DISCRETE EVENT SIMULATION FOR A COMPLEX HIGH POWER MEDICAL SYSTEM

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Abstract: This position paper describes research activities in the scope of targeted lifetime extension of components which are used in medical devices and systems as well as in high energy physics. The considered medical areas are mainly in the therapy field as well as kV-imaging diagnostics. The focus of the analysis of medical machines and systems with high-power tubes is on the x-ray-radiation or rf-power performance. On this occasion, the operational behaviour of such tubes is of special interest. In this paper a methodology will be presented to examine the specific influence of service life-determining parameters. For the implementation of the methodology a discrete event simulation is constructed using the realtime design tool MLDesigner from MLDesign Technologies, Inc. Studies can be carried out with regard to the tube service life in different components. The simulation shows that the targeted specific influence on the service life-determining parameters can prolong useful service life of a high power tube.

1 INTRODUCTION

1.1 Motivation

As part of research work at the Computer Architecture Group of the Technical University Ilmenau (Technische-Universität-Ilmenau) the default behavior of high-power tubes used in medical equipment is investigated. The focus of this research work aims on the development of new business and application models for service life extension of equipment in medical technology. To develop appropriate additional sensors and condition monitoring concepts, it is especially necessary to provide a detailed look at the life-defining parameters. With the help of modeling a realtime discrete event simulation, the theoretical assumptions of the research work, meaning, that by means of a targeted control of service life-determining the parameters, the whole useful service life of high power tubes can be extended essentially, will be investigated. The expected outcome of this investigation is the consolidation of the theoretical assumptions by means of an appropriate physical experiment. The implementation of all required information about the tube specific life-defining parameters will improve the uptime of high power medical systems.

1.2 Context

Functions in a medical system (eg radiotherapy equipment, particle therapy, computed tomography, mammography and angiography equipment) use, for diagnosis or treatment, high-power tubes such as klystrons, magnetrons, thyratrons, x-ray tubes, and linear accelerators. The flow of diagnostic and therapeutic applications is to be modeled and investigated by means of a simulation. An investigation of the relationship between the loadprofile of a system and the service life of a tube used in that system is possible.

Partial models for hardware and software of the control system as well as of the electronic and electromechanical components are necessary. Exemplary models of high tubes are established and inserted into the simulation system (Figure 1). Partial models are to be interchangeable (see also Section 2.1, Figure 6) for use in simulations for different application fields. In Figure 1 a typical structure of a high-power tube-driven medical system is shown.

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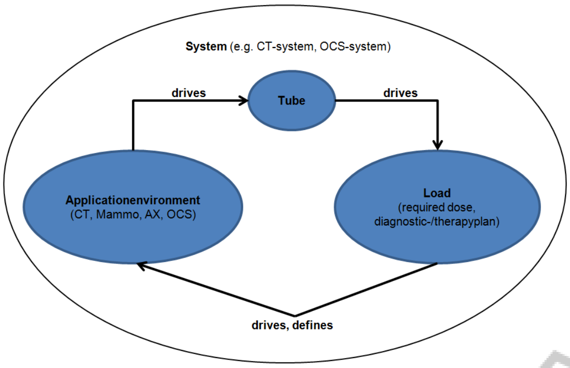

Figure 1: MLDesigner simulation structure overview.

It is necessary to establish a basic tube model for the simulation tool MLDesigner (MLDesign Technologies, Inc. 2007), as well as the implementation of predefined algorithms and methods for evaluation of the tube-data (Heuermann, 2006). The tube data used for the simulation model consist of a tube-specific set of transfer characteristic curves like heater curve (filament voltage and current), uP (relation between filament power and cathode current at a given tension), efficiency, gain, electron beam focussing currents, current density with a given emitter material and -dimension at a certain tension as well as specific cathode activation schedules to convert carbonates to oxide and evaporation rates (see for example Figure 5 and corresponding equation (1)). The required tube data set has to be measured for each tube, digitized, approximated and can then be used to build a tube simulation model.

The structure of the system model is done in several phases. The first priority is the development of a basic tube (realized in the block "Tube", Figure 1 and the equal to the block "Roehrenumgebung_AX#1" in Figure 6), complying with a typical x-ray tube, just the way it is used in most cases in practice. Based on these results of the modeled tube, an optimized design is created, in which the predetermined factors affecting service life-determining parameters are changed selectively. By a direct comparison of the two models, with and without optimization, a very accurate statement on the expected life of such a tube for a certain loadprofile is possible (Wippler, 2007, Krestel, 1988).

2 BACKGROUND

The life of vacuum tubes, used to produce radiation (reception, screening, treatment and therapy) in the medical technology, is determined to a large extent by the emission of the cathode. During the period of usability, in all type of tubes, directly as well as indirectly, heated cathodes, and "cold" emitting cathodes, a reduction of the electron emitting material can be noticed (eg filament evaporation rate and barium evaporation rate). Some of the service life-determining parameters for the vacuum tubes used in medical technology are as follows:

X-ray/Carbon nano tubes:

- anode roughening, anode heat capacity, filament evaporation rate, scan-seconds load (load profile), temperature, timing, arcing

They have a finite, but not in all applications reliable, predictable service life and must be replaced by the facility to ensure availability.

High Power Tubes:

- cathode roughening, barium evaporation rate, beam-seconds load (load profile), temperature, gascomposition/vacuum quality, ion back-bombardement, timing, arcing

They have a finite, but unpredictable service life and must be replaced at short notice by the facility to ensure availability (Heuermann, 2010).

In the field of x-ray tubes, there are procedures for lifetime prediction known, e.g. used in high resolution CT-systems (Figure 2). The analysis of input vectors, taking into account disturbance vectors, generates output vectors. These output vectors do reliably produce predictable lifetime calculations with high confidence. In prior art solutions mostly the condition monitoring is restricted to the view from the "outside" on the physical behaviour of the tube (Heuermann, 2006, 2007).

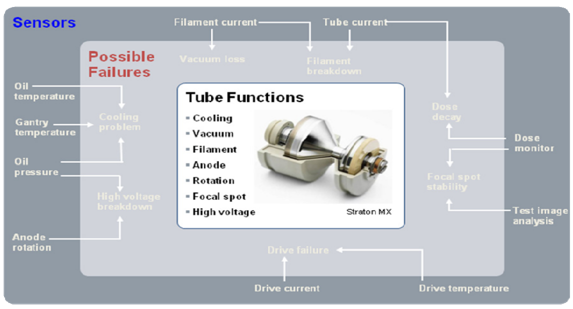

Figure 2: TubeGuard@CT structure overview.

In the field of high power tubes, usually the resistance of the heater coil is measured. With the knowledge of the used materials and the dimensions, a thermal model can be created and the cathode surface temperature of the direct heated tungsten filament can be calculated. The emitter deterioration (Figure 3) is based on sensor data of tube current and filament current (Siemens Guardian Programm, 2007).

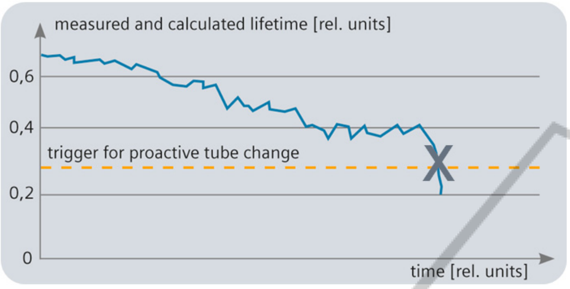

Figure 3: Measurement of emitter deterioration.

This procedure is used for the calculation of the cathode surface temperature, from which the tungsten evaporation rate is dependent. The results are limitedly usable for the cathode but not sufficiently accurate for calculating the anode surface temperature.

Many disturbance vectors, such as tube-stray distribution, time dependant varying parameters of the tube itself, and different ambient temperatures of the object to be considered, alter the thermal balance of the system, which is used for the calculation. As a result, a heating scheme materializes that does not match the actual existing surface temperature. As an example (Figure 4) a thermal investigation done on an e-gun is presented. The simulation was performed by the manufacturer of the e-gun with a COSMOS/M model. Cathode is 40°C, other points 20°C higher in the specific tube model. This results in a shorter predicted service life. On the other hand, if the model does not reflect the real thermal balance the cathode temperature could be much higher. As an example for the given dimensions of the used e-gun, back-heating as a cause of ion-back-bombardement (beam but no RF: 50°C, beam and RF: 110°C) adds 60°C to the cathode surface.

As an example of the importance of accurate surface temperature estimation, the effects in a klystron will be explained as follows:

For a nominal surface temperature given with 890° C, production of only 50° C more temperature on the surface results in twice as high barium evaporation (Figure 5 and corresponding equation (1)). The same is true for all types of high-power tubes (klystron, magnetron, thyratron, accelerator), which use barium enriched materials as an electron

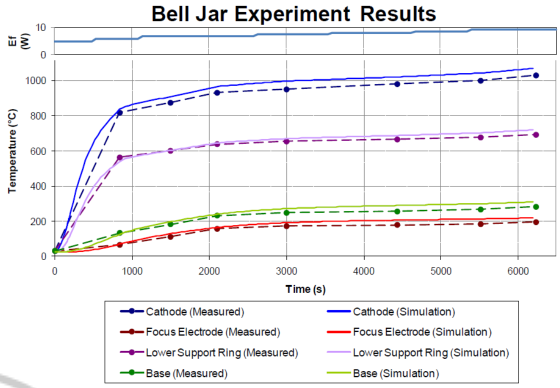

Figure 4: Mismatch between simulated and measured temperatures in an e-gun assembly.

emitter in the gun because of the low work function.

This released barium is deposited on the cold spots in the tube and provides gradually a reduction of dielectric strength in the tube. The result is a high voltage low impedance breakthrough (so called arcing) (Heuermann, 2007, 2010).

$$f(x) = 2\,E\text{-}08\,x^5 - 8\,E\text{-}05\,x^4 + 0{,}116\,x^3 - 84{,}73\,x^2 + 30547\,x - 4\,E\text{+}06 \quad (1)$$

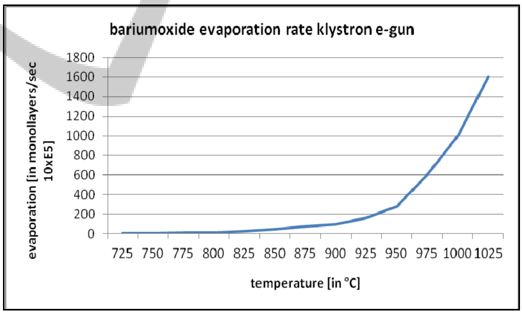

Figure 5: Example of evaporation rate vs. temperature.

Researchers working on that topic, also published solutions like continuously measuring the µP (micro perveance) and keeping the cathode current to 98% of the nominal value (Wright, Oiessen, 2000). Another solution is to implement thermo-couples in the cathode surface structure (Noguchi, 1996).

These solutions represent the state of the art in the field of condition monitoring for electron tubes. The usual practice today is that tubes, depending on the type (x-ray, klystron, magnetron, linac, thyratron), are assigned to according maintenance contracts, which stipulate an exchange at a certain time. It is the top priority of the equipment manufacturers, to avoid tube-failures of this manner from the very beginning. However, there is no possibility to ensure a complete avoidance of incidents. This is why, in so called unavoidable circumstances, one would like to have at least a big enough lead time, to ensure the exchange can be made before there is a downtime of a system.

3 SIMULATION

The hospital-specific diagnostic and treatment requirements are implemented into the simulation environment. The daily routine of a clinic is considered in the simulation, as well as a statistically spread patient number, the load profile given by logging files recorded over months will give all necessary operating points. In a first step, manually selected load profiles are used, the interface for on-site recorded load profiles (.tua files = tube history records) is in work.

Particularly interesting is the implementation of the "optimization". The calculation of residual life is based on the fact that all calculated life-critical values are afflicted with an error reflected from practise of about + -15%. This is due to manufacturing tolerances of the tube and its environmental factors. The thermal balance calculated with the knowledge of the geometries and materials does not show the correct value for the surface temperature of the anode plate or the cathode surface. The "optimization" deals with the simulation exactly as before, but with a smaller error: + -2%. This error is the assumed total residual error of the measurement chain (pyrometer, operational amplifiers, AD-converter) to measure the surface temperature (Heuermann, 2010).

Creating a discrete event simulation, which is extended and detailed as well as driven by real load profiles from customer sites, enables reliable investigations. The work has shown that MLDesigner (MLDesign Technologies, Inc. 2007) is the right tool for the reconstruction of the technically physical processes within a medical system. MLDesigner offers the possibility to use Markov-Chains for the network theorem based system (queuing networks with parallel and serial service units) and probability tools like Poisson-distribution as well as random generators for the patient arrivals.

During observation, it soon becomes clear that the topic is a classic optimization problem. It is a balancing act between maximized service life (carry out the exchange as late as possible), and realizing the avoidance of potential downtime. A statement of this quality on the life of a high-performance tube can not be given to this day in a satisfactory manner.

The existing studies and investigations are only estimates and approaches. The complex relationships and calculations within such a tube are seen analyzed and evaluated from the outside of the tube (Wippler, 2009, Heuermann, 2006).

The underlying research work pursues a fundamentally new approach. This means a direct view on the processes within the tube, instead of just estimating. This allows examining the condition of the tube much more in detail, with the result that the statements on the processes are significantly more related to reality.

A simple example is the surface temperature of the cathode. So far, the temperature is calculated according to complex procedures. Despite all precision and complexity of observation, the result is still estimation. The idea of the research works however is just to measure the surface temperature of the cathode. Thus, it is possible to respond to changes almost immediately. The model to be developed will shed light on whether it is precisely this optimization, that will be prove decisive for the substantial extension of the economic life of a high power tube.

The realization of this comparison is carried out by two simulation models. The basic model corresponds to the current usage of high power tubes, ie without any optimizations. Based on that first developed basic model, a model extension is designed. This serves a direct comparison between the basic and extended model. These extensions include the optimizations as discussed. Thereafter, the data of the two simulation runs can be compared. With the optimization, a service life extension should be observed under normal circumstances. In the simulation a very flexible block structure was realized: An adaptive application environment (rep.-rates, cathode/anode current, filament power, patients/h etc.), a flexible exchangeable tube model block and a load block which reflects the required energy (e.g. 23MV, 21MeV, 160keV ect.) within an individual diagnostic- or treatmentplan was developed (Heuermann, 2007, 2010).

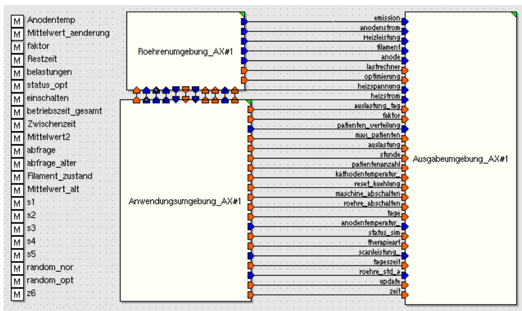

Figure 6: Encapsulated simulation environment for angiography.

4 SIMULATION RESULTS

The simulation run for a klystron (Figure 7) and a x-ray tube (Figure 8) shows patient count per hour, statistically spread over one day, machine load profile, actual condition of the gun and the anode. The optimization option was off. Within the optimization option two specific calculations will be used. Once the exact cathode surface temperature and second the gas pressure inside of the tube. Both parameters will give the control system the most significant service life-determining parameters. The rate of change of µP and ion-back-bombardement will indicate how fast the cathode is loosing emission (Heuermann, 2007, 2009, 2010).

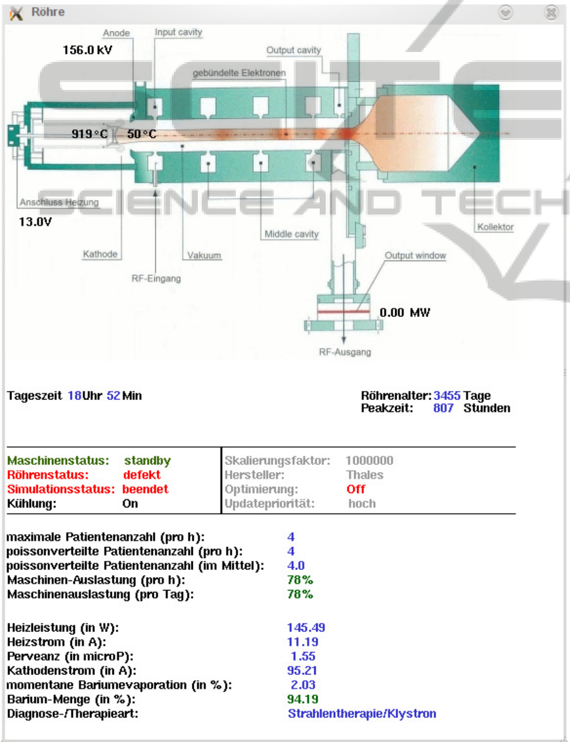

Figure 7: Simulation run example for a klystron.

Simulation result for 21MeV treatments (7,5MW peak pulse power within 7µs beam-on-time) with 12 working hours, 260 working days, 4 patients per hour, 13 minutes patient changing time:
Real beam on time: 807 hours
Useful service life: 3455 days in total results in 13,29 years
Reason for failure: end of life condition µP <= 1,56 reached

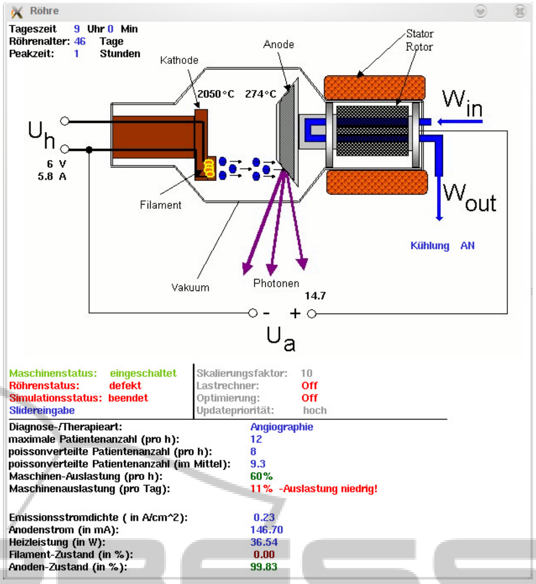

Figure 8: Simulation run example for a x-ray tube.

Simulation result for angiography diagnostic, (15kW peak beam power within 10 sec. scantime) with 12 working hours, 260 working days, 8 patients per hour, 5 minutes patient changing time:
Real beam on time: 1 hour
Useful service life: 46 days in total
Reason for failure: heater overcurrent caused broken filament

5 CONCLUSIONS

In the field of high-power tubes there is a large development potential regarding service life management and condition monitoring services to be found.

A targeted control of the service life-determining parameters extends the life of high-power tubes. As proof of a life extension, a simulation model is used, which provides information about the behavior of service life-critical parameters. Results produced by the simulation model are transferable to reality and can be used in a practical implementation. The simulation shows that a targeted control of service life-determining parameters influences the overall lifetime of a tube. In a next step, real load profiles recorded at customer sites will drive the tube model. These load profiles reflect the daily routine in a hospital with the individual patient distribution and their diagnostic and therapy schedules and, as a result, the real tube load. This novel approach will improve the uptime of medical systems. First results from single x-ray-tube systems (CT, Angiography, Fluoroscopy and Mammography) show that in case of direct heated cathodes the predictive maintenance works well. In case of multiple tube systems like radiation therapy machines, at least three high power tubes are used in one system, the proposed specific methods for life extension of equipment and systems in medical devices will increase the uptime dramatically.

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