CarestreamNDT

WHITE PAPER

Exposure Factors for Film and Flexible Digital Detector Arrays in Action

A practical hands-on guide on how to use them.

INTRODUCTION

At Carestream NDT we want to share not only our technological developments and product portfolio, but also the knowledge and practical experience that our staff obtains by working shoulder-to-shoulder with customers like you. We aim to share this knowledge and experience in a straightforward fashion so that our readers may find practical applications in their everyday activities.

This series is directed but not limited to NDE professionals in the following industries: Oil & Gas, Nuclear, Construction, Foundry and Castings, Energy Generation, Aerospace, Transportation, Automotive, Military and Defense, Agriculture, Art Restoration & Museum Artifacts, and NDE Services Companies.

CarestreamNDT

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Introduction

Exposure factors (R factors) tables provide an essential element of guidance in gamma radiography applications. The exposure time is calculated for a specific source type, activity, thickness of steel, desired exposure factor for a target film density or pixel value, and source-to-detector distance (SDD).

R factors to produce target film densities of 2.0, 2.5, 3.0, and 3.5 have been available for Carestream's M100, MX125, T200, and AA400 films. **Digital R factors are now published for Carestream rigid and flexible digital detector array (DDA) products.** Flexible DDA's can be bent repeatedly around curved surfaces for single wall viewing, as radiography codes and standards require that the detector be in direct contact with the weld whenever practical.

Radiographers utilize R factor tables to enter the appropriate R factor into a commercially available phone-based calculator to determine the exposure time required to obtain the target optical density or grey value through the base metal. **R factors are meant to be a starting point only, as other factors related to the part geometry and technique may also impact the required exposure.** This white paper not only provides the most recent version of our R factor tables for Carestream industrial film and for four of our digital radiographic products, but also integrates step-by-step examples of exposure calculations for both film and Flexible DDAs.

Dose is King

Dose describes the quantity of radiation produced for a specific exposure, and the dose rate is the quantity of radiation produced as a function of time. A Roentgen (R) is a unit of exposure of X-ray or gamma radiation in air, whereby 1 R is the quantity of radiation that would ionize 1 cm' of air to produce 1 electrostatic unit (ESU) of charge, and 1 ESU is equal to 3.3356 × 10-10 Coulombs (C). A Rad is a unit of absorbed energy deposited in a mass of material, and a Roentgen Equivalent Man (Rem) is a unit of dose absorbed by the human body. For X-ray or gamma radiation, a Roentgen is equivalent to a Rad and a Rem. **The R factor is the total Roentgens needed to produce a specific film density or grey value in the radiograph.** Gamma sources (Iridium, selenium, and cobalt radioisotopes) were utilized for the generation of the data that support the integration of the R-factors tables included here.

Experimental setup

Steel step wedges (See Figure 1) with thickness steps of 0.25”, 0.50”, 0.75”, 1.0”,1.25”, 1.5”, 1.75”, and 2.0” were utilized for the exposures used to establish the R-factors included in Tables 1 to 4.

Figure 1: Steel step wedges, from White [1].

The radiographic configuration setup is shown in Figure 2. The SDD for film was 12”, and the SDD for the DDA was 24”. The step wedges were masked with 1” steel plates to control scatter. At least 100 mil of lead was placed between the detector and the wood table to control scattered radiation.

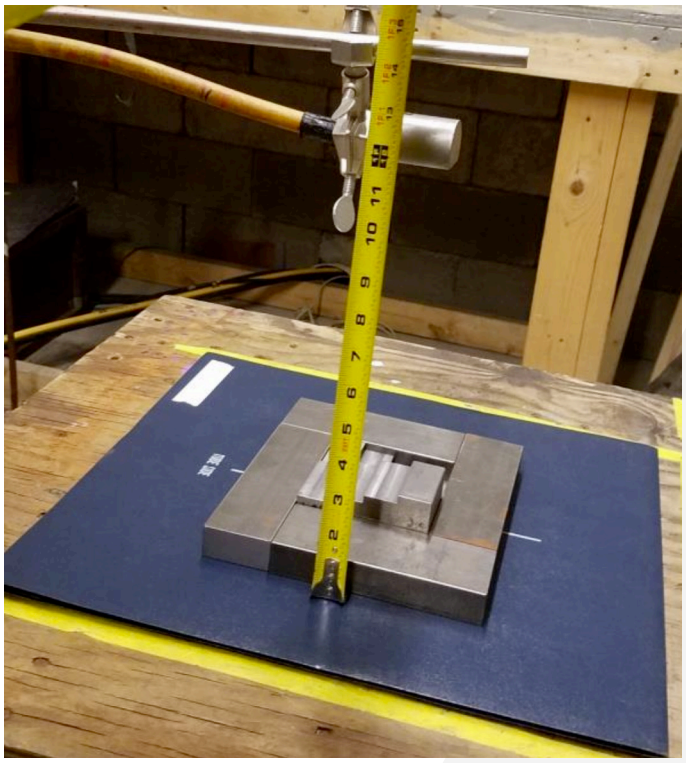


Figure 2: Radiographic shot configuration, from White [1].

Film exposures were done inside vinyl cassettes with 10-mil front-side lead, and 10-mil backside lead. The protective overcoat was peeled off for additional intensification. Iridium sources were approximately 50 Curies, with a diagonal focal spot of 0.15". The selenium source was approximately 30 Curies, with a diagonal focal spot of 0.14". The cobalt source was approximately 100 Curies, with a focal spot diameter of 0.15".

DDA exposures were done with varying integration times and nine averaged frames. Iridium exposure rate to the panel was 65.5 R/HR, selenium was 27.4 R/HR, and cobalt was 356 R/HR. A 16-bit linear greyscale was utilized, and the file types were DICONDE compressed.

Commercially available phone programs were utilized for the exposure calculations. Activity was entered in Curies; steel thickness was entered in inches; the desired R factor was entered; the SDD was entered in inches; and an exposure time was calculated. The optical density or grey value was measured for the 1" step for iridium, for the 0.25" step for selenium, and for the 2" step for cobalt. R factors to produce target optical density or grey values were calculated from the equations generated as a result of the exposure series data.

Results obtained – updated exposure tables for both film and digital radiography

The exposure series of data obtained are compiled into the following four tables.

Tables 1, 2, and 3 are intended for film radiography (one for each of the three different gamma sources in common use for NDE gamma radiography).

Carestream NDT Film Product	Density Desired			
	2.0	**2.5**	**3.0**	**3.5**
INDUSTREX M100 Film	3.2	4.3	5.5	6.6
INDUSTREX MX125 Film	2.3	3.1	3.9	4.7
INDUSTREX T200 Film	1.1	1.5	2.0	2.4
INDUSTREX AA400 Film	0.8	1.1	1.5	1.9

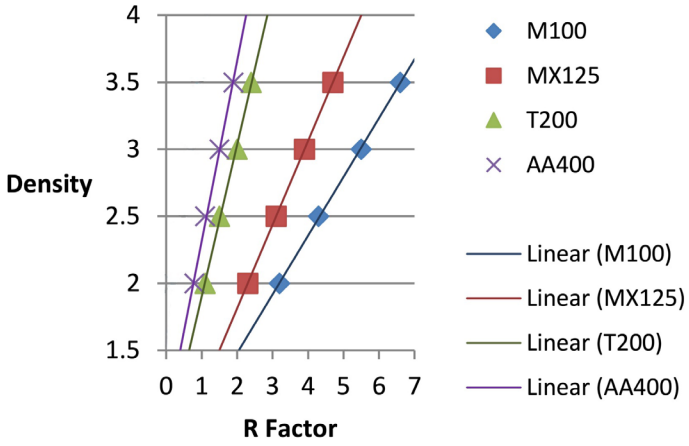


Table 1: R-factors for Iridium Gamma Sources applicable to the Portfolio of Carestream NDT Film Products, from White [1].

Carestream NDT Film Product	Density Desired			
	2.0	**2.5**	**3.0**	**3.5**
INDUSTREX M100 Film	3.6	4.6	5.5	6.5
INDUSTREX MX125 Film	2.2	2.9	3.6	4.4
INDUSTREX T200 Film	1.4	1.8	2.2	2.6
INDUSTREX AA400 Film	0.8	1.2	1.6	2.0

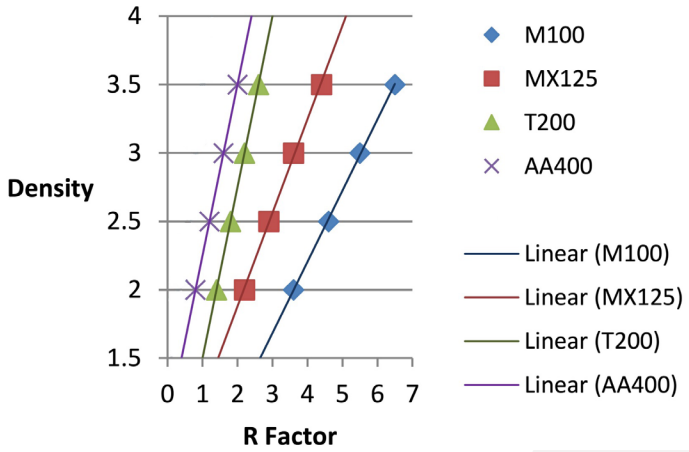


Table 2: R-factors for Selenium Gamma Sources aplicable to the Portfolio of Carestream NDT Film Products, from White [1].

Carestream NDT Film Product	Density Desired			
	2.0	**2.5**	**3.0**	**3.5**
INDUSTREX M100 Film	7.3	9.3	11.4	13.4
INDUSTREX MX125 Film	3.9	5.3	6.7	7.9
INDUSTREX T200 Film	2.3	3.1	3.9	4.7
INDUSTREX AA400 Film	1.2	1.8	2.4	2.9

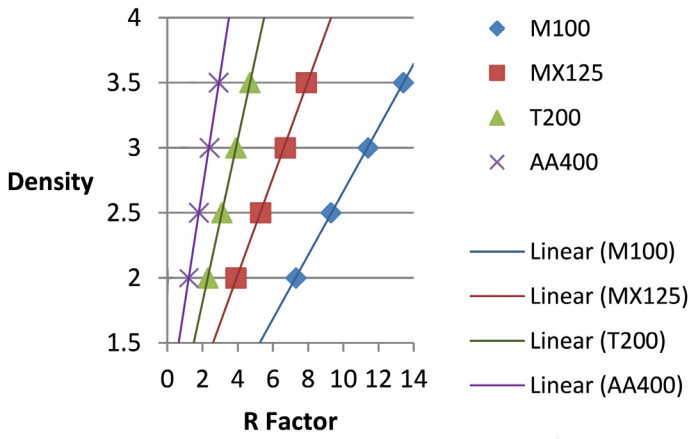


Table 3: R-factors for Cobalt Gamma Sources applicable to the Portfolio of Carestream NDT Film Products, from White [1].

Table 4 compiles the R Factor results obtained by the set of experiments described above for four types of Carestream's DDAs, two rigid and two conformable detectors, using gamma radiation sources. Values in this DR R Factor table are for a single acquired frame.

Digital R Factor per frame for INDUSTREX HPX-DR 3543 PE Non-Glass Detector 16-Bit Linear											
	Pixel Intensity Desired										
Source Type	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000
Iridium	0.0112	0.0237	0.0366	0.0499	0.0635	0.0775	0.0918	0.1065	0.1216	0.1370	0.1528
Selenium	0.0011	0.0072	0.0113	0.0195	0.0258	0.0321	0.0384	0.0448	0.0513	0.0578	0.0644
Cobalt	0.0224	0.0529	0.0838	0.1151	0.1467	0.1787	0.2110	0.2437	0.2768	0.3102	0.3440

Digital R Factor per frame for INDUSTREX HPX-DR 2530 PH Non-Glass Detector 16-Bit Linear											
	Pixel Intensity Desired										
Source Type	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000
Iridium	0.0183	0.0423	0.0663	0.0904	0.1144	0.1385	0.1625	0.1866	0.2107	0.2348	0.2588
Selenium	0.0070	0.0190	0.0311	0.0431	0.0552	0.0673	0.0794	0.0915	0.1037	0.1158	0.1280
Cobalt	0.0586	0.1187	0.1788	0.2390	0.2993	0.3596	0.4199	0.4803	0.5408	0.6013	0.6619

Digital R Factor for INDUSTREX HPX-ARC 1025 PH Digital Solution 16-Bit Linear											
	Pixel Intensity Desired										
Source Type	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000
Iridium	0.0197	0.0377	0.0557	0.0737	0.0917	0.1097	0.1277	0.1457	0.1637	0.1817	0.1997
Selenium	0.0113	0.0233	0.0353	0.0473	0.0593	0.0713	0.0833	0.0953	0.1073	0.1193	0.1313
Cobalt	0.0554	0.1154	0.1754	0.2354	0.2954	0.3554	0.4154	0.4754	0.5354	0.5954	0.6554

Digital R Factor for INDUSTREX HPX-ARC 1043 PH Digital Solution 16-Bit Linear											
	Pixel Intensity Desired										
Source Type	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000
Iridium	0.0215	0.0455	0.0695	0.0935	0.1175	0.1415	0.1655	0.1895	0.2135	0.2375	0.2615
Selenium	0.1140	0.0234	0.0354	0.0474	0.0594	0.0714	0.0834	0.0954	0.1074	0.1194	0.1314
Cobalt	0.0553	0.1153	0.1753	0.2353	0.2953	0.3553	0.4153	0.4753	0.5353	0.5953	0.6553

Table 4: Digital R Factor for Carestream's DDAs, adapted and expanded from White, B. [1]

Brian White, Research Scientist and Level III Radiographer at Carestream NDT, explains the practical implications of the resulting updated R-Factors Tables for radiographers' daily work in the following terms [1]: *"Radiographers can utilize the tables to determine the R factor required for a target density or grey value. They can utilize a commercially available phone-based calculator to determine the exposure time required to obtain the target density or grey value. To calculate the time required, enter the source type, the activity of the source in Curies, the steel thickness, the R factor, and the SDD. These exposure factors are meant to be a starting guideline only, as many other factors related to the part geometry and technique conditions will affect the final density or grey value. These exposure factor tables were verified for all systems presented in this paper. Overall, there was good agreement on exposure factor to target optical density or grey value."*

In the next section, we will follow Brian's advice to obtain exposure times for several inspection conditions.

Film and DDA Exposure Factors in Practical Use

Here is a practical example using a commercially available smartphone app to perform radiographic exposure calculations. This app requires the following input parameters:

1. The activity measurement units should be selected between Curies or Tera-Becquerels (TBq)
2. The distance measurement units should be selected between inches or millimeters (mm)
3. Selection of Gamma source type should be made—here the app allows you to choose between Iridium (Ir-192), Cobalt (Co-60), or Selenium (Se-75)
4. Input the following parameters in the corresponding input fields:
    - Activity in the selected measurement unit
    - Steel thickness
    - The exposure "R" factor:

Typical R factors for film range from 1 up to 7, depending on film type and source type, CR is similar to film for R factors.

R factors for DDA's per frame are significantly lower as DDA's require significantly less exposure relative to film and CR; also note that these exposure factors are meant to provide guidance for a starting point to set integration time.

I. First you need to decide which type of Film or DDA you will be using for performing the radiographic test.

II. Once the Film or DDA type is defined, you should establish:

- In the case of film radiography, the intended density in the base metal portion of the image, according to the density requirements of the applicable code or standard.
- In the case of DR, the intended pixel intensity in the base metal portion of the image.

III. Use Tables 1 to 4 to select the proper “R” factor based on the selected Film or DDA and on which type of gamma-ray sources will be used.

Press the word “Calculate” and the exposition time (or integration time) will appear in the Hours:Minutes:Seconds field in the app.

Let's roll up our sleeves and put the exposure calculation process described above into practice by solving two examples, one for film and one for DR. The radiographic technique test parameters for a single-wall/single-image radiography of a pipe weld are as follows:

1. Gamma radiation source: **Iridium**
2. Source activity: **52 Curies**
3. Steel thickness: **0.75"**
4. Source to detector distance (SDD) = **32"**

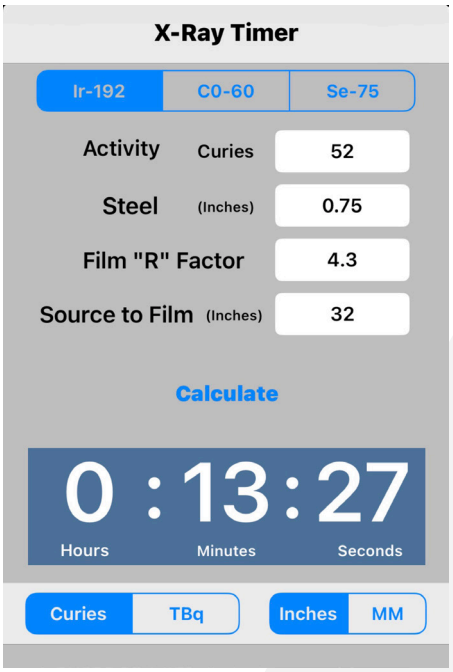
I.- Example using Film Radiography:

- Film type in use: **INDUSTREX M100 Film**
- Base metal target optical density desired = **2.5**

Considering the base metal target density of 2.5 and the use of an Iridium source, the exposure or "R" factor obtained from Table 1 is 4.3 (see image below).

Carestream NDT Film Product	Density Desired			
	2.0	**2.5**	**3.0**	**3.5**
INDUSTREX M100 Film	3.2	**4.3**	5.5	6.6

Capturing all the parameters described above in the exposure calculation app, it results in an exposure time of **13 minutes and 27 seconds** to obtain a target optical density of 2.5 through the base metal.



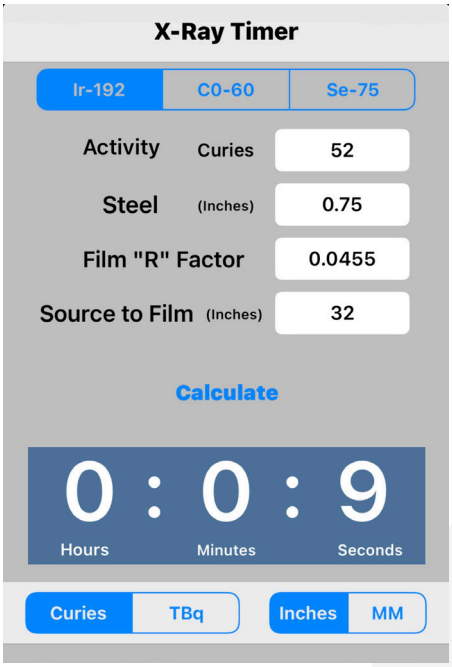
II.- Example using Digital Radiography (same radiographic technique test parameters):

- DDA type in use: **INDUSTREX HPX-ARC 1043 PH Digital Solution**
- Base metal target pixel intensity = **6000**

Based on a 6000 desired pixel intensity and the use of an Iridium source, the exposure or "R" factor is **0.0455** (see image above). Capturing all the parameters above results in an integration time per frame of **nine seconds** to obtain a target grey value of 6000 through the base metal.

Digital R Factor for INDUSTREX HPX-ARC 1043 PH Digital Solution 16-Bit Linear											
	Pixel Intensity Desired										
Source Type	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000
Iridium	0.0215	**0.0455**	0.0695	0.0935	0.1175	0.1415	0.1655	0.1895	0.2135	0.2375	0.2615
Selenium	0.1140	0.0234	0.0354	0.0474	0.0594	0.0714	0.0834	0.0954	0.1074	0.1194	0.1314
Cobalt	0.0553	0.1153	0.1753	0.2353	0.2953	0.3553	0.4153	0.4753	0.5353	0.5953	0.6553

Table 4: Digital R Factor for Carestream's DDAs, adapted and expanded from White, B. [1]



If you want to practice this exposure calculation process using different sets of parameters, Table 5 provides four supplementary examples that you can use.

Table5				
Parameter:	**Example 1**	**Example 2**	**Example 3**	**Example 4**
DDA Type	INDUSTREX HPX-ARC 1025 PH		INDUSTREX HPX-ARC 1043 PH	
Gamma radiation source	Iridium	Selenium	Cobalt	Iridium
Source Activity	60	50	35	75
Steel Thickness:	0.5"	0.375"	2.5"	1.75"
Base metal target pixel intensity	6000	9000	6000	9000
SDD	24	20	48	36
Results				
"R" Factor per frame	**0.0377**	**0.0353**	**0.1153**	**0.0695**
Integration time per frame	**3 seconds**	**6 seconds**	**1 minute 13 seconds**	**46 seconds**

Conclusions

The four tables presented in this paper provided exposure factors for Carestream film and digital detector array systems. **Radiographers can utilize the tables to determine the R factor required for a target density or grey value.** As we have shown above, they can utilize a commercially available phone-based calculator app to determine the exposure time required to obtain the target optical density or grey value. To calculate the time required, enter the source type, the activity of the source in Curies, the steel thickness, the R factor, and the SDD. These exposure factors are meant to be a starting guideline only, as many other factors related to the part geometry and technique conditions will affect the final density or grey value. **These exposure factor tables were verified for all systems presented in this paper.** Overall, there was good agreement between the exposure factor to target optical density or grey value.

- For readers interested in exploring how to different types of film or DDAs radiography can be integrated into your pipeline and other field inspection processes:
  https://www.carestream.com/en/us/nondestructive-testing-ndt-solutions

Here are some supplementary information resources and white papers from Carestream NDT's products and services portfolio:

Products:

- INDUSTREX Film for Non-Destructive Testing
- INDUSTREX Photochemicals
- INDUSTREX HPX-ARC 1025 PH Digital Solution
- INDUSTREX HPX-ARC 1043 PH Digital Solution
- INDUSTREX HPX-DR 3543 PE Non-Glass Detector
- INDUSTREX HPX-DR 2530 PH Non-Glass Detector
- INDUSTREX Fieldview Tablet
- INDUSTREX Digital Viewing Software

Services - Training and Supplementary Information Resources:

- Advanced Industrial Radiographic Training Academy
- Resource Center
- Virtual NDT Showcase

References:

1. White, Brian S. "Exposure Factors for Film and Digital Detector Array Radiography," 20th World Conference on Nondestructive Testing, Incheon, South Korea, 2024.
2. Bossi, R., Nondestructive Testing Handbook, fourth edition: Volume 3, Radiographic Testing, Columbus, OH, American Society of Nondestructive Testing, 2019.

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