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Research and design of the moving system for the cobalt-60 industrial irradiator

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Abstract: On the way of localization of Cobalt-60 industrial irradiators, Research and Development Center for Radiation Technology (VINAGAMMA) has successfully designed and manufactured the first version of Co-60 industrial irradiator, VINAGA1. The second version of Co-60 industrial irradiator has been studied and designed by VINAGAMMA in the frame of the scientific project No. ĐTCB.02/15/TTNCTK. The nucleus of a Co-60 industrial irradiator is a mechanical system inside an irradiation room namely a tote box moving system. This report presents the tote box moving system designed by VINAGAMMA. The tote box moving system contains 52 tote boxes with the dimensions of 50 cm (w) × 70 cm (l) × 150 cm (h) that are moving around the source racks in the manner of 4 passes and 2 levels. The irradiator with this tote box moving system has good specifications: The minimum time of an irradiation cycle is 1h 20 min. and the dose uniformity ratio (DUR) at the product densities of 0.1 g/cm^3 and 0.5 g/cm^3 is 1.4 and 1.8, respectively. Radiation energy utilization efficiency at the product densities of 0.1 g/cm^3 and 0.5 g/cm^3 is 19.7% and 48.8%, respectively. These specifications meet the requirements for a multi-purpose Co-60 industrial irradiator and the present irradiation requirements in Vietnam.

Keywords: *Tote box moving system, irradiator, cobalt-60, density, dose uniformity ratio (DUR).*

I. INTRODUCTION

The first Cobalt-60 semi-industrial irradiator in Vietnam has been put into operation in 1991. Nowadays, Vietnam has 9 industrial irradiators: 2 accelerators and 7 Co-60 irradiators. These Co-60 industrial irradiators are supplied by Hungary (5), by the Russia (1) and by China (1) [1]. With the development of the national economics, the demand of sterilization of medical products and food processing is increased. The localization of Co-60 industrial irradiator is a market requirement for the development of irradiation processing technology in the country.

In order to develop the applications of radiation technology in the national economics, VINAGAMMA has the orientation of design and manufacture of multi-purpose cobalt-60 industrial irradiators. In this development way, VINAGAMMA has designed and constructed the first version of multi-purpose Co-60 industrial irradiator, VINAGA1. This irradiator has some advanced features over imported Co-60 industrial irradiators. VINAGA1 will be installed at Da Nang irradiation center of Vietnam Atomic Energy Institute (VINATOM).

This paper presents the results of research and design work to manufacture the tote box moving system for the Co-60 industrial

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irradiator in the frame of the scientific project No. DTCB.02/15/TTNCTK.

II. OBJECTIVES AND RESEARCH METHODOLOGY

A. Objectives

The objectives of the research and design of the tote box moving system for the multi-purpose Co-60 industrial irradiator are:

- The moving system should be able to work with high source activity, namely more than 800 kCi in the aspect of food irradiation. This activity is required for meeting irradiation demands at present and in future as well as economical ones.

- The system should have high radiation energy utilization efficiency, good dose uniformity in products. For multi-purpose Co-60 industrial irradiators, values of DUR for medical products with low density and for food with high density should be in the acceptable ranges.

- The system is safe, easy operation and maintenance and can be upgraded if needed.

B. Research methodology

For research and design of the tote box moving system the following methods have been applied:

- By using MCNP code version 4C [2], the dose distributions inside a tote box have been determined for various product densities namely from 0.1 to 0.6 g/cm^3. Based on the calculation results such as DUR, irradiation efficiency the selection of the tote box sizes has been made. The selected dimensions of a tote box could give the irradiator high efficiency and accepted DUR value.

- By using some calculation tools in the mechanical design the structure of the tote box moving system, the structure of a tote box has been designed. The following mechanical data for the system should be calculated: Maximum load capacity of a tote box is 220 kg, the maximum load capacity of the moving system is 13,000 kg and static load of bearing 6004zz is 500kg, etc. The Autodesk Inventor 2014, the 3D CAD software [3] has been used as the main tool for calculation of some main data in mechanical design such as deformation, stress, displacement, safety factor of the frame of the tote box moving system. By using the software one could made design drawings, part modeling and assembly modeling as well.

III. RESULTS AND DISCUSSION

A. Preliminary design

Upon the knowledge and results gained from the design and construction of the tote box moving system VINAGA1 and IAEA documents for the Co-60 industrial irradiator [1, 4, 5, 6], the tote box moving system for the Co-60 industrial irradiator could have the following features of preliminary design:

- Tote boxes of the system will have the width less than 60 cm. In order to get more processing rate than the VINAGA1, the height of a tote box is selected about 3 times of the source rod length and the box length should be increased. For that height of a tote box, the source rack will be about 1.5 m.

- The system will have four passes, two levels.

- The system contains 52 boxes with the disposition of 4 boxes at temporary places (at the border of the system) and 48 boxes in 8 rows.

- The system is suitable for the densities of medical products with the density range of 0.1 g/cm^3 ÷ 0.2 g/cm^3 and food with the density range of 0.5 ÷ 0.6 g/cm^3.

- The system can be operated in three main irradiation modes: Continuous irradiation, batch irradiation and stationary irradiation.

The continuous mode is often used for irradiation of a big volume of product with the same density and used for irradiation of required low doses like foods. The batch mode is often used for irradiation of product with the same density and often used for irradiation of high doses like medical products. The stationary irradiation is only used when an irradiation with long dwell time is interrupted by some technical reasons.

In the continuous mode, the system receives one new tote box brought by the transport system from the loading-unloading area and delivers one irradiated tote box which has been went through 52 positions in the system. In the batch mode, 52 tote boxes in the system move defined steps and no tote box either goes in or goes out; in the stationary mode, 52 boxes stay for compensating time that the last dwell time was not completed due to irradiation interruption.

Tote boxes are brought in or out of the tote box moving system by a car of the transport system.

The principle diagram of the tote box moving system is illustrated in Fig. 1.

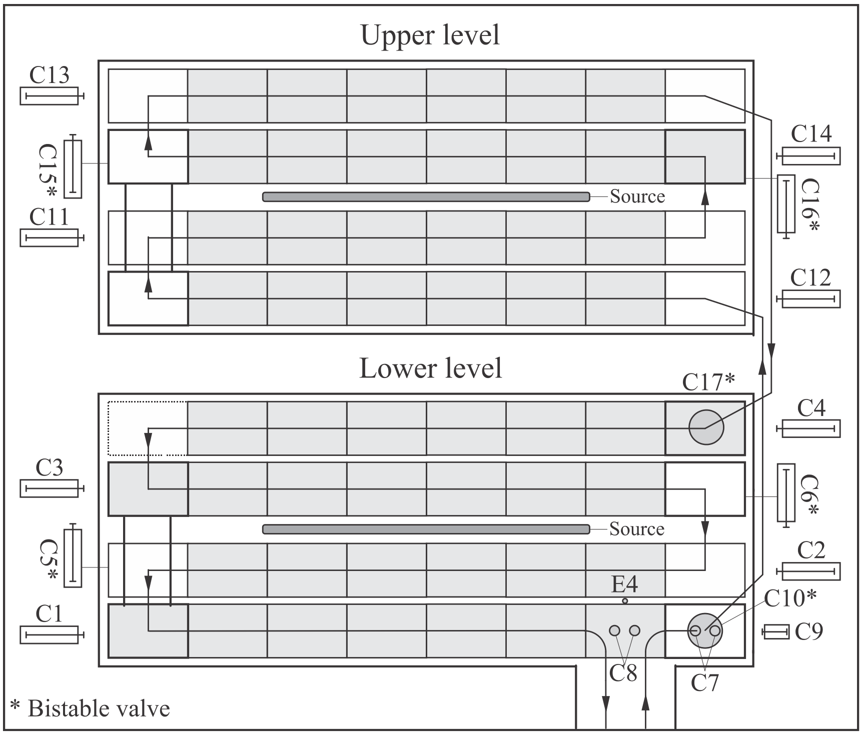

Fig. 1: Principle diagram of the tote box moving system

The moving manner of tote boxes can be explained by the lines with arrow in the above pictures. Cylinder C1, C3, C11, C13 are used for pushing tote boxes in the row 1, row 3 of the lower level and the row 2, the row 4 of the upper level one step right; Cylinder C2, C4, C12, C14 are used for pushing tote boxes in the row 2, row 4 of the lower level and the row 1, the row 3 of the upper level one step left; Two lift mechanisms with C10 and C17 are used change a box between two levels; C5, C15, C6, C16 are used to change a box between rows; C8 is used for unlock a box on the car; C9 is used to prevent a box moving over right in the lift C10 when C1 pushes boxes in the first row one step right [7].

In order to increase the processing rate of the irradiator using the tote box moving system, it is predetermined that the height of a tote box is 150 cm with the useful height of 140 cm, the length of a tote box is 70 cm with the useful length of 66 cm and the width of a tote box should be chosen among three assuming values, namely 45, 50 and 55 cm with the useful widths of 41, 46 and 51 cm, respectively.

B. Calculation of physical parameters of the tote box moving system

For a multi-purpose Co-60 industrial irradiator two main physical parameters should be determined, namely dose uniformity ratio (DUR) and radiation energy utilization efficiency (hereinafter called efficiency) for various densities of product.

These parameters can be calculated if dose mapping data for various densities of product are known. The dose mapping data inside a tote box can be known by experimental measurement or by theoretical calculation. In our case the calculation is carried out by using MCNP code version 4C [2].

Absorbed doses of 63 cells of MCNP code inside a tote box with different dimensions and different densities of product have been calculated. There are three cases of tote box dimensions, namely (45 cm × 70 cm × 150 cm) (Case 1), (50 cm × 70 cm × 150 cm) (Case 2), (55 cm × 70 cm × 150 cm) (Case 3). The densities of product loaded in tote boxes are 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 g/cm^3.

Dose calculations are carried out for the source activity of 800 kCi. It takes 1 hour of computer running time for dose calculation of a point. Fig. 2 presents the dose calculation points inside a tote box.

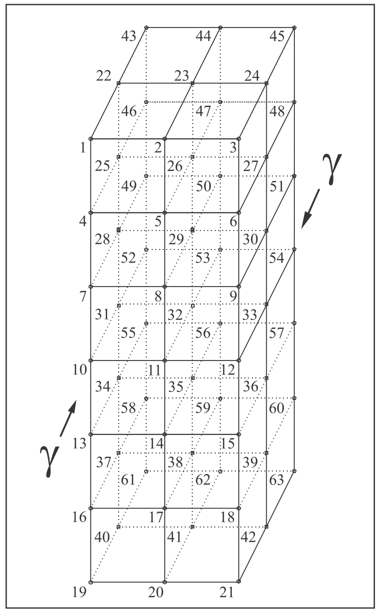

Fig. 2: Dose calculation points inside a tote box

The calculated minimum and maximum absorbed doses for 6 different densities of products with calculation error about 2% and for 3 cases of the tote box dimensions are given in Table I.

Table I. Calculation results of minimum and maximum absorbed doses with different densities of product

Density (g/cm^3)	0.1		0.2		0.3		0.4		0.5		0.6	
Unit: kGy	D_{max}	D_{min}	D_{max}	D_{min}	D_{max}	D_{min}	D_{max}	D_{min}	D_{max}	D_{min}	D_{max}	D_{min}
Case 1	5.53	3.99	4.88	3.38	4.34	2.86	3.90	2.41	3.58	2.09	3.32	1.83
Case 2	5.33	3.82	4.67	3.14	4.15	2.66	3.73	2.23	3.42	1.89	3.16	1.64
Case 3	5.15	3.58	4.49	2.94	3.98	2.42	3.56	2.02	3.27	1.70	3.03	1.45

Table II. The calculation results of DUR values with different densities of product

Density (g/cm^3)	0.1	0.2	0.3	0.4	0.5	0.6
Case 1	1.38	1.44	1.52	1.62	1.72	1.81
Case 2	1.40	1.49	1.56	1.67	1.81	1.93
Case 3	1.44	1.52	1.64	1.76	1.92	2.09

Table III. The calculation results of efficiency values with different densities of product

Density (g/cm^3)	0.1	0.2	0.3	0.4	0.5	0.6
Case 1	18.4%	31.1%	39.5%	44.5%	48.1%	50.5%
Case 2	19.7%	32.4%	41.2%	46.1%	48.8%	50.8%
Case 3	20.5%	33.7%	41.6%	46.2%	48.7%	49.9%

The calculation results of DUR and efficiencies (E) are presented in Table II and Table III.

Based on the calculation results the following conclusions can be drawn:

- In the central lines of two box sides faced to the source there are two locations of maximum dose value. Two locations are about at the distance one fourth of the box height from the top and the bottom and symmetrical through the central point in height of the box.

- The positions of minimum dose value are often located at two ends of the central lines of two box sides perpendicular to the source.

- For a multi-purpose Co-60 industrial irradiator, the tote box dimensions of 50 cm × 70 cm × 150 cm is selected upon the compromise between the DUR and efficiency values [4].

C. Mechanical design

The tote box moving system consists of the following parts: structural frame, guiding structure for box move, lift mechanisms for changing boxes between levels, row-row changing mechanisms for changing boxes between rows.

The tote box and the system are illustrated in Fig. 3 and Fig. 4.

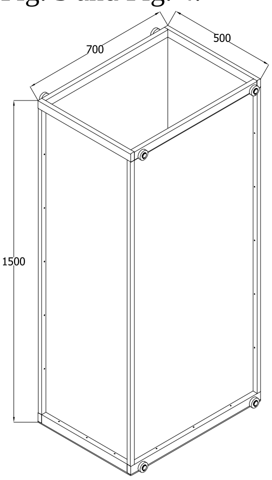

Fig. 3. A tote box of the moving system

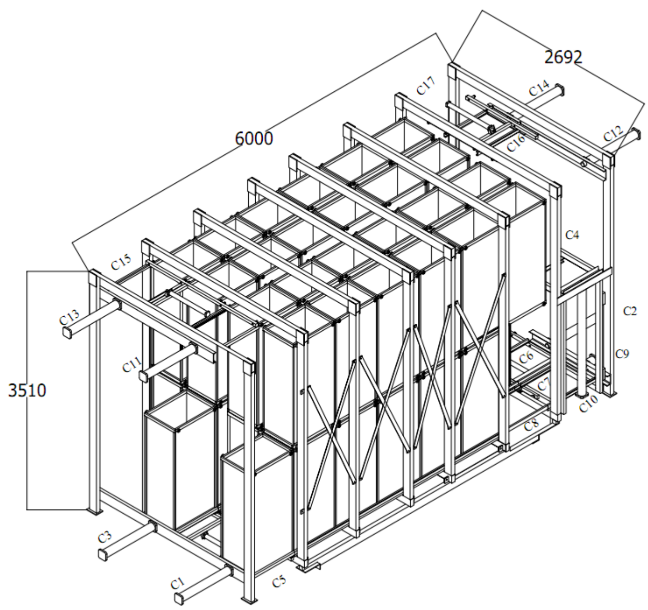

Fig. 4. The tote box moving system

A tote box consists of a base, a rectangular frame, box covers and 4 bearings. The box base is made of 304 stainless steel, rectangular frame is made of box stainless steel with the sizes of 50 cm (w) × 70 cm (l) × 150 cm (h), the box covers are made of aluminum plate with the thickness of 2 mm, 4 couples of bearing 6004ZZ. The tote box has been designed to carry products with the maximum weight of 220 kg.

The tote box moving system is made of CT3 steel. The structural frame is also made of CT3 (σ_{bk} = 345 MPa) [8], box steel with a length of 6 m, a width of 2.692 m and a height of 3.510 m. The lift mechanisms consist of a box container, guiding part for a box and 12 bearings 6004ZZ. The row-row changing mechanisms are located at two outside parts of the system.

The system contains 48 boxes in 8 rows and 4 boxes at temporary places. The tote box carries products with the maximum weight of 220 kg (net weight of a box is 30 kg). The total weight of 48 boxes with the maximum load is 12,000 kg (48 × 250 kg) and the total weight of 4 temporary positions is 1,000 kg (4 × 250 kg). Therefore, the total load of the tote box moving system is 13,000 kg.

By using the Stress Analysis function in environment of Inventor software [3] three main parameters of the tote box moving system namely stress, displacement and safety factor have been calculated. The forces applied on the frame are F1, F2 and F3 with the values of 120,000 N (12,000 kg × 10 m/s^2), 5,000 N and 5,000 N (2 × 250 kg × 10 m/s^2), respectively. Illustrations of stress and displacement calculations are given in Fig. 5 and Fig. 6 and the calculation results are given in Table IV.

Table IV. Result of stress calculation

Name	Steel	
General	Mass density	7.85 g/cm^3
	Yield strength	207 MPa
	Ultimate tensile strength	345 MPa
Stress	Young's modulus	210 GPa
	Poisson's ratio	0.3 ul
	Shear modulus	80.7692 GPa

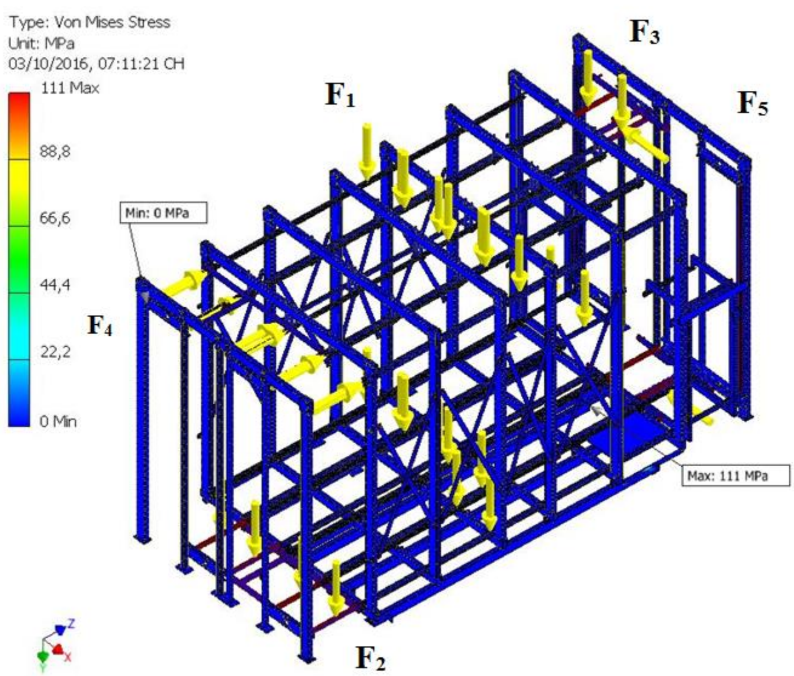

Fig. 5. Von Mises Stress of the frame

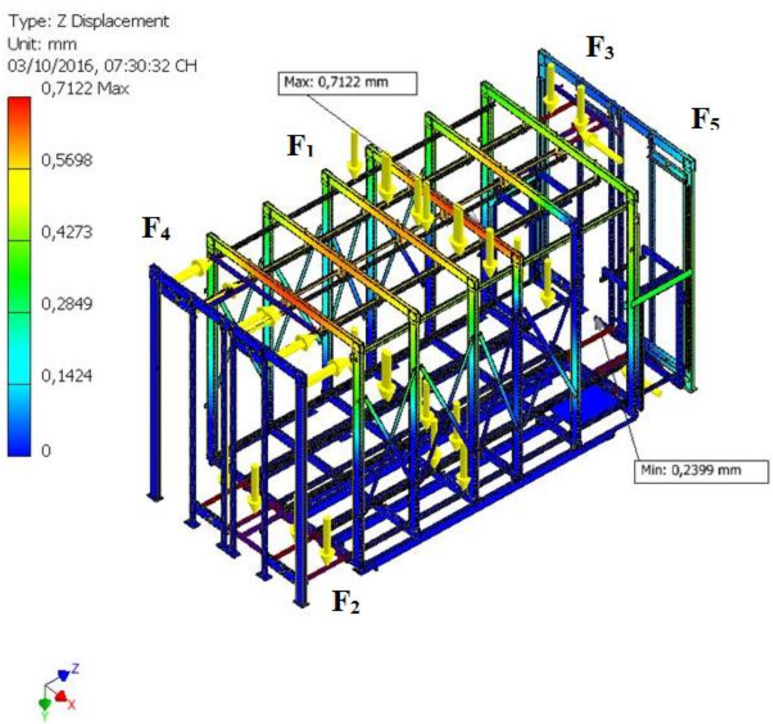

Fig. 6. Displacement of the frame

Based on the above calculated results, the safety factor can be calculated by the equation as $a = \frac{[\sigma]_{bk}}{\sigma_{\max}} = \frac{345}{111} = 3.10$. This result comfirms the designed tote box moving system meets the required safety factor according to standard safety factor of 1.5 [8].

The specifications of the cylinders used in the system are given in Table V and the main mechanical data of the system are given in Table VI.

Table V. Specifications of cylinders used in the tote box moving system

No.	Cylinder name	Quantity	Specifications
1	C1	1	167/Ø100/715 Cylinder with magnetic piston
2	C2, C3, C4 C11, C12, C13, C14	7	167/Ø100/810 Cylinder with magnetic piston
3	C9	1	167/Ø100/110 Cylinder with magnetic piston
4	C5, C15	2	167/Ø50/600 Cylinder with magnetic piston
5	C6, C16	2	167/ Ø50/680 Cylinder with magnetic piston
6	C10, C17	2	167/Ø125/1510 Cylinder with magnetic piston
7	C7	2	167/Ø50/100 Cylinder with magnetic piston
8	C8	2	2700-5 Ø40/25 Cylinder with magnetic piston

Table VI. Main mechanical data of the tote box moving system

No.	Specifications (mm)	Unit	Qty.	Weight /unit (kg)	Total weight (kg)
1	Box steel 5 mm 60 (w) × 120 (h) × 6,000 (l)	piece	28	79.1	2,215
2	Box steel 3 mm 50 (w) × 50 (h) × 6,000 (l)	piece	8	26.2	210
3	Box steel 3 mm 40 (w) × 40 (h) × 6,000 (l)	piece	4	20.6	82
4	Box steel 2 mm 25 (w) × 25 (h) × 6,000 (l)	piece	8	8.5	68
5	Box steel 2 mm 40 (w) × 80 (h) × 6,000 (l)	piece	4	21.7	87
6	U steel 3 mm 25 (h) × 50 (w) × 25 (h) × 6,000 (l)	piece	26	14.13	367
7	U steel 3 mm 25 (h) × 50 (w) x 25 (h) × 3,000 (l)	piece	8	7.07	57
8	U steel 3 mm 40 (h) × 80 (w) × 40 (h) × 3,000 (l)	piece	4	14.13	57
9	Accessories part	set	1		200
Total					**3,342**

The tote box moving system with 52 tote boxes having dimensions of 50 cm × 70 cm × 150 cm has been designed for the multi-purpose Co-60 industrial irradiator. Its specifications are suitable for both sterilization of medical products and food irradiation. This tote box moving system version is timely for the present irradiation demands. Table VII presents the parameters of the tote box moving system.

Table VII. Parameters of the tote box moving system

No.	Parameters	Value
1	Tote box quantity	52
2	Tote box sizes	50 cm × 70 cm × 150 cm
3	Useful box sizes	46 cm × 66 cm × 140 cm
4	DUR at the densities of - 0.1 g/cm^3 - 0.5 g/cm^3	 1.4 1.8
5	Radiation energy utilization efficiency at the density of - 0.1 g/cm^3 - 0.5 g/cm^3	 19.7% 48.8%
6	Minimum time of an irradiation cycle, min.	80
7	Maximum Co-60 activity could be used for food irradiation with the minimum absorbed dose of 3.2kGy, kCi	1,000
8	Maximum throughput of food irradiation with the density of 0.5 g/cm^3 and the required minimum absorbed dose of 3.2 kGy, tons.(h.100 kCi)$^{-1}$	0.83

IV. CONCLUSIONS

The second version of tote box moving system for the Co-60 industrial irradiator has been designed. The tote box moving systems has high performances for multi-purpose utilization namely for food irradiation and radiation sterilization of medical products in comparison with VINAGA1. In addition, the second version of tote box moving systems favorably meets the requirements for a multi-purpose Co-60 industrial irradiator and the present irradiation requirements in Vietnam. Based on pre-estimated price, the designed tote box moving system was lower price compared to imported one with the equivalent irradiation capacity.

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