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Radiation Shielding Development to Increase Radiation Safety of Cobalt-60 Irradiators J.s (9900) big irradiator

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ABSTRACT

Radiation physics, shielding penetration and design engineering are used to modify Cobalt-60 big irradiator 2 megacuries to become multi-uses irradiator by designing a new safe irradiation trace. The new trace will be used for experimental irradiation processing in separate lines during mass production. The work shows a modified design trace where experimental products will be put in two special boxes outside the new maze opening. They will pass through safe maze legs to the of inside irradiation concrete shielding and will stop behind the main system product boxes of radiation facing source rack in irradiation position. After finishing the calculated irradiation exposure period, the boxes will transfer to the outside-proposed design. The work shows maze design system, calculation of maximum exposure rate outside primary concrete shield for walls, roof, and traces lengths (distances). Monte Carlo calculations have been carried out for the big irradiator (new design) of big gamma irradiator, which has complex geometries. The three-dimensional flux was calculated at different positions where the gamma volume dose was obtained.

Introduction and methodology

The radiation shield is designed to reduce radiation leakage levels from inside to outside Cobalt-60 irradiator (Js 9900) (2,000,000 Curies) source activity, to an average exposure rate of less than 2.5 Sv/h (0.25 mrem/h). This allows a person to work near the shield for 40 hours per week and limit the exposure doses to a maximum dose of 5.0 mSv (500.0 m.rem) per year (**Keshk, 2024**).

Maximum exposure rates up to 20μSv/h (2.0 mrem/h) are allowed in small areas adjacent to the shield, where the average exposure rate is not allowed to be above 2.5 μSv/h (0.25 m.rem/h) over any surface (**Ashour and Keshk,**

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2010); **Ali and Keshk, 2011**). Stepped concrete plugs located in the roof are removable to allow lowering of the Cobalt 60 shipping container into the storage pool. Personnel operators and products enter irradiation room through a new designed maze that prevents loss of shield integrity. The product is transported, by a conveyor system, through separate entry and discharge ports. These ports block personnel entry by metal barriers when no product is present (**Keshk et al., 2003; Ashour and Keshk, 2010; Keshk, 2010**).

Mathematical Model

After irradiation in the reactor, each Co^{60} source is sealed inside a double stainless capsule. Over 60.000 individual source elements (pencils) are in use worldwide, corresponding to a total activity of about (4,000-5,000) Bq (about 120megacuries). There has never been a case of major contamination of the immediate environment with irradiation concrete canyon. The Co^{60} pencils are arranged in a source rack, which can be lifted into a radiation area for processing and afterwards lowered back into a safe position, usually at the bottom of a pool of water of (4.-5-7m) depth. During irradiation processing, the source is kept stationary and product boxes are moved on a conveyer system around it. The source-product geometry, product density, source activity and total time of irradiation determine the absorbed dose. Since the first three parameters are normally constant, Co^{60} source decays by about 1% per month and is regularly recalibrated; the irradiation time remains the chief process parameter (**Keshk et al., 2003; Keshk, 2010; Ashour and Keshk, 2010; Ali and Keshk, 2011; Keshk and Ali, 2012**).

Fig (1) shows the irradiation area which is surrounded by thick concrete shielding walls and roofs calculated to prevent radiation exposure of the operators and public. The concrete shielding thickness is determined on the basis of maximum foreseen activity and the criterion that the radiation levels outside the radiation area remain lower than the maximum permissible level. Very often it is shielded room on a mechanical conveyer belt that is exposed to gamma radiation. When the products have been exposed for a sufficient amount of time, the source rack is lowered back into the storage pool and the irradiated products leave the shielded room. The operators operate the irradiator from outside the irradiation room where they are protected by calculated thick concrete walls. The workers enter the irradiation room when the source rack is in the source storage pool (**Keshk et al., 2003; Keshk, 2010; Ashour and Keshk, 2010; Ali and Keshk, 2011; Keshk and Ali, 2012**).

Products and personnel enter the radiation room through 2 mazes: personnel enter irradiation room through an access door that is converted with metallic barriers.

An automatic conveyor system transfers the Cobalt-60 source rack from the bottom of the storage pool to the irradiation position inside the irradiation room. The carriers can be loaded or unloaded in either a horizontal or a vertical position. This system can operate in three different modes. The microprocessor system provides documentation timing and monitoring of machine operation. There are 19 product carriers, each has two compartments where product can be stacked or hung by using hooks. These compartments will accommodate products up to the following dimensions:

Length: 120 cm
Width: 60 cm
Height: 137 cm
Maximum product weight per carrier is 1958 kg (4308.5 lbs.).

Radiation Source Mechanism

The radiation source mechanism is comprised of a vertical mounted source rack maneuvered by a pneumatic hoist. Table (1) shows a comparison between Js (9500) Canadian

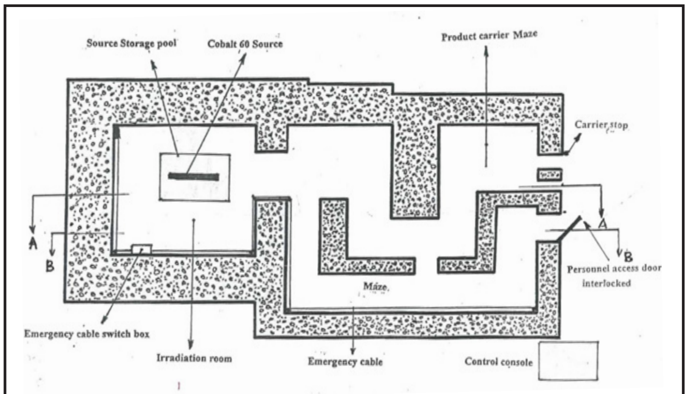


Figure (1): A floor plan of the big irradiation canyon. Cobalt 60 source

irradiator, 1 mega gamma Russian irradiator gamma curies and Js (9900) big gamma irradiator.

Work idea

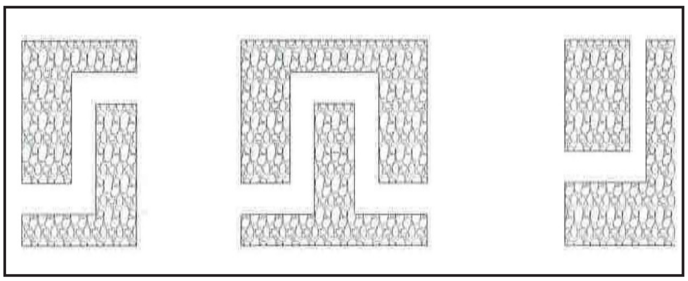
The comparison shows that the three irradiators maintain radiation safety according to international safety standards. Russian and Js 9900 big irradiator were chosen to be modification because they are better than the western irradiator (Js 9500). Concrete shielding penetration is applied on eastern designs (Russian and big design) through designing a new separate concrete trace to change (Js 9900) big irradiator to a multi-uses system. The work appears on the new maze design that will penetrate and pass through radiation concrete shield through safe concrete maze legs that will bend on more than the right angle (**Profio, 1979; Keshk et al., 2003**).

Table (1). Comparison of various design elements for three industrial irradiation facilities using Co^{60} irradiation source (Keshk, 1998).

No	Element	Western	Eastern	
		Js 9500	Russian irradiator	Js 9900
1	Activity	1,000,000 Ci	1,000,000 Ci	2,000,000 Ci
2	Biological shield	Concrete	Concrete	Concrete
3	Storage of source	Water pool	Water pool	Water pool
4	Coating of storage pool	Tile	Stainless Steel	Stainless Steel
5	Poll number an d depth	1-4.5 in	2-4.5 in	1-7.0 in
6	Interior height	3 m	5 m	4 m
7	Source rack, number	1 3 x 2	2 1x2 2x2	1 3 x 2
8	O_3 ducts, intake number	1 lx1	2 1x2	1 1x2
9	Concrete shielding, penetration	Three closed/ lead	No	No
10	Maze and form	2 Z	1 U	2 U
11	Dose rate received 40h/week	2.5 mSv/h	2.5	2.5 mSv/h
12	Ventilation system	20 air change/H	40 air change/H	40 air change/H
13	Boxes transport in /out	Maze boxes	Maze carrier	Maze product
14	Roof plug	No	Three	Three
15	Door	Four	One	Four
16	Research track	No	No	No
17	Product opening	Two Exits	Through main maze	Two exits
18	Push- back plate with pit	No	Exist	Exist
19	Emergency stop cable	Exist	No	No
20	Power failure	Exist	No	No
21	Maze door	Exist	No	No
22	Source rack	Exist	Exist	Exist
23	Source rack guide cable	Exist	Exist	Exist
24	Temperature sensing device	Exist	Exist	Exist
25	Conveying system	Exist	Exist	Exist
26	Source inter lock	Exist	Exist	Exist
27	Side boxes changer	No	Exist	Exist
28	Camera holes	No	Exist	Exist
29	Counter weight	No	Exist	Exist
30	Pool water level (guide)	No	Exist	Exist
31	Source Hoist/Alarm	Exist	Exist	Exist
32	Air pressure	Exist	Exist	Exist
33	Start-up safety daily timer	Exist	Exist	Exist

Work technique

Based on concepts, parameters, elements and equations from radiation physics, shielding penetration and engineering design are used to design a new separate trace through safe penetrating concrete shielding. The new trace design depends on maze legs and bend on more than the right angle. Js 9900 big irradiator was modified too by designing new trace used for experiment irradiation work during irradiation mass production, depending on verification of gamma rays dose attenuation in two-legged concrete ducts. The modified design of new (maze) pass two product boxes with hance inside irradiator during industrial irradiation processing. After a calculated period of irradiation treatment, the two boxes pass through the new maze outside the modified big irradiator. Fig (4) shows a schematic diagram of different maze designs (International Atomic Energy Agency, 1996); Profio, 1979).



Z- Shaped duct U- Shaped duct L- Shaped duct

Figure (2): Schematic diagram of bent ducts and maze designs

Results and Discussions

The modified big irradiator maintains radiation safety limits specified by basic international safety standards for protection against ionizing radiation and for the safety of radiation sources (**Keshk, 1998; MDS Nordion, 1999**), as shown in Table (1). But there are some different points on each of the three irradiators Js 9900 big irradiator and design has several active features such as the thickness of concrete shielding which is larger than the (Js9500) and Russian irradiator interior dimensions, O_3 ducts intake and maze (width and height) which are comparatively larger than the western irradiator (Js 9500) (**Ashour and Keshk, 2010; Keshk and Ali, 2012; Keshk, 2024**).

The proposed design includes some safe penetrations through concrete shielding. The Russian design has a single maze for all uses and ventilation systems better than (Js 9500).

The Js 9900 big irradiator is chosen to modify to multi-uses system by designing a new separate concrete trace that penetrates irradiator concrete shielding. Figs (1 and 2) show the two designs before modification.

Irradiators Penetration

Shield penetration is extremely necessary to maintain radiation safety for radiation and operation for reactors, electron beam accelerator and irradiation facilities, which include electrical cables, piping, mechanical drives, and holes with removable plugs, tunnels for personal access (mazes) and collimators or beam ports. Shield effectiveness is diminished if the material filling such a duct is a weaker attenuator (or generates more secondary y rays) than the bulk of the shield. Because air is the weakest attenuator, its transmission through the shield may be 10^{-8} or even less; it does not take a very sizable hole to destroy the shield effectiveness (**Raso, 1963; Champan and Huddleston, 1966; Profio, 1979; Keshk, 1998; MDS Nordion, 1999**). The work copes with penetrations minimizing the volume of weak attenuator by introducing steps or bonds to avoid direct streaming of radiation down the duct, and by reinforcing the shield with thicker or more effective material around the penetration (Fig. 3).

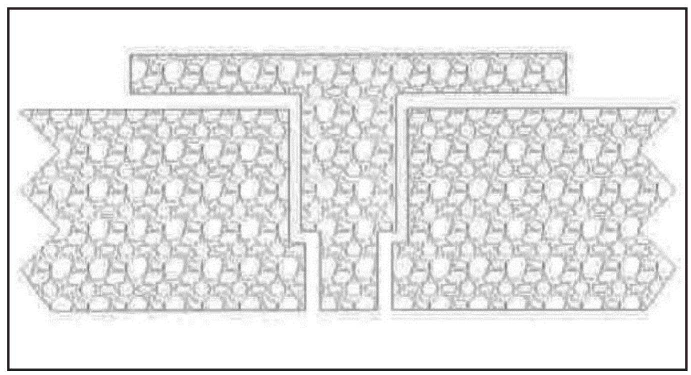


Figure (3): Stepped cylindrical hole and plug with annular gap

The "albedo" refers to the ratio of the current density (or flux density) reflected of backscattered from a shield surface to the current density (or flux density) of radiation incident on that surface. The approximation used in the work assumes that the radiation emerges from the same area on which the radiation was incident. This is valid when surface dimensions are large compared to the effective mean three paths in the shield of the proposed design.

Fig. (3) shows holes or ports which are often closed with removal plugs or doors allowing for manufacturing tolerances, thermal expansion, or clearance for movement; there will be a gap between plug and hole. The plug and hole should have at least one stop to block the line-of- sight component and reduce radiation streaming down the gap. Rotating shafts can also be provided with a step or collar.

The maze

It is a special design entrance (track) that maintains radiation safety and protection from direct exposure radiation.

Maze leads to the core of irradiation room of any irradiations stage and the exterior shielded door. It consists of a group of straight, serial links (legs), and has more than one right angle bend. The maze is used by operators and transports the products boxes inside and outside the proposed irradiator.

Maze Design

Accurate calculations of the exposure rate and energy spectrum of points along a concrete maze are difficult to perform. Based on analytical proceedings given by **Rasso (1963)** and others (**Ashour and Keshk, 2010; Ali and Keshk, 2011; Keshk and Ali, 2012**), detailed calculations of the attenuation in the modified design of concrete mazes depended on two-legged concrete ducts and have been implemented in the present work.

The huge amount of work required for detailed calculations of mazes with more than one right-angle bend becomes prohibitive, and maze designers must either rely on measurements to determine exposure rates at the entrance of the proposed maze with serial legs or make estimates on the anticipated magnitude by using purely empirical formula. Maze entrances for industrial irradiation designed by the Atomic Energy of Canada Limited (AECL) are based on both calculations and measurements (**Ashour and Keshk, 2010; Keshk and Ali, 2012**). The radiation incident upon the maze walls due to single-scattered radiations is calculated by dividing the scattering areas into small segments and calculating the amount of single- scattered radiation from each segment. The dose rate from the small scattering areas is giving by:

$$D = \frac{D_o a(E_o \theta_o \theta_\varphi) A \cos\theta}{r_1^2 r_2^2} \qquad (1)$$

where: $a(E_o, \theta_o, \theta_\varphi)$ is the differential exposure albedo;

A is the area of the scattering surface;

D_o is the exposure rate at one unit length from the source; and

E_o is the initial energy of gamma rays from the source values of the differential

dose albedo.

$a(E_o, \theta_o, \theta_\varphi)$ have been calculated by **Rasso (1963)** using Monte Carlo methods. Using the **Rasso (1963)** data, Chilton and Huddleston developed the following semi empirical equation for the different exposure albedo (**Ashour and Keshk, 2010; Keshk and Ali, 2012**):

$$a(E_o, \theta_o, \theta_\varphi) = \frac{C(E_0)K(\Theta_s)10^{-6} + C^1(E_0)}{1+\cos\Theta_0/\cos\Theta} \qquad (2)$$

where: C (E_o) and Cl (E_o) are constants for a given energy, K (θ_o) is theKlein Nishina differential energy scattering coefficient, and θ_s is the angle through which the radiation is scattered which is given by:

cos= sin θ_o sin θ cos θ cos cos θ_o cos θ

For Cobalt-60 gamma rays we have: E_o = 1.25 MeV, C (1.25 MeV) = 0.0665, and C1 (1.25 MeV) = 0.107.

The calculated values of the differential exposure albedo for Cobalt-60 gamma rays have been verified by measurements at the AECL. The energy of the single scattered radiation is given by the following equation:

$$E=E_o/[1+E_o\,(1- \cos\,)/0.511] \qquad (3)$$

The thickness of maze shielded walls required to attenuate the single scattered radiation of energy E and the corrections for lower multiple scattered radiation were calculated using information obtained from measurement of the radiation fields in and around radiation mazes built by the AECL; they were also applied on different stages of the proposed design.

For maze walls where no single scattered radiation is incident and the maximum radiation energy is due to double scattered radiation, an estimate of the incident double scattered exposure rate was obtained in this work by calculating the scattering from one surface to another for any maze shielded wall.

The energy of the gamma rays impinging on the second area is assumed to be the energy of a gamma ray having one Compton scatter at the centre of the first area and going to the centre of the second area. For the second scattering, the parameters C (E_o) and Cl (E_o) are approximated by the following equation:

$$C(E_o) = 0.0561\, E_o^{0.574} \qquad (4)$$

Primary Shielding

The transmission of Cobalt-60 gamma radiation in concrete is maintained. The exposure rate from 1 Ci point source of Co-60 is 1.3×10^3 mrem and varies inversely with square of the distance to the source plus concrete thickness for the primary shielding (**Ashour and Keshk, 2010**). This is determined by calculating the maximum exposure rate outside the shielding wall for a point source with corrections for source geometry and absorption within the source plaque (**Raso, 1963; Chilton and Huddleston, 1963; International Atomic Energy Agency, 1992; American National Standards Institute, 2001; United States Code of Federal Regulations, 2006**).

Radiation Shield

The radiation shield is designed to reduce the radiation leakage level to the outside, from74.4 PBq (2 MCi) source, to an average exposure rate of less than 2.5 μSv/h(0.25mrem/h). This allows a person to work near the shield 40hours per week and limit the exposure to a maximum dose of5.0 mSv (500.0 mrem) per year. The concrete radiation shield is designed to meet.

Monte Carlo Methods and the Final Proposed Design by cobalt-60 irradiator:

The design of an industrial irradiation canyon must be licensed, regulated and inspected by the national safety and health authorities based on international standards of practice established by both IAEA and WHO. The geometry design of the double maze irradiation canyon is presented in Fig (4), where the research maze direction is indicated, and in Fig (5) showing the products maze, operators maze and research maze with dimensions (given in metres).

The irradiation source is a Cobalt-60 source with an activity of 2 MCi situated on a rack of dimensions: 200 cm ×5.00 cm ×150.0 cm.

The Monte Carlo calculations were performed using the code MULTIKENO-NEW code for the geometry of proposed design corresponding to the final design of the maze. 150 generations were stimulated, each consisting of 127,000 particles.

The three-dimensional flux was calculated at various positions inside the irradiation canyon (Fig. 6), and the gamma volume dose was obtained for these positions. The positions considered are found in (Fig. 6) as follows:

- Position 1 is the Cobalt-60 source region, in the irradiation room,
- Position2 is at 1.75 m away from the Co-60 source, in the irradiation room,
- Positions 3 is at x m away from the Co-60 source, in the irradiation room. Position 3 is the only one with region volume calculated at 1.5 m above the ground, while all the other positions have region volume calculated at 5 m above the ground of the proposed design.
- Positions 4 to 25 are outside the irradiation room, located on the double maze irradiation canyon, both in product maze (positions 12 to 20), operators maze (positions 4 to 11), and research maze (positions 21 to 25).
- Positions K1, K2, K3 and K4 are outside the proposed design at1 m distance from outside the concrete shielding.

(Table.6) shows the gamma dose values given as obtained by the Monte Carlo calculations.

The first maze is used for introducing the products to be

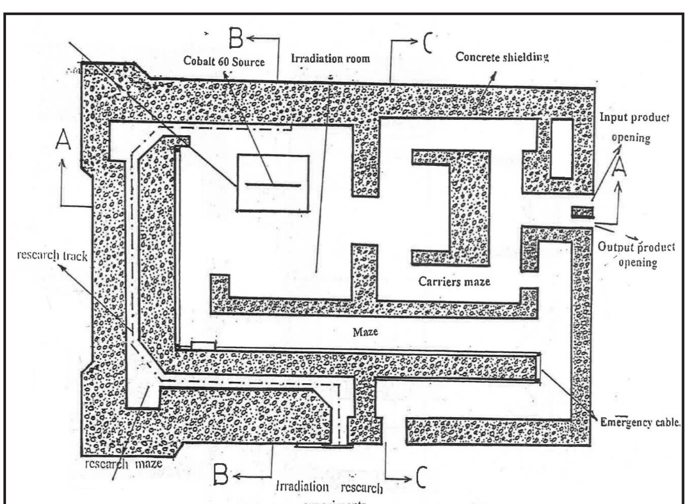


Figure (4): Research maze components and direction

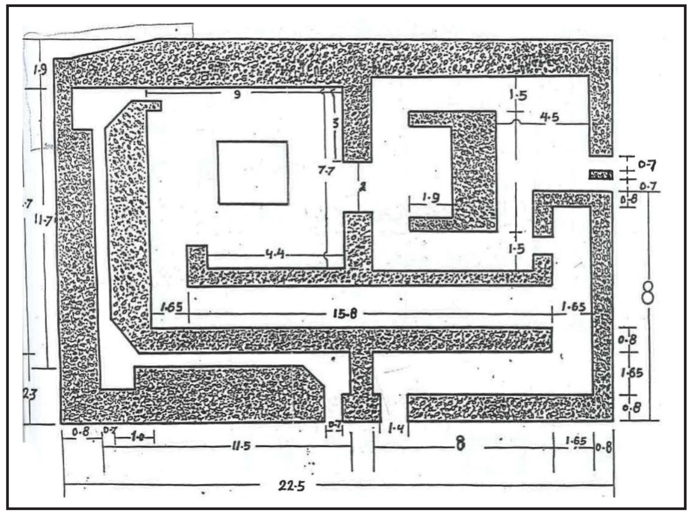


Figure (5): Irradiation canyon with dimensions (in meters)

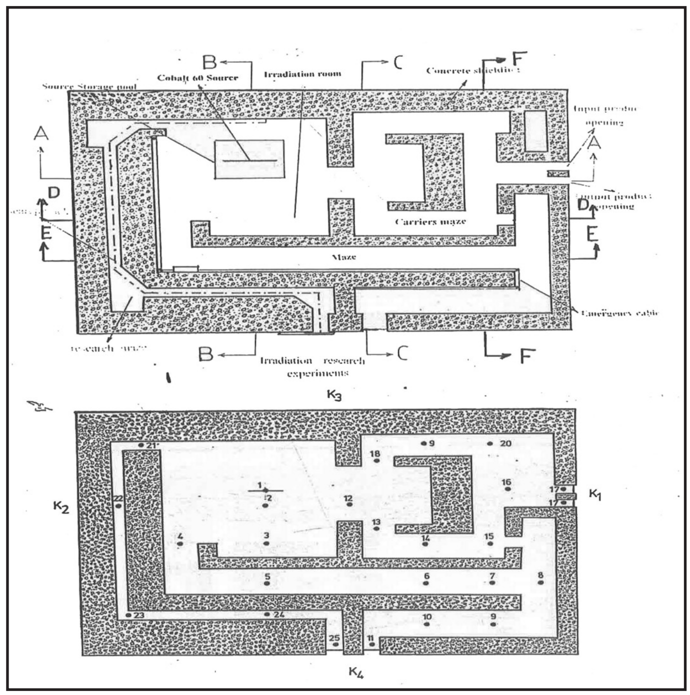


Figure (6): Different positions for calculating the volume gamma doses (current study)

irradiated and removing the irradiated products. (Tables 2 and 3) shows the calculated volume doses at various positions from outside the product maze to inside the irradiation canyon (positions K1, 17, 16, 20, 19, 18, 12, 2, 1), and from inside the irradiation canyon to outside the product maze (positions 1, 2, 12, 13, 14, 15, 16, 17, K1).

The second maze is used by operators. It starts from position 11, bends left on a right angle, and leads to position 4, the entrance of the irradiation room. From the operation maze there is a side door that leads to the product maze (current study).

Table (2): The volume dose at various positions from inside the irradiation canyon to outside the product maze (current study).

Position	1	2	12	12	13	14	15	16	17	K1
Volume Dose (rem/h)	67.5	2.17	0.120	5.24×10^{-2}	1.6×10^{-3}	1.5×10^{-4}	2.2×10^{-6}	2.2×10^{-6}	2.2×10^{-6}	0.0

Table (3): The volume dose at various positions from outside the product maze to inside irradiation canyon.

Position	K1	17	16	20	19	18	12	2	1
Volume Dose (rem/h)	0.0	2.2×10^{-6}	2.2×10^{-6}	1.5×10^{-4}	1.6×10^{-3}	5.24×10^{-2}	0.102	0.02.17	67.5

Table (4): The recorded volume doses at various positions in the operators' maze (current study)

Position	1	2	4	5	6	7	8	9	10	11	K4
Volume Dose (rem/h)	67.5	2.17	0.422	2.87×10^{-4}	2.04×10^{-4}	1.72×10^{-4}	2.15×10^{-5}	0.0	0.0	0.0	0.0

Table (5): The volume dose at various positions in there search maze (current study)

Position	1	21	22	23	24	25	K4
Volume Dose (rem/h)	67.5	0.349	5.08×10^{-3}	0.0	0.0	0.0	0.0

Conclusions

There is a necessity for modifying Co-^{60} (Js 9900) irradiator into a multi-uses irradiator through designing a new maze for research and low density products.
Radiation safety is maintained and the legs of the proposed maze have same dimensions as the western research maze. If dimensions of the new maze legs become longer than those of the western irradiator it is not a problem because the leg dimensions of eastern irradiators are bigger than those of the western ones. The new maze will be safe and will maintain radiation safety outside modified design based on the following aspects:
-Dose level outside the modified design is zero
-Dose level at the entrance of the main maze for operators, mass production and the new suggested maze are zero for the modified design.
- Dose level at the first path from the entrance of each of irradiator three mazes is also zero for the modified design.
The dose rate values calculated at different positions inside and outside the proposed new irradiator maze design have proven that radiation safety of each modified design is maintained.

References

- **Ali, R.A. and Keshk, A.B. (2011):** A comparative study of seismic regulation leads to maintain radiation safety for main structure that contained industrial irradiation facilities. *Arab J. Nucl. Sci. Appl.*, 44(1): 223.
- **Ashour, M.A. and Keshk, A.B. (2010):** Improving the dynamics performance inside industrial irradiation facility. *10th Arab. Conference on the Peaceful Uses of Atomic Energy*, Republic of Iraq.
- **American National Standards Institute (2001):** *Safe design and use of panoramic, wet source storage irradiators (Category IV)* (ANSI-N43.10-1984). ANSI.
- **Champan, J.M. and Huddleston, C.M. (1966):** Dose attenuation in two legged concrete ducts for various gamma ray energies. *Nucl. Sci. Eng.*, 25(1): 66.
- **Chilton, A.B. and Huddleston, C.M. (1963):** A semiempirical formula for differential dose albedo for gamma rays on concrete. *Nucl. Sci. Eng*, 17(3): 419.
- **International Atomic Energy Agency (1996):** International basic safety standards for protection against ionizing radiation and for the safety of radiation sources *(IAEA Safety Series No. 115). Vienna.*
- **International Atomic Energy Agency (1992):** Radiation safety of gamma and electron irradiation facilities *(IAEA Safety Series No. 107). Vienna.*
- **Keshk, A.B. (2024):** Traditional process maintaining safer retrieval fallen cobalt 60 pencils inside radiation source rack preferable to robotic uses. *The 16th Arab. Conference on the Peaceful Uses of Atomic Energy,* Dead Sea – Hashemite Kingdom of Jordan.
- **Keshk, A.B. (2024):** Increasing radiation safety around cobalt 60 irradiators depend on radiation shielding develop-

ment. *The 16th Arab. Conference on the Peaceful Uses of Atomic Energy, Dead Sea* – Hashemite Kingdom of Jordan.

- **Keshk, A.B. and Ali, R.A. (2012):** Fire events effect on concrete shielding of Co60 industrial irradiation facilities. *Arab J. Nucl. Sci. Appl.*, 45(4): 109.
- **Keshk, A.B. (2010):** The impact of different control technique of industrial irradiation processing units cobalt 60 irradiator on maintaining safety for radiation and environment. *J. Rad. Res. Appl. Sci.*, 3(4A): 1047.
- **Keshk, A.B. (1998):** Irradiation environmental characterizes and their effect on architectural design.
- **Keshk, A.B., Ashour, M.A. and Imam, M.M. (2003):** A modified design for the eastern radiation canyon for cobalt60 irradiator maintain attachment for research and production. *6th Arab. Conference on the Peaceful Uses of Atomic Energy*, Cairo (Egypt), 569.
- **MDS Nordion (1999):** Cobalt60 Irradiator JS–9500 Tote, *IR-206 NCRRT, Egypt, Operator's Manual*. Canada.
- **Profio, A.E. (1979):** Radiation shielding and dosimeter. *John Wiley & Sons Inc.*
- **Raso, D. J. (1963):** Monte Carlo calculation on the reflection and transmission of scattered gamma rays. *Nucl. Sci. Eng.*, 17(3): 411.
- **United States Code of Federal Regulations (2006):** *10 CFR 36.2, Title 10 – Energy, Part 36* – Licenses and Radiation Safety Requirements for Irradiators, *Section 36.2 – Definitions*.