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# Effects of fire fighter protective ensembles on mobility and performance

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ABSTRACT

Many studies have shown that fire fighter turnout gear and equipment may restrict mobility. The restriction of movement is usually due to a decrease in range of motion (ROM). It is important to know how much the decrease in ROM affects performance. The aim of this study was to determine the effects of fire fighter protective ensembles on mobility and performance by measuring static and dynamic range of motion (ROM) and job-related tasks. Eight healthy adults (5 males, 3 females), aged 20–40 years, participated in this study. The study consisted of measuring a battery of motions and fire fighter specific tasks while wearing a standard fire fighter ensemble (SE) or regular light clothing (baseline or BL). Several BL ROM tests were significantly ($p < 0.05$) different from the SE test, including a decrease in shoulder flexion, cervical rotation and flexion, trunk lateral flexion, and stand and reach. There was a significant decrease in time from SE to baseline performing the one-arm search task and object lift. These overall findings support the need for a comprehensive ergonomic evaluation of protective clothing systems to ascertain human factors issues. The development of a Standard Ergonomics Test Practice for further use in laboratories that conduct personal protective systems evaluations using human test subjects is recommended.

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## 1. Introduction

Firefighting is one of the most physically demanding occupations, requiring personnel to perform numerous activities with minimal restriction of movement. It is well established that Personal Protective Clothing and Equipment (PPE) may decrease mobility (Saul and Jaffe, 1955; Adams and Keyserling, 1993, 1995; Huck, 1988, 1991) and may negatively affect performance (Saul and Jaffe, 1955; Alexander and Laubach, 1973; King and Frelin, 1984; Adams and Keyserling, 1995). Fire fighter protective ensembles provide limited protection for fire fighters in potentially hazardous environments. These hazards include thermal (flame, radiant and convective heat), physical (impact, debris and rough surfaces), biological (blood borne pathogens), environmental (ambient temperature and humidity extremes) and chemical (skin contact). However, this barrier (PPE) between the worker and the environment may have a negative impact on the wearer, including decreased mobility and increased muscular strain. More than fifty years ago, Nicoloff (1957) and Saul and Jaffe (1955) studied the effects of clothing on range of motion (ROM) and motor performance, respectively, using simple methods and devices. They concluded that clothing significantly affects mobility and performance.

A review of the literature revealed many different approaches to the measurement of mobility and performance. Mainly, the literature can be summarized as studies that measure ROM, usually under static conditions, up to a maximum angular change of a particular joint (Nicoloff, 1957; Adams and Keyserling, 1993, 1995; Huck, 1988, 1991); other types of evaluations involved measurement of the level of performance of different tasks (Alexander and Laubach, 1973; King and Frelin, 1984; Murphy et al., 2001). An early study from Saul and Jaffe (1955) mixed some ROM with motion tasks (walk forward, backward, or sideways). It is only recently that studies began to evaluate ROM while performing various tasks. Dorman (2007) found significant reductions on knee ROM when stepping up or crawling, but no significant differences when walking with the firefighting ensemble compared to light clothing control. While Dorman concluded that significant decreases in ROM could be measured with certain strategies (stepping up), decreases in ROM could not be demonstrated by simply walking while wearing protective ensembles. The British Standards Institute has published a standard assessing ergonomics performance and compatibility of fire fighters' ensembles (BS 8469, 2007). This standard provides

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guidelines for testing ergonomic performance based solely on job-related tasks.

Previously, the evaluation of ergonomics performance while wearing PPE had not utilized a consistent methodology possibly due to the lack of a standard protocol or published guideline. Havenith and Heus (2004) described various test methods used in order to create an ergonomics test battery for further development of standards on PPE. Earlier, Adams et al. (1994) proposed a conceptual model of testing to study the effects of PPE properties on several aspects of worker performance. They reported that few studies have quantified the effects of various parameters on work performance other than those related to heat stress or physiological burden. Based on the literature, it appears clear that guidelines are needed to evaluate the ergonomic impact of PPE.

An ergonomics test protocol was developed by the National Personal Protective Technology Laboratory (NPPTL) Research Physiology Laboratory for the purpose of evaluating the ergonomic characteristics of a prototype fire fighter ensemble with additional chemical and biological hazard protection. The results of that evaluation have been published elsewhere (Coca et al., 2008). As a follow-on using the test protocol developed by NPPTL, the present study evaluated the change in ROM while wearing a standard fire fighter ensemble (SE) compared with wearing light clothing (baseline or BL). In addition, performance was evaluated by timing a representative sample of the movements and actions that fire fighters are required to perform while on training or on duty. The approach strived to quantify ROM and evaluate the effects of a ROM decrease on performance or functional mobility. The null hypothesis was that there would be no significant differences in mobility and performance comparing the SE with the BL condition. To test this hypothesis, the objective measures of mobility of volunteer subjects were evaluated wearing SE compared to BL. This was accomplished by evaluating the static and dynamic ROM and ergonomic assessments of job-related tasks.

## 2. Methods

### 2.1. Subjects

Eight healthy adults (5 men, 3 women), three of whom were fire fighters, between the ages of 20–40 years, who passed a screening physical examination and completed a graded exercise test to maximal $\dot{V}O_2$, participated in this study. Five men, age (mean $\pm$ SD): 27 $\pm$ 6.44 yr; height: 177.5 $\pm$ 8.11 cm; body mass: 83.03 $\pm$ 12.23 kg; body surface area: 2.01 $\pm$ 0.18 $m^2$; body fat composition: 16.32 $\pm$ 2.29%; and three women, age 26.7 $\pm$ 6.11 yr; height: 169.3 $\pm$ 10.97 cm; body mass: 64.33 $\pm$ 10.26 kg; body surface area: 1.75 $\pm$ 0.18 $m^2$; body fat composition: 18.67 $\pm$ 4.14% comprised the study participants. Body fat composition was estimated from skin fold measurements taken from three selected body sites (Jackson and Pollock, 1985). Subjects were all physically active in leisure activities and were not taking any medications except for birth control pills for females. Fewer women were represented in the study because the US fire service has fewer women than men. The research was approved by the NIOSH Human Subjects Review Board, and both oral and written consent were obtained from all subjects prior to their participation in this study.

### 2.2. Experimental procedures

#### 2.2.1. Experimental ensemble

The SE was manufactured by Morning Pride/Total Fire Group, Dayton, OH. The SE used during this reported study was part of a larger project (Williams et al., 2007) supported by the Technical Support Working Group (TSWG) and the International Association of Fire Fighters (IAFF). The SE used in this investigation included turnout coat, pants, boots, gloves, hood, helmet and Self-Contained Breathing Apparatus (SCBA). The SCBA was used during job-related tasks but not during all ROM. The SCBA used in the present study was a Scott NXG2 Airpak with 45-min rated carbon cylinder and integrated Standardized Emergency Management System (SEMS) that uses a quick-disconnect, dual Emergency Breathing Support Systems (EBSS), EZ-FLO Plus regulator. The SCBA assembly meets the National Fire Protection Association's, NFPA, 1981, 2002 edition requirements and is a NIOSH approved Chemical, Biological, Radiological, Nuclear (CBRN) SCBA per U.S. Government Printing Office, 2004.

Baseline (BL) consisted of subjects wearing light clothing. This light clothing included sports cotton t-shirts, cotton/denim jogging shorts, and athletic shoes.

#### 2.2.2. Experimental conditions

The protocol required the subjects to don the assigned ensemble under ambient laboratory conditions of temperature (22° $\pm$ 0.5 °C) and humidity (40% $\pm$ 10%). The ergonomic evaluation was performed with brand new ensembles from the manufacturer before the ensembles had undergone any other testing. Subjects' body sizes were measured by the manufacturer prior to the start of the project and ensembles were custom fit to subjects. Thus, each test participant was provided an individual ensemble that was correctly sized. The baseline clothing had been industrial laundered.

Subjects donned randomly either BL or the SE on separate days, to perform the following 2 tests: BL ergonomics testing (light clothing only) and the same ergonomics testing with the SE (light clothing underneath). All testing was performed in the Research Physiology Laboratory of NPPTL.

#### 2.2.3. Measurements

Measurements included anthropometrics (subject height, weight, body mass, and body fat composition), as well as static and dynamic ROM. Each test followed a previously-described ergonomics protocol (modified from Johnson, 2005) as outlined in the Experimental Procedures section. For both tests, measurements were taken in the same progressive order during the session. Measurements progressed from anthropometrics to static ROM, to dynamic ROM, with job-specific ROM assessed after general ROM.

Anthropometric measurements were made using standard instruments including a flexible tape measure, circumference tape, washable marker, and scale. To standardize each measurement, three repeated values were taken on the side of the body coinciding with the subject's dominant hand. An average (reported in centimeters) of the measured values is the reported measurement for each subject (Results Section).

Static and dynamic ROM was assessed using a goniometer, torso bend device (Acuflex I, Novel Products, Inc., Rockton, IL), digital timing system, multi-colored tape (for marking purposes), tape measure, ladder, weighted rescue mannequin (68.2 kg), obstacles, and a weighted object (10.8 kg). The reported value was an average of the three recorded values.

#### 2.2.4. Experimental protocol

All dynamic and static activities were clearly explained to the subject and demonstrated by experienced laboratory staff before a measurement was taken. Static ROM consisted of measuring the active flexion/extension/abduction of the main body joints: elbow, shoulder, neck, hip, knee, ankle and wrist. All measurements were taken by the same researcher to avoid inconsistencies in the methodology and specific instructions were followed for each measurement. As an example (Fig. 1a and b), measurement of shoulder flexion was done as follows:


**Fig. 1.** Subject performing a shoulder flexion; 1a start position; 1b end position.

- *Start position*: The subject is standing. The arm is at the side, with the palm facing medially.
- *End position*: Subject remains standing, dominant humerus has moved anteriorly and dominant shoulder is fully flexed (without shoulder elevation).
- Goniometer position:
  - *Axis*: Placed at the center and at the lateral aspect of the humeral head. This is approximately 2.5 cm inferior to the lateral aspect of the acromion process.
  - *Stationary Arm*: Lateral to the subject's dominant side. In the sagittal plane, running along the midaxillarly line, and pointing toward the floor.
  - *Movable Arm*: Parallel to the humeral longitudinal axis, and pointing toward the lateral epicondyle of the humerus.

Other ROM measured consisted of reaching forward as far as possible from sitting and standing positions, as well as reaching overhead. General dynamic ROM included the following objective timed motions: kneel and rise, seated squats and step-ups. During job-specific ROM, subjects also performed the following objective timed tests: ensemble donning/doffing, one-arm search, ladder pickup, crawling over and under objects, mannequin drag, and solid object lift. All these tests were timed; the one-arm search was also measured by the number of knee strides (i.e., crawling on the knees) to cover the given distance, to assess any restriction of motion between ensembles. As an example (Fig. 2) of the specific procedures utilized to avoid inconsistencies in the methodology, the one-arm search measurement followed these instructions:

- *Start Position*: Subject in a crawling position with the dominant side parallel to wall, and dominant palm flush against the wall (this is considered the "searching" hand) at shoulder height.
- *Action A*: Subject crawls forward 15 feet, without releasing hand from wall, while moving the searching hand up and down the wall. When the subject's "searching" hand reaches the 15-foot mark, the subject continues onto Action B.
- *Action B*: Subject pivots toward the wall until in reverse start position (using the non-dominant arm on the wall), then repeats the crawling sequence.

This task was completed after three successful performances (using correct form) with a minute of standing rest between the repetitions. An unsuccessful action would cause the subject to repeat the task after a 1 min rest period. This task was timed and the mean of three successful actions was reported as the score. Additionally, number of strides to completion was counted and reported as a mean.

**Fig. 2.** Subject performing a one-arm search task.

- *Measurement*: Time and number of strides to complete task.

### 2.3. Statistical analysis

A comparison between BL and SE tests on ROM and job-specific tasks was analyzed by *t*-test using the SPSS 15.0 statistical package. Percentages of ROM loss from SE to baseline were calculated and percentages of time increase/decrease to perform specific tasks comparing SE and BL were also calculated. The data used in the analyses were the mean values for three measures obtained for each test. For purposes of this study, alpha level was set at 0.05 ($\alpha = 0.05$).

## 3. Results

### 3.1. Anthropometrics measurements

A summary of these measures shows that the ensemble (including boots and helmet) adds 14 cm to height compared to no ensemble (BL). Subjects wearing the SE weighed 10 kg more than when wearing no ensemble. Subjects wearing the SE and the SCBA weighed 20.8 kg more than when wearing no ensemble. Other measures that were taken for BL and SE are as follows ($N = 8$): neck to crotch, BL 65.7 $\pm$ 4.4 cm, SE 69.2 $\pm$ 4.6 cm; Hip Breadth BL 101.4 $\pm$ 11.1 cm, SE 125.0 $\pm$ 7.5 cm; Chest Circumference BL 96.28 $\pm$ 9.1 cm, SE 117.69 $\pm$ 8.3 cm; Waist Circumference BL 85.03 $\pm$ 10.8 cm, SE 118.00 $\pm$ 12.4 cm; Thigh Circumference BL 56.25 $\pm$ 4.8 cm, SE 72.56 $\pm$ 5.0 cm; Upper arm BL 31.50 $\pm$ 3.1 cm, SE 48.81 $\pm$ 6.1 cm.

### 3.2. ROM

ROM determined from 16 measures of the main joints and motions of the body are summarized in Table 1. Several SE tests

**Table 1**
Summary of ROM measurements and percentage of ROM loss from BL wearing SE. Asterisks indicate statistically significant differences ($p < 0.05$) between tests.

| Measure | BL (mean ± SD) | SE (mean ± SD) | % ROM loss |
|---|---|---|---|
| Elbow flexion (°) | 128.6 ± 17.6 | 113.3 ± 14.9 | 11.9 |
| Shoulder flexion (°) | 161.5 ± 10.5 | 138.7 ± 29.1* | 14.1 |
| Shoulder abduction (°) | 137.4 ± 29.1 | 110.7 ± 29.3 | 19.4 |
| Wrist flexion (°) | 56.4 ± 10.1 | 51.5 ± 13.1 | 8.6 |
| Wrist extension (°) | 52.7 ± 11.8 | 44.2 ± 10.0 | 16.1 |
| Knee flexion (°) | 118.5 ± 28.6 | 116.8 ± 10.1 | 1.5 |
| Ankle dorsiflexion (°) | 31.7 ± 14.5 | 22.3 ± 8.4 | 29.6 |
| Ankle plantar flexion (°) | 27.8 ± 11.8 | 21.3 ± 4.0 | 23.3 |
| Cervical rotation (°) | 53.5 ± 9.9 | 35.2 ± 16.4* | 34.2 |
| Cervical flexion (°) | 38.9 ± 13.6 | 22.7 ± 9.1* | 41.6 |
| Trunk extension (°) | 32.4 ± 22.5 | 22.6 ± 3.5 | 30.2 |
| Trunk flexion (°) | 99.4 ± 26.0 | 98.5 ± 23.5 | 0.9 |
| Trunk lateral flexion (°) | 25.1 ± 5.5 | 21.4 ± 5.2* | 14.7 |
| Sit and reach (cm) | 25.1 ± 9.3 | 16.7 ± 5.6 | 33.4 |
| Stand and reach (cm) | 11.6 ± 2.6 | 7.9 ± 2.2* | 31.8 |
| Overhead reach (cm) | 220.1 ± 13.4 | 219.7 ± 12.4 | 0.1 |

were significantly ($p < 0.05$) different from the BL tests, including a decrease in shoulder flexion, cervical rotation and flexion. Trunk lateral flexion ROM also decreased while wearing the SE compared to BL ($p < 0.05$); subjects also reached further when standing during BL testing compared to SE ($p < 0.05$). From Table 1, a decrease of ROM (average % of all the motions in one specific joint) can be seen in the shoulder (16.75%), ankle (26.45%), and neck (37.9%) in those subjects wearing the SE.

### 3.3. Job-specific tasks

Ten measures of dynamic ROM and job-specific tasks are summarized in Table 2. BL tests were significantly slower ($p < 0.05$) from the SE test on one-arm search (time and strides), as well as object lift tests. All the tests, with the exception of the mannequin drag and the alternating step up task, were performed slightly faster wearing an ensemble. The one-arm search task was significantly faster in the SE compared to BL. Subjects performed the task 9.2 s faster and took approximately three strides less to cover the same distance while wearing the SE compared to BL ($p < 0.05$).

## 4. Discussion

### 4.1. ROM and job-specific tasks

At the outset of the study, the null hypothesis was that there would be no significant loss of mobility and performance while wearing SE compared to wearing sports clothes. The lack of significant differences among most of the measurements comparing the SE and BL condition supports acceptance of the null hypothesis. Nevertheless, it is important to mention that the decrease in the ROM at the ankle (26.4%) and the neck (37.9%) can be regarded as important, due to the potential decreased on-the-job mobility (ankle) and loss of peripheral vision (neck). Using a similar methodology for ROM, Huck (1988) found significant differences between different ensemble designs. However, she recognized that measurements of joint motion taken over bulky protective clothing is a challenge and needs to be carefully obtained. This challenge was also experienced in the present study. Using similar methodology but different equipment than our study, Dorman (2007) found significant reductions on knee ROM when stepping up or crawling but no significant differences when walking with the ensemble compared to light clothing control. Dorman claimed that some of those differences were perhaps due to exaggerated movements needed to overcome the constraint of the PPE. However, Dorman concluded that the study could not prove conclusively that PPE restricts movement and ROM simply while wearing the PPE while walking. Nevertheless, it seems clear that ROM will be decreased while wearing restrictive protective ensembles, but these restrictions need to be kept to a minimum in order to limit the impact on performance. Our study shows that, with few exceptions, the decrease in ROM does not affect overall mobility and the job-related performance of tasks (Table 2). All the tests, with the exception of the mannequin drag and alternating step up task, were performed slightly faster wearing an ensemble, which is possibly due to the protection that the ensemble provides during these job-specific tasks. Subjects might feel that the PPE protects them while performing certain motions or tasks. A clear example is the significant difference found on the one-arm search task between the BL and the SE. Subjects performed that task 9.2 s faster and took approximately three strides less to cover the same distance while wearing the SE compared to BL ($p < 0.05$). This is probably related to the greater protection afforded the subjects' knees when wearing the SE compared to wearing shorts. However, despite the similarity in times, there would, of course, be a greater energy expenditure while wearing PPE.

**Table 2**
Summary of dynamic ROM and job-specific task measurements and percentage of time/steps loss/gain from baseline wearing SE. Asterisk indicate statistically significant differences ($p < 0.05$) between tests.

| Measure (seconds) | BL (mean ± SD) | SE (mean ± SD) | % Time decrease from BL |
|---|---|---|---|
| Kneel and rise, one knee | 7.5 ± 1.3 | 7.0 ± 2.5 | 6.6 |
| Kneel and rise, both knees | 10.6 ± 1.8 | 10.5 ± 2.8 | 0.9 |
| Seated squat | 5.5 ± 1.4 | 5.0 ± 1.4 | 9.1 |
| Alternating step up (steps/min) | 25.2 ± 4.0 | 25.9 ± 8.9 | −2.7 |
| One-arm search (strides/distance) | 15.0 ± 2.9 | 12.4 ± 2.8* | 17.2 |
| One-arm search (time) | 23.5 ± 6.6 | 14.3 ± 4.4* | 39.1 |
| Ladder pickup | 6.8 ± 2.8 | 5.7 ± 1.2 | 16.1 |
| Crawl over/under objects | 10.4 ± 3.9 | 9.1 ± 3.4 | 12.5 |
| Mannequin drag | 5.1 ± 1.5 | 5.7 ± 2.1 | −11.7 |
| Object lift | 10.6 ± 3.2 | 8.5 ± 2.4* | 19.8 |

### 4.2. Comparison with other studies

A survey of the literature found few articles related to the ergonomics methodology used in this study, thereby making it difficult to compare the results to other related research. However, the British Standard for ergonomics (BS 8469, 2007) gives a rating of 4 (1–4 scale for less restriction) when time to complete task is <110% of baseline. In our study, all job-related tasks were performed within a measured time of <110% of baseline and thus would have a BS 8469, 2007 rating of 4. This rating indicates that the level of restriction imposed by the SE was minimal or least restrictive of mobility.

One part of the evaluation used here was to examine the ergonomic limitations imposed by a standard ensemble compared to BL. Fire fighter ensembles limit wearer movement to some extent. Yet, the data collected in this study suggest that, in spite of the restrictive nature of firefighting ensembles, the SE design did not adversely affect the wearer's overall functional mobility compared to BL. This study was able to identify specific areas in which differences were found between the SE and BL that permit further development in the design process and guide improvements to the ensemble. These overall findings support the value of a comprehensive (ROM, job-related task and subjective assessments) ergonomic evaluation of protective clothing systems to ascertain human factors issues.

Researchers and manufacturers have tried to develop more comfortable clothing, while including additional features that provide more protection, without affecting mobility and performance. However, there is still a gap between PPE development/ design and human factors (ergonomic) testing that needs to be assessed (Guidotti and Clough, 1992; Stull, 2000; Barker, 2005). Abeysekera (1989) reported the need for national and international ergonomics standards for PPE. His study on the use of PPE in a developing country showed that the main cause for the non-use of PPE is the lack of comfort or ergonomics features. Adams et al. (1994) proposed a model for protective clothing effects on performance, but they concluded that their work introduced a framework and many areas (textile and clothing science, ergonomics, or industrial engineering) needed to be studied before performance effect models can be used. Few studies have covered such problems as mobility and performance using PPE. Recently, the British Standards Institute has published a standard assessing ergonomics performance and compatibility of fire fighters' ensembles (BS 8469, 2007). The main advance of this standard is the evaluation of the fire fighter ensemble as a whole system instead of individual parts of the ensemble. This allows users and manufactures to have a better understanding of interactions between parts of the whole ensemble and their effects on the users. However, there is no standard ergonomics test practice for any other protective clothing system as a whole, which combines ROM and functional mobility. Furthermore, Havenith and Heus (2004) have highlighted the importance of incorporating ergonomic testing into the overall evaluation of PPE. Currently, standard test practices exist mostly for individual items (gloves, helmets and footwear; i.e., Stull, 1992) or whole systems when evaluating materials (i.e., EN469) or physiological loads (i.e., American Society for Testing and Materials, 2007).

### 4.3. Recommendations for ergonomic evaluations and standards development

Currently, there is no standard ergonomics test practice for the evaluation of PPE, despite the fact that there is a demonstrated need for such. American Society for Testing and Materials (2004) could be a closely related standard method but it is very specific and does not allow for ensemble comparisons. Adams and Keyserling (1996) proposed a standard method for assessing PPE effects on worker mobility; however their method only covered ROM and subjective perceptions of comfort. An ergonomics test protocol was developed in our laboratory for the purpose of evaluating the Project HEROES® prototype. The impetus for that development was that the fire fighter prototype ensemble being tested for Project HEROES® (Slepicka and Rogers, 2005) incorporated new technologies that appeared to have the potential to impact the ergonomic characteristics of the ensemble. For instance, the addition of these new technologies further encapsulated the wearer, thus increasing the potential heat stress and further limiting mobility. Ultimately, the ergonomics data proved to be of great value for comparisons between the prototype ensemble and SE (Coca et al., 2008). It is recommended that the development of a Standard Ergonomics Test Practice for further use in laboratories that conduct personal protective systems evaluations using human test subjects be undertaken by a standards development organization (i.e., NFPA, ISO, ASTM, ANSI, etc.). The ergonomics test protocol reported in this study should be considered for use as a template for a standard test practice for the ergonomic evaluation of PPE. Further refinements would be expected as experience with this test protocol expands. Incorporation of a standard test protocol for the ergonomic evaluation of PPE may result in the implementation of improvements in PPE that will enhance mobility and function during use.

## 5. Conclusions

Fire fighter ensembles limit wearer movement to some extent. The data collected in this study suggest that, in spite of some ROM loss wearing the standard fire fighter ensemble compared to wearing sport clothes, the SE design does not adversely affect the wearer's overall functional mobility compared to not wearing protective clothing (BL). Furthermore, this study was able to identify specific areas (ankle, neck) in which differences were found between wearing an ensemble and other clothes to permit further attention in the ensemble design process to guide improvements in ensemble design.

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## Disclaimer

The findings and conclusions of this manuscript are those of the authors and do not necessarily reflect the views of the National Institute for Occupational Safety and Health. Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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