MICRO-X

WHITE PAPER
X-RAY IMAGING: INTRODUCTION TO CNT EMITTER TECHNOLOGY AND LIFE TESTING

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An overview of Micro-X's patented CNT emitter technology,
breaking through historical limitations of CNT x-ray technology.

MICRO-X

1. EXECUTIVE SUMMARY

- Micro-X is the first company globally to bring a medical x-ray device to market using cold cathode, CNT emitter technology. Micro-X's patented CNT emitter technology inside the x-ray tube breaks through historical limitations of CNT x-ray technology by using an amorphous, current sharing CNT matrix in the cathode to enable stable, robust and high-powered CNT x-ray tubes.

- Micro-X has performed significant Accelerated Life Testing (ALT) and Reliability Demonstration Testing (RDT) on its CNT emitter technology to prove the robustness of its CNT emitters over the full expected life of an x-ray tube, and has **demonstrated 5 years of emitter life** (over 125,000 exposures) in a typical daily use scenario with **emitter life extrapolated out to 10+ years.**

2. BACKGROUND

X-ray tubes really haven't changed since Wilhelm Röntgen X-rayed his wife's hand in 1895 – they all use a heated filament like the old-fashioned incandescent light bulb, to generate electrons inside a vacuum tube to create X-rays. The hotter the filament, the more electrons you get and the more X-rays you get. Thus, conventional x-ray tubes are large, heavy, hot, and slow.

Micro-X was the first company to bring a medical product to market using a digital X-ray tube with a cold electron source material, simply controlled by a small voltage. Micro-X's X-ray tube technology enables smaller, lighter, faster, and more precisely controlled medical imaging systems to be developed and brought to medical and security markets.

Micro-X's digital X-ray technology is based on Micro-X's Carbon Nanotube (CNT) electron emitter. Micro-X's patented CNT emitter breaks through the conventional limitations of x-ray technology to deliver a CNT x-ray tube that is stable and consistent over a long life for high performance x-rays while also being inexpensive to manufacture and easily scalable to multi-product manufacturing.

Micro-X's digital CNT X-ray technology is currently being used in two commercially available, FDA cleared products, the 'Carestream DRX Revolution Nano' and the 'Micro-X Rover'. The Nano was launched in November 2018 and is being used in many countries across the world; Micro-X is receiving positive feedback about the Nano and its CNT x-ray tube technology from customers, particularly in its suitability in imaging COVID-19 patients. The Rover received FDA clearance in July 2020, less than two months after Micro-X submitted the 510(k) notification.

3. CNT EMITTER OVERVIEW

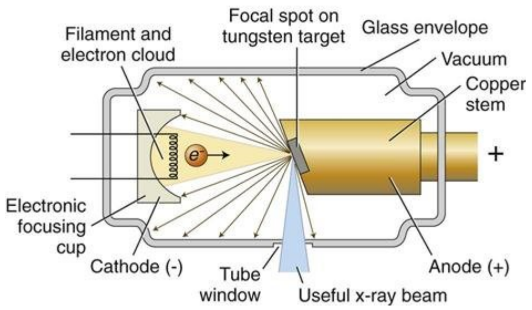
3.1 CARBON NANOTUBE ELECTRON EMITTERS

X-ray tubes generate x-rays by accelerating electrons through a high voltage electric field and then rapidly stopping the high-speed electrons with a dense metal. As the high-speed electrons lose energy, a portion of that energy becomes x-rays.

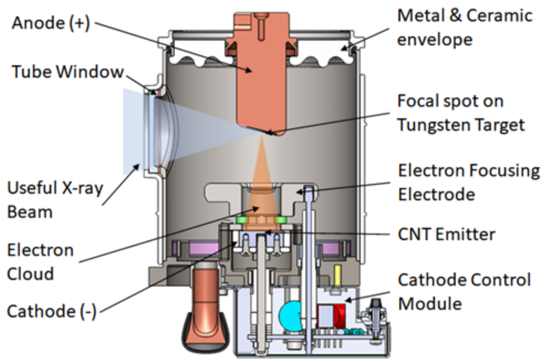
Conventional x-ray tubes create electrons thermally in the tube by boiling them off a thin tungsten filament. An electron current is passed through the thin filament, similar to an incandescent light bulb, and the filament heats up to 1400°C. As the filament gets hotter, more electrons are created. These electrons are sourced from the filament atoms and over time, the filament will run out of material and burn out. This is known as thermionic emission.

Carbon nanotube (CNT) x-ray tubes work differently, they create electrons using field-emission instead of thermionic emission. Field-emission is when an electron current is created due to a very intense electric field at the surface of a metal; a simple example is a spark plug where a large electrical voltage creates a short intense spark of electron current. In any field emission, the electric field is intensified by reducing the aspect ratio of the surface of the metal; if the metal is a sharp tip, the electric field is more intense and the sharper the tip the more intense the field becomes. Carbon nanotubes (CNT) are the ideal field emitter known to physics because they have an extremely sharp tip, CNT are typically 10nm wide but 20-50μm long and have the same electrical properties as metal. Due to their ideal field emission properties, CNT can generate very high electron currents.

CNT x-rays use field-emission to generate electrons, then accelerate those electrons into a dense target material (typically tungsten) to generate x-rays the same way conventional x-ray tubes do. A diagram of a conventional x-ray tube and CNT x-ray tube is compared in Figure 1. The basic structure of the two x-ray tubes is similar and both have most of the same key components. The key difference is the CNT x-ray tube has more structure around the cathode to ensure stable and precise control of the CNT emitter.



Conventional X-ray Tube



CNT X-ray Tube

Figure 1 - Comparing conventional and CNT x-ray tube architectures

3.2 CURRENT TIME

For medical x-ray imaging, the amount of x-rays the tube delivers is defined by the quantity of electrons hitting the dense target material. The number of electrons hitting the target is determined by how many electrons are flowing in the tube (the electron current is measured in milliamperes (mA)), and how long the electrons are flowing (time measured in seconds). Therefore, a standard medical exposure is defined in mAs or milliampere-seconds. For example, a typical extremity exposure (hand or foot) is 0.5mAs-1mAs, a typical chest exposure is 2mAs-3.5mAs, and a typical abdomen exposure is 10mAs-20mAs; the total dose required to achieve a clinically acceptable image increases as the size of the imaged region increases.

Until recently, CNT emitters have not been used for x-ray imaging because it has been challenging to achieve the current required for typical medical exposures. Most CNT emitters have easily demonstrated 0.5-1mA of current; but it requires very long exposures (many seconds) at these currents to achieve the required dose. CNT emitters must get to 50mA-100mA range to achieve all medical exposures in less than 1 second so that patient movement doesn't blur the image.

3.3 HISTORICAL LIMITATIONS OF CNT EMITTERS IN X-RAY TUBES

Since CNTs were synthesised in 1991, there has been global interest in applying them to x-ray imaging. Individual CNTs can show a very large current; up to 0.1mA from a single CNT has been demonstrated. The challenge has been scaling from individual CNTs to larger distributions of CNTs to achieve a higher total current of 50mA-100mA. The common approach has been to try to replicate the best possible CNT structures over a large area. This approach has several limitations:

- Expensive – making ideal CNTs over a large area requires a sophisticated micro-wave plasma manufacturing process which is expensive and challenging to scale as the size of the CNT emitter becomes larger to achieve higher current.
- Unrepeatable – it is very challenging to make the same emitter each time because of the intrinsic variation in a micro-wave plasma process.
- Unstable – if a single CNT is damaged or non-ideal, then the entire structure can become destabilised as the other CNTs are over-stressed to compensate for the damaged or suboptimal CNT emitter.
- Unscalable – as the target current increases, the number of CNTs required and size of the emitter matrix increases. As the size increases, the challenges of stability and repeatability scale exponentially.

There are common misconceptions of CNT electron emitters:

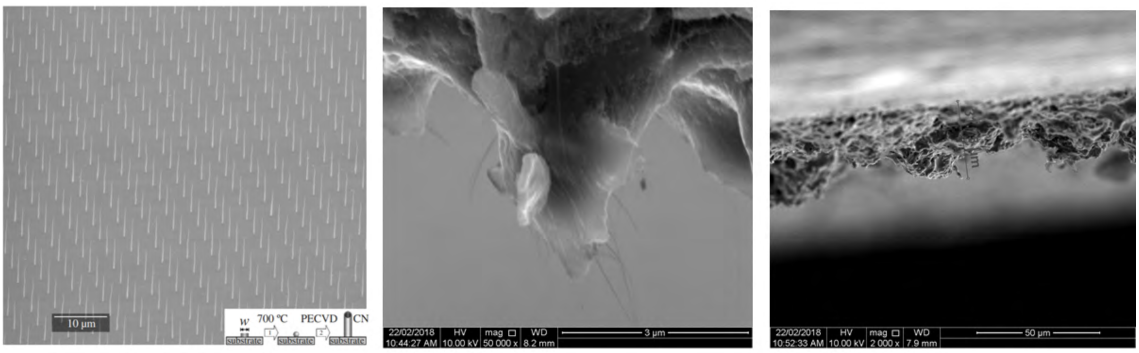
- They are low current – CNT emitters are peceived as too low current for medical x-rays due to the challenges of scaling the CNT emitters to achieve the necessary 50mA-100mA for medical x-rays.
- They are unstable – CNT emitters are perceived as non-stable and unrepeatable which means they cannot demonstrate a stable product for daily medical use and will give a variable performance that could degrade patient image quality.
- They have a short life – CNT emitters are peceived as not delivering enough electron current to provide several years of daily medical exposures. This is because any damage to the emitter can result in the rapid degradation of the entire structure resulting in early life failure.

3.4 MICRO-X'S PATENTED CNT EMITTER TECHNOLOGY

Micro-X has discovered and patented a unique solution to address the limitation of the CNT emitters to deliver an electron emitter that:

- Delivers long stable life – no degradation in electron current performance over at least 5 years of multiple daily exposures.
- Delivers high current - maximum emitter current of 130mA for up to 2 seconds
- Simple, scalable, and repeatable fabrication process:
  - Uses commercially available CNTs
  - Applicable to a wide range of CNTs so not dependent on single supplier
  - Four step chemical process to bond CNTs to metallic plate
  - Design allows for manufacturing variation to deliver consistent performance
  - Chemical process is rapidly and directly scalable to large volume emitter manufacturing.

The difference between Micro-X's approach and other common large area CNT emitters is illustrated in Figure 2 below. The common approach to scaling a CNT emitter has been to try to make a repeated pattern of ideal CNT emitters, illustrated in the left image in Figure 2. The Micro-X approach uses an amorphous distribution reliant on non-ideal CNTs and a unique bonding matrix material, illustrated in the bottom image of Figure 3.



Other CNT large area electron emitters

Micro-X CNT Large area electron emitter

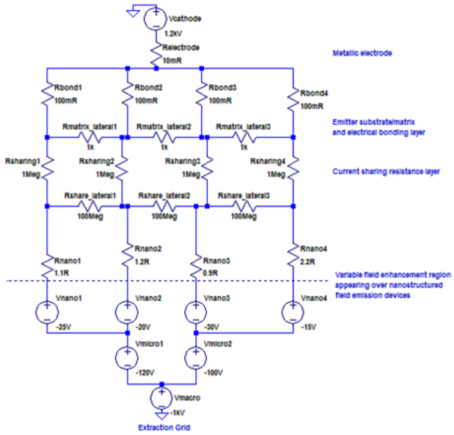
Figure 2 - Comparing images of common large area CNT emitters to Micro-X large area CNT emitter

3.4 MICRO-X'S PATENTED CNT EMITTER TECHNOLOGY (continued)

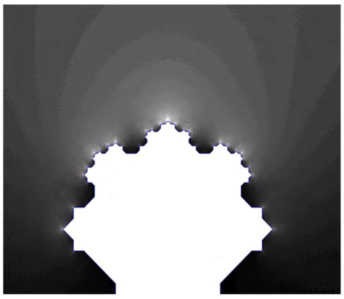
Micro-X has patented its unique approach which relies on an amorphous matrix material that bonds non-ideal CNTs to a metallic plate. The matrix material has two key properties, as illustrated in Figure 3. The first property is the material, it provides resistive pathways between the metallic plate and the CNTs to force an even current sharing among all the CNTs; this overcomes the intrinsic variations in the CNT emitters' performance and ensures uniform high current. The second property is an amorphous structure that provides multiple layers of electric field intensities; this provides layers of CNTs that can turn on with slight increases in the global electric field to provide a designed-in redundancy when any individual CNTs degrade.

These two properties provide the key for Micro-X's CNT emitters to achieve a high current (130mA+) and stable operation over the life of the x-ray tube.

Figure 3 – Two key properties of Micro-X's patented CNT emitter design to ensure long-life stable emitter



Resistive Matrix
Forced current sharing



Amorphous Structure
Designed in Redundancy

4. MICRO-X CNT EMITTER LIFE & ROBUSTNESS TESTING

To demonstrate the stable long-life performance of the CNT x-ray tubes, Micro-X has conducted several Accelerated Life tests (ALT) and Reliability Demonstration Tests (RDT) on multiple CNT x-ray tubes.

These tests were conducted in accordance with the expected typical daily use of the mobile x-ray system, which was determined as:

- 60 exposures per day (21,900 exposures per year)
- 80% chest exposures at 90-110kV, 2-3.5mAs (48 per day)
- 10% abdomen exposures at 80kV, 16mAs (6 per day)
- 5% pelvis exposures at 70kV, 20mAs (3 per day)
- 5% paediatric exposures at 55kV, 0.5mAs (3 per day)

4.1 MEASURING MICRO-X CNT EMITTER LIFE (VGC)

As Micro-X's CNT emitter is used in an x-ray tube, very slow degradation of the emitter will occur proportionate to the level of stress placed on the emitter – higher current and longer time exposures will increase degradation.

To ensure the delivered dose remains accurate, the voltage driving the emitter (known as Vgc, the voltage between grid and cathode) is gradually increased throughout the tube's life, up to a maximum increase of 750V, represented as the red line in Figure 4. The degradation of the emitter is very slow, measurable and predictable, and thus can be used to monitor and predict the end of usable life of the CNT x-ray tube.

4.2 ACCELERATED LIFE TESTING (ALT)

During Accelerated Life Testing, a single exposure was repeated as fast as possible (allowing for heat management on the anode) to demonstrate the basic x-ray lifetime performance of the tube. The results from this test are shown in Figure 4 below. One tube was tested at high 20mAs exposures (abdomen, blue line) and two tubes were tested at more typical chest exposures (2mAs and 3.2mAs, green line and orange line respectively). The effective end of life, as measured by a maximum allowable increase in Vgc of 750V, is represented as the red line.

The data in Figure 4 below demonstrates over 4 years of life, and projecting out the rate of emitter degradation suggests the emitter will last approximately 10 years when taking the maximum 20mAs exposure, and over 20 years when taking a more typical 3.2mAs chest exposures. It also demonstrates that during the testing, the emitter continued to reliably produce the target dose with no impact to performance (mAs) as shown in the right-hand side graph.

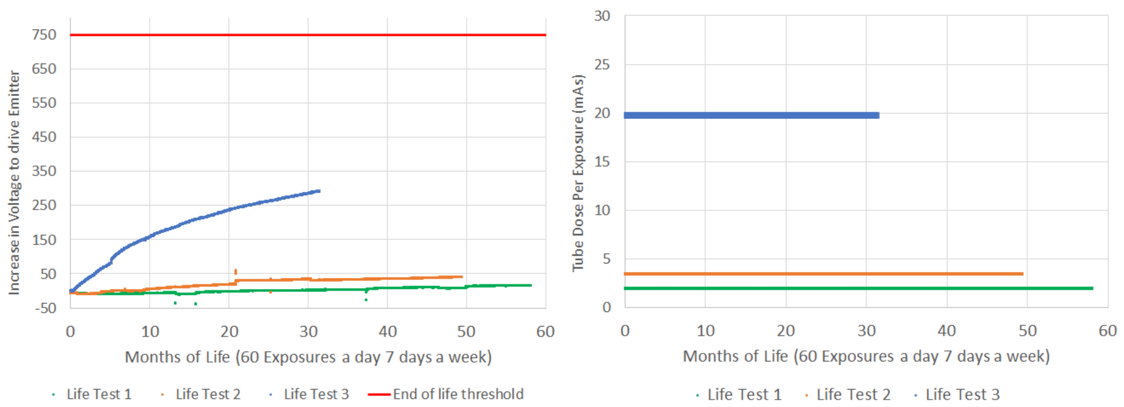


Figure 4 - Accelerated Life test results of three CNT x-ray tubes

4.2 ACCELERATED LIFE TESTING (ALT) (continued)

In the ALT during the high stress 20mAs exposures, the CNT emitter change actually gets better; the rate of Vgc increase slows down as the emitter "learns" how to deliver the high stress exposures. This can be seen in the flattening of the blue curve (20mAs exposure) in Figure 4. Fewer exposures were taken at 20mAs than at 2mAs and 3mAs as more time is required between each exposure to keep the anode cool, and thus the rate of acceleration was decreased. However, over 55,000 exposures have been taken at 20mAs, at which point the emitter has reached a little over 30% of its design life and the rate of degradation is slowing down. As noted above, this slow and predictable degradation indicates an emitter life of 10+ years even at maximum stress.

4.3 RELIABILITY DEMONSTRATION TESTING (RDT)

The RDT testing was focused on the tube integrated fully into a mobile system and included the x-ray tube taking multiple different exposures based on typical daily use and include physical testing moving the system in circuits, over obstacles, and moving the arm around.

Due to the time to perform the extended physical testing, the RDT testing data is shown for eighteen months of life. The results from two systems testing is shown in Figure 5 below. The Vgc is the voltage required to drive the emitter; there are multiple lines because the tube is tested at multiple different exposure currents, increased current requires a slight increase in the voltage.

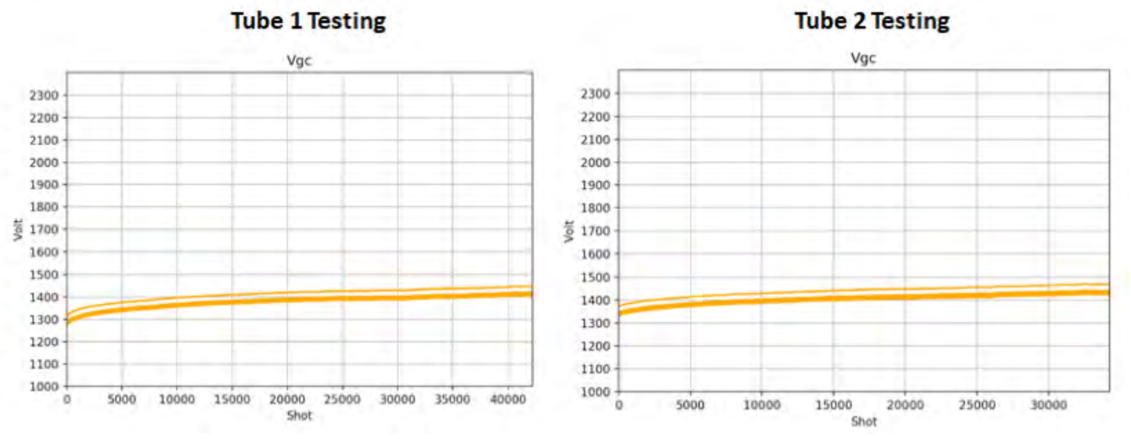


Figure 5 - Reliability Demonstration Test results of Two CNT x-ray tubes

4.3 RELIABILITY DEMONSTRATION TESTING (RDT) (continued)

Full RDT testing demonstrated over five-year's life (125,000 exposures) for different CNT emitters. This test took over 6 months of continuous testing to demonstrate. The results of this test are shown in Figure 6 below. The shape of the emitter change curve matches the shorter tests and the output tube currents remain stable and constant throughout the entire test.

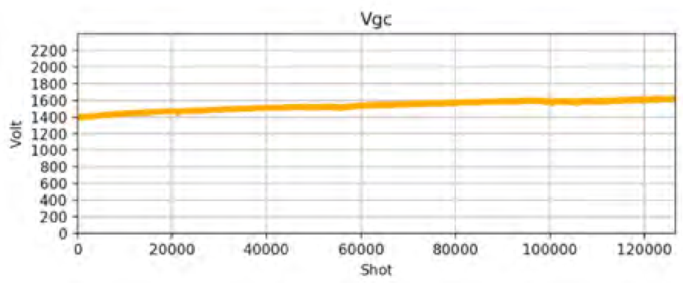


Figure 6 - Five-year life demonstration of full performance

4.4 CONCLUSION OF TEST RESULT

The data from multiple tubes demonstrates that the emitter current performance and the x-ray tube dose performance remains stable and constant throughout the testing. The data demonstrates that the emitter slowly changes over time, but this change is constant and predictable and the redundancy in the design ensures there is no degradation of performance and confirms the stable nature of the CNT emitters Micro-X manufacture.

5 years of life has been demonstrated in tubes, with projections of the degradation rate indicating an emitter life of 10+ years.

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