

Commentary

Keeping Beryllium Workers Safe: An Enhanced Preventive Model

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BACKGROUND

In the late 1990s, leaders in a company that manufactures beryllium materials began a process to re-examine the effectiveness of the existing beryllium safety model. This model was based on the primary goals of keeping worker exposure below $2 \mu\text{g}/\text{m}^3$ time-weighted average (TWA) as determined by the daily weighted-average (DWA) method and prevention of beryllium migration to home and the community.

The company initiated a series of medical surveillance projects, partnering with independent academic and government institutions. The response to findings of patterns of subclinical chronic beryllium disease and beryllium sensitization as measured by the beryllium blood lymphocyte proliferation test was the continuation of traditional process isolation and ventilation engineering to improve air level control. Additional medical surveillance suggested that the efficacy of this approach was limited.

An enhanced safety model was evolved that included very strict control of respiratory exposure, reduction of skin exposure, and migration control at three levels: process, work area, and plant boundaries; maintenance of workplaces in clean and shipshape condition; and worker education. Rather than prioritize with a strict hierarchy of controls, a multifaceted approach to worker protection was adopted, using the slogan “Protect people first, then solve the problem.” Concepts of statistical process control, usual and special variation, were adapted to respiratory protection management and integrated with AIHA exposure guideline tools.

The rate of beryllium sensitization in new employees hired after implementation of the enhanced beryllium safety model was substantially reduced compared with its prevalence in the prior surveys. Because the company implemented multiple changes in a short time, the contribution of individual components of the model cannot be estimated.

INTRODUCTION

The recognition of the varied toxicity of beryllium in the United States^(1,2) was quickly followed by the specific

recognition of clinical chronic beryllium disease (cCBD) as a severe illness with shortness of breath, cough, wheeze, fatigue, night sweats, and weight loss in fluorescent lamp manufacturing workers.⁽³⁾ Investigations were promptly undertaken by the U.S. Atomic Energy Commission (AEC) with the full cooperation of this company.^(4–6) These investigations culminated in the recognition that CBD was an immune mediated disease,^(7,8) and the establishment of a workplace beryllium exposure standard of $2 \mu\text{g}/\text{m}^3$ 8-hour time-weighted average (TWA) by the AEC,⁽⁹⁾ which was successively adopted by AIHA, ACGIH[®], ANSI, and OSHA.

The DWA⁽¹⁰⁾ was used initially to determine compliance with the workplace standard. The DWA was calculated over a quarter-year time frame by weighting hand-held breathing zone task samples and general area samples by average time spent on tasks. A community exposure standard of $0.01 \mu\text{g}/\text{m}^3$ 30-day average was also developed and was successively adopted by ANSI and the U.S. EPA.

Beryllium was abandoned as a component of fluorescent lamp phosphors in 1949, and the industry initiated efforts to be in compliance with the workplace and community exposure standards. Precautions were introduced to reduce beryllium being taken home on workers' clothes. The number of new cases of clinical CBD recognized in the United States declined rapidly. As a consequence, the workplace standard was considered effective.^(6,9) Therefore, the company continued to adhere to the initial preventive model, which focused on the following:

- investigation of elevated air samples
- process and ventilation engineering to meet the standard
- use of personal respiratory protection devices (respirators) to limit exposures encountered with difficult to control tasks, maintenance tasks, and upset conditions
- engineering to prevent release via air into the community and practices to prevent workers carrying beryllium home, such as wearing of company-provided work clothing and showering and changing clothes at the end of work shifts.

Despite these programs the company continued to recognize new cases of cCBD among current and former workers: 0–3 per year with an average 1.4 per year from 1945 to 1985. This was equivalent to an all-employee cCBD lifetime cumulative incidence rate of 1–2%, consistent with the literature quoted rate of 1–5%. Investigation of these cases elicited, in most instances, a history of an accident or incident of possible overexposure. To control such incidents, the company implemented an investigative process of the task samples used in the DWA calculations followed by engineering improvements or temporary control measures. Also, continuous fixed head, general area monitoring was installed in areas where incidents were most likely. When 8- or 24-hour samples indicated unacceptable results, respiratory protection was implemented when indicated, investigation was initiated, and return of the area to usual conditions was documented with further sampling.

Intrinsic to this process was the assumption that because CBD is a lung disease, inhalation exposure was the chief concern. Migration of beryllium within the facility was tolerated insofar as it did not result in elevated air levels. Skin and ingestion exposure were considered irrelevant and therefore were largely uncontrolled. Variation of exposure to individuals was tolerated as long as the DWA remained less than $2 \mu\text{g}/\text{m}^3$. Where task sampling identified potential for high exposures, exposure potential was modified where feasible with engineering and use of respiratory protection.

The company was aware of research to understand the patterns of beryllium sensitization (BeS) and disease in working populations using chest X-rays,⁽¹¹⁾ skin patch testing,^(8,12) and a forerunner of the beryllium blood lymphocyte proliferation test (BeBLPT).⁽¹³⁾ However, interpretation was uncertain because most persons with positive findings of these measures were well workers, and the relationship of these measures in well workers to CBD was not established. When the flexible fiberoptic bronchoscope was adapted to permit a relatively safe tissue diagnosis based on transbronchial biopsy for clinical diagnosis⁽¹⁴⁾ and enabled performance of the lymphocyte proliferation test on bronchoalveolar lavage lymphocytes,⁽¹⁵⁾ these were promptly used and led to a slightly higher rate of cCBD diagnosis beginning about 1985.

However, scientifically useful surveillance of working populations awaited the combination of the BeBLPT with routine bronchoscopy and biopsy of apparently well workers (volunteers)⁽¹⁶⁾ in the late 1980s. These investigations showed a consistent strong relationship in highly exposed beryllium workers between testing positive with the BeBLPT and the presence of noncaseating granulomata on biopsy, leading to the understanding that in CBD, as in sarcoidosis, there exists a sizable fraction of disease in a subclinical (sCBD) form.⁽¹⁶⁾

The company invited a team led by Dr. Kathleen Kreiss to survey the workers and perform analyses at two facilities from 1992–1994. In both facilities, BeS and sCBD seemed associated with a few work processes. In one facility,⁽¹⁷⁾ the highest risk process, machining of fired beryllium ceramic,

had the highest air levels but not by a large margin. In the second, larger plant⁽¹⁸⁾ no relation of air levels to risk was discerned. Other analyses did not find important differences between cases and noncases that could either confirm or contradict the traditional view that the mass of beryllium inhaled from workplace air was the key to disease and prevention. However, the recognition of numbers of workers with BeS and sCBD suggested the need to modify the traditional preventive model.

The company responded to these initial surveys by seeking more consistent control of beryllium air levels using the hierarchy of control philosophy,⁽¹⁹⁾ specifically, by initiating process and ventilation engineering changes. In responding to the survey in the company's largest facility, the company sought also to control risk by limiting the number of workers exposed in the perceived high-risk area by creating a wall-enclosed, restricted-access zone and by reducing turnover of workers assigned to this area until the engineering changes were completed. Some of the workers considering whether to agree to remain in this area thought it a good idea to have a BeBLPT. Among 35 workers hired after the 1993–1994 survey at this plant, 6 (17%) had two positive BeBLPTs and were considered BeS, and a seventh had a single positive BeBLPT. Of 5 workers in their first year of employment, 3 (60%) were BeBLPT-positive.

The company recognized two implications: first was a greater sense of urgency because although clinical CBD usually occurred years and often decades after first exposure, the putative first step, BeS, was occurring in the first months of work. Subsequent surveys in 1998, 1999, and 2000 repeated this finding of high prevalence rates of positive BeBLPT in the first year of employment. The highest rate, 18% (9/50), was in workers who at the time of the survey had between 4 and 8 months of tenure. The second implication was that although the company apparently was proceeding correctly to control exposure through costly engineering controls, in the interim, worker conditions had not changed. It immediately changed its philosophy to "Protect people **first**, then solve the problem." All workers in this area were required to wear full-time respiratory protection.

In the next 2 years, 1998 and 1999, surveys were repeated in the two facilities within the context of a NIOSH-company partnership for beryllium health effect surveillance and research initiated by company request in 1997 and formalized in a Memorandum of Understanding in 1998. In both these surveys, the rates of positive BeBLPT were not improved.⁽²⁰⁾ Among longer-term workers who were negative in the prior surveys 6 years before, the rate was at least as high as in the prior surveys, and the rate in persons hired in the interim was equally high. In the longer tenure workers, the rate of new sCBD in persons previously BeBLPT negative was equivalent to that in the prior prevalence survey. Analysis of risk patterns suggested that whereas in the first surveys; BeS and sCBD were associated with relatively few operations; in the second surveys, risk appeared to be broadly distributed.

Evolution of an Enhanced Beryllium Safety Model

The increased sense of urgency and the increased perception of widespread risk demanded action, but what action?

Fortunately, at the same time these observations were coming in, and by the end of 1998, a vision of an enhanced beryllium safety model was emerging through an evolutionary thought process that incorporated ideas from medical surveillance, observations in the workplace, and general industrial hygiene knowledge.

First, it was possible to control beryllium inhalation exposure to lower levels and in a more consistent manner. Respiratory protection could be required on a full-time basis in high-risk and high air level areas. Respiratory protection traditionally had been worn during short-term, higher exposure tasks and during operations where accidents were known to be possible; for example, spills of metal or oxide powder during powder transfer tasks. This principle was generalized to include any area or operation in which higher than desired air levels might be encountered. In effect, respirators began to be used in a manner directly analogous to use of seatbelts in vehicles: when overexposure potential exists, respirators are worn.

Second, it was conjectured that BeS might occur in the workplace as a result of penetration of the skin by salts or particles. Curtis⁽⁸⁾ had proven this with salts in 1951, but it was biologically plausible that BeO or metal particles might also lead to sensitization via contamination of skin scrapes or cuts. More recently it has been shown that very small particles, one micrometer or less, can penetrate intact skin when the skin is repeatedly flexed.⁽²¹⁾ Based on the hypothesis that the skin was an important route of beryllium sensitization in the workplace, reduction of skin exposure to beryllium was added to the preventive model.

Third, once the goal of reducing skin exposure was added, the need for strict control of beryllium migration became more evident. It was known that even with low air levels, over time significant amounts of beryllium can accumulate on surfaces. Migration of beryllium on clothing was also a known pathway that could produce elevated air levels remote from production areas. With increased use of personal protection (respiratory and skin), the importance of confining beryllium to the work areas where personal protection was worn and not contaminating other areas, offices, break rooms, and meeting rooms where personal protection was removed, was amplified. Thus, a third ring of containment, the work area, was defined, intermediate between the work process and the plant boundary.

Also apparent from both the exposure and the migration points of view was that maintaining high standards of work area cleanliness and organization was a key value. Protecting workers is greatly simplified when workplaces are maintained to be organized, uncluttered, and clean.

Finally, it was also apparent that a more complex beryllium safety model required a higher level of worker sophistication and commitment, so the final aspect of the model was worker preparation via training, education, and motivation.

The above thought process was consolidated into a simple 8-point format known in the company as the "Beryllium Management Plan" or BMP.

Keep beryllium

- work areas clean and shipshape.
- out of the lungs.
- off the skin.
- off clothing.
- in the work process.
- in the work area.
- on the plant site.
- workers prepared to work safely.

Whereas each point was considered a general principle of beryllium safety, it was also necessary to operationalize each concept for application. In contrast to the principles, the operational statements, known collectively in the company as the BMP Operational Goals, were considered situation specific, continually changed as evolution of accomplishment and understanding warranted. They were designed to be specific to this company at a point in time, with the understanding they would and should change.

Implementation

In implementing the BMP with the intent of reducing worker exposure, the company needed to make large changes as rapidly as feasible. The reality was that massive engineering modification of existing facilities was neither economically feasible nor could it occur quickly. Therefore, other choices needed to be made "to protect people first." The following describes those choices.

Keep Beryllium Work Areas Clean and Shipshape

The beryllium manufacturing facilities considered themselves relatively clean compared with other metal materials plants that did not use beryllium. Management focus was on cleaning. Considerable money was spent continually on decontamination crews who spent their work shifts cleaning production areas, particularly, being responsible for cleaning difficult to reach areas such as ceiling support structures, and ceiling-mounted equipment such as cranes, and ceilings. The first decision was to change the objective from "cleaning" to "being clean," a subcomponent of which was to change the cultural idea that it was okay to make a mess as someone else was responsible for cleaning it up.

The second decision was to agree that being shipshape was in fact a desirable management objective. Whereas some progress on both was made, a specific applicable management system was not generally available within the company. Fortuitously, about this time, company operating management initiated programs designed to modify the work culture in a direction consistent with the BMP. Introduced were "productive maintenance" and the Japanese 5S system for organizing work.⁽²²⁾ The idea of productive maintenance, maintaining equipment with the objective of maximizing the

time the equipment is running, is akin to the idea of maintaining a work environment to maximize the time the area is clean. 5S is a systematic implementation of the principle of “shipshape,” in which frequently required materials and tools are organized so they are available where needed and easily located. All production nonessentials and distracting clutter are removed. The workplace is kept clutter-free through continuous systematic cleaning and maintenance of orderliness.

The company therefore adopted 5S implementation as a common pathway to achieve both productivity goals and the BMP goal of clean and shipshape. As 5S is clearly an operator task, this changed the culture from “I can make a mess and someone else has to clean it up” to “I need to work so my area remains efficient and productive, i.e., clean and shipshape.”

At the outset it was deliberately decided not to define “clean” quantitatively, e.g., by wipe samples for beryllium, but qualitatively “visually clean.” This decision was made because it was believed that the big changes needed were cultural and conceptual not technical. The danger seen in adopting a technical quantitative standard was that large costs would be generated and a “sample and clean” bureaucracy would be created that would resist the needed cultural and conceptual changes.

One of these concepts was that funding of the “cleaning establishment” (the traditional decontamination crews) was seen by many workers as a test of management commitment to beryllium safety. There were frequent questions regarding how often ceilings, 30 ft above workers, should be cleaned. Eventually it was necessary to challenge the allocation of resources to high ceiling cleaning, not by deeming it unimportant but by stressing a hierarchy of importance of surfaces relative to the likelihood of worker contact with the surfaces: frequent, occasional, and rare. This was consistent with 5S, which emphasizes organization of the workplace by the frequency of task performance.

Keep Beryllium Out of the Lungs

Like other industries that made advances in industrial hygiene in the 1940s and 1950s, the beryllium industry used the prevalent technology of the time, the daily weighted average (DWA),⁽¹⁰⁾ to determine compliance for many years. The DWA assesses the mean exposure for tasks performed during the day and averages these numbers weighting by the estimated average time spent daily on this task over a quarter year. This number was compared with the occupational exposure limit, $2\mu\text{g}/\text{m}^3$. It is easily recognized that although the DWA may indicate compliance, there is opportunity for continual variation around the DWA for individual workers on a given day due to the variation in air levels during tasks and the variation in time spent on various tasks. A strong belief that prevalent conditions were safe led to the corollary that considerable variation was safe also, so the culture was tolerant of exposure variability.

When it was decided to further reduce lung exposure, the decision was made to reduce both mean exposure levels as well as tolerance for the upper range of variability. The decision was

made first to introduce full-time respirator use in areas with high rates of BeS and sCBD. Then respirators were required to be worn full time in work areas where although the DWA might be satisfactory, there was a history of upset conditions with high air level excursions. In this context the DWA method was abandoned and 8-hour personal exposure monitoring initiated.

To further reduce tolerance for upward variability, a very stringent criterion was adopted for statistical handling of personal exposure data. Rather than accepting a 95th percentile at an occupational exposure limit (OEL), or even 95% confidence that the 95th percentile would be below the OEL, the company adopted the criterion of 95% confidence that the 99th percentile would be at or below the OEL. Thus, if a process was capable of out of control conditions that could exceed the OEL, or if the process was fully controlled but still had an unacceptable probability of producing an exposure above the OEL, respirators were required. Both criteria protect against rare events, with the result that respirator use philosophy approached the philosophy of automobile seatbelt use: that the respirator is worn in any condition in which there could be an excursion above the OEL.

Studies were undertaken to explore the need for a company action level below the OSHA PEL. In 2000, a surveillance survey in a lower exposure plant⁽²³⁾ convinced the company that BeS and sCBD had an exposure threshold at $0.2\mu\text{g}/\text{m}^3$ 8-hour TWA or higher, and the company adopted $0.2\mu\text{g}/\text{m}^3$ 8-hour TWA as its internal action level with the 1% exceedence, 95% confidence criterion. Respirator choice is dictated by the NIOSH assigned protection factor, with the criterion being that the protection factor must equal or exceed the ratio of the upper 95% confidence limit of the 95th percentile of workplace concentration divided by the action level. If beryllium is detectable, a sufficient number of air samples, typically 15, are required to establish this criterion value. Many of these operational decisions were made using AIHA exposure assessment guidelines.⁽¹⁹⁾

Once a task, job, or area is designated as respirator required, to reduce the level of protection the work group is required to complete an evaluation of all usual and special causes of air level variation. The group must develop and implement control of all special causes as well as targeted usual causes, develop and implement management processes to assure future control, and, finally, resample to establish a new baseline for respiratory protection need. If justified and signed by local and corporate management and staff, respirator use may be modified. This process is designed to assure that respirators are worn when they may be needed to protect a worker against upward variation exceeding the action level.

Keep Beryllium Off the Skin

Because of the concern that penetration of beryllium through the skin might be an important route of sensitization to beryllium, the company decided to reduce the opportunity for skin penetration by reducing the amount of beryllium on the skin. The company was aware that beryllium worker

dermatitis was associated with sensitization and that application of beryllium salts to skin could induce sensitization.⁽⁸⁾ Implantation of oxide or metal in or through the skin was known to result in dermal granulomas.^(24–26) The company also had long recognized the occurrence of dermatitis, both allergic and irritant, in its own workers exposed to beryllium salts, such as beryllium fluoride and beryllium sulfate, which was controlled either with transfer to other beryllium jobs without salt exposure or with skin exposure reduction.

The company did not, and does not have any idea of what quantitative level of beryllium on skin induces sensitization. Likewise, it did not, and does not know to what extent nonsalt, superficial, and temporary skin penetration exposure contributes to worker sensitization. Consequently, it deliberately chose not to establish an arbitrary quantitative skin action level nor to initiate large scale measurement of beryllium levels on the skin of workers. Instead it established the simple rule of preventing contact of skin with beryllium particulate or salt contaminated surfaces or with falling or splashing beryllium-containing liquids or dusts. When initially implemented it was assumed that this meant a glove policy. With experience, management realized that in addition to gloves, other covering was needed wherever beryllium particulate or salt contact was possible, including long sleeved shirts, wrist covers, and impervious clothing when liquids could contact clothes and soak through to the skin. Current rules require impervious gloves and long sleeves and trousers, with additional protective clothing as dictated by circumstances.

Some quantitative estimation of skin beryllium levels has been undertaken to identify gaps in technique and to explore pathways of exposure.⁽²⁷⁾ An example of technique improvement is the donning of gloves before handling contaminated boots or respirator hoods. With the knowledge that only very small particles penetrate intact skin⁽²¹⁾ and that the risk is small for skin penetration associated with articles free of liquid or lubricant coating or of similarly clean, large (>10 micron diameter) particles, the company relaxed its criteria to permit skin contact with clean beryllium articles or clean large particulate matter. Generally, this applies to finished articles being packed for shipping or being contacted during further manufacturing or assembly operations in which salts are not produced or small particles are not generated.

Keep Beryllium Off Clothing

Beryllium particulate on clothing and shoes was known as a mechanism of transfer of beryllium between work areas. Also, beryllium on clothes could be resuspended and produce measurable air levels. To reduce the amount of beryllium transferred on clothing to other work areas, or from clothing to lung and skin, the BMP operational goal for keeping beryllium off clothing was for workers to keep their work clothes “visibly clean.” If clothes became visibly dirty, workers were instructed to go to the locker room, disrobe, shower, and don clean clothes. Workers were asked to anticipate when clothes might become soiled, and use overgarments to protect the basic long sleeved shirt and long trousers work clothes. Although some

testing of beryllium levels on clothing has been done, there has been no attempt to define acceptable and unacceptable values for beryllium on clothing. Once the basic concept was implemented, the visible soiling of clothing was assigned the status of an “incident” to be reported and corrected with management action.

Keep Beryllium in the Work Process, in the Work Area, and On the Plant Site

Historically, efforts had been focused on engineering to prevent the escape of beryllium particles from the work process or to capture it with ventilation and then clean it from the captured air. However, added to this was the realization that work practices also played an important role in whether beryllium escaped from a work process. Although opportunities for engineering improvement continued to be identified, prioritized, and worked on, a great deal of improvement has been accomplished with worker involvement in evaluating work processes and identifying ways the process can be improved. Often we find that issues have already been identified and the solution known. What was needed was impetus.

Improvements can often be implemented by the department without major engineering redesign and costs. The operational goals, recognizing the variety of work environments and equipment, the costs and uncertainty associated with further engineering in an already highly engineered environment, all require the identification of possible projects and a process for prioritizing. Actual investment decisions occur via management processes outside the scope of the BMP.

New to the model was major emphasis on a second circle of migration containment, “Keep beryllium in the work area.” With the increased use of respiratory and skin personal protection, the importance of reducing exposure when such protection was removed was recognized. Previously, migration of beryllium between work areas and to break, office, meeting room, and cafeteria areas was evaluated primarily from the standpoint of whether it made a significant contribution to exposure.

Beryllium migration from work areas occurs when beryllium is carried in air and on tools, vehicles, scrap, product, and people. As for keeping beryllium in the work process, much can be accomplished through work practice and simple process changes. However, in some instances large engineering investments are necessary, for instance, to create restricted access zones, control airflow patterns, and to build transition zones.

Similarly, although keeping beryllium on the plant site had been a management commitment for 50 years, additional opportunities were discovered, such as buying contractor vehicles and keeping them on site, improving standards of product cleanliness, and maintenance of cleanliness standards for all shipped materials, including pallets and trailer vans.

Keep Beryllium Workers Prepared to Work Safely

Concepts of safety education and training were revised. Beryllium orientation had emphasized beryllium health risks

and compliance with the initial safety model. General safety training was compliance motivated, a sometimes rote process where one size was assumed to fit all. A fundamental review of safety training revealed at least two levels: awareness and full competency. Compliance-based training either was reduced to the minimum required for awareness, or enhanced to include observation of competency. Training for operator certification was revised from one-on-one, on-the-job instructions to include safety standard operating procedures so that when an operator was ready to perform a task unsupervised, he or she was ready also to perform it safely, from both general safety and beryllium safety standpoints. The realization that sensitization to beryllium developed within months of employment, and sufficient inhaled dose to induce granulomatous lung inflammation could occur within months to a few years, motivated workers and managers alike to ensure safety training was received prior to potential exposure to beryllium.

Training, which had been primarily a safety staff responsibility implemented through monthly safety meetings, became primarily an operating management responsibility, with management leading meetings. Daily, biweekly, or weekly toolbox meetings led by supervisors became the focus for most detailed safety training, with manager-led department meetings and plant wide safety training reserved for department-wide safety priorities or site-wide awareness training.

Integration of the Beryllium Safety Model: Setting Priorities Over Time

In the initial stages of implementation of the BMP, annual goals were assigned by the top corporate safety team, consisting of the company chairman and senior leader/managers, supported by senior corporate staff. This lockstep approach pushed the BMP down through the organization and ensured rapid implementation of improved worker protection through work practice modification and increased personal respiratory and skin protection.

However, the company recognized that priorities also needed to be set by local conditions. For instance, in one department, the most efficient route to worker protection might be by investment in modest additional engineering to keep beryllium at the source and reduce requirements for respiratory protection. In another department, engineering to keep beryllium at the source might not be feasible, and the best strategy to protect workers in the department and other workers in the plant might be personal protection while in the work area, supported by engineering and work practices to keep beryllium from leaving the work area. Consequently, a long-range planning process was initiated to require small plants and departments in large plants to each formulate a plan by which maximum worker protection could be achieved with minimum time and feasible investment. The company used this long-range planning process to convert from a lockstep process to create basic worker protection, to a situation-specific process to maximize beryllium safety over time with the available resources.

Likewise, with nonberyllium safety, the corporate requirement for progress gave flexibility to individual units to choose areas of accomplishment locally, based on analysis of safety experience plus the risk of catastrophic events. Therefore, each unit developed conceptual long-range plans for both beryllium and general safety, and these were translated into specific annual goals with achievement tied to compensation.

RESULTS

Leading Measures

The company was very careful to demand progress in leading measures at an achievable rate, creating an environment in which success in achieving goals was the norm. Knowing a safe environment is created only by accomplishment of leading safety measures, the company developed audit instruments for each of the BMP Operational Goals and initiated a system of annual midyear audits. These audits, conducted by executive champions and corporate staff, measured progress and identified gaps that facilities were required to close by year end. This process documented essentially 100% on schedule progress in the goals of keeping beryllium out of lungs, off skin and clothing, and "workers prepared." Work units developed self-audit processes to measure detailed compliance with work practices. The unit audit responsibilities are shared by workers, supervisors, and "visiting" auditors from other work units.

Achievement of the other operational goals may each require several years of effort. For long-term projects, each facility or department was required to develop specific milestones of achievement and to agree which of these will be completed in a given year. These milestones are tracked against plan and included in the audit/gap closure process. Adjustments to plan do occur during the year, with the concurrence of the line managers and the executive champion, the primary value being assurance of steady, substantive progress.

Executive champions report on facility progress following audits and the year-end gap closure assessment in the corporate safety team. Failure to progress adequately against plan was a rare exception due to the level of support and opportunities for correction through the year. When failure did occur, the management issues were analyzed and corrective action taken by the responsible line management.

In addition to systematic tracking of leading measure accomplishment by the audit/gap closure process, the company's workers and supervisors present accomplishments and best practices at an annual NIOSH-company Project Leadership Team meeting in Morgantown, West Virginia, and at an annual company best practices workshop.

Lagging Measure

The company had learned from surveys conducted in the company's three largest beryllium materials plants performed consecutively in 1998,⁽²⁰⁾ 1999, and 2000⁽²³⁾ that the rate of beryllium sensitization as detected using the beryllium blood lymphocyte proliferation test (BeBLPT) was 18% (9/50) in

TABLE I. Incidence of Beryllium Sensitivity

Hire Group	Rate at 3 Months (%)	Rate at 6 Months (%)	Cumulative 6 Months (%)	Rate at 12 Months (%)	Rate at 24 Months (%)	Cumulative 24-Month Rate (%)
2000–2003	0.9 (3/326)	1.4 (4/292)	2.3	1.0 (2/192)	0.8 (1/118)	4.1
2004–2005	1.1 (1/91)	0 (0/73)	1.1	0 (0/57)	0 (0/53)	1.1

Note: Detected by BeBLPT surveillance of new workers, excluding those workers with positive tests prior to beginning work.

employees surveyed between 4 and 8 months of employment. The company consequently chose these same three plants for surveillance with the BeBLPT at hire, and at 3, 6, 12, and 24 months of employment. Subtracting a background rate of the approximately 2% rate detected at hire, the expected rate combining the 3- and 6-month tests was expected to be at least 16%, were historical rates to continue. Although the BMP was not mature at all three plants, this surveillance nevertheless began in 2000. Among persons in this group hired from 2000 through 2003, the cumulative rate of new BeBLPT positivity was 2.3% at 6 months and 4.1% at 24 months. In a second wave of hiring in 2004–2005, the rates were 1.1%, 1.1% respectively, both suggesting improvement over the prevalence rate seen in the prior surveys (Table I).

CONCLUSIONS

Because many changes were made by the company over a few years, it is impossible to reach definitive conclusions regarding the relative contribution of each of the eight model components. The reality is that work on each of these components contributes to and reinforces success in the others. We believe that it is the comprehensive nature of multipathway exposure control, rather than quantitative achievement in any one component, that is reducing BeBLPT-positive rates, a feature shared with the comprehensive beryllium exposure control model used in the United Kingdom's nuclear weapons industry.⁽²⁸⁾

One practical conclusion is that industrial hygiene concepts developed for the control of general toxicants in relatively high concentrations (mg/m^3) need significant modification when control of very low concentrations ($<1 \mu\text{g}/\text{m}^3$) of airborne particles is the goal. In the latter case, very small process upsets with escape of a fraction of a milligram of particulate matter can generate significant upward air level variation that cannot be perceived at the time. Using respirators with a "seatbelt" philosophy protects workers in this setting where even the most sophisticated and costly engineering may fail. Simply wiping one's face with a contaminated sleeve or glove or plunging into a disordered storage room looking for a tool or part may put enough beryllium in the breathing zone to create a whole day's permitted exposure.⁽²⁹⁾

Put another way, it is unlikely that miniscule amounts of small particulate matter can be kept out of a person's lungs if gross amounts are permitted on work surfaces, skin, clothes, and so on, and no barrier is interposed. The prevention of such cross contamination exposures is best achieved with

a comprehensive control program individually applied as appropriate to specific operations.

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