External Dose Assessment from X-ray Diffraction at Carborundum Company, Niagara Falls, NY

Response Paper

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INTRODUCTION

As a subcontractor to United Nuclear Corporation, the Carborundum Company (Buffalo Ave., Niagara Falls, NY) manufactured ceramic fuel pellets containing PuC-UC. The fuel pellets were evaluated by various means, including X-ray diffraction (XRD) analysis (Breslin, 1960, pg. 5). The X-ray powder diffraction method is used very extensively for compound or phase identification (Gundaker, 1971, pg. 28); Carborundum employed this method to analyze the fuel as part of the fuel fabrication process.

NOTE: During the Sanford Cohen and Associates (SC&A) review of the SEC-00223 Carborundum Evaluation Report (SC&A 2016), reviewers raised various issues related to XRD. A summary of SC&A's XRD comments and the corresponding NIOSH responses are provided in an Attachment at the end of this paper.

DESCRIPTION OF THE X-RAY DIFFRACTION MACHINE AT CARBORUNDUM

XRD machines can have a range of sizes and configurations, from bench-top units or stand-alone devices within a laboratory. The operator's position during operation is also variable, depending on the configuration of the XRD machine.

Both SC&A and NIOSH interviewed a former Carborundum worker who used the XRD machine (SC&A 2016; Jessen, 2016). In the interview with NIOSH, the worker was specifically asked about the configuration of the XRD machine. The worker stated that the XRD machine sat on the floor and was not moved because water was plumbed to it. He stated that people could walk through the room where the XRD unit was located, but that generally only the people who worked with one of the three analytical devices in the room occupied it. According to the worker, these people (about five total) "knew not to stand around" (Jessen, 2016, pg. 2). This worker further stated that the XRD machine operated for about 40 minutes per sample, with about 10 sample runs per day.

The interviewed worker also described some technical details of Carborundum's XRD machine. He mentioned that the machine had a "hood" and a shield. He described preparing the sample, placing it in the XRD machine (with the shutter closed), closing the shield over the assembly, and then opening the shutter to irradiate the sample. Once the assembly was in place, the worker stated that he walked away (Jessen, 2016, pg. 2).

DESCRIPTION OF THE HAZARD FROM X-RAY DIFFRACTION MACHINES

The greatest hazard from XRD machines is from external exposure to the primary beam. This can occur most commonly during alignment procedures, during which the target must be aligned with the output port, the sample with the primary beam, and the detector or film holder with the reflected beam (Lubenau, 1969). The primary beam of K_α characteristic X-rays has a very small area, on the order of 0.01 cm^2 at the exit port (Rudman, 1971, pg. 82). This primary beam is very intense, with an exposure rate in the hundreds of thousands of R/sec (Thomas, 1971, pg. 145). If the X-ray tube is energized during alignment, the operator’s fingers or hands may be exposed to the primary beam. Historically, these types of accidents are the major hazard from XRD machines (Thomas, 1971, pg. 145). No evidence of these types of radiation accidents has been found at Carborundum.

Other than exposure to the primary beam, an operator of an XRD machine would be exposed to leakage, diffracted radiation, and scatter radiation from the sample and other components. Each of these has slightly different properties, as discussed below.

Leakage from the tube housing is assumed to be minimal (De Castro 1986, pg. 10).

The source of the low-energy X-rays striking the sample is the K_α characteristic X-rays from the tube target materials, commonly copper or iron. There is evidence that Carborundum used an XRD unit with a copper target (Strasser, 1963, pg. 30; Carborundum, 1965, pg. 101). The former XRD machine operator at Carborundum interviewed by both SC&A and NIOSH stated that the XRD machine had a copper target (SC&A, 2016, pg. 48; Jessen, 2016, pg. 3). Based on the evidence in two historical documents from Carborundum, and the two different interviews of this worker, NIOSH believes the XRD machine at Carborundum had a copper target. The energy of the $K_{\alpha,1}$ characteristic X-ray of copper is 8.1 keV (Lubenau, 1969).

The diffracted radiation would be emitted from the sample with an energy of 8.1 keV in small, directional beams. Given that the interviewed worker stated that the XRD machine had a shield over the entire assembly (Jessen 2016, pg. 2), it is assumed that most of the diffracted radiation would have been absorbed in the shield material.

Electrons accelerated through a potential difference of about 35-50 kV (typical of a copper target tube) produce a Bremsstrahlung X-ray spectrum in addition to the characteristic X-rays of copper. The average energy of the Bremsstrahlung photons is about 20 keV (Block, 1971, pg. 20). The scatter radiation emitted isotropically with an average energy of about 20 keV is assumed to be the major exposure source to workers in the XRD laboratory. Air attenuation can be quite large at low energies (Granlund, 1971, pg. 181), but is ignored in this work.

DOSE FROM SCATTERED X-RAY BEAM CALCULATION

Lubenau, et al (1969) provides measurements of scatter from a 1966 survey of XRD units in the state of Pennsylvania. Scatter measurements for three XRD units with copper targets are provided, ranging from 0.5 -2.0 mR/hour at the table edge. These measurements are reported as maximum scatter values from the respective machines during operation. The highest scatter measurement of 2.0 mR/hour will be used as the starting point for dose assessment for Carborundum. Lubenau does not specify the measurement distance, so a 30 cm distance will be assumed as a practical distance from an enclosure or barrier for making a measurement (NBS Handbook 93, pg. 9).

Measurement of low-energy X-rays (8-20 keV) may require correction because most ion chamber survey instruments are calibrated at the much higher photon energy from Cs-137 (662 keV). Lubenau (1969) used a Victoreen 440RF ion chamber when measuring scatter from XRD machines in Pennsylvania. Els (1971) provides an instrument correction factor of about 2.5 for a Victoreen 440 RF ion chamber measuring 8 keV photons diffracted from a copper target. The correction for measuring 20 keV photons (average energy of scatter from a 50 kV X-ray source) drops to approximately 1. With the assumption that the major source of worker exposure is the scatter radiation of 20 keV average energy, the instrument correction factor is not necessary.

According to the XRD machine operator interviewed by NIOSH (Jessen 2016, pg. 3), the run-time of the XRD machine was 40 minutes/sample, with about 10 samples/day. Over the course of 50 weeks, the total run-time would be 1,667 hours/year. The operator stated that once the sample was loaded into the XRD machine, he would “close the shield” over the assembly, open the shutter to expose the sample, and then walk away. The operator’s time near the XRD machine after closing the shield and opening the shutter is estimated to be about 2 minutes per sample, or 5% of the time for a total exposure of 83.3 hours/year. Given this description of the XRD configuration and set-up procedure by one of the machine operators, the exposure to the hands and to the whole body are assumed to be the same. NIOSH considers this estimate conservative, as there were undoubtedly other operators who performed some portion of the total workload.

Assumptions:

1. The worker (operator) is exposed near the XRD machine for about 5% of the total run-time, or about 83.3 hours/year.

2. The worker (operator) is exposed to the scattered radiation, not the primary beam. Accidents involving the primary beam would have to be assessed separately on a case-by-case basis. Small, diffracted beams of 8 keV are assumed to be absorbed in the shield or covering over

the device and are not considered in the dose assessment. Leakage from the tube housing is assumed to be minimal, and therefore, is not considered in the dose assessment.

3. Scatter from the copper target and other components is emitted in all directions (isotropically) with an average energy of about 20 keV for a machine operated at 50 kV (Block, 1971, pg. 20).

Calculations:

1. Scattered radiation exposure rate at 30 cm from the nearest accessible surface: 2.0 mR/hour (Lubenau, et al., 1969).

2. Scattered beam exposure rate corrected for occupancy:

   a. Occupancy is estimated at 5% of total run-time of 1,667 hours/year, or 83.3 hours/year.

   b. Exposure rate to the whole body and the hands:

   $$2.0\frac{mR}{hour} * 83.3\frac{hours}{year} = 166.7\frac{mR}{year} = 0.1667 R/year$$

3. Conversion to air kerma (K_a)

   $$= 0.1667\frac{R}{year} * 8.76E-03\frac{Gy}{R} = 1.46E-03\frac{Gy}{year}$$

4. Organ Dose = $1.46E-03\frac{Gy}{year}$ * Organ Dose Conversion Factor (ICRP, 1997)

Table 1: Example of Organ Doses

Organ	Air Kerma (Gy/year)	ODCF[a] (Gy/Gy)	Equivalent Dose[b] (rem/year)
Lens of the Eye	1.46E-03	0.912	1.33E-01
Skin	1.46E-03	0.488	7.12E-02 rem
Thyroid	1.46E-03	0.358	5.23E-02 rem
Bladder	1.46E-03	0.0895	1.31E-02 rem

[a] ODCF is for absorbed dose per unit air kerma free-in-air for 20 keV photons, AP geometry, Tables A-2 through A-20 (ICRP, 1997).
[b] Organ dose converted from Gy to rad, then rad to rem with a radiation weighting factor of 1 for photons.

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ATTACHMENT:

NIOSH RESPONSE TO SC&A COMMENTS ON X-RAY DIFFRACTION AT CARBORUNDUM

June 7, 2016

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During the SC&A review of the SEC-00223 Carborundum Evaluation Report (SC&A 2016), reviewers raised various issues related to XRD. A summary of SC&A's XRD comments and the corresponding NIOSH responses are provided below.

Summary of SC&A comments:

1. Information provided in SEC-00223 ER, Section 7.3.3.1, not detailed enough for DR.
2. NIOSH assumed the worker's body was at or beyond the table edge, and hand dose would be higher.
3. A low energy correction factor should be applied to Lubenau's measured scatter value that is used by NIOSH as the starting point for dose assessment.
4. Lubenau's measured scatter value should be interpreted as an isotropic field measurement.
5. SC&A does not believe the XRD unit at Carborundum used a copper target.
6. Need specific DR methods for XRD.

Summary of NIOSH responses:

1. Agreed, NIOSH will provide a more detailed description of the DR method for assessment of dose from XRD at Carborundum:
   a. Start with the published exposure rate from scatter radiation.
   b. Estimate the exposure time based on information from the worker interview.
   c. Use ICRP 74 ODCF to calculate organ dose.
2. As a result of information obtained from a worker interview about the configuration of Carborundum's XRD machine, and the fact that the worker did not remain in the area, NIOSH did not see a need for a separate dose assessment to the skin of the hands.

3. Agreed, a low energy correction factor would need to be applied to measurements of low-energy X-rays in the 8-20 keV range (characteristic X-rays from copper). However, the new approach assumes the characteristic X-rays from copper are absorbed in the shield covering the XRD machine. The exposure to the operator is considered to be from an isotropic emission of scatter radiation with average energy of 20 keV. At this energy, the correction factor is approximately 1, and therefore, not used.
4. Agreed, Lubenau's measured scatter value will be interpreted as an isotropic field measurement.
5. Based on worker interviews and historical documents, NIOSH believes that Carborundum's XRD unit had a copper target.
6. NIOSH will develop specific DR methods for XRD.