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Economical evaluation of a radiation processing center equipped with an electron accelerator in Iran

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Abstract

In order to develop the private sectors in the country, access to information about the irradiation unit cost is one of the important information that must be provided to the investors to promote and share them. This article focuses on the irradiation unit cost calculation and its dependence on different parameters. Therefore, it is attempted to gather information about the fixed and variable costs required for establishing a radiation processing center equipped with an electron accelerator, domestically. Then, using activity based costing method the irradiation unit cost based on hours of system operation is estimated and compared.

Keywords: Radiation processing of food, electron accelerator, economical evaluation, irradiation unit cost

Introduction

Attention to the progress of radiation application in different industries, especially its uses to improve the human health, decreasing of disease, and increasing the shelf life of foods, to clarify its various aspects from economical point of view is inevitable. Today, hundreds of electron accelerators are used worldwide for research and development purposes or material irradiation at industrial scales (Board, 1991; Bruhn, 1995; CFR, 2004; Diehl, 1994; EC, 1999; Farkas, 1987; Farkas, 2006). Concerns of pollution caused by humans forced to have principles and rules to create the health regulations from governments. There are rules that food and medical device manufacturers are bound for, causing a new market area to provide services. Since services for sterilization and disinfection have been provided through the dozens of existing methods, the focus of this work is on using the radiation technology. According to World Health Organization (WHO) in 1992, about 35% of infectious and parasitic diseases mainly in developing countries lead to death (Loaharanu, 1994). Studies show that thermal pasteurization methods in the decontamination of liquid food lead to acceptable results, but on solid food is not appropriate from the commercial point of view. Hence, radiation processing of food as the best and safest method was considered in many countries (Boisseau, 1994). Meanwhile, this method does not cause any radioactivity in the products (Becker, 1983) and have the cost availability from the business point of view (Farkas, 2004). The radiation sources used in this industry are limited to γ-rays emitting from ^{60}Co and ^{137}Cs, X-rays with energy less than 5 MeV, and electrons with the energies less than 10 MeV (CAC, 2003). The maximum radiation dose needed for treatment of food and medical disposable device are 10 kGy and 25 kGy, respectively. In all irradiators it is attempted to irradiate the products uniformly. In an electron accelerator facility, keeping more dose uniformity in products could be performed by limiting the product thickness in accordance to electron energy or bilaterally irradiation method (Ziaie *et al*., 2001; Ziaie *et al*., 2005; Sádecká, 2007).

Theoretical foundations

Dependence of investment cost on electron beam energy and power

In each radiation processing facility equipped with an electron accelerator the parameters such as size, shape, density and composition of product and desirable radiation dose are taken under consideration by the accelerator manufacturer companies to produce devices at the different ranges of electron beam energy and power. Investment cost for the production of electron beam always is very high due to primarily accelerator cost, building and biological shielding. In this regard it has been shown that the initial investment cost in most cases can be estimated from the following relationship:

$$K_I = Q \cdot K_A \quad (1)$$

where K_A is accelerator cost and Q is constant which estimated as 2.4 ± 0.3 (Zimek & Kaluska 1998; Cleland, 1993). The accelerator price can also be estimated from the following relationship:

$$K_A \propto E \cdot \sqrt{P} \quad (2)$$

where E and P are the electron beam energy and power, respectively. This equation shows that the low-energy electron accelerators are usually more cost-effective than high-energy electron accelerator. It can be noted that the conversion of electrical energy to electron beam current is more efficient for low energy electrons. Also, a low energy accelerator is low cost trend due to their cheaper spare parts, repair and maintenance problem.

Product throughput rate calculation

Generally, the irradiation unit cost decreases with increasing the product throughput rate, therefore, increasing the customers makes to prorate the total cost. Product throughput rate defines as mass throughput rate

(M) or volume throughput rate (V) under the electron beam radiation can be calculated as:

$$M(kg/min) = \frac{60 \times P(kW) \cdot \varepsilon}{D(kGy)} \quad (3)$$

$$V(m^3/min) = \frac{M(kg/min)}{\rho(g/cm^3) \times 1000} \quad (4)$$

where ε is electron beam utilization factor (mainly between 0.4-0.6), D is absorbed dose value in product and ρ is product mean density (numerical coefficients has been entered for the balance of the units). The maximum product conveying speed can be calculated using the mass throughput rate, as well. This is very crucial parameter to choose a conveyor system for radiation processing using electron accelerator. The equation to calculate this parameter is:

$$S\,(m/min) = \frac{M\,(kg/min)}{t(m) \cdot L(m) \cdot \rho\,(g/cm^3) \times 1000} \quad (5)$$

where t is product thickness, and L is electron beam width emerging out from the scanning horn. Considering the widespread product average density and the importance of controlling dose uniformity in the package containing the product, the under irradiation products thickness will be different. Therefore, having the electron beam optimum range in product for different energy and using the following equation the effective thickness of product can be estimated for single-side irradiation.

$$t(cm) = \frac{R_{opt}\,(g/cm^2)}{\rho\,(g/cm^3)} \quad (6)$$

where R_{opt} is the electron beam optimum range in product and is demonstrated in Fig. 1 for different electron beam energies. The data in this figure have calculated using the Monte-Carlo method, previously (Ziaie *et al*., 2002).

Irradiation unit cost calculation

Irradiation unit cost of product can be estimated using the following equation:

$$U(\$/m^3) = \frac{K_E = K_V + K_F(\$/year)}{V(m^3/min) \cdot T_W(hr/year) \times 60} \quad (7)$$

where K_E is the exploitation cost, K_F and K_V are the current fixed and variable costs, and T_W is the accelerator operating time in a year. The above relationship in terms of basic parameters (Eqs. 3 and 4) is converted to the following equation:

$$U(\$/m^3) = \frac{[K_V + K_F(\$/year)] \cdot \rho(g/cm^3) \cdot D(kGy)}{3.6 \times P(kW) \cdot \varepsilon \cdot T_W(hr/year)} \quad (8)$$

As it can be concluded from this equation in addition to operating time, increase the electron beam power have an effective role in reducing of irradiation unit cost of product, as well. However, according to the limited thickness of the package containing product with the electron energy, the volume throughput rate can be increased due to increasing the electron energy and ultimately reduce the product irradiation unit cost.

Results and discussion

The estimated initial investment costs for establishing of a radiation processing center equipped with an electron accelerator with 10 MeV and 20 kW electron energy and beam power, respectively, are depicted in Table 1. The data in this table except the electron accelerator machine were acquired according to the country material, salary and other costs. As is noted, the initial investment cost is in accordance to the Eq. 1 with a good approximation. The specifications of a typical accelerator along with its product mass and volume throughput rate were calculated via Eqs. 3 and 4 and are shown in Table 2.

The details of current project costs including fixed and variable costs per operating hours in a year were calculated and inserted in the Table 3. Considering the existence of a range of food with different density, average density of 0.4 g/cm^3 for calculation and comparison were considered. Therefore the 10 MeV electron beam energy makes it possible to irradiate the product with a thickness of about 10 cm at single side irradiation. However, irradiation of dense or thick materials will be provided using the possibility of bilateral irradiation (Ziaie *et al.,* 2001; Ziaie *et al*., 2005).

According to equation-8 the parameters such as electron beam power, accelerator operating time per year, accelerator price, and product density affects the product irradiation unit cost. By substituting in eq. 8 the values reported in Tables 2 and 3, it is possible to determine the irradiation unit cost as a function of the operating hours per year of the accelerator, the electron beam power, the average product density, and the accelerator price. The results from these calculations have been plotted in Figs. 2, 3, 4 and 5.

Fig. 2 and Fig. 3 show the decreasing of irradiation unit cost with increasing the accelerator operating time and electron beam power. Fig. 4 and Fig. 5 suggest that the irradiation unit cost is in direct relationship with the accelerator price and product average density.

The higher electron beam energy can provide the irradiation of higher density material and it leads to increase the product volume throughput rate and will decrease the irradiation costs, consequently. According to the Fig. 4 increasing of product density, increases the irradiation unit cost, thus, by increasing the electron energy a cost reduction will be occurred.

It can also be concluded that the accelerator price does not changes the irradiation unit cost significantly especially in higher operating time, in comparison to other parameters (Fig. 5).

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Fig.1 Variation of product optimum range as a function of electron beam energy

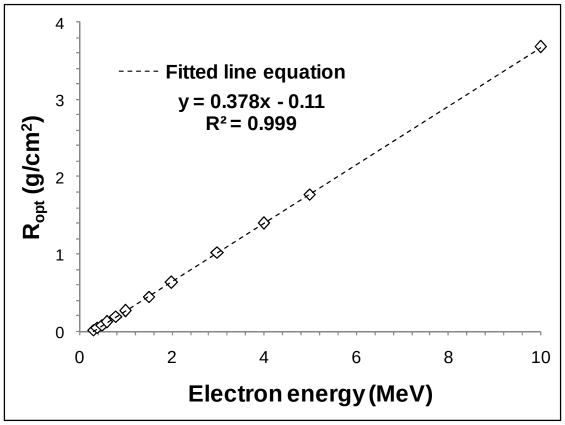

Fig 2. Variation of product irradiation unit cost as a function of operating time (Accelerator price was kept constant)

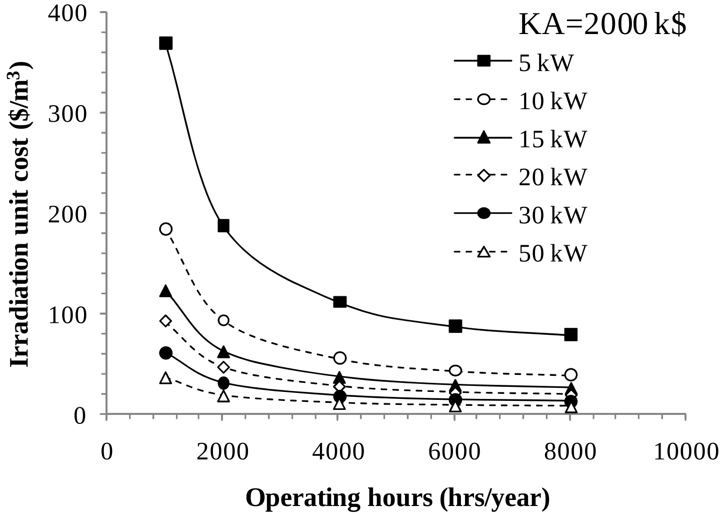

Fig 3. Variation of product irradiation unit cost as a function of electron beam power (accelerator price was kept constant)

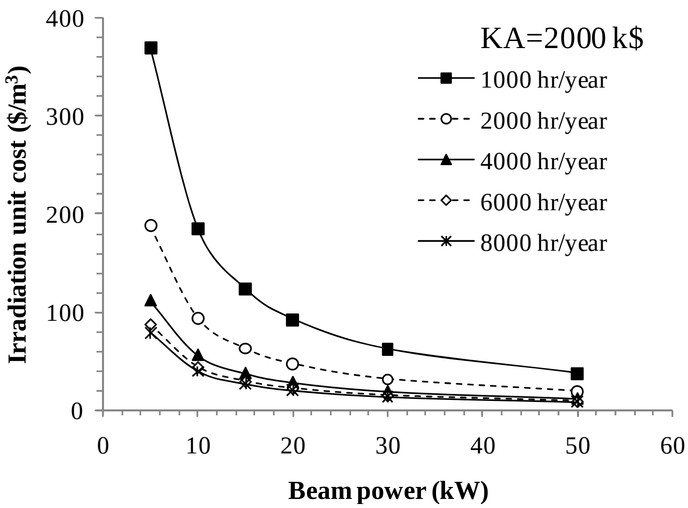

Fig 4. Variation of product irradiation unit cost as a function of average product density (accelerator price and electron beam power were kept constant)

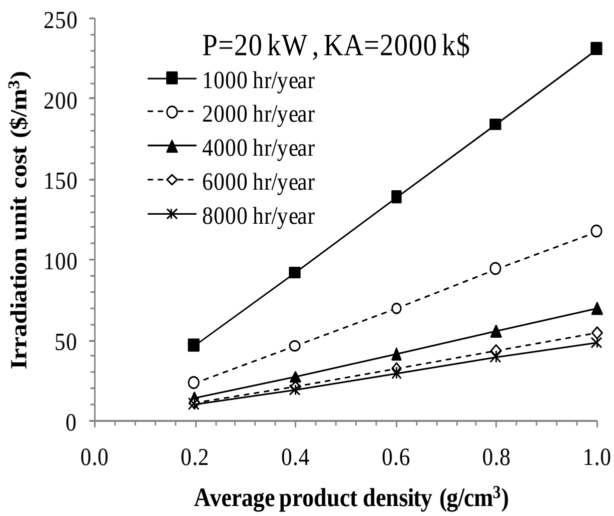

Fig 5. Variation of product irradiation unit cost as a function of accelerator price (Electron beam power was kept constant)

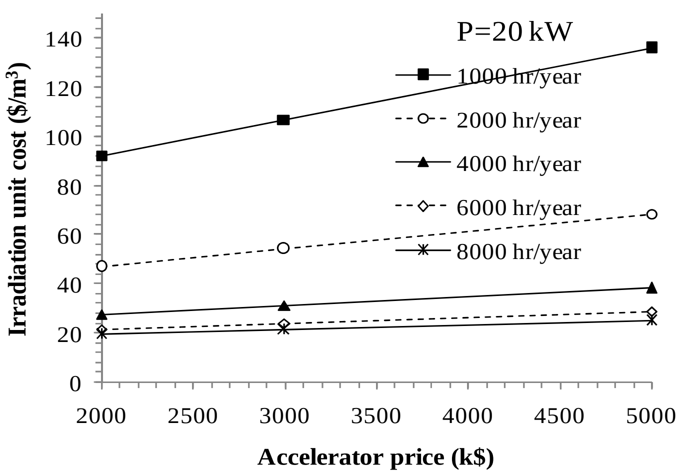

Table.1 Initial investment costs for establishing of a radiation processing center

Title	Cost (k$)
Accelerator	2000
Buildings & accessories	1400
Machinery, equipment and laboratory instruments	770
Pre exploitation costs	390
Unforeseen costs	290
Total	4850

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Table 2. Specification of a typical electron accelerator

Parameter	Specification
Beam energy (MeV)	10
Beam power (kW)	20
Beam utilization factor	60%
Product average density (g/cm^3)	0.4
Minimum required dose (kGy)	10
Throughput rate (kg/min)	72
Throughput rate (m^3/min)	0.18

Table 3. Current project costs for a radiation processing center

	Operating time (hrs/year)				
Fixed cost (k$)	1000	2000	4000	6000	8000
Salary	276	276	379	495	659
Equipment Insurance	10	10	10	10	10
Unforeseen	14	14	19	23	30
Depreciation	377	377	377	377	377
Total fixed cost	677	677	784	905	1076
	Variable cost (k$)				
Salary	118	118	162	212	283
Fuel and energy	14	29	57	86	115
Maintenance	162	162	162	162	162
Unforeseen	26	27	35	43	55
Total Variable cost	321	336	417	504	615
Total	998	1013	1201	1408	1691

The reason behind this result is that only the costs of accelerator depreciation and maintenance were involved in product irradiation unit cost calculation.

As final result, selecting an accelerator strongly depends on the type of application. For low density products, providing accelerator with low electron energy is recommended. On the other hand, to be low irradiation unit cost is not sufficient due to be useless of accelerator for high-density products. Considering the Eq. 2, in cases of interest need to a high product throughput rate with a proper electron beam energy, to use a high power accelerator is suggested.

Conclusion

To select an industrial electron accelerator especially for factories needing to have a private irradiation facility, attention should be made upon the points: firstly to complete all the information about the product specifications including density, product size and package; try to select an accelerator with lowest possible energy; selecting a high power electron accelerator if need high product throughput rate (yearly operating time should be maximized according to beam power) and finally, a high-energy accelerator (10 MeV) is recommended for establishing a radiation processing center to give only irradiation services to other factories and industrial units. This is due to the possible use in a range of products with different density.

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