# X-RAY TUBE ARCING : MANIFESTATION AND DETECTION DURING QUALUTY CONTROL

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*Abstract*— **X-ray tube arcing is a dangerous rarely observed phenomenon, which may occur in all X-ray equipment. It may lead to artefacts and repetition of exposures, but also to costly defects of the X-ray equipment. An arcing X-ray tube should be immediately replaced. The paper presents unique images of X-ray tube arcing and discusses its cause. Several methods for early detection of X-ray tube arcing are presented as part of the Quality Control procedures in Diagnostic Radiology. The paper also aims to be used as a reference material for lecturing and training in X-ray Diagnostic Radiology Imaging.**

*Keywords*— **X-ray tube, Arcing, Heel Effect, Quality Control in Diagnostic Radiology.**

## I. Introduction

Arcing may be expected in all high-voltage (HV) systems. It exists in all medical X-ray equipment. X-ray tube arcing is a phenomenon usually associated with tube ageing, but can be present also in new X-ray tubes.

Arcing is rarely a subject of direct observation, but is present and can lead to serious artefacts (hence repetition of exposures and increased patient dose) and also to significant technical problems with the equipment (arcing is one of the most frequent causes of X-ray tube failure). Routine Quality Control (QC) can often fail to detect the problem as it is with random manifestation. Occasionally radiographers could report hissing noise (or pops) from the X-ray tube during exposure, but this is not always reported to the medical physicists performing Quality Control surveys. Understanding the phenomenon and the methods to detect arcing is an important element of the QC tests.

## II. What causes x-ray tube arcing

The high vacuum inside the X-ray tube (min $10^{-6}$ mbar) assures the undisturbed path of the thermal electrons (anode current, $I_a$) from the Cathode filament to the Anode target. Internal ionization of the X-ray tube leads to vacuum reduction and internal discharges (arcing sparks) between the two electrodes or between the tube envelope and one electrode (usually Cathode). There are two main types of arcing – in new tubes (or unused ones) and in old tubes.

*Arcing in new (unused) X-ray tubes*

During X-ray tube manufacturing the glass envelope is first vacuumed and then sealed. However with time the glass, and the other parts of the X-ray tube inside the vacuum, emit ions (cold emission). Special measures are taken for reducing this emission – such as polishing and degassing the glass and the metal electrode assemblies. However this treatment does not eliminate the problem entirely. The cold emission exists, causing internal ionization of the X-ray tube volume. This leads to discharges in the vacuum (small arcing sparks) what increases the current between Cathode and Anode ($I_a$ plus ionization current). This is effectively a short-circuit, which is associated with disruption of the production of X-rays for short period of time. This may create artefacts or (rarely) damage the X-ray tube and Generator. Due to this reason new tubes and tubes, which have not been used for a long time (or have been stored for a long period) must be "degassed". The method includes slow warming with several low-power exposures before regular use - for more details see EMERALD materials website in Further Reading

*Arcing in old (aged) X-ray tubes*

The arcing inside old X-ray tubes is more powerful and more dangerous. It is most often observed in X-ray tubes with glass envelope, but can also be present in metal X-ray tubes. During each exposure the glass envelope is heated to very high temperature (due to the close proximity of the glass to the glowing-hot Anode - only several centimeters). This is followed by cooling to less than $100^0$C temperature, and new heating during the next exposure, thus leading to thermal stress of the material, what causes microcracks in the glass after several years of work (depending on the power and frequency of exposures). This process increases the release of ions inside the tube. Additionally the evaporation of the Cathode filament and the Anode during the exposures leads to metallization of the glass, what further creates conditions for arcing inside the X-ray tube Fig.1 shows an old X-ray tube (after decommissioning) with many cracks on the glass surface.

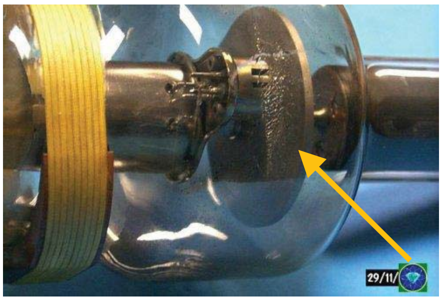


Fig.1 Decommissioned X-ray tube with severely cracked glass envelope (at the side opposite the cathode and anode).

There are various industry methods to decrease this "etching" of the glass of the tube envelope, but they do not eliminate the problem entirely - arcing exists and increases with the ageing of the X-ray tube. The arcing current between the high voltage electrodes of the X-ray tube can reach high values and can damage not only the X-ray tube, but also the X-ray Generator. Severe arcing may also lead to implosion of the X-ray tube. The manufacturers have special tests of the X-ray tube metal housings in order to assure patient safety in case of such dangerous situation.

## III. X-RAY TUBE ARCING MANIFESTATION

There are several stages of X-ray tube arcing manifestation, which may have the following indicative separation. The first one is in case of very small occasional arcing, which can be detected only with an oscilloscope (see below). The second stage is occasional audible hissing noise from the X-ray tube during exposure. The third stage is associated with increased noise (cracking) from the X-ray tube and sometimes also unexpected high noise from the X-ray generator during the exposure (mostly in classical types of generators). The fourth stage may begin with the loud noises in third stage and continue with automatic switch off of the high voltage fuse during the X-ray exposure.

The noise made by moderate arcing inside the X-ray tube is weak, but audible. The random hissing/cracking noise (or pops) in the X-ray tube is associated with very brief arcing sparks, which quickly exhaust the existing ionization inside the X-ray tube, what leads to restoring the initial vacuum (until a sufficient number of new ions are produced by the effects described above and a new arc appears). The visual observation of this phenomenon is very difficult and usually requires industrial environment.

Figure 2 (on the next page) shows the visual appearance of a sequence of sparks inside an old X-ray tube. The images are made through frame-by-frame analysis of a two minutes video of the event. These unique images are extracted from a video of an open X-ray tube housing (see the Acknowledgements) and present a good visual of the manifestation of the arcing phenomenon inside the tube.

Fig.2a shows the normal work of the Anode (left, glowing hot) an the Cathode (right, only the profile of the filament is seen inside the Cathode cup). In front of these is the glass envelope (with a serial number). Fig.2b shows a small spark close to the Cathode (in the form of a bright dot marked with arrow), while Fig.2c shows the restored normal work of the X-ray tube immediately after the brief spark. These events are of the order of microseconds and only the after-glow of the discharge is recorded (in fact integrated) by the slow video recorder (one video frame lasts tens of msec).

Fig.2d shows another similar brief spark (at a different spot near the Cathode); this is immediately followed by a cluster of 3 small sparks in this area, seen on Fig.2e. Each of these events is usually associated with a very quick flash of light inside the X-ray tube. After these small sparks the vacuum could be restored (what is often the case), but also there is a high probability that the phenomenon could continue with increased strength and further clusters of sparks may appear - see Fig.2f. This produces a very bright flash of light inside the X-ray tube, associated with a strong "cracking noise" (sometimes even a noticeable "boom"). This creates significant mechanical stress inside the X-ray tube, what may further crack the glass and in turn - increase the ionization. This positive feedback creates further large cluster (a ball) of sparks – Fig.2g. This leads to the creation of a very strong arc inside the X-ray tube – Fig.2h. At this time the X-ray tube produces a burst of bright light associated with a loud sound (strong arcing, which could even lead to implosion of the tube). During this arc a very strong current passes through the tube electrodes, and further through the Rectifier and the HV Transformer of the X-ray Generator, what in turns activates the electrical safety circuit. This circuit senses the unusually strong $I_a$ (and/or sudden decrease of the kV due to the short-circuit inside the X-ray tube). The safety circuit switches-off the High Voltage (HV) – see Fig.2i, which shows only the remaining after-glow of the cooling-down Anode. After a quick spark the system may restore the work of the Generator during the exposure, but the high current could also turn off the fuse of the equipment. If the sparking event is very fast and strong, and the safety circuit cannot react, it can damage both the X-ray tube and more importantly - the X-ray Generator.

## IV. DETECTION OF THE X-RAY TUBE ARCING

Detection of arcing is very important, as its presence is an immediate sign for the urgent need of X-ray tube decommissioning and replacement. Otherwise artefacts and related repeat of exposures are imminent, and importantly, equipment damage is very likely to occur. There are two methods to asses arcing – Direct (Fig.3) and Indicative.

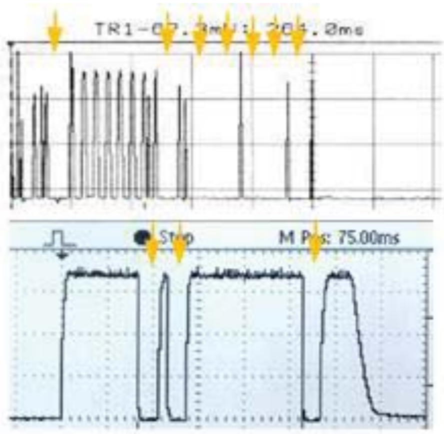


Fig.3 kVp oscillograms of X-ray tubes during arcing (see arrows)
-Above: arcing of tube with classical X-ray Generator - some kVp pulses are missing in clusters, as arcing is associated with these (the uneven kVp amplitudes are another sign of micro sparks).
-Below: arcing of tube with medium-frequency X-ray Generator -note the sharp drops (short-crciut) of the kVp line at 3 instances.
In both cases the arcing has been followed by self-recovery of the vacuum inside the X-ray tube (kVp recovers to its pre-arc value).

*Direct detecting of arcing with kVp meter and oscilloscope*

This is the most efficient way to detect X-ray tube arcing. It requires attaching an oscilloscope to the kVp meter. This direct recording of the kVp fluctuations detects even small arcing inside the X-ray tube. This is due to the fact that the spark between the Cathode and Anode is in fact a short-circuit, what causes a sudden drop of kVp (Fig.3). During this detection, it has to be insured that the kVp meter has sufficient bandwidth (see Annex). This is of special importance when assessing medium-frequency Generators. In case the kVp meter is not fast enough some sudden decreases in kV can remain undetected due to missed signal registration. This detection is a proof of the importance to use an oscilloscope and kVp meter with oscilloscope output for assessment of equipment performance during QC tests

This direct detection is the most reliable one, but it requires a good kVp meter and oscilloscope. If these are not available the arcing phenomenon cannot be observed, but an estimation of X-ray tube ageing (hence potential arcing) can be made.

*Indirect estimation of the time when arcing may appear, using the X-ray tube specific dose output (mGy/mAs)*

The indirect estimation of time when arcing may occur is only used for planning of X-ray tube replacement before potential strong arcing. This will require having a good record keeping of QC surveys, starting with the new X-ray tube. With the age of the X-ray tube its specific dose output decreases, what is an indication of its ageing – see Fig.4 on next page. In practice an X-ray tube will have to be replaced if its initial specific dose output (mGy/mAs) at specific kV (usually 80 kV for Radiographic equipment) is reduced below 60%. This reduction is due to the fact that with the ageing of the X-

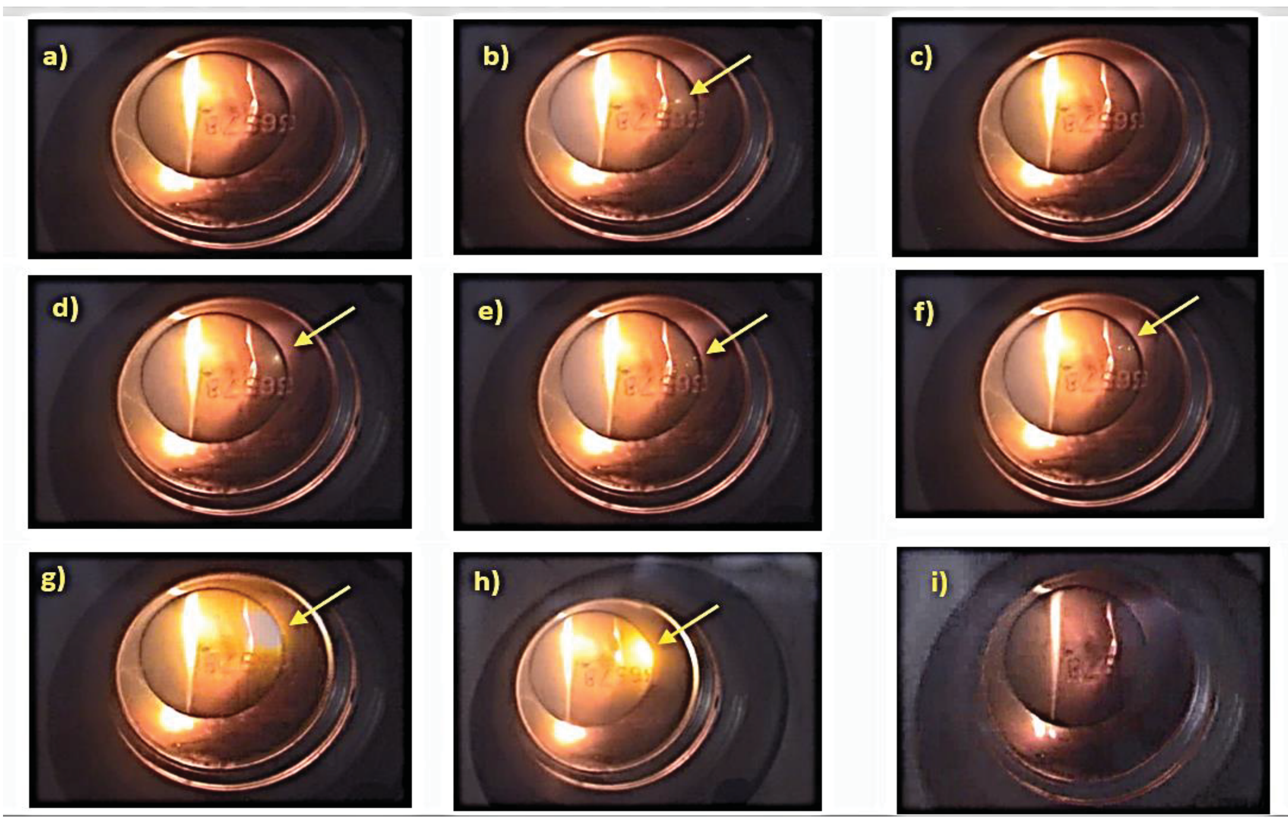


Fig.2 (a-i) Arcing - sequence of sparks inside an old X-ray tube with rotating Anode: a frame-by-frame analysis of a 2 minutes video through an open X-ray tube housing (the explanation of the images is inside the text of the paper); the filming of the video is described in the Acknowledgements ray tube the Anode target begins to crack due to the significant thermal stress after thousands of exposures (i.e. cycles of heating and cooling). The cracks not only decrease the life of the X-ray tube (damaging the anode), but also uneven the target surface. The cracked anode surface causes scattering or absorbing (inside the cracks) of some of the X-rays photons, hence decreases the tube output with time. The cracks increase the untreated surface of the materials leading to increased ion emission.

*Indirect estimation of the time when arcing may appear using the Heel effect*

Measuring the increased Heel effect, associated with the ageing of the X-ray tube is another indirect way to roughly estimate the time of expected X-ray tube arcing, hence tube replacement. Figure 4 shows the shifting of the maximum of the X-ray beam intensity from the central beam ($15^0$) toward the Cathode. This leads to further decrease of the already smaller beam intensity at the side of the Anode – i.e. more prominent Heel effect. The latter can be directly measured from a sufficiently long radiogram of a test object placed in parallel to the Anode-Cathode axis – Figure 5. However this will also require having the initial measurements of the Heel effect of a new X-ray tube, what is very rarely made. This method is even less accurate, as the Heel effect varies with different types of X-ray tubes and equipment.

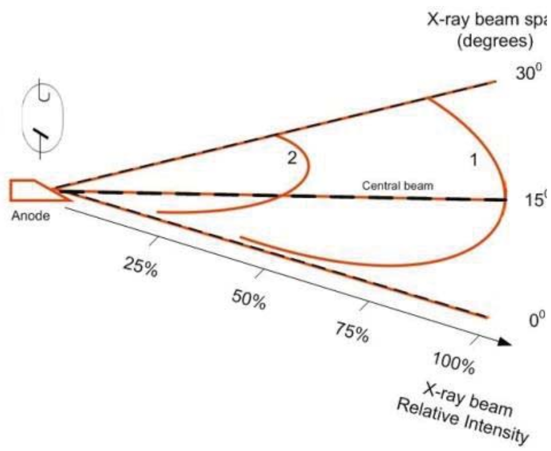


Fig.4 X-ray tube intensity spatial distribution for new X-ray tube (curve 1) and an old one (curve 2). The X-ray intensity is shown in relation to the maximum intensity (100%) at the middle of the central beam of a new X-ray tube. Note also the shifting of the maximum of the intensity from the central beam ($15^0$), what leads to significant decrease of the beam intensity at the side of the Anode – i.e. increased Heel effect.

## V. Conclusion

The presence of arcing can be observed in any type of X-ray equipment – such as CT scanners (where the drop of the kVs during the scan time leads to lack of projections and line artefacts), Radiographic equipment (where the arcing directly underexposes the image or damages part of the image) or Fluoroscopy (where the image brightness and the dose may fluctuate). The article illustrates that arcing can be easily detected, hence avoided.

Quality Control (QC) of X-ray tubes and Generators requires detailed knowledge of the X-ray equipment function. The unique images of arcing manifestation, as well as methods for its detection, described in the article, can be used as teaching/training resources.

Enriching the routine QC surveys with such a knowledge will help to avoid artefacts (i.e. reducing the diagnostic value of the image), or repeated exposures (i.e. increased patient dose). It will also help to avoid increased servicing cost (or possible premature decommissioning). An arcing aged X-ray tube is a source of severe problems. It must be immediately withdrawn from service and replaced.

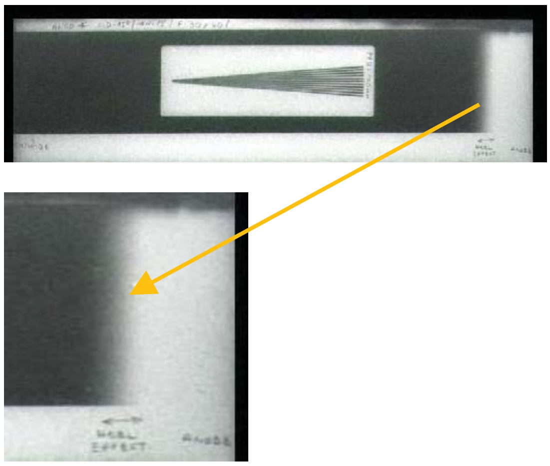

Fig.5 Illustration of Heel effect in old X-ray tube (gradual drop of optical density at the right side of radiograph). Note the zoom of the Heel effect zone (below), which is usually about 2-5 mm wide on the radiograph recording the effect.

## VI. Acknowledgements

Most images/diagrams have been collected by the author and have been included in the EMITEL e-Encyclopedia of Medical Physics (www.emitel2.eu).

The video used for the frame-by-frame extraction of the arcing pictures has been made by Dipl. Ing. A Litchev and Dipl. Ing. G Tatarev from Medical University Plovdiv, Bulgaria. For this purpose the light-beam diaphragm (LBD) of the tube housing has been removed, as well as the inherent Aluminium filtration of the X-ray

tube. The video clip has been made with a small video camera directly attached in front of the radiolucent window of the X-ray tube – Fig.6. Before showing signs of arcing, the filmed X-ray tube has been intensively used for about 7 years, as part of an Digital Angiographic Equipment. The video has been shot during high-dose fluoroscopy mode. Immediately after this the tube has been replaced.

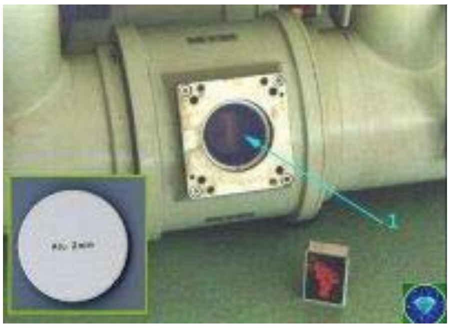

Fig.6 Outside view of an X-ray tube housing. The LBD and the inherent X-ray tube filtration have been removed (Al filtration plate is shown in the left segment of the image). Note that through 1 (the radiolucent window) the cathode and the anode disk can be observed (as in Fig.2), taking all radiation safety measures.

## VII. ANNEX

The assessment of medium frequency X-ray Generators (as well as arcing) requires kVp meters, whose electronics is able to detect quick events. Some old kVp meters were based on low-cost electronic components with insufficient bandwidth. Due to this reason kVp waveforms and fast events were incorrectly presented (Fig.7). Soon after the introduction of the medium frequency Generators the author discussed the problem about misregistration of fast kVp changes with a leading manufacturer. This led to correction of the measuring equipment, but some of the old kVp meters are still available (as second hand equipment). Due to this reason the suitability of the measuring equipment should be checked before using it for arcing detection. Obviously kVp meters without an output for oscilloscope are not suitable for such detection.

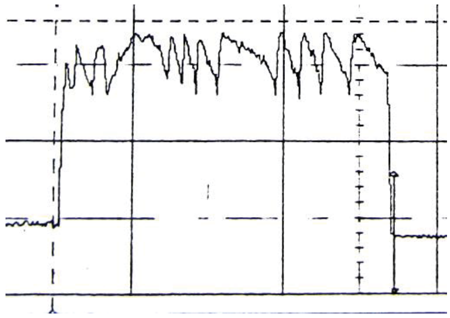

Fig.7 kVp waveform of a medium frequency Generator made with kVp meter with insufficient bandwidth. Note on the oscillogram the uneven kVp pulses due to lack of registration of the high frequency signals. Such kVp meter can miss (or present a false appearance) of the fast arcing events.

## VIII. FURTHER READING

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