

EFFECTIVENESS OF SELF-CONTAINED BREATHING APPARATUS IN A FIRE ENVIRONMENT

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INTRODUCTION

Contemporary industrial facilities and residences contain a rapidly growing inventory of synthetic materials. Because combustion products from these materials and other inherently toxic substances can present a serious threat to fire fighters who must respond to structural fires, it is more important than ever that fire fighters be provided with respiratory protective devices that can withstand the severe environmental conditions they might encounter.

For some time we have been concerned that self-contained breathing apparatus (SCBA) might not operate properly when subjected to adverse environmental conditions. This concern has been elevated by reports of fire fighters being overcome or killed while wearing SCBA. Tests required by the National Institute for Occupational Safety and Health (NIOSH), the respirator testing and certification agency in the United States, do little to dispel this concern because they do not cover many conditions a fire fighter may encounter.¹

Lawrence Livermore National Laboratory (LLNL) is operated by the University of California under a prime contract with the U.S. Department of Energy (DOE). Because of its size and the nature of its work, the laboratory has a 40-member fire department that is sometimes called to fight fires that could involve highly toxic or radioactive materials. As the dangers of inhalation injury and health to LLNL fire fighters are particularly acute, the Laboratory wants to provide them with the best possible protection. Thus, the Safety Science Group in the Hazards Control Department at LLNL began a program to test various SCBA under potential fire and emergency conditions.

From the start, our investigation has been hampered by the small number of written reports on the magnitude of environmental factors such as heat, cold, water, and foam at a fire scene. When reports do exist, they generally conflict. Written reports on the death or injury rate of fire fighters while wearing SCBA are almost nonexistent. We centered our studies on evaluating existing equipment so SCBA could be selected from devices that offer the best protection against conditions that could exist during a fire at the Laboratory. As a literature search revealed very little information on such evaluations, we developed test parameters and criteria to evaluate various makes and models of SCBA. Although our investigations are not yet complete, we have come to several definite conclusions: the value of reporting a SCBA malfunction can be measured in terms of human life; and any condition that adversely affects the operation of an SCBA or causes it to malfunction should be studied.

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TEST PARAMETERS AND EQUIPMENT

Selection of our test parameters was difficult because, unfortunately, a standard fire has yet to be defined. Therefore, we selected parameters from what information was available and began testing. Our rationale for selecting the test criteria is given in other reports, as are the details of the individual tests^{2,3,4}. In this paper, we are reporting a summary of the overall program. Space does not permit details of any one test.

The tests which we have conducted to date are:

A. Temperature Extremes

1. SCBA operation at 38°, 52°, 65°, 79°, and 93°C.
2. SCBA operation at 250°C for 3 minutes.
3. SCBA operation at -32° and -40°C.
4. SCBA operation when thermally shocked from -32° to 93°C.
5. Effects of exposing SCBA facepieces to 93°C air temperatures, followed by light impact.
6. Effects of storing SCBA for 24 hours at -32°C.
7. Subjective tests of SCBA after exposure of 30 minutes to 79°C and 93°C.
8. Flame test of SCBA facepieces (1050°C for 10 seconds total time).
9. Flame test of closed-circuit oxygen rebreathing SCBA.

B. Effects of A Stream of Water on SCBA Operations

C. Effects of Fire Extinguishing Foam on SCBA Operation

Our objectives for the tests are to find out if the SCBA, 1) completely fails to operate during the test, 2) malfunctions during the test, 3) has any component parts damaged because of the test, or 4) the facepiece pressure goes negative with positive pressure units during the course of the test.

For most of the tests, the SCBA was breathed with a breathing machine⁵, (Figure 1) set at a moderate to heavy work rate of 52 liters per minute (1 pm). The exhaled air was humidified to simulate human respiration. Since most of the SCBA use in the United States is now required to be of the positive pressure (pressure demand) type because of the much greater protection it affords the user as compared to negative pressure (demand) units⁶, we measured facepiece pressure continuously with a calibrated pressure transducer and monitored it on a strip chart recorder. We were interested to see if the facepiece pressure was significantly changed under environmental stresses; particularly if positive pressure units went negative inside the facepiece when temperature extremes were encountered.

Temperature extremes were achieved through the use of an environmental chamber (Figure 2) with a range of -40° to 93°C. Special equipment for performing certain of the tests was purchased or constructed as necessary.

With the exception of the units used in the closed-circuit oxygen rebreathing apparatus flame test, most of the SCBA used in the test program were of the open circuit, compressed air type. Most were positive pressure units. although we did test three models of demand SCBA.

The makes and model of SCBA tested were:

A. Positive Pressure

1. Scott 6000
Old style facepiece
New style facepiece
2. Scott 9000
Old style facepiece
New style facepiece
3. Scott 4.5
4. MSA 401
5. Survivair
Neoprene facepiece
Silicone facepiece
6. Survivair Mark I
Silicone facepiece
7. Globe Guardsman
8. Robertshaw

B. Negative Pressure

1. Scott 4.5
2. Globe Guardsman
3. Biomarine Biopak 45 (closed circuit)

C. Closed Circuit Units (Flame Test Only)

1. MSA Chemox
2. Draeger BG-174A
3. Biomarine Biopak 60

TEST RESULTS

Following is a summary of the test results. Some have been reported in detail elsewhere, others will be reported in detail in future University of California LLNL reports.

A. Temperature Extremes

1. SCBA Operation at 38°, 52°, 65°, 79°, and 93°C.

In some makes of SCBA, as the air temperature increased, the inhalation pressures in the facepiece decreased while the exhalation pressures increased. Some positive pressure units actually went negative on **inhalation**, at the higher temperatures. No units failed to operate at even the highest temperature of 93°C.

The negative pressures that showed up in the facepieces of pressure-demand units tested at a moderate to heavy work rate are disturbing because they indicate these units are not providing the protection they were assumed to provide. The facepiece leakage studies done at the Los Alamos Scientific Laboratory,⁷ which showed a 10,000-plus protection factor for **pressure-demand** units, were conducted on men who were standing still and moving their heads slightly (a low work rate). At the moderate to heavy work rate, which we used and which is much more realistic for a fire fighter, some **pressure-demand** units showed negative facepiece pressures at ambient temperatures. At higher air temperatures, many units showed more negative pressures or went from positive to negative. This would be the worst possible time for such an occurrence as the fire fighter would be breathing at a moderately heavy to heavy rate while fighting a fire and would most likely encounter the highest concentrations of toxic materials when closest to the fire. At the same time, the high heat would cause increased negative pressure in the facepiece of a **pressure-demand** unit and increased leakage into the facepiece.

The low air pressure bell alarms on all units operated well and at the proper time while the units were exposed to even the highest temperature. A low air pressure whistle alarm on one model, however, became very weak and was barely audible on the pressure demand units and undetectable on the demand unit; as the temperature increased.

2. SCBA Operation at 250°C for Three Minutes

Since fire fighters could be exposed to very high temperatures for a short period of time (e.g., attempting a rescue or if a flash-back **occurs**), we wanted to perform a test which would indicate whether the SCBA would continue to operate under such a condition. We chose the National Fire Prevention and Control Administration **standard**⁸ for testing fire **fighters'** helmets as our criteria, reasoning that the SCBA should offer equal protection to the helmet. Using this standard which requires no deformation of the helmet when exposed to 250°C for three minutes, we constructed the test apparatus shown in Figure 3 to provide the necessary temperature. For safety reasons, the SCBA compressed air cylinder was not exposed to the high temperatures. Only the facepiece, breathing hose, and regulator were subjected to the heat. The breathing machine was used to operate the SCBA during the test.

One of the head harness straps broke on two of the eight models tested and almost all models exhibited some melting of plastic exhalation valve covers. Facepiece pressures went from positive to negative in the same models as occurred in the 93°C tests, as might be expected. Most important, however, was the fact that none of the eight models tested failed to operate during the

5. Effects of Exposing SCBA Facepieces to 93°C Air Temperatures, Followed by Light Impact.

We exposed five of each model of SCBA facepiece to 93° air temperature for 10 minutes and then hit the side of each facepiece lightly on the edge of the environmental chamber to simulate a fire fighter accidentally bumping his facepiece while working.

With one model, the exposure alone caused all five facepiece lenses to flatten and separate from the facepiece retaining frame, Figure 4. On another model, two of the five facepiece lenses separated from the retaining frame when one or two of the plastic clips holding the lens to the frame popped off, Figure 5. The manufacturer, in this case, had a plastic-ring lens holder available which then corrected the problem with their unit. On yet a third model, a strap retaining button broke on two of the five facepieces tested.

6. Effects of Storing SCBA for 24 Hours at -32°C.

In this test, we stored the SCBA for 24 hours at -32°C, examined the units for defects, then had an experienced SCBA user don the apparatus to determine facepiece fit and to see if the units were still operational, Figure 6.

With one model, the air cylinders were completely empty, the exhalation valve diaphragms were collapsed and frozen, the regulator valves were frozen shut, and the facepiece lenses shattered if the facepiece was accidentally dropped, Figure 7. Problems with other models included various types of air leaks, hard to operate control valves, rigid breathing tubes, and inflexible rubber facepieces (only silicone facepiece retained their flexibility). For this particular test, we also tried to operate a five-minute escape SCBA. The breathing tube to the hood promptly broke (Figure 8) when we tried to activate the unit after cold storage.

After the visual inspection, each unit was donned by an experienced SCBA user to determine facepiece fit. The test subject experienced noticeable throat and chest discomfort while breathing the chilled, dry compressed air. As a result, wearing time was limited to three to four minutes. This discomfort made it difficult to assess what the test subjects described as a sensation of restricted airflow and increased exhalation resistance. The cold, instrumented tests confirmed that airflow was indeed, restricted.

7. Subjective Tests of SCBA After Exposure of 30 Minutes to 79° and 93°C.

We stored two units of each model in the environmental chamber for 30 minutes at 79° and later at 93° and then an experienced SCBA user wore each unit. We wanted to determine subjectively what problems might be encountered that would not be as apparent with the instrumented tests with the breathing machine.

In general, the test subjects observed that black-colored facepieces, particularly those that had the greatest mass (and accordingly retained the most heat), were the most uncomfortable on contact with the face. Lighter weight and lighter colored (blue and yellow) silicone facepiece did not give this impression. All the facepieces were more flexible at these high temperatures and appeared to fit with less tension in the head harness.

At 65°C, the facepiece on one model no longer fit **firmly** because the silicone headbands softened and slipped through the retaining buckles on the facepiece. This was since corrected by the **manufacturer**. The neoprene and Hycar rubber head harness materials did not exhibit any noticeable softening or slippage.

The breathing regulators on all the SCBA tested became increasingly noisy at higher temperatures and interfered with the **user's** ability to communicate. We believe this noise (a sort of honking) resulted from the softening and stretching of the breathing diaphragm housed in the **regulator**, the noisiest regulators being those with silicone breathing diaphragms.

The breathing tubes (most of which were made of rubber compounds) of all devices tested softened and stretched considerably at 65 and 95°C, suggesting the airflow characteristics of the air-supply regulator could be reduced in volume. Such a reduction in airflow would increase the **user's** inhalation resistance and possibly cause leaking around the facepiece. This observation was substantiated with the instrumented tests and breathing **machine**.

8. Flame Test of SCBA Facepiece (1050°C for 10 seconds total **time**).

For the flame test of SCBA **facepieces**, we followed the procedures used by West Germany and described in the Drager Review⁹. The test consist of two exposures of the facepiece to six propane burners for a duration of five seconds per exposure. The West German standard requires tightness tests of the mask to the metal dummy head before and after each five second exposure. We did not perform the tightness tests because we did not have a metal dummy head at the **time**, so our test results were only considered positive if no portion of the mask continued to burn with its own flame after the mask had been swung out of the range of the flames.

The plastic exhalation valve covers caught on **fire** and continued to burn after removal of the facepiece from the flames on three of the eight models tested. In each **case**, as a result of this test, the manufacturer agreed to try to find a nonflammable material for these valve covers.

9. Flame Test of Closed-Circuit **Oxygen** Rebreating SCBA.

For the past year in the **U.S.**, the question has been debated of whether **closed-circuit** oxygen **rebreathing** apparatus, particularly of the positive pressure type, was safe for fire fighting **use**. Since **closed-circuit** oxygen **self-contained** breathing appartus is the only type available with a rated use greater than 30 minutes, it may be needed for fire fighting in high rise buildings, mines, tunnels and below decks on large ships. However, since they may impose an increased hazard to the fire fighters in the event of a poor facepiece fit or other inadvertant oxygen leak that could result in high oxygen concentrations on the exterior of the mask, we ran some tests to try to determine the extent of that hazard.

We chose as our test parameters, a flame of 1000° to 1500°C for two and four second exposures of the facepiece both without and with an oxygen leak around the facepiece to face seal. Our test apparatus, Figure 9, consisted of:

- a. A natural gas jet burner array, consisting of eight (8) gas jets spaced approximately five (5) inches apart. Ignition of the gas jets was by a remotely operated electric spark.
- b. A unistrut frame on which was hung a firefighter's turnout coat, and the breathing apparatus front or back pack. On top of the frame was a silicone dummy human head which wore a 100% wool watch cap, the breathing apparatus facepiece, and a firefighter's helmet.
- c. A breathing machine, located outside of the fire test cell, was connected to the dummy head to "breathe" the apparatus at a rate of 40 liters per minute. All oil in the breathing machine was nonorganic and oxygen compatible. Flame arresters were installed in both hoses connecting the breathing machine to the dummy head. An inline humidifier kept the facepiece air as humid as possible.

Our test parameters were chosen as duplicates of a "flash-back" condition at a fire scene, the worst condition in which a fire fighter might survive. Details of this rationale and the test results are given in our test report. 0

A summary of the test results are given in Table I. The Chemox is a chemically-generated oxygen unit, negative pressure type, the BG-174A has a compressed oxygen source, and is also a negative pressure unit, while the Biopak 60 uses compressed oxygen, but has a positive pressure in the facepiece at a breathing rate of 40 lpm. The "Bioshield" on the Biopak 60 refers to a fire resistance hood placed over the user's head to prevent flame from contacting the wearer, particularly in case of a poor facepiece to face fit and an oxygen leak around flammable materials (e.g., human hair).

We have recommended to our fire department, as a result of this test series that:

- a. The flame tests which were conducted on the three makes of closed-circuit oxygen SCBA did not discredit oxygen for fire fighting use when used only with the proper closed-circuit apparatus.
- b. Firefighters using closed-circuit breathing apparatus, whether demand or positive-pressure type, should keep exposed hair to a minimum.
- c. Each fire fighter should be fit with the facepiece and those not getting a tight facepiece-to-face seal with a particular make of facepiece should not be permitted to use it.

TABLE 1
Flame Test Result Summary

UNIT	NO FACEPIECE LEAK		FACEPIECE LEAK	
	DAMAGE	OBSERVED	DAMAGE	OBSERVED
	<u>2 Sec. Flame Exposure</u>	<u>4 Sec. Flame Exposure</u>	<u>2 Sec. Flame Exposure</u>	<u>4 Sec. Flame Exposure</u>
1. MSA Chemox	None observed	Left breathing hose and speaking diaphragm cover continued to burn after test.	None observed	Breathing hoses and speaking diaphragm cover continued to burn after test. Left breathing hose burned through in several places.
2. Drager BG-174A	None observed	Plastic catches on head harness and wiper knobs showed some melting. Tarry substance appeared on breathing hoses.	None observed	Plastic catches on head harness and wiper knobs partially melted. Tarry substance on breathing hose. Slight char on lens retainer frame.
3. Biomarine Biopak 60				
a) With Bioshield	None observed	Slight singe observed on lense covering Bioshield and breathing hoses	None observed	Some bubbling on lens cover. Some slight singe as on no facepiece leak test. Flame observed where hoses entered Bioshield, but went out after test, no damage found inside Bioshield.
b) Without	None observed	Lower right head harness strap melted and broke	Flame observed at point of induced leak, but went out after test. Watch cap and right ear burned Lower right head harness strap burned half-way through.	Watch cap continued to burn after test. Lower right head harness strap burned half-way through. Right ear singed.

d. Component parts of closed-circuit breathing apparatus should be tested for ease of ignition. Components which do not meet this test should be:

1. Replaced with non-flammable materials or
2. Covered with a non-flammable material.

B. Effects of a Stream of Water on SCBA Operation.

Since fire fighters work in highly moist environments, being subjected to ruptured water pipes or being accidentally or purposely sprayed with a fire hose, we examined the SCBA operation when under a stream of water. We used a shower head with relatively high water pressure for the test, Figure 10. All units tested operated satisfactorily except one positive-pressure model which went very negative in the facepiece, although it continued to operate.

C. Effects of Fire Extinguishing Foam on SCBA Operation.

Since fire fighters occasionally enter rooms or buildings filled with high expansion foam, we conducted tests on operating SCBA while completely surrounded with high expansion, detergent-type foam. A two cubic foot lucite box as shown in Figure 11, was built in which to perform the tests. The units were operated, as before, with the breathing machine. While all eight models tested were positive pressure units and continued to operate for the length of the test (about 20 minutes), four of the models went from positive pressure in the facepiece during inhalation to negative pressure. Two of the models went very negative, to the extent that breathing would be difficult for anyone wearing that particular facepiece.

The cause of the facepieces going negative was the location of pressure equalizing openings in the regulator cover, situated such that foam could be drawn into the regulator. An example is shown in Figure 12. The foam, once inside the regulator cover, caused an adhesive effect between the top of the diaphragm and the inside of the regulator cover. On the four models tested which remained positive throughout the test, the pressure equalizing openings in the regulator cover were protected either by the housing or by the harness straps.

CONCLUSIONS

We have described several tests that we have conducted at the Lawrence Livermore National Laboratory to help us determine the effectiveness of self-contained breathing apparatus operating under some of the stresses imposed on it at a fire scene. We also believe that tests should be devised to measure effects of fire decomposition products and chemicals, either through gradual corrosion or by immediate SCBA failure such as one reported in the Western Fire Journal,¹ which stated, in describing an incident where four Anchorage, Alaska fire fighters were injured, "All airpicks used in the rescue failed, or partially failed, due to deterioration of diaphragms and seals from the JP-4 fumes."

Mechanical stress tests are also needed, because fire fighter SCBA are subjected to vibration stress from apparatus moving over rough roads and rough handling at the scene of a fire or emergency. A unit made inoperable because of loosened fittings will not be of any use at the fire scene. This type of equipment failure appears to occur more frequently with closed-circuit SCBA than with open circuit apparatus, based on the complaints we have heard.

Radiant heat tests are also needed. We and others have done some limited studies on the effects of radiant heat on SCBA straps⁴. The straps appear to be the most susceptible to radiant heat damage and the preliminary results vary from little damage to complete melting and breakthrough of the strapping material, Figure 13.

Finally, SCBA should be tested with a combination of many of the factors we have described. Possibly, some of these factors react synergistically and, since many of these parameters occur simultaneously at a fire, we should know what the net effects are.

Although our tests are or will be directed toward the needs of our own fire fighters, we believe such tests at LLNL and elsewhere are essential to understanding how SCBA operate at a fire scene. We will use information gained from these tests to select equipment that offers our fire fighters maximum protection against the hazards they might encounter. It is our hope that fire service training programs will include this information and, most important of all, that SCBA manufacturers will use it to upgrade their designs.

NOTICE

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Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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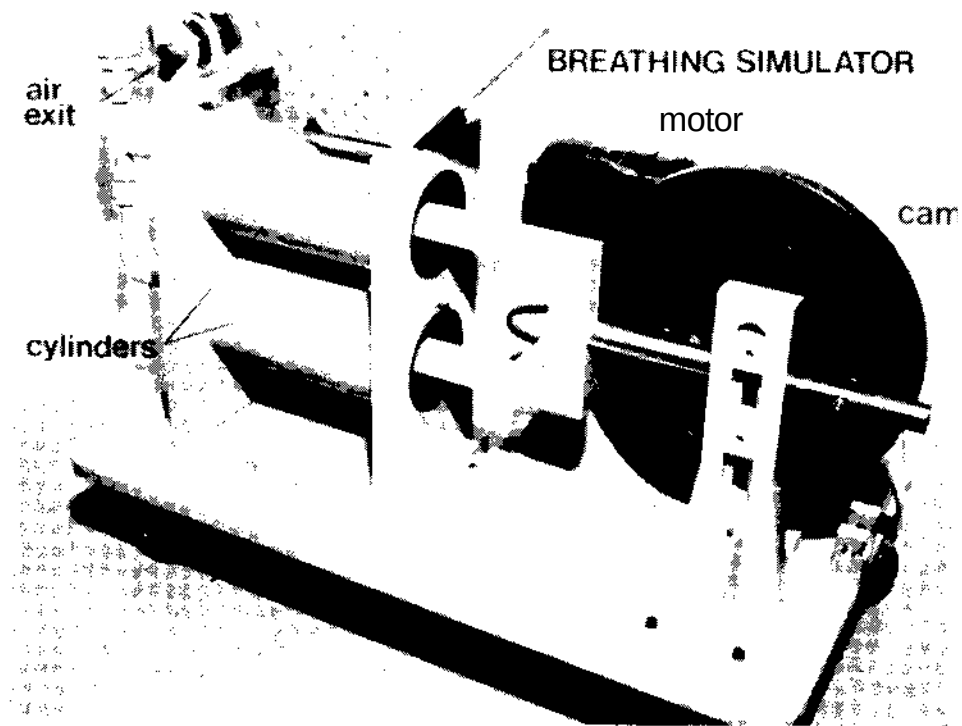


Figure 1. LLNL breathing machine.

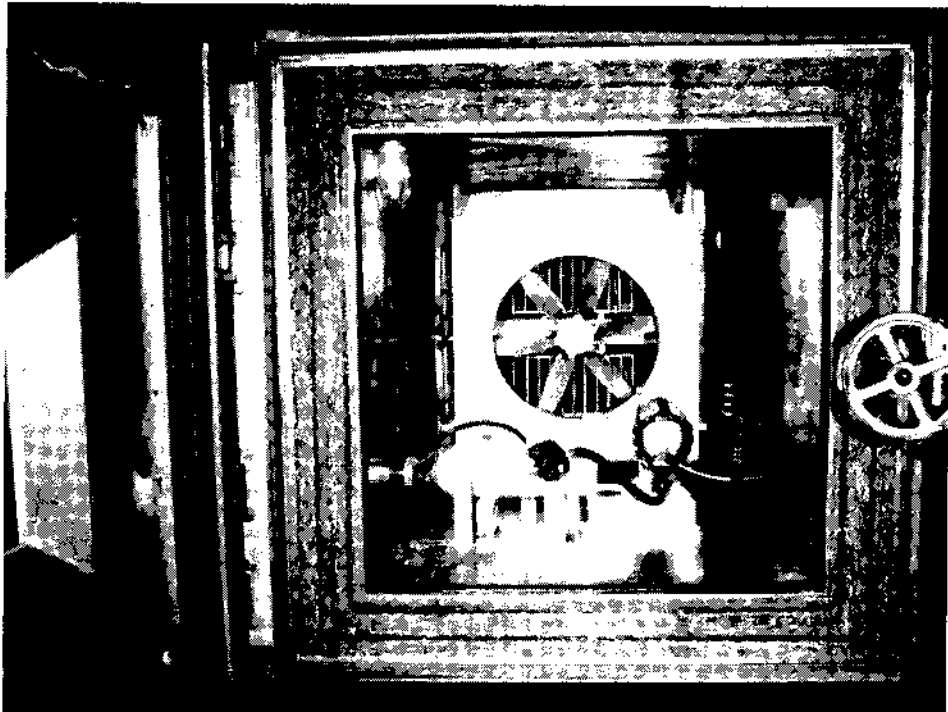


Figure 2. Environmental chamber
used for temperature extreme tests.

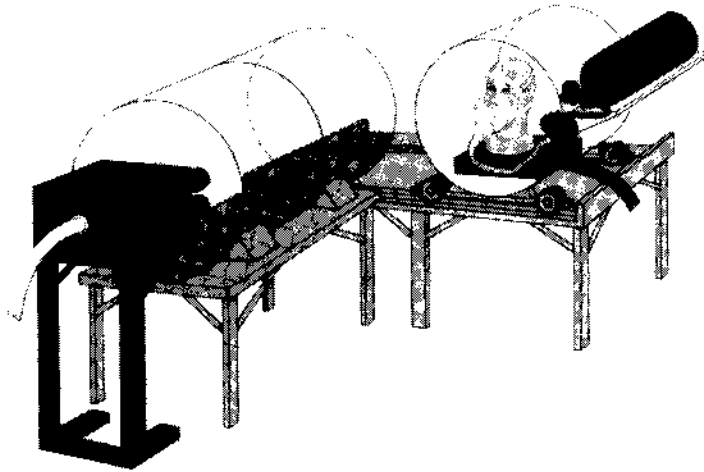


Figure 3. Drawing of apparatus used to test SCBA at 250 degrees Centigrade for three minutes.

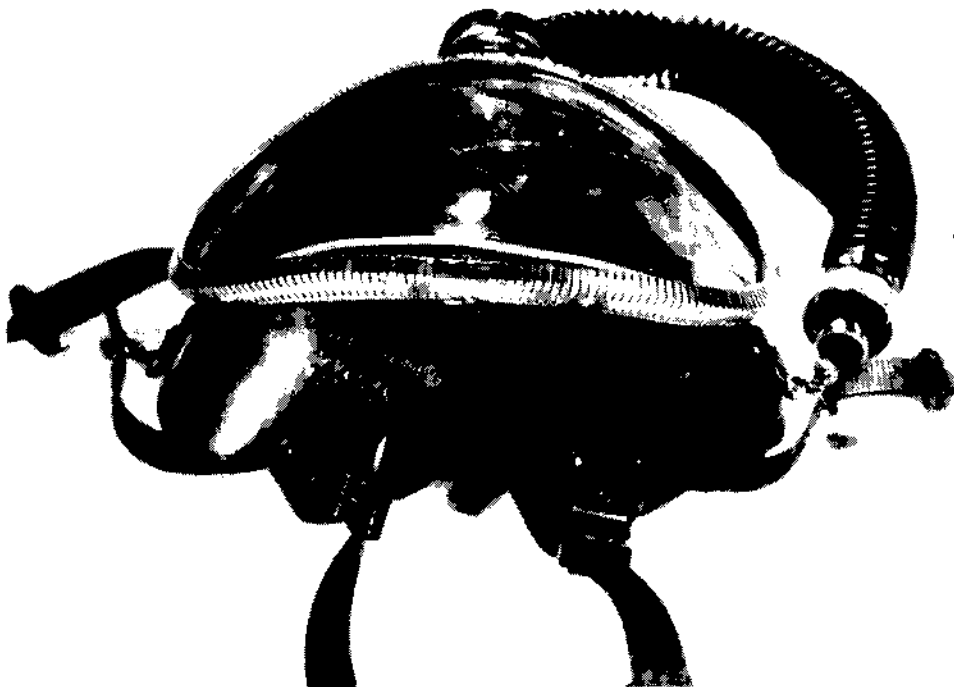


Figure 4. One model of facepiece after 10 minutes exposure to 93 degrees Centigrade. Note flattened lens which has pulled away from retaining ring.



Figure 5. After exposure to 93 degrees Centigrade and then lightly bumping, a plastic clip snapped off, causing the lens to separate from the facepiece.



Figure 6. Checking operation of SCBA which had been stored at -32 degrees Centigrade for 24 hours.

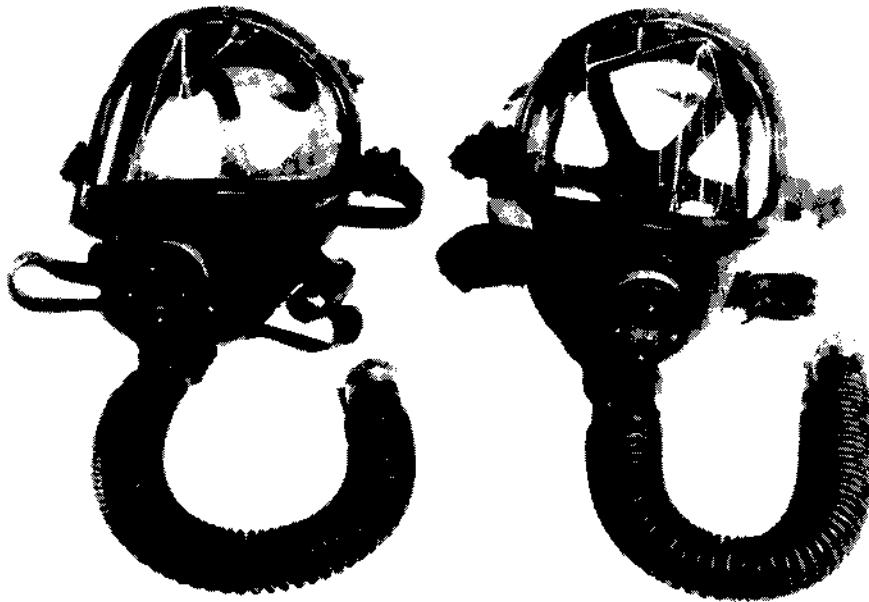


Figure 7. The lenses of these facepieces shattered when bumped after being stored at -32 degrees Fahrenheit for 24 hours.

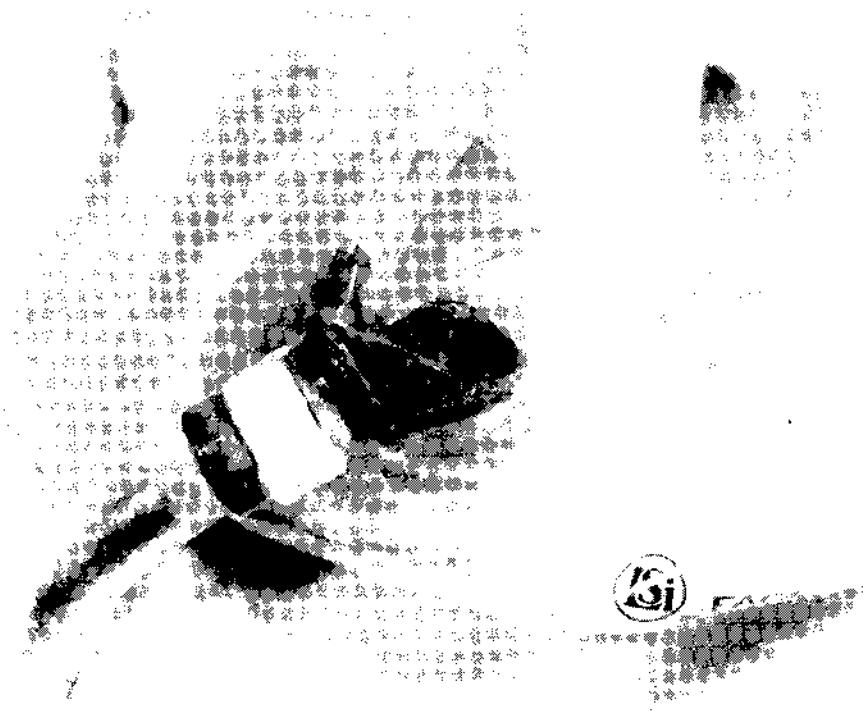


Figure 8. A 5-minute escape unit after being stored at -32 degrees Centigrade for 24 hours and then activated. Note break between breathing tube adapter and plastic hood.

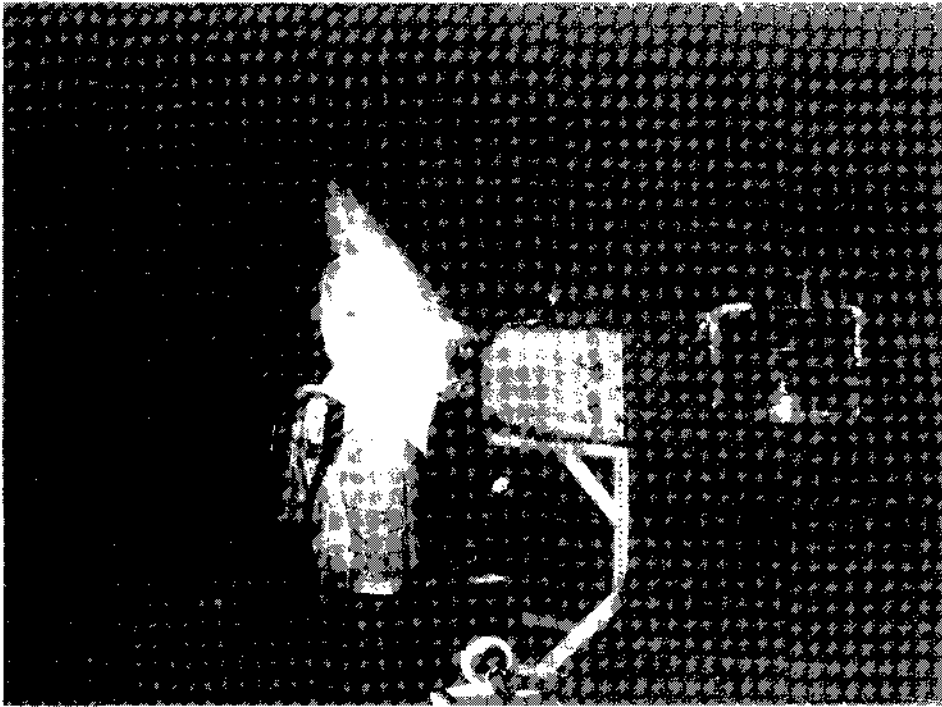


Figure 9. Flame test of a closed-circuit oxygen rebreathing SCBA.



Figure 10. Testing the effects of a stream of water on SCBA operation.

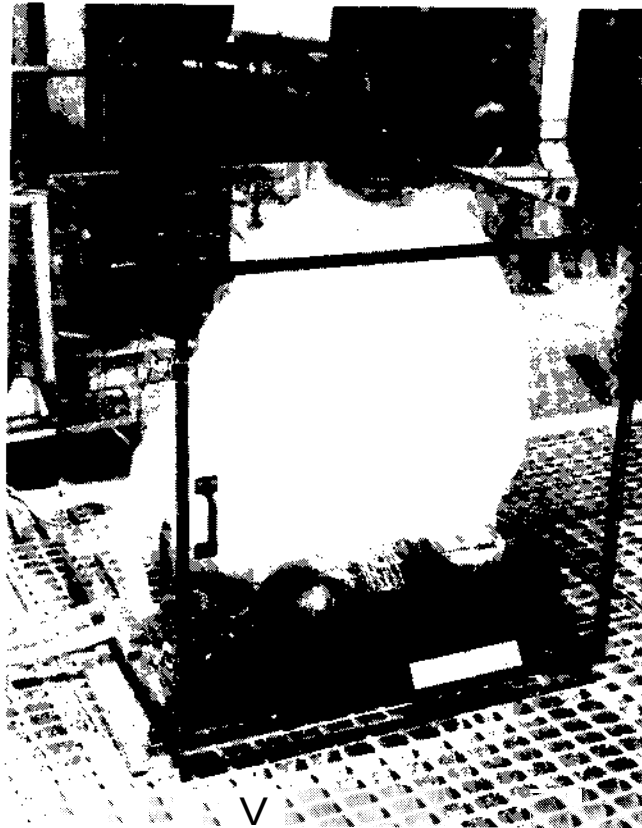


Figure 11. Testing the operation of an SCBA when surrounded by fire extinguishing foam.



Figure 12. Foam drawn inside the regulator of this positive pressure SCBA caused the unit to become negative in the facepiece.

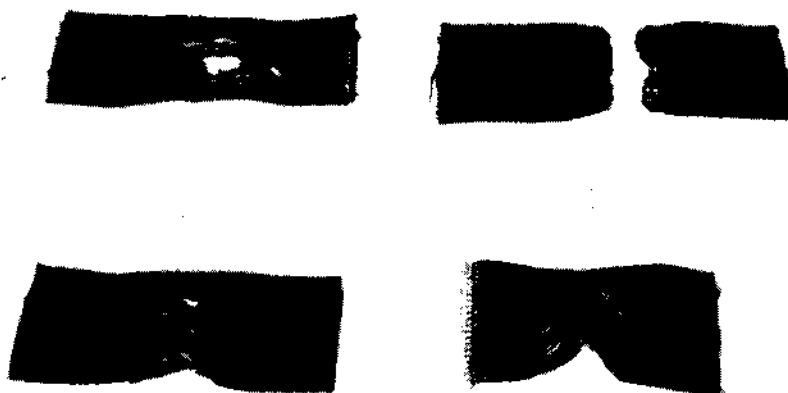


Figure 13. Effects of radiant heat flux of 1.25 w/cm^2 for three minutes on four makes of strapping material.