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TO: Advisory Board on Radiation and Worker Health Work Group on TBD-6000
FROM: Robert Anigstein, Joe Zlotnicki, Dick Olsher, and John Mauro, SC&A
SUBJECT: Review of NIOSH Report on Response of Film Badges to High-Energy Photons
DATE: October 28, 2011

Review of "Evaluation of the Response of Film Badges to High Energy Photons"

On October 4, 2011, NIOSH/DCAS issued a report (Macievic 2011) that was intended to determine whether the film badge dosimeters employed at the General Steel Industries, Inc., (GSI) foundry in Granite City, Illinois[1] were able to properly record the radiation exposures of workers to betatrons. Ted Katz, Designated Federal Official to the ABRWH, asked SC&A to review the NIOSH report.

The history of this issue began in 2007, when [redacted] an [redacted] for former GSI workers, obtained year-end summary records of film badge dosimetry for that facility, spanning the period from November 1963 until the end of 1972, from Landauer, Inc. In 2008, NIOSH obtained complete film badge records for GSI for the years 1964–1972. Both NIOSH and SC&A subsequently reviewed and analyzed these records; these analyses were discussed in a series of reports prepared by both organizations. [redacted] subsequently questioned the ability of the film badges to record the high-energy photons generated by the betatron, to which he assumed the workers had been exposed (Neal R. Gross 2008 and transcripts of later meetings).

We will first review Macievic 2011. In the opening paragraph, the author stated that NIOSH has evaluated the relative response of dosimeter film to high-energy bremsstrahlung. We observe that dosimeter film is a component of a dosimetry system. The use of a dosimeter to derive doses to individuals depends on a number of factors. These include the film holder, the film processing methods, algorithms used to convert the photographic densities in different regions of the film to dose,[2] the dosimeter calibration, and the location of the dosimeter on the body and its orientation with respect to the incident radiation. Issues such as variations in energy response are addressed by the design of the holder and its incorporated filters, the algorithm, and the calibration procedure. Solely looking at the response of the emulsion, or even emulsion plus filter, fails to tell the entire story.

After discussing the energy range of electrons produced in a betatron, Macievic (2011, Table 1) presented the intensity of bremsstrahlung x-ray photons from 20-MeV and 24-MeV electrons as a function of photon energy. This table was based on experimental measurements on a specific electron accelerator, the microtron MT-25, at the Joint Institute for Nuclear Research at Dubna, in the Russian Federation, and subsequent model calculations. According to the cited reference (Tran Duc Thiep et. al. 2005), the results have an experimental error of 10%. We are puzzled

[1] Unless otherwise stated, all references to "GSI" are to the Granite City facility.

[2] The film dosimeter comprises a minimum of three regions: the open window, the film under the plastic filter (i.e., the plastic badge holder), and the film under the metal filter. The algorithm is the mathematical formula used to convert the densities sampled over each of these regions to dose.

that Macievic cited the data from this reference. First, the microtron is a cyclotron used to accelerate electrons—the operating principle is quite different than that of a betatron. Betatrons have been in use since the 1940s. The physics of bremsstrahlung production is well understood. A more standard reference specific to a betatron would be preferable. For instance, the NIOSH calculations of uranium activation, the results of which were reported by Allen and Glover (2007), utilized exposure rates taken from NBS Handbook 55.[3] Furthermore, Table 1 presented photon intensities, i.e., photon flux per cm^2. The photon flux is not the appropriate starting point for a discussion of the response of a dosimeter to photons of various energies. Since high-energy photons deliver more dose per photon than low-energy photons, the fraction of photons in a given energy range is not proportional to the dose received from photons in that range. Thus, Macievic's statement, "The 24 MeV electron, has 92% of the photon intensity in the 0 to 12 MeV range," does not mean that 92% of the *dose* is from photons in that range. Most important, the data presented by Macievic (2011, Table 1) are not relevant to the film badge dosimetry of GSI workers. It is highly unlikely that badged workers were ever exposed to the direct central x-ray beam of the betatron. The energy distribution of the radiation fields to which the workers might have been exposed would have been quite different from that presented by Macievic.

Macievic (2011, Table 2) presented the elemental composition of six nuclear emulsions. Nuclear emulsions are used for the tracking of individual high-energy particles. They are not used for photon dosimeters. These data, which were not further referenced by the author, are not relevant to the purpose of this report.

Macievic (2011) presented two figures that illustrate the relative sensitivities of photographic film to photon radiation of various energies. The author's statement: "Figures 1 and 2 below, which were taken from Attix[2] et al. and Yoder and Zelac[3] . . . ." leads the reader to assume that Figure 1 is from Attix et al. and Figure 2 is from Yoder and Zelac. In reality, Figure 1 is from the reference he identifies as "Yoder and Zelac." This reference is actually a report prepared by a committee of the National Research Council (Lalos 1989). Macievic erroneously listed the authors as R. Craig Yoder and Ronald E. Zelac: Lalos (1989) does not list personal authors. Whereas Dr. Yoder was one of 11 member of the National Research Council committee, Dr. Zelac's name does not appear in the publication. Furthermore, the source of Figure 1 is Figure 2-5 in Chapter 2 (Lalos 1989), not in Chapter 5, as stated in Macievic's list of references. We assume that Figure 2 is from Attix et al.; we were not able to access that publication. In addition, we would suggest that the list of references would benefit from employing a consistent style for the three works cited.

Macievic (2011, Figure 1) illustrated the response of film covered with a tantalum filter to photons with an energy range of approximately 15 keV to 1.2 MeV. Figure 1 in the present memo is reproduced from Lalos 1989, Figure 2-5, the source of Macievic's Figure 1. As stated in the caption, that figure was adapted from Brady and Iverson 1968; it appeared there as Figure 3. According to these authors: "Figure 3 indicates that, for photon energies from 45 keV

[3] Sam Glover, NIOSH, private communication with Robert Anigstein, SC&A, Inc., 2008.

to more than 1 MeV, the tantalum film response for personnel dose is within ± 20 percent of the cesium gamma air calibration."

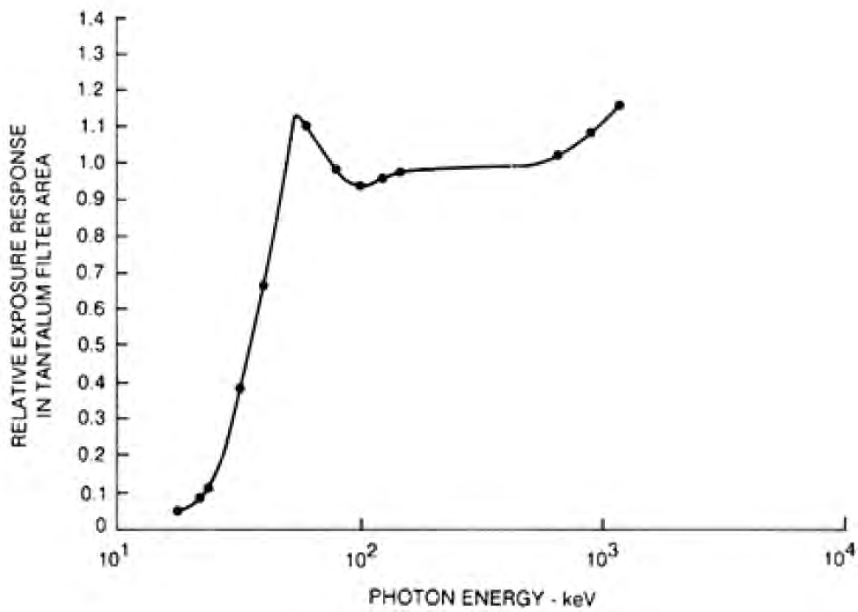

Figure 1. Film Response with 0.020-inch Tantalum Filter (adapted from Brady and Iverson, 1968) (Lalos 1989, Figure 2-5)

Macievic did not explain what quantity the response of the film is compared to. This question can be resolved by referring to Griffith (2007), who stated:

> Instrument and dosimeter calibrations, dose measurements, and dose records were made in terms of exposure in units of milliroentgen. However, as noted above, from 1961 quarterly and annual limits were specified in millirem (AEC 1961), where the general term dose was used without specific reference to *dose equivalent*. As a result, individual monitoring results at NTS were recorded in millirem, although the measurements had been made in terms of *exposure*. However, for photons, the values of *exposure* and dose equivalent were considered to be essentially the same (Griffith 2004; Brady and Iverson 1968). In effect, a *de facto* conversion factor of 1 rem/R was used for dose recording purposes.

Macievic (2011) did not indicate the energy of the radiation source used to calibrate the film. According to Brady and Iverson (1968), film badge dosimeters were calibrated by exposing them in air to a ^{137}Cs source. We independently confirmed the use of this radionuclide as the calibration source by digitizing the data points in Figure 1 and observing that the third point from the right approximately corresponds to an energy of 662 keV (the principal γ-ray emitted following ^{137}Cs decay) and a relative response of 1.

Macievic (2011) did not identify the type of film used to generate the data in his Figure 1. Brady and Iverson stated that the film was part of the "du Pont Type 556 film packet, including 519 low range and 834 high range components." Such information is needed to apply these data to the present issue.

Figure 1 does not include data above 1.2 MeV, although the curve is rising at that point, suggesting a continuing overresponse at higher energies. According to Lalos (1989): "Exposure to photons with quantum energies above 2 MeV may result in a situation in which the density under the filters is greater than the density in the open window area, with the greatest density occurring under the high-Z filter." This indicates that the film would overrespond to high-energy photons. The low sensitivity of the tantalum-covered portion of the film to low-energy photons shown in Figure 1 is due to the shielding by the tantalum filter. These photons are also detected by the plastic-covered portion of the film, and a processing algorithm uses the readings from both portions of the film to derive the dose to the film-badge wearer. In fact, a major motivation for the original use of metal filters was to account for the overresponse of the unshielded emulsion to low-energy photons, a primary source of radiation exposure of individuals employed in medical radiography.

Macievic (2011, Figure 2) illustrated the response of Kodak RM (Radiation Monitoring) film covered with a Sn-Pb filter to photons over a range of approximately 15 keV to 1.2 MeV at different angles of incidence. This film has been used in film-badge dosimeters (Bomford and Kunkler 2002). As was the case with his Figure 1, Macievic gave no information as to how the film was calibrated nor to what radiometric quantity the response is being compared. Based on the fact that one of the data points for normal incidence lies at the value 1.0 on the abscissa (Y axis) and at approximately 1.2 MeV on the ordinate, we conclude that the film was calibrated against ^{60}Co, which emits photons with an unweighted average energy of 1.25 MeV. We observe that the curve for normal incidence shows a peak at ~85 keV, showing an overresponse at this energy of ~30% compared to ^{60}Co. This curve has a local minimum in the vicinity of 662 keV, the photon energy emitted by ^{137}Cs, with an underresponse of ~13% at this energy. The curve rises steadily above this energy, depicting an overresponse of ~28% at ~2.8 MeV, the highest energy shown in the figure. The relative response at normal incidence decreases at energies below ~85 keV; such lower-energy photons are recorded by the plastic-covered portion of the film. The relative response at angles of incidence of 35º, 45º, and 80º is lower than at normal incidence.

Macievic (2011) comes to the following conclusion:

> Film badges worn in an environment where high energy photons (>1 MeV) are present, such as a betatron, have an increase in response over photons below 1 MeV, with the magnitude of the over response increasing with increasing photon enegy [*sic*]. A dose based on the film density underneath the metal filter would be biased in the high direction.

This conclusion is overly broad. According to Macievic (2011, Figure 2), 1-MeV photons normally incident on the film cause a response of only ~73% compared to 85-keV photons. The degree of overresponse would depend on the filter, the method of calibration, and the shape of the energy spectra being compared. More important, any such conclusion should be relevant to the film badge dosimetry and exposure conditions at GSI, and should be supported by the evidence presented by the author.

In order to resolve the lingering questions posed by Macievic (2011), we performed an independent analysis of this issue. We began by repeating one of the analyses that we had performed in support of a previous report (SC&A 2008). In that study, we used the MCNP radiation transport code to simulate the exposure rates in various locations in and around the New Betatron Building during the radiography of a steel casting. In the current analysis, we used the same exposure conditions, but tallied the exposures in 279 energy bins. We then used these results to generate a table of exposure rates vs. photon energy. Figure 2, which is adapted from SC&A 2008, Figure 14, shows the two exposure locations assessed in the present analysis.[4]

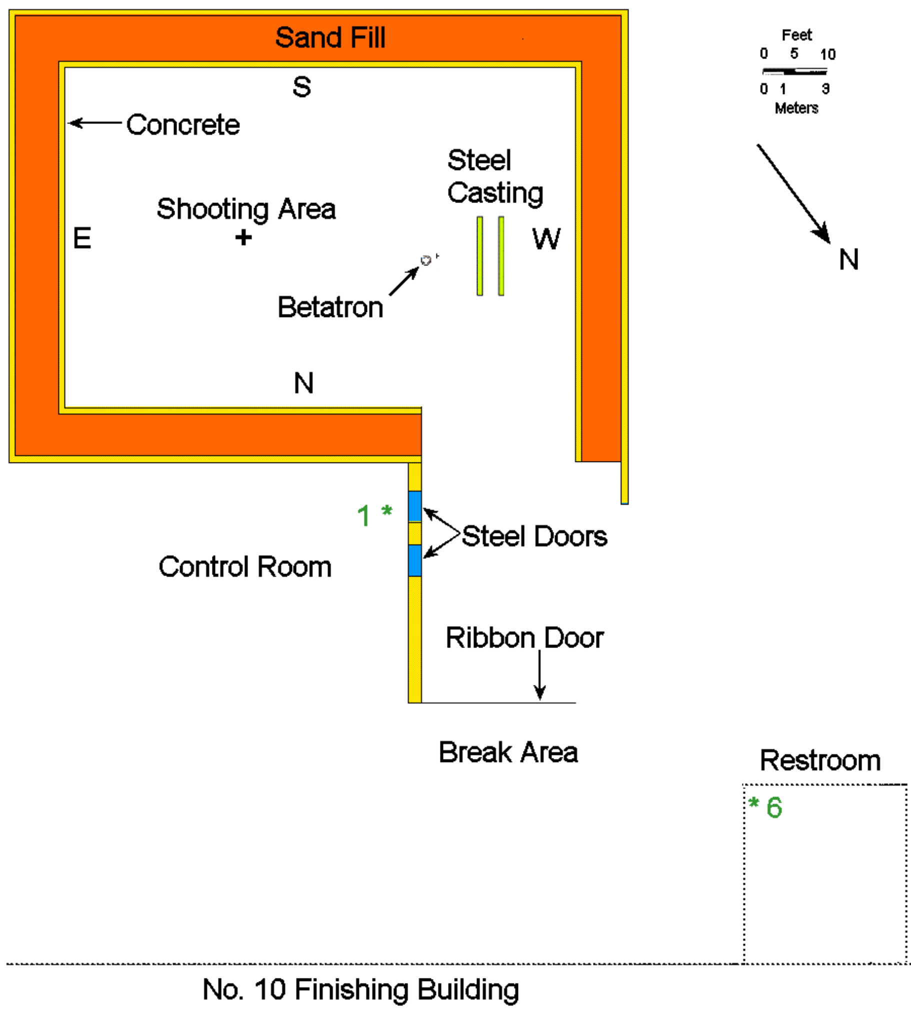

Figure 2. MCNP Model of New Betatron Building, Showing Locations of Exposure Assessments

[4] We identified the locations using the same numbers as in SC&A 2008. Thus, the locations are numbered 1 and 6.

Figure 3 shows the exposure-rate spectrum (i.e., exposure rate vs. photon energy) in the control room, near the door to the shooting room. Our analysis shows that 99% of the exposure rate is from photons E < 3.6 MeV, while 90% of the spectrum lies between 45 and 540 keV. The exposures in this energy range fall within the ±20% relative sensitivity range of the film described by Brady and Iverson (1968), as quoted earlier in this memo.

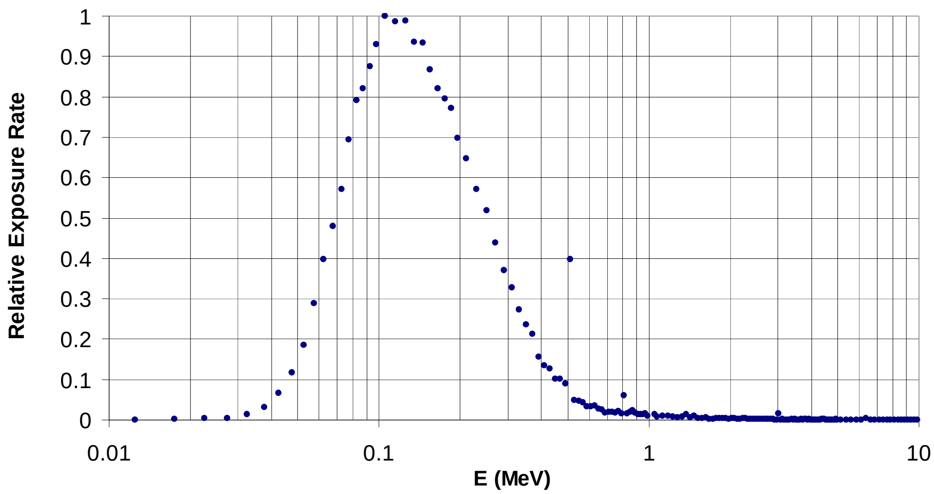

Figure 3. Exposure Rate vs. Photon Energy in Control Room (location #1 in Figure 2)

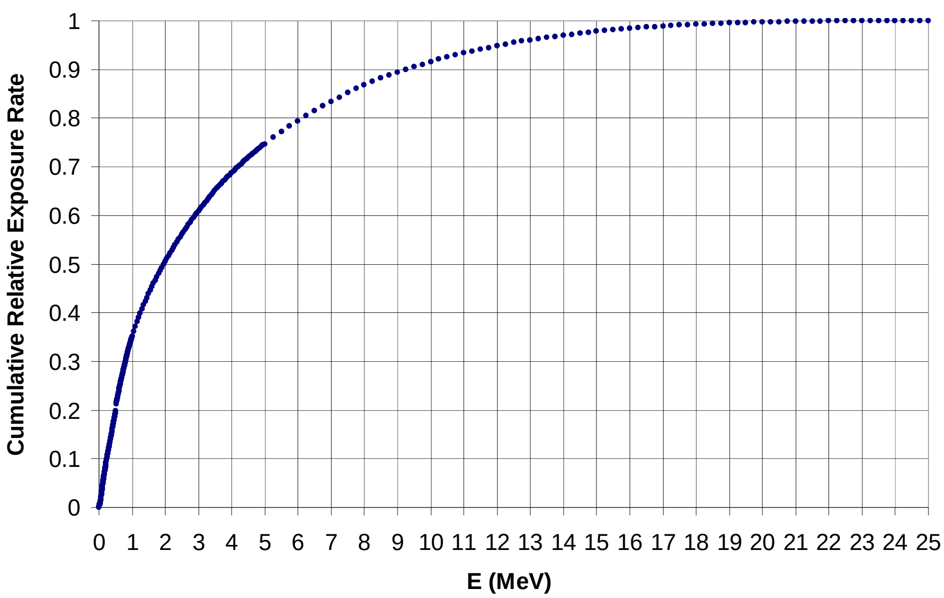

Figure 4. Cumulative Exposure Rate vs. Photon Energy in Restroom (location #6 in Figure 2)

Figure 4 shows the cumulative exposure-rate spectrum in the restroom. As shown in this figure, 50% of the exposure rate is due to photons E < 2 MeV, while 90% is below 9.25 MeV. This analysis was based on the drawings of the betatron building in reports available at the time of the original SC&A (2008) analysis, which indicated only a thin wall along the rail tunnel on the northwest side of the building. A drawing that accompanied the report of a radiological survey of an 80-Ci ^{60}Co source in the New Betatron Building (NRC 2009, p. 16) showed that this wall was 2 ft thick, which would have significantly attenuated the radiation field in the restroom. The additional scattering caused by the thicker wall would soften the spectrum, bringing it closer to that in the control room. However, the spectrum derived in the present analysis can be used to represent a limiting case, encompassing other lightly-shielded locations.

The data cited by Macievic (2011), and the underlying references, do not directly address the response of film badges to photon radiation E > 2 MeV. However, this issue was resolved by Storm (1951), who investigated the response of two photographic films to high-energy photons, include those emitted by the 22-MeV Allis-Chalmers betatron at Los Alamos. According to his abstract:

> The response of Eastman type K and DuPont 552 film to high energy x-rays was investigated. Both types of film were found to be energy independent from 0.4 to 2.0 mev. For a given roentgen (r) value, a greater response in terms of density is obtained on the film as the effective energy is increased beyond 2.0 mev. (Storm 1951)

To relate these findings to the film badge dosimeters used at GSI during the 1963–1966 period, we obtained the following information from Landauer, Inc.[5]

- Badges had large filters including a lead one. This had two consequences: Fairly good response in the high-energy range (pair production in the lead) and good angular response except at very large angles.
- Badges were calibrated to ^{60}Co. Craig Yoder does not expect deviation for high energy gammas by more than +10% to 15%
- Badges were calibrated in air.
- Badges contained DuPont film.
- The general characteristics of film and film holder design did not change appreciably over 50 years. One can generally look at response curves from one era and apply them to another. (However, this will not apply to beta rays and to the cut-off for low-energy x-rays, nor to mixed radiation.)

We conclude that the Landauer film badge dosimetry reports for GSI during the 1963–1966 time period are comparable in accuracy to reports of other film dosimeters used at other facilities during that era, and are also comparable to current dosimetry practices. Film falls down in the sensitivity to high-energy photons at very low doses, so the minimum detectable dose may have been 20 mrem rather than 10 mrem.

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[5] Craig Yoder, Ph.D., Sr. Vice-President of Marketing & Technology, Landauer, Inc., private communication with Joe Zlotnicki, SC&A, Inc., October 12, 2011.

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