RESEARCH ARTICLE

Elements of a Glovebox Glove Integrity Program

Programmatic operations at the Los Alamos National Laboratory Plutonium Facility involve working with various amounts of plutonium and other highly toxic, alpha-emitting materials. The spread of radiological contamination on surfaces and airborne contamination and excursions of contaminants into the operator's breathing zone are prevented through the use of a variety of gloveboxes. The glovebox gloves are the weakest part of this engineering control. As a matter of good business practice, a team of glovebox experts from Los Alamos National Laboratory has been assembled to proactively investigate processes and procedures that minimize unplanned openings in the glovebox gloves, *i.e.*, breaches and failures. Working together, they have developed the key elements of an efficient Glovebox Glove Integrity Program (GGIP). In the following report, the consequences of a glove failure or breach are identified, the acceptable risk is clarified, and elements needed to implement an efficient GGIP are discussed.

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INTRODUCTION

Plutonium requires a high degree of confinement and continuous control measures in nuclear research laboratories because of its extremely low permissible body burden.[1] Methods and equipment must be designed toward the ultimate accomplishment of preventing any internal deposition of plutonium in organs such as the liver, even though such a degree of control may often seem extreme. This is in contrast with the control of external radiation where some reasonable fraction of permissible dose is expected. Inhalation is generally considered the most common mode of intake of plutonium for the nuclear facility worker. Uncontrolled releases of plutonium usually result in some contamination of the atmosphere near the site of release, whether the plutonium is in a liquid, solid, or gaseous state. To preclude uncontrolled release, gloveboxes are used to confine plutonium during laboratory work. The glovebox is an "absolute barrier" barrier, *i.e.*, a sealed enclosure. A typical glovebox train is shown in Figure 1.

The weakest link of this system is the glovebox gloves (hereafter referred to as gloves) themselves. They are easily punctured, torn, cracked, will deteriorate, and have selective permeability for various chemicals. Careful inspection of the gloves before each use is necessary.

Through an integrated approach, controls have been developed and implemented that come from input from glovebox workers, scientists, health physicists, statisticians, and physical therapists. Working together, they have developed an efficient Glovebox Glove Integrity Program (GGIP). Recent accomplishes of this team have been previously reported.[2–5] In the following report, openings in gloves are defined, the consequences of a glove failure or breach are identified, the acceptable risk clarified, and elements needed to implement an efficient GGIP presented.

DEFINITIONS

- **Glove failure** an unplanned opening in a glove caused by degradation of the mechanical properties of the material over time, *e.g.*, exposure to chemicals and nuclear materials. The primary means of minimizing glove failures are through a robust glove inspection program and by controlling glove service life.
- **Glove breach** is an unplanned opening in a glove caused by mechanical damage during operations, *e.g.*, penetration with a sharp object; rotating equipment, pinch points, thermal sources, etc. The primary means of minimizing breaches is through administrative controls and overgloves.

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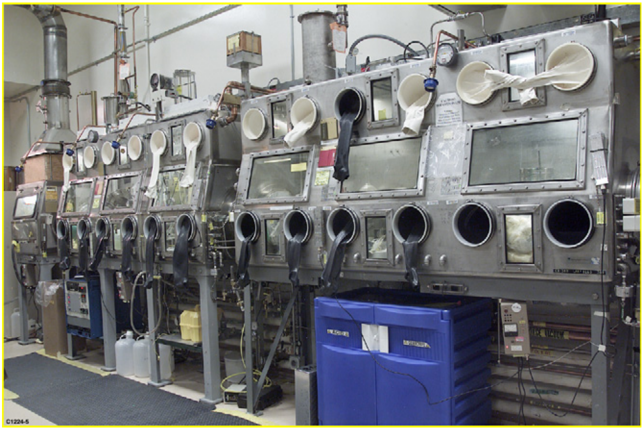

Figure 1. Typical glovebox train.

A break in a glove that results in plutonium penetration into the skin or internal deposition of plutonium in the lungs can lead to serious injury in the form of cancer.

Table 1. Open-Front Hood Limits

	Radionuclide				
Operation/material type	^{237}Np	^{238}Pu	^{239}Pu	^{241}Am	^{243}Am
Storage and stock solution (g)	5700	0.2400	60.0	1.200	20.0
Simple wet operations (g)	570	0.0240	6.0	0.120	2.0
Normal operations (g)	57	0.0024	0.6	0.012	0.2
Open powders (g)	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]

[a] N/A: not applicable.

CONSEQUENCE OF A GLOVE FAILURE OR BREACH

A typical glove failure can result in worker exposure/contamination, waste generation, and work stoppage. Before work continues, the room containing the glovebox with the failed glove is usually shut down until it is cleaned up and recertified for operations. A simpler way of understanding this accident scenario is to realize that once a glove is ruptured, the containment system is now only as effective as an open-front hood. For review, the limits of radioactive material allowed in open-front hoods based on the amount of material used modified by the exposure adjustment are shown in Table 1.[6] Clearly, no operations with open powders are acceptable.

Glove breaches and failures do not usually result in radiological workers receiving a significant intake of radioactive material. Most glove breaches and failures result in alpha contamination of protective clothing, the lab worker, or the immediate laboratory area (floor).

A break in a glove that results in plutonium penetration into the skin or internal deposition of plutonium in the lungs can lead to serious injury in the form of cancer. Thus, the likelihood of a breach or failure must be kept to a minimum in order for the risk of doing glovebox work to be kept at an acceptable level, as shown in Figure 2.[7]

The sooner a breach or failure is discovered, the lower the severity. In increasing order of severity, a breach or failure is detected during the following task:

1. The glove is replaced before breach or failure occurs.
2. The radiological control technician (RCT) detects contamination during a routine survey.
3. The glovebox worker discovers a breach or failure during a daily inspection.
4. The glovebox worker discovers a breach or failure while working in the glovebox.
5. The glovebox worker discovers a breach or failure after completing a task in the glovebox. This is usually determined with the monitor next to the glovebox.
6. The continuous air monitor (CAM) alarms, this greatly increases the likelihood of an uptake of plutonium into the lungs.
7. The glovebox worker discovers a breach because his or her skin has been penetrated resulting in a bleeding wound.

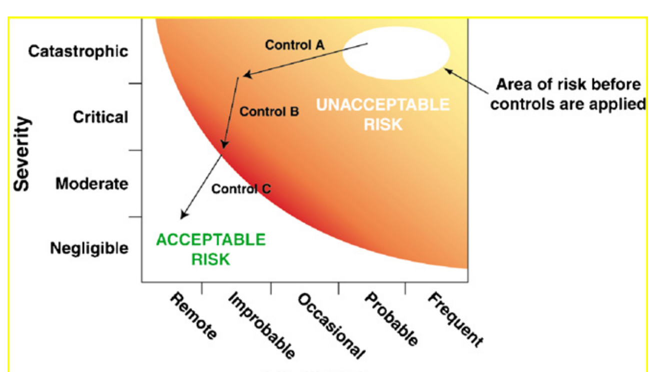

Figure 2. Concept of controlling risk.

In the past, the boundary between acceptable and unacceptable risk was the discovery of a breach or failure at step 5. The current boundary is step 3. Detecting a breach or failure before this is considered a noteworthy practice. Detecting an unplanned opening after step 3 requires action by line management.

THE GLOVEBOX GLOVE INTEGRITY PROGRAM (GGIP)

In the previous section, the reasons why breaches and failures must be minimized were clearly outlined. The program elements that are in place to achieve this objective are presented.[8]

- **Glove inspections** Daily inspections must be performed each day before gloves are used. These include a visual inspection and self-monitoring for radiological contamination by operators.
- **Glove date markings** When gloves are installed, they must be labeled with their install and expiration dates. The exact date of installation is needed because some gloves have failed in less than a month. Only the month and year are used for the expiration date; this gives the glovebox owner the whole month to inspect the glove. The required standard inspection (service life) intervals for gloves are 1 year for ^{238}Pu operations and 2 years for ^{239}Pu operations. For ^{235}U, ^{238}U, ^{241}Am, ^{237}Np, and other nuclear material operations, default to ^{239}Pu operations service life intervals. Depending on the usage of the gloves and working environment, the line manager can limit the service life interval to a shorter time frame. For the appropriate service life interval for a specific glovebox environment, leaded versus unleaded, and type of glove material, a guide developed from the combined glove experiences from both Rocky Flats and the Los Alamos National Laboratory Plutonium Facility (TA-55) is provided.
- **Glove date lifetime limits** The maximum ceiling life for a glove is 10 years from the date of manufacture (The date of manufacture is stamped on the inside surface of each glove). If a shortage of gloves exists, this requirement can be suspended for up to a year, provided that the glove passes the radiological, visual, and dexterity inspection. A shortage of gloves may occur when switching from one type of glove to another, *e.g.*, leaded gloves to unleaded gloves. The glove manufactures may need up to 6–12 months to adjust their production cycles.
- **Glove service life extensions** An extension of glove service life is allowed after a team comprised of a RCT and a glovebox subject matter expert (SME) performs an inspection (A best practice adopted from Savannah River Site). A maximum of four extensions is allowed. The glovebox SME must have the following qualifications: works in the glovebox on a regular basis; is familiar with the operations of the glovebox; understands the environmental hazards associated with the glovebox; and is trained to do glove inspections. After extending the glove outside of the glovebox, the RCT surveys the surface of the glove. If no contamination is found, the glovebox SME inserts a hand into the glove and performs a visual inspection. The glovebox SME looks for signs of wear or degradation; exposed color from the lead liner; signs of cracking, thinning or damage; and significant loss of dexterity. If the glove fails the radiological or visual inspection a glove change is schedule. The condition of each glove is documented (a form is provided) and entered into the GGIP database. If a glove passes the radiological, visual, and dexterity inspection, line management may approve the extension for another service life interval. Crossing out the old expiration date and adding the new expiration date implement this step.
- **Inactive gloveports** Plugging ports that are never or infrequently used is allowed and encouraged for the following reasons: gloves that are not frequently manipulated degrade at more rapid and unpredictable rate than gloves that used on routine basis and gloves that are left outside the gloveport are subject to being breached from and object outside the glovebox, *e.g.*, a ladder or Dewar flask. A properly plugged port should have a *stub glove* and a glove port cap installed. Removal of a cap from a port that has been *out of service* (plugged with a stub glove and a glove port cap) must be treated as a radiological task, *i.e.*, “hot job,” similar to a glove change with RCT coverage because plugged and capped ports are not subject to routine radiation monitoring or inspection. For capping round glove ports, solid plastic caps are recommended.
- **Expired gloves** A glove that is past its expiration date, and that has not had its service life extended is considered *out of service* and not used without additional compensatory measures. Compensatory measures required for use of an expired glove include a pre-use inspection, a Radiological Work Permit (RWP), and respiratory protection. Gloves that require scaffolding in order to conduct the radiological, visual, and dexterity inspection are not considered *out of service*. A radiological, visual, and dexterity inspection is required before these gloves are used (This requirement is not be used on a routine basis.).
- **Glove changes** The changing of a glove is documented (a form is provided) and the information is entered into the GGIP database.
- **Glove breaches and failures** The discovery of any detectable contamination on a glove, or visual identification of a breached glove, requires additional information gathering. The attributes of the glove breach or failure are also documented and a “*Lessons Learned*” critique is conducted. A *Lessons Learned* critique is not conducted for breaches and failures found by a RCT surveying the surface of a glove. The key attributes of the event are also entered into the GGIP database. General controls developed from the “*Lessons Learned*” critiques are incorporated into the GGIP.
- **Performance assessment** Each of the elements the GGIP is assessed at least annually and the results are documented.

IMPLEMENTATION

Glove information at TA-55 has been tracked on the GGIP database since 1993. This information is used to recommend service life intervals, determine an optimal schedule for changing gloves, select glove types for specific working environments, and document "*Lessons Learned*" from glove breaches and failures to improve the hazard control process. The key attributes tracked include those related to location, the glove, type and location of breaches, the worker, and the consequences resulting from breaches. A more detailed description of this statistical analysis has been reported previously.[2]

Robust statistical methods have been developed to better analyze and interpret data and to construct statistical models that allow for an accurate assessment of the data set, identify root causes of glove failures, and ultimately minimize breaches and failures and decide the replacement strategy for glovebox gloves.[9–11] A fundamental understanding and interpretation of the data on glove failure has been achieved. These results were pivotal to the next focus of the research which was minimization of unplanned breaches and decision on the replacement strategy. Reliability models were developed to predict mean time to failure (MTTFs). The MTTF for gloves is approximately 7 months. Considering that the replacement period for a glove used in LANL was a 3-year period, too many gloves have a short period of service life of less than 1 year. This conclusion leads to replacing the change-out program for gloves to a glove inspection program. Identifying root causes for failure and the actions adequate to prevent breaches helped control unplanned breaches and increase the current replacement period for a glove. In addition, this analysis lead to more effective inventory cost reduction. A thorough investigation of all breach cases and associated tasks has been achieved. Among all the tasks investigated, most critical tasks that need further investigation for root cause analysis were identified. Root cause analysis was performed for a cleanup breach case. Root causes were reasonably identified from the analysis. Recommendations generated directly addressed these root causes and have been effective in preventing recurrence of the event.

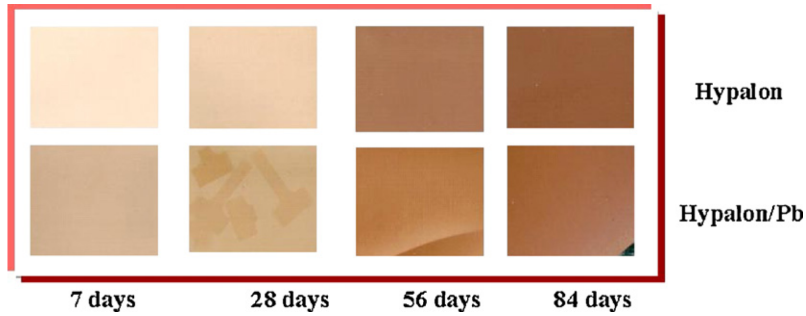

Figure 3. Color change correlates with aging.

A working team meets periodically (monthly, if possible) to address glove issues. The focus of the team is to proactively investigate processes and procedures so as to minimize glove breaches and failures. The membership of the team consists of glovebox workers, as well as Health Physicists and Industrial Hygienists. The team reviews recent glove breach and failure incidents, identifies barriers to minimizing glove failures and breaches, considers measures that lower the overall risk of glovebox operations, and identifies mechanisms (processes) that systematically reduce glove failures and breaches. The team recommends to line management measures that minimize glove breaches and failures. This includes inspection and change intervals for gloves and glove material selection. The team also responds to audit findings related to gloves at TA-55 and participates in the GGIP assessment.

To obtain a better understanding of the environmental effects that glovebox operations have on gloves, and to qualify a new glove material, a material-testing laboratory has been developed. The American Society for Testing and Materials (ASTM) provides widely used standard material tests. In addition, aging studies are conducted to correlate changes in mechanical (physical) properties with degradation chemistry. Predictive models are then derived that estimate glove service lives. Towards this aim, accelerated aging studies have been performed on Hypalon and Hypalon/lead oxide-Neoprene/Hypalon tri-layered gloves to assist in determining both the shelf life and the use life of these gloves in a thermal and oxidative environment.[4,12–14] During a temperature dependent aging study, a color change associated with the aging process was observed. The appearance of the chromophore in Hypalon appears considerably before the mechanical properties of the Hypalon fall out of specifications.

It was also shown in this study that the lead oxide in the tri-layered material has a dramatic effect on the difference in tensile behavior for the two materials. In contrast, the Hypalon-lead samples all demonstrate greater degradation of tensile properties under the same aging conditions. Once the onset of degradation is observed, the degradation of the mechanical properties accelerates. The presence of lead oxide contributes to or enhances the aging rate of the material (Figure 3).[4]

After a series of glove failures were attributed to an inferior batch of gloves from the manufacturer,[15] specifications were developed, such that gloves of required thickness, dimension, and

Table 2. Unplanned Glove Openings at TA-55

Year	Unplanned Glove Opening	
	Breach	Failure
2004	34	4
2005	23	13
2006	46	3
2007	29	14
Total	132	34

shape are supplied.[16–19] Parameters for certain physical properties, including factors such as tensile strength and material continuity, are now used as criteria. Suppliers must develop, implement, and maintain an approved Quality Assurance (QA) system (including program/plan, procedures, and process control documents) based on appropriate industry consensus standards.

Glove failures account for about a quarter of all unplanned openings at TA-55, as shown in Table 2. The primary means of minimizing these types of glove failures is through a robust glove inspection program. Through a collaborative effort with Getinge La Calhène, pressure decay methodology was used to detect glove failures in an active negative pressure environment found in the nuclear industry.[20] These results are the first step in determining the realistic opening size that is needed to contaminate a glovebox worker under normal working conditions. Small punctures are much more difficult to detect than small rigid holes due to the self sealing property of a puncture. Using the Getinge La Calhène commercially available *In-situ* Glove Leak Tester (GLT2) to detect punctures in a glove represents a significant improvement over visual inspection. The GLT2 cost about $30, 000 and can test four gloves every 10 min. When fully implemented, excursions of contaminants into the operator's breathing zone and excess exposure to radiological sources associated with glove failures in the glovebox will be reduced significantly, since glove failures will be detected before the glovebox worker is at risk, i.e., before step 3 in the *Consequence of a Glove Failure or Breach section*. The information from this study represents an important baseline in gauging the acceptable standards for polymeric gloves used in a laboratory glovebox environment.

To familiarize glovebox workers with glove issues and performance in a glovebox environment, a thorough glove inspection-training program has been implemented. This training includes hands-on participation, in which workers must identify early warning signs that the glove is degrading and its performance is being compromised, such as blistering and cracking as shown in Figure 4. To help mitigate glovebox operation injuries, the science of ergonomics has been integrated into the training program.

Figure 4. Example of a crack in a glove.

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Efforts aimed at reducing glovebox operation injuries sometimes clash with new safety procedures, *e.g.*, replacing Anti'C gloves made of latex with those made of Nitrile may give the glovebox worker more protection against a puncture, but also increases the risk of ergonomic injury. All factors should be looked at. Several design features of glovebox are being studied to see if not only reducing injuries but improving comfort and productivity of the worker can be achieved.

The lead-loaded glove made from Hypalon was the workhorse of TA-55 programmatic operations and represents over 75% of the gloves used (6000). As part of an effort to replace these gloves with unleaded gloves, we are in the process of conducting time trials. The lead is used to shield against low energy and moderately penetrating gamma rays and X-rays (less than 56-keV) and this results in a reduction of the radiation dose to the hands. The disadvantage of lead-load gloves versus unleaded glove is that a task takes longer to complete secondary to reduction of dexterity, and weighs more producing excessive force to be utilized by the body. Furthermore, lead-loaded gloves do little to shield against neutrons and more penetrating gamma rays (more than 56-keV). Line managers and Health Physics Operations could make better decisions on which glove is better suited for an operation if they knew how much longer a task takes in a leaded glove versus an unleaded glove. This data is being obtained by having glove workers perform the following acceptable dexterity tests: Purdue Pegboard and the Minnesota Dexterity Test. In addition, we will use the JAMAR dynamometer to test strength.

LANL has a Continuous Improvement Program in which efficiency, cost effectiveness and formality of operations are constantly being improved. In this vein, LANL implement the "Lean Six Sigma (LSS)" program that incorporates the practices of Lean Manufacturing and Six Sigma technologies and tools to effectively improve administrative and engineering controls and work processes. One tool used in LSS is the use of control charts,

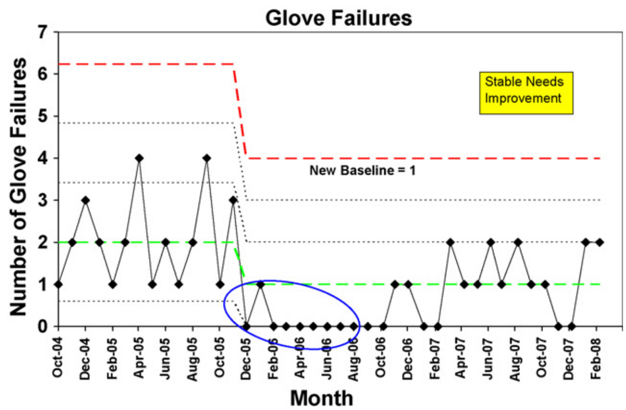

Figure 5. Control chart for monthly glove breaches.

which is an effective way to characterize data collected from glove breaches and failures. The benefit management receives from using this tool is twofold. First, control charts signal the absence or presence of systematic variations that result in process instability, in relation to glove breaches and failures. Second, these graphical representations of process variation determine whether an improved process is under control. Control charts are used to identify statistically significant variations (trends) that can be used in decision making to improve processes. An example of a control chart is shown in Figure 5.

In this regard, line management uses these charts along with other tools to determine if actions taken to improve GGIP are effective.[5]

DISCUSSION

The main objective of an effective GGIP is to maintain the risk associated with a glove failure at an acceptable level. From a business viewpoint, the acceptable level may be achieved when the costs of decreasing a given risk further are greater than the costs realized from excursions of contaminants into the breathing zone of the operator and the spread of radioactive contamination. Because the magnitude of a risk involves both the likelihood and the severity of the associated harm, the performance metrics for a GGIP can be reasonably based on reducing either the severity or the likelihood, or both. To be reported later, trending analysis has shown that the likelihood of glove breaches and failures have remained stable with the overall severity of each event decreasing. This is due in part that glove breaches and failures are being detected sooner due to better training and management involvement.

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The cost–benefit analyses can be extrapolated to unusual occurrence triggers, loss of control of radioactive material/spread of radioactive contamination (contamination of lab), and personnel contamination (contamination on worker). In a previous paper, it was shown that about five off-normal occurrences associated with glove failures are reported per year.[2] Therefore, up to $250,000 a year could be expected to be dedicated to minimizing glove failures.

In an effort to reduce glove breaches and failures further, "*Lessons Learned*" from all nuclear facilities in the DOE complex are being shared. In this regard, a Glovebox Glove Improvement Workshop was held at the American Glovebox Society National Meeting in 2006.[21] The workshop promoted the sharing of expertise, experience, and "*Lessons Learned*," as they relate to glove breaches and failures, among working-level peers within the DOE complex. The workshop targeted the DOE and contractor field personnel doing the actual work. SMEs from LANL, Lawrence Livermore National Laboratory, Savannah River Site, and the Atomic Weapons Establishment (AWE) participated. In addition, Joint Operational Working Group 30, Facility Safety (JOWOG 30) between the DOE Nuclear Complex and the AWE has Minimizing Glovebox Glove Failures and Breaches" as one of its focused exchanges. This focused exchange identifies controls presently employed, compare their effectiveness and determine if alternative controls should be explored. Information exchanged includes "*Lessons Learned*" from documented glove failures and breaches, glove selection for specific applications, and the use of mechanical property data on glove material to predict service life of gloves.[22–25]

A significant observation from the "*Lessons Learned*" critiques is that **every** breach or failure could have been prevented. An expectation of upper management at LANL is that at some point the number of glove breaches and failures that occur per month from unplanned opening (after step 3) will change to the number of months without an unplanned glove opening being record. While we are not there yet, the elements of the GGIP are sufficient to attain this goal.

In a series of reports to follow, issues that test the robustness of the TA-55 GGIP will be addressed. Topics that will include: using information from the tracking of glove incidents and tensile strength data to make better glove selections; leaded gloves are no longer used for the majority of ^{239}Pu operations; whether respirators should be used while conducting glovebox work at TA-55; using "*Lessons Learned*" to improve the hazard control system of glovebox operations; and the real time difference observed between working in leaded gloves and unleaded gloves.

SUMMARY

A primary objective of an organization should be to conduct all operations in a disciplined and controlled manner, to maintain a safe and healthful workplace for personnel, and to protect the public and the environment. As it relates to gloves, an effective GGIP achieve these objectives. The efforts presented in this report represent the state of the art in reducing the number of unplanned failures and breaches associated with glovebox operations with alpha-emitting materials. As with all other elements of business, there are costs associated with implementing an effective improvement program. Last, the GGIP has a lofty goal of changing from reporting the number of glove breaches and failures that occur per month to the number of months without an unplanned glove opening being recorded.

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