RELIABILITY OF HIGH POWER ELECTRON ACCELERATORS FOR RADIATION PROCESSING

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Abstract

Accelerators applied for radiation processing are installed in industrial facilities where accelerator availability coefficient should be at the level of 95% to fulfill requirements according to industry standards. Usually the exploitation of electron accelerator reviles the number of short and few long lasting failures. Some technical shortages can be overcome by practical implementation the experience gained in accelerator technology development by different accelerator manufactures. The reliability/availability of high power accelerators for application in flue gas treatment process must be dramatically improved to meet industrial standards. Support of accelerator technology dedicated for environment protection should be provided by governmental and international institutions to overcome accelerator reliability/availability problem and high risk and low direct profit in this particular application.

1. INTRODUCTION

The present status of development and manufacturing of electron accelerators is suitable for high capacity radiation processing. Automatic control, reliability and reduced maintenance, adequate adoption to process conditions, suitable electron energy and beam power are the basic features of modern accelerator construction. Electron beam plants can transfer much higher amounts of energy into the irradiated objects than other types of facilities including gamma plants. That provide opportunity to construct technological lines with high capacity and they are more technically and economically suitable with high throughputs, short evidence time and grate versatility.

The progress in accelerator technology is tightly attached to the continuously advanced development in many branches of technical activity. The computers and automatic control systems, electronic components including power switches, modulator macropulses technology, new generations of microwave sources are the best examples availability of the power determine components in modern accelerator technology. The new accelerators ideas and constructions are being developed continuously. The most significant advantages of application electron beam sources in radiation processing facilities are related to:

- Availability of high power electron beam suitable for high capacity process with very short exposure time,
- Strictly controlled irradiation zone defined by parameters of electron beam scanning system,
- High fraction energy of electron beam deposited in irradiated object,
- Simple product handling systems for continuous and unit operation irradiation process,
- Safety (electron beam shut off capabilities to stop irradiation),
- Well established accelerator technology and accelerator producers,
- Economic advantages of electron beam processing,
- Easy control of irradiation process,
- Facility compactness,
- Economy of the process.

Accelerators which have been developed and are being used for radiation processing can be divided on following three main groups depend on their construction and electrical field implementation in electrons accelerating process:

- Direct DC transformer accelerators (*low and medium energy level*),
- RF resonance cavity accelerators (*medium and high energy level*),

- Microwaves linear accelerators (*medium and high energy level*).

The most suitable type of accelerator for certain application depends at first on required electron energy which is directly related to density and structure of irradiated objects and beam power which defines total capacity of the installation. The accelerator selection criteria are as follow:

- Average beam power *(productivity),*
- Electron energy *(penetration),*
- Price *(investment cost),*
- Electrical efficiency *(cost of accelerator exploitation),*
- Size *(building geometry and size),*
- Reliability *(availability >95%).*

It should be noticed that accelerators are not primarily optimized with respect to reliability.

2. RELIABILITY/AVAILABILITY OF ACCELERATORS APLLIED IN ACCELERATOR PROCESSING

High accelerator reliability is especially important during intense accelerator exploitation in the field of radiation processing. Share of maintenance and spare parts cost in exploitation cost grows significantly when accelerator reliability is poor. Electron accelerators spare parts and major maintenance services are available and usually provided by accelerator manufacturers. Presently highly trained personnel are not required to run accelerators because of simplicity of its operation under computer support. High frequency accelerators are more costly to operate due to their more complex construction and much more expensive spare parts like klystrons and magnetrons to compare with direct ones.

Reliability of the accelerators has not been recognized for a long time as real problem of radiation facility exploitation [1]. Only relatively recently high priority of reliability issue is given in accelerator design for very few specific applications like medical accelerators and future huge facilities for high-energy physics exploration [2, 3]. The following definitions are used to describe accelerator reliability/availability problem:

RELIABILITY: PROBABILITY that a system can perform its intended function for a specified time interval under stated conditions. *High reliability is required when repair of sensitive sub-components are long (or difficult). On the other hand if each failure can be repaired in a very short time so that the system has a high availability, and the maintenance costs are reasonable, the poor reliability may be acceptable.*

AVAILABILITY: fraction of TIME during which a system meets its specification. *High availability is required if continuous service is priority.*

MEAN TIME BETWEEN FAILURE (MTBF) is the mean number of time units during which all parts of a system perform within their specified limits, during a given time interval. *Long period between failures (MTBF) indicates high accelerator reliability.*

MEAN DOWN TIME (MDT), the average time a system is unavailable due to a failure. This time includes the actual repair time plus all delays associated with the repair (finding the spare part, etc). *Short accelerator down time (MDT) is characteristic for accelerators with high availability level.*

MEAN TIME TO REPAIR (MTTR) is the sum of corrective maintenance time divided by the total number of failures during a given time interval. *Short accelerator repair time (MTTR) is characteristic for well trained personnel and easy access for spare parts.*

REDUNDANCY is the existence of more than one means for accomplishing a given function. Equipment should not work at full capacity, and some margin must be allowed. *Redundancy well describes quality of accelerator design.*

Low accelerator reliability/availability (means high risk investment decision) can be recognized as result of following reasons:

- Prototype accelerator construction (*limited exploitation experience*),
- Parameters on the edge of present limits (*unproven working conditions*),
- Components with limited life time (*magnetron*)
- Difficulties in spare parts availability (*limited access*),
- Poor accelerator reliability (*improper design and poor quality components*).

When weak point of certain accelerator construction is established a suitable availability level can be achieved by redesign and reconstruction of critical components or subsystems but it is a matter of finance, manpower and time.

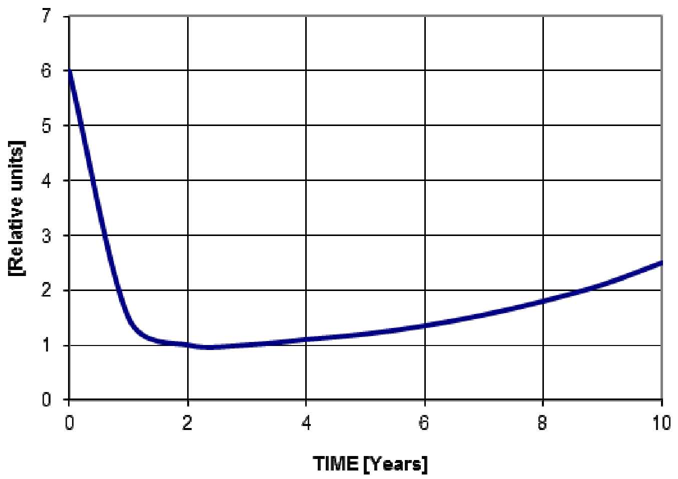

FIG. 1. Typical statistic of failures during accelerator exploitation

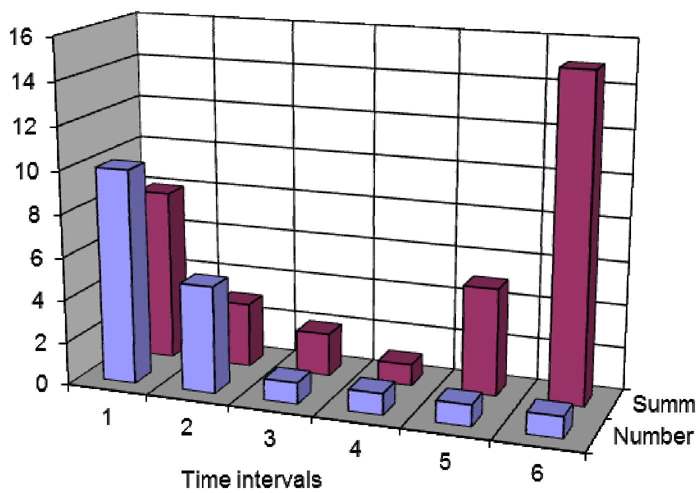

FIG. 2. Typical relation between number of failures and sum of the time when a system can not perform its intended function

Fig. 1 shows typical statistic of failures during the first period of accelerator exploitation. Typically starting up and accelerator commissioning periods are the most difficult in respect to accelerator reliability. Ageing of components and subsystems becomes a problem for longer exploitation time. Typical relation between number of failures and sum of the time when a system can not perform its intended function is displayed on Fig. 2. The most common are short breakdowns. Only few events are responsible for large downtime. Critical parts of accelerator construction in relation to accelerator reliability are as follow:

– Subsystems;
  - Beam scanning system,
  - Vacuum system,
  - Control system (overload conditions of voltage, current, temperature and other),
  - Cooling system (also emergency switch off).
– Components short life time;
  - Power component (klystrons, magnetrons, thyratrons, vacuum triodes),
  - Electron gun.
– Output window construction;
  - Thickness, dimensions and shape,
  - Window material,
  - Window cooling system.
– Voltage isolation**;**
  - Electrical breakdowns,
  - Oil/Gas isolation,
  - Withstand voltage level.
– Other**;**
  - Unsuitable construction.

2.1. Major failure examples

Accelerator failures are not predictable events in general. The most common problems are different for different accelerator construction. The most characteristic failures are connected to electron gun (cathodes) replacement, electrical breakdowns consequences, vacuum and cooling systems inefficient wok. The chain of events can be observed in some separate cases. Such situation can be illustrated on example of RF window breakdown (Fig. 3.a) happened in linear accelerator Elektronika 10/10. The primary event was related to electrical spark (breakdown) which damaged ceramic window. RF window separates waveguide where nitrogen under 5 at pressure is applied and accelerating section with vacuum level 10^{-6} Torr. In consequence nitrogen stream enter accelerating section and destroy output window (Fig. 3.b). The same time electron gun cathode was damaged.

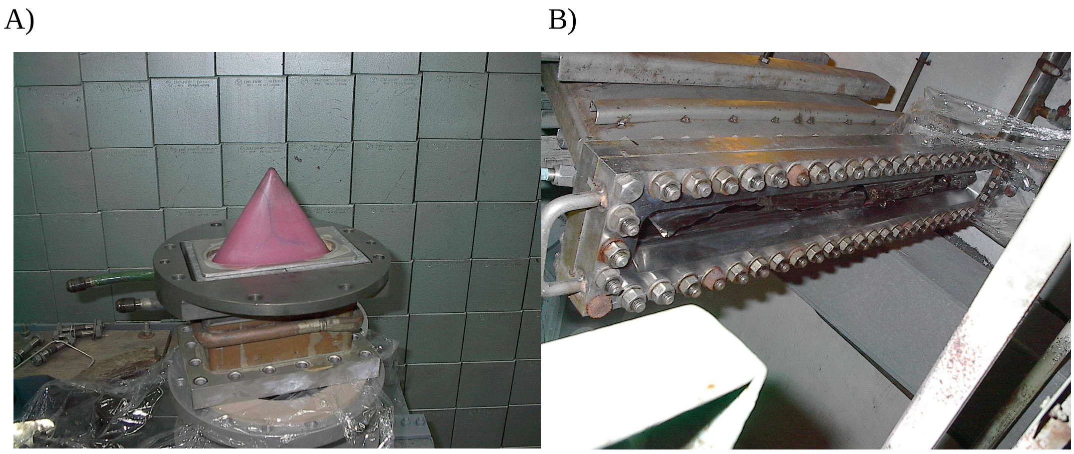

FIG. 3. RF ceramic window breakdown and its consequences related to output window: A - broken RF window; B - broken output foil

Some accelerator constructions suffer from frequent problems with electron gun. It is related mainly to quality of the cathodes used in certain gun construction. The failures are mainly connected to heater damage and breakdowns between heater and cathode material. Construction of gun cathode installed in linear microwave accelerator LAE/13/9 is shown on Fig. 4. The quite good statistic was collected over the period 30 years of accelerator exploitation (Fig. 5).

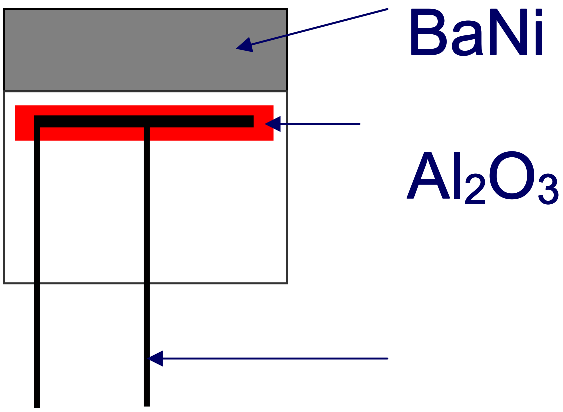

FIG. 4. Construction of gun cathode installed in linear accelerator LAE/13/9

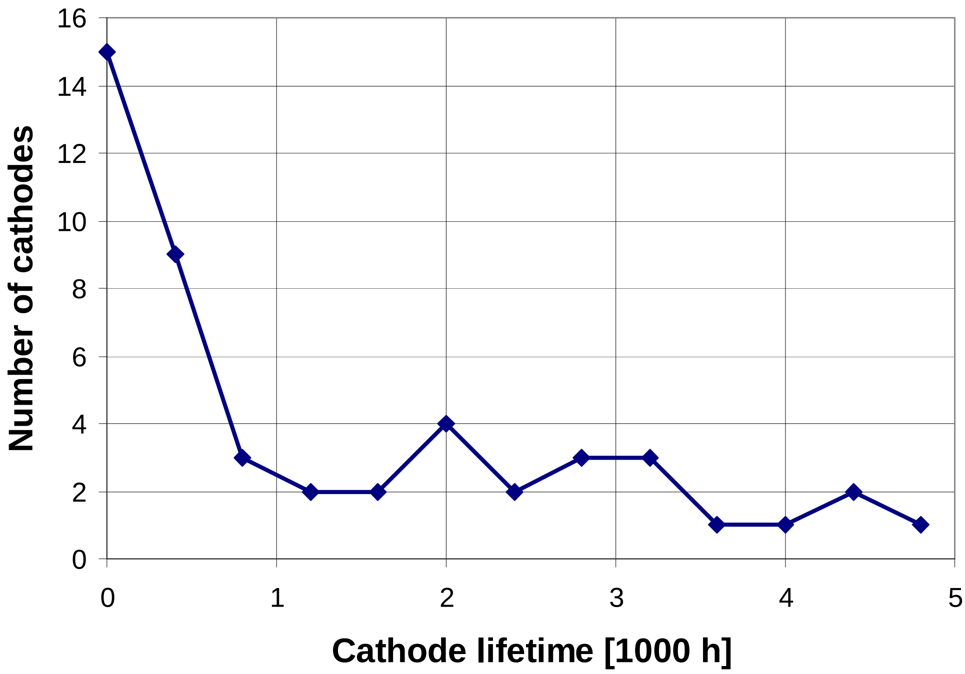

FIG. 5. Electron gun cathodes installed in linear accelerator LAE 13/9

As it can be easily notice 24 cathodes lifetime is bellow 400 h. Life time of other 24 cathodes is uniformly distributed in time interval 400-5000 h. It is obvious that cathode has some technical capabilities. Unfortunately non proper technology was applied by manufacturer to provide Al_2O_3 isolation between cathode material and heater. On the other hand cheap cathode units do not created economical problem and quick cathode replacement procedure do not affect significantly accelerator availability.

Much better results regarding cathode lifetime are observed during exploitation linear microwave accelerator Elektronika 10/10 used for radiation sterilization and provided by different manufacturer with different cathode construction with similar technical capabilities. The statistic covers period of 15 years accelerator exploitation is shown in Table I. The cathode life time is over 8000 h and cathode replacement is due to weak emission not due to cathode failure.

The typical reasons of accelerator failure are connected to life time of power components applied in certain accelerator. In case of accelerator Elektronika 10/10 magnetrons are applied as a source of microwave energy. The statistic connected to those devices is provided by Table II. Average lifetime of the magnetrons is to be 1155 h only. It can be easily noticed that quality of such components is not perfect. Only one from 12 units is characterized by weak emission which usually indicates ageing effect. Quite different situation is related to accelerator LAE 13/9 where klystrons are applied as microwave sources (Table III).

TABLE I. EXPLOITATION OF ELECTRON GUN CATHODES INSTALLED IN LINEAR ACCELERATOR ELEKTRONIKA 10/10

No	Year of installation	Life time [h]	Remarks
1	1992	9000	Weak emission
2	1998	4500	Replaced in a good condition together with accelerating section
3	2001	600	Damaged as a result of broken RF window and output foil
4	2001	8200	In operation
Average lifetime		8600	

TABLE II. EXPLOITATION OF HIGH POWER MAGNETRONS IN LINEAR ACCELERATOR ELEKTORNIKA 10/10

No	Life time [h]	Remarks
1	1200	Heater breakdown
2	948	Bad vacuum
3	792	HV breakdowns
4	22	HV breakdowns
5	829	Bad vacuum
6	613	HV breakdowns
7	184	HV breakdowns
8	2338	HV breakdowns
9	2130	Weak emission
10	1468	In operation
11	2042	Heater breakdown
12	1300	In operation

Average lifetime 1155 [h]

The average lifetime of applied klystrons was found to be 6648 h. This is much higher than in the case of magnetrons used as source of microwave energy. It should be noticed that both devices operate based on different concepts. KlysSoutbreaktron acts as amplifier with stable operating conditions, whereas magnetron is self excited generator which stability and life time is the main technical issue.

TABLE III. EXPLOITATION OF HIGH POWER KLYSTRON IN LINEAR ACCELERATOR LAE 13/9

No	Life time [h]	Remarks
1	4820	Heater breakdown
2	8937	Bad vacuum
3	6222	Weak emission
4	3167	Weak emission
5	2814	Weak emission
6	7481	Weak emission
7	8723	Weak emission
8	4689	Bad vacuum
9	12981	Weak emission

Average lifetime 6648 [h]

Accelerating sections applied in direct accelerators are usually composed from metal electrodes and isolation rings made of ceramic or polymeric materials. Vacuum welding technology are used to connect together metal electrodes and ceramic rings. That difficult and expensive method is replaced by polymer glue which is applied when metal electrodes and polymer isolations rings are used. Unfortunately in certain construction deformation of accelerating structure is being observed (Fig. 6) which directly interferes with electron beam optics and leads in result to beam current reduction and consequently eliminate that device.

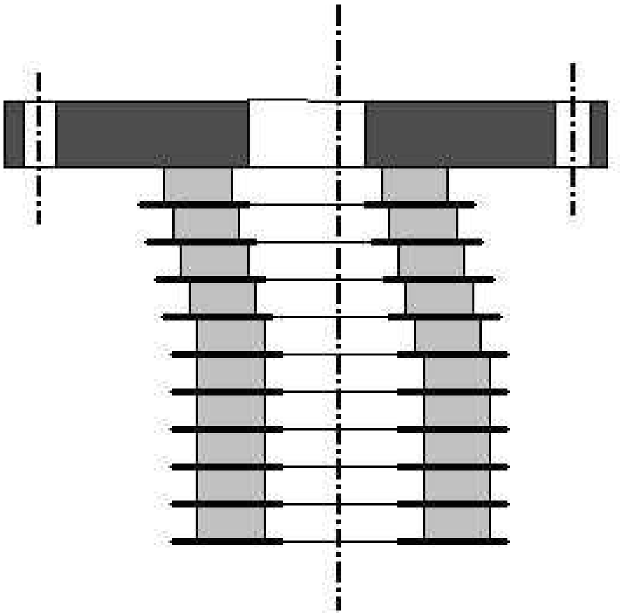

FIG. 6. Deformation of accelerating section at place of installation electron gun

Such deformation process of accelerating structure can be initiated under specific condition of accelerator exploitation and its construction. The most significant reasons which may lead to accelerating section deformation are listed bellow:

– High power of cathode heater what leads to high temperature (>80^{o}C) of accelerating section elements located in close distance to electron gun,

– Lack of sufficient cooling system,

– Application of polymer glue with not suitable properties,

– Heavy mechanical load located on the top of accelerating section which creates forces leading in long period of time to mechanical deformation.

The output electron beam system construction is very important from point of view technological performance of accelerator facility. The most sensitive part of the output system is thin output window foil usually made of titanium. It can be recognized several reason when inadequate quality of output system with titanium foil creates long and expensive breakdown in accelerator exploitation as a result of window foil implosion (Fig. 7):

– Bad quality of titanium foil,

– Distortion of beam scanning pattern,

– Insufficient interlock system which is not able recognize on time distortion of beam scanning pattern,

– Insufficient air cooling system,

– Hard particles in cooling air which could damage output foil,

– Improper design the shape of foil and its supporting system.

A) B)

FIG. 7. Scanner after implosion (A) and broken accelerator titanium foil (B)

The characteristic features of accelerator design which may leads to frequent failures events and consequently reduce accelerator availability are as follow:

– Prototype accelerator construction with limited exploitation experience,

– Parameters on the edge of present limits,

– Improper design of selected systems,

– Difficulties in spare parts availability,

– Difficult interchangeability of the components,

– No share reliability experience policy,

– No active efforts to redesign faulty systems according to exploitation experience.

3. QUALITY OF ACCELERATOR CONSTRUCTION AND EXPLOITATION

High-power electron accelerators for radiation processing are composed from the following main systems and components:

– Injector (gun and gun supply system),

– Main power support system (DC power supply and/or pulse modulator; RF or microwave sources),

– Output device (beam delivery system),

– Control and safety interlock systems,

– Auxiliary systems (air and water cooling, vacuum system, power line supply).

Quality requirements regarding accelerator construction and exploitation can be divided on following three main directions:

– Quality of components and subsystems,

– Design quality,

– Quality of exploitation and servicing.

Parallel efforts are necessary regarding: components, design, exploitation and servicing quality to achieve suitable accelerator availability/ reliability. Share reliability experience is also needed to reduce accelerator down time and apply technical solutions already tested.

3.1. Quality of components and subsystems

Quality of the components and subsystems are characteristic for certain manufacturing technology applied by producers of different devices. Components can be divided on those which are characterized by limited (like RF tubes) or unlimited (like semiconductors components) lifetime. Accelerator reliability/availability can be improved in respect to component quality by proper design and exploitation. The following steps can be taken:

- Implementation of component redundancy (design),
- Components with limited lifetime (like RF tubes) can be replaced after a pre-determined operation time,
- Unlimited lifetime components should be periodically inspected and tested,
- Components and system upgrades based on lost time,
- Replacement of 25-30 years old components.

Reliability of electronic components is characterized by random failures and is differ to mechanical components reliability which is mostly described by aging and overstresses. As a starting point of any reliability oriented design should be identification in advance the causes of all possible failures that may occur in the system. The following components can be recognized as critical from point of view accelerator reliability/availability:

- Gun (type of gun, cathode life time),
- RF source (klystron, magnetron, life time),
- Output foil,
- Pulse power components.

3.2. Design quality

The principal criteria of accelerator design optimized with respect to reliability are listed bellow:

- Design for fast interchangeability of components,
- Fault diagnostics included to accelerator control system,
- Separation of vacuum sub-systems with shut-off valves,
- Automation to avoid human mistake („Plug and play” design concept),
- Design optimization with suitable margins (redundancy),
- Electrical mains drops consequences should be foreseen and avoided,
- Modular design at all levels,
- Automated ramping procedure to recover HV or RF power and electron beam,
- Ability for long exploitation (18 h/day, round o'clock)

3.3. Quality of exploitation and servicing

The terms of accelerator exploitation and servicing have a great influence on accelerator reliability/availability. The following actions can significantly improve quality of exploitation servicing:

- Existence accelerator repair and component replacement procedures,

- Suitable operator’s training,
- Experts on standby ready to intervene,
- Quick troubleshooting procedures,
- Recording and analyzing failures, implementation strategies to make them disappear,
- Rigorous spare parts policy (ready-to-operate units available and spare parts),
- Preventive maintenance (devices are replaced after predetermined operation time),
- Built in preventive maintenance scheduling and monitoring,
- Missing cooling abilities,
- Starting up and closing down procedures (switching of power line abruptly causes faster ageing).

Preventive maintenance procedures should be established for certain accelerator because of differences in construction and requirements connected to applied concept of accelerator design (direct, RF, microwave accelerators). Accelerator manufacturers should provide sufficient information related to preventive maintenance activity (every day, week, quarter, year). The maintenance should also include such activity as:

- Regular replacement of water and air filters,
- Regular replacement of belts, hoses, and lubricants,
- IR detection of electrical connections (3 years cycle),
- Cleaning of HV cables and components (6 months cycle),
- Vibration/frequency analysis of rotating equipment (3 months cycle).

Repair time may have considerable influence on the availability of the accelerator. Repair procedures provided by accelerator manufactures should describe in details:

- Fault detection and diagnosis process,
- Preparation time needed to start the repair,
- Fault correction,
- Post-repair parameters verification,
- Restart of the system.

Electron accelerators for radiation processing are being applied since 1956 were first commercial facility has been used. Quick progress in accelerator technology eliminated early accelerators design. The present level of accelerator development can fulfill requirements (electron energy, beam power) coming from industry applying radiation technology. Long exploitation of accelerators becomes current issue. Extended time of accelerator exploitation (over 20-30 years) creates problem with spare parts availability. The other common problem is related to available technical parameters which are usually different to compare with nominal parameters specification. The typical equipment aging problems are related to:

- Electrical connections oxidizing,
- HV breakdown of dirty cables,
- Availability of spare parts,
- Communication faults,
- Calibration and stability problems.

Maintaining accelerator availability over the long term will require significant resource commitment or a reduction of the machine performance requirements.

4. CONCLUSIONS

Accelerator reliability should be recognized as very important for any industrial facility including environmental applications. Particularly the reliability of high power accelerators for environmental protection must be drastically improved with respect to the present situation. High accelerator reliability/availability according to industrial standards can be achieved by parallel efforts related to components, design, exploitation, and servicing quality. Reliability (availability) should be now a priority for electron accelerators designers. Reducing the downtime due to long failures is mostly financial issue. It should be noticed that reliability oriented accelerator design may increase cost of the accelerator by 30-50 % to compare with a nominal design. Life time of certain accelerator components should be extended. The terms of accelerator exploitation and servicing have a great influence on accelerator reliability/availability.

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