Development of a Seasoning and Screening Procedure for X-ray Tubes

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Abstract

Each Microdose Mammography L30 unit built by Sectra Mamea is carefully calibrated and thoroughly tested before leaving the assembly line. However, to perform these test the x-ray flux need to be relatively stable, and for brand new tubes the flux is not stable at all but rapidly decreasing. Performing exposures in the calibration areas in the assembly line until the flux stabilises is time-consuming and inefficient. An automated seasoning procedure that the x-ray tubes could go through before entering the main production line was proposed as an alternative. This thesis evaluate the requirements on a seasoning procedure with the purpose of taking the x-ray tubes to through this unstable region.

Four seasoning benches were completed, guaranteeing capacity enough enough for the needs of both production and spare part demand. Other x-ray tube quality issues that caused costly delays in the main production line led to a broadening of the scope; the seasoning procedure should see to it that tubes with ripple, arc and noise problems did not enter the production line. It should also be proven that the seasoning procedure do not cause defects in the seasoned tubes.

After evaluation of available test equipment 15 x-ray-tubes were measured through their whole the seasoning cycle - 9 went through a 300 exposure cycle and 6 went through a longer cycle of 500 exposures. From these measurements it became evident that there was large differences between individual x-ray tubes, and also that the decline in flux continued in what had been assumed to be the stable region. This made it difficult to define a good end criteria for an adaptive seasoning process.

Based on the data from these 15 tubes the recommendation was instead to use a fixed seasoning program, as the main requirement - taking the x-ray tube past its fast decline region - was fulfilled by a simple exposure program without the need for further investments in expensive instruments and development of test software. And while the seasoning procedure might be good for screening for other problems like arcs, ripple and noise, to actually solve them the supplier must be more involved.

Sammanfattning

Varje Microdose Mammography L30 kalibreras och testas noggrant innan den lämnar tillverkningslinan. Men för att utföra dessa tester behöver röntgenflödet vara relativt stabilt, och för nya röntgenrör är det inte stabilt alls utan snabbt avtagande. Att utföra exponeringar i kalibreringsarean i tillverkningslinan tills dess flödet stabiliserats tar tid och är ineffektivt. En automatiserad inbränningsprocedur föreslogs som ett alternativ. Det här exjobbet utvärderar krav och utformningav en inbränningsprocedur med syfte att ta röntgenröret genom denna region med instabilt röngenflöde.

Fyra inbränningsbänkar färdiställdes, nog för att garantera kapacitet för både produktions- och reservdelsbehov. Andra problem med röntgenrören orsakade kostsamma förseningar i tillverkningslinan vilket ledde till att omfånget på denna studie ändrades; inbränningsproceduren borde även se till att rör med rippel', arc-, och missljudsproblem stoppades innan de nådde tillverkningslinan. Det borde även visas att inbränningsproceduren inte orsakar defekter hos de inbrända rören.

Efter att ha utvärderat tillgänglig testutrustning gjordes det mätningar på 15 röntgenrör under hela dess inbränningscykel. 9 rör genomgick en 300 exponeringar lång inbränning och 6 rör genomgick en längre 500 exponeringars inbränning. Av dessa mätningar blev det uppenbart att det var stora skillnader mellan individuella röntgenrör, och även att flödet fortsatte avta i vad man antagit var en region med stabilt flöde. Detta gjorde det svårt att definera bra slutvillkor för en adaptiv inbränningsprocess.

Baserat på data från de 15 röntgenrören blir studiens rekommendation istället att använda ett fast inbränningsprogram, eftersom huvudkravet - att ta röntgenröret genom regionen med instabilt röntgenflöde - uppfylldes lika bra av ett enkelt exponeringsprogram, utan vidare investeringar i mätutrustning eller mjukvaruutveckling. Och även om inbrännningsproceduren är bra för att screena rör för andra kvalitetsproblem såsom rippel, arcar och missljud går det inte att komma till bukt med dessa om inte leverantören blir mer involverad.

Contents

1 Introduction

1.1 Mammography

Breast cancer is the most common cancer found among women and early detection is the key to successful treatment. The most efficient way of detection breast cancer is by screening. One of the foremost advocates of screening, Dr Lázló Tabár have proven the benefits of screening again and again[11]. In Sweden all women of ages 40-74 are offered mammography screening every 18th-24th month.

Huge progress has been made from the early days of mammography (an account of the technological development in the age of analog mammography can be found in [8]) and the transition to digital detector technology has decreased the dose to the patient whilst increasing image quality.

The good detection rate in combination with the high throughput rate have kept x-ray mammography as the backbone in screening programmes even in competition with MRI and ultrasound. Even though the mammography has one major disadvantage compared to those technologies; ionizing radiation is harmful and exposure should be kept at a minimum (the guiding principle for radiology is ALARA - As Low As Reasonably Achievable). Sectra Mameas Microdose L30 is the market leader in low dose mammography screening, and utilizes a photon counting detector in a scanning multi-slit system[2] to provide excellent image quality while subjecting the patient to lower dose than any other system.

But while the detection side of the x-ray mammography has developed a lot, moving from film to screen-film system and then on to different kinds of digital mammography systems, very little has happened on the x-ray *generating* side. The X-ray tubes used today are not all that different from those used in the 1960s, but with increased detector sensitivity the requirements on the quality of the generated x-rays are higher than ever. Especially for the Microdose L30 - even though the patient is subjected to less radiation the load on the tube is higher. This is due to the fact that it is a scanning system instead of a true full field detector - increasing exposure time - and due to that so much radiation is simply blocked, as it is only the x-rays that will reach the active detector area that is of interest.

Applying the ALARA principle also have the consequence that having to retake an image in a mammography examination is a serious matter indeed - and any quality issues that might affect image quality is a big problem. To ensure excellent image quality each unit built undergo rigorous calibration and testing before being delivered to the customer.

1.2 The Objective

This thesis project was done at Sectra Mamea AB, Solna, Sweden (henceforth referred to as Sectra). The aim was to construct an automated seasoning[1] and test bench for the X-ray tubes used in the Sectras Microdose Mammography^{TM}L30.

In the initial specification[7] for this thesis the objective is stated as follows (translated from Swedish):

> For patient safety and to ensure the high image quality required for mammography examinations it is of great importance that X-ray tube delivers X-ray output of high and consistent quality. When the X-ray tubes are delivered to Sectra Mamea they are therefore controlled to see that they fulfil the geometric beam quality, ripple and flux requirements.
>
> However, ripple and flux measurement can not be carried out on the newly produced X-ray tubes, as the X-ray flux is not stable initially. The X-ray flux is initially high and decreases exponentially until levels stabilize at the ”proper” level. This is time-consuming work where an operator manually implements a large number of exposures until the tube is stabilized.
>
> The goal of this project is to automate the burn-in process with the equipment whose high-level high-level requirements are specified in *Specification for Automatic X-ray tube burn in and test bench DOC-NOK-783CLX-0.1.*

1.3 Constraints

I was to work close to production - a very basic seasoning procedure was already in use when I started. One seasoning bench was already operational, and one of my tasks was to see to it that the remaining three were completed. The constraints were pretty clear - the number one priority was the production line, although it was stated that I could dispose one of the seasoning benches it was soon evident that the available seasoning equipment was not the limiting factor.

The work-flow for an x-ray tube when I started was described as follows:

1. Perform ripple test (FFT). Pass if peak at approx 160 Hz is <20.
2. Burn-in with 100 exposures at 32 kV, 206 mA.
3. Repeat 1-2 until at least 500 exposures have been performed OR tube have failed test.

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[1] Burn-in is an alternative term commonly used. In this report I will use seasoning throughout.

4. If PASS, mount mechanichal interface and filters and align tube. Check that beam coverage is within specification.

In practice this was not implemented in a structured way, data was not saved and there was no traceability on the number of exposures for tubes.

After this the x-ray tubes wre passed on to the main assembly line where they were mounted in the mammography modality. The completed x-ray assemblies were a kanban[6] item as a true one-piece flow was not realizeable due to the nature of the demand (both material for production line and spare part for installed base) and the unreliable quality of the tubes.

It turned out that there were additional quality problems with the x-ray tubes - a lot of units had to be replaced due to issues in final test. This affected my work in two ways - first, it was evident that the seasoning procedure should, if possible, mitigate these problems in some way. Secondly, due to the quality issues the projected purchases of tubes were far lower than needed - there could be no tubes available at all for long periods of time, and and when they finally arrived the production line needed them right away. With production being priority number one I had to squeeze in the tests I could.

Before christmas, I had the opportunity to perform a number of preliminary measurements and familiarize myself with the available equipment. I also did interviews with the different stakeholders to get a better understanding of the different scenarios that would lead to the tube being replaced in the production line.

The main series of tests performed have been burn-in with output measured for each exposure, with ripple tests done before and after the seasoning procedure. The seasoning configuration has intentionally been kept as simple as possible - as there was very little data I did not want to introduce more complexity before I had any reason to do so.

1.4 Black box

A major problem with studying an x-ray tube is that from my perspective it was essentially a black box - I could define input and measure the output, but I could not open the tube to get more information about the state of the individual components. E.g. I could not inspect the physical state of the line focus track. However, we can control the input and measure the output and observe the tube during operation. Based on the output and our observations we can then make more or less informed choices.

The tubes also had no history - we knew nothing of what the tube had been through before it was sent to us. It is reasonable to assume that there is some sort of outgoing quality test at the supplier, but we know little about the extent of those test. And, more importantly, we cannot assume that all tubes have identical history.

This is a common problem in manufacturing. You are stuck with a chosen component, which fail in some way not directly related to the specification you have. Relations with the supplier might not be at their best so the suppliers expertise is not available for the purpose of solving your problem, instead you have to make do with what you actually have.

1.5 Stakeholders

There were many stakeholders with interest in the x-ray tube, or at least with an understanding of what was the problem with the component. I present them here to give a better understanding of the surrounding situation.

- Production: Priorities are stability first and reducing time secondly. Open-ended troubleshooting activites are not popular.
- Development: Are mainly interested in the function of the product. Replacing an x-ray tube 15 times doesen't bother the designer as long as the 16th tube fulfills specification. Want better data regarding failures but rarely define exactly what they need.
- Service: Interested in quality of the product and spare parts after delivery. Tubes failing too soon after installation and spare part tubes failing out-of-box had created mistrust.
- Marketing: Interested in competetive advantage, concerning the tube this might be more exams per hour which direcly result in an increased load on the x-ray tube.
- Purchasing: Concerned with the gulf between "not good enough for production" and "a defect we can claim a refund for from the supplier".

1.6 Lean Production

The production line at Sectra was a new production line implemented with Lean methodology in the style of Toyota. The implemented seasoning should make sense in this context.

2 Expanding the problem description

In order to better understand the problem I set out to get a better understanding of x-ray tube - how x-rays are generated and what changes can be expected over the lifetime of the tube. I have also examined the different failure modes in the production line as to better judge if and how the seasoning process should take them into account.

2.1 The X-ray Tube

An x-ray tube generates x-ray radiation by accelerating electrons toward a solid heavy metal target. X-ray photons are then generated by two processes - bremsstrahlung and characteristic emission.

Bremsstrahlung (German for braking radiation) is as the name suggest produced when an electron pass close to a nuclei in the target. The electron is accelerated by the nucleus' electrical field and a photon with energy equal to the kinetic energy lost by the electron is emitted. This photon cannot have an energy larger than the incident electron, but it can assume any lower value - resulting in a continuous spectrum. The ideal spectrum would be a right-sided triangle with the highest relative intensity at photon energy 0 eV, but in reality the lower energy photons are likely to be reabsorbed in the target.

Characteristic emission take place when the electron impact ionize a core electron in the target. Relaxation can then take place - an outer shell electron fill the hole in the inner shell and the difference in energy result in emission of a photon of that energy. Characteristic emission result in a line spectrum (since the energies are discrete) that is characteristic for the target material

The heavier the element, the higher the energy of the characteristic radiation. For tungsten the first usable characteristic emission lines are at 59,3 keV and 67,2 keV. The kV settings used in the L30 range from 26 to 38 kV, so there will be no contribution from characteristic radiation.

The x-ray generation process is less than 1% effective, with almost all of the energy being converted to heat instead of useful x-ray radiation. Cooling is thus necessary, and in this application oil is used as the cooling medium.

The insert is placed in a housing which also contain the stator. The cooling medium fill the volume between the inserts outer wall and the housings inner wall. As the energies used for mammography are quite low, a beryllium window is used in tubes for mammography applications to offer less filtration of the x-ray output compared to the glass of the vacuum bottle walls.

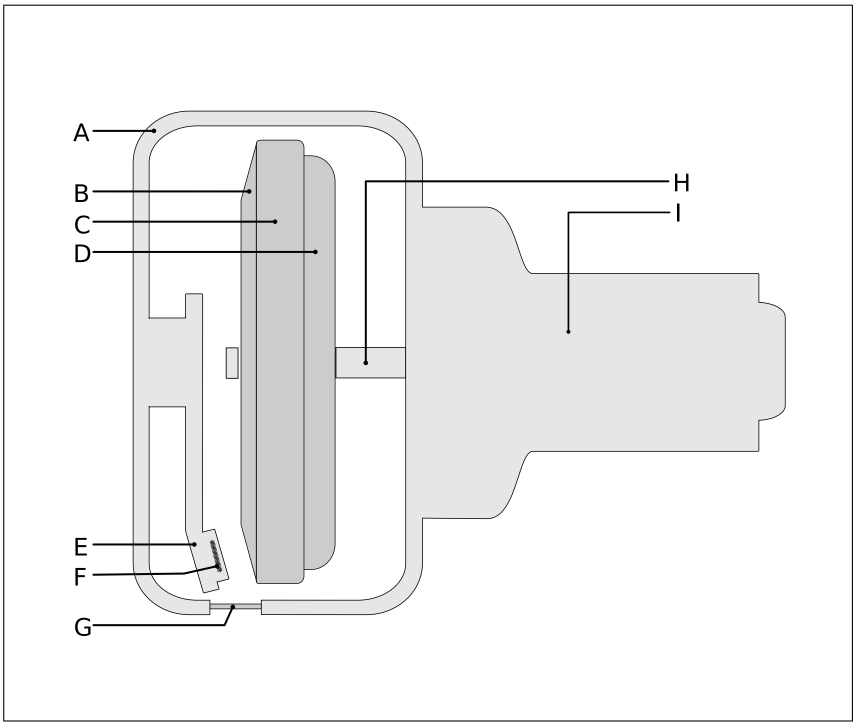


__Figure 2.1.__ A Simplified Illustration of the X-ray Tube Insert A) Glass casing. B) Tungsten/Rhenium target. C) Molybdenum core. D) Graphite back target E) Cathode. F) Tungsten filament. G) Beryllium window. H) Anode axis I) Rotor

2.2 The Cathode

The cathode filament is a spiral thread made of tungsten. And, exactly as for the old incandescent light bulbs, it has a limited lifetime. Replacing x-ray tubes at hospitals is almost always because of a broken filament, or preventive replacement when the tubes have been used more than the expected filament lifetime.

2.3 The Anode

The anode is a 102 mm in diameter disc with a Tungsten-Rhenium alloy facing on a molybdenum body with a graphite back target.The target surface is at a 16 degree angle to the primary direction of emission, thus keeping the focal spot small but using a large part of the anode surface. The anode is rotated at high speed (9600 rpm) and the track of the focal spot on the anode is called a strip focus (see figure 2.2). The rotation is to allow a higher input power without melting the anode. As the efficiency is less than 1% (In [9] the efficiency is approximated as $\epsilon = 0,92 \times 10^{-11} ZV$, with Z being

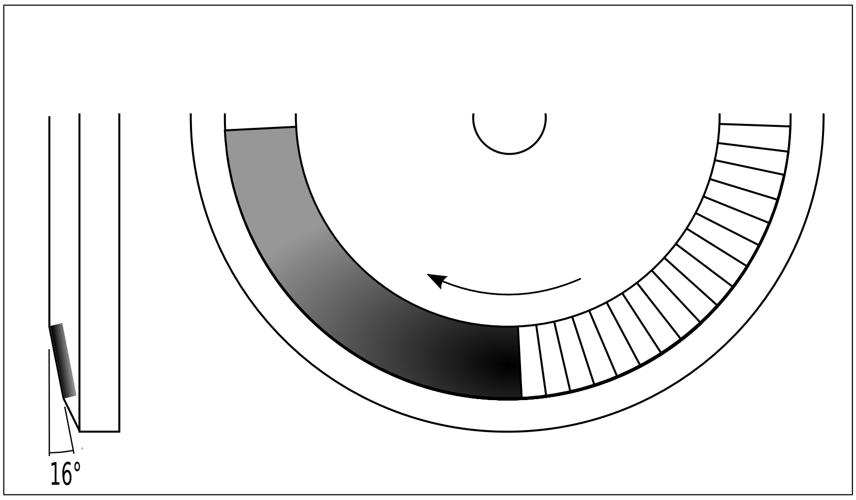


Figure 2.2. *Strip focus*

the atomic number of the target and V the accelerating voltage. This would mean an efficiency of between 0,18% and 0,26% for the voltages used in the Microdose).

The maximum x-ray intensity is at 90° to the incident electron beam, but it is spread in all directions. As one moves toward the back of the image area the angle toward the anode surface become steeper. And as the angle become steeper the intensity decreases. This is known as the heel effect. As long as the anode angle is constant this is not a problem, but should the anode start to wobble this would cause intensity variations in the output.

The maximum heat load of the anode is 445 kJ - and the normal operating maximum should be 90% of that. Furthermore, the cooling can remove approximately 1,5 kW. In the Microdose, the tube operate at a predefined set of 5 different kV/mA combination, limited by the maximum effect the anode surface can handle.

2.4 Failure modes

In the following section I will describe the modes of failure which will lead to problems in the production line, often resulting in time-consuming tube replacements and having to redo several tests.

2.4.1 Output

There are two kinds of output-related problems. One is as stated in the formulation of the original problem (in 1.2), that the output changes too fast. This will only lead to delays, but those are costly enough as the operator must perform each exposure manually (there is no automatic exposure option available on the modality due to safety regulations). The other problem is if the tube output become too low, which will necessitate a tube replacement.

As stated in the formulation of the original problem it was known that the tube underwent rapid change during the first exposures. However, there was little actual data available. The informal hypothesis was that there was an initial decline, rather fast, and after that the output was more or less constant until the tube broke down for some other reason.

In [1], one of the few sources I found which covered the long-term behaviour of X-ray tubes there is a comparison of the output as a function of the number of exposures for Tungsten anodes with different amounts of Rhenium. The comparison start at 300 exposures, with approximately 93% of initial output for an anode with 10% Rhenium, and end at 10000 exposures and approximately 86% of initial output. So, the tube output goes down approximately 7% during the first 300 exposures (the length or intensity of these exposures were not given, so we will only use this for discussing general behaviour). So in part this agree with the problem as formulated in 1.2, in that there is a big change in the beginning of the tube output. However it contradicts it in that there is no stable level reached, the rate of decline lessens but the decline go on for the entirety of the tube's lifetime. The mechanism responsible is roughening of the anode surface, making it more likely that there is anode material in the path of newly generated x-rays.

Tube output being too low is very uncommon in production (remember, these tubes are new and are expected to last over 50K full exposures - and when they fail it is expected to be due to the filament failing). I had no examples of such tubes available - otherwise I could have matched the output level of those with the levels measured in the test set-up.

2.4.2 Ripple

Ripple in x-ray output is periodic variations on the x-ray output. This can be attributed to either ripple in the anode-cathode voltage, in the tube or variations.

Historically, small periodic variations has not been a big problem as for non-scanning systems - the whole image get the same variations for any given time. A pixel in this type of detector is made up from readouts from the same detector element in the same position The Microdose L30 however is a scanning multi slit detector system, and the scanning make it susceptible to variations in the x-ray source during the scan. A pixel in this detector is virtual, an aggregate of readouts from a number of detector elements at the moment they are in that position. So if the output from the x-ray-tube varies the accumulated dose in virtual pixel row a and virtual pixel row b can differ. If you have periodic variations in the x-ray intensity you can get periodic variations in the image, manifesting as visible "lines" in the image perpendicular to the scan direction.

There was already a ripple measurement procedure implemented in the X-ray tube sub-assembly area. The output from this measurement is a file with three "header" rows and one row for each sampling of the signal. The first header row is the number of samples, the second is the total time period sampled and the third is configuration data (not used). A scilab script is used to analyse the data, and the algorithm used for checking for ripple can be described as follows:

1. Read the two first rows and use data to determine the time per sample (1/frequency).
2. Read in all samples. Discard pre-defined parts of signal (beginning and end) to avoid initial filament current regulation artefacts and artefacts from signal end.
3. Scale samples, and remove mean.
4. Use FFT to transform signal
5. Use fftshift to center the transformed signal around zero.
6. Display frequency graph and signal graph (see figure 2.3).

The original objective (1.2) stated that ripple and flux measurement could not be performed on the new tubes. But there was of course nothing preventing the actual ripple measurement, but it was "common knowledge" that ripple increased during these initial exposures. I would have to document ripple before and after seasoning to see if this was true.

The problem with ripple in the production line had turned out to be much larger than anticipated. The new L30 seemed to be more sensitive to

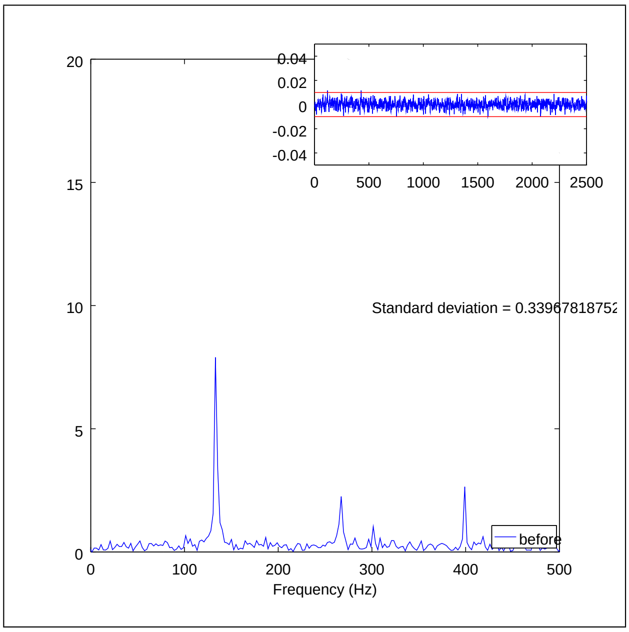


Figure 2.3. *Example of ripple graph as presented to the operator*

ripple than the older mammography model the D40, and the tubes could change during the production tests - if you were unlucky ripple artefacts would suddenly crop up in images during final quality tests and then you would have to replace the tubes and redo all image tests, adding days of work.

The implementation in use in production use scilab, but for this report octave has been used instead. The results from the two have been compared and no major differences in the results have been observed.

2.4.3 Cooling

As the efficiency of the x-ray generation process is so low efficient cooling is critical. The maximum heat storage in the anode is limited by the anode composition and its black-body radiation (as it placed in vacuum) but the insert must be cooled to remove all that heat.

There are two hardware safety functions implemented to prevent damage from overheating - one is a flow switch in the heat exchanger, the other is a temperature switch in the x-ray tube. The purpose of the flow switch is to ensure that the cooling medium is circulating - if the flow of the cooling medium through the heat exchanger stops new exposures will not be possible. This does not ensure that the circulation in the x-ray tube housing is optimal. The temperature switch will prevent further exposures if the temperature in the x-ray housing is too high. This is the temperature in the housing - not the anode temperature - so it will stop exposures when the cooling is insufficient but it will not prevent the insert from going over the allowed heat load

The efficiency of an oil-cooled system is greatly reduced if air is introduced in the system. Because of that, the supplier specify that the number of connections and disconnections of the oil hoses should be kept at a minimum.

Another source of air in the system can be low pressure. If the pressure drop in the system is bigger than what the pump can handle one end up with the oil pressure in parts of the system being lower than the surrounding ambient air pressure. This will cause air to be sucked into the system if the system is not perfectly sealed. The quick-connectors on the hoses are a good example of a non-perfect seal.

Problems with heat dissipation can have severe consequences - not only do we have the immediate problems with the anode surface melting, but high temperatures can also cause solder joints to re-melt and bearing lubrication to vaporize. One consequence of all these is that the vacuum in the tube insert will be contaminated, and that will in turn cause arcs.

2.4.4 Arcs

Arcs are a classical ray tube problem, [1] mention arcs as common reason for tube replacement for tubes with high tube voltages. However, this was largely based on the situation for old film system. X-ray imaging has moved on to digital detectors, which has increased x-ray sensitivity [3]. So for most applications the load on the tube is lower.

But for the the scanning multi-slit detector used in the Microdose, a pre-collimator block all x-rays except those that would reach the active detector area. This reduces the dose to the patient, but it also means that the load on the tube is higher than for other FFDM systems, with longer exposure times.

During the lifetime of an x-ray tube, material from the anode (or other vaporized material inside the vacuum tube) will be deposited on the glass walls of the tube. When enough material is deposited on the surface it will become conductive enough, so at high voltages there will be an arc from the anode, via the deposit, to the cathode, shorting out the tube. When this has formed, the effects will continue to increase with arcs happening at lower and lower kV and the tube has to be replaced.

So, if that would be the case the. Investigation of the matter also showed that arc was used for anything that the HVG reported as an arc - this would also be triggered by faults in the HVG during the generating sequence. And to complicate things further the variations between different units could be large for both components. So even if a combination of X-ray tube A and HVG B would fail, both might work paired with another.

In production, arc events were not uncommon for new tubes - especially when running higher kV exposures with a cold tube. The definition of when arcs become a tube defect was a bit vague. Single arcs now and then could be OK, but repeated arcs were not.

Any seasoning process should at least keep track of arc incidents. Investigation of arc issues on the test set-up revealed that a hardware reboot of the HVG seemed to be necessary to resume exposures after some arc incidents. This should be taken into consideration for the automated seasoning case.

2.4.5 Noise

Noise does not necessarily affect image quality. Or to be correct, noise in itself does not affect image quality, but the cause of the noise may also contribute to image artefacts. A wobbling anode, for example, may give rise to both ripple (see 2.4.2) and considerable noise due to uneven load on the bearings.

Noise is also something that lessens the perceived quality of the mammography system - bad noise will be reason enough to replace an x-ray tube even if the performance of the x-ray tube in all other aspects is stellar.

Noise is evaluated by experienced operators and team leaders in production. Evaluating the noise is not in the scope for the seasoning process, but seasoning give the tubes time to develop any inherent noise-generating defects. The net effect should be less replacements in the main production line due to noise.

2.5 Summary

The extended problem description thus present us with the following requirements on a seasoning procedure.

The seasoning procedure *must* :

- take the x-ray tube past the initial region of rapid decline in flux.
- be standardized and automated - the process should have a known maximum time and preferably an expected standard time, and is should not require an operator except to start the process and check results afterwards.

The seasoning procedure should:

- have standardized criteria for pass and fail.
- have standardized amount of work.
- catch ripple before the tube enters the production line.

- catch arc events.
- give the operator opportunity to judge noise.

The seasoning procedure should *not*:

- subject the x-ray tube to work loads higher than in the mammography application.
- cause ripple or other quality defects.

3 Methods

3.1 The Set-Up

The test bench set-up used was basically a metal cupboard with the necessary equipment mounted on it. The idea was to have a set-up as simple as possible, yet to be as close to the modality set-up as possible. Exposure is controlled by a modified version of the control system from the L30, stripped from all unnecessary functions. The main reasons for this approach are 1) it is easier to manufacture - we use parts used in the L30 whenever possible, and 2) the closer to the L30 the test bench is in terms of functionality, the less risk of getting errors during seasoning that would not show up in the L30. For example, all cables connecting the x-ray tube to the HVG and cooler were the same length as those used in the L30. The only notable difference was that the coolers were in the same room - on the modality the cooler is mounted in a side cabinet and during production tests the side cabinet is kept in a cooling tunnel.

The basic set-up that was available when I started utilized a simple serial interface to set exposure parameters and initiate exposures. I used this during preliminary measurements and evaluation and it was rather unforgiving and gave little feedback. For the main series of measurements, I got a version of the SCS (Stand Control System) calibration tool that had support for exposure control as well as ability to run predefined scripts for series of exposures.

To ensure that no exposures could accidentally be made whilst the operator was in risk of getting exposed to the x-rays a set of three security switches were built into the set-up - these would ensure that:

1. the x-ray tube was secured in the fixture,
2. that the fixture was correctly positioned, and
3. that the fixture door was locked.

Should any of these switches be open it would prevent the system from going to exposure state. The switches were connected to the emergency stop circuit, which in the modality ensure that exposure is interrupted or cannot be initiated if the circuit is broken.

This system is by no means fail-safe,it is meant to prevent accidents and can of course be tampered with. Measurements around the test bench indicated that front end of the X-ray tube leaked trace amounts of radiation during exposure, at the limits of the instruments sensitivity - a 2 mm steel metal cover was added as additional shielding around the front half of the tube.

3.2 The Instruments

I used two different instruments in this study - both are instruments primarily aimed at the radiology technician. If there was an established work process for a measurement in production I used the same process in my tests. For dose measurements I was interested in the change over time. Given that the instruments were made for measuring on a modality with other levels of filtration et c, the exact values for a given measurement may not be correct but it should be proportional to the true value. When comparing values I will only use average dose/second, and I will only compare exposures with the same kV and mA.

The Barracuda, manufactured by RTI, is a multi-purpose-instrument that can be connected to a number of detectors. With the MPD (multi purpose detector) it is used to perform ripple tests outside the modality, in an already established procedure. With the software used for ripple measurements, it is very configurable - results depend on the operator following the exact "recipe" to get the correct results. It is not a robust set-up - it was quite common that there were some problems when trying to connect to the instrument and connection was often lost.

For preliminary measurements I used an Magna CC ion Chamber connected to the MPD and collected the readouts directly from the display on the PDA connected to the Barracuda. This set-up proved very sensitive to temperature variations (one could see the the effects of opening or closing the door in the measurements, as the temperature levels changed) and it was a hassle to transfer the results. This presented major obstacles for the potential test design:

- Real-time review of the data by another software program would not be possible.
- Temperature variations of a few degrees Celsius is to be expected in the production environment. As the tests were performed in the intended production area this suggested that we either control the temperature better or chose another instrument.

It is not feasible to control the temperature with such precision around the clock *and* it and would be hard to implement the kind of real-time evaluation requested in the project specification I decided not to use the Barracuda with the ion chamber for further studies.

Instead I used Unfors Xi. This instrument had less configurability , but for an automated set-up this is not necessarily a problem. It stores measurements automatically in XML-format and can export data to an excel sheet continuously. The semi-conductor based detector also has better thermal stability, compared to the ion chamber.

The Xi is not suited to ripple measurements - in its out-of-the-box configuration it automatically take the average of the input signal, thus smoothing out the very oscillations that seem to be the problem. Even with this feature cancelled the sampling period is significantly shorter than that of the MPD, although the sampling rate is sufficient. I had hoped to get a version with a longer sampling period for this project but it was not released in time.

3.3 Seasoning cycle

The exposure setting used throughout this report is 32 kV and 206 mA - this is in the middle of the kV range used in the L30. The range is 5 discrete kV levels (26, 29, 32, 35, and 38 kV) combined with an appropriate mA (limited the number effect permitted by the anode). The choice to use only one kV was to reduce the number of variables, as the primary aim was to understand how the flux of a new x-ray tube behaved during the first exposures.

THe seasoning interval used is 5 second exposures, with 60 seconds between exposures. This allows the program to run continuously while having ample margins to the maximum heat load of the anode. The anode is boosted before each exposure and braked after.

3.4 The X-Ray Tubes

In this report I have chosen to use Roman numerals for the tubes rather than the serial numbers since there is no need for anyone outside Sectra Mamea to connect the data to the the physical tubes. Hopefully, the use of simple numbers instead of the serial number will also improve readability. I will however note, for the sake of completeness, which tubes that are produced in the same month.

Preliminary measurements were made on the RAD-70 tube. For the primary series, the measurements were performed on the new RAD-70B. The main difference between the two tubes is that the RAD-70B uses a thicker filament. This will hopefully lead to a drastically improved lifetime of the filament. Only data from RAD-70B tubes is presented in this report. The main impact of the new tube revision was that existing seasoning benches had to be upgraded with a new HVG, which caused some delays.

4 Results

4.1 Tube Output

In an effort to anonymize the tubes they are identified by Roman numerals I-XVI in this report.

- I-V are tubes manufactured in 2007. The remaining tubes are manufactured in early 2008.
- I-IX have had 300 5-second exposures at 32kV/206mA
- X-XV have had 500 5-second exposures at 32kV/206mA
- XVI have had less than 300 exposures, but have still been included as the modes of failure give some insight into weaknesses and problems with the test set-up. Also, the ripple measurements are useful.

All tubes have been seasoned using the same High Voltage Generator, Oil cooler and controlling HW/SW.

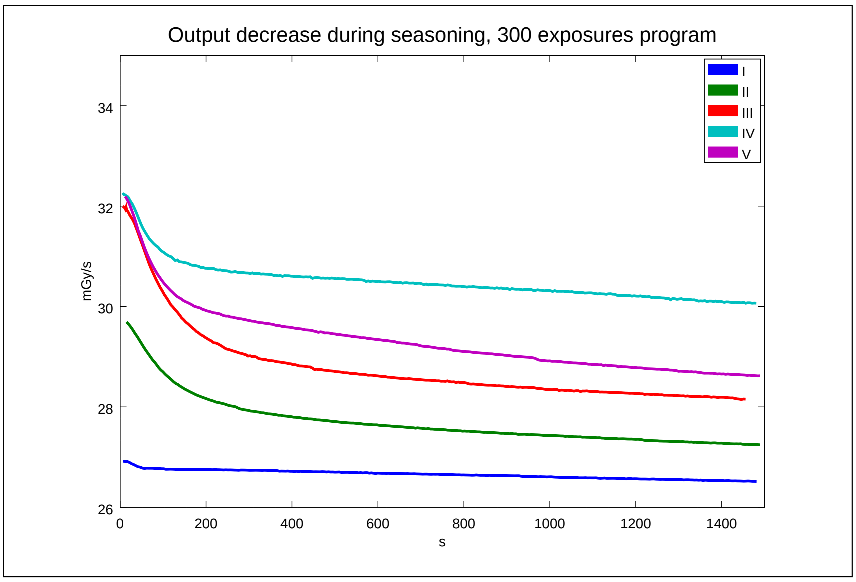


Figure 4.4. *Output decline during the first 300 exposures, tube I-V*

Evident from Figure 4.4 is that while tubes I-V share the same high-level behaviour in that they have an initial fast-decreasing region followed by a more flat region it is also easy to identify differences between them. Had all curves looked like II and III it would have been reasonable to suggest a model with a "tube constant" but is there a reasonable approach that could include them all?

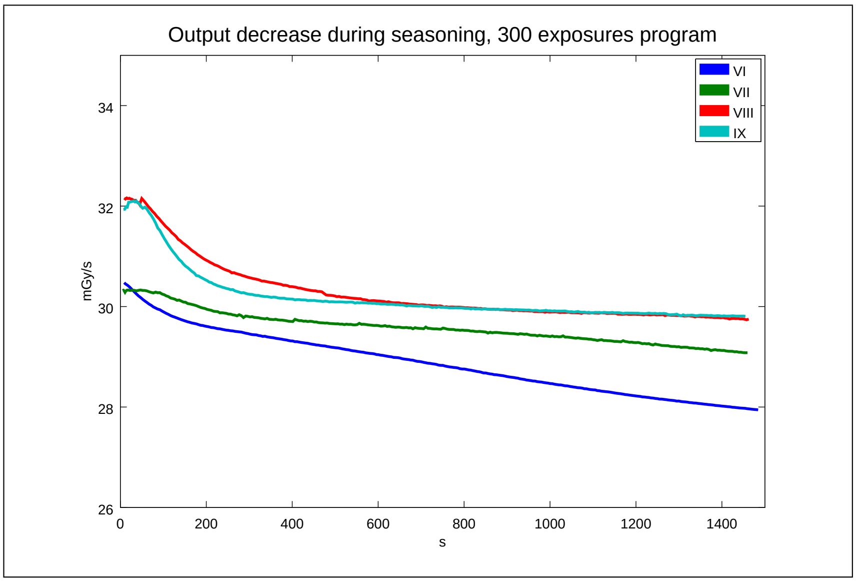


Figure 4.5. *Output decline during the first 300 exposures, tube VI-IX*

VI-IX (figure 4.5) also show large differences between tubes. Here one can also see that the curves are a bit jagged. This must be taken into account if one aim to construct an end-criteria for seasoning based on rate of change. How many points should it average over to get the correct results?

The tubes with the 500 exposure program (figure 4.6) show no surprises for exposure 301-500. Some of the tubes have irregularities that should be mentioned:

- The curve for tube X has a downward spike in the beginning, this is due to an arc event, resulting in an interrupted exposure. The jaggedness afterwards is likely due to varying (and longer than expected) time between exposures - the regular 1 minute pause between exposures is stabilized first after 150 s of exposures.

- XIII had trouble with the instrument during the initial exposures, where we got dose measurements and exposure times that were way off. I chose not to remove or replace this data as it is a good example of what might happen. From t = 70 s the exposures go according to plan.

- XII has dip at approximately 2200 s of exposure. This is because there was a 36 minute delay allowing the tube to cool down. The delay was caused by a power outage.

- XVI had a measurement system malfunction where the data for exposures 14-53 were discarded. I have not been able to replicate this

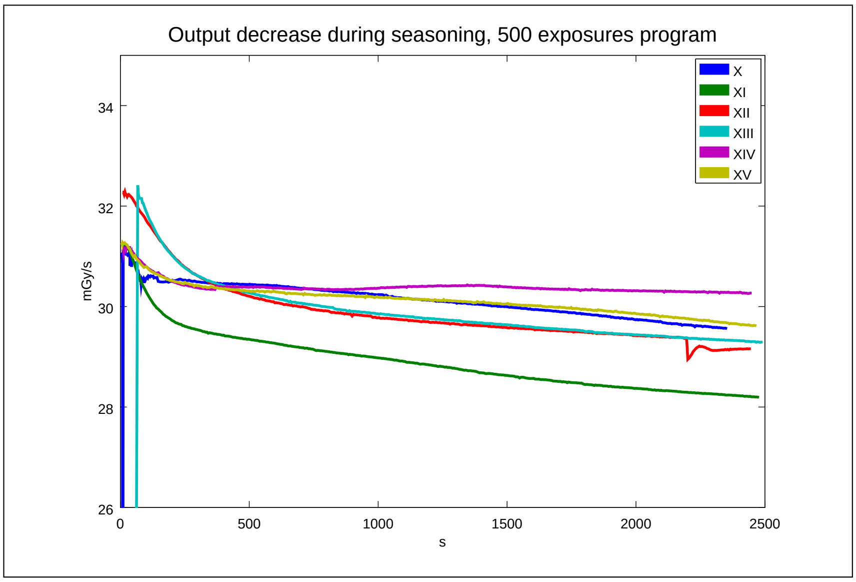


Figure 4.6. *Output decline during the first 500 exposures, tube X-XV*

error, and I got little information from the operator who restarted the exposure sequence. If the exposure counter in the measuring instrument was correct, there is still almost an hour unaccounted for. As such, we cant really use the data. The dip shortly after 1000 s is due to a malfunction that stopped seasoning program. The stop was 13 minutes, and the dip is due to the tube cooling down.

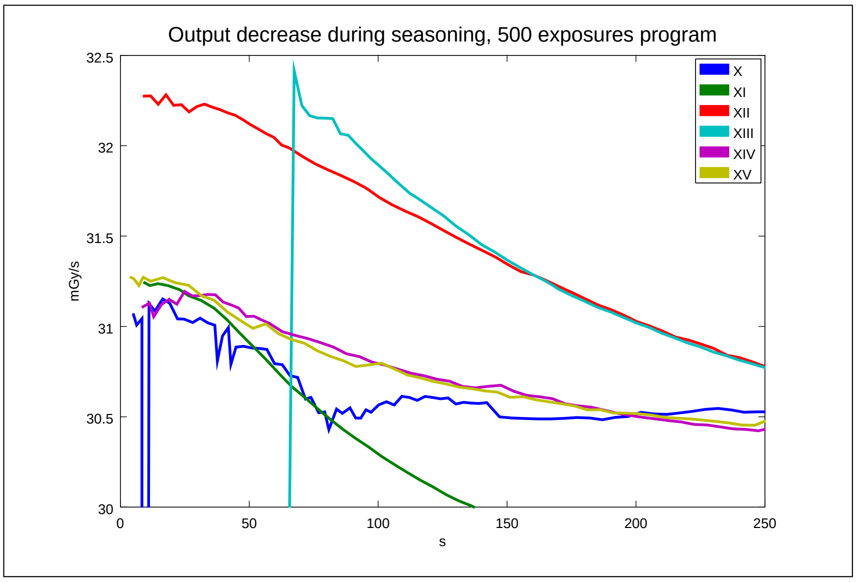


Figure 4.7. Detail of the initial exposures, tube X-XV

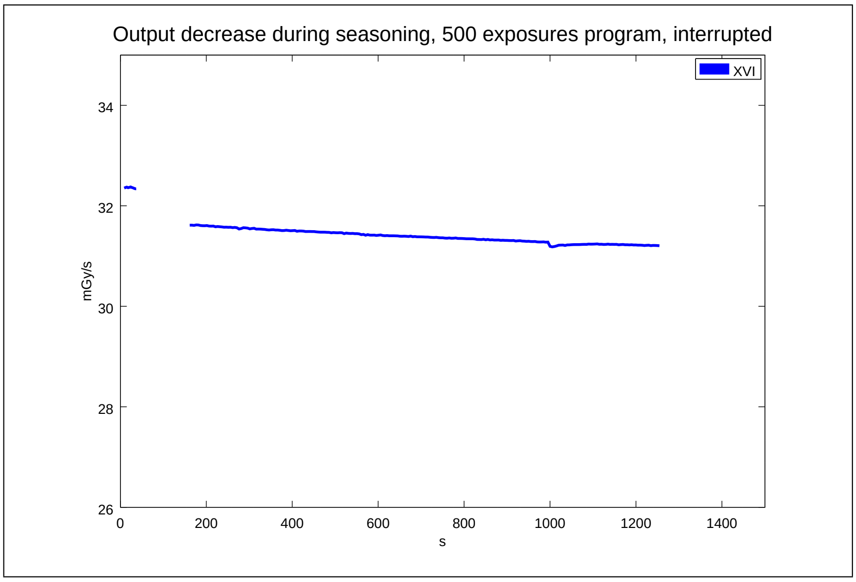


Figure 4.8. Output decline during seasoning, 300 exposure program attempted, tube XVI

4.2 Ripple

As a part of the seasoning procedure, ripple was measured before and after each seasoning procedure.

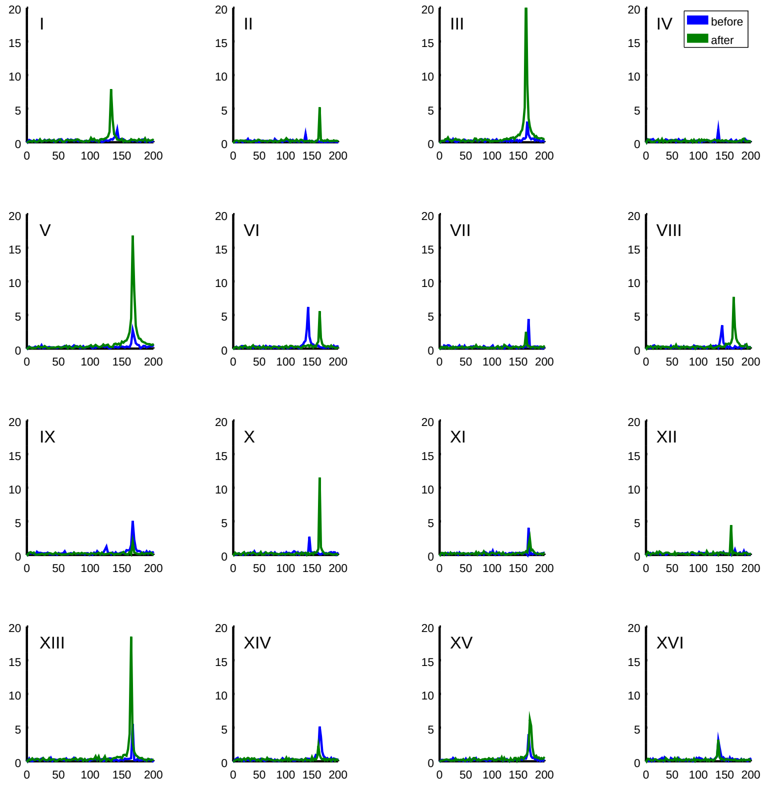


Figure 4.9. *Ripple per tube, before and after. The horizontal axis is frequency (Hz), the vertical is amplitude.*

A few interesting observations can be made from these plots:

1. There is a surprisingly large number of tubes with rotational speed below 150 Hz. Two tubes have this low rotational speed *after* seasoning.
2. There are no tubes with extreme ripple (<15) prior to seasoning but 3 after.

"Sticky" bearings might be seen on brand new tubes but when a tube cannot reach proper rotation speed after 300 start/stop-sequences it must be seen as a defect.

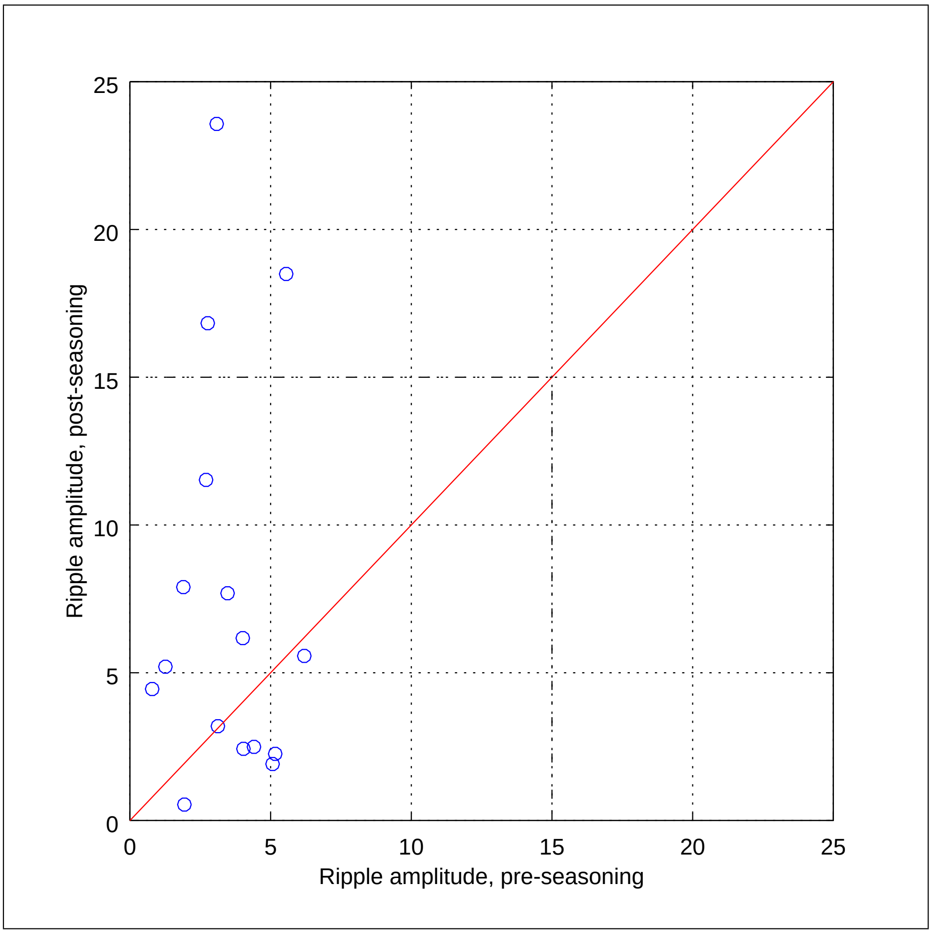


Figure 4.10. *Ripple evolution overview*

In figure 4.10 the evolution of ripple for all tubes is displayed, with the magnitude of ripple before seasoning on the x-axis and the magnitude of ripple after seasoning on the y-axis. When the ripple problems increased in production there was mumbling that the seasoning procedure caused the problems, but this show that ripple can both decrease and increase during seasoning. If anything, ut shows that the ripple will vary during the tube lifetime.

If we look at the three tubes that have failed the ripple test after seasoning (tubes III, V, and XIII) there is nothing remarkable with their dose curves. This fit our understanding of the problem - the effects causing ripple should not affect the rate of dose decrease and vice versa. These tubes also have no problem with reaching the proper rotational speed, which might indicate that in the short term the effects of low rotational speed does not contribute to ripple.

5 Discussion

5.1 Dose change

From the data presented it is evident that there is a big difference between individual x-ray tubes. One can argue that the effects we can see can be grouped into an initial region of fast decrease in tube output, which then gives way to a slower decrease. If we skip the first few exposures of the curve (lets define these as the number of exposures to thermal equilibrium) we can fit each curve to a two-factor exponential function $y = Ae^{-Bt} + Ce^{-Dt}$ and get a very good fit (as seen in figure 5.11).

tube	A	B	C	D
I	0.2007	$4.225 * 10^{-2}$	26.79	$6.888 * 10^{-6}$
II	2.090	$8.877 * 10^{-3}$	27.91	$1.678 * 10^{-5}$
III	3.702	$9.525 * 10^{-3}$	28.95	$1.968 * 10^{-5}$
IV	2.124	$1.872 * 10^{-2}$	30.81	$1.660 * 10^{-5}$
V	2.850	$1.366 * 10^{-2}$	29.90	$3.152 * 10^{-5}$
VI	0.7795	$1.402 * 10^{-2}$	29.84	$4.568 * 10^{-5}$
VII	1.344	$1.392 * 10^{-2}$	29.98	$2.009 * 10^{-5}$
VIII	2.490	$5.462 * 10^{-3}$	30.20	$1.001 * 10^{-5}$
IX	3.027	$9.676 * 10^{-3}$	30.18	$8.672 * 10^{-6}$

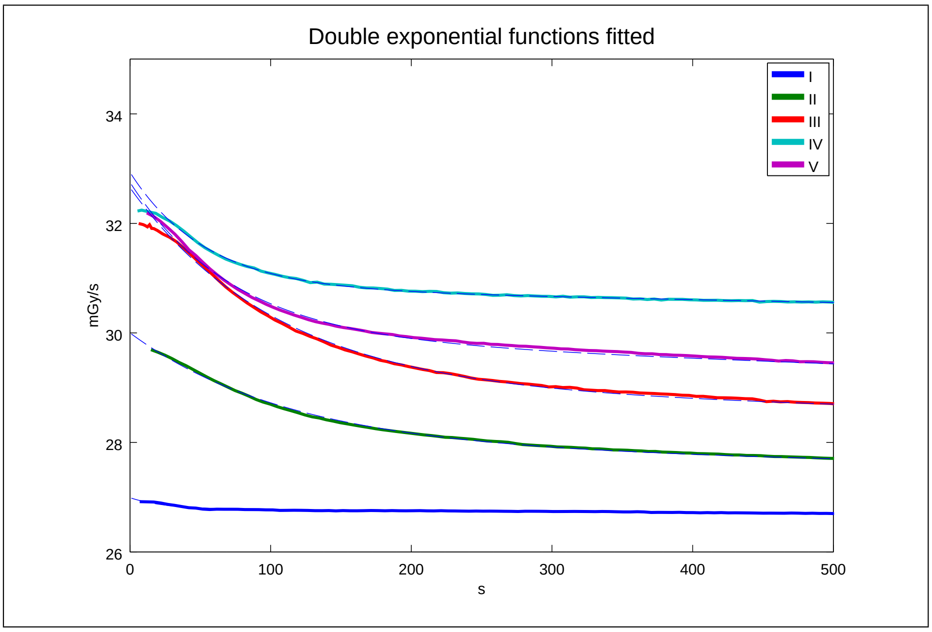


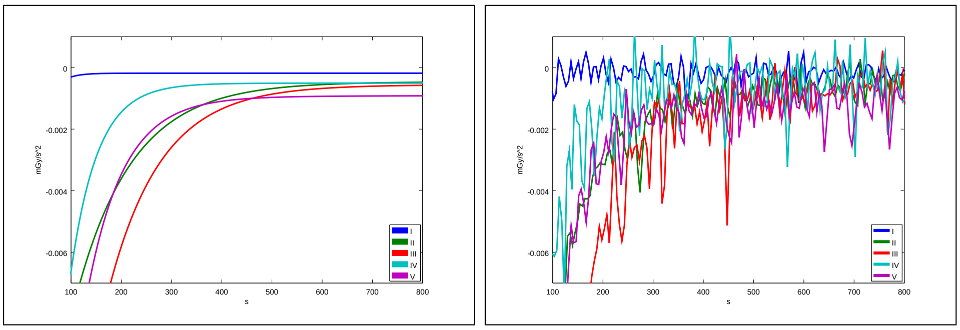
Figure 5.11. *Dotted lines are the fitted functions* $y = Ae^{-Bt} + Ce^{-Dt}$

The graphs are too much of a hockey stick to fit a function $y = Fe^{-Gt}$ Even if the tubes are individuals this give some indication that we are looking at two processes. One fast and one slower. As for the mechanisms behind this decrease in output we must look at the changes within the tube.

- the beam path
- the filament
- the anode

To start with the beam path, it is true that during the lifetime of the tube material from the anode is deposited on other surfaces. As mentioned before, this is a root cause for arc problems in older tubes. However, it has been shown[10] that this build-up has no significant effect on the tube filtration over the lifetime for diagnostic tubes so we may safely assume that it is not the mechanism behind the decrease in output in the beginning of a tubes lifetime. Neither is there evidence of a filament-related effect that could account for this qick change. Instead, the process behind both the fast and the slow decline in dose output is the anode surface, which quickly change during the first exposures and continue to change during the tube lifetime.

From the installed base we also know that the tubes do not decline steadily until the output reach zero - the output is seen as more or less constant and the tube fail due to broken filament or mechanical failure. Based on this the rate of decrease for the second term are much too fast, and we should probably add a constant K for a better model. But with all the tubes at different levels that would just be pointless extrapolation.

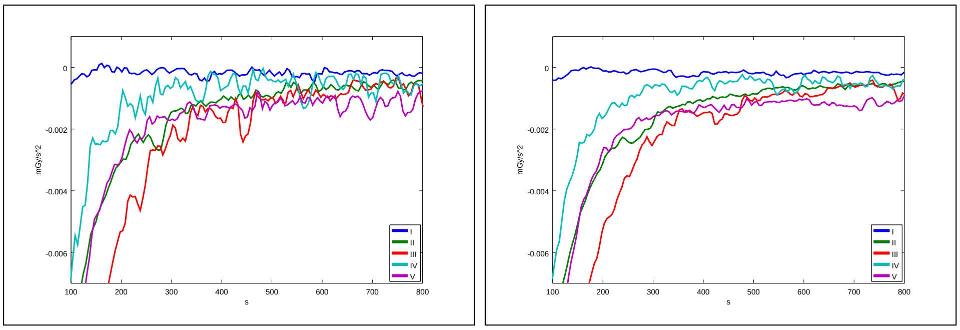


(a) *Rate of control, fitted functions*

(b) $\Delta(flux)/\Delta t$*, actual*

Figure 5.12. *Comparison between ideal derivative and approximate rate of change calculated from dose curve*

But the aim was to make an adaptive seasoning procedure that detect when the rate of decline has slowed down "enough" - we should define an ε such that we can say that the seasoning is completed when $|d(flux)/dt| < \varepsilon$. But remember, the variations between exposures gave the dose curves a jagged look if we looked at them in detail. This presents some challenges if we want to have a cut-off criteria on the rate of change of the dose curve measured. In figure 5.12 I compare the derivative of the fitted functions (a) with a rate of change calculated from the measurements data (b) using the estimate $\Delta flux(i) = \frac{flux(i+1)-flux(i-1)}{t(i+1)-t(i-1)}$. As you can see, the seemingly smooth curves in figure 4.4 give a wildly oscillating rate of change with this simple approach.



(a) *Using mean value of 5 points* ***(b)*** *Using mean values of 11 points*

Figure 5.13. *Smoothing out the curve with averages*

Of course, one could smooth out the differences - a simple approach is the one shown in figure 5.13, replacing the individual points with the mean value of a series of points. So, if we smooth out the data enough we can use it, is this something we *want* to use?

The data suggests different tubes do indeed share some characteristics. The differences between individual tubes both in output and evolution are still far to large make any detailed predictions on tube development.

As seen in figure 5.14 fastest change is in the initial region - for all tubes except VI most of the decline in dose happened during the first 300 seconds of exposures. In this region the tubes show an exponential decrease in output. However nost tubes show no sign at stabilising at a steady dose level after that, and we see a large spread in the rate of the slow decline between individual tubes. With an added margin to allow this initial fast change to decline we can set a limit at 500 seconds - or 100 5-second exposures.

100 exposures is much lower than the 300 exposures readily accepted as a reasonable length of a seasoning procedure prior to my measurements. And by choosing a set program instead of performing exposures until the tube is good enough we give all the x-ray tubes the same history, which will make documentation much easier. We also have no need to measure the flux during the seasoning, so we avoid many of the technical problems identified in this study.

All tubes that passed the ripple test after seasoning has been used in

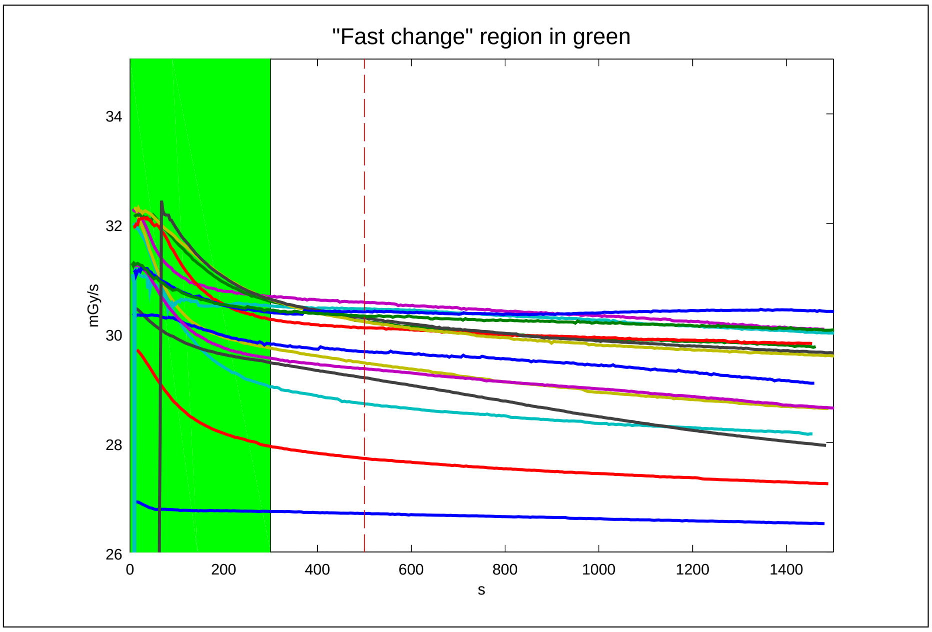


Figure 5.14. *The fast decline region*

production, and none have had to redo exposures due to rapidly changing output. This is true even for VI that showed no sign of stabilizing during the seasoning procedure.

To get an fully automated test bench, the ideal would be to use a single instrument for both dose measurements and ripple tests. The Unfors Xi have this capability, provided that the next version will be able to take 1,2 second samples instead of 160 ms. I have not had the opportunity to evaluate how complicated it would be to extract the information from the instrument.

5.2 Ripple

Although the ripple was not part of the original task, when the problems with ripple in production made it a higher priority. There was also people claiming that the seasoning caused ripple. This study indicate that this is not the case, ripple can both increase and decrease during seasoning. Seasoning has the benefit that it will allow extreme ripple, which we assume is due to some latent defect in the x-ray tube from manufacturing, to develop before the tube enters the main production line. More data is needed on whether a 100/300/500 exposure series seasoning is enough for extreme ripple due to latent defects to reveal itself, but that should not be a reason to extend seasoning. Rather, revisit seasoning length if it turns out that there is a recurring problem with ripple popping up in production tests. And to verify that these extreme ripple levels are indeed due to latent defects the supplier need to examine the insert.

A more important finding in this regard is that a large portion of the tubes did not reach proper rotating speed - some even after burn-in. This show that the anode is not accelerated to proper rotation speed, and as a consequence the risk of melting the anode focal point increase.

5.3 Robustness

A strong argument against an 'adaptive' seasoning procedure is the added demand on robustness of the test set-up. There are several issues that would complicate an adaptive seasoning procedure. I have already shown both that just flux level is an insufficient seasoning end criteria (as the difference between different tubes is so large), and that the variations in measurements will present some challenges to estimate the rate of change.

The measurement today is based on that the measuring equipment trigger on incoming radiation. For a more stable test set-up, the exposure and measurement should have the same trigger. This mode was not available on the instruments used.

Connection to the instrument could be lost in some way. In the set-up used in this study the instrument has pushed the collected data to the controlling computer, but there have been no active feedback. The test script on the controlling computer used in these test is just a script - the tool used has no capability to evaluate input during its run.

Events such as power outages must also be taken into consideration - even if the test equipment can be made robust with the use of UPS solutions the high voltage generator cannot continue operation without regular mains power. A power outage will result in delays and the tube will cool down. Arc events would also interrupt the program with similar consequences.

5.4 But is it Lean?

So how well does this fit in a lean production scenario? By implementing a seasoning program an unspecified variable process that did not have to be performed in the production line was moved to a preparatory work area. Automating the exposures freed up valuable operator time. Choosing a program with a fixed number of exposures will reduce the variability of the preparatory work. All this is in line with methods described in [5]- "Creating Initial Process Stability".

If one is crass, the screening function in the seasoning procedure is little more than delayed incoming quality control - 100% acceptance control on the X-ray tubes. According to Deming's all-or-none rule [4] , if you define a consequence cost K of a defect unit entering the production process, a control cost C for incoming quality control of a unit, and the expected defect ratio p, the rule is to check all units if $p > C/K$. If we assume that the main portion of both incoming quality control and consequence cost is labour (this simplification will cause a much larger under-estimation of consequence cost than of control costs, as we skip more complicated consequences like replacement after delivery, loss of goodwill should the error reach the customer et c) , we can play around with some numbers. 15 minutes is a good estimate for the total operator test time, and a *very* conservative estimate of the average added time by tube replacement is 5 hours - so if we think that 1 out of 20 tubes might have some sort of quality issue, we should test all.

However, as [4] also point out, acceptance control is an outdated method, and current quality control best practices favour early preventive actions and process improvements *at the supplier* - preventing defective units from being made, or at least shipped, in the first place. So rather than asking *"how can we detect problems before the tubes enter the production line?"* we should perhaps ask *"how can we make the supplier understand our problems so they can deliver the quality we need?"*

There is also the case of things which cannot be properly screened. As we have seen the ripple change during seasoning can go both ways, and there is nothing to indicate that ripple will stabilize at a certain value. Tubes that had been seasoned still could develop ripple, noise and arcs later during tests in the production line. We could season the tube longer, but this would only decrease tube lifetime and increase production costs without real benefits to quality. Only bringing the problem to the supplier could we actually increase quality.

5.5 Outlook

There are many ways to continue with this project, even if the adaptive seasoning turned out to be an overly complex solution.

First, one should consider moving more of the preparatory work to the seasoning bench. Right now, additional work like mounting of a pre-collimator and verification of the image field and focal spot is performed on a similar equipment. The seasoning bench can be upgraded with these capabilities - thus reducing work hazards (lifting the tube) and removing tasks that do not add value.

There is much work to be done on the software side - first one must decide the grade of automation. As discussed earlier, there is no indication that an adaptive process would be worth the time and money needed to develop it. The main quality issue is ripple, and there is no sign that it is connected with x-ray output, the one variable that is easy to measure automatically. Automatic ripple measurement of ripple is possible, but since the instrument used for measuring is not all that robust and an operator has to sign off on the result anyway, there is little gain in additional automation.

Should tube output be of interest, this can also be implemented in the same script as ripple detection. The test itself is trivial, but since output is dependent on tube temperature some thought should go into formulating the exact conditions for testing - preferably by defining a warm-up exposure program to ensure that the tube is at working temperature.

A seasoning procedure with a fixed number of exposures will ensure that all tubes have the same history. And by setting the exposures to 100 5 seconds exposures at 32 kV/206 mA we have a safe seasoning procedure that ensure - for all tubes tested in this study - that we have passed the initial region of very rapid decrease in output.

For an adaptive process one would preferably use some sort of criteria for the rate of decline of the output and total output. There are many problems that must be solved to implement this, but the most evident is that it does not relate at all to the main tube problem: ripple. There seem to be no connection between ripple or either output or rate of output decrease - an since ripple at the time of this study is a much larger problem than any other concerning the tubes focus should be to solve that, in cooperation with the supplier.

A project that would be more beneficial would be to collect output data from each exposure during the tubes lifetime to try and get a model for long time behaviour of x-ray tubes. This would make it possible to formulate a better model for how tube output change over time. It is possible that the data could also be used to construct models to predict when a tube is about to fail. This would be very useful for service - planned downtime is always preferable to unplanned downtime.

And a closing reflection - many of the problems concerning the x-ray tube come from the fact that the normal operating window for the L30 is close to the tubes maximum capacity. Using an x-ray tube designed for higher loads could be a better option than trying to handle the effects of continuously operating near the limit of what the current tube can handle.

5.6 Recommendations

Based on the study performed I recommend the following

For the seasoning procedure:

- A standard seasoning procedure of 100 5-second exposures at 32 kV/206 mA should be used for all x-ray tubes.
- Existing seasoning benches should *not* be fitted with equipment for continuous measurement of flux.
- For process stability, the equipment should in some way announce if the exposure cycle is interrupted, be it from arc events, communication loss or something else. There should also be a log so the number of exposures performed is saved in some way if the seasoning cycle is interrupted.
- Ripple and noise level should be evaluated according to current best practises at the end of the seasoning procedure. For the purpose of data collection, continuing with the ripple measurement at the start of the seasoning is also recommended.
- Arc events should be recorded.

For the x-ray tube:

- Further work is needed to establish consensus with the supplier regarding what is a fault and what is acceptable variations.
- The only way to actually improve quality, and not only screen the tubes, is by making changes in the manufacturing process at the supplier.
- Further work to improve the quality of the X-ray tube should be driven by the supplier, with Sectra as an active partner.
- The long-term plan should be to move all work now performed on the x-ray tube before it enters the main assembly line to the supplier. To do this the requirements need to be specified in a clear and unambiguous way.

5.7 Aftermath

For the ripple problem, a software based approach was done instead - during exposure a sample wave was recorded and the image data weighted based on this during image reconstruction.

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