Technical Information Report

GEX CORPORATION
THE DOSIMETRY COMPANY

High Energy Ebeam Energy Calculation Using GEX Wedge Array Cards in Risø Aluminum Wedge (4.5 to 12 MeV)

1. PURPOSE

To provide detailed explanation of the history and most current understanding of the method of using an array of discrete B3 film dosimeters for measuring depth-dose distribution in a wedge-shaped absorber for the purpose of penetration range assessment and/or electron beam energy.

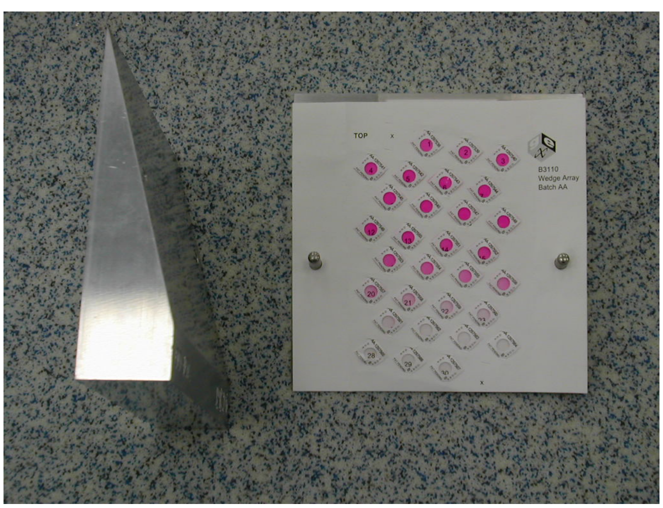
2. SCOPE

Wedges are not practical below a certain electron energy threshold because of the inability to fabricate a wedge with absorber material thin enough and accurate enough to be useful. The document here concerns itself with measurement of electron energies greater than 1.5 MeV to approximately 11 MeV and does not consider any requirements for testing outside of this range that may be different or additional to what is discussed herein.

3. BACKGROUND

The method of using an array of film dosimeters within the Risø Aluminum Wedge was developed by Mr. Changsin Lee while working for Gary Pageau at what was Titan Scan Corporation in Denver, Colorado in 1991. The company was trying to qualify the first 10 MeV electron beam facility in the U.S.A. built exclusively for the purpose of medical device sterilization and was using film strips shipped to and from Risø HDRL in Denmark with analysis by Arne Miller for measuring the beam energy. The delays in getting results combined with the unavailability of film strip reading equipment for use at the site (Risø's strip reading instrument was custom built), Mr. Lee put graphing paper on the wedge and cut slits with a razor blade to insert the corners of FWT-60 film dosimeters in an array that put each dosimeter at an increasing depth in the Risø Aluminum Wedge.

When GEX was founded in 1998 a pre-packaged product was envisioned and developed to save end-users the time of loading the dosimeters. A die-cut card with B3 film dosimeters loaded on the card which was placed over the posts on the aluminum wedge was created and became a popular GEX product. The "B3 Wedge Card" became a widely used product in the high energy electron beam business among companies working with 4.5 to 11 MeV electron beams for the purpose of medical device sterilization. The time that companies spent in measuring beam energy was dramatically reduced with the supply of a product that could be ready for irradiation in 1 minute or less. As of this writing, more than 17,000 wedge cards have been produced and sold and the product remains widely used around the world.



First generation B3 wedge array card after irradiation - mounted on the P4701 Risø Aluminum Wedge

In 2018, after 20 years of use, the knives in the original die used to manufacture the wedge cards were in need of replacement. GEX determined that additional improvements needed to be made and an entirely new die was produced. The challenge was to make the desired improvements while still allowing the new card to be used by legacy customers that had validated their electron accelerators using the original card design.

A new Energy Wedge Array Card design was developed to meet existing and new requirements. The original array card could not be used with the Risø Aluminum Wedge effectively below 4.5 MeV due to a lack of resolution, whereby the result would not yield 3 or more data points to define the slope of the depth-dose curve. So, there was a desire to be able to use the same array card design in other aluminum or polymer wedges with different angles for measuring beams below 4.5 MeV, such as the new P4705 GEX Aluminum Wedge. The new card design also improved the reproducibility of the dosimeter positioning on the card to ensure accuracy of measurements at lower energies and to improve quality and effectiveness of the card assembly procedures used at GEX.

The new die is used to make the Energy Wedge Array Card products which are currently used with the GEX Part No. P4701 (Risø) and P4705 (GEX) aluminum wedges. Thus, the current range of use for the wedge card has been increased (defined by successful repeatability testing) from 1.7 MeV to greater than 10 MeV. Currently, GEX is working on design and development of a polymer wedge for use below 1.7 MeV that will also utilize the same wedge array card.

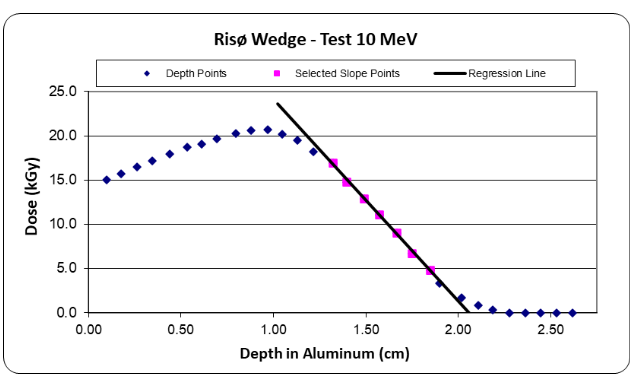
4. GENERAL INFORMATION

Penetration range measurement is an established technique for energy estimation of electron beams. In principle, this technique creates a profile of energy deposition in respect to depth within a homogenous absorber. In practice, discrete dosimeters or strips of dosimeter material are positioned at increasing depths in the absorber material (e.g., aluminum, polystyrene, etc.). The method may involve stacking material or making a solid wedge of the absorber material, but regardless of the implemented methodology, the analysis of measurements is always the same. The depth and dose of each dosimeter measurement point in the absorber are plotted, creating a dose deposition profile. Then, a range parameter of the energy deposition profile is calculated and functionally correlated to the incident energy of the electrons from the electron accelerator. In the case of the radiation processing industry, ISO/ASTM Standard Practice 51649 contains recognized functional energy vs. range relationships (i.e., equations) that are used to estimate the energy from the calculated range of penetration, yielding a single value representing the 'energy of the electron beam' or more precisely, the incident energy of the electrons that were used in the irradiation of the absorber.

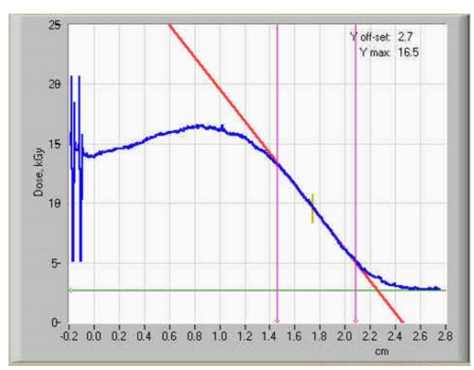
During the qualification of the electron accelerator, the energy is tested repeatedly under varying operating conditions to verify reproducibility of the electron energy from the accelerator. The same test method can then be used to verify that an accelerator is yielding the same energy that was originally qualified after elapsed time or maintenance to the accelerator and its integral components.

Comparison of Different Depth-Dose Measurement Methods

In the early 2000's, GEX compared three different depth-dose distribution test methods all employing the B3. The first test method used the B3110 B3 Energy Wedge Array Card with a Risø Aluminum Wedge. The second method used a stack of aluminum plates with pairs of individual radiochromic film dosimeters hand mounted between each layer of plates. The third method used a continuous strip of B3 dosimeter film mounted on the Risø Aluminum Wedge. Dosimeters from Methods 1 and 2 were measured on a Thermo GENESYS 20 spectrophotometer and plotted against the calculated depth for each dosimeter position. The film strip used in Method 3 was measured using an Epson flatbed scanner to capture a bitmap image and analyzed using the RisøScan Software developed by Risø High Dose Reference Laboratory (HDRL) in Denmark. The results from all three methods were used to calculate the energy of the electrons using the empirically derived formulas for aluminum absorber from the ISO/ASTM 51649 that was published at the time of testing (***Note:*** the formulas used remain unchanged to this day). Results from each of the 3 Methods were ±0.1 MeV, proving the efficacy of the array card method against the two other previously established methods.



B3 Energy Wedge Array Card Result Plotted and Analyzed in MS Excel



B3 film strip analyzed using RisøScan

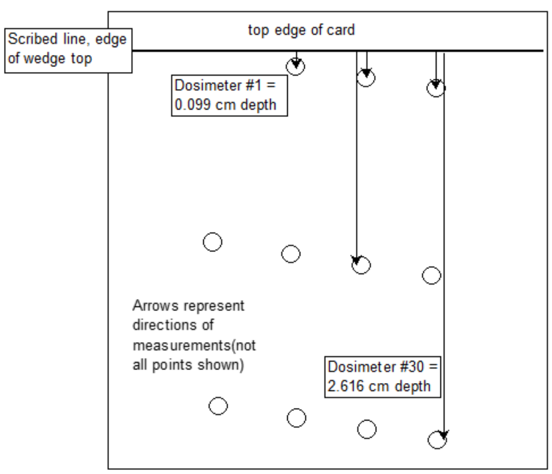
"Risø Method"

The biggest challenge with introducing the original B3110 Energy Wedge Array Card was determining the correct depths of all the dosimeter positions. Initially in 1998, the depths were determined using the "Risø Method" which was the same method used to mark the entry point of strips of film in a wedge. A line was drawn at the top of the card while the card was positioned in the wedge; this became the reference point from which dosimeter depths could be calculated (see Risø Method Diagram below). Customers that adopted the wedge array card between 1998 and 2002 were provided a set of depth values using the Risø wedge with a starting depth of 0.099 cm.

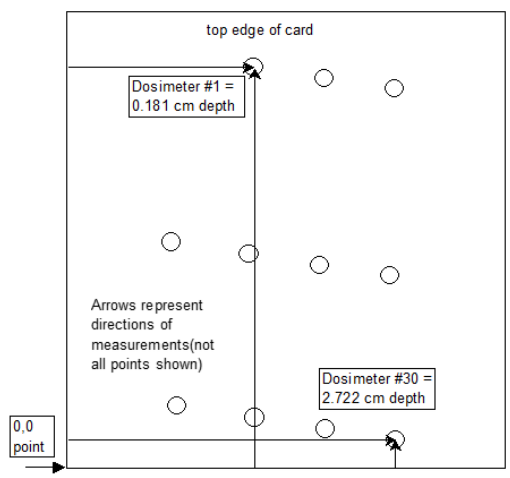
An inherent potential problem exists in the use of this method because by its practice, the user is defining an entry point that is slightly below the actual surface of the wedge. The issue is magnified when the user then uses the trigonometry to calculate the depth of all the positions based on this scribed line. The actual depth of each position is understated if the scribed line is not drawn perfectly at the entrance to the wedge, which is hard to accomplish in practice since some of the aluminum is missing on the edge so that the edge is not razor thin and dangerous to the user. Since all Risø Method depths are mis-stated, any user of these depths would calculate a beam energy that is under-stated. When an engineer adjusts the beam parameters to increase the beam energy slightly, say to raise it from 9.8 MeV to 10.0 MeV to match the wedge output, the result is the actual energy of the beam is greater than the wedge calculation. For example, if the measured energy is 10.0 MeV, the actual energy is something like 10.2 MeV.

"GEX Method"

An effort was undertaken in 2000 and 2001 to better understand the actual depth of the dosimeters because it was assumed that by drawing a line in the 'gap' of the wedge that GEX calls the 'entrance', it is very probable that the line will be slightly below the actual surface of the wedge. Marian Strzelczyk, since retired GEX employee and physicist, defined a new "GEX Method" for calculating the depths based on a definable position that was not subject to user error - the base of the wedge (see GEX Method Diagram below). The result was a significant increase in the depth of each position of 0.082 cm of aluminum. Subsequently, from 2002 to 2019, GEX provided the new GEX Method depth values to new customers (although some existing customers installing additional beams would use the original Riso Method depths).



Risø Method Diagram



GEX Method Diagram

"GEX Method 2"

In 2018, GEX began the process of designing and developing a revised array card that had a new dosimeter mounting die cutting design and to include new printing on the array card that could aid the user in ensuring the positioning of the centers of each dosimeter to provide more reproducible positioning of the dosimeters. The design change was prompted by a desire to improve the product and because the knife edges on the original die that was used to cut around 20,000 cards was getting very dull and would soon require re-knifing or retirement.

In the process of researching the history and the methods previously used at GEX, a discovery was made while measuring actual wedges and comparing measurements to those made by Marian Strzelczyk in the years 2000 and 2001. The total thickness of the aluminum wedges that Risø was producing in 2018 was not the same. In 2000/2001, the Risø wedges were very close to 3cm thick (2.99 cm), as stated by Risø's nominal dimensions on each wedge's documentation. Since that time, the Risø and GEX Methods have been used to determine the depth in the wedge that were given to all users. Therefore, the 0.181 cm value that Marian determined was (and has since been confirmed) to be very accurate, but it was accurate for wedges that were 2.99 cm thick.

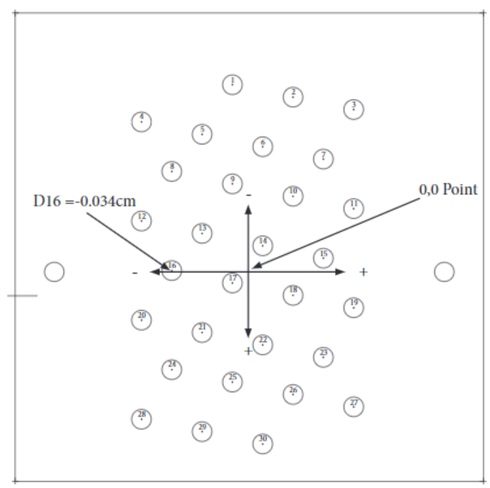
Beginning some time in 2003, all Risø wedges were provided with a nominal thickness of 2.93 cm, and meant that the actual depth of the dosimeters for anyone using the GEX Method depth values was biased because the depths were measured from the base of the wedge and the wedge thickness change would cause bias. Due to the change in wedge thickness, the actual depths of the dosimeter were less than the published values and the new starting depth was recalculated using the GEX Method to be 0.138 cm for the 2.93cm Risø aluminum wedge. GEX started issuing a new set of depths with this value in 2018 to new e-beam sites.

Frustrated by the issues discovered so many years after the fact, GEX developed another method for determining the depth of each dosimeter position, this time using the center of the wedge pins as the basis for measuring instead of the entrance of the wedge or the base of the wedge. The new method was suggested because the array card design has the positions of the dosimeters evenly spread on either side of the pins and dosimeter position 16 was lined up to be centered on the pins. Since the pins are exactly halfway along the hypotenuse in the Risø wedge design, and because the position of dosimeters in the array were relatable to the location of the post/pin holes in the card, the location of all other dosimeters can be calculated based on half the thickness of the wedge which is equal to the depth at position D16.

The drawings of the Risø Method or GEX Method shown above, taken from the original documentation, do not show the post holes. However, the mounting of the card on the posts of the Risø Aluminum Wedge is the essential element to control the positioning of the card. The original wedge card design drawing has each position on the card equidistant from the others (evenly spaced length of 0.3175 cm); this means the depths of the centers are all 0.0875 cm different from one another. Therefore, the calculation of the D1 depth in the 2.99 cm thick wedge using this new GEX Method 2 matches the original GEX Method value of 0.181 cm that Marian calculated all those years ago.

The bias from both the Risø and the original GEX methods was calculated and depth values for existing customers to use are provided in Annex A of this document - these depth values allow customers to match their previous depth for the Risø Aluminum Wedge when using the new revision of the wedge card sold today.

Therefore, ***legacy users of the GEX Wedge Array Card must refer to this document to obtain the depth values to use with the new Energy Wedge Array Card design that match the set of depths they have always used with the previous (original) design of the card***. Otherwise, the original bias is not maintained, and the user's process qualification may be affected.



GEX Method 2 Diagram

The dimensions of any given P4701 Risø Aluminum wedge are predicated by the physical locale of the loading/coupling pins in the wedge. The pins are designed to locate at the center of the measurement zone, which occurs between the vertices along the slope of the A side of a wedge and are subject to the manufacturing tolerances of the wedge itself (± 0.015cm). The design specifications of the B3110 and its outputs, estimate depths based on known wedge thickness at an assumed exact angle of 16 degrees. Attenuation depths are very close estimates. More exact attenuation depths can be provided when specific wedge dimensional qualities are factored. Contact GEX Customer Service if interested.

The wedge array card when pinned into a wedge, inherits the X, Y, and Z values of that wedge and the manufacturer's documented dimensions have historically been used to assign attenuation depths. Exact measured dimensions versus assumed dimensions may or may not affect depth-dose profiles; this is true in all measurement methods that employ stacks or wedges.

5. OPERATIONAL CONSIDERATIONS

Depth-Dose Method Selection Using B3 Film

Below is a comparison of standardized means of electron beam energy estimation for high energy electron beams using B3 film. Each has advantages and limitations when compared with each other but the only widely used method is the B3 Wedge Array Card:

Method	B3 Array Card in Wedge	B3 films in Stack	B3 Strip in Wedge
User Interface	Easy to learn and use - prepackaged die-cut cards align over fixed posts of wedge	User time intensive to set up -requires hand placement of dosimeters with small pieces of tape needed to secure individual dosimeters in the stack	Requires some user skill - positioning and placement of film strips to align and secure.
Test Preparation Time	< one minute	30+ minutes	5 minutes
Measurement Time	9 to 14 minutes	11 to 14 minutes	6 minutes
Time to Result*	10 to 15 minutes	40+ minutes	11 minutes
Technical Considerations	• Can utilize routine dosimeter batch calibration. • Yields 5 or more discrete data points used for determination of the slope and y-intercept.	• Can utilize routine dosimeter batch calibration. • Yields 5 or more discrete data points used for determination of the slope and y-intercept.	• Scanner or Strip Reader requires a separate dosimeter batch calibration. • One more system to maintain. • Provides the best resolution.

*Assumes 5-minute heat treatment of films at 60C post-irradiation and does not include irradiation time.

6. SUMMARY

GEX recommends the use of the Energy Wedge Array Card mounted on an aluminum wedge versus the stack method or the use of a strip of B3 film, not only because it is just as accurate and reproducible, but is the simplest to put into procedure, and easiest to train personnel to execute. Only if there is a need for very high resolution does the strip method provide any advantage, such as detailed analysis of the beginning or 'tail' end of the depth-dose profile.

GEX has settled on GEX Method 2 for the calculation of the depth in aluminum for each dosimeter in array (Method 2) and will use this method to derive and publish values to provide to users for the foreseeable future.

7. LIMITATIONS/PRECAUTIONS

The primary objective of depth-dose distribution mapping and e-beam energy estimation is to characterize the energy of a specific electron accelerator for the purpose of qualification and re-qualification. Known biases exist in the equations of the ISO/ASTM 51649 standard and unknown uncertainty associated with any test method the user chooses. The user should focus on achieving a highly reproducible test method to verify the beam energy performance over long time periods to help ensure a consistent and continually valid electron beam process.

8. RELATED DOCUMENTS

1) ISO/ASTM 51649 - Standard for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 300 keV and 25MeV.
2) GEX Doc# 100-102, B3110 Energy Wedge Array Card – Product Specification and Usage
3) GEX Doc# 100-119, P4701 Risø Aluminum Wedge – Product Specification and Usage
4) GEX Doc# 100-140, P4705 GEX Aluminum Wedge (2 to 4 MeV) – Product Specification and Usage

9. REVISION HISTORY

DATE	CHANGE DESCRIPTION	REVISION
08/07/2007	Initial Release	A
04/28/2021	Major revision. Scope change and related title change – removed discussion of continuous strip and stack methods and but discuss the results of this original comparison of the methods. Simplification and consolidation of previous information with addition of information about new revision B3110 and B3150 Energy Wedge Array Card. Publication of new depth values for customers to use when using the new revision of the B3110 product. ECO 70567	B

ANNEX A

Bias Consistent Depths for 2nd Generation GEX B3 Energy Wedge Array Cards

Please contact cs@gexcorp.com to request a copy of the values below in an MS Excel workbook suitable for copy/paste.

Note 1 – Values below are valid for Risø Aluminum Wedges with nominal thickness 2.93cm and should not be used with Risø wedges circa 2002 or prior.

Note 2 – Depth values used may deviate by +/-0.0001 cm from the values used below in practice.

	Existing Ebeams - Use depths corrected for new card bias		
	Original Depth for Position D1		
Dosimeter Positon (D)	0.099 Depth (R) cm	0.138 Depth (R) cm	0.181 Depth (R) cm
1	0.1320	0.1710	0.2140
2	0.2195	0.2585	0.3015
3	0.3070	0.3460	0.3890
4	0.3945	0.4335	0.4765
5	0.4821	0.5211	0.5641
6	0.5696	0.6086	0.6516
7	0.6571	0.6961	0.7391
8	0.7446	0.7836	0.8266
9	0.8321	0.8711	0.9141
10	0.9196	0.9586	1.0016
11	1.0071	1.0461	1.0891
12	1.0947	1.1337	1.1767
13	1.1822	1.2212	1.2642
14	1.2697	1.3087	1.3517
15	1.3572	1.3962	1.4392
16	1.4447	1.4837	1.5267
17	1.5322	1.5712	1.6142
18	1.6198	1.6588	1.7018
19	1.7073	1.7463	1.7893
20	1.7948	1.8338	1.8768
21	1.8823	1.9213	1.9643
22	1.9698	2.0088	2.0518
23	2.0573	2.0963	2.1393
24	2.1448	2.1838	2.2268
25	2.2324	2.2714	2.3144
26	2.3199	2.3589	2.4019
27	2.4074	2.4464	2.4894
28	2.4949	2.5339	2.5769
29	2.5824	2.6214	2.6644
30	2.6699	2.7089	2.7519