Functional Role of X-ray Generators in Industrial Applications

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ABSTRACT:

X-ray generators and tubes work together to provide the performance and reliability demanded in today's industrial X-ray applications. An X-ray generator should offer users the sophistication and flexibility to customize how the generator powers X-ray tubes, provided by all manufacturers, in order to meet the specific requirements of an application.

Since the introduction of the thermionic (hot cathode) X-ray tube in the early 20th Century the same basic design concept is still used in modern X-ray tubes. The primary differentiators are that materials and processes used in the manufacturing of the X-ray tubes have greatly improved performance and reliability has vastly increased since the early days of radiography. To this day, X-ray tubes remain the most critical components of X-ray systems considering their limited life, failure modes and sensitivity to proper application. High voltage power supplies (X-ray generators) designed to drive X-ray tubes need to provide stable and well-controlled electron-acceleration voltage and filament current in order to ensure high quality dose output and maximize tube life. X-ray generators come in two distinct forms: a Monoblock®, where the X-ray tube is integrated into a single package along with the power conversion hardware and high voltage assembly, or a discrete power supply that powers the X-ray tube via a high voltage interconnecting cable. This paper discusses major failure modes of X-ray tubes: arcing, filament breakdown and focal spot overload and how they influence X-ray generator design. An X-ray generator should absorb high energy developed during arcing events and prevent excessive damage to the X-ray tube; it also needs to ensure maximum tube life by active control of the filament current and adequate cooling of the electronics and X-ray tube, in the case of a Monoblock®. The importance of fundamental X-ray generator design techniques to ensure optimal performance and long X-ray tube life in industrial applications should never be underestimated.

Keywords: X-ray generators, X-ray tubes, high voltage, X-ray tube arcing, X-ray tube filament control, Monoblock®

1. INTRODUCTION

An X-ray tube is a vacuum device that converts electrical input power into X-rays. X-ray tubes have evolved from experimental Crookes tubes with which X-rays were first "officially" discovered on November 8, 1895 by the German Physicist, Wilhelm Conrad Röntgen. Although earlier experiments by other scientists may have unknowingly created X-rays, Rontgen is widely recognized as the first to systematically study X-rays as early as 1895. William Coolidge improved upon the Crookes tube in 1913 and by 1920 the Coolidge tube had become the most commonly used hot cathode type X-ray tube.
In the Coolidge tube, electrons are produced by thermionic effect, most commonly, from a tungsten filament heated by an electric current. The filament acts as the cathode of the tube. The high voltage potential is applied between the cathode and anode, the electrons are thus accelerated and then hit the anode.

Although basic operation of the X-Ray tube appears to be very straight forward, choosing the proper X-Ray generator to address an application can make all the difference in achieving optimal performance, reliability and long tube life.

2. END-OF-LIFE FAILURES OF AN X-RAY TUBE

A well-designed, quality-made and properly applied X-ray tube can have a reliable and trouble-free operating life extending over many thousands of hours. Due to irreversible aging effects, there are two major end-of-life failures: catastrophic arcing and filament burn out.

2.1 Arcing

During normal operation, the filament operates at very high temperature (above 1500°C). Over time, a slow process known as Tungsten evaporation metalizes the X-ray tube envelope opposite to the parts at high potential (anode and cathode). The metalized layer increases surface conductivity of the envelope (made out of glass or ceramic) which eventually causes arcing to the wall of the tube. In the case of glass tubes, this arcing can puncture the glass, leading to a permanent failure of the X-ray tube as shown in Figures 1 and 2.

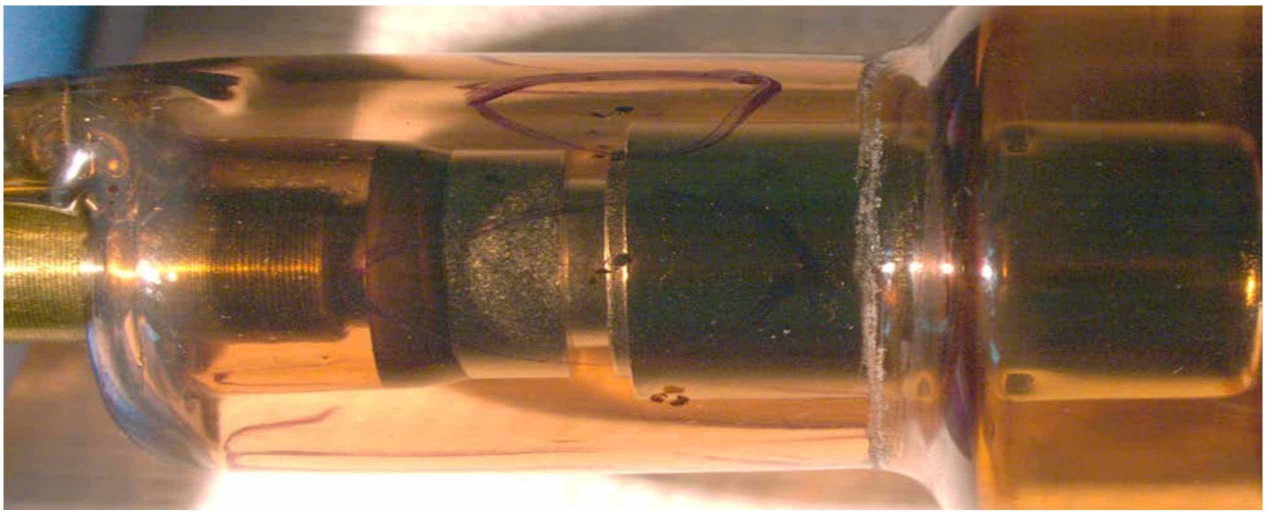


Figure 1: Glass tube with multiple arc marks, some of which punctured the glass envelope.

Figure 2: Magnified arcing area on the glass, showing a damaged tube wall.

This type of failure is predominant in X-ray tubes used close to their maximum voltage ratings. Tungsten evaporation is less of a factor in metal ceramic X-ray tubes since their inherent design minimizes the deposition of Tungsten on the tube wall. However, due to the inevitability of tungsten evaporation in all X-ray tubes, an X-ray generator must manage arcing events through passive and active circuitry to quench and recover from them and prolong the life of the X-ray tube.

2.1a Example of Arc Fault Management by the X-ray generator

In many generator designs, Arc management is handled by a DSP (digital signal processor) or microcontroller with the goal of quenching the Arc, most often referred to as "rolling back". When a discharge occurs it's important that the generator quickly turn off the high voltage output and re-ramp the HV back to -5% of the arcing event value, providing the tube time to recover and absorb any residual gas molecules. The above steps are all taking place at speeds of <1μsec. Modern X-ray generators have fully programmable Arc handling schemes that can be adjusted by the user for various applications and tube requirements.

Arc Detect and Scaling

Arc currents are sensed by a current transformer in the high voltage feedback loop of the X-ray generator as shown in Figure 2a

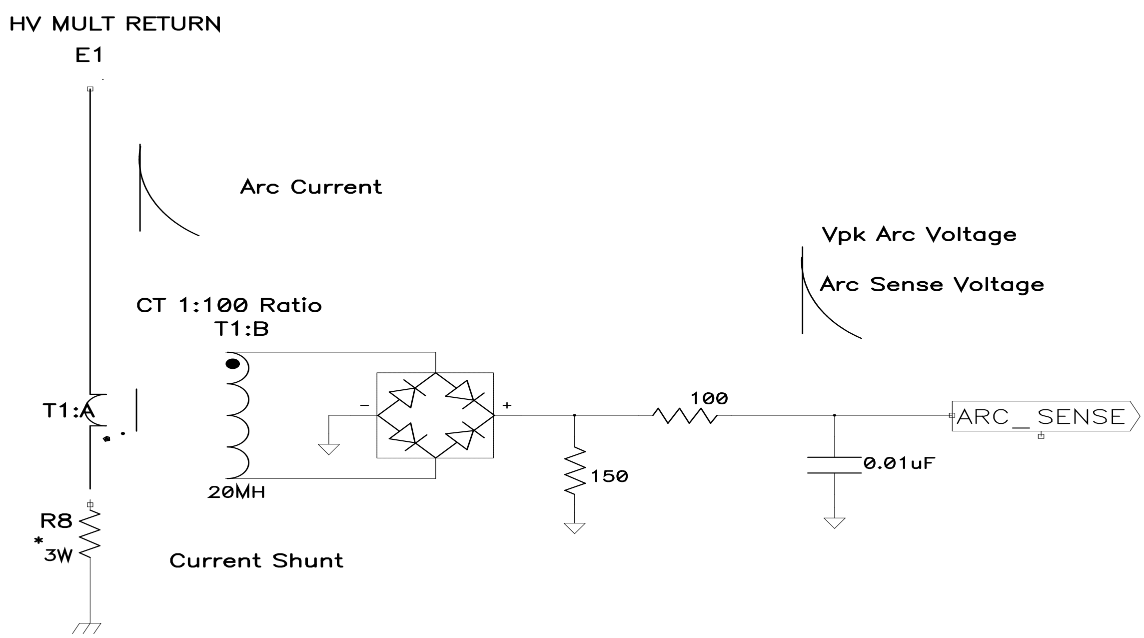


Figure 2a: Example of an Arc Sensing Circuit in an X-Ray Generator

2.1b Example of Arc Detect Scaling to kV Program

The scaled arc feedback voltage (ARC SENSE) is fed into a comparator on the system control board which has been scaled to peak arc current limits and the kV program reference level. This scheme helps to avoid false arc detection and micro-arcs are ignored. The ARC signal will be received and latched by the FPGA within hundreds of nanoseconds and disables the kV regulator with the goal of quenching the arc. This quenching is also known as “rolling back”.

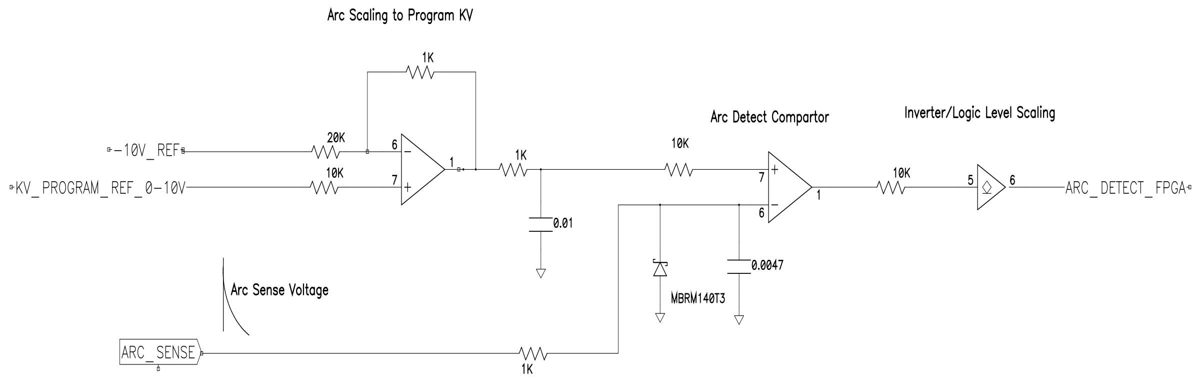


Figure 2b: Example of an Arc Detect to Scaling kV circuit in an X-Ray generator

2.1c Example of Ramp Up After Arc Detection

After an arcing event is detected the kV will “roll back” and the DSP has the responsibility of determining if it is appropriate to ramp up the kV or issue a Hard Arc Fault. With each arcing event, the DSP will increment an Arc Counter. If this is the first arc that is detected and the Arc Threshold is >1, the DSP times out an Arc Quench Time interval and re-enables the kV output. This sequence can continue until the number of arcs detected exceeds the number of arcs programmed into the arc counter threshold register. The Arc Quench Time and the Arc Counter threshold settings can be set by the user through configurable User Settings.

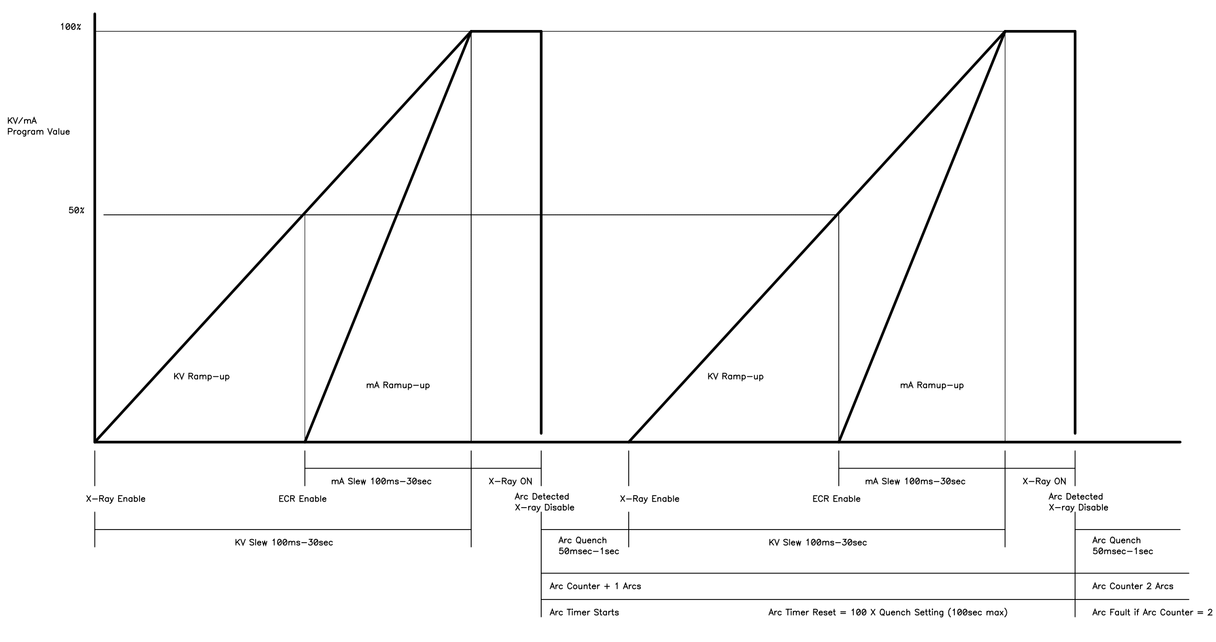


Figure 2c: Example of an Arcing Event with Roll Back, Quench and Ramp Up

2.2 Filament burn out

Even in applications where X-ray tubes operate far below their maximum voltage ratings, the envelope metalization still occurs. However, due to the slower rate of metal deposition and higher voltage rating, arcing is not the predominant failure mode. As evidenced by the tube characteristic mA vs Filament current curves shown in Figure 3, when the tube output current is fixed, as the output voltage decreases the filament current increases.

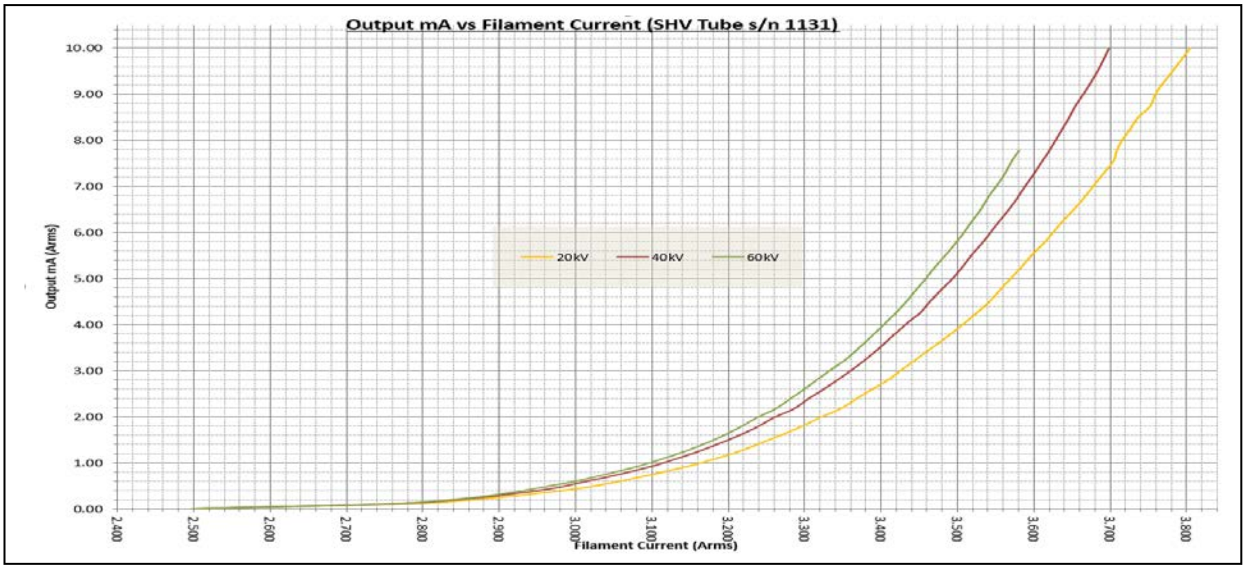


Figure 3: Typical X-ray tube characteristics. When the tube voltage decreases, in order to maintain constant output current, the filament current must increase.

Higher filament current, which reflects the need for higher filament temperature, accelerates filament evaporation proportionally to T^4 (where T is filament temperature, in Kelvin): even a minor increase in filament temperature, when raised to the power of four, is significantly increasing filament evaporation.

As filament evaporation continues, the filament becomes thinner, eventually leading to the mechanical break of the filament wire. A reduction of about 10% of the filament wire mass is considered to be the practical end of filament life (the filament has reached 98% of its life). This is equivalent to only about 5% reduction of the wire diameter.

Not all X-ray tubes have the same filament characteristics. Different filament characteristics require a different control response to provide stable emission current output. A sophisticated, versatile generator will have an emission control response designed to work with many X-ray tubes. Some X-ray tubes may fall outside of this category and require custom emission loop compensation to insure stable emission output.

3. ABNORMAL X-RAY TUBE FAILURES

Early failures of X-ray tubes are often the result of inadequate manufacturing processes, materials or misapplication. The former two causes are within the scope of the X-ray tube manufacturer's QA processes, while we are more interested in the proper operation of the X-ray tube from the X-ray generator perspective.

An X-ray generator can help extend tube life by providing stable output voltage with low ripple, low stress start-up conditions and proper HV insulation in an adequate cooling environment, as in the case of an industrial Monoblock®.

3.1 Filament ramp-up

One of the most critical items for longevity of industrial X-ray tubes is a low-stress filament turn-on. Filaments need several hundreds of milliseconds to reach operating temperature. If the filament drive ramps-up current through the filament too quickly, there will be a significant mechanical stress on the filament, while the benefits of fast X-ray output ramp up will be minimal. **Figure 4** illustrates such a scenario.

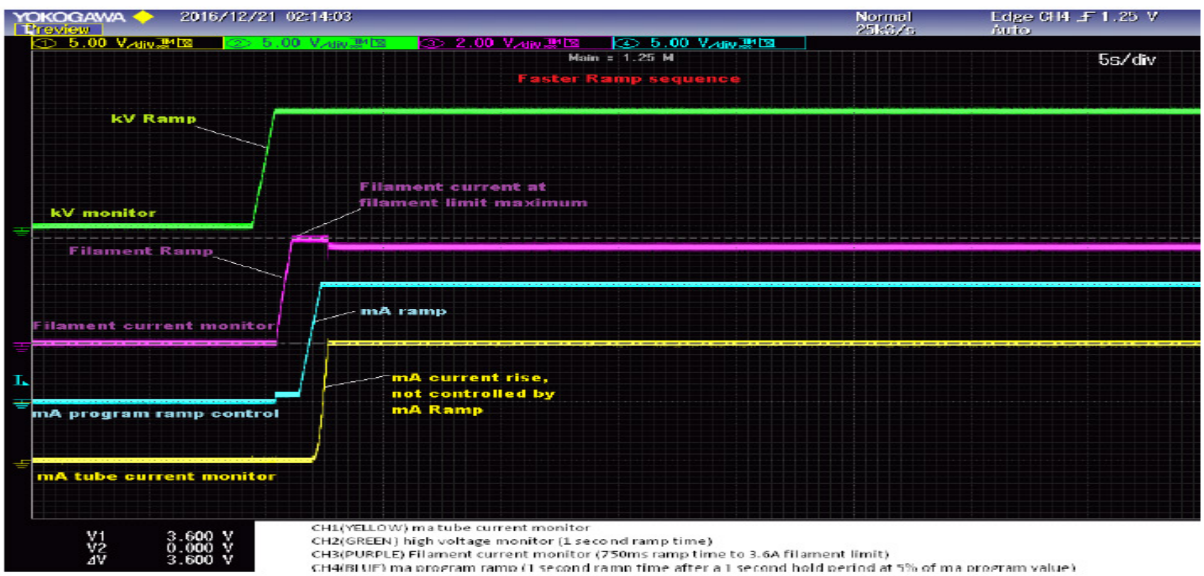


Figure 4: Filament and output currents during fast ramp.

In this case, the filament current (purple trace) increases quickly, but filament temperature, which is responsible for the output current (yellow trace), cannot reach the operating current set point quickly. As a result, the mA feedback loop will force the filament current to the designed maximum until the filament heats up enough to start emitting X-ray generating electrons. At that point, mA will rise quickly and no longer be controlled as defined by the mA ramp (cyan trace). The filament winding is exposed to a high current for several hundreds of milliseconds and this process is repeated at every turn on of X-rays. The high stress can be a major contributing factor to premature filament failures.

To minimize filament stress, a properly designed X-ray generator will employ programmable filament current ramp and limits which can be customized to manufacturer recommendations for the selected X-ray tube. One such example is shown in Figure 5.

The most critical setting for protecting the filament of an X-ray tube is the Filament Limit. The Filament Limit setting is the maximum current setting specified by the X-ray tube manufacturer to achieve the maximum emission current at the lowest kV. There is no one setting to meet this requirement and it needs to be set up during tube installation. The maximum filament values can be set below the manufacturers recommended specifications if the required emission current is reached in the application.

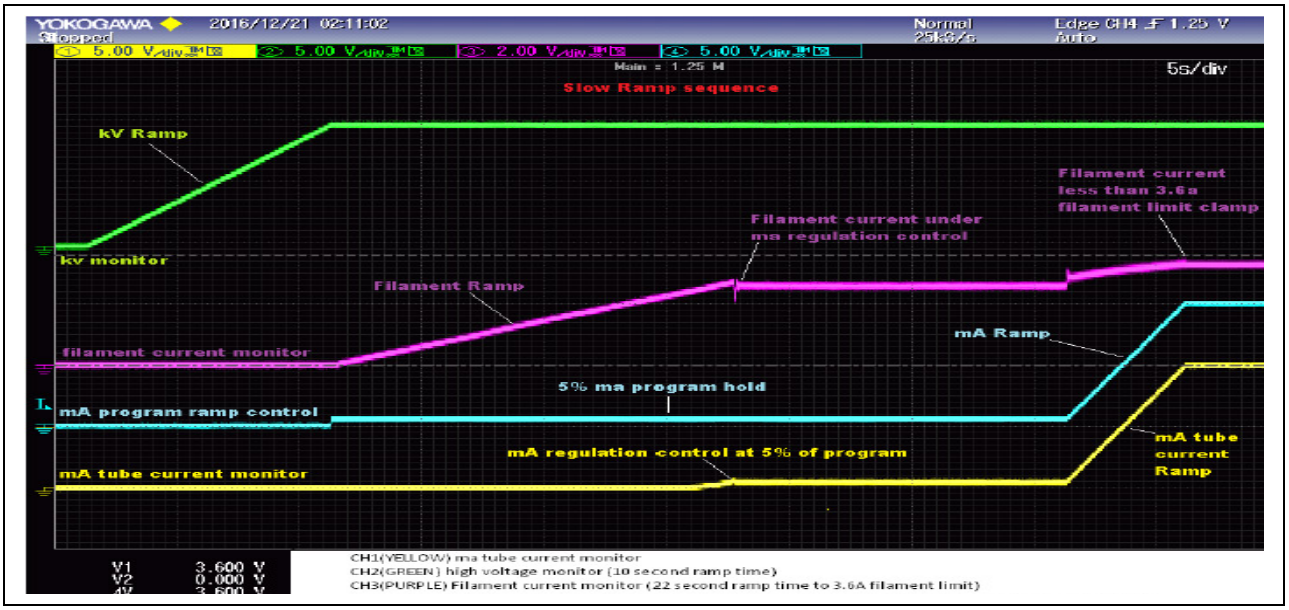


Figure 5: Optimized Filament Current Ramp Up Reduces Stress on the X-ray tube Filament.

When the filament current rise time is controlled in line with the filament's thermal properties, the current limit is never reached and maximum current is the same as the operating current. Moreover, the filament reaches the operating temperature by the time emission current control activates, resulting in a well-defined tube current rise (yellow trace), as dictated by the control circuit (cyan trace).

3.1a Effects of HV Cable Length on AC and DC Filaments

As previously discussed, one of the most critical tube settings is the Filament Limit. The Filament Limit set point limits the maximum output current of the filament power supply to protect the filament of the X-ray tube. This should be set at or below the X-ray tube manufacturer's specification. However, other factors within the imaging chain set up need to be considered.

AC Filament Supply: AC filaments operate at high frequency which introduces potential difficulty to drive power through long HV cables due to impedance. Changing the HV cable length may have an effect on filament calibration so the filament settings should be re-calibrated.

DC Filament Supply: With DC filaments, the copper losses of the HV cable need to be considered due to wire gauge and cable length concerns. Using a DC filament power supply with a current regulation scheme will eliminate the need for any additional adjustments provided the HV cable does not exceed a predetermined maximum length.

3.1b X-ray Generator User Configurable Parameters

A versatile X-ray generator will be capable to power a wide variety of X-ray tubes across many applications. Standard ramp ups for kV, mA and filament should be defaulted to slew rates that will meet the application requirements but stay within manufacturer recommended guidelines for safe control of the tube. For tubes that fall outside of those default speeds the X-ray generator should allow for simple setting adjustments.

Some standard X-ray generators take the above to higher levels of configurable and customizable settings. Figure 5a shows a GUI screenshot that provides Users with the ability to tailor the X-ray generator settings specifically to their application and can help optimize performance of the tube/generator combination as well as protect and prolong the life of the X-ray tube. Many of the critical parameters discussed already can be quickly and easily loaded.

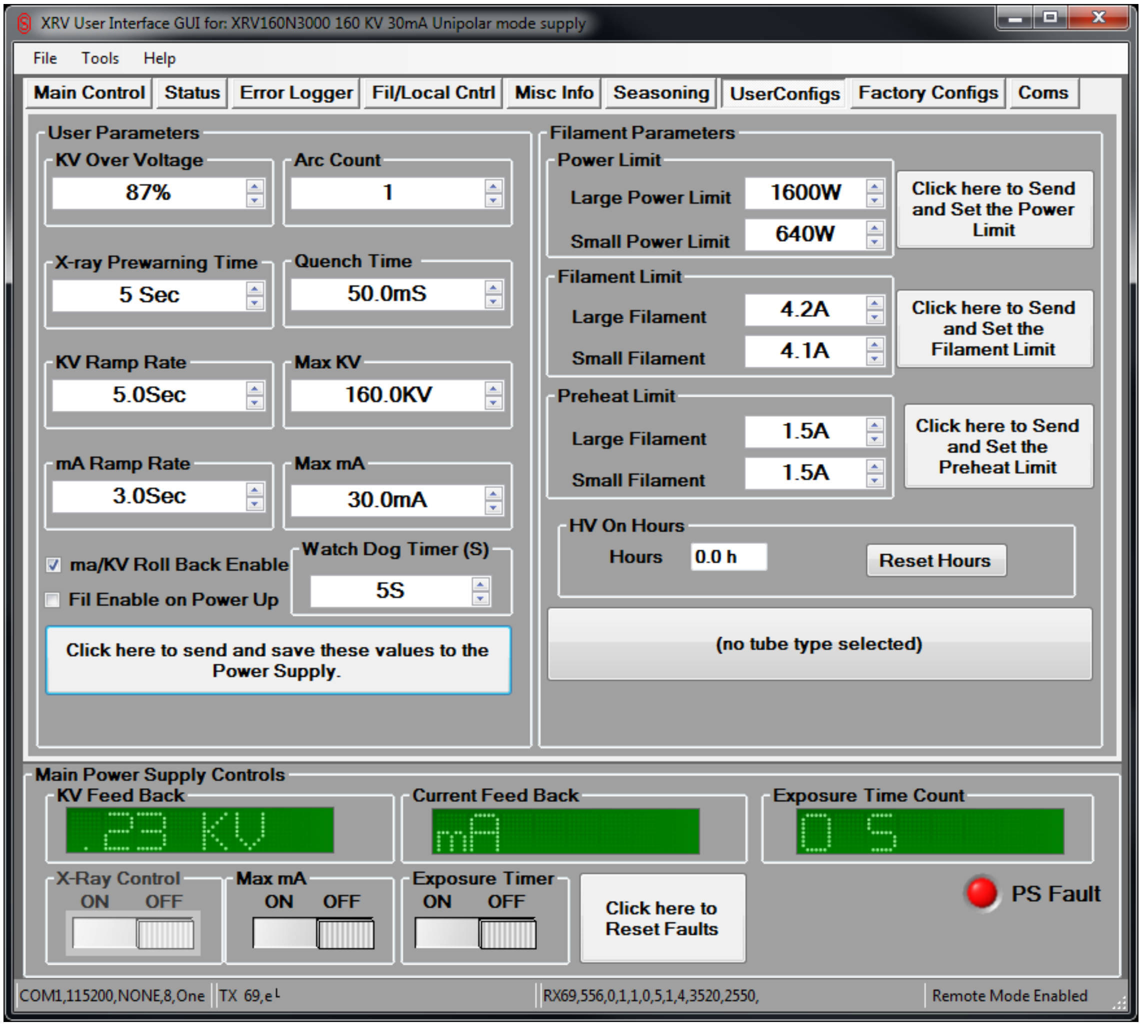


Figure 5a – GUI (Graphic User Interface) User Tube Configuration Screenshot

The below table provides a snapshot into the level of configurability some X-ray generators allow. Every X-ray application has its own differentiating factors and the ability to operate the X-ray tube as required while protecting it has been proven to be a very useful feature.

Parameter/Function	**Range**	**Default**	**Notes**
Large Filament Power Limit XRV160,225 XRV320,450	 0-4000 Watts 0-4500 watts	 3000 watts 4500 watts	 See tube data
Small Power Limit XRV160,225 XRV320,450	 0-4000 Watts 0-4500 watts	 3000Watts 4500 watts	 See tube data
Max kV XRV160 XRV225 XRV320 XRV450	 0-160kV 0-225kV 0-320kV 0-450kV	 160kV 225kV 320KV 450kV	
Max mA	0-30 ma	30ma	
Filament Current Limit Large	0-6 Amps	4 Amps	Cal. Current with actual load
Filament Current Limit Small	0-6 Amps	4 Amps	Cal. Current with actual load
Filament Preheat Current Large	0-6 Amps	2 Amps	Typical value: Current Limit Large/2
Filament Preheat Current Small	0-6 Amps	2 Amps	Typical value: Current Limit Samll/2
Arc Trip Counter	0-30	1	
Arc Quench Time	10msec-1sec	50 sec	Counter will reset in 100X set value (100sec max.)
kV Slew Time	100 msec-30sec	5 sec	Typical 5 sec
mA Slew Time	100 msec-30sec	5 sec	Typical 5 sec
Pre-warn Time	0-30sec	1 sec	Warning before HV ON (X-Ray ON)

Figure 5b – Example of the Range of Configurable Parameters in the X-ray Generator

As simple as inputting X-ray tube profile values into the generator is, the process can be simplified significantly. If a standard "off the shelf" X-Ray tube is to be used in the application it is easy for the generator manufacturer to input the values into a database so that the User can simply select the proper tube model and load the appropriate settings in automatically. This simplifies the set up process and has the added benefit of eliminating the human error aspect of readying the tube and generator to operate together. Tubes not included in the database can be added and saved to it easily.

In the next section the discussion moves to the generator having the ability to automatically load the X-ray tube settings into the generator by selecting the tube model from a drop down list.

3.1b Auto Loading of Tube Parameters with a Drop Down Menu

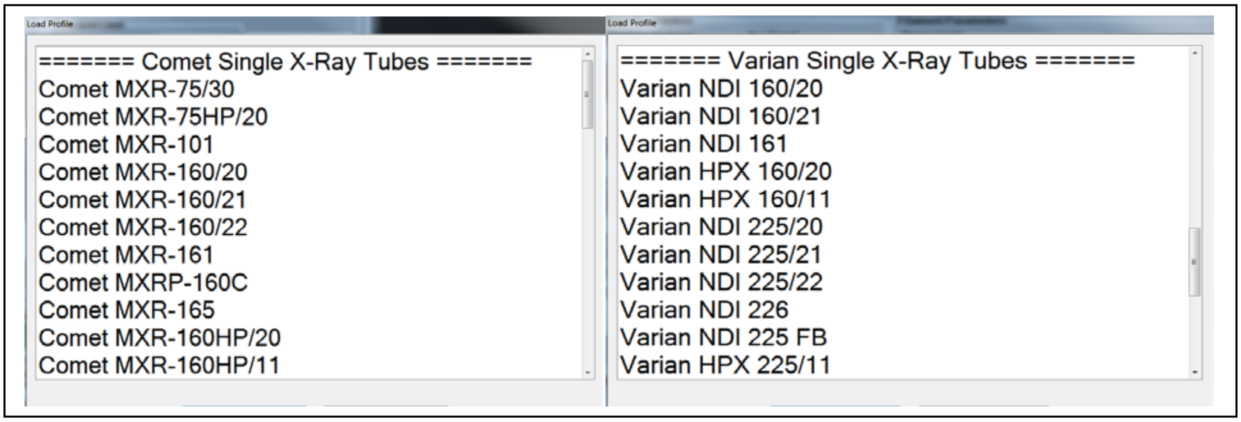


Figure 5c – GUI Drop Down Menu to Auto Load Critical Tube Settings

In a situation where the X-ray tube being used is custom or not included in the drop down menu, the tube profile settings can be manually entered, saved and recalled with ease.

3.1c Auto & Custom Tube Seasoning Profiles:

Along with the ability to select the tube model from a drop down menu and load profile information, comes the availability of manufacturer recommended tube seasoning programs as well. Dependent upon the last time the X-ray tube was used or seasoned, the generator can automatically select an appropriate seasoning profile. Daily, weekly and monthly seasoning profiles are available for all tubes in the drop down menu and custom profiles can be created for tubes not included.

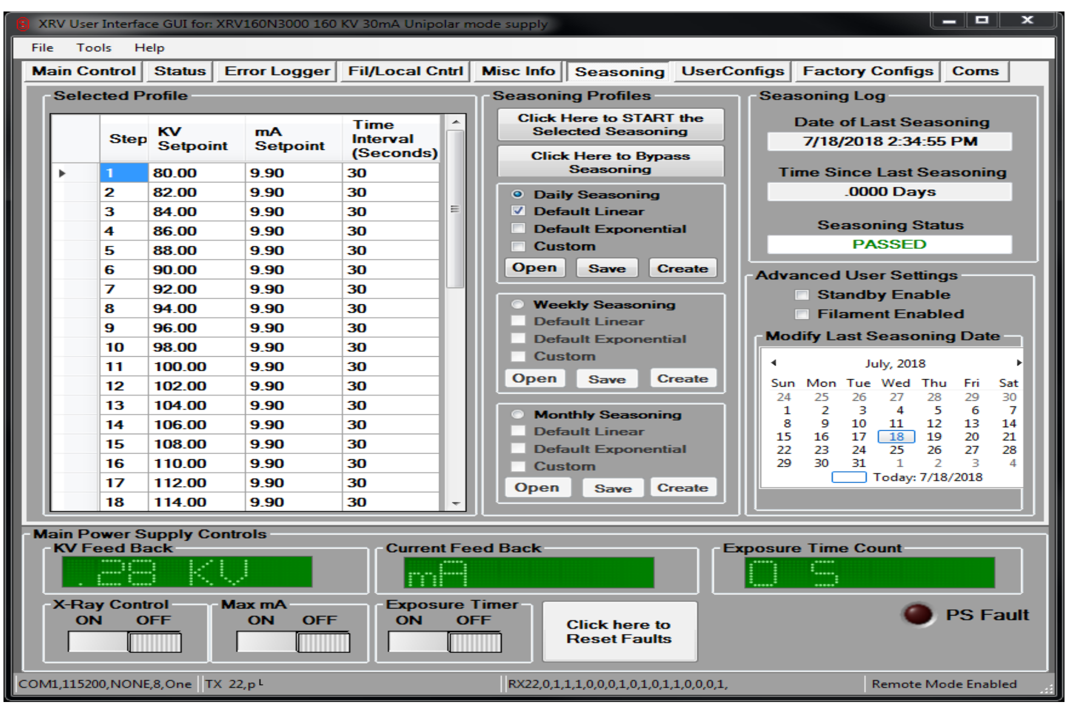


Figure 5d – GUI (Graphic User Interface) Seasoning Profile Screenshot

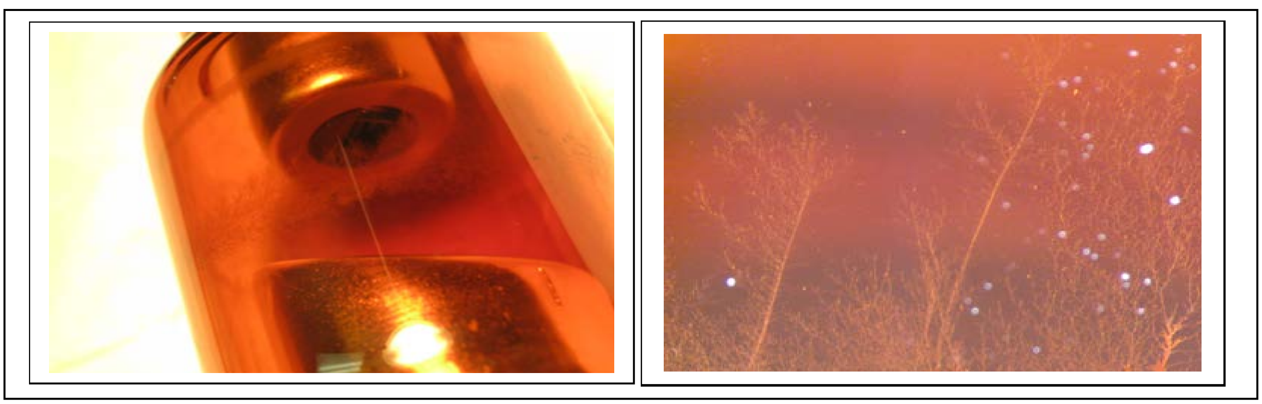
3.2 High Voltage insulation

One of the major challenges in the design of industrial Monoblocks® is providing a low-electrical-stress environment for the X-ray tube operation. Besides proper high voltage insulation, considerations around maximum electric field and field-control techniques are important. The problems caused by inadequate electrical stress controls could result in sudden, fast failures, such as glass punch through, as illustrated in Figure 6.

Figure 6: Tube glass puncture caused by high electrical stress.

In the case of the tube in Figure 6, the glass envelope was punctured by a single arcing event. A typical characteristic for this type of failure is that there are no black marks, more common for end-of-life punctures, where there are multiple arcs causing carbonization before the final breakdown.

Another problem caused by inadequate E-field modelling are the latent failures, where the charged particles start etching the glass, causing increased leakage current and slowly leading to increased arcing events and, finally, to the terminal breakdown. This type of failure is illustrated in Figures 7 and 8.



Figures 7, 8: Glass envelope etched in the presence of high E-field.

This type of failure develops over several weeks, or even months. It is especially critical in the early stages as it is difficult to notice: leakage current starts to increase, causing errors in the output current measurement as part of the measured current does not contribute to the x-ray generation. Effectively, the X-ray dose starts decreasing, even though it appears that the tube current is well controlled. Next, an occasional nuisance arc occurs and, as time goes by, the arcing rate increases leading to a permanent failure.

3.3 Thermal Management

X-ray tubes are very inefficient devices. Less than 1% of power is emitted in the form of X-rays, while more than 99% is dissipated as heat. In order to ensure longevity of the X-ray tube, this heat needs to be well managed to prevent high temperature rise. Dielectric oil is typically used as a cooling medium with an optimal combination of electrical insulation and thermal properties. These properties make it reasonably easy to circulate the oil through various heat exchangers for cost effective thermal management which can be suited to different applications.

Without proper thermal management, the X-ray tube can be affected in three major ways:

1) Increased internal temperatures and rate of evaporation, leading to fatal arcs
2) Increased glass temperatures, resulting in burned oil which increases X-ray filtration and reduces the oil's insulation capabilities, which can result in dielectric breakdown in multiple parts of the high voltage assembly. An improperly cooled tube with this type of problem is shown in Figure 9.
3) Inadequate heat removal from the anode assembly, resulting in the X-ray tube's target operating above Tungsten's melting point: this results in focal spot melting with three critical side effects:
    a. Focal spot size increases
    b. X-rays become harder, due to the additional filtration
    c. Additional Tungsten evaporation increases metallization process and leads to terminal tube failures

Figure 9: An X-ray tube operated in a hot oil environment with a thin layer of carbonized oil etched onto its surface.

Figures 10, 11: Focal spot damage caused by inadequate anode cooling and thermo-mechanical stress

3.3 Dose Stability

Advances in detector technology are opening doors to new applications and improvements in imaging quality. This, in turn, drives the need for higher quality X-ray sources. One of the critical requirements is X-ray dose stability. X-ray dose stability is greatly dependent upon the operating temperature of an X-ray tube. The tube temperature drift can exceed 10%. This is best illustrated in Figure 12.

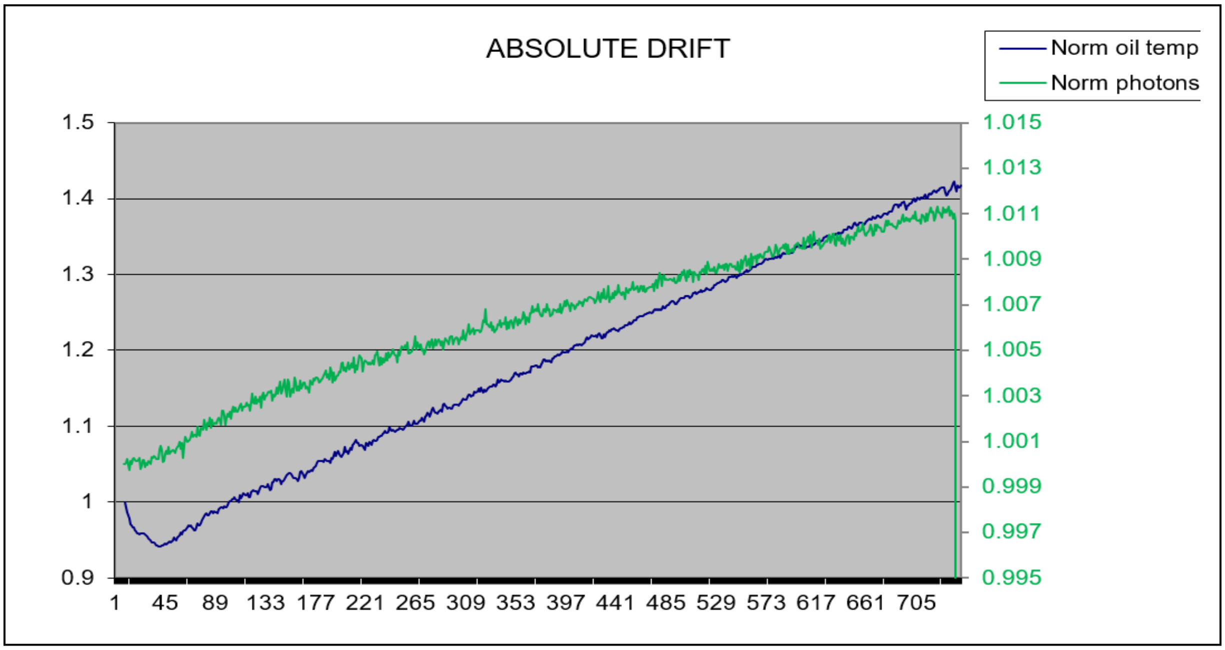


Figure 12: X-ray dose drift as a function of operating temperature. Horizontal axis shows time in seconds.

By employing a combination of analog temperature compensation along with digital characterization and compensation, this significant drift can be minimized to negligible levels. Performance of an optimized x-ray source is shown in Figure 13. It shows maximum drift compensated to the level below 0.4%.

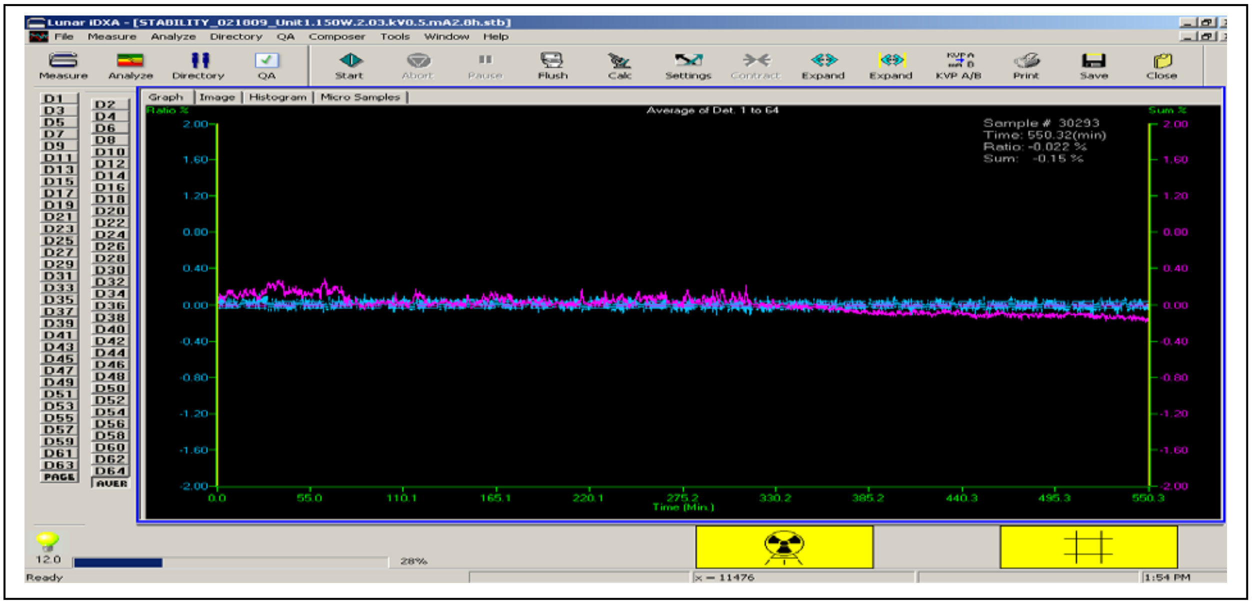


Figure 13: Performance of a compensated X-ray source. The traces show the sum of low and high energy photons (purple trace - proportional to the equivalent mA stability) and ratio of high and low energy photons (blue trace – proportional to the equivalent kV stability).

3.4a Dose Loss as a Result of Ramp-Down.

If the tube output power is disabled instantaneously, the anode target will see a steep temperature drop at the surface of the target, resulting in mechanical stress within the target surface layer. This can result in cracks on the target surface, degradation of the focal spot and dose loss. The relative dose loss could be 80% of initial dose after 10000 cycles. Running at power levels 20% below maximum values or implementing power ramp-down into the generator on/off switching will significantly reduce stress on the target.

4. CONCLUSION

As industrial imaging technologies evolve and X-ray source requirements become more demanding, it is becoming exceedingly important that tubes and generators work together to provide optimal performance, reliability and value. Even the best X-ray tube requires an exceptional generator to perform at its peak and protect it from common failure modes. It's a mistake to underestimate the importance of using a generator that has been designed with the needs of the X-ray tube in mind. As discussed in this paper, an X-ray tube has a useful life cycle based on well known, inevitable failure modes. A generator, designed to enhance the life and performance of an X-ray tube, that is reliable, serviceable, flexible, simple to integrate and has a low cost of ownership should always be a top consideration in the selection of imaging chain components.

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