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Evaluation of Exposures to Fluorocarbon 113 in a Horizontal and a Vertical Laminar Airflow Clean Room

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Exposures to 1,1,2-trichloro-1,2,2-trifluoroethane or fluorocarbon (FC) 113 were evaluated in a horizontal laminar airflow (HLAF) clean room and a vertical laminar airflow (VLAF) clean room. A full period consecutive samples measurement strategy was employed. Data were used to calculate 8-hour time-weighted averages (8-TWA) for major work groups and to characterize exposures associated with specific cleaning tasks. The MIRAN® 1B infrared analyzer was used to estimate peak concentrations. In the HLAF clean room, 8-TWAs ranged from 193 to 439 ppm; in the VLAF clean room, 8-TWAs ranged from 110 to 935 ppm. These levels were below the current Occupational Safety and Health Administration permissible exposure limit and the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit for FC 113 of 1000 ppm. Short-term sample concentrations ranged from 104 ppm (inspection) to 1080 ppm (assembly) in the HLAF clean room and 51 ppm (packaging)-3380 ppm (flushing) in the VLAF clean room. In the VLAF clean room, several short-term concentrations measured during the flushing task—1421 ppm and 2522 ppm—were above the NIOSH short-term exposure limit (STEL) of 1250 ppm. These data suggest the possibility that the STEL may be exceeded for tasks involving direct work with liquid FC 113. Peak exposure levels may be reduced by modification of worker position in the HLAF clean room and by use of open wire tables in the VLAF clean room.

Keywords: 113, clean room, fluorocarbon 113, Freon®, 1,1,2-trichloro-1,2,2-trifluoroethane

APPLIED STUDIES

Mention of company or product names does not constitute endorsement by the Centers for Disease Control and Prevention.

The compound 1,1,2-trichloro-1,2,2-trifluoroethane, a colorless, noncombustible, highly volatile, low surface tension liquid, also known as Freon® 113 or fluorocarbon (FC) 113, is used as a cleaning solvent in the electronics and aerospace industries.[1,2] Cardiotoxic effects of exposure to FC 113 have been previously documented in animals.[3,4] Lethal cardiac arrhythmias have been implicated as the cause of sudden death among workers exposed to high concentrations of FC 113 during cleaning tasks. These tasks were carried out in areas classified as confined spaces: the interior of a military tank, a vapor degreasing tank, and a storage tank. Exposure was measured for the first scenario at 7600 ppm.[5] There is little information in the published literature regarding FC 113 exposures experienced by clean room workers.

The current Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for FC 113 is 1000 ppm as an 8-hour time weighted average (8-TWA).[6] The National Institute for Occupational Safety and Health (NIOSH) concurs with the current OSHA PEL and has also recommended a short-term exposure limit (STEL) of 1250 ppm as measured over a 15-minute sample period.[7] However, NIOSH also has determined that 4500 ppm is immediately dangerous to life and health. NIOSH considers FC 113 to have poor warning properties because it is nearly odorless and its irritant effects are only slight and transient at concentrations near the PEL. The OSHA PELs may be required to take into account the feasibility of controlling exposures in various industries where the agents are used; the NIOSH

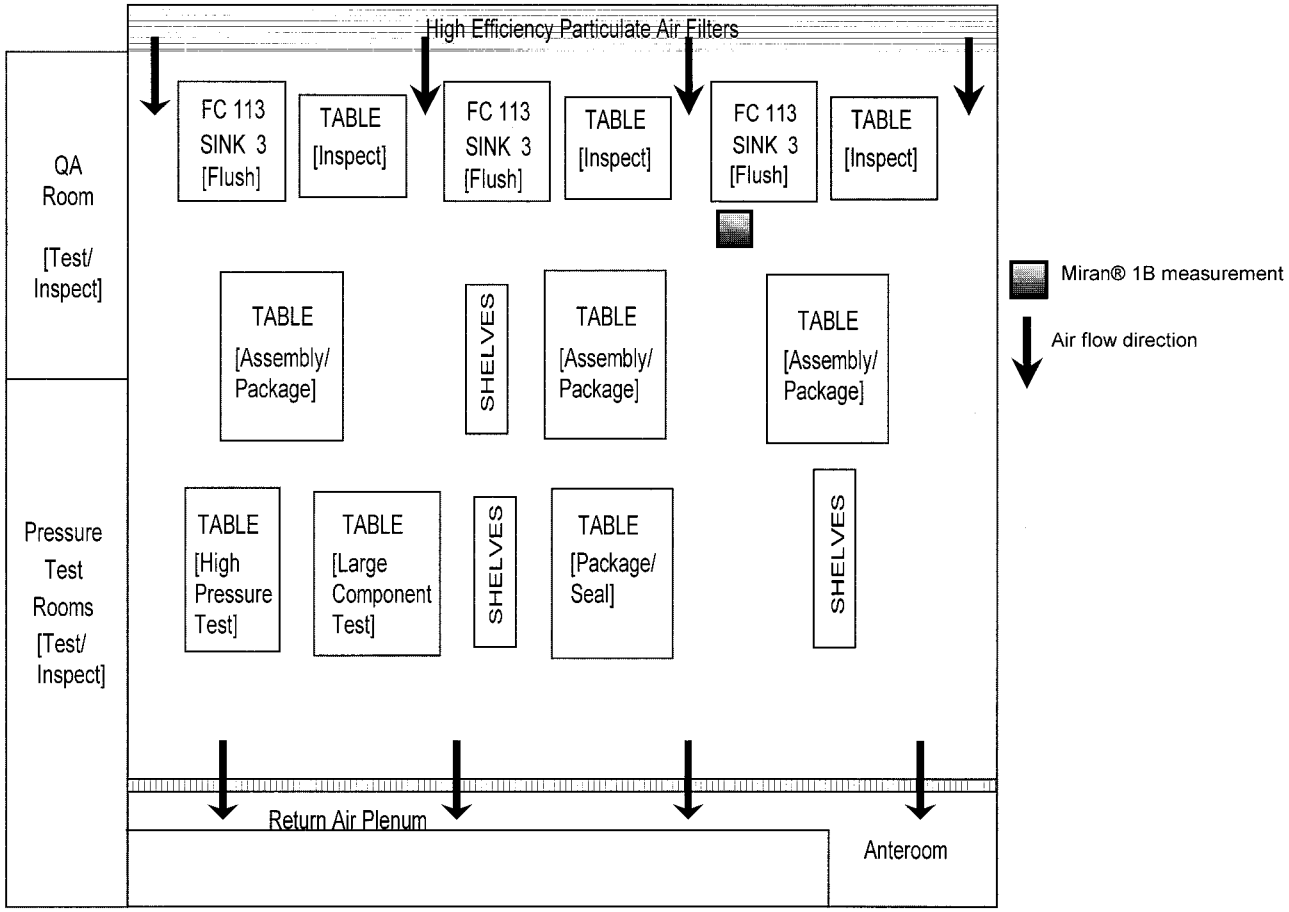

FIGURE 1. Plan view of horizontal laminar airflow clean room (figure not to scale)

recommended exposure levels (RELs), by contrast, are based primarily on concerns relating to the prevention of occupational disease.

The current American Conference of Governmental Industrial Hygienists' threshold limit value (TLV®) for FC 113 is identical to the PEL for both 8-TWA and STEL. The TLV-TWA and STEL are recommended to minimize potential for systemic toxicity and cardiac sensitization.[1]

This article describes an evaluation of FC 113 exposures in two clean rooms. Short-term sample measurements were made as part of a study to determine whether FC 113 exposure was associated with an increase in cardiac dysrhythmias.[8] 8-TWA data for the two major groups as well as exposures to five specific cleaning tasks were computed from the sample data. A more in-depth presentation of the sample data is presented elsewhere.[9]

BACKGROUND

Description of Workplace

Both clean rooms were contractor-operated, National Aeronautics and Space Administration-owned facilities. One clean room used a horizontal laminar airflow (HLAF) scheme; the other clean room used a vertical laminar airflow (VLAF) scheme. Both clean rooms cleaned parts of a wide variety of shapes and sizes used in aerospace equipment. These included nuts, bolts, tees, pipe fittings, metal nipples, flexible metal hoses, laboratory glassware, valves, small components, filters, filter holders, and gaskets.

General concepts, design considerations, and operating principles related to clean rooms are discussed in the available literature.[10,11] For this investigation, Figure 1 shows a plan view of the HLAF clean room. This clean room was rated as a Class 400; i.e., particle concentration was restricted to no greater than 14,130 particles/m^3 (400 particles/ft^3) 0.5 μm in diameter or larger.[11] Dimensions were approximately 13.1 m wide × 15.5 m deep × 2.7 m high (46 ft W × 51 ft D × 9 ft H). The HLAF clean room was designed for 20% fresh make-up air and approximately 26 fresh air changes per hour (AC/hr). The average number of parts cleaned in this clean room annually was reported to be about 200,000.

Figure 2 shows a plan view of the VLAF clean room. Dimensions of this clean room were approximately 6.1 m wide × 11 m deep × 2.8 m high (20 ft W × 36 ft D × 9 ft H). This clean room was rated as a Class 1000; i.e., particle concentration was restricted to no greater than 35,700 particles/m^3 (1000 particles/ft^3) of 0.5 μm in diameter or larger.[11] This clean room was designed for 10% fresh make-up air and approximately 66 fresh AC/hr. Average annual number of parts cleaned was reported to be about 50,000.

In both clean rooms, recirculated air was not filtered to remove

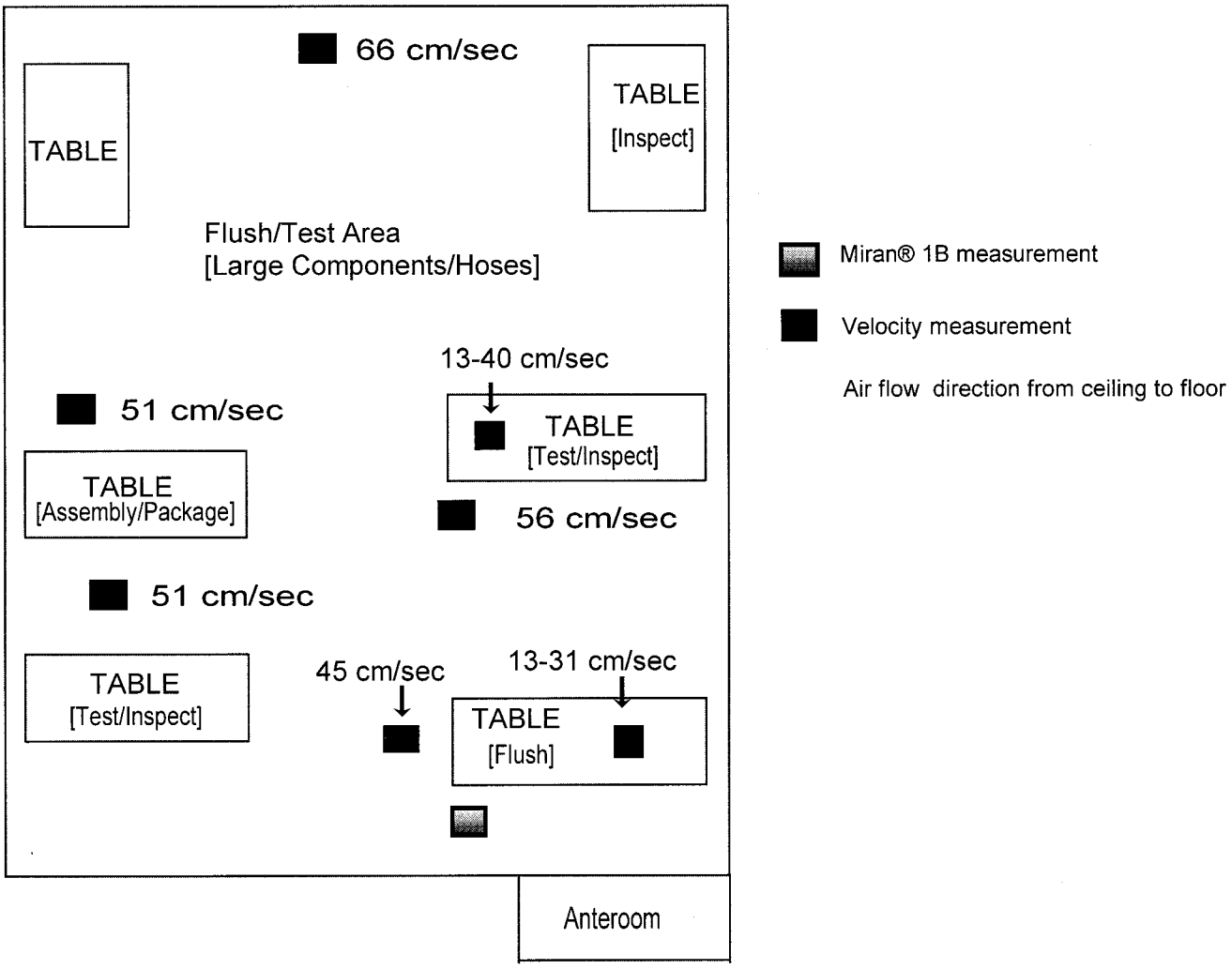

FIGURE 2. Plan view of vertical laminar airflow clean room (figure not to scale). Velocity measurements made with a hand-held velometer (TSI Inc., St. Paul, Minn.).

FC 113 vapors. For both clean rooms, the nominal work shift period was 7:00 am to 3:30 pm.

Description of Cleaning Process and Work Groups

In this investigation the component cleaning process was similar at both facilities. An individual part, or more typically a batch of parts, was first cleaned in a preclean room using a series of detergents, after which the part or parts were brought to the clean room for the final cleaning step—flushing with FC 113. Flushing accomplished two purposes: (1) removing impurities that were not removed during the precleaning process and (2) providing a means to evaluate the adequacy of the cleaning.

After flushing, inspection for adequacy of cleaning commenced. A sample of the flushed FC 113 solution was first collected and filtered. The filter was placed under a microscope and a particle count performed. If the particle count was less than a rejection criterion level, thus indicating sufficient cleaning, the part or batch of parts then went on to physical testing (as necessary), assembly (if the part or parts were from a larger component), and packaging (wrapping of the cleaned parts in plastic followed by heat sealing of the wrap) phases.

If the particle count exceeded the rejection criterion, the part (or batch of parts) was cleaned again. This usually involved reflushing with FC 113. If more rigorous cleaning was deemed necessary, an ultrasonic cleaner containing FC 113 was used. This process was repeated as necessary to reduce the filter particle count to a level below the rejection criterion.

In each clean room there were two major work groups: clean room mechanics and quality assurance (QA) mechanics. Flushing, assembly, packaging, and physical testing tasks were performed by the former group. The QA mechanics performed all inspection-related tasks. These included (a) FC 113 flush solution sample filtration and subsequent filter particle counting, (b) observing and validating all physical testing-related tasks, and (c) analysis of FC 113 flush solution samples for nonvolatile residue content. Each defined task encompassed a variety of subtasks associated with the (identified) main task. For example, the flushing task would include not only the actual flushing of parts but also related subtasks incidental to the actual flushing. Figures 1 and 2 show the primary locations where each of the five tasks was conducted.

In each clean room the primary source of FC 113 exposure was that used during the flushing task. In the HLAF clean room

there were two additional FC 113 exposure sources: the ultrasonic cleaner and a process filter testing apparatus. Both pieces of equipment contained standing baths of FC 113. Although the baths were covered, they were not airtight. As a result, FC 113 vapors could escape into the ambient clean room environment and become dispersed throughout the clean room via air recirculation.

While the cleaning process was essentially the same at both facilities, the FC 113 flushing methods differed between the clean rooms. The HLAF clean room used a dip method for flushing parts. Individual parts were grasped with tongs and then dipped into a cylindrical container of FC 113 situated in a metal sink (see Figure 1). FC 113 flowed continuously from a spigot into the container. Overflow drained from the sink and was piped to a filtration system located external to the clean room. All flushing tasks were performed within the sink.

In contrast, a spray method was used in the VLAF clean room. Here, small parts to be cleaned were placed in a rectangular metal tub situated on a table (see Figure 2). The FC 113 was sprayed onto the parts by a worker using a spray wand. The tub was connected via a hose to a drain, which was connected via pipe to a filtration system located external to the clean room. Periodically, however, it was necessary to flush long hoses or large objects that could not fit into the small rectangular sink. In these cases it was necessary to perform flushing in an open floor area in the clean room (see Figure 2). To accomplish this, the part or hose was placed in a large rectangular pan on the floor and then flushed with FC 113. The flushed FC 113 contained in the pan was later drained into the filtration system.

METHODS

Exposure Assessment

Personal Measurements

Personal exposure measurements were obtained from each of the 15 individuals who worked in the HLAF clean room and each of the 9 individuals who worked in the VLAF clean room. Measurements were obtained during the day shift at each location.

To examine the association between FC 113 exposure and the occurrence of cardiac events, a full period consecutive samples measurement strategy was employed for the exposure assessment.[12] Air samples were collected from each worker for the entire shift. A nominal 30-minute sampling period was chosen. Selection of the sample time was based on several considerations: (a) maximizing the likelihood of associating specific exposure levels with cardiac events, (b) the need to minimize interference with clean room operations, (c) the need to minimize impact on clean room cleanliness requirements, and (d) the limitations on the number of workers that could be monitored within a given period by NIOSH investigators. Ultimately, sampling times ranged from 13 to 79 minutes, with 75% of the sampling times ranging between 30 to 60 minutes.

Prior to entrance into the clean room at shift commencement, employees donned the air sampling equipment in an anteroom (see Figures 1 and 2). When employees left the clean room during break periods, the air sampler was shut off and removed from the person in the anteroom before exit and then donned (in the anteroom) before reentry. Air sampling equipment was again removed from the person at the conclusion of the work shift in the anteroom prior to departure. Workers were queried as to their job titles; at the conclusion of each sampling period, the worker was queried as to the predominant task(s) performed during the period.

Sampling and analysis for FC 113 was performed according to NIOSH analytical method 1020.[13] Samples were collected by drawing air at a rate of approximately 50 cm^3/min through a coconut charcoal tube attached to the lapel. Gas chromatography was used for sample analysis. Field and media blank samples were also obtained. The calculated minimum detectable concentration for the FC 113 samples was 0.7 ppm (based on a 2-L, 40-min air sample). All analytical results did fall within the working range of the FC 113 analytical method.

Real-Time Measurements

To estimate peak FC 113 concentrations associated with the flushing task, real-time (continuous monitoring) data were collected during one full shift (see Figures 1 and 2 for sampling locations) in each clean room using a MIRAN® 1B Infrared Analyzer (Foxboro Co., South Norwalk, Conn.) connected to a Rustrak® Ranger (Rustrak Co., East Greenwich, R.I.) data logger. To obtain breathing zone measurements during performance of the actual flushing, a sampling probe attachment available with the MIRAN 1B was held manually near the breathing zone of the worker.

The MIRAN 1B was first calibrated in the laboratory. Known concentrations of FC 113 were injected via microliter syringe into the Closed Loop Calibration System available from the manufacturer. A least-squares regression function computed from the calibration curve was used to convert signal output from the Rustrak Ranger data logger to FC 113 concentration.

Data Analysis

Computation of 8-TWA Exposures

8-TWA exposures were calculated for each employee by time-weighting the applicable short-term samples according to the formula:

$$E_{8\text{-TWA}} = \frac{\sum_{i=1}^{n} C_i T_i}{\sum_{i=1}^{n} T_i}$$

where $E_{8\text{-TWA}}$ = the 8-TWA exposure estimate for the employee, and C_i = measured concentration of sample i for the employee during sampling time T_i. For an 8-TWA, the sum of the time periods (T_i) is 8 hours.

A zero exposure outside the clean room was assumed. Therefore, in computing 8-TWAs, a zero concentration was assumed for the time difference between the sum of the times of the short-term samples (for each employee) and 480 minutes (8 hours). The median number of short-term samples used in computing the 8-TWAs for employees in both clean rooms was 7. Mean 8-TWA exposures for each of the two work groups were then computed by taking the average of the 8-TWAs of the individuals assigned to each work group.

Computation of Task Exposures

Among the five specific cleaning tasks—flushing, assembling, inspecting, testing, and packaging—there was variation in the number of workers who performed individual tasks as well as variation in the number of short-term samples collected from each worker performing a given task. This was due not only to the variation in sampling times among the tasks, but also to the predominance of some tasks in the overall cleaning process. In addition, an employee may perform more than one task during the work shift.

Therefore, a mean task exposure based on individual employee task means was computed using a two-step procedure: (1) calculation of a mean task exposure *for each employee* using the appropriate task related short-term samples, followed by (2) calculation of an overall mean task exposure from the individual employee means for each task.

The two-step calculation procedure can be illustrated by the following equations:

$$\overline{E_j} = \frac{\sum_{i=1}^{n_j} E_{ij}}{n_j} \qquad \text{(Step 1)}$$

where

$\bar{E}_j$ = mean exposure of employee j to a given task
E_{ij} = measured concentration of sample i for employee j associated with the given task
n_j = number of samples obtained from employee j for the given task

and

$$E_{Task} = \frac{\sum_{j=1}^{p} \overline{E_j}}{p} \qquad \text{(Step 2)}$$

where

E_{Task} = mean exposure to the given task
$\bar{E}_j$ = mean exposure of employee j to a given task
p = number of employee task means

Analysis of Variance (ANOVA)/Underlying Population Distribution

ANOVAs were conducted to test the null hypothesis of no significant difference between the means of the 8-TWA exposures of the two work groups and also among the exposure means of the five tasks. As part of the ANOVAs, the residuals from each of the models were evaluated to determine the appropriate underlying distribution. All statistical analyses were performed using SAS® PC Version 6.12 (SAS Institute, Cary, N.C.)[14]

Analysis of the residuals using PROC UNIVARIATE along with the Shapiro-Wilk test for normality indicated that the log transforms of both 8-TWA and task concentration data were normally distributed. Therefore, geometric means were used in describing measures of central tendency; and the log transforms of the FC 113 8-TWA exposure data and of the task data were used for the ANOVAs. Empirical and theoretical bases also justify assumption of the lognormal distribution to occupational data sets.[15]

RESULTS

Table I summarizes 8-TWA data for the two major work groups in each clean room. In the HLAF clean room, 8-TWAs ranged from 193 to 439 ppm; in the VLAF clean room, 8-TWAs ranged from 110 to 935 ppm.

For clean room mechanics the geometric mean 8-TWA exposure was 291 ppm in the HLAF clean room and 226 ppm in the VLAF clean room. For QA mechanics the geometric mean 8-TWA exposure was 251 ppm in the HLAF and 197 ppm in the VLAF clean room.

Table II summarizes short-term concentration data related to the five tasks performed by clean room workers. Over the entire clean room, sample concentrations ranged from 104–1080 ppm in the HLAF clean room, 51–3380 ppm in the VLAF clean room. Geometric means for the five tasks ranged from 260 ppm (testing) to 518 ppm (flushing) in the HLAF clean room. For the VLAF clean room the range was from 123 ppm (packaging) to 512 ppm (flushing).

TABLE I. FC 113 8-TWA Work Group Exposures by Location

Work Group	No. Employees[A]	AM[B]	GM[C] (GSD)[D]	Range[E]
HLAF Clean Room				
Clean room mechanic	11	301	291 (1.3)	193–439
Quality assurance mechanic	4	254	251 (1.2)	208–304
VLAF Clean Room				
Clean room mechanic	7	294	226 (2.0)	110–935
Quality assurance mechanic	2	213	197 (1.8)	133–293

[A] Number of employees in work group.
[B] Arithmetic mean (in ppm).
[C] Geometric mean (in ppm).
[D] Geometric standard deviation.
[E] Range of 8 TWAs (in ppm).

Figures 3 and 4 show real-time (continuous monitoring) data collected in the two clean rooms near the flushing task. In the HLAF clean room (Figure 3) peak concentrations of 1851, 1555, and 1532 ppm were measured near the surface of the sink, while a peak concentration of 1500 ppm was measured within the breathing zone. The maximum 15-min breathing zone concentration computed during this task was 964 ppm.

In the VLAF clean room, a peak concentrations of 1170 ppm was measured within the breathing zone during the flushing task; the maximum 15-min breathing zone concentration was computed to be 963 ppm. Another peak concentration of 979 ppm was measured outside the breathing zone near the flushing task.

Table III shows the ANOVA of the 8-TWA data for each location. The factor of most interest is the work group—clean room mechanic or QA mechanic. In both clean rooms, differences between the means of the two work groups were not statistically significant ($p=0.34$ for HLAF clean room and $p=0.59$ for VLAF clean room).

Table IV shows the ANOVA of the task data for each location. Here, there were several factors included in the model: task, worker, and worker/task interaction. The latter two factors were added to the model to account for differences among workers performing the same task and for differences in the effect of tasks for different workers. In the HLAF clean room, differences among the means of the five tasks were statistically significant ($p=0.03$). In the VLAF clean room, overall means among the five tasks were not statistically significantly different ($p=0.16$). However, differences among task means were not the same for each worker (because the worker × task interaction effect was statistically significant).

DISCUSSION

The ranges of 8-TWAs found in each clean room show that all exposures were below the current OSHA PEL and NIOSH REL of 1000 ppm. The results were, in general, unremarkable with the exception of one 8-TWA in the VLAF clean room. The 935 ppm, which is close to the PEL and REL, was experienced

TABLE II. FC 113 Task Exposures by Location

Task	No. Samples[A]	Concentration Range[B]	No. Employees[C]	AM[D]	GM[E] (GSD)[F]	Means Range[G]
HLAF Clean Room						
Flush	24	222–961	8	555	518 (1.4)	314–851
Assemble	19	174–1080	4	403	358 (1.3)	236–458
Test	7	191–612	2	402	260 (1.7)	335–433
Package	25	135–761	5	412	372 (1.2)	268–424
Inspect	29	104–653	4	358	329 (1.1)	276–358
VLAF Clean Room						
Flush	17	174–3380	6	805	512 (2.3)	194–2143
Assemble	6	76–557	2	207	178 (1.0)	171–184
Test	4	52–636	2	424	289 (3.0)	130–636
Package	17	51–626	5	163	123 (1.9)	57–247
Inspect	11	77–1726	2	557	378 (1.8)	247–572

[A] Number of short-term samples collected for task.
[B] Range of sample concentrations (in ppm).
[C] Number of employees performing task.
[D] Arithmetic mean of worker task means (in ppm).
[E] Geometric mean of worker task means (in ppm).
[F] Geometric standard deviation of worker task means.
[G] Range of worker task geometric means (in ppm).

by a clean room mechanic for whom flushing is the primary task. This worker was visibly shorter than co-workers. Consequently, the breathing zone of this individual was unusually close to the opening of the rectangular metal tub situated on the worktable, where FC 113 was applied to parts using the spray wand. The result was an 8-TWA considerably greater than 8-TWAs of the other clean room mechanics, which ranged from 70 to 298 ppm.

For both clean rooms, the geometric means of the 8-TWA FC 113 exposures for each of the two major work groups in each clean room were well below OSHA and NIOSH exposure criterion. The assumption of log normality of the underlying populations allows for computation of the maximum frequency for which exposures exceed a certain concentration (in this case, the PEL and the REL) based on the *arithmetic* mean (of the lognormal distribution) only. This is because the mean and variance are not independent (as is the case with a normal distribution). Based on computations reported by Rappaport, for an arithmetic mean of 301 ppm (for the clean room mechanic in the HLAF clean room)

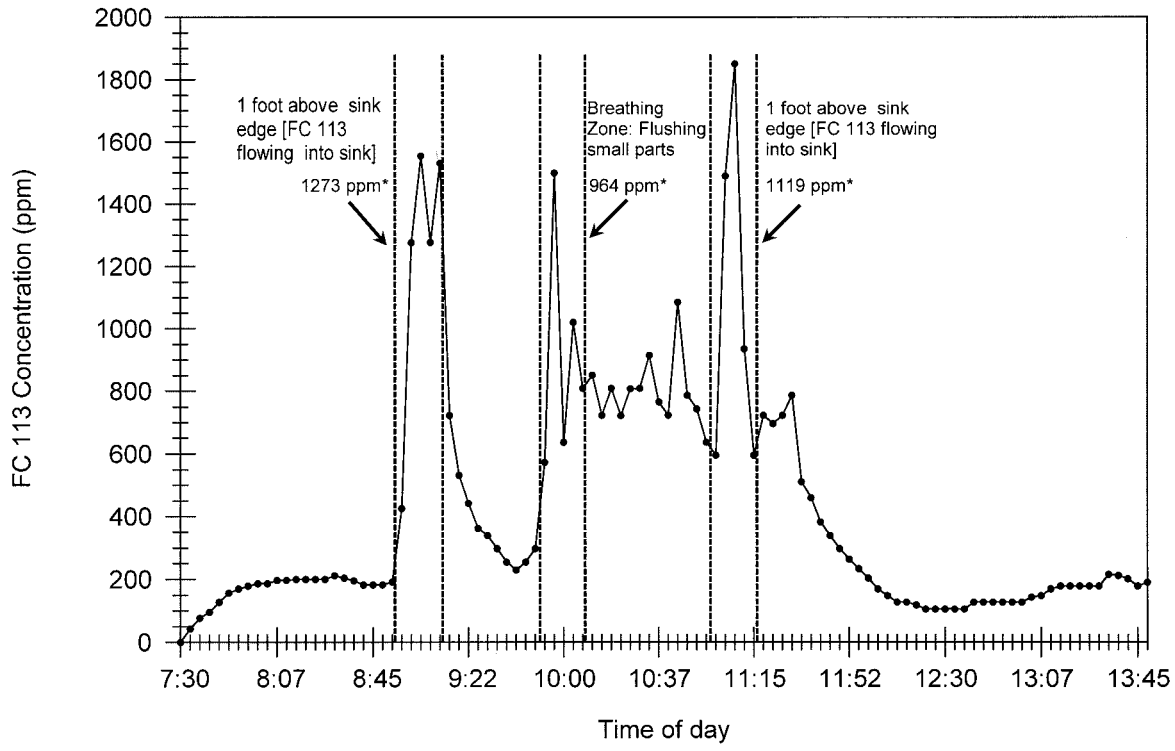

FIGURE 3. FC 113 concentration versus time measured with MIRAN 1B near flush sink in HLAF clean room. Nominal shift period: 7:00 a.m.–3:30 p.m.; measurement period: 7:27 a.m.–1:50 p.m. *Average exposure for 15-min interval.

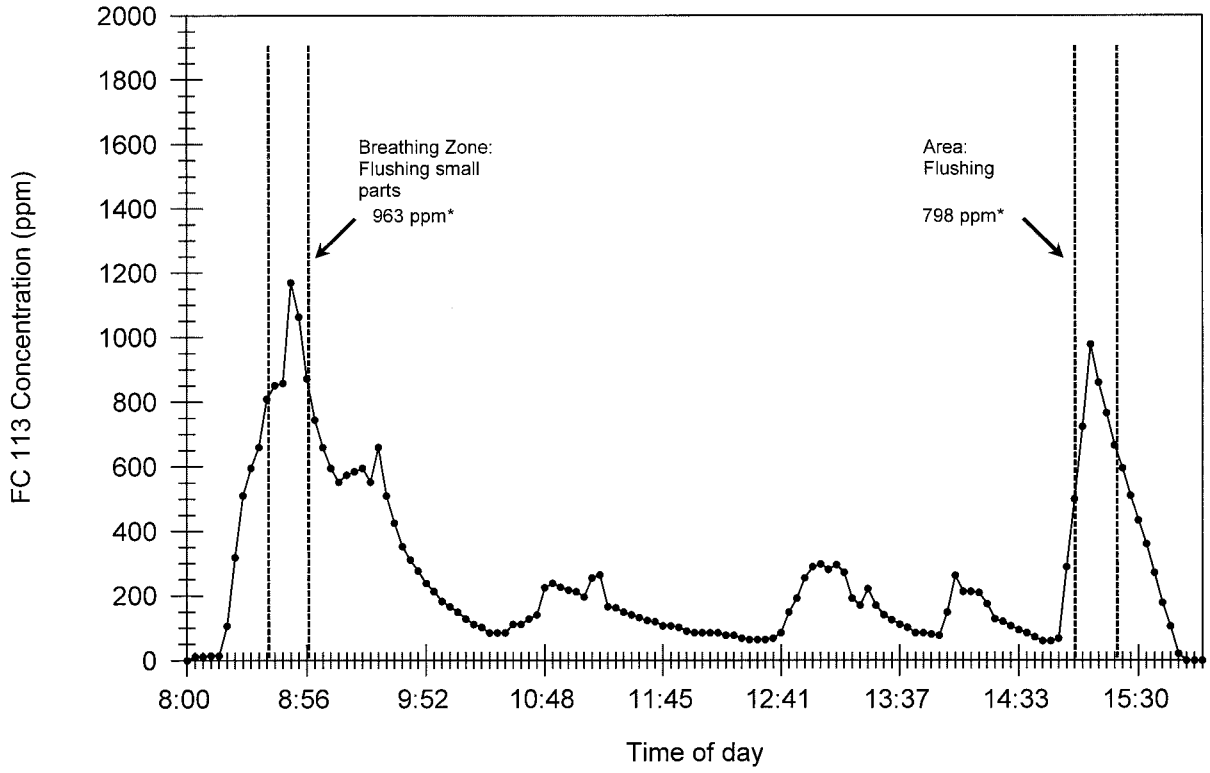

FIGURE 4. FC 113 concentration versus time measured with MIRAN 1B near rectangular flush sink in VLAF clean room. Nominal shift period: 7:00 a.m–3:30 p.m.; measurement period: 7:57 a.m.–4:00 p.m. *Average exposure for 15-min interval.

and a PEL/REL of 1000 ppm, approximately 6% of clean room exposures would be expected to exceed the PEL/REL.[15]

Because none of the short-term samples were obtained over defined 15-min sampling intervals, concentration data (shown in Table II, column 3) are not directly comparable with the NIOSH STEL of 1250 ppm. Based on measured short-term concentrations and task geometric mean data, however, performance of the flush task would appear to represent the greatest opportunity for exposures exceeding the STEL. Several concentrations measured during performance of the flush task in the VLAF clean room exceeded the STEL. Specifically, a concentration of 2522 ppm was measured during a 13-min sample period for one individual; for a second individual a concentration of 1451 ppm was measured during a 14-min sample period. No samples collected in the HLAF clean room exceeded the STEL.

The real-time data, in contrast, indicated that maximum 15-min breathing zone concentrations during the flushing task did

TABLE III. ANOVA of FC 113 8-TWAs by Location

Source	DF[A]	Sum of Squares	Mean Square	F Ratio	P[B] Value
HLAF Clean Room					
Work group	1	0.06	0.06	0.99	0.34
Error	13	0.83	0.06		
VLAF Clean Room					
Work group	1	0.03	0.03	0.07	0.80
Error	7	3.15	0.45		

[A] Degrees of freedom.
[B] P-value is the probability that the null hypothesis (no difference between the means of the source levels—in this case, the means of the two work group populations) is true. Analysis is based on the log-transformed data. A level of significance of $p = 0.05$ is used. A computed p-value of less than 0.05 would result in a rejection of the null hypothesis.

TABLE IV. ANOVA of FC 113 Task Means by Location

Source	DF[A]	Sum of Squares	Mean Square	F Ratio	P[B] Value
HLAF Clean Room					
Task	3	1.81	0.60	3.06[D]	0.03
Worker	13	3.53	0.27	1.38[D]	0.19
Worker × Task[C]	4	0.86	0.22	1.10	0.36
Error	82	16.1	0.20		
VLAF Clean Room					
Task	3	18.7	6.25	2.67[E]	0.16
Worker	7	6.74	0.96	1.81	0.11
Worker × Task[C]	5	11.7	2.34	4.41	0.003
Error	38	20.1	0.53		

[A] Degrees of freedom. Because of the unbalanced design that was a consequence of the measurement strategy, the degrees of freedom are altered from those for a completely balanced design.
[B] P-value is the probability that the null hypothesis (no difference among means of the source levels) is true. Analysis is based on the log-transformed data. A level of significance of $p = 0.05$ is used. A computed p-value of less than 0.05 would result in a rejection of the null hypothesis.
[C] Effect of interaction between worker and task; this is a test to determine if the differences among the task means are the same for each worker.
[D] Tested against a "new" error term formed by pooling worker × task and random error terms.
[E] Tested against worker × task interaction.

not exceed the NIOSH STEL in *either* clean room. It should be pointed out, however, that for both clean rooms, real-time monitoring took place on days *other* than those on which the highest short-term concentrations were measured. Such a finding, therefore, may be more reflective of the presence of a day-to-day component of exposure variability. Nevertheless, the peak concentration levels measured in each clean room do lend support to the observation that performance of the flush task, which involves working directly with liquid FC 113, can result in exposures exceeding the STEL.

Overall task exposure means for each of the five tasks were unremarkable. The flush task geometric mean in each clean room was elevated over that of the other four tasks. This reflects increased exposure due to direct work with liquid FC 113 during this task.

The ANOVA indicated that the means of the 8-TWA exposures were not significantly different between the clean room mechanics and QA mechanics in each clean room. One possible explanation for the lack of detecting a significant difference among the means of the two work groups (assuming that a significant difference does exist) may be the limited sample sizes for 8-TWA exposures. Due to small sample sizes—11 values for the clean room mechanic, 4 the QC mechanic in the HLAF clean room; 7 values for the clean room mechanic, 2 for the QC mechanic in the VLAF clean room—the ability to detect a true difference within each clean room is reduced. Larger worker populations available for study would increase the ability to detect a significant difference among means, if it does exist. It should be pointed out that failure to reject the null hypothesis (i.e., no significant difference between the means of the work groups) does not justify a conclusion that the means of the two work groups—clean room mechanics and QA mechanics—are equal. It implies only that the difference between the two work group means, if any, is not large enough to be detected with the given sample size.

Another possible explanation for the lack of a significant difference among 8-TWA means of the two work groups is movement of QA mechanics into and out of areas where the clean room mechanics perform their tasks and vice versa. Random movement over the work shift of both work groups into all areas of the clean room could result in similar exposure means.

Averaged over all workers, means among the tasks were significantly different in the HLAF clean room, but were not significantly different in the VLAF clean room. However, the significance of the worker × task interaction effect in the VLAF clean room indicates that the difference in means varies by individual. Thus, at least for some workers in the VLAF clean room, there were significant differences among the task means.

The real-time data obtained near the sink in the HLAF clean room (see Figure 3) indicated the existence of a preshift "background" concentration as well as an emergence of a postshift "background" FC 113 concentration of approximately 200 ppm. It is possible that this level represents the exposure contribution from the ultrasonic cleaner and process testing equipment, both of which contain FC 113. If these two components are the source of the background in the HLAF clean room, it is clear that substantial reduction in 8-TWA and task exposures could be achieved by minimizing escape of FC 113 vapors from these sources.

Workstation design associated with the flush task in the HLAF clean room appeared to enhance FC 113 exposure. The sinks were positioned such that the mechanics stood directly in front of the sink to carry out the task. Air flowing horizontally from the filters would sweep across the sink opening and would entrain the FC 113 vapors. The vapor-laden air would then strike the chest of the worker and be diverted upward into the breathing zone. This effect can be seen in Figure 3 by comparing the (similar) peak FC 113 vapor levels measured at 0.3 m (1 ft) above the sink opening level with a similar level measured in the breathing zone during flushing of small parts.

In the VLAF clean room, the reduction of airflow velocity at worktable surfaces (see velocity data in Figure 2) likely results in less efficient removal of FC 113 vapors from the breathing zone during performance of the flush task. Depending on the height of the worktable surface above the floor and the personal height of the worker, an increase in exposure could result. The reduced efficiency of vapor removal near the table surface may have contributed to the elevated STELs obtained for the one worker.

No analyses were undertaken to evaluate work group or task exposure differences *between* the two types of clean rooms. From an exposure control perspective, it would be of interest to identify what airflow direction (i.e., the horizontal flow or vertical flow) confers a lower 8-TWA exposure for a given work group or short-term exposure for a given task. However, the ability to obtain a definitive answer is hindered by the presence of many physical differences between the two clean rooms that affect exposure. In addition to the direction of airflow, major differences include (1) the method of FC 113 application, (2) floor area and room volume, (3) production rate, (4) size of parts being cleaned, and (5) the number of air changes per hour. Because of the limited amount of data collected during this study and the presence of the aforementioned confounding factors, it would be difficult to attribute exposure differences to the direction of airflow only.

CONCLUSIONS AND RECOMMENDATIONS

Study data suggest a low probability that 8-TWA exposures to FC 113 in either type of clean room will exceed the current OSHA PEL and NIOSH REL. Several short-term concentrations measured in the VLAF clean room during the flushing task were above the NIOSH STEL of 1250 ppm, indicating that this exposure limit may be exceeded for tasks involving direct work with liquid FC 113. Peak concentration levels measured in each clean room lend support to this conclusion.

Data suggest that the means of the FC 113 8-TWA exposures are likely to be similar among major clean room work groups. Movement of all workers throughout all areas of each of the clean rooms is thought to be a possible explanation.

Redirection of FC 113-laden air into the worker's breathing zone due to worker position during flushing of parts in the HLAF clean room appears to contribute to occurrence of peak exposures. One option for minimizing airflow redirection in this and other HLAF clean rooms employing a similar cleaning process arrangement is to modify the worker position such that the air flows at right angles to the worker. For this HLAF clean room, the sinks would be modified so that the work position is moved 90°. Air would then flow unimpeded past the sink, and vapors would be pulled horizontally away from the breathing zone.

In the VLAF clean room, worktable surfaces appear to impede the movement of air descending vertically causing a loss of air velocity at the surface and likely reducing the efficiency of FC 113 vapor removal during FC 113-using tasks (e.g., flushing of parts) performed atop the worktable. One option for minimizing airflow interruption would be to use tables with open wire grills as work surfaces. Such an open surface would reduce the impediment to FC 113-laden air reaching the floor where it can be exhausted.

Steel trays and tubs situated atop the wire grill would be used for flushing and where necessary to contain parts.

In the HLAF clean room, the feasibility of a local exhaust system installed near each sink to remove vapors generated during the FC 113-using tasks (e.g., the flush task) should be investigated. One possible scheme would involve covering the sink opening with a transparent rigid cover or hood, and then locally ventilating the enclosed sink. Openings in the cover/hood would be created as necessary to allow for access to the sink for parts flushing as well as to provide a source of supply air.

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