nucleus and electrons in the shells surrounding the nucleus [2].

Electrons are bound to the nucleus by the electromagnetic force. Ionization energy is the energy needed to remove the outermost electron from an atom. The ionization energy needs to be higher than the electromagnetic force to expel an electron. Expelling an electron leads to empty positions in the electron shells. Electrons in lower electron shells can excite to the position in the higher energy level. The excited electron, when relaxed, emits the extra energy it holds, usually in the form of light [1].

#### 2.1.2 Isotopes

The atomic number is decided by the number of protons. Isotopes have the same number of protons, but a different number of neutrons. For example, all hydrogen atoms contain one proton, but they may contain zero, one or two neutrons. All three types of hydrogen atoms exist, but they have a different mass. The atom's mass number is the sum of the number of neutrons and protons in the atom. It is common to indicate isotopes with their chemical symbol followed by their mass number. For example, an isotope with one proton and two neutrons is hydrogen-3 or H-3 [1].

### **2.1.3 Radioactivity**

The emission of subatomic particles or high-energy electromagnetic radiation by the nuclei of certain atoms is called radioactivity. A radioactive substance is unstable and will emit small pieces of themselves to gain stability. Radioactive substances can give off alpha particles, beta particles and gamma radiation [3].

#### Alpha radiation

Alpha radiation occurs when an unstable nucleus emits an alpha particle. An alpha particle consists of two neutrons and two protons bound together. Since this particle is identical to the nucleus of the helium-4 atom, the symbol for alpha radiation is the symbol for He-4. When an alpha particle is emitted, the number of protons changes and the original element changes into a different element. Alpha particles travel with a high speed, but can only travel a few centimeters in air. A piece of paper can stop the particles [1].

#### Beta radiation

Beta radiation occurs when a neutron ( $n$ ), from the unstable nucleus, converts into a proton ( $p$ ) and emits an electron ( $e^-$ ). Beta radiation is a stream of electrons. The radiation is described by Equation (1).



When an atom emits a beta particle, its atomic number increases by one and becomes a different element. Beta particles are smaller than alpha particles and therefore have a lower ionizing power. However, they have a higher penetrating power than alpha particles, but a thin piece of metal can stop them [1].

#### Gamma radiation

When a nucleus emits a particle, it leads to a situation where the new nucleus has to rearrange its neutrons and protons to find a lower energy state. To achieve this lower energy state, the new nucleus emits a gamma particle. Gamma radiation has very short wavelengths, and is the most energetic form of electromagnetic radiation. It usually accompanies one of the radiation forms mentioned above.

A gamma-ray has no mass and no charge. Therefore, when a gamma-ray photon emits from a radioactive atom, the mass number or the atomic number does not change. Gamma radiation has the lowest ionizing power, but the highest penetrating power. The high penetrating power can cause damage in internal organs and bone marrow [4].

### **2.1.4 Half-life**

When an unstable nucleus emits all its excess energy in the form of ionizing radiation, a stable state is achieved and the nucleus is no longer radioactive. Consequently, a radioactive source will become weaker with time and eventually become more stable. The half-life describes the average amount of time it takes to reduce the activity by half, and depends on the isotope. An example is the isotope radon-222, which has a half-life of approximately four days. Uranium-238, on the other hand, has a half-life of 4.5 billion years. In order to calculate the strength of an isotope, it is necessary to know the activity it had when it was produced and its half-life [5]. Figure 2 shows number of half lives until 0% of a substance is remaining. This is a general example and does not show a particular isotope.

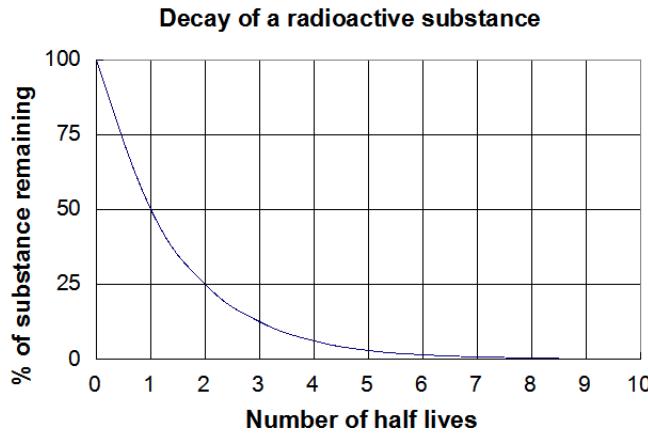


Figure 2: The decay of a radioactive substance over time [6].

## 2.2 Electromagnetic radiation

Electromagnetic radiation is a form of energy that occurs as waves and photons. This radiation is a consequence of electric and magnetic fields, which are perpendicular to each other. The radiation has different names in terms of wavelength, visible light for example, has wavelengths in the area 400-700 nm. The wavelength says a lot about the properties of the radiation, shorter wavelengths cause higher energy and frequency [7]. All electromagnetic radiation travels at the same velocity ( $c$ ), which is about  $3 \times 10^8$  meters per second in vacuum [8]. The energy of a photon ( $E$ ) is described by Equation (2):

$$E = hf = \frac{hc}{\lambda} \quad (2)$$

Where  $h$  is Planck's constant,  $f$  is the frequency of the photon,  $c$  is the speed of light, and  $\lambda$  is the photon's wavelength.

X-radiation and gamma radiation, known as X-rays and gamma-rays, are also a type of electromagnetic radiation. X-rays and gamma-rays have relatively short wavelengths and are, as well as electromagnetic radiation, ionizing radiation. Ionizing radiation is radiation with enough energy to free electrons from an atom when the radiation passes through an object. The atom then becomes charged or ionized [9]. Only the high frequency portion of the electromagnetic spectrum is called ionizing. Alpha and beta particles are also categorized as ionizing. The particles carry a charge, which can interact with electrons in other atoms. Neutrons are ionizing due to the production of charged particles during collisions with atomic nuclei.

Both X-rays and gamma-rays have enough energy to remove an electron from an atom or molecule [10]. They cannot be detected by human senses and travel at the speed of light in straight lines [11]. X-rays have wavelengths from  $10^{-8}$  to  $10^{-12}$  meters. Gamma-rays have the shortest wavelengths, down to less than  $10^{-10}$  meters. Consequently, gamma-rays have the highest frequency and energy, even higher than X-rays [12][13].

Becquerel (Bq) is the unit used to measure the activity caused by radiation sources, and it is also a unit in The International System of Units (SI). One Bq is defined as one disintegration per second. Previously, curie (Ci) was the unit used for measuring the activity, but in 1978 the International Commission of Radiation Units and Measurements (ICRU) recommended a transition to Bq. One curie is equal to 37 GBq [5][11].

## 2.3 Imperfections in solids

Solid materials are often classified by how the atoms or ions are arranged in relation to each other. If atoms are arranged in a repeating pattern over large atomic distances, it is a crystalline material. The crystal structure consists of several unit cells, which indicates the simplest repeating array of atoms in a crystal. A unit cell consists of lattice points that represent an atom, an ion or a molecule in the crystal.

All solid materials contain defects or imperfections, which occur when the crystallographic patterns are interrupted. Defects in the structure affect the properties of the material, both beneficial and adverse. Crystal defects are classified according to the geometry or the dimension of the defect: point defects (zero dimension), linear defects (one dimension), and interfacial defects (two dimension) [8].

### 2.3.1 Point defects

Defects where an atom is missing or is in an irregular place is called point defects. Point defects occur only at or around single lattice points. A vacancy is an empty position in the crystal structure and is the simplest of the point defects. Vacancies exist in all crystalline solid materials, in fact, it is impossible to create a material without these defects. Another type of point defect is the self-interstitial, where an atom from the crystal occupies a small void space in the crystal structure, that usually is unoccupied. Self-interstitials introduce distortions in the lattice, because an interstitial position is originally smaller than the atom that occupies this position. Consequently, self-interstitials rarely occur in metals and only in low concentrations, lower than for vacancies [8]. Both a vacancy and a self-interstitial defect are shown in Figure 3.

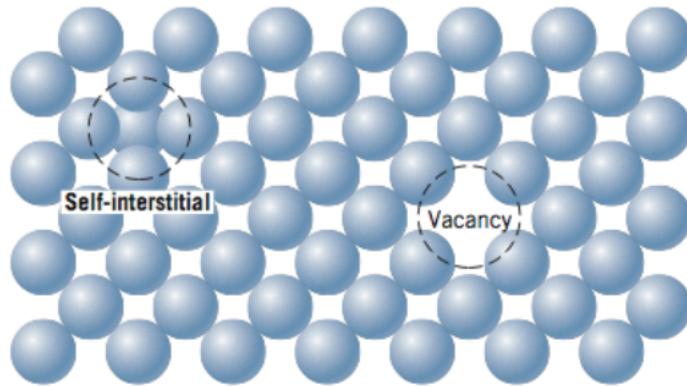


Figure 3: A vacancy and a self-interstitial defect [14].

Impurities in the crystal structure are also a form of point defects. A substitutional solid solution is when the impurity atoms replace the host atoms in the lattice. The impurity atom and the host atom are usually close in size. Foreign atoms are often added intentionally to affect the characteristics of the material, which creates an alloy. Alloys are used to improve mechanical strength and corrosion resistance. Interstitial impurities can also occur in the lattice structure. They are smaller than the bulk atom, and fill the voids among the host atoms. An example here is steel, which is made when carbon atoms are added into iron [8].

### 2.3.2 Linear defects

A dislocation is a linear defect, where atom groups occur in irregular places. Dislocations exist in all materials and move when a stress is applied. This motion of dislocations causes plastic deformation, which is a permanent distortion. A dislocation has important impacts on the mechanical properties, such as yield strength, hardness and ductility. There are two types of dislocations: edge dislocation and screw dislocation.

An edge dislocation is a defect that appears as an extra half-plane of atoms in the lattice. When enough forces are applied on one side of the crystal structure, the extra half-plane starts moving. This dislocation motion leads to rearranging and new atom bonds will occur, until the grain boundary is reached. When several edge dislocations are located in the structure, the deformation occurs easier than with less dislocations. Figure 4 shows an edge dislocation [15].

Screw dislocations are displacements relative to the lattice. The motion of these defects are perpendicular to the dislocation line, and are also caused by stress. Figure 4 shows the motion of a screw dislocation. The upper front region of the crystal moves one atomic distance to the right, relative to the bottom portion [8].

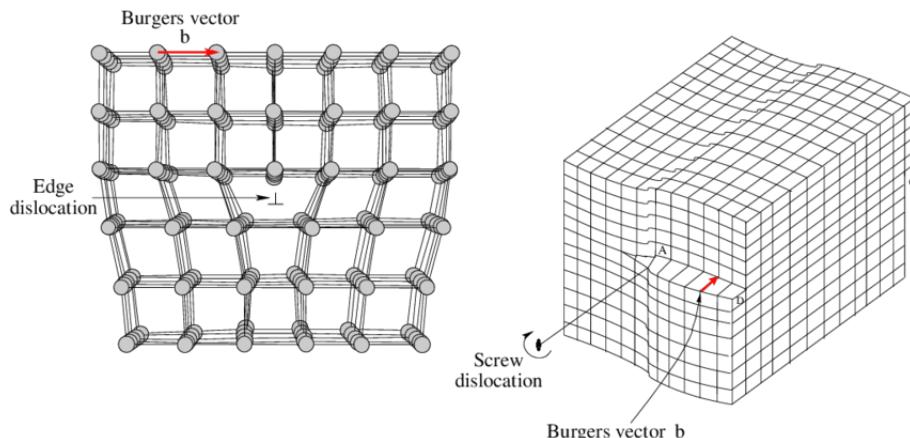


Figure 4: An edge dislocation and a screw dislocation [16].

Most linear defects found in crystalline materials are neither a pure screw or edge dislocation, but a combination of these dislocations [8].

### 2.3.3 Interfacial defects

Interfacial defects are interfaces between parts of the material that have different crystal structures. A grain boundary is a interfacial defect that separates two grains or crystallites in a polycrystalline material. Because of the orientation mismatch along the grain boundary, the grain boundary energy increases. To minimize the energy, the grains tend to grow in size at the expense of smaller grains. Grain boundaries are more reactive than grains themselves. Consequently, impurities often segregate along these boundaries [8].

Another type of interfacial defects are phase boundaries. They exist in multiphase materials where there is a sudden change in physical or chemical characteristics [17]. Both grain boundaries and phase boundaries play an important role in order to control the mechanical properties in metallic materials [8].

## 2.4 Non destructive testing

Non destructive testing (NDT) are methods used to identify defects or weaknesses of a material without affecting its chemical or physical properties. Due to the fact that the testing does not destroy the material, these methods are commonly used in the industry. There are several different NDT methods used for detecting defects, each of them having limitations and advantages. NDT methods can be categorized by the type of defect that can be detected. Visual testing (VT), magnetic particle testing (MT), penetrant testing (PT), and electromagnetic testing (ET) identify surface defects. Ultrasonic testing (UT) and radiographic testing (RT) evaluate volumetric characteristics and defects, such as wall thickness and internal flaws [5].

### 2.4.1 Ultrasonic testing

UT is one of the most important NDT methods in the industry. It is used to detect flaws in materials and welds, as well as dimensional measurements. The equipment used for inspection consist of a pulser/receiver, transducer and a display device. The pulser produces high voltage electrical pulses, which the transducer converts into mechanical energy, sound waves, in the form of high frequency ultrasonic energy [18]. The waves are sent through the material being tested. If the waves hit a discontinuity, like a crack, the energy will be reflected back to the receiver. The transducer then transforms the wave signal into an electrical signal, which is displayed on a screen [19]. This principle is shown in Figure 5.

In most cases, UT is performed manually, which requires professional qualifications of the operator [5]. UT can be used on most materials as long as the sound transmission is good, but cannot be used on porous materials because the acoustic will not pass through air, and will not provide usable results. An example of a material that will provide good results with UT is low alloy carbon steel [20].

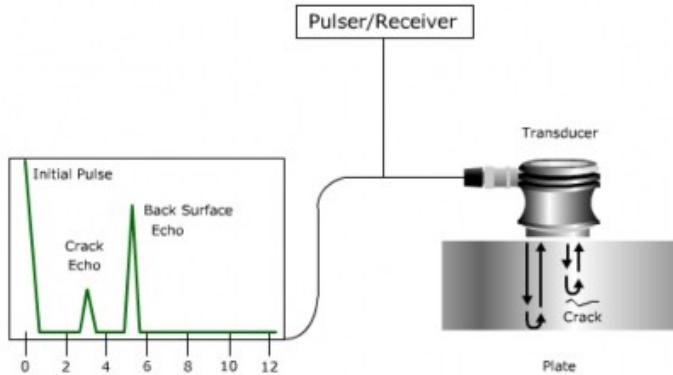


Figure 5: The principle of ultrasonic inspection using a single transducer [21].

An advanced method within ultrasonic testing is phased array ultrasonic testing (PAUT). The difference between conventional ultrasonic testing and PAUT is the number of elements in the probe, which consist of a pulser/receiver and a transducer. The probe in conventional ultrasonic testing usually consist of a single element that generates and receives high frequency sound waves. On the other hand, PAUT has 16 to 256 individual elements in the probe. Each element can be pulsed individually [22].

#### 2.4.2 Industrial radiography

Industrial radiography (RT) is used to monitor volumetric defects in materials and welds. RT can be used on all types of materials regardless of the thickness [23].

In industrial radiography the source of the ionizing radiation is placed at a certain distance from the test object. A collimator or an X-ray tube (depending on source of radiation) is placed in front of the test object. The collimator narrows the beam of radiation, and insures that the beam is emitted in the wanted direction. On the other side of the test object, a radiographic film is placed, the film is a detector of radiation.

Ionizing radiation is emitted from the source and penetrates through the material. Defects can be identified on the film through increased density due to less material being penetrated. Lighter areas on the film indicates that the beam has passed thicker goods. In darker areas, the beam encountered less resistance, which indicates errors in the structure. The rays will move in a straight line, causing the detected error to be placed in the same location in the object as on the film. The defect will appear on the film after photographic development. Photographic development transforms the latent image into a visible image. Figure 6 shows a beam of radiation that is sent from a radiation source and hits an object with a defect [5].

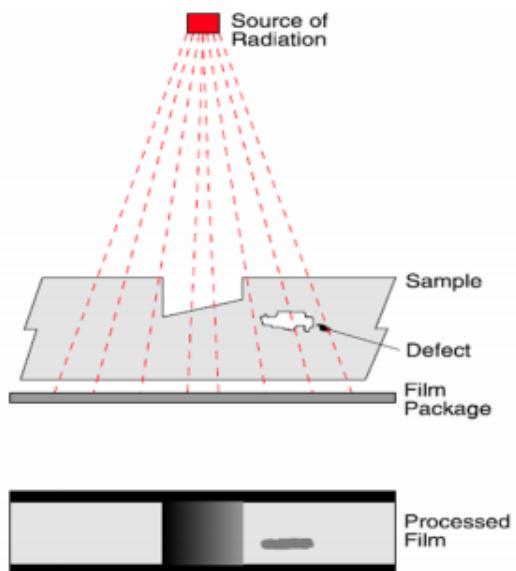


Figure 6: The principle of a radiographic test. The beam of radiation hits an object with a photographic film. The film will show any defects after photographic development [5].

#### 2.5 Radiation sources

Different sources of ionizing radiation can be used in RT, based on for example the thickness of the object and access. The sources of radiation that are commonly used are X-ray tubes that produce X-rays and certain isotopes that emit gamma-rays.

### 2.5.1 X-ray tubes

X-ray tubes are used as a source of radiation in industrial radiography. The tube consist of two electrodes, a positively charged anode and a negatively charged cathode. They are placed inside a vacuum tube made of glass. The cathode is a filament of tungsten, and is heated by an electric current. It is made of tungsten, because of its high atomic number and melting point. The cathode then expels the electrons, and the steam of electrons are focused into a beam. When the accelerated electrons collide with a target on the anode, a small part of their energy is converted into X-rays. The rest of the energy (98-99%) is transformed into heat. The anode must be cooled down due to its high temperature. This can be done in a number of ways, for example by natural radiation, forced circulation of liquid or gas, convection or conduction [11]. An example of the inside of an X-ray tube is shown in Figure 7.

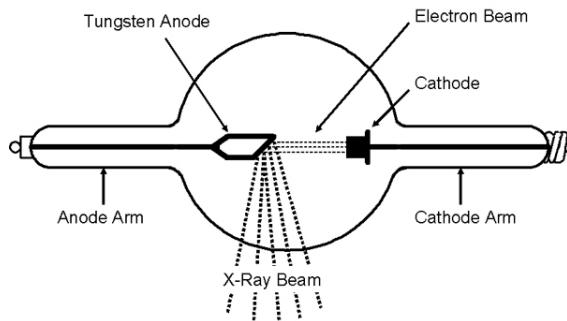


Figure 7: The inside of an X-ray tube [24].

The focal spot is the area on the anode struck by electrons from the cathode. It has to be large enough to avoid overheating, but at the same time as small as possible to achieve maximum sharpness of the image. The effective focal spot size is one of the factors that determines the sharpness of the image, and ranges from  $4 \times 4$  mm down to less than  $50 \mu\text{m}$  diameter. X-ray tubes with focal spots in  $0.5 \times 0.5$  mm range are called fine-focus tubes, and tubes with focal spots down to  $50 \mu\text{m}$  are called microfocus tubes. If the focal spot is smaller than this, they are called nanofocus tubes [11].

The voltage across the X-ray tube determines the hardness of the radiation. With high voltage X-ray tubes, the tube produces shorter waves (hard radiation), and with lower voltage the tube produces longer waves (soft radiation). The harder the rays, the greater the penetration capacity [25]. The maximum energy an X-ray tube can produce is determined by the voltage applied across the cathode and anode [5].

There are many different types of X-ray tubes, and they are often categorized by voltage. Tubes with voltages up to 320 kV are usually of the unipolar alternating current type. A commonly used 300 kV X-ray tube from Xylon is shown in Figure 8. They are mainly used for irregular, ambulatory work [11]. There are also battery powered X-ray generators and mobile X-ray systems in this category. Battery powered X-ray generators are very light and portable, but the voltage is below 200 kV, which means they cannot penetrate more than 25 mm of steel [26]. Mobile X-ray systems with high voltage cables with lengths up to 20 meters in the 100-225 kV range is shown in Figure 9 [27]. Tubes with voltages from 320 kV to 450 kV are usually of the bipolar direct current type. They are mainly for use on continuous, stationary work [11].



Figure 8: A 300 kV X-ray tube [27].



Figure 9: A 225 kV mobile X-ray system [27].

On the most common objects being tested, X-ray tubes with voltages up to 450 kV are suitable. For objects of extreme thickness Megavolt equipment is required. Megavolt equipment is built to operate in the 1 MeV to 16 MeV range. Examples of Megavolt equipment are Betatrons and linear accelerators [11].

X-ray tubes are also categorized as either pulsed or constant potential (CP). Both types of X-ray tubes have a transformer that charges a capacitor to a very high voltage. In pulsed X-ray tubes, a spark is generated when the capacitor is charged. This leads the electrons to the anode, which generates X-rays. In CP X-ray tubes the capacitor directly supplies the X-ray tube with voltage. The number of pulses and their frequency can be modified in pulsed X-ray tubes, but not the Kilovolts (energy of the electrons) and Milliamps (amount of electrons generated), like with CP X-ray tubes. More kilovoltages cause higher energy X-rays, which will result in deeper penetration. On the other hand, more mA generate more heat and reduce the exposure time. CP also has a longer lifetime than pulsed X-ray tubes [28].

The weight of the tubes is an important factor in industrial radiography. There are many aspects that determine the weight of a tube, and maximum voltage is one of them. Some examples are tubes in the 160-300 kV range, which weighs from 22-36 kg [27]. 320 kV tubes weigh about 40kg, and 450 kV tubes can weigh as much as 95 kg. These are all CP X-ray tubes [29]. As mentioned earlier in this section there are also mobile X-ray systems, shown in Figure 9. These mobile X-ray systems weigh approximately 180-190 kg.

### 2.5.2 Radioactive sources

Cobalt-60, iridium-192 and selenium-75 are the most commonly used isotopes in RT, and the isotopes are used as a source for gamma-rays [11]. Gamma radiation is used because it has the shortest wavelengths of all electromagnetic radiation, and therefore has an even greater penetrating power than X-rays [30]. The isotopes that are used in industrial radiography are shown in Table 1.

Table 1: Isotopes used in industrial radiography [11].

Element	k-factor	Average energy level (MeV)	Half-life
Cobalt-60	0.35	1.25	5.3 years
Caesium-137	0.09	0.66	30 years
Iridium-192	0.13	0.45	74 days
Selenium-75	0.054	0.32	120 days
Ytterbium-169	0.05	0.2	31 days
Thulium-170	0.001	0.072	1.9 years

As shown in Table 1, Co-60 and Ir-192 have the highest k-factor. The k-factor is defined as the activity, specific gamma-emission, measured at one metre distance. A higher k-factor will improve the sharpness of the radiograph, because the higher the k-factor is, the smaller the source can be [11]. However, there are many other factors than k-factor to consider when it comes to quality of an image. More about this in section 2.6.3, radiographic sensitivity.

The average energy level in MeV is also shown in Table 1, which is the energy of a single photon. Co-60, Cs-137 and Ir-192 are sources that produce high-energy radiation (hard radiation), and are therefore well suited for testing thick objects. Yb-169 and Tm-170 produce soft radiation, and are therefore more suitable for testing thinner objects.

It is important to use source holders and shielding, due to the fact that isotopes cannot be turned off. The source holders are usually made of nickel alloys, vanadium or titanium and are supplied in sealed, corrosion resistant capsules. Inside this container there is a layer of uranium, to shield the radiation. Uranium constitutes the largest weight proportion of the container [11].

During use, the radioactive source will be pushed forward through the tube into the collimator by a mechanical crank, and pushed back into a shielded position after ended exposure. Operators must control with a hand monitor that the radioactive source really is brought back into the sheltered position [31]. An illustration of the mechanical crank, source holder with an isotope and shielding, guide tube and collimator are shown in Figure 10.

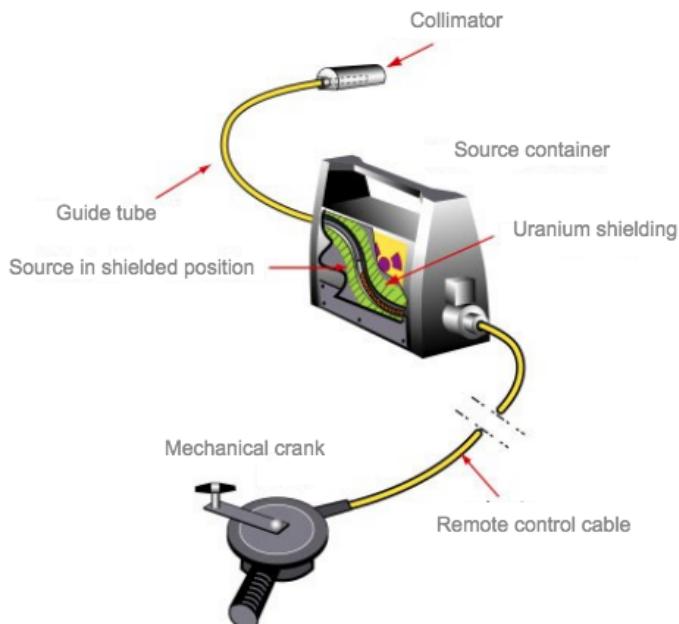
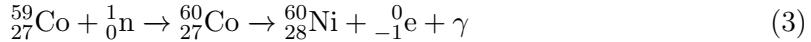


Figure 10: Isotope equipment used in industrial radiography [32].

The most commonly used isotopes in industrial radiography, Co-60, Ir-192 and Se-75, are produced artificially in nuclear reactors. Production of isotopes in reactors are based on neutron captures in a target material [33]. Co-60 is produced by bombarding Co-59 with neutrons in a nuclear reactor. The following decay produces the gamma radiation ( $\gamma$ ), as shown in Equation (3).



When neutron bombarding Co-59, it turns into Co-60. Co-60 emits beta and gamma radiation, while an isotope of nickel will remain [34]. Ir-192 is also produced in a reactor, where Ir-191 is bombarded with neutrons.

## 2.6 Radiographic films

The detector used in industrial radiography is usually a sheet of photographic films, also called radiographic films. They are held in a light tight cassette (vacuum package). The film has a very thin front surface that allows the X-rays to pass through easily. Behind the film there is a sheet of lead that is at least 0.25 mm thick to control backscatter radiation. Liquid chemicals are needed to develop the image on the film, which is why this process is called a "wet process" [11].

### 2.6.1 Structure

The radiographic film and the radiation source are placed on opposite sides of the test object. The film consists of seven layers. A cross section of the different layers are shown in Figure 11. In the middle there is a transparent cellulose triacetate or polyester base. The base gives the film its mechanical strength. On both sides of the base there is a very thin layer called the substratum, which bonds the emulsion layer (see Figure 11) to the base. The emulsion layer consist of microscopically small silver halide crystals. On the outer side of the film there is applied a layer of hardened gelatine to protect the emulsion [11].

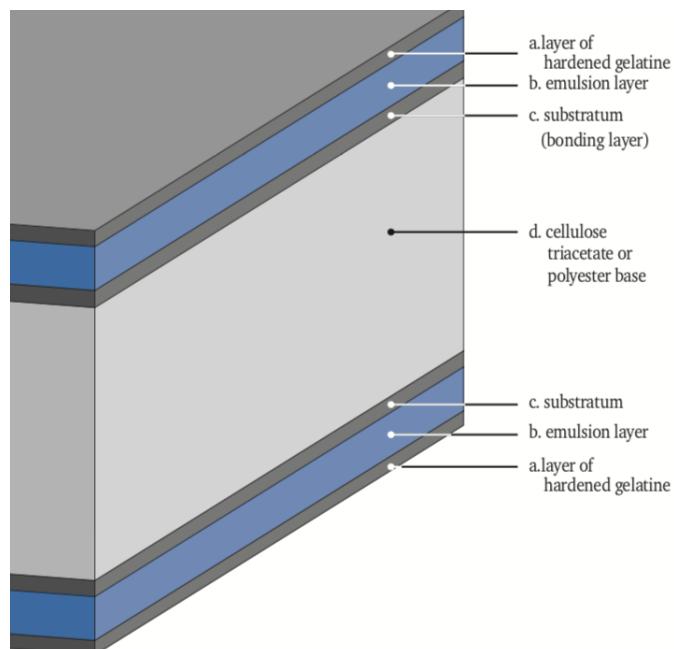


Figure 11: Cross section of a radiographic film [11].

### 2.6.2 Film system class and film types

The latent image is formed by ionizing the silver halide crystals upon exposure to radiation. It is the granularity and film speed (exposure time) that separates the different types of radiographic films. If the emulsion consists of very fine silver grains it is called a ultra-fine-grain film, which has a longer exposure time than films with bigger grains.

The EN 584-1 standard is used for classification of films in industrial radiography, and the classification is shown in Table 2.

Table 2: Classification of radiographic films [5].

Film system class	Grain size	Film speed
C2	Ultra fine grain	Very slow
C3 og C4	Fine grain	Slow
C5	Medium grain size	Fast
C6	Coarse grain	Very fast

The different films produced by Agfa are the following types in sequence of increased speed and granularity: D2, D3, D4, D5, D7 and D8, and the very fast films F6 and F8.

The exposure time of a film can be set relative to the exposure time of the manufacturer's standard film. The relative exposure factor is one for the standard films. For example if a film has a relative exposure factor of two, the exposure time needs be twice as long [11]. The relative exposure factors for the film types are shown in Table 3.

Table 3: Relative exposure factors and classification of films produced by Agfa [11].

Film type	Relative exposure factors					EN 584 -1
	100 kV	200 kV	300 kV	Ir192	Co60	
D2	9.0	7.0		8.0	9.0	C1
D3	4.1	4.3		5.0	5.0	C2
D4	3.0	2.7		3.0	3.0	C3
D5	1.7	1.5		1.5	1.5	C4
D7	1.0	1.0	1.0	1.0	1.0	C5
D8	0.6	0.6		0.6	0.6	C6
F6	0.174		0.132	0.389	0.562	
F8	0.03		0.022	0.035	0.040	

### 2.6.3 Radiographic sensitivity

An image with the highest amount of detail is desirable. To get as much detail as possible, careful control over a number of variables is needed. Radiographic sensitivity is measured by the smallest detail that can be detected, and depends on the contrast and definition of the image [35].

The density is measured by the darkness of the film after exposure and processing. The darkness increases with increased density. Low density means underexposure and high density means overexposure. The density is defined mathematically as the logarithm of the light in ( $I_i$ ) and light out ( $I_o$ ) as shown in Equation (4) [11].

$$D = \log \frac{I_i}{I_o} \quad (4)$$

Contrast describes the differences in photographic density in a radiograph [35]. It is measured by difference in blackening at two different areas on the film. High contrast means large differences in blackening. Usually, high contrast is desired to be able to find errors. However, if the contrast becomes too high, the radiograph will be either black or white [11][5]. High contrast compared to low contrast is shown in Figure 12. Radiographic contrast has two main contributors; subject contrast and film contrast. Subject contrast is dependant on the absorption differences in the material, the wavelength of the source of radiation, and intensity and distribution of secondary radiation due to scattering. Film contrast refers to density differences of the type of film being used, how it was exposed, and how it was processed [35].

Radiographic definition is the change from one density to another. Definition, also called sharpness, is used to indicate the separation of the boundary between different densities and the clearness of the fine detail in an image [36]. High density compared to low density is shown in Figure 13. Geometric factors of the equipment, the radiographic setup, and film and screen factors have an effect on the definition [35].

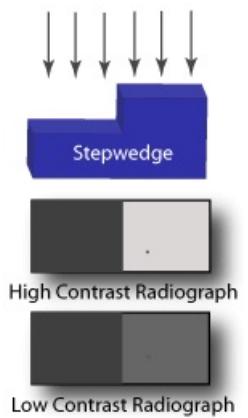


Figure 12: How the contrast impacts the radiograph [37].

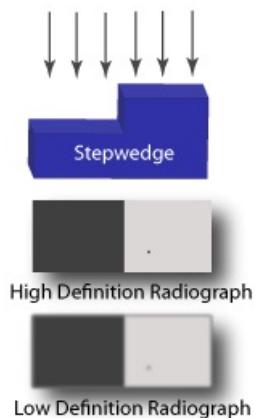


Figure 13: How the definition impacts the radiograph [37].

## 2.7 Computed and digital radiography

Methods that do not require chemicals to produce images are called "dry" processes. These methods use computers, and are therefore called computed radiography (CR) and digital radiography (DR). CR and DR have different strengths, advantages and limitations [11].

CR was the first dry technology available [38]. Even though CR is very similar to film-based systems, films are not used [39]. CR uses phosphor coated semi-flexible imaging plates in combination with computer processing, and is a two step process [11]. The imaging plate is run through a special laser scanner, also called a CR reader. The CR reader reads and digitizes the image. The image can then be viewed and enhanced using software with functions, such as contrast, brightness, filtration and zoom [40].

DR uses X-ray-sensitive rigid flat panel- or flat bed detector that directly captures data. This is immediately transferred to a computer system without the use of an intermediate cassette as in CR [41].

## 2.8 Cost

When it comes to equipment costs, this is typically 400 000-500 000 NOK for both radioactive source containers and X-ray tubes. In return, they last very long, maybe 20-25 years.

There are many other aspects than equipment cost to be considered when it comes to expenses. Some examples are source-replacements, emergency preparedness and response, transportation, storage, and development and maintenance of emergency procedures. When an Ir-192 isotope has been through a source-replacement and reaches 40 Ci, it costs 37 000 NOK, approximately 1000 NOK per Ci. Replacing a Se-75 isotope costs approximately 85 000 NOK, due to the fact that it has a maximum allowed energy level of 80 Ci during a source-replacement. When radioactive sources are used, there are own requirements for emergency preparedness and response. Equipment for rescue, emergency containers for storing sources after salvage and equipment for carrying a source are needed. Use and transport expertise and security systems adapted to the storage of radioactive sources are also a great expense, that is not needed with X-ray equipment. Developing and maintaining emergency procedures are needed for both gamma radiation and X-radiation, but it becomes much easier when the current can be cut, which stops the X-radiation [42].

## 2.9 Radiation hazards

Ionizing radiation, such as gamma- and X-rays, can cause changes in living cells due to absorption of radiant energy in the body. These changes can cause biological damage to humans. The most vulnerable organs are the bone marrow and the gametes. If irradiating of the genitals occurs, genes can be destroyed. These damages to the DNA can lead to malformations in descendants, often several generations after the radiation exposure [5].

Unlike X-ray tubes, gamma-isotopes cannot be turned off and will constantly emit radiation. The use of isotopes therefore requires a lot of shielding and safety measures. This applies to both the source containers and the equipment used, but also affects buildings and safety systems. During storage and transportation, the radiographic source must be located in an associated shielding container.

When performing a radiographic examination at a workplace, safeguards must be used to prevent personnel being exposed to radiation. These measures can for example be barriers, warning signs, signal lamps and acoustic indicators. It is common to have separate rooms for radiographic equipment, which must satisfy the requirements made by The International Commission on Radiological Protection (ICRP). The walls of the radiographic room usually consists of concrete and another material, such as lead or steel, to reduce the exposure. Those who use the radiographic equipment must have full control over the radiation area, stay where the radiation level is below set limits and protect themselves from radiation exposure. Anyone constantly working with ionizing radiation is required to record the radiation dose. This can be controlled with a personal dosimeter, worn by the personnel and the industrial radiography testers. The maximal dose rate the personnel can be exposed to in the radiation area is  $20 \mu\text{Sv}/\text{h}$  and outside it should not exceed  $7.5 \mu\text{Sv}/\text{h}$  [31][5]. In Norway, the personal dosimeters are sent to Norwegian Radiation and Nuclear Safety Authority (DSA) approximately every other month. DSA performs measurement services, which include dosimeter preparation and dispatch, and dose rate reporting. Then, each individual company must follow up the dose rate results for its own employees. If the dose exceeds 0.1 mSv per measurement period, the causes of the exposure are examined. DSA also helps examining to find the reasons for the high dose rates [43].

### **3 Approach**

This chapter consists of two parts. The first part concerns the preparation and execution of the interviews. The object with the interviews was to talk to people with experience in the industry, and ask them about their thoughts on the use of radioactive sources. The interviews also gathered information about radiographic testing and the industry. The second part describes the experimental work, carried out at the radiography strong room facilities at Axess AS in Orkanger. The objective with the experimental work was to enlighten one of the challenges connected to replacing X-ray tubes with radioactive sources. An Ir-192 isotope and a 300 kV X-ray tube was used on different pipes to compare the results.

#### **3.1 Interviewing preparation and execution**

There are different types of interviews and approaches that could be used in this type of project. In order to make up a conclusion, it was desirable to choose a method that could extract as much information as possible.

##### **3.1.1 Format of the interview**

A semi-structured interview was the method used throughout these interviews. Semi-structured interviews are an open form of interview, which allows the respondents to discuss the various questions and come up with new ideas [44].

The interviewer uses the questions, written down beforehand, as a guide to the conversation, but does not have a particular order or necessarily asks them all. The interviewer should use open-ended questions rather than close-ended questions that can be answered with "yes" or "no". This leads to longer and more supplementary answers, which later on must be interpreted and necessary information will be extracted from the answers. Leading questions should also be avoided [44]. The interview must contain terms and a language that the respondents understand, given their knowledge. This results in an interview guide, which is divided into different themes [45].

The order of the questions was considered when making the interview guide. It may be an advantage to start an interview with the less important, non-sensitive questions. This can, among other thing, make the respondents more comfortable [45]. Some basic questions related to industrial radiography were asked to start with. This was to get a soft start, but also to survey the respondents different experience and knowledge about industrial radiography. Further, questions related to the thesis question were asked.

The various respondents in this survey had different relations to industrial radiography, such as clients or suppliers. It was therefore important to consider the different relations when creating the interview guide. Research about each company was necessary before making the questions. The companies was sorted into three different groups, which resulted in three different interview guides; clients, suppliers and manufacturer. All of the interview guides started with the same basic questions about industrial radiography. Further, the respondents knowledge and position within industrial radiography had to be considered. The next questions were different in every interview guide, due to the different relations. Despite the different division, the last part in all three interview guides were related to this project's thesis question. Some of the questions had to be adjusted or omitted during the interviews, because of the respondents earlier answers.

Based on the information gathered from the first interviews, it was necessary to make some extra questions related to ultrasonic testing. The first basic questions about industrial radiography and the questions related to this project's thesis was still present, but the middle part was mainly about ultrasonic testing. As these questions were different from the three interview guides, and only made for one company in a retrospect, it was not a part of the interview guide.

### **3.1.2 Selection of respondents**

The selection strategy used to chose respondents was to find people working with industrial radiography, and with knowledge about the development in the industry. The external supervisor helped finding relevant people and their contact information. The respondents were also asked if they knew anybody that could be contacted regarding this project, which led to more people with knowledge concerning the thesis question. The selected respondents were employees from following companies: Aker BP, FORCE Technology, Holger Hartmann, NDT Nordic, Oceaneering, Teledyne ICM and Wintershall. Also Norwegian Radiation and Nuclear Safety Authority (DSA) was contacted, with the aim of receiving literature relevant for this project.

### **3.1.3 Speech to text**

When the interviews were carried out there were two interviewers present. One person asked questions, while the other one wrote down the respondents answers. Most of the interviews took place over the phone. One of the selected companies called in for a meeting, that consisted of presentations and discussion, which later on was converted into an interview. After the interviews, the answers were written from an oral to a written language. Then the interviews were sent back to the people involved, so they could approve their answers and add more information if wanted. The approved interviews are attached in Appendix A-G.

### **3.1.4 Interpretation of data**

In the process of interpreting data, information that had similar contents was put together and compared to make it easier to evaluate data against theory. The various answers were interpreted and divided into different sections. The division of the sections was based on recurring similarities and differences in the respondents answers, which for example could be different meanings surrounding disadvantages and different future solutions. Finally, the different sections was decided to be use, transport, safety, possible replacements and economy. This division will also appear in the discussion chapter.

## 3.2 Experimental work

### 3.2.1 Materials

In the experimental work, three different test objects were examined with both an Ir-192 isotope and a 300 kV X-ray tube. To be more specific, a YXLON smart evo 300D was used as the X-ray source. It features a combination of 300 kV and 900 W constant potential X-ray power, and weighs 29 kg [46]. Table 4 shows the different test objects' parameters, such as lift-off, and their dimensions. Lift-off is the spacing between the cladding and the pipe.

Table 4: The different dimensions of the three test objects.

	Test object 1	Test object 2	Test object 3
Pipe diameter [mm]	114.3	168.3	90
Material thickness [mm]	3.05	9.1	18
Cladding [mm]	2.00	1.00	-
Lift-off [mm]	45	40	-

### 3.2.2 Radioactive source

A crank-out mechanism was attached at one end of the source holder, and a guide tube was attached on the other side. A collimator was connected to the other end of the guide tube, and set up to make the radiation beam hit the pipe and film. The collimator was placed a certain distance from the film. Duct tape was used to attach the film on the other side of the pipe from the collimator. The parameters chosen for the different test objects are shown in Table 5. They were chosen based on experience, but a number of radiographic modeling programs are also available. Conditions, such as type of film, density, activity, thickness and source-to-film distance, impact the exposure time, and are therefore put into the radiographic modeling program to find the necessary exposure time.

Table 5: Test matrix for the test objects inspected with an Ir-192 isotope.

Test object	Source-to-film distance	Exposure time
1	700 mm	20 sec
2	700 mm	3 min
3	500 mm	3.5 min

Setup for test object 1 is shown in Figure 14. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 5.



Figure 14: Setup for test object 1 with an Ir-192 isotope as radiation source.

Setup for test object 2 is shown in Figure 15. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 5.



Figure 15: Setup for test object 2 with an Ir-192 isotope as radiation source.

Setup for test object 3 is shown in Figure 16. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 5.



Figure 16: Setup for test object 3 with an Ir-192 isotope as radiation source.

### 3.2.3 X-ray tube

The pipes were also tested with a 300 kV X-ray tube. The tube was put on a lift, and set to the same height as the pipes. The parameters chosen for the different test objects are shown in Table 6. They are chosen the same way as for radioactive sources, based on experience and/or radiographic modeling programs.

Table 6: Test matrix for the test objects inspected with a 300 kV X-ray tube.

Test object	Source-to-film distance	Exposure time	Current
1	700 mm	20 sec	1.5 mA
2	700 mm	25 sec	3.0 mA
3	500 mm	25 sec	1.5 mA

Setup for test object 1 is shown in Figure 17. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 6.



Figure 17: Setup for test object 1 with a 300 kV X-ray tube as radiation source.

Setup for test object 2 is shown in Figure 18. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 6.



Figure 18: Setup for test object 2 with a 300 kV X-ray tube as source of radiation.

Setup for test object 3 is shown in Figure 19. The dimensions of the test object are shown in Table 4 and the source-to-film distance is shown in Table 6.



Figure 19: Setup for test object 3 with a 300 kV X-ray tube as radiation source.

### 3.2.4 Film processing

After the film was exposed to either gamma radiation or X-radiation, the film was scanned in a HD-CR 35 NDT portable Imaging Plate Scanner. The scanner is shown in Figure 20. After scanning, the digitized images were viewed and enhanced using a software with functions, such as contrast, brightness, and zoom. If possible, the wall thickness was found using known measurements.

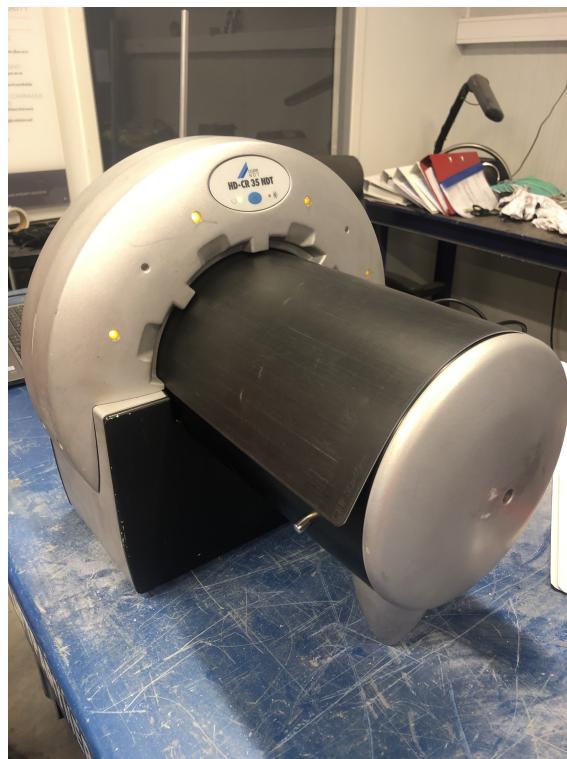


Figure 20: HD-CR 35 NDT portable Imaging Plate Scanner.

## 4 Results

The experimental work was carried out to look at the difference in image quality when using an Ir-192 isotope and a 300 kV X-ray tube on three different pipes. This section presents the test results from the experimental work. The results from test object 1 are presented first, followed by the results from test object 2 and 3. Computed radiography was used to produce the images.

### 4.1 Test object 1

Figure 21 shows the image taken with an Ir-192 isotope on test object 1, and the dimensions of this test object are shown in Table 4. The parameters associated with this set up are shown in Table 5. This image shows a clear inner wall. Consequently, precise measurements were found.

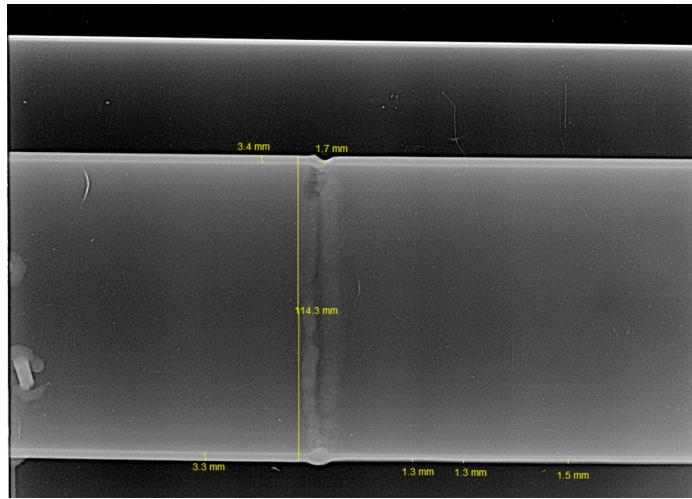


Figure 21: Test object 1 inspected with an Ir-192 isotope.

Figure 22 shows the image taken with a 300 kV X-ray tube on test object 1, and the dimensions of this test object are shown in Table 4. The parameters associated with this set up are shown in Table 6. This image also shows a clear inner wall.

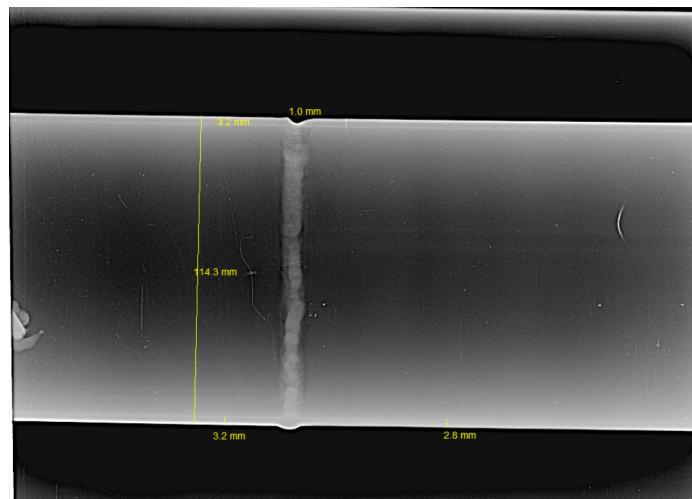


Figure 22: Test object 1 inspected with a 300 kV X-ray tube.

## 4.2 Test object 2

Figure 23 shows the image taken with an Ir-192 isotope on test object 2, and the dimensions of this test object are shown in Table 4. The parameters associated with this set up are shown in Table 5. This image shows a clear inner wall and a pipe clamp.



Figure 23: Test object 2 inspected with an Ir-192 isotope.

Figure 24 shows the picture taken with a 300 kV X-ray tube on test object 2, and the dimensions of this test object are shown in Table 4. The parameters associated with this set up are shown in Table 6. This image shows a pipe clamp, but no inner wall. Consequently, it is impossible to find the measurements, and this image cannot be used to find a corrosion rate.

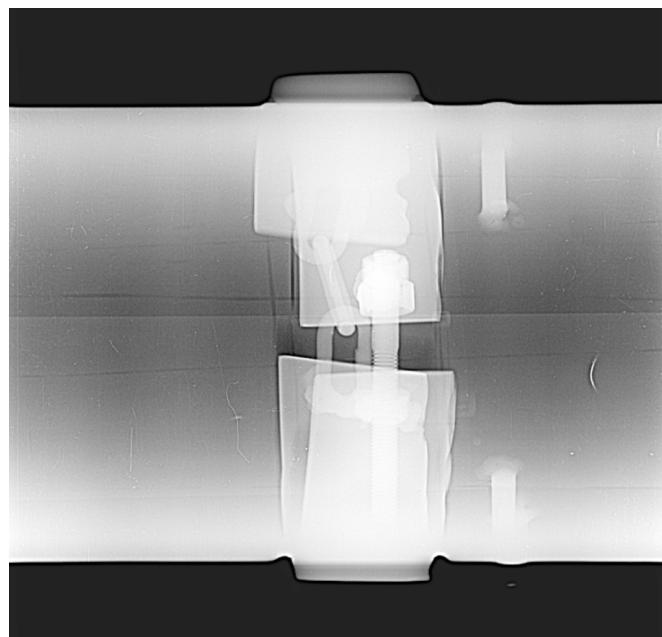


Figure 24: Test object 2 inspected with a 300 kV X-ray tube.

### 4.3 Test object 3

Figure 25 shows the picture taken with an Ir-192 isotope on test object 3, and the dimensions of this test object are shown in Table 4. The parameters associated with this set up are shown in Table 5. An inner wall was detected, and the measurements were found.

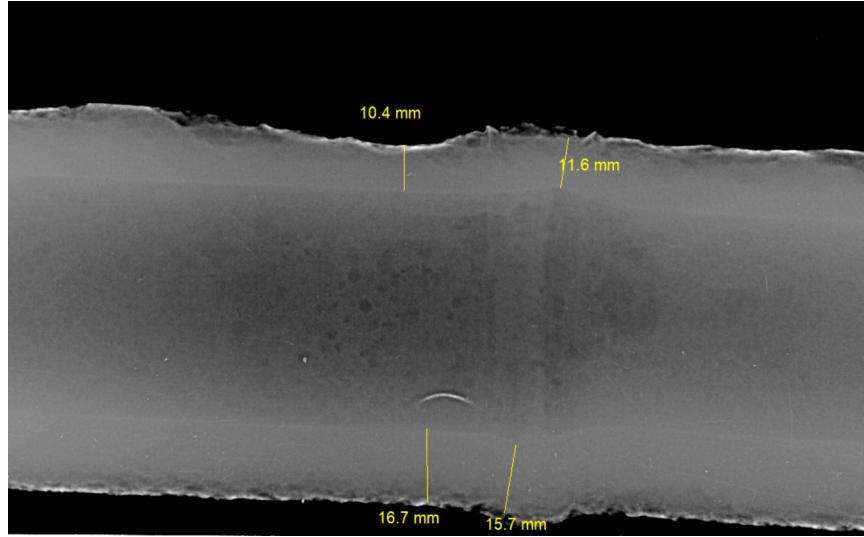


Figure 25: Test object 3 inspected with an Ir-192 isotope.

Figure 26 and 27 show the pictures taken with a 300 kV X-ray tube on test object 3, and the dimensions of these test objects are shown in Table 4. The parameters associated with this set up are shown in Table 6. The images are blurry and no details were detected in these figures.

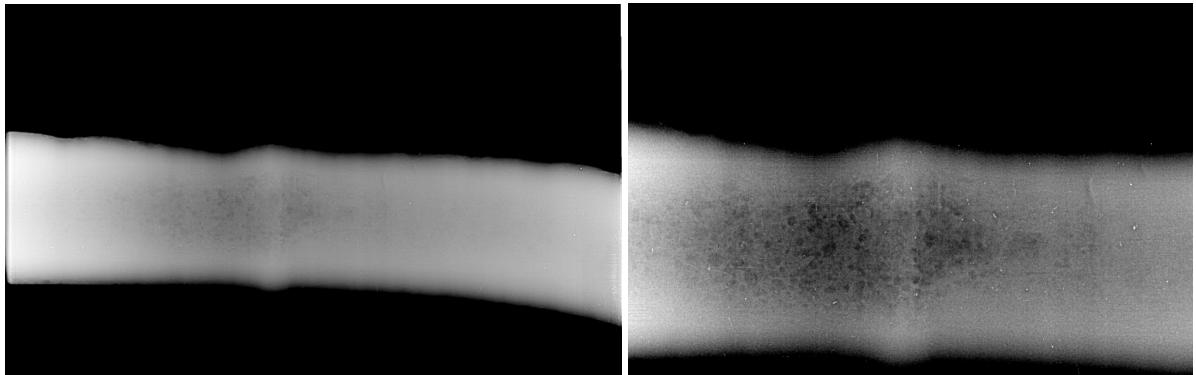


Figure 26: Test object 3 inspected with a 300 kV X-ray tube. This picture has a low tonal contrast.

Figure 27: Test object 3 inspected with a 300 kV X-ray tube. This picture has a high tonal contrast.

## 5 Discussion

This section contains a discussion about the possibility of eliminating radioactive sources in industrial radiography. First, the challenges and advantages of replacing radioactive sources are discussed. Then, the possible replacements, such as X-ray tubes and UT are presented. The results regarding the experimental work are discussed together with image quality in the section about X-ray tubes. The interesting findings from the interviews regarding the thesis question are also taken into consideration and discussed. The interviews are attached in Appendix A-G. The interview with Wintershall is attached as Appendix A, Oceaneering as Appendix B, FORCE Technology as Appendix C, Holger Hartmann as Appendix D, NDT Nordic as Appendix E, Aker BP as Appendix F and Teledyne ICM as Appendix G.

### 5.1 Challenges related to radioactive sources

Replacing radioactive sources in industrial radiography creates challenges, because it is difficult to maintain the benefits these sources. It is desirable to eliminate the use, but the replacement must be favorable and the substitute should preferably be better. The use of radioactive sources may be avoided by using a different source of radiation or inspection method.

#### 5.1.1 Use

An important situation to be aware of is the exposure of ionizing radiation during use of radioactive sources. During inspections, the radioactive source will be pushed forward in an irradiation position, and pushed back to a shielded position after use (see Figure 10). After use, it is important to control that the source has returned to its container. The operators are responsible for this, and they control the return with a hand monitor [31]. Wintershall mentioned this as a challenge with isotopes during use. When using isotopes as the source of radiation, the radiation must constantly be measured. This helps the operators to be sure that the source has returned to its container.

When performing a RT inspection, specific guidelines must be followed. The requirements are a consequence of the ionizing radiation, which can cause damages to people if the source of radiation is not properly handled. One of the requirements for performing an RT inspection is that there must be two operators, which is an economic argument for the elimination of radioactive sources. Even though the amount of radiation needs to be carefully controlled at RT inspections, other activities, like flying an aircraft, can expose people to greater amounts of radiation [47].

Another aspect to consider is the isotopes' lifetime. They have to be replaced approximately once or twice a year, due to their half-life. FORCE Technology and Oceaneering mentioned this as an issue connected to the use of radioactive sources. The source activity is halved every 120 days for Se-75 and every 74 days for Ir-192, shown in Table 1 [11]. There are also requirements for maximum source activity when a source-replacement is necessary. Se-75 has a maximum allowed source activity of 3000 GBq and for Ir-192 it is 1500 GBq [48]. The isotopes are normally usable until 185-740 GBq, which means they have to be replaced based on their half-life and source activity. Even though the source activity drops below a usable level, the isotopes still emit radiation.

As the radioactive sources never stop emitting radiation, they always require shielding. When the isotopes are useless, the companies send them back to the supplier, who sends the isotopes back to their country of origin. There, the sources are placed in barrels or boxes and molded into a suitable landfill, for example in excavated rooms inside mountains. The waste should be stored there for a long time. A landfill must be designed such that the nature on the outside of the landfill is not contaminated by radiation [49]. This is not the most demanding or most expensive part of the process, but also desirable to avoid.

### 5.1.2 Transport and safety

Radioactive sources release radiation constantly, which requires several safety measures during transportation, storage and use. FORCE Technology pointed out transport as a problem with the isotopes, because they are more expensive to transport and handle due to the safety requirements of dangerous goods. The isotopes also need their own approved space for storage. The transportation takes place in shielded containers, made of powerful damping material, specially designed for radioactive sources to minimize the exposure to the surroundings. These sources require a vehicle that is marked with radiation warning signs. The driver also needs to be qualified to transport dangerous goods. If inspections with radioactive sources take place offshore, the sources need to be transported by boat. Transportation by boat takes longer time than a helicopter, which may be unfortunate considering the isotopes' half-life. This transportation, compared with a helicopter, will not be a problem at first, but could make a difference in the long run as the isotopes become weaker.

Concerning safety, a big problem with the radioactive source is if the isotope gets stuck after use, and cannot return to the container. This can occur if there is any damage to the guide tube or if the guide tube has been exposed to high temperatures. In this situation, the operator no longer has control over the radiation area, which in the worst case scenario can cause radiation injuries to the people. If such a situation occurs, the area needs to be blocked and assistance must be called. This is an extreme case, which rarely happens, but is worth mentioning when it comes to potential unfortunate situations regarding exposure of radiation [31]. This is a situation that can be avoided if radioactive sources are replaced by other sources or inspection methods.

### 5.1.3 Image quality

An important aspect to consider when using RT as an inspection method is the quality of the image. High quality images usually mean images with high contrast and high definition. Wintershall mentioned that the companies using RT to inspect pipes and welds, often want to choose the source of radiation that produces the highest quality image, to get as much details as possible. Wintershall has tried to use X-ray tubes instead of isotopes, for technical reasons, which resulted in better images (higher contrast). They also prefer using a Se-75 isotope if it has enough power to penetrate the thickness that is relevant, because the image resolution becomes better than with an Ir-192 isotope. Oceaneering also stated that Se-75 has less energy than the Ir-192, but gives better contrast in the images. This is due to the fact that harder radiation, causes more silver halide crystals in the film to be exposed to radiation at the same time. Consequently, the image can become more grainy. Generally, sources with lower voltages will result in pictures with high contrast. FORCE Technology also pointed out that X-ray tubes provide images with better resolution, which makes it easier to detect small cracks [35].

The hardness of the radiation is only one of the factors that determines the quality of the image. The factors mentioned in the section above determines the subject contrast. Type of film being used, how it was exposed and how it was processed determines film contrast. Wintershall also said that the focal spot size and the size of the isotope have an impact on the quality of the image. The focal spot size has to be large enough to avoid overheating, but at the same time as small as possible to achieve maximum sharpness [11]. As the source size decreases, the radiograph will become clearer. Focal spot size and the size of the isotope are factors that determines the definition (sharpness), but source-to-object distance and film and screen factors also effect the sharpness of the radiograph. A longer source-to-object distance causes the sharpness to increase. However, a longer source-to-object distance will lead to a reduction in radiation intensity [35]. The last set of factors concern the film and screen factors. An image with a higher level of definition appears when using a fine grain film rather than a coarse grain film.

## 5.2 X-ray tubes

X-ray tubes usually produce a better image than isotopes, if they have enough penetration capacity. They are also easier to transport, due to the ability to turn the tube off, and they have a longer lifetime. However, there are some factors that make it difficult to replace radioactive sources with X-ray tubes.

### 5.2.1 Practical application

Explosion (EX) rated equipment was mentioned in the interviews with Oceaneering, FORCE Technology and NDT Nordic. At a facility there are several potential dangerous situations, which can cause major consequences in case of incorrect handling. For example, it will be necessary to prevent sparks formed by currents, especially related to the oil and gas industry, due to the explosion danger [50]. Electrical equipment being used in hazardous areas must be specifically designed, tested and certified to make sure it does not ignite an explosion [51]. The isotopes do not need an electric current, since they constantly emit radiation. This makes them a better source of radiation than X-ray tubes on for example oil production platforms.

One of the most important properties of the isotopes are mobility, due to their small size. Holger Hartmann stated that the access when using an X-ray tube creates challenges. The isotope containers are light compared to X-ray tubes, and have a guide tube which makes it easier to reach difficult areas. The X-ray tubes are big and heavy, and they have to be placed close to the area being tested [29]. Use of X-ray tubes will therefore be challenging in narrow areas. Lifting X-ray tubes, when areas of height should be inspected, is also a challenge worth mentioning. The mobility and light weight of isotopes are therefore something the industry takes great advantages of, which was pointed out in several interviews. Consequently, it will be difficult to reach the area that needs inspection with an X-ray tube.

### 5.2.2 Image quality

The X-ray tubes' penetration capacity, compared to isotopes, is also an important aspect to consider. The different isotopes have different penetration capacity. Co-60 has the highest penetration capacity, but are not used as much due to the fact that large areas have to be sealed off. Sometimes, the areas are even larger than a whole oil production platform. Ir-192 has a higher penetration capacity than Se-75. Both Se-75 and Ir-192 are commonly used in RT, and the choice of source depends on the thickness of the gods [11].

To get X-ray tubes with the same penetration capacity as Ir-192, the tubes become large and heavy, which make them difficult to use. The isotopes' penetration capacity is highly necessary to penetrate through thicker materials.

All the companies that were interviewed pointed out the penetration capacity as one the major reasons why isotopes cannot be replaced. X-ray tubes will provide clear pictures if the thickness is manageable. In many cases, the thickness will create problems when using an X-ray tube. This is because X-rays have a lower wavelength than gamma-rays, which results in a lower penetration capacity. When the X-rays hit an object with an higher wall thickness, the waves will not penetrate through the material due to the materials density. This leads to an unclear image. However, gamma- and X-rays have an overlap in the electromagnetic spectrum, from  $10^{-10}$  meters to  $10^{-12}$  meters [12][13]. This means that gamma- and X-rays can have the same penetration capacity in this area, but an X-ray tube with the same penetration capacity as an Ir-192 isotope will be heavy and unpractical. Se-75 isotopes are easiest to replace, because they have approximately the same penetration capacity as a 300 kV X-ray tube [11]. However, Ir-192 will be almost impossible to replace, due to the size of the tubes. An experimental work was carried out to look at the difference in image quality of the images taken with an Ir-192 isotope and the X-ray tube with the highest voltage available (300kV) at Axess in Orkanger.

#### Test object 1

Both tests performed on test object 1 resulted in clear pictures, with high contrast and definition. The images from both the Ir-192 isotope and the X-ray tube show the inner wall, which is important to find during an inspection. Wall thickness says something about how much of the material has corroded. Although both pictures are clear, a small difference in quality can be detected. Figure 21 (Ir-192) has higher definition, and Figure 22 (X-ray tube) has higher contrast. Consequently, the wall thickness on Figure 21 is easier to detect. Image quality depends, among other factors, on the penetration capacity, as mentioned. This test object has a relatively small wall thickness, which leads to good penetration for both X-rays and gamma-rays. The big difference in image quality will therefore not occur in this test.

#### Test object 2

On test object 2, a difference in image quality is more apparent than for test object 1. This is evident when comparing Figure 23 and Figure 24. The image in Figure 23 is taken with an Ir-192 isotope, and shows a clear inner wall and a pipe clamp. This image is sharper than the image taken with the X-ray tube in Figure 24. It is not possible to detect an inner wall, and therefore not possible to take measurements of wall thicknesses and other objects inside the pipe. The different image quality is probably due to the wall thickness of the pipe. Test object 2 had a wall thickness three times as thick as test object 1. The penetration capacity is less for the 300 kV X-ray tube than for the Ir-192 isotope, which has an average energy level of 450 kV, shown in Table 1. This means that the X-rays will not pass through the material, as the gamma-rays do. Consequently, the Ir-192 gives a usable image, but the X-ray tube will not.

#### Test object 3

The difference in image quality is quite obvious for test object 3, as seen in Figure 26 and 27. Test object 3 had the highest value of wall thickness. Figure 25, which is the test inspected with an Ir-192 isotope, shows a clear inner wall and it is therefore easy to measure the wall thickness. Due to this, a corrosion rate can easily be calculated. Figure 26 and 27 show the digitized images taken with a 300 kV X-ray tube, and by using a software the brightness, contrast and zoom are adjusted. By adjusting the contrast, a difference can be detected, but neither will give a clear picture. No matter how much the image is edited there is no possible way to find an inner wall. Consequently, the result when using an

X-ray tube on test object 3 is not usable. Both the sharpness and contrast are significantly better when using the Ir-192 isotope. Ir-192 reaches a higher energy level than the X-ray tube, which makes it possible to penetrate through thicker materials. On the other hand, it was written in section 5.1.3 that using a low kilovoltage generally will result in high contrast imaging [35]. However, there has to be enough energy for the radiation to pass through the material thickness. To get the best possible image the trick is to balance the kilovoltages to the material thickness. Consequently, X-rays will not penetrate completely through this test object, and Ir-192 will give a clear and usable image [52].

### 5.3 Ultrasonic testing

Several of the clients, suppliers and manufacturers who were interviewed suggested UT as a possible alternative for ionizing radiation in RT. PAUT, to be more specific, was the method suggested, which is an advanced type of UT [22]. One of the main advantages mentioned was that ionizing radiation could be avoided. Consequently, the strict shielding and safety measures associated with ionizing radiation will disappear. UT is safe for inspection personnel. A great advantage using UT, instead of RT, is that areas do not have to be sealed off, which means that the production can go on. Level indicators or flame detectors, will neither be affected when using UT. Others mentioned that benefits of using UT, are mobility and light weight. UT also only requires access on one side of the test object. This allows inspection in narrow and twisting areas, which also is one of the benefits related to radioactive sources [53].

However, some disadvantages make it difficult to replace RT with UT completely, which also appear in the interviews. The main restriction, according to FORCE Technology, Oceaneering and Aker BP, is that UT can not be used on pipes with isolation. The isolation will cause disturbances in the acoustic [20]. Wintershall and Holger Hartman also pointed out hot pipes and welds as limitations with UT. The probe can melt if the temperature gets too high. Contact between the probe and the hot pipe is unavoidable when using UT [54]. Contact between the probe and the test object can also present other challenges. Corroded objects requires sensitive handling not to be destroyed. If a probe comes in contact with a pipe with a very thin wall thickness, it can create damage to the pipe, which is unfortunate. Therefore, direct contact between the corroded area and the probe should be avoided, which is impossible when an inspection using UT should be implemented. Unpractical geometries can also cause problems when using UT, due to the incomplete contact between the probe and the test object. Examples of geometries that makes full contact difficult are corners and uneven surfaces.

Another disadvantage using UT is the necessary interpretation of signals. Inspection with RT can give a concrete image through the pipe or weld, where the wall thickness among other things can be detected. UT will also give an illustration of the pipe or weld, but the signals must be interpreted, which can be challenging according to FORCE Technology and Aker BP. As mentioned, PAUT is an advanced inspection method. This method has been repeatedly suggested by several companies as a possible substitute for radioactive isotopes. The most advanced methods require advanced knowledge and skills. According to Aker BP, training and maintenance of these skills can present challenges due to lack of competence. An image produced with RT, on the other hand, is much easier to read [5]. There may also be situations where the UT results are uncertain, and RT still must be used to confirm or disprove the UT result. The advantages of replacing RT with UT then disappears.

## 5.4 Economy

The industry is driven by customers' demands and willingness to pay. Economy is therefore an aspect to examine when considering eliminating radioactive sources in RT. Although the theory might say that replacing these sources is possible, it also has to be economic favorable for different sectors of the industry.

The radioactive sources used in RT need to be replaced several times during a year, due to their half-life. Replacing an Ir-192 isotope costs approximately 40 000 NOK each time. Replacing a Se-75 isotope costs approximately twice as much. On the other hand, Se-75 has a longer half-life, which means they do not have to be replaced as often [11]. Depending on how often a source-replacement is necessary, this can lead to a larger expense over time. A source container for the radioactive sources cost approximately 400 000-500 000 NOK, but this is a one-time investment and will last for 20-25 years, maybe more. Together with the cost linked to emergency preparedness and response, transportation, storage, and development and maintenance of emergency procedures, isotopes could be an extensive expense. An X-ray tube can cost approximately 500 000 NOK or more, which is considerably more than changing the radioactive source [42]. At the same time, the X-ray tubes do not need replacements, unless a part of the tube breaks. Then, there will be subsequent costs for new parts or repairs. This means that it should initially only be one investment cost when the X-ray tube is purchased. The financial gain therefore depends on the X-ray tube's lifetime. As Teledyne ICM pointed out the initial investment is cheaper for the isotope compared to the X-ray tubes, but in the long term the isotope will cost more, which makes the X-ray tubes favorable in the long run.

It will not be clear what is overall cheapest, but an assessment of each case is needed. This is mainly because of the small difference in investment cost. During the interviews, it was also confirmed that price is not the main deciding factor when the source of radiation is selected. Wintershall said that other factors, such as penetration capacity or available equipment, are more important. However, price will be a part of the total evaluation. If they have to purchase new equipment, they will look at what is available on the market, what it costs, efficiency and operating cost.

As the cost is not the most important factor when considering replacing radioactive sources in RT, other parts need to be involved in this replacement process. To accomplish the replacement, rules and requirements need to be set. This has to be done by the authorities, but maybe in cooperation with the industry. The bigger companies, such as Equinor, have a great impact on industry, that requirements can also be set by such companies. This was stated by FORCE Technology. Regulatory requirements related to radioactive sources seem to be a solution to reduce the use of radioactive sources.

UT was mentioned as a possible replacement for radioactive sources in some cases. According to Aker BP, UT is usually used as long as it is possible, and cost is not an important factor. However, UT is not accepted when international standards indicate radiography as a method of testing, also mentioned by Aker BP. Standards are therefore necessary to change if the proportion of inspections done with radioactive sources should decrease. If regulations attached to ionizing radiation are determined, UT is, currently, the best solution. Regulation attached to radioactive sources alone will make it possible to replace inspections done with the radioactive sources with both X-ray tubes and UT.

According to Wintershall, the marked is controlled by the suppliers. This is mainly because the clients do not have same technical expertise as the suppliers or manufacturers. The clients will therefore not have the necessary information to be able to make demands. As the suppliers depend on costumer requests, the lack of information and requirements by the costumers will also impact the suppliers and manufacturers. The suppliers and manufacturers make money by doing what the costumers want. As the costumer's desire

to discontinue the use of radioactive sources in RT is not strong enough, it will be more difficult for the suppliers and manufacturers to implement this. The market will meet the customer's needs, which today mean continuing the use of radioactive sources in RT.

## 5.5 Suggestions for further work

To implement the use of X-ray tubes in inspections, more testing is required. Portable X-ray tubes, with the highest penetration capacity possible, need to be tested to find the limits of maximum thickness they can penetrate. It is also necessary to test different materials, with different densities, to find a clear result and context. Even though more experimental work can figure out limits where X-ray tubes can give high quality images, the disadvantages of X-ray tubes mentioned in this project still makes it difficult to implement the use X-ray tubes in operational inspections.

There are also constantly new X-ray tubes appearing on the market. The advantages with the new tubes are considerably better image quality, and the fact that they are more compact and more powerful than ever. These tubes could be tested against applications where isotopes are considered necessary today.

To be able to make a strong conclusion, the thesis question needs to be more specific and restricted. RT inspections are used in many different situations, such as inspection of welds and corroded pipes. It is therefore necessary to look into a specific situation with different limitations. For example, look at operational inspections on corroded steel pipes under a certain thickness onshore.

## 6 Conclusion

The objective of this work was to assess the use of radioactive sources in industrial radiography. The sources are desirable to eliminate, due to radiation hazards. Technical reasons were also mentioned as an argument to eliminate radioactive sources. Interviews and an experimental work was conducted to look at challenges and disadvantages of radioactive sources, and to come up with possible replacements, such as X-ray tubes and UT.

Based on the interviews, several companies could inform and confirm that reducing the use of radioactive sources in RT with X-ray tubes is possible. Today, mobile X-ray systems and battery-powered X-ray tubes have the greatest potential to replace the sources. However, all of them said that X-ray tubes cannot replace isotopes in all applications yet, and that current technology still needs a development to implement a complete elimination. The experimental work confirmed that X-ray tubes do not have enough penetration capacity to be used on thicker pipes. On thicker pipes the Ir-192 isotopes' penetration capacity was needed to get images with high enough quality to detect the wall thickness.

Replacing radioactive isotopes with UT can be possible on pipes to a certain extent. The advantages are the mobility, light weight and no use of ionizing radiation. The challenges will occur with isolated, hot or corroded pipes and welds. Problems can also be related to areas where full contact between the probe and test object cannot occur, such as corners or uneven surfaces. If UT is going to be a possible replacement, the operator's competence and knowledge also need to be maintained and developed.

Additionally, requirements from customers or the authorities are necessary to implement the elimination of radioactive sources. Today, there are no guidelines saying that these sources should be avoided.

## 7 References

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# **Appendix**

## **Appendix A: Interview Wintershall**

### **Hva bruker dere industriell radiografi til i deres arbeid?**

Hovedsakelig bruker vi radiografi til kontroll av korrosjon på rør hvis de har stått i drift en stund. I noen tilfeller benyttes radiografi til testing på offshore strukturer, men dette er veldig sjeldent, stort sett bare dersom det lages nye sveiser.

### **Hvordan utføres testingen?**

Wintershall har en inspeksjonskontrakt med Oceaneering. Dersom noe skal testes har vi en inspektør offshore i en uke, før det kommer en til, så har en uke med to inspektører. Etterfulgt av en uke med en inspektør igjen. Deretter har vi en tre ukers perioden uten inspektør. Dette utgjør til sammen en 6 ukers periode. Den uken hvor to inspektører er tilstede utfører de radiografi dersom det er behov for det. Vi har en Se-75 isotop på plattformen, dersom det er behov for det.

### **Hvilke type røntgenrør og gamma isotoper bruker dere i deres testing?**

Vi bruker fortrinnsvis Se-75 isotop dersom den har nok kraft til å komme gjennom den tykkelsen som er aktuell. Da får du en mye bedre oppløsning på bilde enn med Ir-192.

### **Har dere noen standarder for hvilke type kilder som skal benyttes?**

Vi vil ha en best mulig teknisk kvalitet på bildet, slik at vi får sett mest detaljer. Det er i grunn det som er styrende for hva som velges. Så må vi selvfølgelig ha en kilde som er kraftig nok, slik at vi kommer gjennom den tykkelsen det er behov for.

### **Er pris er faktor som blir vurdert når dere vil ha undersøkt mulige feil/defekter?**

Det er ikke stor forskjell med tanke på eksponeringen, det betyr ingenting for vår del. Men dersom man bruker røntgenrør i motsetning til isotoper blir det mye mer riggetid.

### **Hva er fordeler/ulemper med gamma isotoper og røntgenrør?**

Jeg ser ingen vanskeligheter med å bruke isotoper. Det er en enkel testing, men uhell kan forekomme, selvom det er veldig lenge siden sist uhell. I bruk er isotoper veldig enkle, men ulempene er at man aldri kan slå de av. De må derfor plasseres en trygg plass. Røntgenrør, derimot, kan slås av, men her vil utfordringen være at de er tunge. Dette gjør at, selv med de minste røntgenrørene, vil det være vanskelig å komme til i høyden. En isotop vil da være mye enklere å ta et bilde med enn et røntgenrør, da det rett og slett ikke vil være fysisk plass til et røntgenrør enkelte plasser.

Co-60 har stort sett aldri vært brukt på plattformer, fordi det vil være så store områder som må sperres av, at hele plattformen må stenges. Det er ikke så veldig mange aktører i Norge som har Co-60 tilgjengelig. Betatron har blitt relativt enkle og kraftig i bruk, slik at en må skjerme primærstrålen og sørge for at den stråler rett opp.

Jeg er en av de som har jobbet hardt for å bruke røntgenrør fremfor isotoper, på grunn av tekniske årsaker. Vi vil få bedre bilder med røntgenrør. Men som sagt vil det, rent jobbmessig, vil det være enklere å jobbe med isotoper. Ved bruk av isotoper må en være påpasselig med å måle, da man ikke er 100 % sikker på at kilden fulgte med sveiven inn igjen.

### **Hva gjør dere med gamma isotopene når de ikke lenger er brukbare, sender ut nok stråling? Kildehåndtering?**

Da sender vi isotopen tilbake. Det er en viss tillatt styrke når en isotop kjøpes og skal benyttes til industriell radiografi. Vi kjøper ofte isotoper med litt lavere styrke enn det som er maksimalt tillatt fordi det gir mindre stråling, som til vår bruk passer bedre. Vi presser ikke grensen til den som er maksimalt tillatt for isotopene. Vi er mer interessert i å få en isotop med en liten fysisk størrelse, gjerne  $1,2 \times 1,2$  millimeter. Jo større fysisk størrelse en isotop har, jo dårligere kvalitet får vi på bildet. Det samme gjelder et røntgenrør. Brennflekken er avgjørende for hvor skarpe bilder vi får. Det er så enkelt at hvis en tegner en linje ut fra et punkt, så vil det være enkelt å se at bildet blir mye skarpere, enn om en opererer med et område.

**Drives utviklingen til NDT-bransjen mest av leverandørene som vil tjene penger eller de som har behovene, f.eks. oljeselskapene?**

Jeg tror at utfordringen er at oljeselskapene ikke har den tekniske ekspertisen som er nødvendig for å stille spesifikke krav. Derfor blir det veldig mye styrt av leverandør industrien. De store innenfor NDT Norge som Oceaneering og Aker Solution, blir nok styrt etter det utstyr det har på lager allerede. Det er klart det at hvis de skal kjøpe inn nytt utstyr vil de se hva som er på markedet, hva det koster der, effektivitet og driftskostnader.

**Hvordan kommer teknologien til å utvikle seg de neste årene? Hvor ser du for deg at vi er om fem år?**

Jeg har vært i bransjen i 45 år. Når jeg ser tilbake er nok den viktigste utviklingen at vi har fått tilført Se-75 isotop, som vi ikke hadde før. Det brukes også mye mindre Co-60, der er det begynt å bruke betatron som er et kraftig røntgenrør. Så på radioaktive isotoper tror jeg at det blir veldig liten utvikling de neste årene.

Det vi har sett de siste fem, kanskje åtte årene, er at det har kommet batteridrevne røntgenrør, som er mindre i størrelsen. Tidligere var det umulig å få et røntgenrør som ikke var noe særlig mindre enn 25-26 kg, noe som er litt tungt å håndtere. Nå har de blitt lettere og mindre. På dette området vil utviklingen gå fremover ved at de får bedre batterikapasitet, kraftigere røntgenrør og gjerne mindre størrelse, men jeg tror ikke de krymper noe veldig. Jeg håper en utvikling på CP-anlegg, at de blir mer robuste og enklere å bruke i felt. Jeg har lite tro på at det kommer til å skje, men det er et ønske.

Trenden i markedet nå er at man går mer og mer over på ultralyd, istedenfor å bruke radiografi, der det er mulig. Men på raffinerier er utfordringen det at det er så høye temperaturer at lydhodene smelter. Da er det enklere å sette opp en røntgenfilm, som kan plasseres noen cm ifra. Det blir ikke like godt bilde, men det blir bedre enn ingenting. Derfor må nok radiografi brukes lenge enda.

28.02.19

## **Appendix B: Interview Oceaneering**

### **Hva bruker dere industriell radiografi til i deres bedrift?**

Radiografi utgjør en stor prosent av det vi driver med.

Vi bruker radiografi i 2 hovedgrupper i vår bedrift.

1. Nysveis. Dette er stort sett landbasert industri. Her benyttes mest røntgenrør, CP-anlegg. I noen tilfeller benyttes også isotop.
2. Driftsinspeksjon. Det meste foregår på diverse installasjoner offshore, men også på noen landbaserte anlegg.

### **Hvilke typer røntgenrør og gamma isotoper bruker dere i deres testing?**

Vi eier 24 isotopbeholdere samt 5 røntgenrør 225 kV, 2 CP anlegg 160 kV.

Vi bruker selen (SE75) og iridium (IR 192) isotoper.

### **Finnes det standarder for hvilke typer kilder som skal benyttes? For eksempel hva skal til/hvilke typer feil skal til for at gamma-isotoper benyttes fremfor røntgen?**

Vi har prosedyrer vi bruker. Prosedyrene er bygd på internasjonale standarder (ISO 17636, ASME V) og kundekrav. Generelt kan en si at radiografi avdekker 3 dimensjonale feil. 2 dimensjonale feil kan være vanskelig å påvise. For å oppnå best mulig følsomhet vil det på ny sveis bli fortrukket bruk av røntgen. Røntgen gir «mye» bedre følsomhet. For å oppnå krav til følsomhet som er gitt i standarder er røntgen foretrukket.

Utfordringer som værforhold, tilkomst og geometri kan være avgjørende av strålingskilde.

### **Hva er forskjellen på isotopene? Hvilken type isotop brukes på hvilke typer feil som skal testes?**

Forskjellen på isotopene har med energien å gjøre. Se-75 har mindre energi enn Ir-192 men gir bedre kontrast på bildene og er derfor fortrukket isotop på ny sveis. Hverken Se-75 eller røntgen har nok energi til å penetrere tykke materialer, noe som gjør at Ir-192 da kan benyttes. Ir-192 er på grunn av sin høye energi fortrukket ved tangentiel teknikk. Dette er en teknikk for å teste rør for innvendig/utvendig korrosjon, erosjon (også gjennom isolasjon). Denne teknikken er mye benyttet.

ISO 17636 gir klare føringer på material tykklesegrenser for de forskjellige isotoper. Ved bruk av ASME V standard er Ir-192 en godkjent metode på tynnere gods.

Det ble nylig gjort en inspeksjon på 200 mm stål i Tyskland. Her ble det benyttet Co-60, selv om Betatron også kunne vært et alternativ. Oceaneering eier ikke Co-60 selv, så isotopen måtte leies inn. Grunnen til at Co-60 ble benyttet var at tyske myndigheter var skeptiske til pulset røntgenrør, da det er uenigheter rundt hvilken påvirkning dette røntgenrøret kan ha. I dette tilfellet kunne røntgenrøret gitt bedre bilder enn det isotopen klarte.

**Hva er fordelen med gamma isotoper? Hvorfor bruker dere det isteden for røntgenrør?  
Hvorfor strekker gamma isotoper til, men ikke røntgen på disse områdene?**

En stor fordel med isotoper er EX-sikre, som betyr at de alltid kan brukes i olje&gass industrien. Det finnes ikke røntgenrør som er EX-sikre. Den høye energien til Ir-192 er en fordel. Isotoper har fordeler når det er vanskelig geometri og tilkomst da utstyret trenger lite plass.

**Hvor lang “levetid” har et røntgenrør i forhold til gamma-isotopene ved industriell radiografi. Altså hvor lang tid tar det før utstyret må byttes ut? Kildehåndtering?**

Røntgenrør har lang levetid, men det kommer an på hvor mye en bruker det. Røntgenrør kan ha opp mot 15 års levetid. Isotopene skiftes ca. en gang i året (halveringstid isotoper). Beholderne til isotopene har en i mange år. Det er Holger Hartmann som distribuerer isotopene. De tar ut den gamle isotopen og skifter til nye isotoper i beholderen.

**Hvordan kommer teknologien til å utvikle seg de neste årene? Hvor ser dere for dere at vi er om fem år?**

Equinor er blant annet noen av de som jobber for å bruke mindre radiografi og benytte seg av mer ultralyd. Ultralyd kan gi gode resultater på korrosjon i små rør og det har vært en stor utvikling på ultralydfronten de siste årene. Ved uisolerte rør kan en bruke ultralyd fremfor radiografi. Grunnen til at man vil benytte ultralyd istedenfor radiografi er for å unngå stråling og avstenging av områder på anlegg. I tillegg er det nivåmålere på tanker og lignende vil bli påvirket ved bruk av radiografi. Dette er ønsket.

CUI, korrosjon under isolasjon, er et stort problem. Ved CUI vil stort sett kun røntgen (virvelstrøm i noen tilfeller, men det er ikke så effektivt) fungere.

**Har dere noen tanker/ideer om hva som kan erstatte gamma isotoper og om dere har noen tro på at dette kommer til å skje i nærmeste fremtid?**

Jeg tror ikke at batteridrevne røntgen vil erstatte isotoper fullstendig fordi de har ikke nok energi. Utvendig korrosjon kan en se med batteridrevne røntgenrør, men det blir for lite energi i røntgenrøret til å kunne se en utvendig og innvendig vegg (tangentiell teknikk). Så jeg sliter med å se hvordan dette skal kunne gå per i dag. Det har først og fremst med energi og sensorene å gjøre, men det er mange ting som spiller inn. Utvikling går raskt, så kanskje i fremtiden!

Batteridrevne røntgenrør er dyre og kan plutselig slutte å fungere. Med en isotop er dette stort sett ikke problemer, da isotopen er mekanisk. Det skal lite til før at røntgenrøret ikke fungerer. Den typen stråling en får fra et røntgenrør, i motsetning til strålingen fra en isotop, er ikke nødvendigvis noe bedre for HMS. Isotoper har høy energi, men ikke et bredt spekter. Det kan være verre å bli utsatt for røntgen, fordi en vil få et bredt spekter av stråler som inkluderer lavenergistråler. Volumet stråling en da blir utsatt for vil være mye større.

## Appendix C: Interview FORCE Technology

### **Hva bruker dere industriell radiografi til i deres bedrift?**

I FORCE brukes radiografi hovedsakelig til inspeksjon av rør i drift (*on-stream*) på offshore olje&gass-installasjoner. Også til samme bruk på landanlegg og til kontroll av nysveis onshore. Generelt brukes radiografi til å finne volumfeil (korrosjon/erosjon, porer, ufullstendig sveis, osv.). Radiografi egner seg spesielt godt til små dimensjoner (rørdiameter og veggtykkelse) der f.eks. vanlig ultralyd sliter med å få godt signal. Det er også nyttig med radiografi for å inspisere isolerte eller sterkt korroderte rør, siden man kan utføre inspeksjonen direkte uten mye forarbeid. Med andre NDT-metoder må man vanligvis fjerne evt. isolasjon, korrosjonslag og av og til også maling for å komme i direkte kontakt med metallet.

### **Hvilke typer røntgenrør og gamma-isotoper bruker dere i deres testing?**

Isotoper: Kobolt-60, Iridium-192, Selen-75

Røntgenrør: Mange forskjellige typer, fra store Betatron til mindre, batteridrevne røntgenrør

### **Finnes det standarder for hvilke typer kilder som skal benyttes? For eksempel hva skal til/hvilke typer feil skal til for at gamma-isotoper benyttes fremfor røntgen?**

Ja, det finnes mange standarder, f.eks. ISO, EN, ASTM, og ASME-standarder, som gir retningslinjer om hvilken type stråling som kan brukes til forskjellig godstykkelser eller feiltyper. Noen av disse standardene er vist under. Se f.eks. tabellen under neste spørsmål som er basert på EN ISO 17636.

Vanligvis vil selskapet som utfører radiografi ha en egen prosedyre for utførelse, og disse prosedyrene er basert på noen av disse standardene. Ofte benyttes ulike standarder etter hvor man befinner seg i verden.

Eksempel på standarder/koder:

- EN ISO 17636-1/2: *Radiographic testing. X- and gamma-ray techniques with film / digital detectors*
- ISO 5579: *Radiographic examination of metallic materials by X- and gamma-rays – Basic rules*
- EN 12679: *Determination of the size of industrial radiographic sources – Radiographic method*
- ASTM E 94: *Standard Guide for Radiographic Examination*
- ASME V / III: *Boiler and Pressure Vessel Code*
- ASME B31.3: *Code for Pressure Piping*

Eksempel på akseptkriterier:

- EN ISO 10675: *Acceptance levels for radiographic testing*
- ASME VII Div.1: *Welded vessels*
- ASME B31.3: *Chapt. Inspection, examination and testing*

Hvilken metode som benyttes handler ofte også om hva som er tilgjengelig på plassen, og hva slags type erfaring inspektøren har. Ofte må man finne et kompromiss med f.eks. én isotop eller ett røntgenrør som kan fungere til alle jobbene for å unngå for høy kostnad (utstyrssleie), selv om man ideelt sett ville brukt flere typer.

### **Hva er forskjellen på isotopene? Hvilken type isotop brukes på hvilke typer feil som skal testes?**

Hovedforskjellen er energinivået i strålingen og halveringstiden. Det er først og fremst tykkelsen på inspeksjonspunktet som bestemmer hvilken isotop man vil bruke – ikke feiltype. Man ønsker som regel å bruke så lite stråling som mulig pga. bedre bildekvalitet og mindre behov for avsperring, men til tykkvegget gods må man bruke det kraftigste utstyret for å klare å trenge gjennom. Tabellen under viser hvor tykt gods de ulike isotopene og røntgenrør klarer å trenge gjennom for akseptabel kvalitet på inspeksjonen.

Det er også stor forskjell i halveringstid for strålingen til de ulike isotopene, se eget spørsmål under ang. dette. Dette vil også påvirke hvilken isotope man ønsker å benytte, avhengig av hvor lenge man har behov for å kunne bruke isotopen.

Vi bruker en god del Se-75 istedenfor Ir-192. Selen-isotopen har en annen bølgelengde som gir finere bilder enn Ir-192, men kan ikke brukes på like tykt gods som Ir-192. På det aller tykkeste godset må det benyttes Co-60. Man kan også bruke kraftige røntgenrør (f.eks. Betatron) på relativt tykt gods.

<b>Radiation source</b>	<b>(Ref. EN ISO 17636)</b>	
	<b>Penetrated thickness, w, in [mm]</b>	
	<b>Test class A</b>	<b>Test class B</b>
<i>Thulium-170</i>	$w \leq 5$	$w \leq 5$
<i>Ytterbium-169<sup>1)</sup></i>	$1 \leq w \leq 15$	$2 \leq w \leq 12$
<i>Selenium-75<sup>2)</sup></i>	$10 \leq w \leq 40$	$14 \leq w \leq 40$
<i>Iridium-192</i>	$20 \leq w \leq 100$	$20 \leq w \leq 90$
<i>Cobolt-60</i>	$40 \leq w \leq 200$	$60 \leq w \leq 150$
<i>X-ray equipment with energy from 1 MeV to 4 MeV</i>	$30 \leq w \leq 200$	$50 \leq w \leq 180$
<i>X-ray equipment with energy from 4 MeV to 12 MeV</i>	$w > 50$	$w > 80$
<i>X-ray equipment with energy above 12 MeV</i>	$w > 80$	$w > 100$

<sup>1)</sup>For aluminium and titanium the penetrated material thickness is  $10 < w < 70$  for class A and  $25 < w < 55$  for class B

<sup>2)</sup>For aluminium and titanium the penetrated material thickness is  $35 < w < 120$  mm for class A

Ulike testklasser (A og B) etter hvor strenge akseptkriterier man benytter, dvs. hvor små feil man er avhengig av å kunne finne.

## **Hva er fordeler og ulemper med gamma-isotoper?**

Den største fordelen med isotopene er at utstyret er mindre i størrelse og vekt, og mye lettere å plassere der man ønsker. Dette er på grunn av den fleksible framføringsslangen der isotopen sveives ut under testing. Det vil si at man kan få plassert strålingskilden mer optimalt, spesielt når inspeksjonspunktet befinner seg i trangt område, for eksempel med mange rør ved siden av.

En annen fordel er at isotoper ikke trenger strømtilkobling, og kan derfor brukes «overalt». Det er dermed også EX-sikkert utstyr, som vil si at det ikke er en antenningskilde i tilfelle gasslekkasje. Dette er en fordel på olje&gass-installasjoner, der mest mulig utstyr må være EX-sikkert for å brukes i prosessanlegget. Man kan også bruke utstyr som ikke er EX-sikkert (f.eks. røntgenrør) hvis man har en arbeidstillatelse der man kontinuerlig utfører gassmålinger på arbeidsstedet, slik at man kan slå av utstyret i tilfelle det oppdages gass i området.

Isotoper har generelt noe større gjennomtrengningsevne enn røntgenrør, og kan derfor brukes på litt tykkere gods, men det er forskjell på gjennomtrengningsevnen til ulike isotoper og ulike røntgenrør, så de overlapper ofte.

Utstyret til isotoper er enklere og billigere i innkjøp enn røntgenrør, men selve isotopen må skiftes ut oftere pga. halveringstiden til strålingen. Isotoper vil være dyrere å transportere og håndtere på grunn av sikkerhetskravene til farlig gods, og behøver en egen godkjent plass å lagres på. Til offshore-bruk kan man ved behov transportere røntgenrør med helikopter, mens isotoper alltid må transporteres med båt. På land må man bruke en merket bil som er godkjent for radioaktive kilder.

Den største ulempen til isotoper er den kontinuerlige strålingen som medfører større HMS-risiko. På et røntgenrør kuttes strålingen når strømmen slås av, mens en isotop må skjermes kontinuerlig for å ikke være farlig.

En annen ulempe er dårligere oppløsning på bildene med isotop. Røntgenrør gir finere bilder og bedre oppløsning, slik at man av og til kan se feil som man ikke kan se med isotop – f.eks. større sjanse for å oppdage små sprekker. Men isotoper kan ofte gi bedre kontrast på bildene, slik at f.eks. rørveggen kommer tydeligere fram på bildet. Dette kan gjøre det enklere å se korrosjon.

## **Hvorfor bruker dere gamma-isotoper istedenfor røntgenrør? Hvorfor strekker gamma-isotoper til, men ikke røntgen på disse områdene?**

Hovedsakelig fordi det er lettere å plassere riktig, ref. spørsmål over. Det meste av dagens isotop-bruk kan erstattes av røntgenrør, men i noen tilfeller kan det være for trangt rundt inspeksjonspunktet til å plassere røntgenrøret i riktig posisjon. Dette kan forbedres etter hvert som det kommer mindre og lettere utstyr, men det skal mye til å slå plasseringsvennligheten til isotopen, der man har en fleksibel framföringsslange som kommer til omtrent overalt.

Tradisjonelt har også isotoper vært billigere i innkjøp pga. mindre komplisert utstyr, selv om det kan koste mer i drift f.eks. når isotopen skal transporteres og skiftes ut. Pris er en viktig driver for hva slags utstyr kundene ønsker til jobben.

## **Hvor lang “levetid” har et røntgenrør i forhold til gamma-isotopene ved industriell radiografi. Altså hvor lang tid tar det før utstyret må byttes ut?**

Levetiden for røntgenrør er veldig avhengig av hvor mye det brukes, der det først og fremst er Wolfram-glødetråden som gradvis forbrukes mens testingen pågår. Den forbrukes også raskere jo høyere strømstyrke det benyttes. Typisk levetid for et røntgenrør kan være 3–15 år.

Generelt har røntgenrør derfor en del lengre levetid enn isotoper, som der strålingen reduseres gradvis uavhengig av bruk. Ulike isotoper har forskjellig levetid, både pga. forskjellig halveringstid mellom de ulike typene, men også fordi det varierer hvor mye stråling de leveres med i utgangspunktet. Ofte kan strålingsdosen halveres noen ganger (ca. 3–4 ganger for Selen og Iridium) før den blir for svak, slik at isotopen typisk varer fra 6–18 mnd. Kobolt-isotopen varer mye lenger pga. svært lang halveringstid, men avgir så mye stråling at det er sjeldent den kan brukes offshore. Beholderen som inneholder Kobolt-isotopen kan fort veie 120 kg, og man må omtrent sperre av hele plattformen før bruk, så dette gjør den mindre egnet.

Halveringstid for de mest brukte isotopene til NDT:

- Iridium-192: 75 dager halveringstid
- Selen-75: 118 dager halveringstid
- Kobolt-60: 5,3 år halveringstid

## **Hva gjør dere med gamma-isotopene når de ikke lenger kan benyttes til inspeksjon/sender ut nok stråling? Kildehåndtering?**

De brukte isotopene sendes til land for opplading eller destruering, eller byttes med en ny isotop. Det er egne spesialfirmaer som tar hånd om disse. Isotopene må alltid sendes med båt, og det er strenge krav til hvordan de pakkes og transporteres.

## **Hvordan kommer teknologien til å utvikle seg de neste årene? Hvor ser dere for dere at vi er om fem år?**

Mindre, lettere og batteridrevne røntgenrør som blir mer plasseringsvennlige vil trolig overta for en del av dagens isotop-bruk, og på sikt kan dette overta helt for bruk av isotoper. Dette vil drives fram av krav og ønsker fra kundene (typisk oljeselskapene), i tillegg til forskjeller i kostnad mellom de to metodene. Det er vanskelig å si hvor mange år det vil ta, men kan gå fort hvis innkjøpsprisen for røntgenrørene går ned, eller hvis det kommer krav til det fra de største selskapene (spesielt Equinor).

Automatiserte NDT-metoder kan også overta en del for radiografi og andre manuelle NDT-metoder (ultralyd, virvelstrøm). Noen av disse kan erstatte deler av dagens radiografibehov.

## **Hva er utfordringene med å erstatte? Er det noe typer som er lettere å erstatte enn andre?**

De fleste inspeksjonsmetoder kan i prinsippet erstattes, men det blir et spørsmål om kostnad og sannsynligheten til å finne ulike feiltyper. Det meste i bransjen er drevet av kostnader, der laveste kostnad som regel vinner fram så lenge man kan leve med ulempene. Røntgenrør kan i prinsippet erstatte isotop i nesten alle tilfeller, bortsett fra der det er svært lite plass til å plassere strålingskilden.

Også andre NDT-metoder, f.eks. automatisert ultralyd (f.eks. P-scan) eller Phased Array ultralyd, kan erstatte mye av dagens radiografi-bruk. Disse gir ikke et bilde gjennom røret, men figurer som f.eks. fremstiller rørveggen for tolkning og rapportering. De fleste vanlige veggykkelsesmålinger kan i de fleste tilfeller erstattes helt av disse metodene.

Utfordringer med å klare seg helt uten radiografi (både isotop og røntgen):

- I noen tilfeller vil det være behov for å se på innsiden av røret, f.eks. belegg-oppbygning (scale) eller korrosjonsprodukter. Det er vanskelig å se for seg andre metoder enn radiografi for å kunne detektere dette. Termografi kan i noen tilfeller benyttes til dette, men avhenger da av at det er temperaturforskjell på utsiden av røret.
- Vansklig å benytte andre metoder enn radiografi for å undersøke andre materialer enn metaller, f.eks. betong/tre/kompositter.
- Det krever fjerning av isolasjon og evt. korrosjonsprodukter på utsiden av rør for å kunne benytte andre metoder. Dette blir en ekstra kostnad, selv om det lar seg løse med tid og ressurser.
- Komplekse geometrier (ventiler o.l.) kan være tilnærmet umulige å ta med vanlige ultralydmetoder, siden signalet er avhengig av refleksjonene til lyden som sendes gjennom.

**Har dere noen tanker/ideer om hva som kan erstatte gamma-isotoper og om dere har noen tro på at dette kommer til å skje i nærmeste fremtid?**

Etter hvert som mindre og batteridrevne røntgenrør blir lett tilgjengelig og til en akseptabel pris, vil dette trolig erstatte mye av dagens bruk av gamma-isotoper. Dette vil i stor grad drives fram av krav og betalingsvilje hos kundene. Røntgenrør kan erstatte isotoper til det meste av industriell radiografi allerede i dag, og har allerede gjort det på noen av installasjonene.

På andre installasjoner må de uansett klare seg uten radiografi allerede pga. at strålingen fra røntgenrør/isotop forstyrrer nukleoniske sensorer/nivåmåtere ombord og dermed skaper trøbbel for prosessen. Her har mer avanserte ultralydmetoder (Phased Array) overtatt for rør/utstyr som vanligvis ville vært inspisert med radiografi, dvs. tynnvegget gods eller små dimensjoner. Alternativt må all radiografi utføres mens anlegget er nedstengt (revisjonsstanser).

Et annet poeng er at man i større grad bør tenke på inspeksjon i designfasen på nye anlegg eller modifikasjoner, slik at det f.eks. konstrueres med større avstand rundt hvert rør slik at man får plass til plasskrevende inspeksjonsutstyr mellom. På noen områder er det i dag veldig vanskelig å komme til for å kunne inspirere skikkelig, og dette gjelder ofte også visuell inspeksjon og andre NDT-metoder. Hadde alt vært designet med tanke på inspeksjon, kunne man fint klart seg uten isotoper.

01.03.19

## **Appendix D: Interview Holger Hartmann**

### **Hva selger dere mest av til selskaper som bruker industriell radiografi til inspeksjon?**

Vi selger mest av vanlige røntgenapparat (220V) og isotop (Ir-192), deretter (Se-75). Vi kan også levere Co-60, men markedet er svært begrenset. Ir-192 og Se-75 brukes ofte i Nordsjøen, fordi energien de gir ofte er nødvendig ved on-stream (tilstandskontroll) og på grunn av at isotoputstyret egner seg bedre ved vanskelig tilkomst.

### **Hva er forskjellen på de ulike isotopene?**

Ir-192 har en høyere gjennomtrengningsevne og høyere energi. Ir-192 har sammenlignet med røntgen typisk 500kV, mens en Se-75 isotop trenger gjennom adskillig mindre, har ca. 180 kV. Her er det en ganske stor forskjell.

Se-75 penetrerer ca. 30mm stål og Ir-192 gjennom 60-80mm stål. Ved røntgenrør er gjennomtrengningsevnen avhengig av hvor mange kV de leverer. En kan få røntgenrør opp i 420 kV, men de fleste stopper på 300 kV som kan trenge gjennom ca. 64mm stål. Et røntgenrør på 200 kV kan gå gjennom ca. 42mm, mens 160kV gjennom ca. 28mm.

### **Hvor lenge varer de ulike røntgenrørene/gamma isotopene? Leveres disse tilbake til dere?**

Røntgenrørene varer i utgangspunktet evig. Det er ingenting på røntgenrøret som må byttes ut med mindre det går i stykker eller at brennflekkens blir for stor/slitt. Isotopene byttes ut når eksponeringstiden blir uakseptabel lang og dette kan variere fra 5-20 Ci. Ir-192 bytter man ofte ut ved under 10 curie. Noen har isotopene også ned i 2 curie, men det er sjeldent. Se-75 erstattes omtrent to ganger i året og Ir-192 erstattes opp til tre ganger i året.

### **Hvordan er det kildehåndtering av isotoper og røntgenrør?**

Vi sender de tilbake til leverandøren i Tsjekkia. Leverandøren i Tsjekkia sender deretter isotopene tilbake til USA, hvor de opprinnelig kommer fra. Der blir de deponert i egnete deponier.

## **Hva tenker du/dere om utviklingen ved industriell radiografi? Hvor er vi om fem år?**

Jeg tenker at per i dag klarer man ikke erstatte isotopene fullt ut. Det har litt med hvilke funksjoner man holder på med. Noen applikasjoner kan erstattes med ultralyd (phased array) og røntgenrør. Ved ultralyd vil varme rør være et problem, da lydhodene smelter i kontakt med rørene. Det finnes lydhoder for varme overflater, men dekker ikke alle tilfeller av arbeid med varme rør.

Det er to utfordringer med å erstatte isotoper. Det første er tilkomst. På en plattform kan det være høyt under taket og trangt. Det å få opp et røntgenapparat på 10-25kg er en stor utfordring i forhold til en isotop som kun har en fleksibel slange som må festes. Det er en av fordelene med isotoper. Dersom utstyret på røntgensiden vil kunne være så bra at det kan erstatte isotoper, må det også være så lite som isotoper. Det finnes batteridrevne røntgenrør ned til 5kg, men disse har sine begrensninger og kan ikke erstatte fullt ut da de har for lav energi. Dagens batteridrevne røntgenrør kan oppnå 160-180 kV.

Det andre problemet er energi. Ved tilstandsrapportering (on –stream), der en måler hvor mye som er igjen på veggen, altså hvor tykk veggen er, må en ha en viss energi for å kunne komme gjennom. Den energien som kreves der mangler på batteridrevne røntgenapparat i dag. Dersom en har en veggtynnkelse på over ca. 12mm vil en ikke ha nok energi med batteridrevne, da er det Ir-192 som gjelder. Ved tykkere gods (over 30mm) må man ha Ir-192, for da går ikke Se-75 gjennom.

## **Har dere noen konkrete forslag til hva som kan erstatte Se-75, Ir-192 og/eller Co-60?**

Jeg har egentlig ikke noen konkrete forslag, utover kjente metoder som Phased Array og røntgen, med de begrensingene det utstyret har i forhold til isotopbruk. Vi har utstyr som kan erstatte isotoper på noen områder, men ikke som kan erstatte helt og jeg tror det kommer til å ta mange år før det vil skje. Man kan begrense bruken, men man kan ikke bli kvitt isotopene helt. Dersom en kun vil teste på tynnvegg kan man erstatte, men det er mange forskjellige tykkelser og som krever mer energi. Dersom det er olje og gass i røret kreves det mer energi for å trenge gjennom. I dag brukes det mindre isotoper enn hva som ble brukt før.

05.03.19

## **Appendix E: Interview NDT Nordic**

### **Hva selger dere til selskaper som bruker industriell radiografi til inspeksjon?**

Batteridrevne bærbare røntgenrør.

### **Hvor lenge varer de ulike røntgenrørene? Leveres disse tilbake til dere?**

De holder ganske lenge, omrent 13 år. Når de ikke lenger kan brukes leveres de tilbake til oss.

### **Hva tenker du/dere om utviklingen ved industriell radiografi? Hvor er vi om fem år?**

Det har vært en stor endring siden vi tok opp dette i NDT foreningen for 1,5 år siden. Vi har solgt 6-7 røntgenrør det siste året, noe som er veldig mye. Til vanlig selger vi bare 1 røntgenrør. Det er spesielt en leverandør (ICM Belgia) som utmerker seg, på grunn av vekten til røntgenrørene og gode bilder.

EX-sikkerhet er en utfordring, men vi har solgt et røntgenrør til Aker BP offshore.

Radiografi erstattes også mer og mer av ultralyd (phased array).

### **Har dere noen konkrete forslag til hva som kan erstatte Se-75, Ir-192 og/eller Co-60?**

ICM batteridrevne røntgenrør (9kg og 160kV) kommer gjennom gods som er 3-4 cm, noe som er et ganske tykt rør, men så er det jo dobbel vegg.

### **Hva brukes røntgenrørene til?**

Primært til kontroll av sveis. Pulsrøntgen brukes til kontroll av tykkelse.

08.03.19

## **Appendix F: Interview Aker BP**

### **Hva bruker dere industriell radiografi til i deres bedrift?**

Vi bruker det til primært til to ting. Driftsinspeksjon for kartlegging av skader, både innvendig og utvendig (korrosjonsskader). Ekstern korrosjon på rør som er isolert. Også bruker vi det til fabrikkeringskontroll av nysveis, for prosjekter og diverse. For eksempel om vi skal ha inn en ny modul, så er det en del krav til at radiografi skal brukes.

### **Hvilke typer røntgenrør og gamma isotoper bruker dere i deres testing?**

Vi bruker Ir-192 og Se-75. Det brukes ikke røntgenrør på Ula, men på Valhall bruker de det. Det vil bli mer bruk av røntgenrør, og dette er en av de tingene vi ønsker å forbedre oss på.

### **Hva er fordelen med gamma isotoper? Hvorfor bruker dere det isteden for røntgenrør?**

Det har først og fremst med tilkomst og praktiske hensyn å gjøre. I tillegg så vil det være en del tykkere vegger som skal testet, og da vil ikke røntgenrør ha nok kV. Man trenger styrken til en iridiumkilde for å få frem kontrast på bilde/filmen når tykke rør testes.

### **Hva gjør at dere velger ultralyd fremfor radiografi? Brukes det mer nå enn det gjorde før?**

Vi prøver å bruke ultralyd der vi kan. Litt av årsaken til at det ikke brukes mer ultralyd er at det er avansert. Det kan være problematisk å forstå, og krever gode kunnskaper og ferdigheter fra operatøren. Av og til spekuleres det på om resultatet kan stemme, og da må både ultralyd og radiografi benyttes for å være på den sikre siden.

### **Hva er utfordringer med å erstatte radiografi med ultralyd?**

Geometri. Dersom en skal ta bilder av en flens er det ikke sikkert ultralyd kommer til alle plasser. Med radiografi trenger man derimot ikke nødvendigvis å komme helt inntil med utstyret.

## **Hvordan er prisforskjellene?**

Den store bakdelen med røntgen er at det må sperres av store områder. Dette fører til at folk som arbeider må ta en pause fra det de holder på med og man må derfor også regne total tapt arbeidstid. Har man god tilkomst kan det ta kort tid, men tapt arbeidstid blir det uansett.

Ultralydutstyr koster ca. 100 000 og en isotop koster ca. 30 000 hver gang man skifter den ut, og dette må gjøres 1-2 ganger i året. Isotopene må også fraktes med båt, dette er en annen bakdel ved isotop bruk. Totalt litt dyrere å holde radiografien i drift. Det er vanskelig å si hva som koster mest, men pris er ikke den viktigste faktoren når det kommer til valg av metode.

## **Hvordan kommer teknologien til å utvikle seg de neste årene? Hvor ser dere for dere at vi er om fem år?**

Det vil nok bli brukt mye mer ultralyd, spesielt PAUT. Jeg tror Aker BP kommer til å kjøpe inn PAUT-utstyr i år. PAUT kan brukes til forskjellige bruksområder. Da vil et av målene være å begrense bruken av radiografi.

## **Hva er utfordringene med å erstatte gamma istoper?**

Nysveis. Når nysveis skal testes angir internasjonale standarder radiografi som teknikk for testing. Forankre ultralyd som metode her kan være en utfordring. Et forslag kan være at selv om en byggestandard sier at vi skal bruke røntgen, kan bedriften som tester si at PAUT er like bra.

Kvalifikasjoner er også en utfordring. Når en kommer over på PAUT, som er en avansert metode, krever det høy brukerterskel. Det er en metode hvor folk må trenes opp og vedlikeholde kompetansen. Kompetanse er en stor utfordring. PAUT er forholdsvis kompleks å bruke. Det er enklere å lese en radiografifilm, men en som er veldig god på ultralyd synes ultralyd er enkelt.

**Har dere noen tanker/ideer om hva som kan erstatte gamma isotoper og om dere har noen tro på at dette kommer til å skje i nærmeste fremtid? Kan ultralyd og røntgenrør til sammen erstatte bruken av gamma isotoper?**

Tror det er veldig vanskelig å erstatte gamma isotoper helt. Når en kommer opp i en viss godstykkelse på rør, må man ha styrken som isotoper har. Ir-192 tilsvarer røntgenrør på 600kV (veldig kraftig). Når denne styrken trengs, må man ha et beist av et røntgenrør. Det vil være mer fokus på å minimalisere bruken fremover, men det vil ikke erstattes 100%.

28.03.19

## **Appendix G: Interview Teledyne ICM**

**What are the benefits with radioactive isotopes in industrial radiography? Why are these isotopes used instead of X-ray tubes?**

Advantages of radioactive isotopes compared to X-ray generators:

1. No need for mains power supply connection
2. Smaller and more compact to carry
3. No technical/electrical breakdown
4. No overheating issues
5. Higher penetration power (Cobalt)

**What are the benefits with X-ray tubes? Why does some people in the industry want to replace radioactive sources with X-ray tubes?**

Advantages of X-ray generators compared to radioactive isotopes:

1. No risk of radioactive contamination
2. No need to reload the source (unlimited usage)
3. Sharper image quality
4. Limited health risks
5. Easier to transport
6. Can be used everywhere

The NDT industry wants to get rid or avoid radioactive source usage as much as possible due to the high contamination risk. In case of mechanical breakdown while the isotope is out, the radiation level can be deathly.

**What are the challenges of replacing these isotopes? Are there any isotopes that are easier to replace than others?**

Some inspections can't be done with portable X-ray generators. This is the case when the thickness is really thick. Portable X-ray generators aren't powerful enough and only radioactive

isotopes can penetrate. In some isolated places there is no access to a power source to connect the generator to. In these situations, only an isotope could work.

**What is the “lifetime” of an X-ray compared to the isotopes? How long does it take for the equipment to be replaced?**

The average lifetime of an x-ray generator is 8-10 years. After 10 years replacement is advised. In the Scandinavian countries, the x-ray generators are used more intensively and frequently. The lifetime of the generator can be affected. Companies usually replace unrepairable units or invest in new units before large projects.

**Is there a price difference between X-ray tubes and isotopes? If it is, what is cheapest and why?**

The isotope itself is cheaper to purchase than an x-ray generator. The initial investment is cheaper but as you have to reload the isotope source frequently, it gets more expensive. Especially the transport of radioactive sources is expensive.

To resume: Initial investment is cheaper for the isotope compared to the x-ray generator but in the long term the isotope will cost more money to the company than the x-ray source. ROI is lower with an isotope than with a x-ray generator.

**Is there any difference in theory between using an isotope with an average energy level of 300 kV and a 300 kV X-ray tube? If it is, why?**

Yes, the focal spot is smaller on an x-ray source. The image quality will be better with X-ray generator.

**How will the technology evolve over the next few years? Where do you see the industry in five years?**

X-ray generators are getting lighter, more compact and powerful. We will get closer to the capacities of isotope sources but I don't believe we will ever reach the same penetration power due to physical/electrical limits. The only solution would be to compromise on weight and size, making the x-ray generator not possible to move anymore so this isn't a solution either.

**Do you have any thoughts/ideas on what can replace radioactive isotopes and whether you have any beliefs that this will happen in near future?**

I don't believe that portable x-ray generators will ever reach the same penetration power as radioactive sources due to physical/electrical limits. The only solution would be to compromise on weight and size, making the x-ray generator not possible to move anymore so this isn't a solution either.

**Do you have any X-ray tubes that is not out on the market yet? If you do, what are the benefits with these?**

Yes. This information is confidential unfortunately. The advantages will be better image quality, a more compact/battery powered unit and... more powerful than ever.

10.05.19

## Appendix H: Risk assessment



Detaljert Risikorapport

ID	31194	Status	Dato
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	04.02.2019
Opprettet av	Tone Marie Åsen Bastiansen	Vurdering startet	04.02.2019
Ansvarlig	Tone Marie Åsen Bastiansen	Tiltak besluttet	Avsluttet

### Risikovurdering:

### Risikovurdering for eksperimentelt arbeid

#### Gyldig i perioden:

1/7/2019 - 5/20/2022

#### Sted:

Radiografirommet til Axess AS i Orkanger

#### Mål / hensikt

Hensikten med det eksperimentelle arbeidet er først og fremst bare å observere hvordan det forgår for å kunne bruke dette til å finne andre metoder enn gamma-isotoper til industriell radiografi. Dersom vi finner alternative metoder kan vi eventuelt teste disse.

#### Bakgrunn

Axess AS ønsker å avvikle bruken av gamma-isotoper. Isotopene er krevende og kostbare i framstilling, lagring, transport og bruk. Dette skyldes flere ting men hovedsakelig:

- Isotoper stråler hele tiden og krever derfor mye skjerming og sikring. Dette gjelder både selve kildebeholdere og utstyr som brukes, men påvirker også bygninger og sikkerhetssystemer.
- Det er svært kostbart å framstille kildene og de har forholdsvis kort halveringstid, dvs de blir fort ubrukelige.
- Det finnes gode systemer i Norge for kildehåndtering, men uansett har dette et klart miljøaspekt.

Axess AS ønsker å avvikle bruken av gamma-isotoper både av hensyn til miljø og økonomi.

#### Beskrivelse og avgrensninger

Laboratoriearbeidet utføres ved at vi bruker gamma-isotoper og/eller røntgenrør til å finne feil i rør eller sveiser.

#### Forutsetninger, antakelser og forenklinger

For å gjennomføre testingen må man ha et strålevernskurs som vi ikke har. Derfor må vi få hjelp av to andre ansatte i Axess AS med dette kurset.

#### Vedlegg

[Ingen registreringer]

#### Referanser

[Ingen registreringer]



## Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

**Farekilde:** Ioniserende stråling

**Uønsket hendelse:** Utsatt for stråling

**Konsekvensområde:** Helse

Risiko før tiltak: Risiko etter tiltak:

**Farekilde:** Farer på verkstedet

**Uønsket hendelse:** Arbeidsskader

**Konsekvensområde:** Helse

Risiko før tiltak: Risiko etter tiltak:

**Farekilde:** Støy fra røntgenrør

**Uønsket hendelse:** Redusert hørsel

**Konsekvensområde:** Helse

Risiko før tiltak: Risiko etter tiltak:

**Farekilde:** Eksponering til kjemikalier

**Uønsket hendelse:** Kontakt med fotokjemikalier

**Konsekvensområde:** Helse

Risiko før tiltak: Risiko etter tiltak:

Ytre miljø

Risiko før tiltak: Risiko etter tiltak:

## Endelig vurdering



## Involverte enheter og personer

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

### Enhet /-er risikovurderingen omfatter

- NTNU

### Deltakere

Eline Kjørsvik

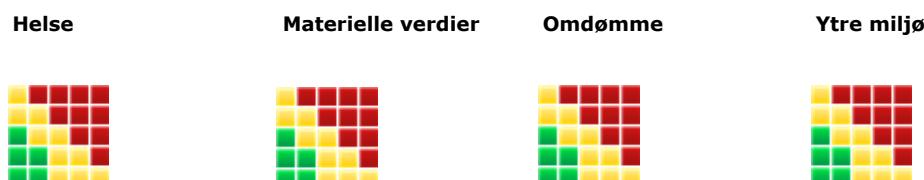
### Lesere

Marte Sørtveit Mørkve

### Andre involverte/interessenter

Kristian Nelvik har hovedansvar for å hjelpe oss i radiografirommet, eventuelt finne andre ansatte på Axess AS i Orkanger som kan bistå.

## Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):





## Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Ioniserende stråling	Utsatt for stråling	Bruker en lukka installasjon
	Utsatt for stråling	Jobber sammen med to ansatte med strålevernksurs
Farer på verkstedet	Arbeidsskader	Før jobb samtale
	Arbeidsskader	Vernesko, hansker og vernebriller
Støy fra røntgenrør	Redusert hørsel	Hørselvern
Eksponering til kjemikalier	Kontakt med fotokjemikalier	Vernesko, hansker og vernebriller

### Eksisterende og relevante tiltak med beskrivelse:

#### **Bruker en lukka installasjon**

Radiografirommet er en bunkers med skyvevegger i stål og bly som beskytter oss fra å bli utsatt for ionisert stråling (gamma og/eller røntgen).

#### **Jobber sammen med to ansatte med strålevernksurs**

For å utføre industriell radiografi må man ha strålevernksurs. Dette har ikke vi og får derfor hjelp av andre ansatte med dette kurset på Axess AS i Orkanger. Vi fungerer som en tredje part.

#### **Før jobb samtale**

Ansatte som skal jobbe med oss på verkstedet kommer til å gi en samtale/gjennomgang av det som skal foregå ved eksperimentelt arbeid.

#### **Vernesko, hansker og vernebriller**

Vi må ha på vernesko, hansker og vernebriller hele tiden på verkstedet på grunn av farer som kan oppstå når det er mye trafikk der.

#### **Hørselvern**

Det vil til tider være mye støy fra røntgenrøret på grunn av kjølesystemet.



## Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

**Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:**

- **Ioniserende stråling**
  - Utsatt for stråling
- **Farer på verkstedet**
  - Arbeidsskader
- **Støy fra røntgenrør**
  - Redusert hørsel
- **Eksponering til kjemikalier**
  - Kontakt med fotokjemikalier

**Detaljert oversikt over farekilder og uønskede hendelser:****Farekilde: Ioniserende stråling****Uønsket hendelse: Utsatt for stråling**

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Svært lite sannsynlig (1)**

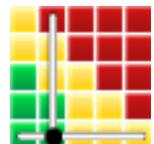
*Kommentar:*

På grunn av tiltakene er sannsynligheten for å bli utsatt for stråling svært liten, men hvis det først skulle skje er konsekvensene stor.

**Konsekvensområde: Helse**

Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

**Risiko:**

**Farekilde: Farer på verkstedet**

Når det er mye trafikk på verkstedet kan det oppstå skader på grunn av tunge gjenstander i bevegelse, kjøretøy i fart og bruk av kjemikalier.

**Uønsket hendelse: Arbeidsskader**

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

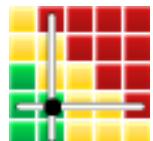
[Ingen registreringer]

**Konsekvensområde: Helse**

Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

**Risiko:**



**Farekilde: Støy fra røntgenrør**

Kan til tider være mye støy fra røntgenrøret på grunn av kjølesystemene.

**Uønsket hendelse: Redusert hørsel**

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

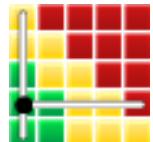
Kommentar:

[Ingen registreringer]

**Konsekvensområde: Helse**

Vurdert konsekvens: **Liten (1)**

Kommentar: [Ingen registreringer]

**Risiko:**

**Farekilde: Eksponering til kjemikalier****Uønsket hendelse: Kontakt med fotokjemikalier**

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

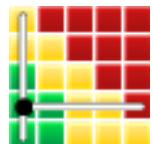
Kommentar:

[Ingen registreringer]

**Konsekvensområde: Helse**

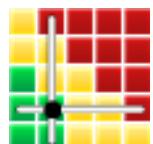
Vurdert konsekvens: **Liten (1)**

Kommentar: [Ingen registreringer]

**Risiko:****Konsekvensområde: Ytre miljø**

Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

**Risiko:**



## **Oversikt over besluttede risikoreduserende tiltak:**

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

### **Detaljert oversikt over besluttede risikoreduserende tiltak med beskrivelse:**



**Detaljert oversikt over vurdert risiko for hver farekilde/uønsket hendelse før og etter  
besluttede tiltak**

### Is it possible to eliminate radioactive sources in industrial radiography?

**Radioactive isotopes are used as a source of radiation in industrial radiography (RT). These isotopes are demanding to handle and expensive to produce, store, transport and use. This is mainly because they cannot be turned off, and therefore require a lot of shielding and security. They also have a relatively short half-life. It is therefore desirable to eliminate the use of these sources. In order to implement this, other sources of radiation or inspections methods must be considered.**

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RT is an inspection method for non-destructive testing (NDT). It is used to inspect volumetric defects in materials and welds by using X- and gamma radiation [1]. X-ray tubes and isotopes are used as radiation sources. NDT methods are important to the industry, due to the fact that NDT do not affect the test objects chemical or physical properties [2]. Figure 1 shows a beam of radiation that is sent from a radiation source onto an object with a defect. After photographic development the defects are shown as darker areas, because more of the radiation reaches the film where the defect is present.

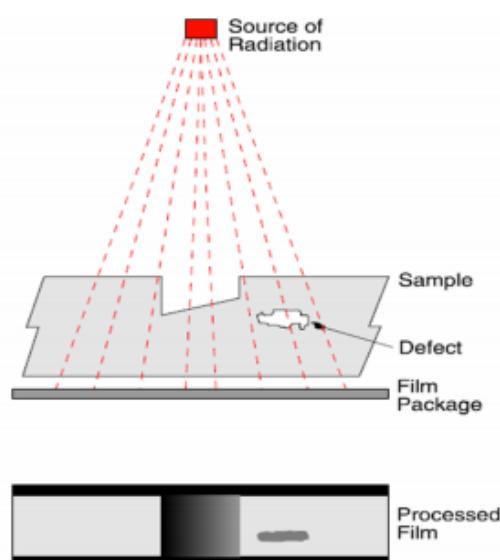


Figure 1: The principle of a radiographic test [2].

In order to find a solution regarding the thesis question, several interviews and experimental work were carried out. Companies in the industry were asked questions about radioactive sources today and future aspects. The experimental work was carried out to look at the difference in image quality when using an Ir-192 isotope and a 300 kV X-ray tube on three different pipes. Both, the interviews and the experimental work showed that an elimination is not possible today, but the use of these sources can be reduced with the use of X-ray tubes and ultrasonic testing (UT).

#### CHALLENGES

**A replacement must have the same benefits as the radioactive isotopes. The isotopes are small, and its mobility and penetration capacity is hard to replace. X-ray tubes with the same capacity as an isotope will be very large and heavy, which makes the mobility poor. UT is also a possible replacement, but this method requires full contact between the probe and test object. This will create challenges with isolated, hot or corroded pipes or welds. Problems can also be related to areas where full contact between the probe and test object cannot occur, such as corners or uneven surfaces.**

To conclude: Today, it is not possible to eliminate the use of radioactive sources in RT completely. However, it is possible to reduce the use of these sources considerably. To completely eliminate the use of radioactive isotopes, smaller and higher energy X-ray tubes must be developed.

#### REFERENCES

1. Norsk Sveise og Materialinspeksjon AS, RT (Industriell radiografi) [online]. Available at:  
<https://norsksveis.no/tjenester/ndt/rt-industriell-radiografi/> [accessed: 26.05.2019]
2. A. Loland and P.A. Lid (2010), NDT-håndboken