X-ray Inspection in food production
Requirements, technology and recommendations of use

- Core components of an X-ray inspection system
- Influencing factors on the detection sensitivity
- Foreign body detector maintenance and repair
- Manual sorting and automatic ejection mechanisms
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1. An introduction to X-ray inspection

Ever since Wilhelm Conrad Röntgen discovered the ‘invisible rays’ on 8 November 1895, X-ray diagnostics has become an established practice in many fields. Today, X-rays are not only used for medical purposes, but also support the food industry in its aims to ensure food quality and safety.

X-ray technology offers a reliable method of food inspection. It is used to detect physical foreign bodies or examine the internal structure of foods. As a component of the HACCP concept (hazard analysis and critical control points), it helps meet the increasing requirements of consumers and regulatory bodies.

An X-ray inspection system can be used to identify a number of physical foreign bodies such as metals, glass, rubber, stones and even certain types of plastics. The process of generating an X-ray image does not leave any traces behind on the product. For this reason, this method is preferred for use with packaged finished products, especially products in bottles, cans, glasses and bags.

X-ray inspection systems have been more powerful, reliable and user-friendly in recent years. Some systems not only detect foreign bodies but also check weight, the number of product ingredients, the fill levels or the sealed seam integrity of the packaging. Thanks to technological progress, modern X-ray inspection systems help reduce production costs.

This white paper focuses on the detection of foreign bodies and physical defects using X-rays and provides an insight into the technology behind this method.

2. X-ray inspection

2.1 Core components of an X-ray inspection system

An X-ray inspection system consists of the three core components – the generator, detector and image processor – and the mechanical and conveyor systems. Special hardware configurations are available for different application areas, which allow the core components to be used in a wide range of applications.

2.2 Generator setup

Modern X-ray tubes in their simplest form consist of the following components:

- Glass envelope
- Heated cathode
- Copper anode
- Tungsten disc

All components are placed inside a vacuum in a sealed glass or ceramic housing. The heated cathode serves as the electron source and consists of a tungsten filament that glows when electric current passes through it.

The heated cathode (A) generates electrons. High voltage between the cathode and anode (C) accelerates these electrons and pushes them towards a tungsten disc (B). Upon impact with the disc, the electrons slow down significantly, generating X-rays.
Applying a high voltage (kV) between the copper anode and the heated cathode accelerates the electrons and pushes them towards the tungsten disc. At this point, the electron current is known as an X-ray tube current (mA). When the electrons collide with the tungsten disc, they slow down significantly. This deceleration causes the emission of X-rays. In an X-ray generator, the tube is shielded with lead or copper. The usable X-rays are emitted from the generator through a small opening (see red waves in the figure).

Generating usable X-rays releases heat and makes it necessary to cool the generator. For this reason, the X-ray generator is often placed in a housing filled with a coolant such as oil. Heat dissipation is often further supported with the use of cooling fans. The required equipment for cooling depends on the generator’s power and the ambient temperatures.

As a general rule of thumb, the following applies:
- For X-ray detectors from 65 W to 100 W, it is sufficient to use simple fans to circulate the warm air.
- For devices from 100 W to 320 W, powerful air conditioning units should be used.
- For high-performance detectors with 1000 W and more, a pump system with active water cooling is required.

2.2.1 Focal spot
The X-ray source dimension (‘focal spot’) is determined by the size of the electron beam when it strikes the anode. It can affect the detection result. If the foreign body is radiated with a broad light source, the result is a ‘blurry’ transition between the core shadow and the light areas. This transition is called the penumbra (see figure). A small X-ray source, by way of comparison, leads to a sharp-edged shadow and therefore sharper image definition.

2.3 Detector setup
A detector is similar to an optical sensor, except that it consists of a linear arrangement of photo diodes because X-rays cannot be focused with a lens.

The X-ray detection area consists of a scintillating material (scintillator) that can convert invisible X-rays into visible light. This area is located under a small window on the top of the detector. Since the X-ray generator is normally situated in the top part of the housing, the X-ray is directed down through the product and the conveyor belt before it reaches the detector.

The beam is approximately 2 mm wide and spreads out in a triangular shape in the direction of transport. The window and the scintillating material therefore cover the entire width of the conveyor belt.

The following rule applies: the more X-rays reach the scintillator, the brighter it illuminates. This means that the output power of the scintillator is proportional to the amount of X-radiation it receives.

The photo diodes under the scintillator are positioned an even distance apart and convert the light into an electrical signal. This signal is sent to the X-ray inspection system’s integrated computer as a grey value. The size and distance of the photo diodes to one another determine the resolution of the detector. Resolutions between 0.4 mm and 0.8 mm are recommended for inspecting pre-packaged foods.

With high-quality detectors, the scintillating material is not applied over the entire detector as a layer; instead every single photo diode is individually assigned. This approach prevents the X-ray beam diffusion within the detector, which increases the contrast of the individual diodes.
If the scintillating material is assigned individually to each photo diode, grey value diffusion can be prevented.

### 2.3.1 Detector resolution

The image processing software of the X-ray inspection system records the grey value of every single photo diode. The following rule applies: the more a foreign body covers a photo diode and the greater its density, the darker the grey value transmitted by the photo diode in question.

The following figure shows the effect of the different detector resolutions on the probability of detecting an identical foreign body.

The resolutions available on the market for standard detectors are between 0.1 mm and 1.6 mm. The selection of resolutions leads to the supposition that a lower detector resolution leads to better detection sensitivity. This hypothesis can only be confirmed in part: if a 0.4 mm detector is compared to a 0.1 mm detector, the latter has an area that is four times smaller but needs four times the X-ray energy to generate an image of comparable quality.

If the same amount of energy is used in both cases, comparable quality can only be achieved with a significantly reduced throughput. In practice, therefore, detector resolutions of 0.4 mm to 0.8 mm have become accepted.

### 2.4 Film processing software function

An X-ray inspection system works similarly to an office scanner. As the product passes the X-ray at a constant speed, a new line of image data is generated for each movement of the product (every 0.8 mm, for example). As soon as the image is completely captured, a greyscale picture of the product is generated on the computer, which is then analysed using special inspection algorithms and examined for foreign bodies. If a foreign body is detected, a signal is sent to the downstream ejection process.

To ensure the right aspect ratio for the image, an X-ray inspection system automatically synchronises the scan speed of the generator with the speed of the conveyor belt. If the product speed is variable, the X-ray inspection system should receive an external signal to indicate the belt speed, e.g. via a speed sensor. The scan speed of the detector can then be synchronised with the belt speed.

For complex products such as metal cans or glass jars, advanced systems have appropriate parameters that allow for reliable detection of foreign bodies under even the most challenging conditions.

With greyscale analysis, an X-ray inspection system can be used for more than just detecting foreign bodies. The system’s image processing software also supports:

- Integrity checking
- Counting
- Weighing
- Fill level checking
- Checking of shape, volume and dimensions
- Detection of hollow spaces and tears in the product
- Trend monitoring, e.g. for slicers
2.4.1 Threshold image analysis

A measured value is defined as a threshold for threshold image analysis. In this process, the grey value of every photo diode identified during product inspection with the X-ray system is compared with the threshold. If this grey value exceeds the defined threshold, a foreign body is assumed to be the cause. This is the most simple method of image processing and is especially suitable for homogeneous products that produce a consistent grey value.

2.4.2 X-ray image analysis

In X-ray inspection, inhomogeneous products are more common. If the threshold method cannot be used, X-ray image analysis is the recommended method for detecting foreign bodies. In this process, each pixel from the photo diode is analysed and compared with all of the pixels around it. A number of algorithms are used simultaneously for this comparison.
3. Influencing factors on the detection sensitivity of X-ray inspection systems

There are a number of factors that affect the detection sensitivity of an X-ray inspection system. Very few of these can be optimised, but identifying them helps determine the limits of what is feasible with X-ray inspection.

Influencing factors on X-ray inspection systems

As explained in the previous chapters, the three core components of each X-ray inspection system determine a grey value. When X-rays reach a foreign body, it absorbs part of the energy. The intensity of the unabsorbed X-rays affects the basic grey value. This brings us to the conclusion that X-ray detection is basically density determination: the greater the density of the foreign body, the darker the corresponding grey value.

Density therefore affects the amount of X-ray energy absorbed by the product. This absorption is known as the linear attenuation coefficient. The measurement of the difference in absorption between the product and the foreign body forms the basis for foreign body detection using the X-ray inspection system.

3.1 Detection sensitivity in the food industry environment

X-ray inspection seeks out foreign bodies that absorb a higher amount of X-rays than the product being inspected. Therefore, reliable detection of foreign bodies is only possible if they have a comparably greater density than the product.

Many foods are manufactured on a water basis or are based on water due to their natural composition, e.g. fruit and vegetables. They therefore have a similar density to water (1000 kg/m³). This corresponds to a specific weight of 1.0 g/cm³. This value is usually used as a reference point.

The following table demonstrates the detectability of different types of materials. Materials in red cannot normally be detected because their density is too low or virtually equal to that of the product. Materials in green can be detected due to their higher density.

The table is sorted by density in descending order. The higher in the table a material is, the greater the attenuation coefficient and therefore the better this element is detected in foods. This means that smaller particles are also easier to detect.
Attention: when defining detection sensitivities for the quality management system, the density of the materials which pose a risk according to the hazard analysis should also be specified.

For example, not all glass is equal. Lead glass has a density of 3.5 – 4.8 g/cm³. In contrast, soda-lime glass (also known as soda-lime-silica glass, the most commonly used material for glass containers such as bottles or jars) has a density of 2.52 g/cm³. Obviously the absolute detection sensitivity for these two types of glass is very different.

For this reason, it is important to ensure that, when defining the detection sensitivities of an X-ray inspection device, the exact materials which pose a risk in the production environment are rated.
3.2 Product dimensions and density
When designing an X-ray inspection device, it is important to note that, when the density and thickness of the product increases, \textit{more X-ray energy is required to penetrate the product. Increasing the X-ray power (kV) leads to a decrease in the contrast caused by the foreign body, and therefore to a decrease in sensitivity. The thicker the product, the more X-ray energy required to penetrate it, and the lower the sensitivity of the system.}

Different grey values while designing an X-ray inspection system

3.3 Atomic mass
The \textit{chemical composition of a product, foreign body or test object} affects the overall sensitivity of an X-ray inspection system. Foods generally contain chemical elements with an atomic mass of 16 (oxygen) and below. Provided the foods are composed of elements with a lower atomic mass, the \textit{absorptive behaviour} of these foods \textit{is proportional to their density and thickness}. Foreign bodies such as glass and stones often contain trace concentrations of \textit{elements with a very high atomic mass}. These elements \textit{act as multipliers in X-ray absorption}.

Drastic \textit{changes in the salt content} (sodium chloride) also affect the intensity of X-ray absorption and detection sensitivity. This is especially the case when an X-ray inspection system is simultaneously used to determine weight. \textit{Strong fluctuations in the salt content have a negative effect on mass determination using X-rays}. Nevertheless, as the salt content of most modern food products is very low and carefully controlled, this does not often pose a problem.

3.4 Homogeneity of the product
The homogeneity of a product is a determining factor for which inspection method is used. X-ray inspection of products with a homogeneous structure and packaging is straightforward. The constant signal means that even slight changes in the attenuation coefficient are easily detected. By contrast, heavily loaded images, such as nuts in plastic packaging, cannot be analysed using the threshold method. Instead they must be examined using a complete X-ray image analysis.

3.5 Different angle of view for optimal detection of foreign bodies
The positioning of the generator and detector to the product has a significant effect on the detection result. The same applies to the position of the foreign body in the product.

The shortest side of the product should always run through the X-ray beam

Product orientation
\textit{The power required by a generator greatly depends on the density of the product to be inspected. The greater the density of the product, the greater the energy required for obtaining an optimal grey value in the detector. For this reason, the inspection system is always set up so that the shortest side of the product runs through the X-ray beam.}

\textit{Two basic variants of X-ray inspection systems have been established in the past.}
- \textit{Top-down shooter}
- \textit{Side shooter}
3.5.1 Top-down shooter

The top-down shooter is the most commonly used system in X-ray inspection of foods. X-ray inspection systems are usually situated at the end of the packaging line and inspect individual packages lying flat. Since the product has a smaller thickness when the packaging is lying flat, which allows for better detection sensitivity, vertical inspection is the most suitable method in this case. Generally, the X-ray inspection system at this point in the packaging line has a separate conveyor belt and an integrated ejection system.

Example of vertical inspection with a top-down shooter

The maximum width and depth of the product to be inspected determine the size of the X-ray beam, which in turn determines the size of the opening and scan width of the machine. To generate a wide triangular beam for larger (wider or deeper) packaged products, the focal distance (distance between the opening on the X-ray generator and the surface of the image detector) must be increased. Systems with a vertical beam and integrated conveyor belt are available in different widths. These systems are suitable for a number of applications, from extremely small products to larger batch containers. The same approach is also used for unpackaged products.

3.5.2 Side shooter – single beam

Side shooter X-ray inspection systems are used for packaged products which are taller than they are wide. The same principle applies here: the product must run through the X-ray beam with its flattest side facing the beam.

A side shooter X-ray inspection system has an X-ray generator that scans the product parallel to the surface and perpendicular to the direction of transport of the conveyor belt. The advantage of these systems is that an existing conveyor belt can be reused because it does not enter the detection range of the X-ray beam. Extra transitions between the conveyor belt and drive are not necessary. This also simplifies installation and integration in an existing packaging line.

Maximum product dimensions in height and width using the example of a side shooter

The size of the X-ray beam defines the maximum product dimensions in height and width (400 mm belt)
Products such as metal cans or plastic bottles often have complex packaging shapes. The high density of the material affects detection sensitivity. ‘Teaching in’ these types of products in the software is often seen as a complicated task. In this case, dynamic software filters are used, which, while requiring a number of parameters for optimal use, do optimise detection performance and minimise the number of erroneous ejections from the line. Nevertheless, even when using complex algorithms, having an additional angle of view can be beneficial.

3.5.3 Side shooter – double beam

Glass jars and bottles probably pose the greatest challenge in X-ray inspection, especially because glass foreign bodies are the most likely contaminants to occur.

In addition to the packaging, the product itself also affects glass-in-glass inspection. These products are often liquid/viscous, which can affect any foreign bodies in them. While foreign bodies sink to the bottom of the bottle or jar in thin liquid products, foreign bodies in marmalade, for example, often lie directly under the jar cover. Both the bottom and top cover of a glass container are especially difficult to examine with an X-ray inspection system because the greatest fluctuations in signal occur at these points. Systems with only one X-ray beam often reach their limits here. The following figure shows a drastic reduction in detection sensitivity in front of and behind the raised bottom of a glass jar.

The solution to this problem is a patented system in which an additional X-ray beam is placed at a position offset by 90° and a second detector is used. This ‘double-beam side shooter’ allows for complete inspection of the raised bottom of a glass jar, ensuring maximum reliability when detecting foreign bodies.

An X-ray inspection system with double-beam side shooter not only improves inspection of the raised bottom of jars, but also inspection along the glass wall.

Small foreign bodies which come directly into contact with the glass wall suddenly come into focus in the image processing software when inspection is rotated by 90° and are more reliably identified as foreign bodies.
3.6 Foreign body orientation

The chapter on product orientation showed in detail the extent to which the position of the product can affect the inspection result. The same applies to the position of the foreign body.

A foreign body is best differentiated from the product when it absorbs as much X-ray energy as possible. However, a very thin metal foreign body may be positioned opposite the X-ray beam, generating only a very low attenuation coefficient. Detecting this foreign body is more difficult as a result. A parallel position to the X-ray beam would be beneficial as this would result in the greatest possible absorption of the X-ray energy.

With vertical packaging, the double-beam technology can again prove useful, as inspection of the foreign body is rotated by 90° to allow for better detection.

3.7 Foreign body position

3.7.1 Foreign bodies on the product

If the foreign body is on the outside and not inside the product, none of the product is displaced or replaced by the contamination. This means a higher attenuation coefficient and improved detection sensitivity.

With foreign bodies of greater density such as iron or stainless steel, a difference in the foreign body position is of little relevance. The influence on the detection result is that much greater with foreign bodies of lower density.

A plastic foreign body, for example, has a medium density. If this foreign body is situated on a product of medium density (such as cheese), it will very likely be detected. By contrast if the foreign body is inside the product, it will sometimes go undetected.

Foreign bodies in the product

If a foreign body passes very close to the generator, a ‘shadow’ forms behind the foreign body, which is cast over a larger area on the detector and is affected by secondary shadows. The image of the foreign body is blurry and may not be detected in some cases.

The same foreign body passing directly in front of the detector generates a high-contrast, sharp shadow that makes detection more easy.

Tests show that the effective position of the foreign body has little to no influence on the detection result. The great number of possible variables, such as product depth, composition, the type of packaging, the size of the diodes, the focal distance and the X-ray strength, does not allow for any generalisations to be made.
4. Foreign body detector maintenance and repair

When it comes to X-ray inspection systems, there is a distinction to be made between ‘servicing’ and ‘repair in the event of a defect’. *Maintenance is a scheduled procedure* that depends on the wear of the unit and can be performed efficiently during downtimes through regular visual inspections. *Repairing an unforeseen defect involves immediately shutting down the production line.*

4.1 X-ray maintenance

The following criteria are relevant, depending on the device type, when carrying out maintenance of X-ray inspection systems:

**Daily maintenance**
- Check light barriers / sensors and clean if necessary
- Check cooling system and fresh air inlets
- Check for wear on curtains, if there are any
- Check radiation emission
- Check early warning messages for the system

**Weekly maintenance**
- Check safety devices such as emergency stop switch, protective switches and the like

**Monthly maintenance**
- Check the ball bearing for wear
- Check the conveyor unit (motor in particular)
- Check the conveyor belt
- Check the separator unit
- Check the dust filter in the cooling system (do this more often in dusty environments)

**Annual service**
- Annual inspection by manufacturer’s service technician

An inspection of the *test objects used* (e.g. test balls) and testing intervals should be carried out *via hazard analysis*. Potential causes of defects include crushing of the test parts, mechanical damage or tampering.

4.2 Recommended replacement parts

*Professional replacement part management can minimise downtimes during production. It effectively reduces the procurement period for replacement parts when they are urgently needed. Downtimes represent an enormous setback for line efficiency especially at a critical control point.*

Choosing a supplier with an international network and fast delivery times ensures quick responses, but keeping a reserve of critical replacement parts at the production line is the fastest solution for maintenance personnel. *Original replacement parts are essential for maintaining the performance and usability of the X-ray inspection systems in use. This is particularly the case for replacement parts that affect detection performance.*

*Conveyor belts, ball bearings and other elements wear individual.*

The *detection-specific components of X-ray inspection systems are subject to wear. The elements are sensitive and maintenance is more complex. Generators in particular are the core components that cost the most to replace. Replacing these components must be carried out by trained personnel.*

5. Ejection process for X-ray inspection systems

Depending on the result of the *hazard analysis within the HACCP concept*, X-ray inspection systems are used within the production line or at the end of a production line. It is inevitable that some products will not meet the safety requirements, so risks must be detected via the critical control points.

If a product has a defect, it must be separated from production through an ejection process. The different forms of product separation will be shown and explained in detail below. Ejection systems are often an *integral part of the X-ray inspection system*, but free-standing or independent mechanical solutions are not uncommon.
5.1 Manual sorting of contaminated products with belt stop and alarm message

X-ray inspection systems allow for the activation of a signal lamp and an acoustic signal emitter, as well as the triggering of a belt stop. The user is now responsible for removing the product from the production process. This solution is used in particular for very heavy products for which automated separation would be complicated.

The key disadvantages of this approach in comparison with the automatic ejection units listed below is the risk of the operator acting incorrectly (human error) and the reduction of overall system efficiency.

5.2 Automatic ejection mechanisms

Various types of ejection systems are available. The choice of the correct system depends on numerous factors, such as type of environment, belt speed, product weight and product size.

Pulse blow out ejector

The simple compressed air nozzle of a pulse blow out ejector is the ideal solution for packaged foods under 500 g, for example. Stronger compressed air nozzles can also be used for heavier products.

This ejection system consists of a compressed air nozzle which emits a high-pressure air pulse. The air flow that this creates blows the contaminated product off the conveyor belt.

Whether or not this solution is feasible greatly depends on the air resistance of the product. The product distribution within the packaging also has an influence. It requires constant availability of compressed air.

5.2.1 Pusher

Pushers can be used for a variety of products. They consist of a compressed air cylinder and a plate. During separation, compressed air is used to extend the plate, which pushes the product from the conveyor belt. This separator is suitable for light products up to 7 kg.

For very flat products, there is a risk of crushing the product under the pusher plate. For this reason it is a good idea to fix a brush under the pusher plate when inspecting flat products.

Pushers for heavy loads are available. These generate very strong forces, which must be considered in the structure and in machine safety.

For successful separation, it is important that the pusher meets the middle of the product and that the product does not absorb the impact by buckling. This can damage products.

5.2.2 Swivel arm

A swivel arm can carefully deflect the product flow of products. It is particularly useful in comparison with pulse blow out ejectors or pushers in the case of fragile products. In this case it is also a good idea to use a brush for flat products.

The ejection device is also used in combination with gravity roller conveyors. In this case the product usually remains undamaged in its original position and does not tip over like in a collection container. Low-friction conveyor belts are beneficial here so that the product can be moved across the belt without a lot of resistance.
5.2.3 Flap/trapdoor

For a flap or trapdoor there needs to be a height difference in the production line, which is bridged by a slope in the belt system. The pivot point can be varied according to the application. This ejection type is suitable for small, non-ordered individual products or unpackaged bulk goods (dry or sticky) which are transported on a flat, wide or curved belt system.

5.2.4 Telescopic conveyors

The tensioner at the end of the conveyor belt is retracted on a telescopic conveyor, which creates a gap in the conveyor belt through which the product can fall. As soon as the separation process is complete, the tensioner returns to its original position and closes the gap in the conveyor belt. Particularly suitable for multiple track applications.

5.2.5 Ejection mechanisms for pumped products

A contaminated product which is transported by a pump should be ejected via a 3-way valve.

In this case it is important to ensure that the valve diverts the product into the ejection flow (‘bad product flow’) as far as necessary until a completely empty area between the X-ray inspection system and the separator is guaranteed.

5.2.6 Multi-lane ejection systems

In a multi-lane application on a single conveyor belt, a multi-segment ejector has great advantages over a telescopic or flap/trapdoor ejection solution.

A telescopic conveyor may crush a product when the belt returns to its original position. This can lead to a fault where the gap is not completely closed. The risk of product loss is relatively high in this case, as multiple products are mistakenly ejected from the production line.

Precise-position detection using X-ray inspection devices makes it possible to control the diversion of products to the bad flow in each individual lane.

A collection container is often used here to catch the products. It is essential to ensure that this container is protected against access by unauthorised personnel.
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