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ORIGINAL PAPER

Economical evaluation of radiation processing with high-intensity X-rays

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Abstract. X-rays application for radiation processing was introduced to the industrial practice, and in some circumstances is found to be more economically competitive, and offer more flexibility than gamma sources. Recent progress in high-power accelerators development gives opportunity to construct and apply reliable high-power electron beam to X-rays converters for the industrial application. The efficiency of the conversion process depends mainly on electron energy and atomic number of the target material, as it was determined in theoretical predictions and confirmed experimentally. However, the lower price of low-energy direct accelerators and their higher electrical efficiency may also have certain influence on process economy. There are number of auxiliary parameters that can effectively change the economical results of the process. The most important ones are as follows: average beam power level, spare part cost, and optimal shape of electron beam and electron beam utilization efficiency. All these parameters and related expenses may affect the unit cost of radiation facility operation and have a significant influence on X-ray process economy. The optimization of X-rays converter construction is also important, but it does not depend on the type of accelerator. The article discusses the economy of radiation processing with high-intensity of X-rays stream emitted by conversion of electron beams accelerated in direct accelerator (electron energy 2.5 MeV) and resonant accelerators (electron energy 5 MeV and 7.5 MeV). The evaluation and comparison of the costs of alternative technical solutions were included to estimate the unit cost of X-rays facility operation for average beam power 100 kW.

Keywords: X-rays • Economical evaluation • Radiation processing

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Introduction

W. C. Roentgen received the first Nobel Prize for Physics in 1901 for his discovery of X-rays in 1895. It was the first of six to be awarded in the field of X-rays in 1927 [1]. This discovery can be recognized as one of the best achievements in nuclear science applied commonly not only in science but also in medicine and industry during the last century. X-rays present applications are still growing and cover fields such as 3D medical and technical diagnostic systems, micro-fabrication 3D components, collecting information from deep space by X-rays detecting devices in astronomy and radiation processing devoted to radiation sterilization and food product treatment.

Radiation processing on the massive scale can be performed by electron beam (accelerators), gamma rays from radioactive nuclides, and X-rays (electron beam – EB/X-rays conversion), but electrons, gamma rays and X-rays transfer their energies in the absorption of materials by ejecting atomic electrons that ionize other atoms. All types of ionizing radiations produce similar effects. Owing to that, the question was formulated long time ago [2] "Do we need X-rays in radiation processing?". The choice of a radiation source depends on the practical aspects of the treatment process, such as absorbed dose, material thickness, processing rate, capital and operating costs, and unit cost of operation. The right answer should be connected to the question of what kind of radiation processing (electron beam, gamma- or X-rays) is beneficial for the treatment of certain processor and product.

Before one should decide which source of ionizing radiation is the most suitable for certain application, the study should be performed to analyse clearance conformity, system flexibility, integration and availability, and investment and treatment costs. Currently, the global sterilization market is divided between EtO gas which is around 50%, gamma service which is above 40%, and electron beam which is less than 5%. Productivity in the X-rays mode is about 20 times lower than in the EB mode. X-rays processing has own advantages (penetration) and disadvantages like poor dose homogeneity, what requires special conveyor arrangement (four pass irradiation or beam intensity correction along the scanner). Advantages of X-rays compared with gamma rays are listed as follows:
- broader energy spectrum,
- more narrow angular X-rays dispersion,
- greater penetration in materials,
- more uniform dose distribution,
- product transport system much more simpler than in gamma irradiators,
- higher power utilization efficiency,
- X-ray source can be easily turned on and off,
- save money when there is no need for production,
- simplifies shipping, installation, and maintenance procedures,
- perceived to be less dangerous than isotope sources,
- new high-power accelerator and target constructions,
- growing data base regarding X-ray radiation processing, and
- difficulties with gamma sources production and transportation.

In general, radiation sterilization performed by stream of X-rays became already a competitive solution to gamma process.

X-rays processing was initiated many years ago in several EB facilities located in different countries as a new option for the radiation treatment [3–6]. The biggest facility of this type was established based on accelerator Rhodotron type. Electron beam with 7 MeV energy and 560 kW average beam power was successfully converted on high-intensity X-rays stream [7]. Currently, different accelerator facilities for radiation processing can offer treatment by:
- electron beam (only),
- electron beam or X-rays stream,
- electron beam and X-rays stream operated simultaneously (the newest option), and
- X-ray stream (only).

EB/X-rays converter construction

EB/X-rays converter construction is relatively simple. The general construction idea of EB/X-rays converter for radiation processing is presented in Fig. 1. The scanned electron beam is deposited in target material with possibly high Z number to achieve high efficiency of the conversion process. The cooling water system is required when beam power density is within the range of 10–50 W/cm². With beam power density above 50 W/cm², water temperature may rise above 100°C. Stainless steel (or aluminium) cover is necessary to complete adequate cooling system. Cover thickness should be minimized and selected according to water pressure requirements.

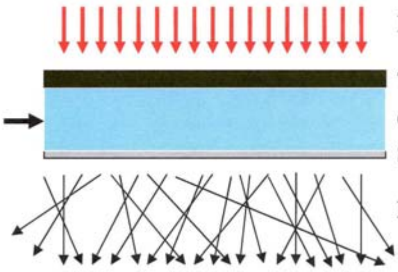

Fig. 1. General construction idea of EB/X-rays converter for radiation processing.

General view on water-cooled EB/X-rays converter with tantalum target design for scanned electron beam with energy 2 MeV is presented in Fig. 2 [8]. Tantalum foil with thickness of 0.5 mm was applied as a target. Layer of water (20 mm thick) was used to provide necessary cooling. In addition, stainless steel sheet (0.8 mm thick) was used to complete cooling system. Total photon transmission (1.7%) was achieved when electron beam at an energy of 2 MeV and beam power of 20 kW. It corresponds to Co-60 source equivalent 25 kCi and mass throughput 500 kGy kg/h. More specific characteristics of such converter construction were described in the literature [9].

The thickness of target material should be optimized for certain electron beam energy to obtain the maximum conversion efficiency (X-rays emission) due to strong X-rays absorption effect in target material. Conversion efficiency was calculated using Mode-XR-v 2.3 software program based on the Monte Carlo method [10]. The principal parameters that were used during calculation are listed as follows:

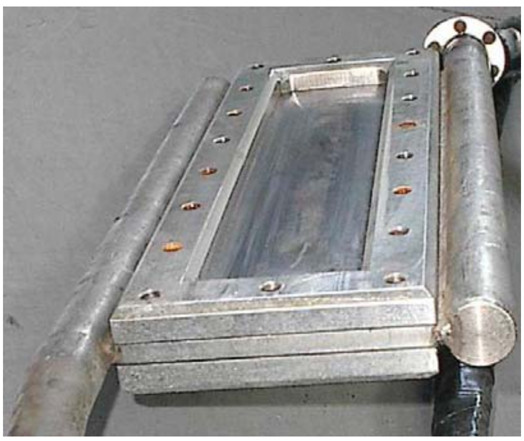

Fig. 2. General view on water cooled EB/X-rays converter with tantalum target design for scanned electron beam (tantalum foil thickness 0.5 mm).

I. Source and scan parameters:
- continuous beam current with average power: 100 kW,
- mono-energy beam: 2.5, 5, and 7.5 MeV,
- average current (respectively): 40, 20, and 13.3 mA,
- angular spread of the beam: 0.4°,
- beam diameter: 3 cm (width on half maximum 2 cm),
- conveyor width: 120 cm,
- scan frequency: 10 Hz,
- scanner height: 200 cm,
- parallel beam configuration,
- distance scan-conveyor: 60 cm,
- width of scanning 100 cm.

II. Irradiated object:
- water with density: 1 g/cm^3,
- water layer thickness: 50 cm,
- width of irradiated object: 100 cm.

III. EB/X-rays converter:
- tantalum foil width: 10 cm,
- tantalum foil length: 100 cm,
- tantalum foil with different thicknesses: 0.25–1.3 mm.

Optimal tantalum foil thickness was established by conversion efficiency calculation performed for certain electron energy level and different tantalum foil thickness. The results of calculations are presented in Table 1 for electron energy of 2.5 MeV. The results of calculations show that target thickness should be optimized with respect to the initial electron energy level to obtain higher efficiency of the conversion process and to avoid electron passing through the target.

The calculations were repeated for different electron energy of electron beam and optimal thickness of tantalum target related for certain electron energy. The results of calculations are presented in Table 2. As it can be easily noticed, X-rays stream emitted in forward direction strongly depends on initial electron energy. Electron energy of 2.5, 5, and 7.5 MeV was applied with adequate tantalum foil thickness 0.45, 0.8, and 1.3 mm.

Table 1. Conversion efficiency for scanned beam with electron energy of 2.5 MeV and target made of tantalum foil with different thickness

Energy 2.5 MeV	Tantalum foil thickness		
	0.25 mm	0.45 mm	0.65 mm
Photons transmission	0.032	0.036	0.034
Reflection			
electrons	0.2	0.21	0.21
photons	0.017	0.023	0.024
Target component			
tantalum	0.42	0.66	0.72
water 20 mm	0.33	0.069	0.013
steel 0.8 mm	0.0014	0.0015	0.0012

Table 2. Conversion efficiency for electron energy 2.5, 5, and 7.5 MeV and target made of tantalum foil with optimal thickness

Electron energy	2.5 MeV	5 MeV	7.5 MeV
Ta target thickness	0.45 mm	0.8 mm	1.3 mm
Transmission			
photons	0.036	0.084	0.133
Reflection			
electrons	0.21	0.11	0.071
photons	0.023	0.032	0.037
Energy absorption			
tantalum	0.66	0.62	0.63
water 20 mm	0.069	0.15	0.13
steel 0.8 mm	0.0015	0.0027	0.0045

X-ray irradiation process is characterized by specific depth dose distribution, which is similar but not the same like in gamma sources. Figure 3 illustrates spatial dose distribution deposited by X-rays stream emitted by conversion parallel electron beam with energy of 5 MeV, scanned over 100 cm long Ta target with thickness of 0.8 mm, and deposited in water layer of 50 cm thick and 100 cm wide. As can be easily noticed, the dose intensity along the scanned beam path is not uniform. It can be improved but converter construction and suitable beam current pattern. Four-pass system should be also applied in most cases to obtain suitable dose homogeneity.

Figure 4 shows the depth dose distribution deposited in the center of water layer of 50 cm thick and 100 cm wide by X-rays streams emitted in Ta target with different thicknesses: 0.45 mm for electron energy of 2.5 MeV (A), 0.8 mm for electron energy of 5 MeV (B), and 1.3 mm for electron energy of 7.5 MeV (C).

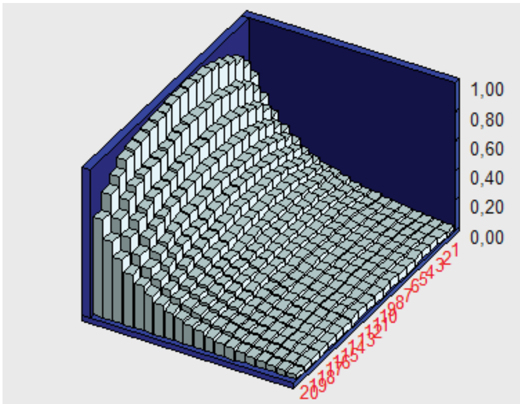

Fig. 3. Spatial dose distribution deposited by X-rays stream in water layer of 50 cm thick. Ta target with thickness of 0.8 mm, and electron beam with energy of 5 MeV scanned over 100 cm.

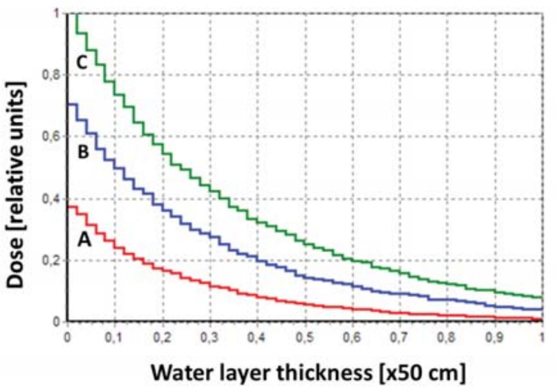

Fig. 4. Depth dose distribution deposited in the center of water layer of 50 cm thick by X-rays streams emitted in Ta target with different thicknesses: A – 0.45 mm for electron energy of 2.5 MeV; B – 0.8 mm for electron energy of 5 MeV; C – 1.3 mm for electron energy of 7.5 MeV.

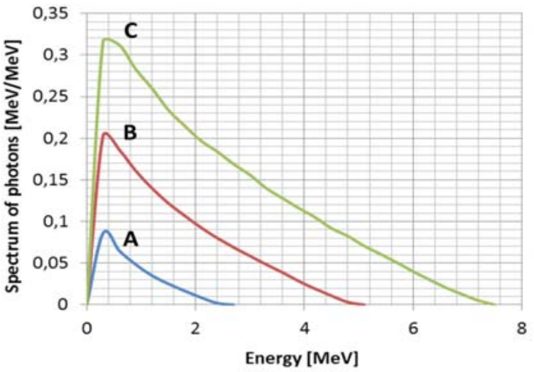

Fig. 5. Spectrum of photons emitted in Ta target with different thicknesses: A – 0.45 mm for electron energy of 2.5 MeV; B – 0.8 mm for electron energy of 5 MeV; C – 1.3 mm for electron energy of 7.5 MeV.

Figure 5 shows the spectrum of photons emitted in Ta target with different thicknesses: 0.45 mm for electron energy of 2.5 MeV (A), 0.8 mm for electron energy of 5 MeV (B), and 1.3 mm for electron energy of 7.5 MeV (C).

Conversion efficiency factor of electron beam beam with nominal energy of 5 MeV is in practice within the range of 4.5–7%. It depends on energy distribution (energy spread) and converter construction. In the best case, the practical value is 1.2 times lower than the theoretical one. The conversion efficiency at electron energy of 7.5 MeV is nearly 60% higher than for 5 MeV what is presented in Table 2 and described in published data [11]. The other advantages of higher energy application means better photon utilization and the optimum product thickness that may leads to higher production capacity and lower unit cost. The specific issue is connected to induced radioactivity of irradiated products (food and medical devices), when treated by 7.5 MeV X-rays stream. According to the performed experiments made with tantalum target, the measured activities are higher than theoretical expectation but are located significantly below levels described in regulations [12].

Productivity of the facility applying radiation processing

Radiation process productivity of the facility equipped with electron beam X-ray converter can be calculated according to the following formula:

$$\text{Productivity [kg/h]} = 3600\, P \cdot \eta \cdot \eta_x / D$$

where P – beam average power [kW]; η – X-rays stream utilization coefficient (0.3–0.5; depends on irradiated product characteristic and acceptable D_{max}/D_{min} ratio); η_x – EB/X-rays conversion coefficient (0.03–0.07; depends on target material and converter construction, electron energy, and energy distribution); and D – dose [kGy].

The calculation of economic parameters was performed for the conversion efficiency for different energy reduced by 1.2 factor (2.5 MeV – 3%; 5 MeV – 7%; and 7.5 MeV – 11%). This factor represents the losses of X-ray stream due to target dimensions and other type of losses. Overall, practical electron beam energy utilization coefficient in X-rays processing depends also on X-rays stream utilization. In general, 40% of total X-rays is deposited in treated object, and total utilization coefficient can be found for different electron energy as: 2.5 MeV – 1.2%; 5 MeV – 2.8%; and 7.5 MeV – 4.4%.

Cost analyses of radiation process performed by X-rays (electron energy 2.5 MeV and 5 MeV)

Cost of the X-rays radiation processing can be estimated using the following assumption:

- Accelerator (C_A) and accelerator installation (C_I) costs:
  - Direct accelerator (electron energy 2.5 MeV, beam power 100 kW): C_A = 0.7 M$; C_I = 0.05 M$; electrical power consumption 125 kW,
  - Resonant accelerator (electron energy 5 MeV or 7.5 MeV, beam power 100 kW): C_A = 3.85 M$; C_I = 0.75 M$; electrical power consumption 260 kW,
- Cost of building (shielding, conveyor, and engineering): 160% of accelerator and installation cost: $C_B = 1.6\,(C_A + C_I)$,
- Total investment cost: $C_T = C_B + C_A + C_I$,
- Amortization payment (rate 25% for 5 years): $C_i = 0.25\, C_T$,
- Interest rate: 0.1 C_T,
- Operation time during the year: 2000 h – one shift; 6000 h – three shifts operation,
- Price of electricity: 0.1 $/kWh (depends on the country).

Comparing treatment options annual cash flow projection was applied. This method is based on the expenditures made and revenues received during the facility exploitation period. The main components of capital investment cost are related to spending on accelerator and auxiliary equipment but also refers to installation and building construction. Fixed costs include depreciation (usually 5 years), interest rate (e.g. 10%), and management cost.

To calculate the fixed annual payment for the amortized capital cost, the following well-known formula can be applied:

$$\text{Annuity} = \text{capital cost} \cdot (i) \cdot \{1/[1 - (1 + i)^{-n}]\}$$

where i – interest rate and n – facility expected life time.

The main components of variable costs (operating costs) are as follows: electricity (0.1 $/kWh), labour and facility maintenance, and spare parts cost. Product volume, which is the source of facility revenues, depends on electron beam power, utilization and conversion coefficients, and required dose rate.

The principal economic assumptions of X-rays facilities based on different accelerator construction are presented in Table 3. Both selected direct (2.5 MeV) and resonant accelerators (5 MeV and 7.5 MeV) provide the same average beam power of 100 kW and are characterized by different electron

Table. 3. Economic assumptions of facilities where 100 kW average beam power is converted on X-rays

Electron energy	2.5 MeV	5 MeV	7.5 MeV
Accelerator type	Direct	Resonant	Resonant
Accelerator price	0.7 M$	3.85 M$	3.85 M$
Investment cost	1.95 M$	5.8 M$	5.8 M$
Exploitation cost	1.075 M$	2.496 M$	2.496 M$
Conversion efficiency	3%	7%	11%

energy and different level of accelerator price. It should be noticed that in terms of unit cost of operation, the lower conversion efficiency for low-energy electron beam conversion on X-rays may be compensated by relatively low price of direct (transformer) accelerators.

The results of calculations presented in Table 4 reveal that X-rays process in facility equipped with different construction accelerators and accelerator price, but with the same average beam power 100 kW and electron energy 2.5 MeV and 5 MeV operated during one shift per day (2000 h/year) can provide similar unit cost of operation. The situation would be only slightly different when higher electron energy (5 MeV) is applied. It should be noticed that the conversion efficiency for 2.5 MeV is 2.3 times smaller to compare with conversion efficiency for 5 MeV electron energy. Lower conversion efficiency is compensated by lower price direct accelerator compared with price for resonant accelerator (factor 5.5). The results calculation may be slightly different

Table 4. Yearly cost estimates for X-rays irradiation facility based on 2000 h/year and 6000 h/year facility operation

Cost element [k$]	Direct accelerator		Resonant accelerator	
Beam power 100 kW	2000 h	6000 h	2000 h	6000 h
Capital investment:				
accelerator	700	700	3850	3850
installation	50	50	750	750
building	1200	1200	1200	1200
Total investment costs	1950	1950	5800	5800
Fixed costs:				
investment depreciation (5 years)	488	488	1450	1450
interest 10%	195	195	580	580
management	50	50	50	50
Total fixed costs	733	733	2080	2080
Variable costs:				
electricity (0.1 $/kWh)	26	78	53	159
labour	140	420	140	420
maintenance	5	15	15	45
Total variable costs	171	513	208	624
Total yearly costs	904	1246	2288	2704
Cost [$/h]	452	208	1144	451
Productivity (X-ray; dose 1 kGy) [kg/h]	4320	4320	10 080	10 080
Unit cost (X-ray; dose 1 kGy) [$/kg]	0.105	0.0475	0.1125	0.045

Table 5. Unit cost of operation estimates for X-rays stream irradiation process (2.5, 5, and 7.5 MeV electron energy and 100 kW beam power)

Cost element [k$] 4000 h/year – two shifts facility operation Beam power 100 kW	Beam energy 2.5 MeV	 5 MeV	 7.5 MeV
Capital investment:			
accelerator	700	3850	3850
installation	50	750	750
building	1200	1200	1200
Total investment costs	1950	5800	5800
Fixed costs:			
depreciation (5 years)	488	1450	1450
interest 10%	195	580	580
management	50	50	50
Total fixed costs	733	2080	2080
Variable costs:			
electricity	52	106	106
labour	280	280	280
maintenance	10	30	30
Total variable costs	342	416	416
Total yearly costs	1075	2496	2496
Cost [$/h]	269	624	624
Productivity (X ray; dose 1 kGy) [kg/h]	4320	10 080	15 840
Unit cost (X ray; dose 1 kGy) [$/kg]	0.0625	0.0625	0.0400

for different economic assumptions (interest rate, depreciation or building spending).

Cost analyses for facility operated with X-rays stream (electron energy 2.5, 5, and 7.5 MeV and beam power 100 kW)

Cost of the radiation processing can be estimated using the aforementioned assumption.

The cost analysis was performed for facilities equipped with direct accelerator (2.5 MeV electron energy and 100 kW beam power), resonant accelerators (5 MeV and 7.5 MeV electron energy and 100 kW beam power), and two shifts operation (4000 h/year). The results of calculations are displayed in Table 5.

The situation is slightly better when higher electron energy (5 MeV) is compared with 2.5 MeV case. Again, the lower conversion efficiency for 2.5 MeV (factor 2.3) is practically compensated by lower price direct accelerator (factor 5.5). Significant difference is observed for 7.5 MeV when conversion efficiency is much higher and suitable factor amounts 3.7 (2.5 MeV) and 1.6 (5 MeV). The process efficiency of facility operated at 7.5 MeV is nearly 60% higher than the same facility operated at 5 MeV, what is in agreement with data presented in the literature [12]. It should be noticed that tantalum target is acceptable at 7.5 MeV without the risk of production detectable activity of equipment and product with conversion efficiency higher that at 5 MeV. Electron energy level 5 MeV is commonly applied for EB/X-rays conversion process in many countries. Activation for this energy level is no issue. That became a problem at energy level 7.5 MeV, due to such level energy during conversion process is not accepted in some countries.

Conclusions

Major steps of decision on which radiation technology has been selected should take into account that EB treatment has limitation in penetration, gamma ray processing is characterized by low dose rate, which means low productivity, and finally X-ray application means less efficient use of electrical energy than EB process.

The calculations reveal that X-rays process in facility equipped with different construction accelerators and accelerator price, but with the same average beam power of 100 kW and electron energy of 2.5 MeV and 5 MeV operated during one shift per day (2000 h/year) can provide practice the same unit cost of operation. The situation would be only slightly better when higher electron energy (5 MeV) is applied on three shifts. It should be noticed that lower conversion efficiency for 2.5 MeV (factor 2.3) is practically compensated by lower price of direct accelerator (factor 5.5). The results calculation may be slightly different for different economic assumptions (interest rate, depreciation or building spending). The situation is much better when higher electron energy (7.5 MeV) is compared with 2.5 MeV and 5 MeV cases. A high difference is observed for 7.5 MeV when conversion efficiency factor in relation to other cases amounts 3.7 (2.5 MeV) and 1.6 (5 MeV). The process efficiency of facility operated at 7.5 MeV is 50% higher than the same facility operated at 5 MeV, what is in agreement with data presented in the literature. Radiological safety: tantalum target is acceptable at 7.5 MeV without the risk of production detectable activity of equipment and product, with conversion efficiency nearly 50% higher than at 5 MeV.

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