The Palletron: A High Dose Uniformity Pallet Irradiator With X-Rays


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Abstract. A new concept of X-ray irradiator for high-density products on pallets is proposed. Monte Carlo simulations are applied to predict the performance of this system and compare it to alternative pallet irradiators. The Monte Carlo predictions are in good agreement with experimental data obtained using pallets of different densities.

INTRODUCTION

IBA is actively involved in the development of X-ray irradiation systems for medical devices and food products. The superior penetrating quality of high-energy X-rays versus electron beams or $^{60}$Co gamma rays enables the treatment of products in large containers [1]. However, the double-sided method that is generally used can lead to an unacceptably large dose uniformity ratio (DUR), defined as the ratio of the maximal to the minimal dose absorbed in the product, for high-density products such as foodstuff on standard industrial pallets.

Recently, a new concept was proposed by MDS Nordion to improve the treatment of high-density palletized products with X-rays [2]. This concept makes use of a turntable in front of the X-ray beam to irradiate the product from all sides and a collimator to shape the beam. IBA and MDS Nordion have decided to jointly develop this concept under the name Palletron and IBA is pursuing the engineering and development using Monte Carlo simulation tools.

THE PALLETRON SYSTEM

To obtain a rather uniform dose in a high-density pallet, it is crucial to be able to deposit a sufficient amount of dose at the center of the product as compared to its surface. In the Palletron, the pallet is rotating around its vertical axis. The center of the pallet is then constantly facing the X-ray target while a surface section only spends a limited amount of time in front of the target. To further amplify this effect, a collimator absorbs the X-rays emitted at large angle with respect to the initial beam direction, these radiations contributing only to the surface dose.

FIGURE 1. The Palletron: main elements (schematic view).

The main elements of a Palletron system are schematically represented in Fig. 1 (from [2]). An electron accelerator (20) is used to produce a high-energy electron beam (15) that is sent on an X-ray target (30) usually made of a high-Z material such as tungsten or tantalum. High-energy X-rays (45) are produced by Bremsstrahlung and are emitted in all directions from the target. An adjustable collimator (110) is used to shape the initial X-ray beam into a collimated radiation beam (50) passing through a well-
defined aperture (170). The product (60) rotates on a turntable (70) in the path of the collimated X-ray beam. The electron accelerator, the collimator, and the turntable are connected to the control system (120) so that the beam intensity, the size of the collimator aperture and the turntable rotation speed can be determined and adjusted either before or during the product irradiation.

The design of the Palletron is created by IBA thanks to CERN’s Monte Carlo (MC) simulation tool GEANT 3.21 [3]. This MC package allows a detailed simulation of the interactions between electrons/photons and materials disposed in complex geometries. GEANT is able to simulate the dominant processes that can occur in the energy range from 10 keV to 10 TeV for electromagnetic interactions.

The basic elements of the Palletron have been introduced in the MC. The X-ray target consists of a 1.2 mm tantalum sheet in front of a 2 mm cooling channel filled with water and backed by 2 mm stainless steel. The collimator is represented by a stainless steel plate with a 14 cm thickness. Rotating the product by 2° at a time approximates the pallet movement. The product dimensions correspond to standard US pallets: 40” (width) x 48” (length) x 70” (height).

The dose distribution obtained inside a rotating pallet depends on two main factors: the collimator’s aperture and the rotation speed profile. These two parameters must be chosen as a function of the pallet bulk density in order to obtain a rather uniform dose. As an example, the speed profile optimized for a pallet of 0.8 g/cm$^3$ density is shown in Fig. 2.

![FIGURE 2. Rotation speed profile used for high-density pallets irradiated with the Palletron.](image)

Using this speed profile and a constant collimator aperture of 12 cm, the relative dose distribution obtained in the pallet horizontal plane is shown in Fig. 3. The electron beam energy is equal to 5 MeV. The dose sampling is done in a 15 cm thick layer in the middle of the pallet and the DUR is equal to 1.3.

![FIGURE 3. Relative dose distributions obtained in the central plane of a pallet of 0.8 g/cm$^3$ density.](image)

To obtain a uniform dose distribution along the vertical axis $z$, the electron beam is scanned along the X-ray target. Due to the large height of the pallets, the use of a homogeneous electron density on the target is not appropriate, a scanning width of about 260 cm being needed to reduce the dose variations along $z$ below 10%. A better solution consists in using a non-homogeneous electron density as the one presented in Fig. 4(a). With a scanning width of 210 cm, it is then possible to limit the dose variations to about 5% along the pallet vertical axis as demonstrated in Fig. 4(b). Such an electron density can be obtained by applying a sinusoidal current to the sweeping magnet.

Thanks to the good dose uniformity maintained along the $z$-axis, the global DUR obtained inside a whole pallet is only slightly affected, becoming 1.4 for a $\rho = 0.8$ g/cm$^3$ pallet instead of 1.3.

![FIGURE 4. Choice of the scanning function along the X-ray target: (a) electron beam density along the scanning axis; (b) relative dose distribution along the pallet vertical axis for a product density of 0.5 g/cm$^3$.](image)
PALLETRON PERFORMANCE

In this section, we present the performance figures for the Palletron and compare them with alternative X-ray pallet irradiators.

The evolution of the DUR as a function of the product density \( \rho \) is presented in Fig. 5(a) for electron beam energies \( T_0 \) of 5 MeV and 7.5 MeV. For densities below or equal to 0.4 g/cm\(^3\), no collimators are needed and a constant rotation speed is applied to the turntable. For densities larger than 0.4, collimators are introduced to limit the X-ray beam lateral expansion and a non-uniform rotation speed profile is required. Figure 5(a) shows that very similar results are obtained at 5 and 7.5 MeV for densities above 0.4 g/cm\(^3\). For light products, the DUR has a tendency to increase due to the larger penetration of the X-rays leading to an over-exposition of the pallet center compared to its surface. This effect increases with the beam energy but can be controlled by the insertion of an absorption bar between the target and the product in order to subdue the intensity of the beam in the forward direction.

The treatment capacity obtained with the Palletron is shown in Fig. 5(b). These calculations are based on a beam power of 300 kW, a minimal dose requirement of 2 kGy and a pallet transfer time of 20 seconds. The Palletron being a single load system, this transfer time corresponds to the time needed to unload the treated pallet from the rotating table and load a new one.

The Palletron performance at 5 MeV is compared to alternative X-ray systems in Fig. 6. Three systems are presented: (a) a simple rotating system without collimators and a constant rotation speed in front of the beam; (b) the classic double-sided system; (c) the X-wave system that is an IBA internal development. In the X-wave concept, pallets are treated on all four sides by using multiple passes with 90° rotation between passes. In addition, a variable conveyor speed and a collimator are used to obtain the best possible dose uniformity.

Figure 6(a) shows that the double-sided system rapidly leads to large DUR values when the product density increases. The rotating system enables to maintain good dose uniformity for densities up to 0.6 g/cm\(^3\). The Palletron and X-wave systems give comparable results for the DUR.

The treatment capacity obtained with these four systems is compared in Fig. 6(b). Due to the absence of collimators, the rotating system offers a small

FIGURE 5. Palletron performance figures at 5 and 7.5 MeV: evolution of (a) the DUR and (b) the treatment capacity as a function of density.

FIGURE 6. Comparison of the performance figures obtained with various X-ray irradiation systems (see text for details): (a) DUR; (b) treatment capacity.
advantage when compared to the Palletron since the rotating table can be placed closer to the target. The double-sided system has a clear advantage compared to the rotating system for small and medium densities, as this is a batch system with a continuous line of product in front of the target. To be realistic, the throughput for the batch systems has been reduced by 10% to take into account the efficiency lost between batches.

**EXPERIMENTAL VERIFICATION**

In order to validate the MC predictions, experimental tests have been conducted at the IBA facility located in Bridgeport, New Jersey. Pallets with footprint 40”x48” corresponding to different bulk densities ranging from 0.18 g/cm$^3$ up to 0.76 g/cm$^3$ have been irradiated at 5 and 7 MeV with a beam intensity of 25 mA. Due to the scanning width of 200 cm and the homogeneous electron distribution along the target used at Bridgeport, the pallet height was limited to 60”. The dose distributions inside the pallets were measured by horizontal grids of CTA and Far West dosimeters located at various heights. The collimator consisted of 9 cm thick steel plates located on both sides of the X-ray target. The collimator was used together with a variable pallet rotation speed for the tests corresponding to densities of 0.57 g/cm$^3$ and 0.76 g/cm$^3$. The collimator was removed for the 0.18 g/cm$^3$ test and a constant rotation speed was applied to the pallet.

The relative dose distribution measured in the middle of the high-density pallet irradiated at 5 MeV is presented in Fig. 7. The measured data is in good agreement with the MC prediction. Results from the Palletron tests are presented in Table 1. The minimal dose rate measured in the pallet middle plane is shown in column 3 while the DUR obtained in the data and the MC is compared in columns 4 and 5.

**TABLE 1. Results from Palletron experimental tests.**

<table>
<thead>
<tr>
<th>Density (g/cm$^3$)</th>
<th>$T_0$ (MeV)</th>
<th>$D_{\text{min}}$ (Gy/min)</th>
<th>DUR$_{\text{Data}}$</th>
<th>DUR$_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>5</td>
<td>300±15</td>
<td>1.32±0.09</td>
<td>1.27±0.02</td>
</tr>
<tr>
<td>0.57</td>
<td>5</td>
<td>157±8</td>
<td>1.26±0.09</td>
<td>1.27±0.02</td>
</tr>
<tr>
<td>0.76</td>
<td>5</td>
<td>98±5</td>
<td>1.50±0.11</td>
<td>1.45±0.03</td>
</tr>
<tr>
<td>0.76</td>
<td>7</td>
<td>259±13</td>
<td>1.41±0.09</td>
<td>1.27±0.02</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The Palletron is a new concept for an X-ray pallet irradiator aimed at treating high-density pallet loads with a high dose uniformity.

Monte Carlo studies demonstrate that it is possible to reach a DUR better than 1.5 for all densities up to 0.8 g/cm$^3$ while preserving a high treatment capacity. Experimental verifications are in good agreement with the MC predictions.

**REFERENCES**

3. GEANT: Detector Description and Simulation Tool, CERN Program Library W5013.