



# Cancer and noncancer mortality among aluminum smelting workers in Badin, North Carolina

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## Abstract

**Background:** Badin, North Carolina, hosted an aluminum smelting plant from 1917 to 2007. The Concerned Citizens of West Badin reported suspected excess cancer mortality among former employees. This study aimed to investigate these concerns.

**Methods:** The study cohort was enumerated from United Steel Workers' records of workers employed from 1980 to 2007. Cause-specific mortality rates in the cohort were compared with North Carolina population mortality rates using standardized mortality ratios (SMRs), standardized by age, sex, race, and calendar period. We estimated cause-specific adjusted standardized mortality ratios (aSMRs) using negative controls to mitigate healthy worker survivor bias (HWSB). Standardized rate ratios (SRRs) were calculated to compare mortality rates between workers ever employed vs never employed in the pot room.

**Results:** All-cause mortality among Badin workers was lower than in the general population (SMR: 0.81, 95% confidence interval [CI]: 0.71-0.92). After adjusting for HWSB, excesses for all cancers (aSMR: 1.55, 95% CI: 1.10-2.21), bladder cancer (3.47, 95% CI: 1.25-9.62), mesothelioma (17.33, 95% CI: 5.40-55.59), and respiratory cancer (1.24, 95% CI: 0.77-1.99) were observed. Black males worked the highest proportion of their employed years in the pot room. Potroom workers experienced higher respiratory cancer (SRR: 2.99, 95% CI: 1.23-7.26), bladder cancer (SRR: 1.58, 95% CI: 0.15-15.28), and mesothelioma (SRR: 3.36, 95% CI: 0.21-53.78) mortality rates than never workers in the pot room.

**Conclusions:** This study responds to concerns of a group of former aluminum workers. The results, while imprecise, suggest excess respiratory and bladder cancers among pot room workers in a contemporary cohort of union employees at a US smelter.

## KEYWORDS

aluminum, cancer, mortality, occupational cohort

## 1 | INTRODUCTION

Production jobs at aluminum smelters involve demanding and difficult work under adverse environmental conditions.<sup>1,2</sup> Aluminum smelting poses a wide range of occupational hazards, including extreme heat,

airborne metal dusts, asbestos, polycyclic aromatic hydrocarbons (PAHs), silica, and other chemical vapors which can be absorbed through inhalation or contact with the skin.<sup>1,3-5</sup> Toxic work exposure constituents include asbestos, beryllium, coal tar pitch volatiles, lead, PAHs and others.<sup>1,3,5</sup> Aluminum smelting workers have also been shown

to experience a higher risk of injury due to exposure to physical hazards, such as heat and noise.<sup>1,3,6-9</sup> Exposures in the aluminum production industry cause bladder<sup>10-17</sup> and lung cancer<sup>14,16</sup> as classified by the International Agency for Research on Cancer (IARC),<sup>1</sup> in addition to being positively associated with other cancer sites, including central nervous system cancer<sup>3,6,18</sup> and cancer of the digestive system.<sup>3,18-20</sup>

The Concerned Citizens of West Badin (CCWB), a group of former aluminum smelter workers and their families in Badin, North Carolina, have voiced concerns about excess mortality among plant employees in oral histories, at state conferences, and before panels of government officials.<sup>21,22</sup> The aluminum smelting plant in Badin was established in 1913 and continued operations until 2007. During its peak of operations, the plant produced over 100 000 tons of aluminum annually.<sup>23</sup> Workers reported that the most dangerous jobs in the plant involved work in the pot room, and that these jobs were most frequently assigned to Black workers.<sup>22</sup> Specifically, community members have voiced concerns regarding a high prevalence of cancer in relation to work exposures at the plant.<sup>24</sup>

The analyses described here are part of a collaborative research project, in which the CCWB and the United Steel Workers (USW) union are active partners. They requested epidemiologic support to investigate these concerns. While some previous research is consistent with workers' reports (eg, pot room jobs being the most dangerous<sup>5,20,25</sup>), most epidemiological publications focus on company-initiated health and safety intervention effectiveness and advances in statistical methodologies.<sup>26-29</sup> Existing studies do not directly address the health concerns described by workers and community members in Badin, including racial disparities in worker exposures. Recent literature calls for increased use of the community-engaged participatory methodology in epidemiologic research to improve health equity.<sup>30</sup> Community-engaged methods are particularly underused in occupational epidemiology, given that workplace justice is of central importance for employee health and safety.<sup>31</sup>

The purpose of this study is to investigate concerns regarding excess and disparities in mortality among union members employed at the Badin aluminum smelting plant. Cause-specific mortality rates in the study cohort were compared with North Carolina general population rates, quantified as standardized mortality ratios (SMRs). We also estimated cause-specific adjusted standardized mortality ratios (aSMRs) using a negative control to adjust for unmeasured differences between the occupational cohort and the reference population related to healthy worker effects.<sup>32</sup> Finally, we estimated associations between time worked in the pot room and mortality rates overall and according to race and sex using standardized rate ratios (SRRs). This investigation involves de novo enumeration of a cohort with vital status and cause of death ascertainment.

## 2 | METHODS

### 2.1 | Study setting

The town of Badin is located in Stanly County, rural western North Carolina, near Charlotte. Badin was the site of an aluminum smelting

plant, operated by the Aluminum Company of America (now, Alcoa Inc), for most of the 20th century. The smelter in Badin was the major employer in the town for the entirety of its time of operation.<sup>23</sup> The workforce at the plant was unionized with the USW through the plant shutdown in 2007.<sup>33</sup> Despite being closed and employing no residents for over a decade, hazardous pollutants remain at the plant site and throughout the town as of 2020. Residuals from the smelting process known to be toxic—cyanide, fluoride, and polychlorinated biphenyls (PCBs)—leached from an unlined landfill and have been identified in Badin Lake,<sup>34,35</sup> a central recreational feature of the town. These environmental exposures also are of concern to these former workers, as Badin is a company town where many workers and their families lived and continue to live after operations at the smelter ceased.

### 2.2 | Study population

The study cohort includes 754-hourly USW members employed at the Badin smelting plant. The cohort was enumerated for this study from seniority records collected and stored by the USW, Local 303; due to limitations of available union records the study cohort is restricted to workers employed between 1980 and 2007. There is no available record of total employees during the Badin plant's peak production period, but we believe the study period overlaps with high production years. A second dam was constructed for additional hydropower in 1962,<sup>36</sup> and Alcoa conducted a major layoff (377 workers) in 2002.<sup>34</sup> Seniority records were collected at least once per year to evaluate incidents, complaints, and payroll and membership changes. All hourly USW members employed between 1980 and 2007 were included in analyses—no restrictions based on the duration of employment or otherwise were applied. Full name, department, and social security number (SSN) were available for workers ever employed between 1980 and 2007. Records also included work histories with month and year start dates for the company and department, including the "pot room." The continued presence of a worker on the USW Local 303 seniority records was interpreted as a continuation of active work at the Badin plant. Workers were allowed to accumulate active work time after the absence of documentation if documentation was present on subsequent records.

The current USW president for the Local 303 gave access to paper seniority records with permission from the regional supervising team. The USW president and study team are not aware of any missing records during the study period. Three members of the study team scanned the seniority records on site over 2 days in March 2018. The images were then processed through text recognition software and converted to text files. Three study team members manually cleaned the text files for fidelity based on the scanned images to ascertain each individual's name and SSN from May to August 2018.

A commercial database (LexisNexis Accurint) was used to obtain birth date, sex, and race for workers in the cohort. The search

included driver's license and the US voter registration databases and was conducted using a complete name and SSN. The search provided birth date and sex for all individuals in the cohort and provided information on the race for 93% of individuals. Of those missing race data who were deceased, the race was obtained from the death certificate, leaving 30 workers with missing race information (4%). The race was identified by name for the remaining 30 workers by members of the concerned citizens who knew them. LexisNexis searches and worker reports indicate that the vast majority of non-White workers at the Badin plant identified racially as Black and are, therefore, referred to as Black throughout.<sup>22</sup> There were no exclusions applied to the study cohort due to missing data. The study protocol was approved by the University of North Carolina Institutional Review Board.

## 2.3 | Exposure characterization

The USW data include department histories for workers in the cohort. However, no agent-specific exposure information, industrial hygiene monitoring data, or job-specific work histories were available for this study. Therefore, we conducted analyses based on comparisons of those ever employed as hourly, USW members at the Badin Alcoa plant between 1980 and 2007 to an external reference population. Because of the potential for a broad range of hazards and toxic exposures, as well as limited chemical exposure measurement data, this approach is similar to several prior studies on aluminum smelting work and health which have characterized exposure simply as ever employment in an aluminum smelting plant.<sup>29,37</sup>

In addition, we conducted internal analyses using employment in the pot room as a proxy for potential exposure to hazards associated with pot room processes. This proxy was informed by both worker testimony and previous studies. Two of the authors (PV and EM) participated in several CCWB meetings and interviews with former workers. In these conversations, former workers in Badin report that the most dangerous and highest exposure jobs in the plant involved laboring in the potrooms with combusting petroleum and inhalation of black soot, and that these jobs were most frequently assigned to Black workers. The workers assigned to these tasks were informally known as "the bull gang," although their official job titles were varied.<sup>22</sup> Workers describe exposure to extreme heat as well as concerns about asbestos and toxic chemicals involved in the repair of and waste management related to spent pots at the plant.<sup>24</sup> Scientific literature also suggests that jobs in the pot room are the most hazardous at an aluminum smelting plant. Workers in pot room production jobs are likely to have elevated exposure to carcinogens, heat, and other agent classes of concern here (eg, PAHs including benzo-a-pyrene, sulfur dioxide, and trace metals including chromium and nickel), relative to those working in other departments.<sup>5,20,25,38</sup>

The two most common pot room technologies are (a) the "Soderberg," method in which coke-pitch paste is fed into pots and baked, and (b) the "prebake" method, in which coke-pitch paste is baked into a solid in a separate carbon plant before use in the pots.

Emissions are much higher when the Soderberg process is used,<sup>39</sup> but the prebake method is associated with greater peak particulate matter exposure potential and higher task-related exposure variability.<sup>40</sup> The Badin plant used the prebake method during the entire study period.

## 2.4 | Mortality and cause of death ascertainment

The vital status of the study cohort was ascertained through 31 December 2017 using the National Death Index (NDI). All 754 workers were searched in the NDI from 1980 to 2017, using name, SSN, date of birth, sex, and race. The NDI provided the date of death and underlying cause of death codes listed on the death certificate of decedents. The NDI probabilistically identified decedents, and we included all those designated as "likely matches," with probabilities above the threshold imposed by the NDI.<sup>41</sup> Of the likely matches, date of birth and sex were concordant with a date of birth obtained from LexisNexis. The race was discordant among four workers, and these were verified with concerned citizens members who knew the decedents. The underlying cause of death code was classified according to the International Classification of Diseases revision that was in effect at the time of death.<sup>41</sup> Individuals not identified as deceased in the NDI as of 31 December 2017 were presumed to be alive.

## 2.5 | Statistical analysis

We estimated all-cause and cause-specific SMRs using the National Institute of Occupational Safety and Health's Life Table Analysis System (NIOSH LTAS).<sup>42</sup> The SMR serves as a summary measure of the USW study population's mortality experience relative to that of the general population in North Carolina. It is the ratio of observed deaths in the USW study population to the expected deaths had the study population experienced the mortality rate of the general North Carolina population over the same time period. Expected deaths are estimated within strata of age, race, and sex distribution to remove any confounding effect of these factors.<sup>43</sup> Assumptions required for this interpretation are (a) that the person-time distribution in the study population would have been the same in the absence of work exposures and (b) that the reference mortality rates represent the rates the cohort would have experienced in the absence of exposure.<sup>32,44</sup> For all SMRs, cause of death categories are based on the NIOSH-119 underlying cause of death classification scheme.<sup>41</sup>

Workers' person-time at risk of mortality in the study cohort began accumulating on the first observed date of hire or on 1 January 1980 if hire occurred before that date. Follow-up ended on 31 December 2017 for those presumed alive and on the date of death for decedents. Person-time at risk was stratified by years of work in the pot room (never, ever, 0-5 years, 5-years, and <10 years), attained age (5-year groups), calendar period of hire (5-year intervals), sex (male and female), and binary race (White and Black). Referent rates

were based on North Carolina mortality rates in the general population from 1980 to 2017. All-cause and cause-specific SMRs were stratified by race and sex to assess disparities in mortality patterns. We calculated confidence limit ratios (CLRs) for cause-specific SMRs by taking the absolute value of the ratio of upper to lower confidence bounds to provide a readily comparable indication of precision for each SMR.

We used a negative control to adjust for healthy worker effects, a known limitation of SMRs wherein the SMR may be biased in worker populations, because working populations tend to be healthier (and, therefore, tend to have lower mortality rates) than the general population.<sup>45,46</sup> A negative control adjusted estimate of the SMR may reduce bias related to healthy worker effects by reproducing a condition that involves the same healthy worker selection effect but does not involve the causal effect of work exposure. The aSMR is estimated by comparing the observed cause-specific mortality rates in the worker population to cause-specific mortality rates in the worker population that satisfy these bias reduction conditions.<sup>32</sup>

All cancer, bladder cancer, mesothelioma, respiratory cancer, and nonmalignant respiratory disease (chronic obstructive pulmonary disease and asthma)-specific aSMRs were estimated using negative control mortality rates from the worker cohort. These causes were identified as outcomes of interest a priori because they have been associated with known workplace exposures at the Badin smelter and other plants with similar processes in previous studies<sup>1,10,20,28,38,47-53</sup> and/or were of specific concern among former workers.<sup>24</sup> To meet the assumptions required to reduce healthy worker bias in the aSMR, negative control causes of death were chosen that were (a) unlikely to be affected by smelting work exposures and (b) shared the sources and directions of healthy worker survivor bias as the causes of death of interest.<sup>32</sup> The negative control causes of death included: nonmalignant disorders of blood and blood-forming organs, diabetes mellitus, mental and psychological disorders, nervous system disorders, diseases of the circulatory system (other than heart disease), diseases of the digestive system, diseases of the skin and subcutaneous system, diseases of the musculoskeletal and connective system, and diseases of the genitourinary system. For adjusted estimates, the negative control mortality rates are used in place of the referent rates when estimating the SMR. aSMRs were estimated using SAS<sup>32</sup> (SAS Institute Inc, Cary, NC).

We used SRRs to compare all-cause mortality and select mortality causes defined a priori (all cancer, bladder cancer, mesothelioma, respiratory cancer, and respiratory disease) among individuals who ever worked in the pot room to that among those who never worked in the pot room. Comparisons were also made according to the duration of employment in the pot room. SRRs were used rather than SMRs, because SMRs for two different groups are not readily comparable due to the use of different standards of age and demographic characteristics in each group. SRRs are mutually standardized to the covariate distribution of the total cohort. Distributions of person-time worked in the pot room by race and sex, alongside the pot room

SRRs were estimated to assess disparities in mortality related to work in the pot room and workplace segregation. SRRs were estimated using LTAS.<sup>41</sup>

### 3 | RESULTS

Table 1 shows the characteristics of the study cohort. The cohort of 754 workers had a median age of 33 (25th percentile, 75th percentile: 28-40) at the beginning of follow-up and was mostly male (94%). A total of 493 (65%) of the workers were White, with 35% identifying as Black or other (96% Black and 4% other). At the end of follow-up, 31 December 2017, 507 (67%) of the cohort was presumed to be alive, while 247 (33%) were deceased. The cohort had a median of 31 (25th percentile, 75th percentile: 26-36) years of follow-up and a median attained the age of 67 (25th percentile, 75th percentile: 60-74) at the end of follow-up. The oldest presumed alive worker at the end of follow-up was 95. Black males spent a disproportionate amount of time working in pot rooms compared to their White counterparts. Black males spent 38.5% of their total employed person-time in pot rooms compared to 19.9% among White males, 7.6% among White females, and 15.6% among Black females. The full cohort spent 25.5% of employed person-years in the pot room. A total of 479 (64%) of the cohort was already employed in 1980, and 275 (36%) were hired in or after 1980 (incident hires). Incident hires had a lower median age at the start of follow-up (24; 25th percentile, 75th percentile: 18, 32) than the full cohort (33; 25th percentile, 75th percentile: 28, 40). Race and sex distributions were similar: 31% of incident hires were Black, compared to 34% in the full cohort; and 8% were female compared to 6% in the full cohort. The full cohort accrued a median of 13 (25th percentile, 75th percentile: 6-17) active work years during the study period.

#### 3.1 | Standardized mortality ratios

Table 2 shows all-cause and cause-specific mortality relative to the North Carolina general population. After standardizing for age, race, sex, and calendar period, the all-cause mortality rate in the overall worker population was lower than that in the general population of North Carolina (SMR: 0.81, 95% confidence interval [CI]: 0.71-0.92, CLR: 1.30). However, there was imprecise evidence of excess mortality due to mesothelioma (SMR: 15.00, 95% CI: 3.82-40.82, CLR: 10.69), bladder cancer (SMR: 2.27, 95% CI: 0.62-5.82, CLR: 9.39), urinary cancer (SMR: 1.52; 95% CI: 0.56-3.30, CLR: 5.89) cancer of male genital organs (SMR: 1.42, 95% CI: 0.71-2.55, CLR: 3.59), multiple myeloma (SMR: 1.65; 95% CI: 0.34-4.81, CLR: 14.15), and leukemia (SMR: 1.93, 95% CI: 0.63-4.49, CLR: 7.13). Combining urinary tract and bladder cancer (both are predominantly transitional cell carcinomas<sup>54</sup>), the SMR is 1.72 (95% CI: 0.88-3.07, CLR: 3.49). There were relatively fewer deaths than expected due to heart disease (SMR: 0.84, 95% CI: 0.65-1.07, CLR: 1.65) and other diseases of the circulatory system (SMR: 0.49, 95% CI: 0.25-0.86, CLR: 3.44).

**TABLE 1** Descriptive characteristics of 754-hourly USW members ever employed<sup>a</sup> at the aluminum smelting facility from 1980 to 2007 in Badin, North Carolina

Characteristic	Black female	Black male	White female	White male	Total
Total number of workers, N	19	238	29	468	754
Presumed alive at end of follow-up, n (%)	14 (74)	134 (56)	27 (93)	332 (71)	507 (67)
Deceased at end of follow-up, n (%)	5 (26)	104 (44)	2 (7)	136 (29)	247 (33)
Age beginning of follow-up, median (25th percentile, 75th percentile)	33 (30, 35)	35 (28, 41)	30 (25, 37)	33 (27, 40)	33 (28, 40)
Attained age at end of follow-up, median (25th percentile, 75th percentile)	66 (57, 69)	68 (61, 75)	63 (59, 69)	67 (60, 74)	67 (60, 74)
The median duration of follow-up, (25th percentile, 75th percentile)	34 (28, 36)	29 (23, 36)	34 (26, 36)	33 (27, 36)	31 (26, 36)
Person-years of active employment, n	218	2791	225	5456	8690
Ever worked in the pot room, n (%)	6 (32)	132 (55)	5 (17)	203 (43)	346 (46)
Never worked in the pot room, n (%)	13 (68)	110 (45)	24 (83)	261 (57)	408 (54)
Person-years of active employment in the pot room, n (%)	34 (15.6)	1075 (38.5)	17 (7.6)	1087 (19.9)	2213 (25.5)
Person-years of active employment not in the pot room, n (%)	184 (84.4)	1716 (61.5)	208 (92.4)	4369 (80.1)	6477 (74.5)

Abbreviation: USW, United Steel Workers.

<sup>a</sup>One day or more of continuous employment in the plant.

There was relatively lower mortality among both Black men (SMR: 0.80, 95% CI: 0.65-0.96) and among White men (SMR: 0.82, 95% CI: 0.69-0.97) than expected based on reference population rates. Black females in the study cohort experienced more deaths than would have been expected based on North Carolina reference rates (SMR: 1.23, 95% CI: 0.40-2.86), and Black males experienced more deaths due to cancer than would have been expected (SMR: 1.11, 95% CI: 0.79-1.51). Only two deaths occurred among the 29 White females in the study cohort, whereas four were expected. Because of the small cohort size and sparse numbers in stratified estimates, detailed race and sex-stratified SMRs are not shown.

Table 3 reports observed all cancer, bladder cancer, mesothelioma, respiratory cancer, and respiratory disease mortality in the study cohort relative to the negative control mortality reference rates in the study cohort. The SMR for the negative control outcomes in the study cohort was 0.65 (95% CI: 0.50-0.87). The adjusted all cancer SMR is 1.55 (95% CI: 1.10-2.21) after correcting for healthy worker bias, suggesting excess cancer mortality among USW-member workers at the Badin aluminum plant. The aSMRs also indicated excesses of bladder cancer and mesothelioma mortality (aSMR: 3.47, 95% CI: 1.25-9.62 and aSMR: 17.33, 95% CI: 5.40-55.59, respectively).

### 3.2 | Standardized rate ratios

Table 4 shows SRRs comparing rates of all-cause and cause-specific mortality among ever pot room workers to those among workers in the cohort who never worked in the pot room. Ever workers in the pot room had higher all-cause mortality (observed cases: 89) than never pot room workers (observed cases: 158) (SRR: 2.83, 95% CI:

0.88-9.10). Ever workers in the pot room also had higher cancer mortality (observed cases: 35) than never pot room workers (observed cases: 51) (SRR: 1.48, 95% CI: 0.92-2.39). Workers who ever worked in the pot room had higher rates of respiratory cancer mortality (observed cases: 13) than never pot room workers (observed cases: 11) (SRR: 2.99, 95% CI: 1.23-7.26). Relative to never pot room workers, those who worked 0 to 5 years in the pot room had elevated respiratory cancer mortality rates (SRR: 2.28, 95% CI: 0.66-7.81), and the excess was more extreme among workers who spent 5 to 10 years in the pot room (SRR: 4.27, 95% CI: 1.17-15.62). Those with over 10 years in the pot room had lower respiratory cancer mortality than the never pot room workers (SRR: 0.71, 95% CI: 0.19-2.69).

## 4 | DISCUSSION

All-cause mortality in the study population of USW members working at the Badin smelter was lower than that of the general North Carolina population, adjusted for age, sex, race, and calendar year. This is consistent with other studies of SMRs comparing aluminum smelting workers' mortality patterns to those in general populations.<sup>50,52</sup> However, the cohort experienced excess mortality due to bladder cancer and mesothelioma, causes identified a priori to be of concern based on exposure to PAHs and asbestos, respectively, in production processes<sup>24</sup> and the IARC classification of exposures in this industry as carcinogenic to the bladder.<sup>1</sup> These findings are based on only four and three deaths, respectively. Elevated rates for other causes of interest were indicated, including cancers of the urinary tract, male reproductive cancer, and leukemia/lymphoma mortality.<sup>55</sup> While the numbers of deaths due to these causes are

**TABLE 2** Standardized mortality ratios comparing cause-specific mortality among 754 USW members ever employed from 1980 to 2007 to North Carolina referent rates<sup>a</sup>

Cause of death	Obs	SMR	95% CI	CLR
All causes	247	0.81	0.71, 0.92	1.30
All cancers	86	1.02	0.81, 1.26	1.56
Buccal and pharynx	2	1.00	0.12, 3.61	30.08
Digestive and peritoneum	19	0.94	0.57, 1.47	2.58
Esophagus	3	0.97	0.20, 2.82	14.10
Liver, biliary passages, and gall bladder	2	0.67	0.08, 2.42	30.25
Respiratory	24	0.75	0.48, 1.12	2.33
Trachea, bronchus, and lung	23	0.75	0.48, 1.13	2.35
Mesothelioma <sup>b</sup>	3	15.00	3.82, 40.82	10.69
Male genital organs	11	1.42	0.71, 2.55	3.59
Urinary	6	1.52	0.56, 3.30	5.89
Kidney	2	0.91	0.11, 3.29	29.91
Bladder and other urinary site	4	2.27	0.62, 5.82	9.39
Lymphatic and hematopoietic	9	1.28	0.58, 2.43	4.19
Non-Hodgkin's lymphoma	1	0.41	0.01, 2.28	228.00
Multiple myeloma	3	1.65	0.34, 4.81	14.15
Leukemia	5	1.93	0.63, 4.49	7.13
Other and unspecified	7	1.14	0.46, 2.34	5.09
Diseases of the respiratory system	17	0.69	0.40, 1.10	2.75
Chronic obstructive pulmonary disease	10	0.74	0.35, 1.36	3.89
Asthma	1	2.33	0.06, 13.01	216.83
Heart diseases	66	0.84	0.65, 1.07	1.65
Hypertension with heart disease	4	0.94	0.25, 2.40	9.60
Ischemic heart disease	49	0.84	0.62, 1.11	1.79
Conduction disorder	3	0.68	0.14, 1.98	14.14
Other heart diseases	3	0.61	0.12, 1.77	14.75
Other diseases of the circulatory system	12	0.49	0.25, 0.86	3.44
Cerebrovascular disease	11	0.69	0.34, 1.23	3.62
Diseases of the arteries, veins, and lymph	1	0.17	0.00, 1.47	147.00
Diseases of the genitourinary system	4	0.55	0.15, 1.40	9.33
Acute glomerulonephritis and renal failure	1	1.05	0.03, 5.84	194.67
Chronic nephritis and renal failure	2	0.43	0.05, 1.57	31.40
Diseases of the digestive system	10	0.77	0.37, 1.41	3.81
Cirrhosis and other liver diseases	6	0.97	0.36, 2.11	5.86
Other diseases of the digestive system	4	0.73	0.20, 1.86	9.30
Nervous system disorders	9	1.09	0.50, 2.07	4.14
Other nervous system diseases	9	1.13	0.52, 2.15	4.13

**TABLE 2** (Continued)

Cause of death	Obs	SMR	95% CI	CLR
Mental and psychiatric disorders	1	0.11	0.00, 0.64	64.00
Diabetes mellitus	7	0.70	0.28, 1.45	5.18
Diseases of skin and subcutaneous tissue	2	4.33	0.52, 15.66	30.12
Diseases of blood and blood-forming organs	4	2.72	0.74, 6.97	9.42
Transportation injuries	3	0.42	0.09, 1.24	13.78
Falls	1	0.47	0.01, 2.64	264.00
Other injury	5	0.72	0.23, 1.67	7.26
Violence	7	0.83	0.33, 1.70	5.15
Intentional self-harm	6	1.17	0.43, 2.55	5.93
Symptoms and ill-defined conditions	3	1.53	0.32, 4.48	14.00
Other and unspecified causes	10	0.93	0.44, 1.71	3.89

Note: Confidence limit ratio—the absolute value of the ratio of upper to lower confidence bounds.

Abbreviations: CI, confidence interval; CLR, confidence limit ratio; Obs, observed number of deaths in study cohort; SMR, standardized mortality ratio; USW, United Steel Workers.

<sup>a</sup>SMRs standardized by age, sex, race, and calendar year.

<sup>b</sup>Pleural cancer and mesothelioma deaths are combined.

small, the patterns are consistent with observations in prior studies of smelters. Cancer, and specifically bladder cancer and mesothelioma, have documented associations with smelting work.<sup>1,10,22,28,38,52</sup> Soot is a known cause of scrotal cancer.<sup>56</sup> Benzene and other PAHs as well as PCBs (which are potential occupational hazards in the aluminum smelting industry, and also may be environmental hazards in Badin as these agents have been detected in Badin site wastewater evaluations<sup>34,35</sup>) have been associated with lymphatic and hematopoietic cancers.<sup>57-60</sup>

Black workers spent a greater proportion of their employed person-years in the pot room than White workers. Black female workers at the Badin smelter experienced excess mortality overall, relative to the general population of North Carolina, and Black male workers experienced excess death due to cancer. These findings support the narratives of former workers that were collected as qualitative evidence to contextualize the quantitative findings of the current study; we note some of those here as they were collected to afford the opportunity for the investigators to get feedback from the workers themselves.<sup>22</sup> SRRs comparing mortality among workers with more time in the pot room to that among those who never worked in the pot room provide support for former workers' concerns related to long-term employment in dangerous conditions at the plant. Workers ever employed in the pot room had 1.5 times the rate of cancer mortality as never pot room workers. They reference that the "25 year club," which came with some corporate benefits and was only opened to Black workers after establishment of the Badin USW Local 303 division in the 1960s,<sup>61</sup> was often referred to as

**TABLE 3** Standardized mortality ratios for deaths due to select causes of death among USW members ever employed from 1980 to 2007 adjusted using negative control outcomes observed in the same cohort<sup>a</sup>

Cause of death	Obs	Adjusted SMR (95% CI)
Negative control outcomes <sup>b</sup>	58	1.0 (ref)
All cancers	86	1.55 (1.10, 2.21)
Bladder and other urinary site	4	3.47 (1.25, 9.62)
Mesothelioma <sup>c</sup>	3	17.33 (5.40, 55.59)
Respiratory	24	1.24 (0.77, 1.99)
Diseases of the respiratory system	17	1.05 (0.61, 1.82)

Abbreviations: CI, confidence interval; Obs, observed number of deaths in study cohort; SMR: standardized mortality ratio; USW, United Steel Workers.

<sup>a</sup>SMRs standardized by age, sex, race, and calendar year.

<sup>b</sup>Negative control outcomes were: nonmalignant disorders of blood and blood-forming organs, diabetes mellitus, mental and psychological disorders, nervous system disorders, diseases of the circulatory system (other than heart disease), diseases of the digestive system, diseases of the skin and subcutaneous system, diseases of the musculoskeletal and connective system, and diseases of the genitourinary system. Standard SMR for the combined outcomes: 0.65 (95% CI, 0.50-0.87).

<sup>c</sup>Pleural cancer and mesothelioma deaths are combined.

“the graveyard,” because so many workers died after working in the plant for 25 years. However, we do not see a positive dose-response with regard to pot room work, as workers with the longest pot room work time had lower mortality than never pot room workers. Our findings are consistent with previous studies suggesting that the pot room process entails greater worker exposure to carcinogens than others at the plant.<sup>5,20,25,38</sup> Much of the literature distinguishes between the two most common smelting approaches with regard to carcinogenicity. Workers' exposure to emissions are higher when using the “Soderberg” method,<sup>62</sup>

**TABLE 4** Standardized rate ratios comparing mortality due to select causes of death among USW members ever employed from 1980 to 2007 who worked in the pot room to workers who never worked in the pot room<sup>a</sup>

Cause of death	Pot room SRR (95% CI) (Obs)	
	Never	Ever
All cause	1.0 (ref) (158)	2.83 (0.88, 9.10) (89)
All cancer	1.0 (ref) (51)	1.48 (0.92, 2.39) (35)
Bladder and other urinary site	1.0 (ref) (3)	1.58 (0.15, 15.28) (1)
Mesothelioma <sup>b</sup>	1.0 (ref) (2)	3.36 (0.21, 53.78) (1)
Respiratory	1.0 (ref) (11)	2.99 (1.23, 7.26) (13)
Nonmalignant respiratory disease	1.0 (ref) (15)	0.33 (0.07, 1.71) (2)

Abbreviations: CI, confidence interval; Obs, observed number of deaths in study cohort; SRR, standardized rate ratio; USW, United Steel Workers.

<sup>a</sup>Estimates are standardized by age, sex, race, and calendar.

<sup>b</sup>Pleural cancer and mesothelioma deaths are combined.

but the prebake method (which was used at the Badin plant during the study period) is associated with higher peak particulate matter exposures and greater variability in particulate exposure by job task.<sup>40</sup> Our study provides evidence of elevated cancer risk among pot room workers despite the use of a smelting method that is generally presumed to be safer with regard to carcinogenic exposures.<sup>3,39</sup>

The reduced all-cause mortality in this study cohort relative to the general population may be due to healthy worker biases, as this has been documented in similar occupational cohort studies.<sup>32</sup> Furthermore, the rates of mortality and poverty were high in North Carolina, relative to the general US population during the study period.<sup>63,64</sup> Individuals in the study cohort were able to obtain employment in a unionized plant, where they likely gained access to better health and retirement benefits as well as higher income than the general population. This is likely to have conferred mortality advantages within the study population that limit their comparability to general population reference rates. aSMR estimates attempt to mitigate biases related to unmeasured differences between the study cohort and the general population of North Carolina.

If the assumptions of our negative control choice are met, that is, (a) the negative control causes are not influenced by work exposures, (b) the same healthy worker survivor bias affects the negative control causes as the causes of interest, and (c) the bias is in the same direction and of similar magnitude for the negative control and causes of interest, then the aSMRs represent less biased estimates than the SMRs using the external population reference rates. There are exposures likely to be encountered in aluminum smelting work that may cause some of the outcomes we included in our negative control reference rates. If these effects exist, it would likely attenuate the aSMR by making the mortality patterns in the negative controls look more similar to those among the causes of interest. Our aSMR results suggest occupationally associated excesses of mortality due to all cancer, bladder cancer, and mesothelioma, and they also provide support for excess respiratory cancer and other respiratory disease-related mortality. Previous studies have documented excess respiratory disease and cancer incidence among aluminum smelting workers.<sup>20,25,50,51</sup> Moreover, the results are consistent with the general conclusions of IARC, which classifies aluminum smelting occupational exposures as a group 1 carcinogen indicating “sufficient evidence of carcinogenicity in humans.”<sup>1,2</sup>

The mortality deficit we find among Black men relative to the general population may be due to a greater difference in mortality between workers and the general population among Black than White men and a higher all-cause mortality rate among Black men than White men in the general population. A similar property of these disparities has been observed in previous southern occupational cohort studies in the US south during similar time periods to this study.<sup>65</sup>

Our findings are consistent with “inverse hazard law,” as described by Krieger et al. The inverse hazard law states that “the accumulation of health hazards tends to vary inversely with the power and resources of the populations affected.”<sup>66,67</sup> This structural bias manifests in the epidemiologic study in the form of data

limitations and affects who is included in the study population. For example, former workers expressed concerns about take-home exposures related to laundering of clothing worn in the pot room. However, we do not have a mortality follow-up on family members of the workers in the study.

This study has several limitations, the first of which is the lack of specific exposure quantification. There is consistency in former workers' reports about specific agents of concern, but the prevalence and intensity of exposures in the cohort over time has not been quantified. This limited our ability to make mortality comparisons within the Badin workforce with respect to exposure. However, we were able to characterize mortality relative to work time in the pot room, a department known to be more dangerous than other smelting departments.<sup>5,20,22,24,25,38</sup>

Second, the small numbers of some cancer outcomes reduced statistical precision and limited our ability to make a reliable inferences from stratified estimates. Specifically, it precluded our ability to conduct stable race and sex-stratified analyses. A large proportion of the cohort was younger at the end of follow-up than the typical age at which some causes of disease result in fatality. For example, the median attained age at the end of follow-up is 67 while the national median age at lung cancer diagnosis is 70.<sup>68</sup> We plan to update this cohort in the future to improve the statistical precision of estimates.

Third, the data were collected for administrative purposes and did not include some relevant information to our research questions. Specifically, we have no smoking or other behavioral health-related data to contextualize the mortality outcomes examined. In addition, the source of the data (union records) included only hourly union member workers at the plant. When workers transitioned into salaried positions, moved away, or retired, they were all censored from the cohort, and we had no way to account for different reasons for termination.

While this study addresses community concerns about mortality, mortality studies have a general limitation of not reflecting the underlying burden of disease in populations. This is particularly salient when interpretations regard mortality as a proxy for morbidity, especially for nonfatal conditions and diseases with long periods of morbidity. Under registration of some causes of death is known to affect several diseases of interest to former workers, including lung and bladder cancer.<sup>69</sup> Death certificate coding also has documented misclassification of disease diagnoses associated with the cause of mortality.<sup>70,71</sup> Diseases of interest were captured in our analyses only if they were reported as underlying causes on the death certificate.

The strengths of this study include that it used available data to address the concerns of former workers at the Badin aluminum smelting plant. It involved the enumeration of a novel cohort and preliminary analysis of mortality with the potential for further follow-up in the future. The work history records ranged 27 years, covering a relevant period of exposure for concerned former workers. The cohort was followed for a median of 31 years—adequate time to

ascertain mortality related to most causes of interest. In addition, we used advanced statistical methodological techniques for dealing with healthy worker biases—calculation of aSMRs using negative controls. This study contributes a novel internal comparison of mortality rates between workers who ever worked in the pot room and other plant employees. This study also includes an exposure assessment process involving input from the USW and CCWB. The research substantiates and documents workplace injustices in the pot room that are consistent with worker complaints<sup>24</sup> and involves an application of community-based participatory methods which are underused in occupational epidemiology.<sup>31,72,73</sup>

Our study suggests that this study cohort of hourly, union-member aluminum workers experienced higher rates of bladder cancer and mesothelioma mortality than the general population of North Carolina, standardized by sex, age, race, and calendar period. However, the SMRs for these outcomes are based on small numbers. Black females experienced excess all-cause mortality, and Black males experienced excess cancer mortality relative to the general population. Workers in the pot room experienced more all-cause and cancer mortality than those who never worked in the pot room. After adjusting for healthy worker survivor bias, we found that the study population had elevated rates of all cancer, bladder cancer, and mesothelioma mortality—all causes of a priori interest due to worker concern and previous scientific findings.<sup>1,10,22,24,28,38,52</sup> Former workers at the plant and their families have expressed concerns related to cancers, as well as race and sex disparities in harmful work exposures.<sup>22</sup> These findings provide the foundation for future mortality follow-up of this cohort and potential follow-up of broader worker and family cohorts at risk of aluminum smelting work exposures.

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## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

## DISCLOSURE BY AJIM EDITOR OF RECORD

John D. Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

## AUTHOR CONTRIBUTIONS

ESM conceptualized and designed the study, drafted the initial manuscript, analyzed the data, created the tables and figures,

assisted with the literature review synthesis, and approved the final manuscript as submitted. PV contributed to the data collection, provided content to the analysis, assisted with the literature review, contributed to editing of the manuscript, and approved the final manuscript as submitted. ND contributed to the data collection, assisted in study design, provided commentary on the analysis, contributed to editing of the manuscript, and approved the final manuscript as submitted. WRR assisted in conceptual and analytic design, advised on the analytic strategy, provided commentary on the analysis, contributed to editing of the manuscript, and approved the final manuscript as submitted. SWM advised on analytical strategy, contributed to editing of the manuscript, and approved the final manuscript as submitted. DR provided overall supervision and guidance of the present analysis, assisted in conceptual and analytic design, advised on the analytic strategy, provided commentary on the analysis, contributed to editing of the manuscript, and approved the final manuscript as submitted.

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