A review of:

The physiological consequences of wearing industrial respirators: A review

The following is not meant as a review of the review but is to assist the reader of the review.

This is an excellent report when read by the per group it was intended for, however to many sections assumes the reader is fully up to date with the expressions, and as a result if that is not the case the reader is fully justified to draw conclusions by the "referred" but not stated assumptions that at times can be 100% opposed to the writers intentions.

The paper clearly identifies that no significant research has been documented of what is today accepted as normal breathing during work, and clearly spells out the fact that most documented research mainly deals with far too small breathing volumes and basically ignores flow rates.

The paper then sets out to clarify the past research that indicates that there are different amount of work required to breath different volumes of air and the impact of this on the end user.

Most of this work seems to be sampling of groups and getting the individual users responses and then graph this to set a standard.

As this work was done by numerous people many different ways where used to report, and a mixture of metric and imperial formulas have been mixed up including specific "trade" jargons.

In today's environment we refer Energy in two ways, one is on our electricity bill where it is in kWh (kilo Watt hours) but when we refer to the more human environment we refer to calories consumed for any physical activities.
Likewise for power we no longer use horsepower but we use Watt except if we talking cars where the old system is now "trade" jargons.

As a side item I think it is about 90 years since the HP was dropped from the metric system and a metric horsepower has never been the same as an imperial horsepower.

Although the paper makes a clear distinction between flow rate and volume some sections referring to different sources do not do this.

To put this into perception we need to remember the working capacity of our (average) lungs that is "normally" 0.5 litres at rest and up to 5 litres at heavy work all dependent on size of the person and personal physical fitness.

If we then look at the lose term 500 litres per minute:

From above that would indicate 100 breaths per minutes, but in order to consume that air we have to breath out as well hence the breathing in is actually for a smaller part, normally we breath in then rest then breath out then rest and so on, but to achieve 100 breaths per minute we can ignore some facts and assume half and half hence we know we did breath in 100 times for a total time of 30 seconds and we got 500 litres of air. (And out 100 times for 30 seconds.) To achieve this we did breath in 5 litres in 0.3 seconds now if we convert this to the standard of ***litres per minute*** we get 1000 litres per minute "flow rate".
Fit subjects can easily achieve over 400 litres per minute flow rate but a sustainable rate over 500 is rear.

If we now look at a more sustainable rate of 100 litres per minute volume and look at different equal breathing patterns of:

1. IN-OUT this will give us a flow rate of 200 litres per minute.
2. REST-IN_OUT this will give us a flow rate of 300 litres per minute.
3. REST-IN-REST-OUT this will give us a flow rate of 400 litres per minute.

All for the same volume.
In real life we all breathe at different pattern and at different period for each section.

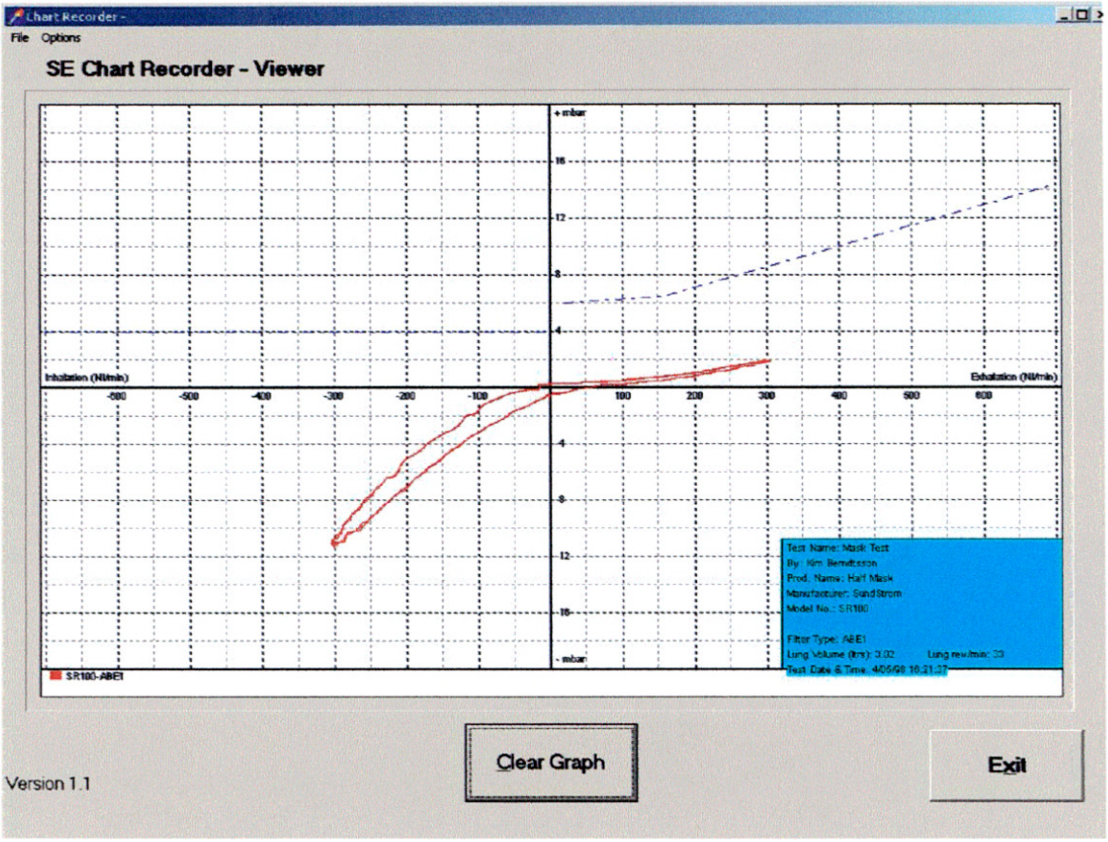
In conclusion there is a correct assumption that the litres per minute is significant in our "Power" calculations but it is the litres per minute (flow rate) and not litres per minute (volume).

On the small range of flow that has been documented by all the pioneers and wrongly interpolated by the modern user for a larger range has all wrongly assumed that the air resistant is constant in the filter or at best been acknowledged it and then ignored.

To calculate the "Power" we need to know more than the flow rate, the simplest way would to measure the pressure drop across the filter and use that together with the flow rate, the metric system does this in pascal (Pa) but our trade does it more in bar or millibar and imperial measurements refer to mm Hg or torr or some older documentation uses lbf/sqin.

The formula for this is: Flow in litres per minute multiplied by the pressure in MPa and divided by 60 to give the power in kW.

To put this to perspective a good multi filter (ABE) at a flow of 300 litres has a pressure drop of 10mbar giving a "Power" requirement of 0.005 kW or 5 Watt.



Test Name: Mask Test
By: Kim Berndtsson
Prod. Name: Half Mask
Manufacturer: SundStrom
Model No.: SR100

Filter Type: A8E1
Lung Volume (ltrs): 3.02 Lung rev/min: 33
Test Date & Time: 4/05/98 16:21:37

This is basically where the paper ends so lets look at some figures quoted.

kgm/min	Silverman Volume litres	Time minutes
6	50	1
13.3	64.4	1
28	90.3	1

This can now be converted to different expressions of "Power" meaning the same:

6 kgm/m = 0.1 kpm/s = 0.980667 W = 0.001333 HP

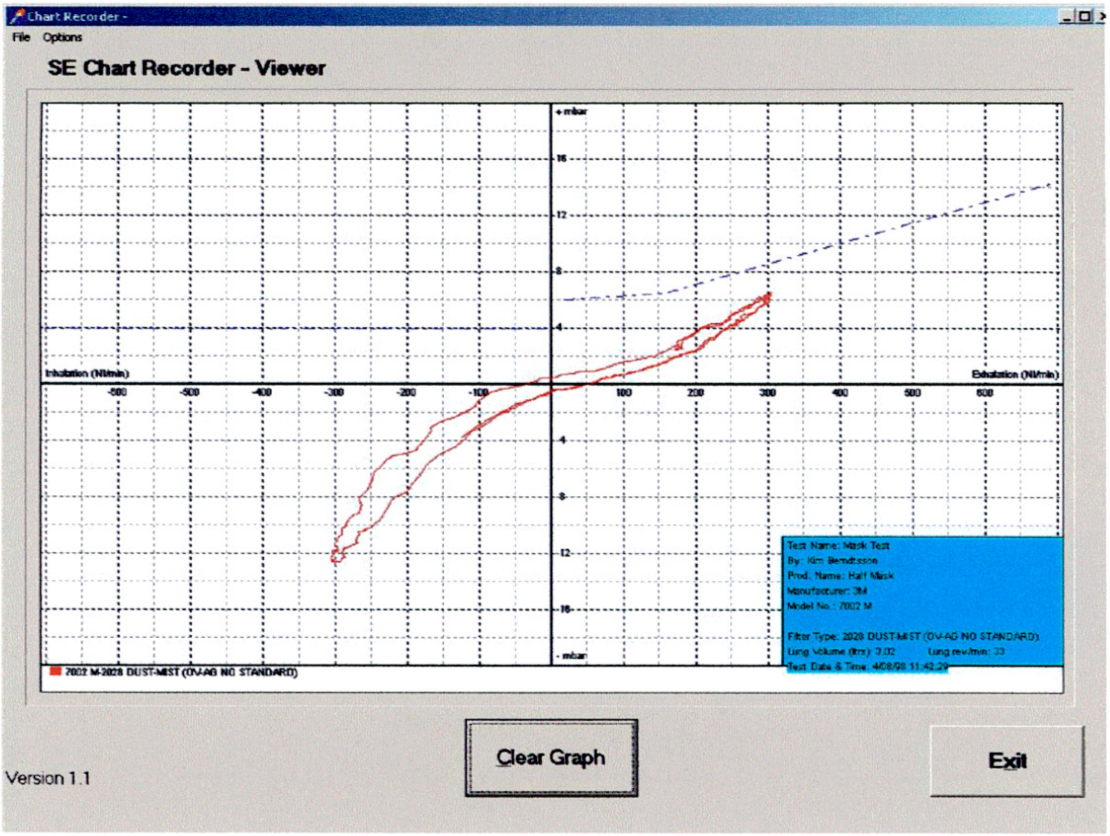
13.3 kgm/m = 0.221666667 kpm/s = 2.173811 W = 0.002956 HP
28 kgm/m = 0.466666667 kpm/s = 4.576444 W = 0.006222 HP

If we compare this with our sample of a volume of 100 litres and a flow rate of 300 litres we got 5 W and Silverman talks about 4.5 watt for 90 litres.
Hence we all agree but the problem is Silverman measured his at a volume and did not report the flow pattern hence no given flow rate and we have shown that for 100 litres the only time it is correct is for a flow rate of 300 litres.
But in Silverman's time filters had a higher air resistance hence we know his flow rate would have been lower.
Today we still seem to argue about the shape of the breathing curve. This is interesting and of some value when looking into the physics of the human body, but in the industry we should be more concerned by the impact of the wearing of the filter as we know sufficient about the death that comes

of not wearing the filter, hence the option is not to, not wearing protection but minimise the real but equal perceived impact.
We can now turn this known "Power" into the real interest of the ENERGY consumed by the user. The simplest way is to express the energy in calories and compare with the number of calories used walking or running down the street.

For our sample we have 5 Watts and we were breathing in for one third of the minute hence we have a time of 20 seconds giving us a simple ENERGY consumption of 100Ws per 60 seconds or 6000Ws per hour or 24000Ws per 4hour shift.
To be able to compare with the "walk" we need convert to calorie and the formula is:
The international calorie, which equals 1/860 international watt-hour (4.1868 J). A large calorie, or kilocalorie (Cal), usually referred to simply as a calorie and sometimes as a kilogram calorie, equals 1,000 calories and is the unit used to express the energy-producing value of food in the calculation of diets.
24000Ws=400Wm=6.67Wh=5737calories
A 75 kg man burns about 24 calories per minutes running at 16kmh or 5760cal per 4 hours.
Now read the paper:
The physiological consequences of wearing industrial respirators: A review

Now having read the paper we can look at the only weak part, the paper acknowledges the sample range is to small but stills try to construct a fixed relation between "volume" and work we already know that this is not the case but even the flow can not be used with a constant as each filter and even "same" filter but different manufacturer is significant different the only common part seems a relative linear rate at very short variations. But with a sharper increase in pressure drop as the flow increases the sample below is an "average" filter at low rates.
100l = 3 mbar, 200l = 8mbar, 300l = 13mbar

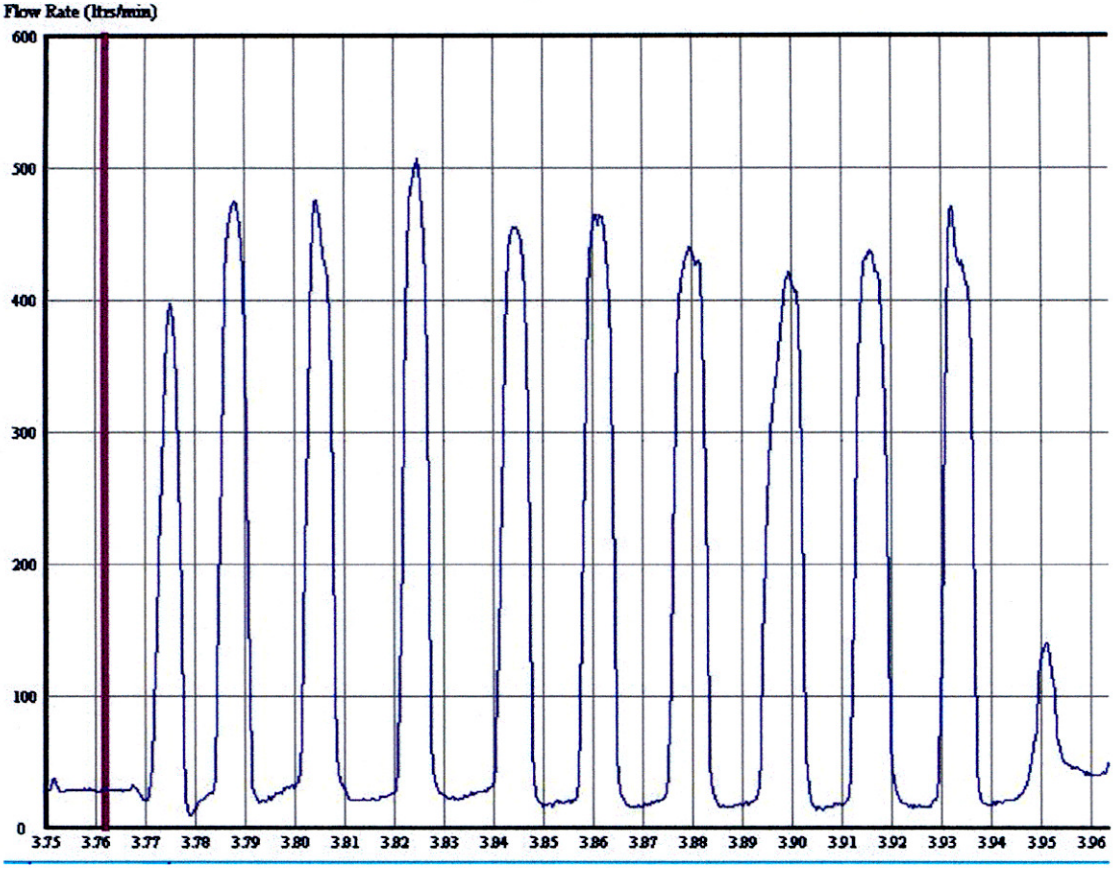


Test Name: Mask Test
By: Kim Berndtsson
Prod. Name: Half Mask
Manufacturer: 3M
Model No.: 7002 M

Filter Type: 2028 DUST-MIST (OV-AG NO STANDARD)
Lung Volume (ltrs): 3.02   Lung rev/min: 33
Test Date & Time: 4/08/98 11:42:29

🟥 7002 M-2028 DUST-MIST (OV-AG NO STANDARD)

Finally a sample of a breathing curve



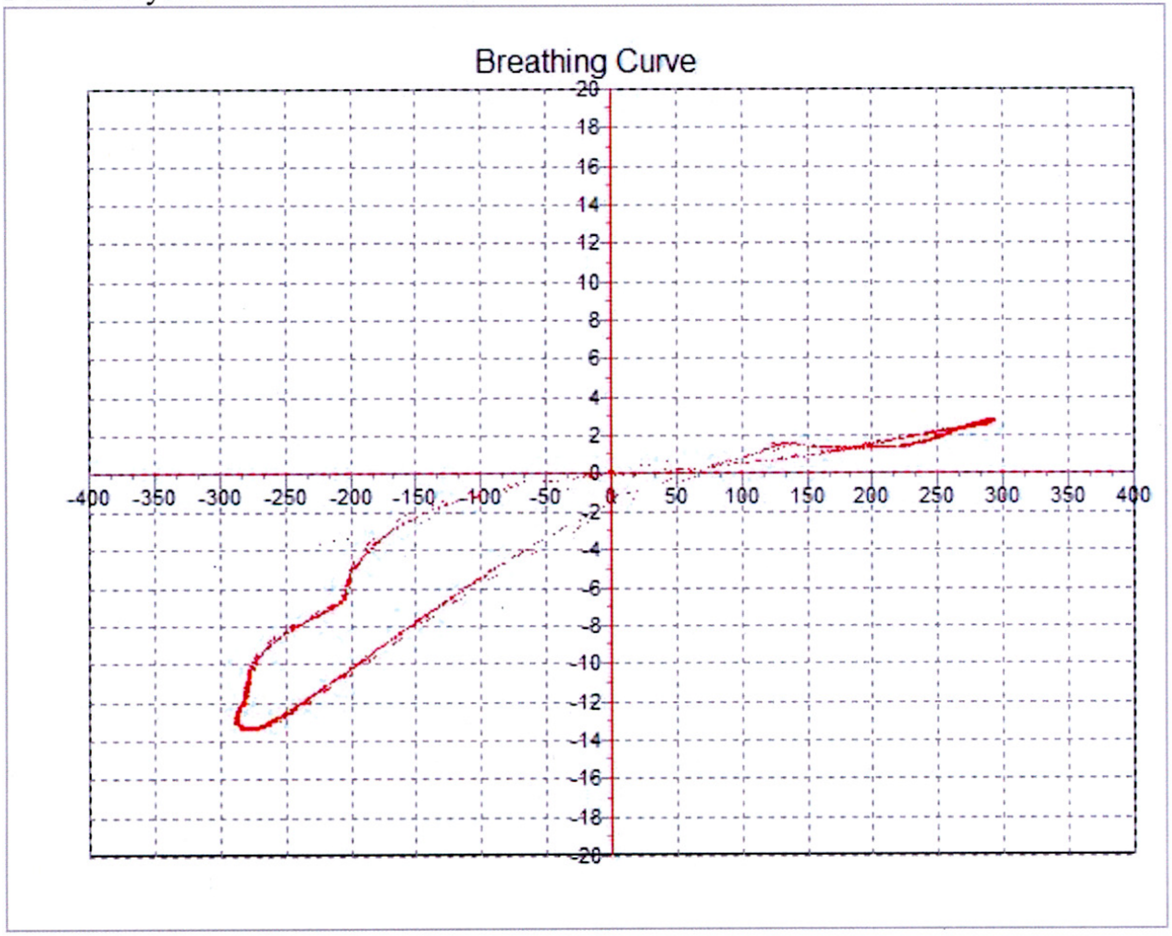
Leif Ekman
August 2002

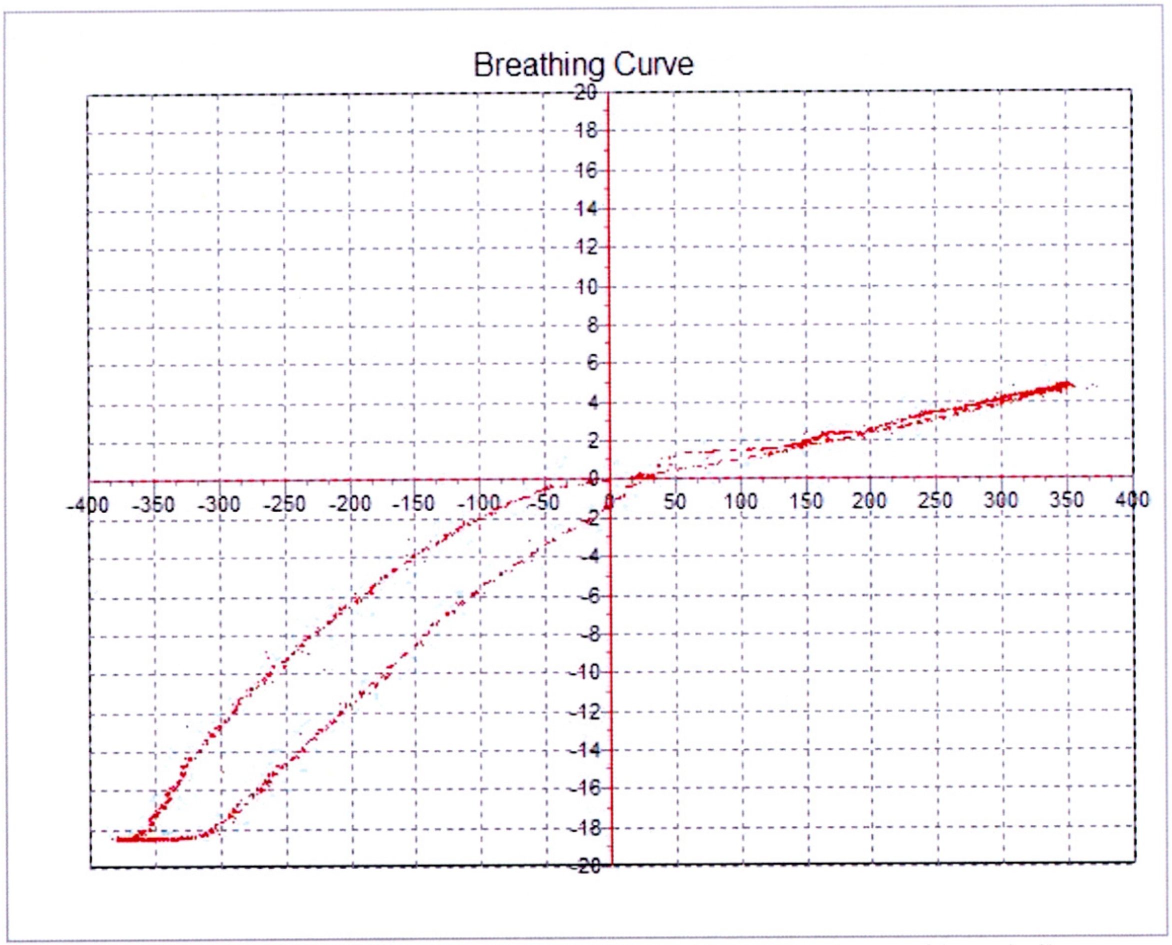
Hi Les,
Good to talk to you last week, I trust you have had a pleasant labor week end.
A few comments on the latest draft.

6b1b, Gasket Material; Is there not another way to achieve what we need to achieve than specifying the material? Specifying the material makes it design restrictive.

6b2a, Breathing resistance, face piece. Is this Inhalation or Exhalation? Both are important.

6b2b, Breathing resistance, I just got a number of approvals from NIOSH and according to those the requirement now is 50 mm water column @ 85 Liter, it that wrong?
As I mentioned earlier we can eliminate non desirable filter material with the pressure drop, but you should introduce more than one flow rate as no filter are linear, the pressure drop increases quite a lot as flow increases, see graph.
I will send you more information soon on this.





The first graph is 3M P100 filter the second graph is M40 with M41A1 filter I believe that is the current NBC filter.

6b2c, Same as a bow.

6b2e, Face piece Leakage; Describe the size of the test panel instead of specifying that you need tree sizes. It is design restrictive and not necessary. Should the diameter of the aerosol not be 0.3 micron?

6d3, Same as 6b2a and b.

Locking forward to you 17 September 2002 at 9.00 am. We should discus some of this then.

Regards

G

RAN BERNDTSSON

THE DETERMINATION OF PEAK INSPIRATORY AIR FLOWS (PIAF) AT VARIOUS LEVELS OF WORK AND THE INCREASED AIR FLOWS THAT RESULT WHEN COMMUNICATING IN THE WORKPLACE.

John Wallaart* and Chris Winder

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Acknowledgement: This work was completed in the laboratories of Safety Equipment Australia Pty Ltd.

Keywords: Respiratory protection, Air flow rates, Standards.

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Abstract

The 'Peak Inspiratory Air Flows (PIAF) was recognised over 7 decades ago as one of the critical values that needed to be taken into account in the design, testing and wearing of respirators and filters. However, the values are rarely quoted in the research literature, standards testing and certification or manufacturer's information related to their products. It is an important value particularly for PAPR respiratory equipment and for values related to particle or gas retention of respirator filters or cartridges as well as the effect on inspiration resistance. This was recognised as long ago as 1951[i]. It is astounding that the importance of the criteria so fundamental to respiratory protection, particularly as it relates to PAPR equipment as well as the retention of all filters and cartridges, has been ignored in almost all publications including those from Standard organisations[ii] and Government bodies[iii].

The air flow values more often quoted are the Minute flow values. The emphasis on Minute Volumes is contributing to confusion. For example, PAPRs are often referred to as positive pressure equipment including in official documentation[iv] and trade literature[v] when this is clearly not the case. Standards add to the confusion by referring to PAPRs and needing to "provide positive air pressure in the breathing zone[vi]". While the development of PAPRs offers significant advantages for many users, there are significant limitations in peak flow requirements leading to negative pressure particularly at high work rates[vii]. The situation is more complex with helmet designs and Minute Volumes of 280 lpm have been shown to be inadequate to maintain a positive pressure[viii].

PIAF has often been quoted to be about 3 times the minute flows[ix] [x], but the values from the work here has shown that this can be much higher. Particularly while communicating, a very large range of values and disturbances in the airflow was found, well beyond those found without communication. The findings from this work has significant implications for the design, testing and certification of respiratory equipment as well as ultimately leading to better respiratory protection for the users.

Introduction

The Peak Inspiratory Air Flows (PIAF) are important values for the designers and users of all types of respiratory equipment. This was recognised years ago by the Silverman et al team investigating the breathing requirements of people required to wear a respirator. As long ago as 1943 Silverman and his team stressed the importance of peak flows and even then quoted that "Peak Inspiratory Air Flows are more important than Minute Flows[xi]". Subsequently, other writers have expressed concern about the lack of importance placed on the PIAF values[xii].

The values of Minute Flow have tended to dominate the literature in both international standards and the resources distributed by manufacturers. It has also influenced recommendations from manufacturers particularly in regards to PAPR (Powered Air Purifying Respirators) which are often, and incorrectly, been referred to as Positive Pressure Respirators.

The purpose of these trials was to:

- To determine the PIAF rate at various levels of work and compare these against published data (the values are more often only referred to as approximately three times the Minute Flow) at various levels of work,
- To determine the PIAF increase due to disturbances in the airflow and pattern due to communicating. Considerable variation in airflows can be expected when people communicate, but more specifically there was a need to note how the patterns alter and what increases could be expected. This is particularly important in the design of respiratory equipment. Individuals may have to wear the equipment while shouting warning messages or otherwise communicating as in a typical industrial environment and at various work rates.

Method

A total of 25 volunteers of both genders and average age 36.7 years (this is generally older than a typical test group) were asked to perform a number of exercises as described below.

All subjects were initially required to complete a face-fit test using Portacount®equipment which measured the particulate present inside the respirator worn by the test subject versus that outside the respirator. A face-fit pass of 100 (1% leakage) was considered a minimum to carry out the remainder of the exercises. This was necessary as flow leaks from a badly fitting respirator would result in significant experimental errors.

Monitoring of heart rate, minute flow and Peak Inspiratory Air Flow continued throughout all the exercises. The exercises were only completed once per day, i.e., volunteers did not complete more than one exercise per day.

The exercises that were completed by all subjects were:

Part 1: Standing upright, facing directly ahead, and then talking continually.

Part 2: Simulating light work, i.e., picking up a light article from the floor, standing upright and placing the article on a table. This process is repeated at a leisurely pace. The exercise was then repeated while talking.

Part 3: Walking on a treadmill at 6.5 kph set horizontally (i.e, no incline). Volunteers were then asked to shout a warning message.

Part 4: Some volunteers wanted to repeat the above treadmill exercise while setting the treadmill at a 5 degree incline upwards. Again, the exercise was repeated both with and without talking.

Determining Peak Inspiratory Air Flows (PIAF) walking on a treadmill

Equipment used and calibration

The equipment for monitoring and recording air flows was specifically built and calibrated by SEA Pty Ltd[♣]. The test equipment utilised a standard SR-90® respirator, the size dependent on previous testing results from a face-fit test.

The test equipment utilised the pressure drop over a standard Sundstrom P3 particulate filter to measure the air flow. The pressure drop was measured by a Honeywell differential transducer. The output was converted to a 12 bit converter and communicated to a standard PC. Sampling rate was every 50 Hz (20ms).

The unit was calibrated using a certified Interspiro IPZ test bench. Calibration was based on a two-point calibration with a high and low limit flow value. The high value point was obtained by sampling 1500 times over 30 seconds. The low value was obtained similarly after entering the numerical value via a keyboard. Gain and offset values were calculated and stored in a separate file as calibration sconstants. Calibration was repeated at the end of the test series to check for any change in flow resistance due to contamination. The difference was negligible.

The maximum error due to equipment and calibration factors was calculated at 10% of the flow value obtained in this work.

[♣] Safety Equipment Australia Pty Ltd, Warriewood, NSW 2102, Australia.

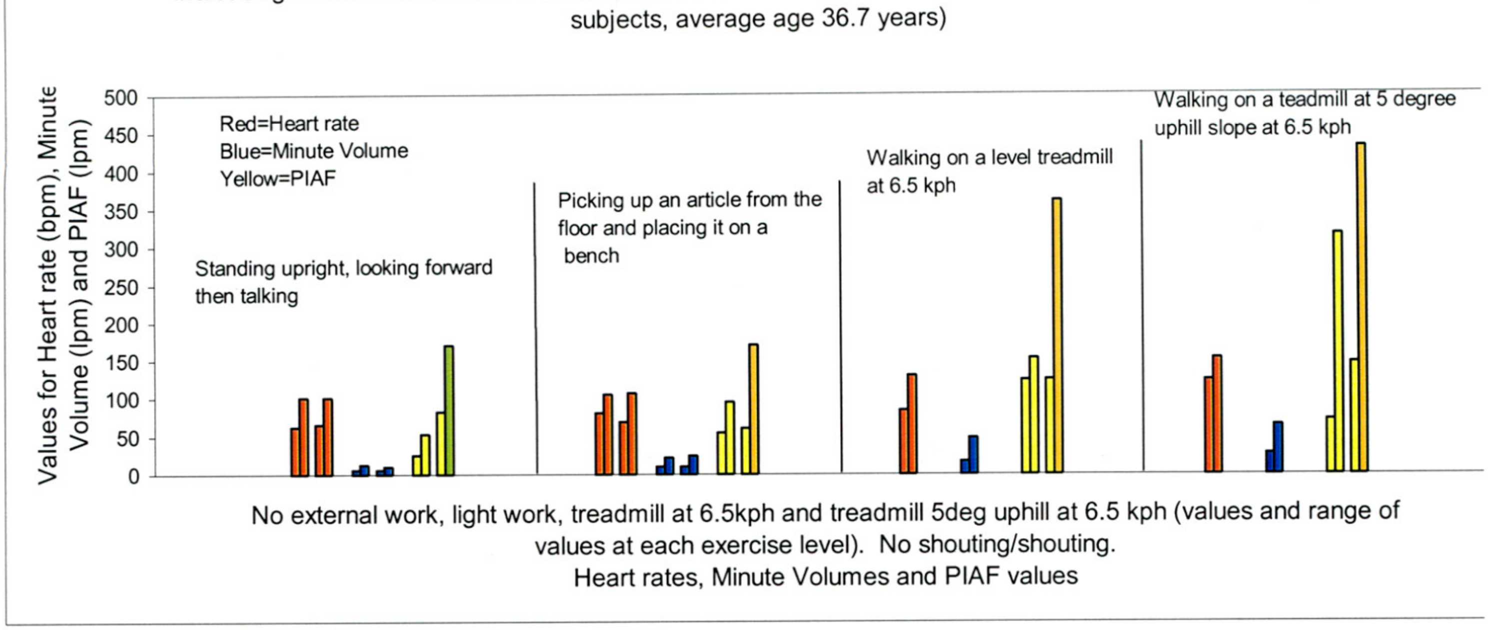
Summary of results

Exercise	**Monitoring for Heart Rate, Minute Volume and Peak Inspiratory Air Flow.**	**Results** **(25 volunteers, average age 35.7 years of both genders)** HR in bpm (beats per minute) MV in lpm (litres per minute) PIAF in lpm (litres per minute)			
		No activity		**Shouting**	
PART 1 **Standing upright, looking forward and then talking (i.e., no useful work)**	HR=Heart Rate MV=Minute Flow PIAF=Peak Inspiratory Air Flow	HR	62-101	HR	66-101
		MV	6.1-12.9	MV	6.1-12.2
		PIAF	25.0-53	PIAF	82.5-170
PART 2 **Picking up an article from the floor and placing it on the bench.**	HR=Heart Rate MV=Minute HR=Heart Rate MV=Minute Flow PIAF=Peak Inspiratory Air Flow	HR	81-105	HR	69-107
		MV	9.8-21.8	MV	9.7-24.3
		PIAF	55-95	PIAF	61-170
PART 3 **Walking on a treadmill at a 0 degree slope uphill at 6.5 kph**	HR=Heart Rate MV=Minute Flow PIAF=Peak Inspiratory Air Flow	HR	84-130	HR	No data collected
		MV	17.2-48.4	MV	No data collected
		PIAF	124-153	PIAF	125-360
PART 4 **Walking on a treadmill at a 5 degree slope uphill at 6.5 kph**	HR=Heart Rate MV=Minute Flow PIAF=Peak Inspiratory Air Flow	HR	124-153	HR	No data collected
		MV	27.1-65.2	MV	No data collected
		PIAF	72-315	PIAF	147-430

Results of Heart Rate, Minute Volume and Peak Inspiratory Air Flow while talking and exercising up to a 5 degree incline at 6.5 kph on a treadmill.

Note in particular the values of PIAF.

The information is presented graphically below:



Discussion

Communication is a normal social practice and can be an essential activity while people are wearing respirators in the workplace. In practice wearers regularly remove respirators to converse, to communicate instructions or to shout warning messages. All of these needs are important, but in an industrial situation, the need to communicate warning messages may also be a critical health and safety issue. In terms of protection, it is obviously undesirable to remove the respirator while in the exposed environment.

PIAF can be in excess of 400 litres/minute for individuals walking at 6.5 kph and at an incline of 5 degree upwards and shouting a message. However, at even low levels of work, PIAF values can easily exceed 170 litres/minute.

Communication processes have a significant impact on normal breathing patterns and volume. The regular pattern of breathing is disturbed and the rate of air required increases substantially beyond the normal values.

The PIAF values are much higher than is normally quoted and used by manufacturers in the design of respiratory equipment, filters an cartridges particularly PAPR and powered air respiratory equipment. The recognition of both the high values and the individual variations will need to be better recognised as designers and certification bodies become aware of the limitations of the current designs and testing procedures and even more seriously, the potential of exposing people to the hazardous environment[♣].

[♣] There are few workplace studies carried out by respirator manufacturers to ensure that their equipment functions as intended in the workplace. The certification or Standard requirements only applies to the equipment meeting limited and minimum requirements in a laboratory setting.

Conclusion

The determination of the Peak Inspiratory Air Flow (PIAF) is an important value that has been largely ignored in publications to date by both respirator manufacturers and users of the equipment. However, even literature over 60 years ago[xiii] stated the importance of these values to designers of respiratory equipment. Silverman et al in 1943 stated that in the opinion of the researchers "Peak Inspiratory Air Flow is more important than minute flows".

The results of these trials show that the values of PIAF can be much higher than previously thought.

Communicating, while wearing a respirator resulted in even higher and significant values of PIAF and disturbed the pattern of flow. This has implications for the design, certification and workplace use of respirators. There is a wealth of information which supports the need for people to communicate in the workplace, either without or with the use of respirators. Current respirator design ignores the implications of the increased air flows required and the disturbance in the airflows which has implications particularly for the user of respiratory equipment if the requirements of pattern and peak flows are unable to be met.

Values of PIAF reached over 400 litres per minute-much higher than any PAPR (Power Assisted Air Purifying Respirator) on the commercial market today. The implications to respirator users are that the airflows from currently available equipment will be insufficient to meet the minimum requirements of users in the workplace. Even while no external work was being performed, PIAF values exceeded 170 lpm for while communicating. As soon as light work was being performed, the PIAF exceeded 228 lpm. When the subjects were walking at a brisk pace of 6.5 kph, the PIAF value increased to 360 lpm and when the subjects were walking on an incline of 5 degrees uphill, this increased to over 430 lpm.

It is likely that respirator cartridges are tested and certified at values which are much lower than is necessary to simulate workplace needs. PAPR respirators in commercial use do not appear to provide sufficient airflow to adequately provide protection to the user, particularly while users are communicating in the workplace setting.

The higher required airflows when working are documented in literature related to airline BA (Breathing Apparatus) in such situations as fire fighting, where subjects may be exposed to high heat and high rates of work for periods of time. Yet these same values of airflow are not translated to PAPR (Power Assisted Air Purifying Respirators) use or the certification and testing of half-face respiratory cartridge equipment. Respirator manufacturers do not normally quote values for

PIAF in their literature but quote minute flows which are easier to attain with current technology.

PAPR equipment does have numerous and significant advantages for the user in the workplace such as a continuous supply of clean air, comfort and the ability to install communication facilities by means of amplifier or radio. The equipment is widely used worldwide in such applications as agriculture, military and industrial uses. Generally, the "protection factors" quoted for PAPR's are significantly higher than for other respiratory equipment, although many appear to be questioning this approach.

It is hoped that this work and that to follow will contribute to the development and implementation of improved respiratory equipment. There are severe limitations for users in current designs of respiratory equipment that are unlikely to significantly contribute to the reduction of occupational disease.

End

This data is the background information to the paper.

Detailed results of Parts 1, 2, 3 and 4

PART 1

Results of Part 1 of the trials, i.e, standing upright, looking directly ahead and not talking (i.e., no physical work performed).

Identification	**NO TALKING**			**WITH TALKING**		
	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)
10	65	7.5	31.5	76	8.4	92
11	84	10.4	NR	79	11.1	115
12	90	8.1	35	93	7.6	126
13	58	11.3	25	68	10.9	170
14	80	7	44	94	10.6	127
16	62	9.2	30	66	12	148
17	84	12	53	88	12.2	123
18	101	12.9	37	101	9.7	111
21	98	8.6	39	99	9.2	122
23	75	9.5	108	96	11.6	160
24	73	10.3	51	78	8.4	107
25	60	8.7	37	74	10.8	172
26	86	10.1	54.5	95	11.5	100
27	76	8.2	32	76	8.4	117
28	79	6.5	27	90	6.1	82.5
29	67	7.5	25	82	10.5	133
33	81	6.2	22	78	8.1	60.5

Note: NR=Not Recorded

Heart rate, Minute Flows and Peak Inspiratory Air Flows for subjects standing stationary and then talking only (i.e., no external work done).

PART 2

Results of Part 2, i.e., subjects performing light work. Subjects placed a light object from ground level to a table and back.

Identification	NO TALKING			LIGHT WORK AND TALKING		
	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)
10	78	11.3	53	78	12.5	142
11	85	15.3	41.5	86	16.9	164
12	93	9.8	55	93	10.3	77
13	86	21.8	77	89	23	228
14	90	10.6	80	89	14.8	168
16	69	12.8	91	69	13.4	123
17	100	18.8	68	100	22.7	160
18	106	21.8	93	110	24.3	135
21	102	13.3	65	106	15.9	160
23	77	17.2	95	74	17.9	118
24	88	17.7	88	87	20	162
25	73	15.6	92	79	13.4	178
26	91	11.6	55	91	13.5	88
27	81	10.8	62	87.5	9.7	61
28	105	12.9	54	137	17.1	111
29	86	15.9	71	96	15	170
33	96	13.4	67	90	15.7	92.5

Heart rate, Minute Flows and Peak Inspiratory Air Flows for subjects performing light work and then talking only.

PART 3

Results of Part 3. Subjects were asked to walk on a treadmill at 6.5 kph at a 0 degree incline. They were then asked to shout a warning message.

Identification	NO TALKING, WALKING ON A 0 DEGREE INCLINE AT 6.5 KPH			NO TALKING, WALKING ON A 0 DEGREE INCLINE AT 6.5 KPH		
	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)
11	111	21.7	70	NR	NR	200
13	101	30.7	140	NR	NR	260
	115	25.2	178			300
	105	30.6	108			275
14	110	20	78	NR	NR	88
15	108	21	90	NR	NR	360
	113	27.1	118			290
16	100	27.2	140	NR	NR	320
	91	31.5	130			345
	90	30.9	138			308
	83	24.3	115			270
	84	27.7	95			285
	91	29.6	185			270
17	122	44.2	175	NR	NR	315
	130	48.4	165			340
20	113	24.8	87	NR	NR	154
21	120	23.3	115	NR	NR	215
23	106	24.7	191	NR	NR	267
24	105	32.9	220	NR	NR	325
	114	30.3	223			325
25	105	25.2	145	NR	NR	240
	115	23.8	178			242
	109	26.8	165			320
	109	28.1	180			285
	101	29	135			265
	108	30	130			260
26	108	21.7	90	NR	NR	305
27	85	18.6	73	NR	NR	180
28	115	17.5	73	NR	NR	NR
29	120	22.6	105	NR	NR	295
30	130	21.3	88	NR	NR	125
31	102	23.1	80	NR	NR	215
32	95	21.3	104	NR	NR	355
33	104	26.9	90	NR	NR	143
34	110	16.4	96	NR	NR	161
	115	17.2	95			152

NR=Not Recorded

Heart rate, Minute Flows and Peak Inspiratory Air Flows for subjects walking on a 5 degree incline at 6.5 kph.

PART 4

Results of Part 4. Subjects were asked to walk on a treadmill at 6.5 kph at a 5 degree incline. They were then asked to shout a warning message.

Identification	**NO TALKING, WALKING ON A 0 DEGREE INCLINE AT 6.5 KPH**			**NO TALKING, WALKING ON A 5 DEGREE INCLINE AT 6.5 KPH**		
	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)	Average Heart Rate (bpm)	Average Minute Flows (lpm)	Peak Inspiratory Air Flow (PIAF) (lpm)
11	138	38.7	72	NR	NR	260
13	144	47.4	215	NR	NR	340
	135	58.4	210			335
	141	57.1	225			330
	133	51.8	165			430
14	142	42.3	210	NR	NR	285
15	124	29.5	124	NR	NR	310
20	NR	35.1	138	NR	NR	250
23	135	46.7	210	NR	NR	320
24	162	65.2	315	NR	NR	325
25	138	38.1	190	NR	NR	190
	143	39.8	185			320
	123	52.9	240			290
	147	47.4	180			290
	136	45.8	235			300
	145	43.4	228			290
26	153	32.3	140	NR	NR	230
	145	37.2	135			280
27	124	29.1	123	NR	NR	231
28	158	27.1	100	NR	NR	147
31	127	35.1	140	NR	NR	283
32	135	29.138.5	108	NR	NR	313
	125		162			410

NR=Not Recorded

Heart rate, Minute Flows and Peak Inspiratory Air Flows for subjects walking on a 5 degree incline at 6.5 kph.

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THE DETERMINATION OF MINUTE AIR FLOWS AND HEART RATES FOR A TYPICAL INDUSTRIAL WORK GROUP AT VARIOUS LEVELS OF WORK

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Keywords: Respiratory protection, minute air flows, heart rate, work rate, OHS standards.

ABSTRACT

Two aspects of air flows are critical to the development, maintenance and testing of respirators and filters. These are the minute flow (the air flow per minute) and the peak inspiratory air flow (PIAF, the peak inward rate of air flow in each breath). Both values have to be known and incorporated in design and testing of respirators and cartridges. This paper investigates minute flows while a later paper will describe the PIAF. The paper describes the wide variation in air flows at various levels of work and the implication for design and testing as well as to TIL (Total Inward Leakage) testing of respirators. The TIL of respirators is dependent on a number of factors, including leakage past the respirator/face seal and the volume and rate of air drawn through the filter. This paper gives the results of measuring minute flows in a volunteer work force of average age 36.7 years and of both genders at various levels of work. Unless air flows can be standardised in testing methods, wide variation in TIL results can be expected, particularly those between the laboratory and the workplace.

INTRODUCTION

Minute flow air volumes (the volume of air used per minute), as used in the workplace by respirator wearers are important values in respiratory protection. Equipment including filters are tested and certified at specified volumes and these should reflect those used in the practical situation. Manufacturers and standard organisations[1,2] have typically used minute volume values that were originally generated, for example, by Silverman et al[3,4,5] over 40 years ago.

The certification process involves Total Inward Leakage (TIL) testing. Certification implies suitability for respiratory protection in the workplace by the user but this may not be the case. Inward leakage will be partly dependent on the volume and rate of air being drawn past the face/respirator contact surface. A large variation in air volumes drawn through and around the respirator will affect the TIL results.[6]

Protection factors obtained from laboratory settings are known to differ substantially from workplace results[7,8]. One of the likely reasons is the wide variation in airflows that can be experienced between individuals performing the same levels of work, particularly in the workplace setting. The variation in TIL in standard situations may be partially removed by the method of "calibrating" to approximately the same values of airflows of test subjects.

The retention capacity of filters is partly dependent on the volume and rate of air flows that are drawn through the cartridge. Any expression of results needs to reflect the practical air flow rate used in the workplace.

As air flows can vary depending on work rates, the present study investigated air flows typically used by respirator wearers in industrial workplaces at a known levels of work.

METHOD

Study Objective

The objectives of this study was to:

- Confirm the published minute flow values at various levels of work.
- Generate a set of values for minute flow that represented a typical workforce found in an industrial situation whom could be expected to wear the protective equipment, that is, a wide age range and both genders. Standard bodies often use student volunteers who exhibit physiological characteristics different to this, for example, in heart rate and minute flow volumes.
- Investigate the possibility of using an individual's heart rate to establish a rate of work that could be compared with another individual to obtain the same approximate minute flow volumes. This would allow better comparison with other Standards for respiratory protection and standardise TIL results between laboratories and the same classes of equipment over a wide range of practical work outputs.

Subjects

All twenty five volunteers were employees of SEA Pty Ltd, Sydney, Australia, with a wide range of ages (19 to 50 years, and an average age of 36.7 years) as well as fitness levels. All volunteers had the experimental procedure explained to them. The range of age and fitness level of these individuals was considered more representative of workers found in industrial situations. All subjects were fitted with a Sunstrom® half-face respirator. All males were clean shaven.

Investigative Procedures

Subjects were asked to walk at a of 6.5 kph on a Spectra Mattan treadmill while heart rate and Minute Flows (the volume of air used by the subject in one minute) were logged electronically. The trials were repeated on at least 3 times on separate occasions for each subject.

Subjects were asked to walk at a steady rate on the treadmill inclined at various angles at 6.5 kph (a fast walking speed). Initially, the treadmill was set at a level incline (0°) and then gradually raised at an increasing incline of 3°, 5° and 7° from the horizontal.

The fit of the respirator/face seal was verified with Portacount® particle fit tester. Subjects who passed with a fit value of 100 or greater (that is, a leakage of less than 1%) were considered acceptable to take part in further trials.

Each subject wore a Sunstrom SR-90 half-face respirator fitted with a flow meter, designed, built and calibrated by SEA Pty Ltd in Sydney. Calibration of the equipment was traceable to a reference standard. The flow meter utilised a pressure drop over a standard P3 Sundstrom® particulate filter. The pressure drop was measured using a Honeywell Differential Pressure Transducer®. Minute Flows and heart rates were measured continually over three minutes and repeated over three separate days.

Heart rates were measured with a chest mounted Polar Electro belt which electronically recorded values that were downloaded to a PC.

Mean minute flow and standard deviations were calculated from Minute Air Volume data.

Equipment

The respirator was calibrated using a test bench at SEA Pty Ltd, using a two-point calibration at low and high values. Software was developed for the process. Low and high flows were recorded via a pressure drop across a P3 filter. The calibration procedure was automated in the software. The software requests a high limit value and average 1500 samples over 30 seconds. The numerical value was entered via a keyboard. The process was repeated for the low limit value. Gain and other offset factors are calculated and stored in separate files as calibration constants. Prior to each test, an equipment calibration was performed.

Data and Statistics

Data was collected and loaded into the Microsoft Excel Spreadsheet and Statistics program (1997 edition). Data was summarised descriptively using means and standard deviations. Measures of association were calculated using the χ^2 test.

RESULTS

A steady heart rate was observed for each level of exercise for any given individual. The results from each stabilised values for heart rate and minute volume flows are given below.

To ensure that the data obtained from the individuals could be repeated, a number of subjects volunteered to return for seven to ten days so that the tests could be completed once a day over this period. Once again, minute flows and heart rates were recorded while the subjects gradually increased the work load on the treadmill from walking at 6.5 kph at 0-7° incline of the treadmill. Apart from a slight improvement in parameters almost certainly the product of training and increase in fitness, there was no significantly consistent variability in this data (see Table 1, showing typical data from two volunteers (Subjects 13 and 16), and Figure 1 showing Heart Rate data for Subjects 13 and 16 (note: Subject 13 only attended for Days 1-7). Indeed, calculations of probability for this data invariably gave values above 0.95.

Table 1: Heart Rate and Airflow Data for Subjects 13 and 16

Subj ID	**Parameter**	**°Incl**	**Day**										**Statistics**	
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**	**SD**
13	**Heart Rate**	**0**	114	109	115	108	101	115	105				109.6	5.4
		3	137	131	136	126	120	127	120				128.1	6.9
		5	147	146	149	144	135	141	133				142.1	6.1
		7	162	159	154	148	150	148					153.5	5.9
	Airflow min 1	**0**	37.2	38.1	29.9	29.5	27.4	21.6	26.6				30.0	5.9
	min 2	**0**	38.0	39.4	32.1	35.5	33.7	26.7	34.4				34.3	4.2
	min 3	**0**	39.0	41.3	36.6	36.1	31.2	27.3	31.0				34.6	5.0
	Airflow min 1	**3**	48.7	48.3	42.8	41.3	42.5	46.2	42.8				44.7	3.0
	min 2	**3**		49.3	49.2	49.4	47.9	51.4					49.4	1.3
	min 3	**3**			47.7	51.5	48.4	52.2	46.7				49.3	2.4
	Airflow min 1	**5**	67.9	66.5	58.3	59.4	52.1	54.7	54.1				59.0	6.1
	min 2	**5**	63.8	66.3	67.7	60.9	60.5	56.8	52.2				61.2	5.4
	min 3	**5**	74.0	0.0	70.4	68.0	62.5	59.7	54.1				55.5	25.4
	Airflow min 1	**7**	83.7	78.9	77.8	70.9	64.8	71.5					74.6	6.8
	min 2	**7**	92.7	82.0	79.9	77.6	72.6	61.2					77.7	10.5
	min 3	**7**	97.7	90.1	86.0	72.0	75.5	66.4					81.3	11.9
16	**Heart Rate**	**0**	103	96	100	91	89	90	86	83	91	84	91.3	6.6
		3	114	115	108	102	101	105	99	95	105	100	104.4	6.4
		5	129	123	122	115		118	115	107	112		117.6	6.9
		7	146	143	146	128			129	126	123	118	132.4	11.0

Subj ID	Parameter	°Incl	Day										Statistics	
			1	2	3	4	5	6	7	8	9	10	Mean	SD
	Airflow min 1	0	34.8	26.3	21.4	30.0	24.2	26.9	24.4	17.5	25.8	23.9	25.5	4.7
	min 2	0	37.6	31.8	26.1	21.0	30.8	32.1	30.8	28.0	31.1	29.5	29.9	4.3
	min 3	0	37.0	31.7	32.2	32.9	31.8	33.6	31.8	26.4	31.9	29.8	31.9	2.7
	Airflow min 1	3	43.2	36.0	39.2		35.2	34.4	35.4	35.5	42.6	35.5	37.4	3.4
	min 2	3	47.8	41.3	48.3	41.2	40.5	42.5	45.5	40.7	46.9	40.6	43.5	3.2
	min 3	3	47.4	44.6	46.8	40.7	47.9	44.4	42.7	44.3	47.9	41.4	44.8	2.7
	Airflow min 1	5	46.5	46.7	47.3	47.6		51.3	47.6	38.7	48.9	44.0	46.5	3.5
	min 2	5	50.1	51.2	58.9	51.2		57.6	53.4	41.8	51.2	45.0	51.2	5.4
	min 3	5	56.7	49.5	58.2	54.0			55.3	50.2	48.9	48.1	52.6	3.9
	Airflow min 1	7	55.1	55.0	60.1	60.2				60.4	54.2	52.6	56.8	3.3
	min 2	7	64.2	64.0	68.7	66.6			66.0	65.1	61.7	54.8	63.9	4.2
	min 3	7	69.3	69.3	73.2	64.0			68.3	64.0	59.9	57.3	65.7	5.3

Figure 1: Heart Rate data for Two Subjects over the Ten Day Trial

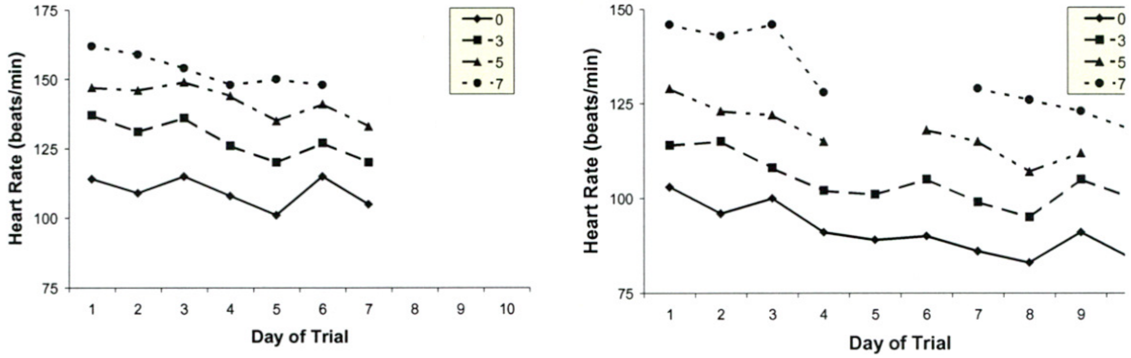
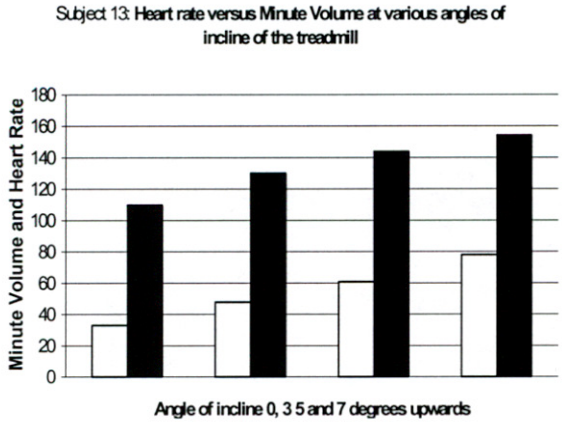
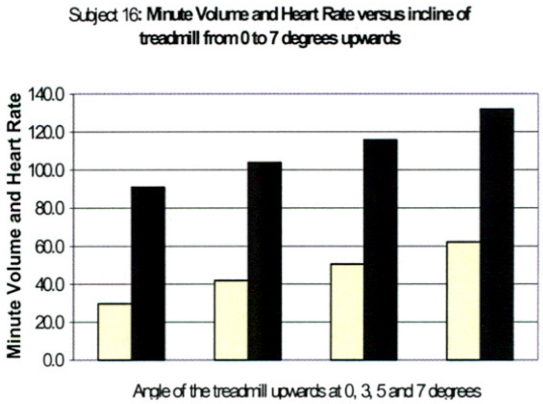


Figure 2 shows the relationship of work rates (angle of incline) and heart rate.


Subject 13: **Heart rate versus Minute Volume at various angles of incline of the treadmill**

n sul


Subject 16: **Minute Volume and Heart Rate versus incline of treadmill from 0 to 7 degrees upwards**

The physiological results from 25 volunteers are summarised graphically in Figure 2, Figure 3 and Figure 4.

Figure 2: Angle of Incline and Heart Rate

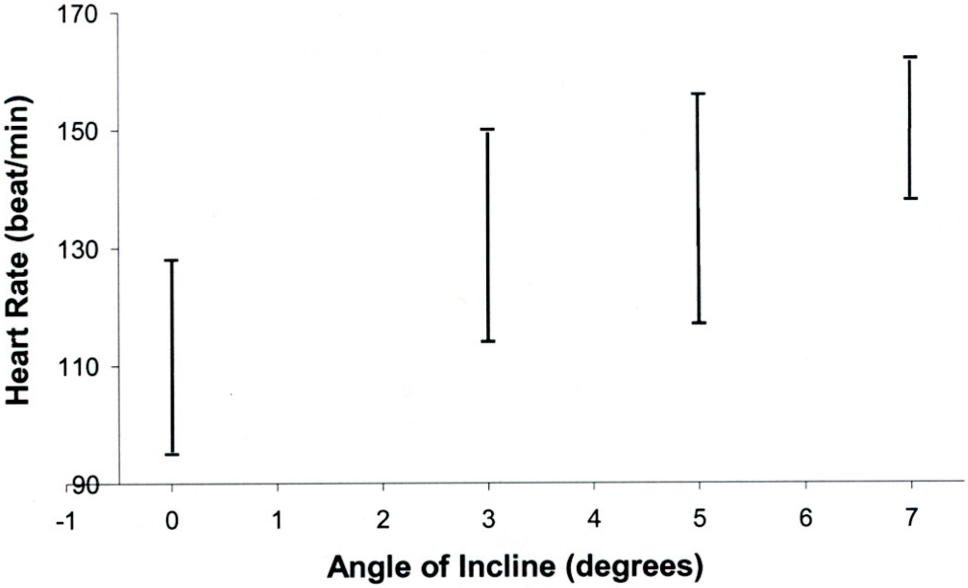


Figure 3 shows the relationship of work rates (angle of incline) and minute airflow.

Figure 3: Angle of Incline and Airflow

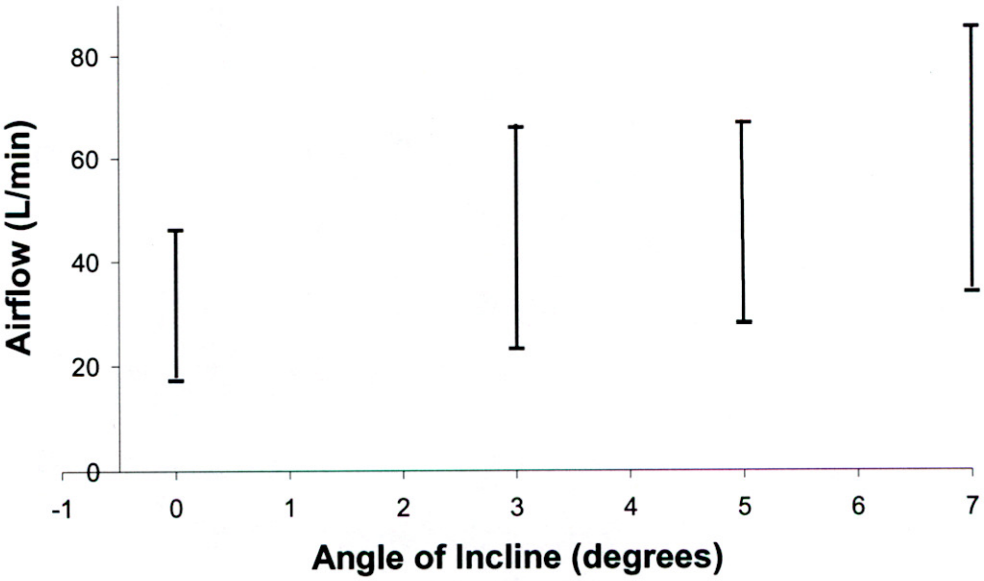
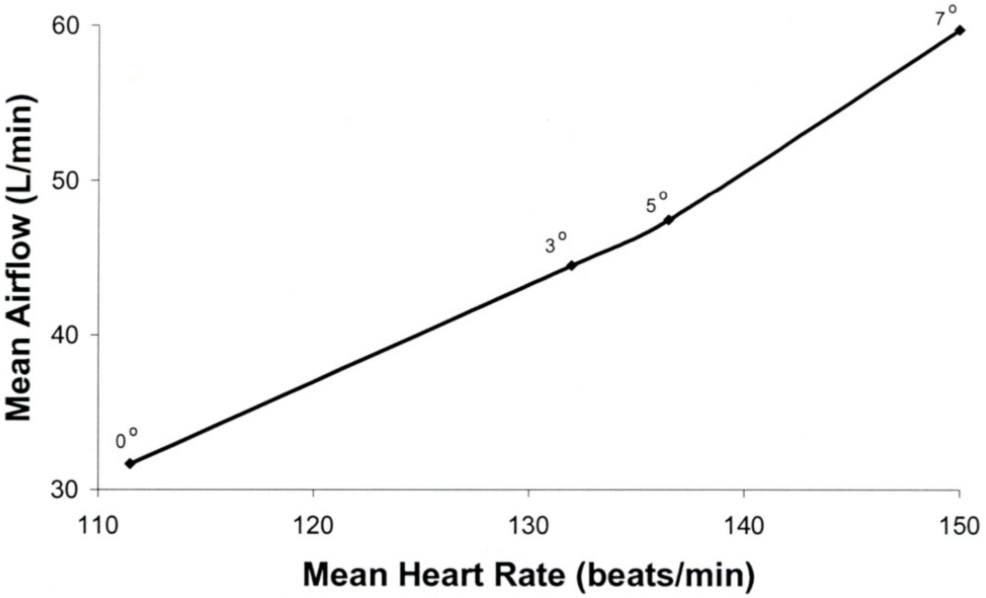


Figure 4 shows the relationship of heart rate to minute airflow at different work rates (angle of incline).

Figure 4: Interactions between Heart Rate, Minute Airflow and Work Rate



DISCUSSION

The determination of Minute Flows and heart rate for a range of increasing workloads was determined. These results differ from some of the published information available possibly because the sample population (that is, volunteers) was significantly different to that from previous studies in that a wide age group was used and volunteers included both genders. It is important to sample values from a population that is typical of the workplace, that is, an older age group (a mean of 36.7 years in these trials) and of both genders.

Values which are typically quoted include the following[9]:

Work load	Metabolic range (W)	Minute Volume (lpm)
Resting	117 or less	<6
Low	118-234	8-16
Moderate	235-360	16-24
High	361-468	24-31
Very high	Above 468	>31

Typical published values for work rate and minute volume

In these trials, the following results were obtained (for comparison, this is repeated from the results section). Note the *range* of results.

Work rate†	Heart rate (bpm)	Minute Volume (lpm)
0	95-128	17.2-46.1
3	114-150	23.1-65.9

5	117-156	28.1-66.8
7	138-162	34-85.5

† Angle of treadmill (sloped upwards) at shown angle while subjects walked at 6.5 kph for up to three minutes each day for 7-10 days

The variation of physiological parameters such as heart rate and minute flows are critical values as they are used in the testing and certification of both respirators and filters and should reflect the wide range of values used by a typical workforce. The data shown here indicate that heart rate and airflow are related, and increase in a linear fashion as work increases. However, the range of results from different people is very large. The wide variation in range is critical. This will have an impact on the use of respiratory protection, particularly where heavy work is being carried out. In addition, the "worst case" (that is, the highest values) need to be incorporated into respirator testing and certification.

Currently, Standards such as the AS/NZS 1715[1] use minute flow volumes that under-represent those from a typical workforce. For example, in the testing of filter capacity test gases are drawn through the filter at 30 l/min. Certification and testing of respiratory equipment must reflect true values of minute flows in the workplace.

CONCLUSION

Previous published values for minute flows appear not to be most suitable, particularly for an older age group of wide variation in fitness and more representative of a typical Australasian workforce. This has significant implications for the testing, certification and use of respiratory equipment of all types including half-face negative respirators and PAPR equipment. In addition, the range of values expected was much wider than may be expected. For example, the range of values experienced was from 34 to 85 l/min at a heart rate of 138 to 162 beats/min. Published figures (as shown in the discussion section) would indicate Minute Flows of about 43-56 l/min - a much narrower and lower range than could be expected in a practical Australasian working environment.

It is important to test and certify respiratory equipment at relevant flow rates. However, these flow rates should be those that could reasonably be expected in a typical workplace. Inhalation resistance of respirator filters and assembled respirators is tested at 30 and 95 l/min,[2] while the filter capacity for gases is tested at 30 l/min continuous flow volume - a very low flow that does not reflect normal and practical usage.

The design, certification and use of future respirator development must take into account these higher values and the range of values for minute flow. In addition, the implications of PIAF (Peak Inspiratory Air Flow) need to be taken into consideration (that is, the flow rate required to meet the inhalation breath speed). This has further serious implications for the users of respiratory protective equipment and forms the subject of the topic in a later paper. .

The wide variation in airflows obtained from a typical Australasian workforce demonstrates the need to "calibrate" test subjects prior to obtaining TIL (Total Inward Leakage) values to remove the wide variation between laboratories situated in different parts of the world and to allow better comparison between laboratory and workplace values of protection factors.

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9 Standard prCR 529:1991. Appendix 5

The American Industrial Hygiene Association (AIHA) and American Conference of Governmental Industrial Hygienists (ACGIH) Respiratory Protective Devices Manual, published in 1963, has as its primary source of physiological background the work of Silverman and co-workers performed during World War II. The adoption of permanent OSHA standards governing work tasks requiring workers to use respirators has created a need for further evaluation of the physiological effects of wearing a respirator. This review was undertaken to meet the need of an in-depth evaluation of the currently available psychophysiological data. It was concluded that it was of the utmost importance to develop a physiological and psychological medical screening examination to determine the capability of the worker to use a respirator.

The physiological consequences of wearing industrial respirators: A review*

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introduction

The last review on the physiological aspects involved in the use of respirators was published in 1962.[1] However, like the earlier works of Silverman et *al.*,[2–4] the major emphasis of that report was to provide basic physiological data concerning the man-respirator interface in order that the engineer would have some basis on which to evaluate newer designs of respirators. Indeed, the data of Silverman et al., obtained in World War 11, provided the basis of all modern-day government certification tests of individual respirators.

Further developments in man-respirator designs have been stimulated by the primary need for wearing a respirator, i.e., the protection offered against toxic atmospheres, particulates, and oxygen-deficient atmospheres. Development of specific tests for face-mask fit and aerosol penetration (DOP and NaCl) has led to improvements in face-mask design and modes of protection. These modern day requirements are outlined in a series of authoritative publications.[5–7]

Since the enactment of the Occupational Safety and Health Act in 1970, however, the need to develop criteria by which individuals can be evaluated for respirator wearing is becoming important. Industrial respirators should be designed to operate with minimal decrement in the work efficiency of the operator. Therefore, the first requirement of the physiologist is to determine the degree of work impairment that occurs during the wearing of each respirator. Additionally, the adjustments of involved physiological systems, along with psychological determinants, should be quantified. Cooper[8] succinctly has outlined the problem facing the industrial physician and, as a consequence, has challenged the medical research community to provide specific evaluative techniques.

The most serious difficulty in this field is the plethora of designs and the types of respirators available; all have unique properties and uses. From an engineering viewpoint and specific protection requirements, it is customary to divide the designs into three major sections: 1. air-purifying respirators; 2. supplied-air respirators; and 3. self-contained breathing apparatus (SCBA). Each major section can be subdivided further into various categories: full,

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*This work was performed at the Institute for Aerobic Research, Dallas, Texas under contract to the Respirator Research Division (H-5). Los Alamos Scientific Laboratories, Los Alamos, New Mexico.

half, or quarter facepiece devices; powered or nonpowered; and/or open-circuit or closed-circuit devices. The multiple forms and purposes of the many respirators available have been adequately summarized on pages 28-30 of a previous report.“)

To the physiologist, the design of respirator used is of minimal importance. Hence, in this review the effects of a specific portion of the man-respiratory interface are generalized, i.e., the specifics of design or purpose. The changes that occur within physiological systems, however, are outlined.

maximal and submaximal work performance

The industrial respirator, in general, is utilized to perform submaximal tasks (light or moderate effort) in types of work in which inhalation of the atmosphere may prove injurious or fatal. However, specific types of work such as mine rescue, fire-fighting, and certain military purposes require maximal work performance while wearing a respirator.

Van Huss ***et al.***(9) required 13 highly trained subjects to run both a timed ***half-mile*** on an outdoor track and to exhaustion at ***10 mph*** with ***0%*** grade on a motordriven treadmill. These tasks were carried out under four conditions: 1. control, 2. wearing an M-17 respirator with mask and filter by-passed, 3. wearing an M-17 respirator intact, and **4.** wearing an M-17 respirator and filter plus an M-6 hood (thereby increasing exhalation resistance). Unfortunately, inspired and expired resistances were not reported. Average group time for the ***half-mile*** run increased progressively from conditions 1-4, but times to exhaustion on the treadmill were progressively reduced from conditions 1-4. Other investigations into air-purifying respirators similar to the M-17 also demonstrated like reductions in maximal work performance and/or endurance capability.*(10-13)* Interestingly, although physical fitness played some part in absolute work performance while wearing a respirator, exercise training did not alter the ratio of endurance when masked to endurance when unmasked.**(10,13)** These ratios suggested that the mask played a major part in the reduction of maximal work capacity. Furthermore, Craig ***et al.***(13) reported that the facepiece without filters had a degrading effect upon endurance time. Reduction of work capacity utilizing the air-purifying respirators approximated 21 to 27 percent of performance time; however, the result might not be indicative of a reduction in maximal oxygen uptake ($\dot{V}O_2$ max).

Similar decrements in work performance have been observed in evaluating fire fighters wearing full equipment including a SCBA respirator.(14,15) In a later **investigation**(16) the subjects were **15** volunteer firemen with a mean age of 31.0 years; 8 were nonsmokers and seven, smokers. Each performed a Bruce“” protocol maximal treadmill stress test under four separate conditions: **1.** without SCBA, 2. carrying SCBA without mask, 3. with SCBA wearing mask and in “demand” breathing mode, and **4.** with SCBA wearing mask and in “pressure-demand” breathing mode. A 17.5 to 21 percent decrement in maximal work performance was noted, primarily due to the increased load of carrying the SCBA. No significant differences were observed between smokers and nonsmokers and/or breathing modes although the greatest mean decrement (21 percent) in work performance occurred with the “demand” breathing mode.

Submaximal responses during these **tests**(14,16) verified previous reports.(18-22) Davis and Laine Santa **Maria,**(14) in determining energy costs of wearing fire-fighting equipment and breathing apparatus (23.6 kg), found a 34 percent increase in metabolic work and a 27 percent increase in submaximal heart rate as compared to responses obtained while working in everyday street clothes. Raven ***et al.***(16) found similar increases in submaximal heart rates with weight bearing of the SCBA compared to control conditions during the submaximal stages of the Bruce treadmill test. Spioch ***et al.***(18) monitored heart rate, blood pressure, blood oxygen saturation (by ear oximetry), respiratory rate, and inspiratory and expiratory pressures of their subjects following a **5** minute Harvard Step Test performed with and without respirators. Unfortunately, the design of the respirator was not described. Following work, they observed a minor difference in heart rate (+ 7 beats/min with respirator) and a **24** percent increase in systolic blood pressure (151-188). These changes suggested an increased cardiac and stroke work

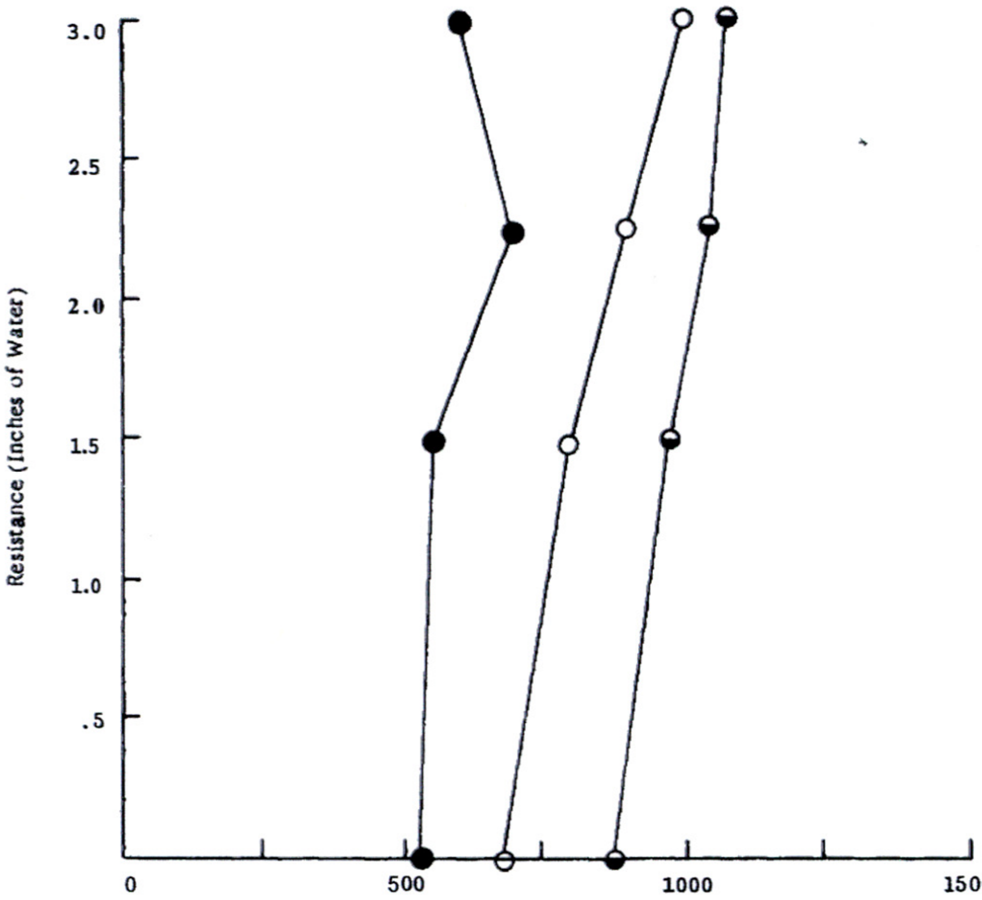

Figure 1 – Oxygen uptake values obtained during the initial 3 minutes of recovery after walking up 0%(●), 5% (○), and 10%(◓) grades at 3.5 mph with various respiratory resistances. (Calculated from ref. 19).

resulting from the increased thoracic activity in overcoming the added resistance to respiratory flow. Resting inspiratory pressures of –35 mm H_2O and expiratory pressures of +18 mm H_2O changed to –174 mm H_2O and +78 mm H_2O, respectively, following exercise. There were no changes in arterial oxygen saturation.

In a more controlled investigation, Thompson and Sharkey(19) studied the physiological cost of using air-purifying respirators by determining the oxygen debt of five subjects after 5 minutes of walking at 3.5 mph with slopes of 0, 5, and 10 percent grades on a motordriven treadmill. They argued that since respirator usage decreased oxygen uptake of a given workload and also reduced work capacity, anaerobic work must increase and could be measured by determining changes in oxygen debt. They also hoped to establish an air-flow resistance to energy cost relationship. Air-flow resistance for the three types of respirators was measured at 85 and 170 L/min. The changes in 3-min recovery oxygen uptake values are plotted against resistance across the mouthpiece in Figure 1. These data showed that the greater the resistance, the greater the 3-min recovery oxygen uptake; and, in general, the higher the workload, the greater the effect. However, 3-min recovery oxygen uptake values might not be truly representative of oxygen debt, particularly if the difference in debt ranged from 96 mL O_2 to 759 mL O_2 total oxygen uptake in 3-min and if no corrections for differences in resting oxygen uptake were made. Indeed, these data might represent changes in recovery oxygen which might or might not be linked with the accepted processes involved in the accumulation of oxygen debt. A more definitive investigation is required to test this interesting hypothesis.

TABLE I
Alterations in Inspired Resistance of an Electrostatic Filtered Respirator (RU645) with Increased Time of Usage in the Mine'

Inspired Resistance (mm H_2O)	Time of Use (hrs)
1.5	0
2.0	60
2.5	150
3.0	220
3.5	320
4.0	370
4.5	450
5.0	550
5.5	600

'Data from reference no. 20

Further reports concerning submaximal work while wearing air-purifying respirators(21,22) showed that efficiency of work and physiological parameters were unaltered if workloads were low, i.e., heart rate = 130 beats/min and caloric costs of less than 6 Kcal/min. However, if the workload was increased to **9** Kcal/min, significant decrements in work efficiency were **noted.**(22) In a more practical demonstration Martire et *al.*(20) related the increased obstruction to air flow from using a respirator in an industrial setting with a decreased tolerance to heavy work even though measured inspired resistance was only 5.5 mm H_2O; see Table I. The major physiological change was an increased heart rate (~ + 10 beats/min) and a decrease in arterial hemoglobin saturation (~ **4** percent). However, it is unlikely that the degree of these reported physiological changes explain the decreased tolerance to work.

A major factor in the use of respiratory protective devices on the tolerance to physical activity has been the resistance such devices offer to breathing.(2–4,23) Along with the increase in respiratory dead space, this factor has received the major proportion of the investigative attention in the past. Although the results have provided physiological insight into exercise ventilation and have resulted in providing data for determining tolerable limits of respirator design, these investigations have little value in providing the industrial physician a means of evaluating the worker for respirator use.")

TABLE II
Maximum Inspiratory Flow Resistance for Respirators*

Conditions	Inspiratory Flow Resistance (cm H_2O at 85 L/min)
Rest	5.0
Light to moderate exercise	2.5
Heavy exercise	1.0
Maximal exercise	0.7

'Data from reference no. 25

resistance to air flow

Silverman *et al.*(2) had concluded in **1945** that "a limit on the internal respiratory work appears to be the best basis for stating tolerable limits of resistance." In their **work**(2–4) they investigated the effects of breathing against resistance while working for 15 min at various rates on a bicycle ergometer. The work rates selected ranged from 0 to 1660 kg·m/min and were used in conjunction with inspiratory resistances ranging from 0.6 cm to 10.6 cm H_2O and measured at a flow rate of ***85*** L/min. Increases in respiratory resistance resulted in a decreased submaximal oxygen uptake and ventilation volume with increased'respiratory exchange ratio. Although not measured, they concluded that oxygen debt would increase. In addition, they calculated a beneficial increase in oxygen deficit. Unfortunately, the definition of oxygen deficit used by Silverman appears to be different than the accepted definition. If measured today the deficit would be regarded as an increase in anaerobic contributions to energy production and, therefore, a detrimental response to efficient submaximal work performance. Below 1107 kg·m/min the workload increases in resistance did not affect tidal volume or respiratory rate although the greater resistance increased the time phase of the respiratory cycle related to the higher resistance, i.e., the inspiratory phase. In the overall analysi- the responses indicated that most subjects were able to tolerate the increased resistance if the total external respiratory work did not exceed **2.5** kg·m/min at the low workloads and 13.3 kg·m/min at the high workloads. The data contained in these **reports**(2–4) on the air flow changes in each respiratory cycle provided the basis of the engineering requirements for pump design used to simulate human breathing apparatus.

TABLE III
Airflow Characteristics of Typical Respiratory Apparatus in Current Use*

Apparatus	Range of Airflows (liters/min)	K	n
Canister respirator	60-300	1.0×10^{-2}	1.45
Dust respirator	85-125 125-300	3.1×10^{-3} 3.0×10^{-3}	1.44 1.46
Closed-circuit, compressed oxygen breathing apparatus	140-300 85-150	1.4×10^{-3} 1.7×10^{-3}	1.58 1.56
Closed-circuit liquid oxygen breathing apparatus	150-300	5.3×10^{-4}	1.86

*Data from reference no. 24

Cooper(23) has suggested that the estimation of the work done in ventilating respirators was the most useful, single measurement in providing knowledge of resistance to respiration. He likened the human respiratory system to a reciprocating pump with sine-wave flow; hence, estimation of the work done was best performed using bench experiments. However, it recently has been shown that the respiratory waveform can be expressed sinusoidally, triangularly, or rectangularly.(24) From his work Cooper generalized that the use of a simple air filter of very low resistance could increase the work of respiration by 20 to 30 percent, and a standard closed-circuit breathing apparatus, by 100 percent.

Cotes,(25) in his review of the literature, indicated that the acceptable resistance varied with the ventilatory volume of the subject as this value would change appreciably with measures in resistance at high rates of flow. Thus, he suggested that any specification should include the anticipated work level as outlined in Table 11.

Shephard(26) noted that the respiratory load of a rebreathing respirator was increased by ventilation of the "external dead space" and by flow resistance of the absorbent canister and valves of the apparatus. He expressed this increased resistance (R) as a simple power function of flow (F); thus, $R = K(F)^n$ where the exponent has a value of about 1.7 in the normal respiratory system. Examples of K and n for some typical respirators are summarized by Bentley *et al.*(24) in Table 111.

An operator wearing a respirator is exposed to intermittent negative pressure respiration (INPR) due to the inspiratory resistance. INPR could cause pulmonary edema; however, this result was not confirmed in dog experiments even after 3 hours of exposure to **−40** cm H_2O, although significant decreases in arterial oxygen saturation were recorded.

Shephard(26) further evaluated the pulmonary resistance of man prior to and following 1 hour of respiration through an inspiratory resistance of 23 cm H_2O at 20 L/min. However, there was no change in pulmonary resistance prior to or following the exposure to the resistance (INPR X_{pre} 2.61 cm $H_2O/L/sec$ to $\bar{X}_{post}$ 2.19 cm $H_2O/L/sec$). In addition, he calculated that the effects of dead space ventilation and inspired resistance were 150 percent greater than the unimpeded load of respiration at 18 kg·m/min. When related to body capacity, he predicted that as the mechanical efficiency of the respirator system was only **5** percent, the total energy cost of the respirator system would be 360 kg·m/min (6W) with an oxygen uptake increase of 160 to 170 mL/min (i.e., 6 percent of capacity) as compared to whole body metabolic cost increase of 3 to **4** L/min oxygen uptake. Hence, he concluded such increases in resistance and dead space would have negligible effects on the working performance of man. Since then, his conclusion has been shown to be **incorrect,**(9–16) thereby suggesting that the reduction in work capacity is related to the increased respiratory oxygen cost of breathing through a respirator.

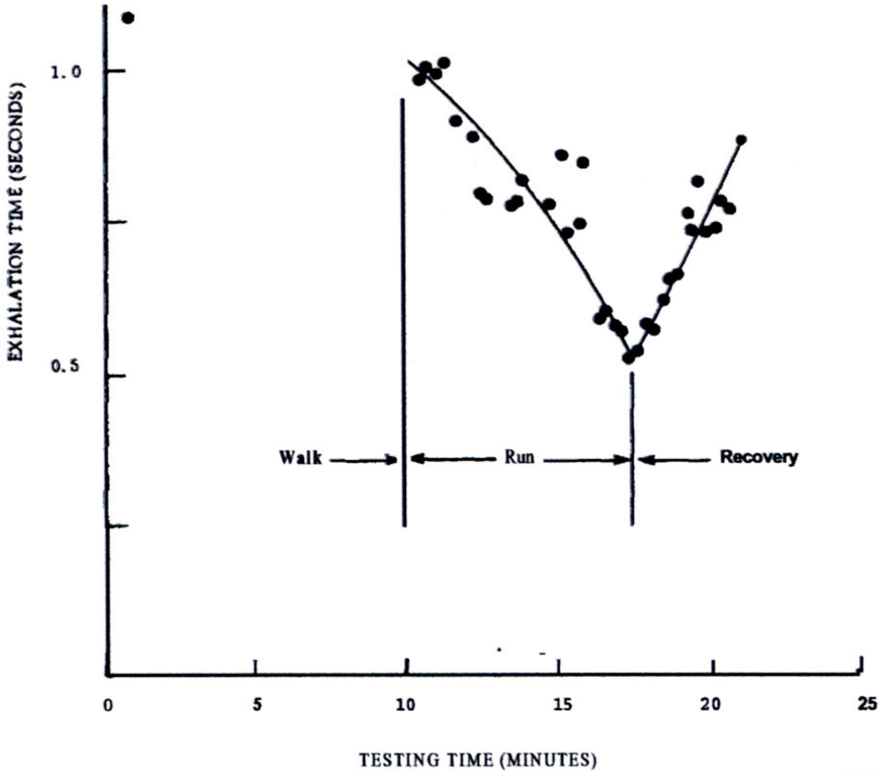

Figure 2 – Exhalation time as a function of test time for one subject.[12]

Gee et *al.*[27] utilized a 1 cm plastic tube to produce a **5** cm **$H_2O/L/sec$** external airway resistance at **2** L/sec flow and demonstrated that relative ventilation at progressively increased workloads was reduced with a combination of increased inspired and expired resistances. If expiratory resistance alone was increased, tidal volume was decreased; if inspiratory resistance was increased, the respiratory frequency was decreased. However, no effects were observed on diffusion capacity, alveolar-arterial oxygen gradients, oxygen uptake, and heart rate up to work levels of 80 percent of the maximal oxygen capacity (80% $\dot{V}O_2$ max). Using a similar technique of increasing external resistance, Cerretelli et *al.*[28] also found that ventilatory volume was decreased as resistance was increased at any level of work. Maximal oxygen uptake and exercise tolerance time were reduced with increased resistance; yet, the relationship between oxygen uptake and submaximal workload remained unchanged. Furthermore, they discovered greater impairment of muscular work by increasing the external resistance to breathing to a level of 68 cm **$H_2O/L/sec$** and demonstrated the impairment to be intolerable when the difference between peak inspiratory and expiratory pressures reached 100 cm of water whether at rest or during exercise. Ventilatory volume decreases produced an increase in the alveolar carbon dioxide tension. Thus, breathing against resistance during work resulted in an impairment of the capacity for muscular work which could be explained by respiratory fatigue; inadequate ventilation; retention of carbon dioxide leading to an increase in alveolar carbon dioxide; the magnitude of the pressure change from inspired side to the expired side; or a possible shift early in work to anaerobic processes, thereby causing an increased rate of accumulation of oxygen debt. In recent years numerous investiga-

TABLE IV
Exhalation Times at Exhaustion of Men with
Various Inhalation and Exhalation Resistances**

Number of Subjects	Exhalation Time at Exhaustion (sec)	Inhalation Resistance* (mm H_2O-min/liter)	Exhalation Resistance' (mm H_2O-min/liter)
5	0.67	0.25	0.33
5	0.61	2.6	0.33
13	0.721	0.25-2.6	0.33-0.76
18	0.647	0.11	0.22
18	0.643	*0.50*	0.22
18	0.674	0.66	0.22
3	0.671	0.015	0.015

'Data from reference no. 12
**Systems measured at 85 liters/min airflow

tors(11,12,29,30) have studied these factors and have realized that man minimized the total respiratory work by reducing the time of exhalation within each respiratory cycle in order to maintain as a constant the time of inspiration in spite of the apparent detrimental physiologic consequences.

Craig *et al.*(11) studied 13 men who worked to exhaustion on a treadmill from 0 to 22 percent grade at 3.5 mph and/or 8 mph with inspired resistances on an M-9 mask ranging from 1.5 to 15.5 cm $H_2O/L/sec$ and expired resistances of 2.0 and 3.9 cm $H_2O/L/sec$. Increased resistance to breathing significantly reduced times to exhaustion with the greatest percent change occurring at the lighter workloads. The exhaustion at different conditions of resistance produced large variations in attained oxygen debt, expired carbon dioxide, and peak pressures during inspiration; but the time of expiration approached a constant value. In 110 tests the mean time of expiration at exhaustion for the 13 men varied from 0.48 to *0.97* sec with variation in standard deviation of 0.03 to 0.12 sec. Hence, as the frequency of respiration increased during work, the time for inspiration was conserved at the expense of the time for expiration. As a follow-up to this idea, Johnson and **Berlin**(12) confirmed that the minimum exhalation time (0.66 sec) characterized the voluntary end-point of work for ten subjects. See Figure 2 for the effect on one subject. In addition, they summarized the data (Table IV) relating various inhalation and exhalation resistances with time of exhalation at exhaustion and verified its minimal variation as long as the exhalation resistance remained constant. It was noted that any increase in exhalation resistance resulted in a corresponding increase in exhalation time. This finding is also common to work reported from East Germany by Von Schleusing and Leers; see list of supplementary references.

Using this concept of minimizing average respiratory power, **Johnson**(29) and Johnson and Masaitis(30) have developed equations of respiratory regulation to predict inhalation/exhalation time ratios for both the man-respiratory system and the respiratory system alone. The equations demonstrated that if the respiratory period was known, exhalation time could be calculated. Unfortunately, the optimal respirator design to reduce the effect of exhalation resistance, inhalation resistance, and mask dead volume for any given work rate on operator performance has yet to be achieved. However, their **work**(29,30) has provided engineers with the necessary data and theoretical treatments of the obtained data to achieve improvements in the design of respirator and respirator test equipment.

Shephard(31) raised another theoretical consideration in respirator design and induced respiratory resistance. In his treatise he considered the effects of reducing the inhalation resistance of demand systems such as valve oscillation creating an unstable situation. Since man could not modify externally induced oscillations, the design and engineering of the respirator should overcome this problem. Furthermore, he argued that increases in resistance and capacitance of the man-respirator system should be maintained at a minimum.

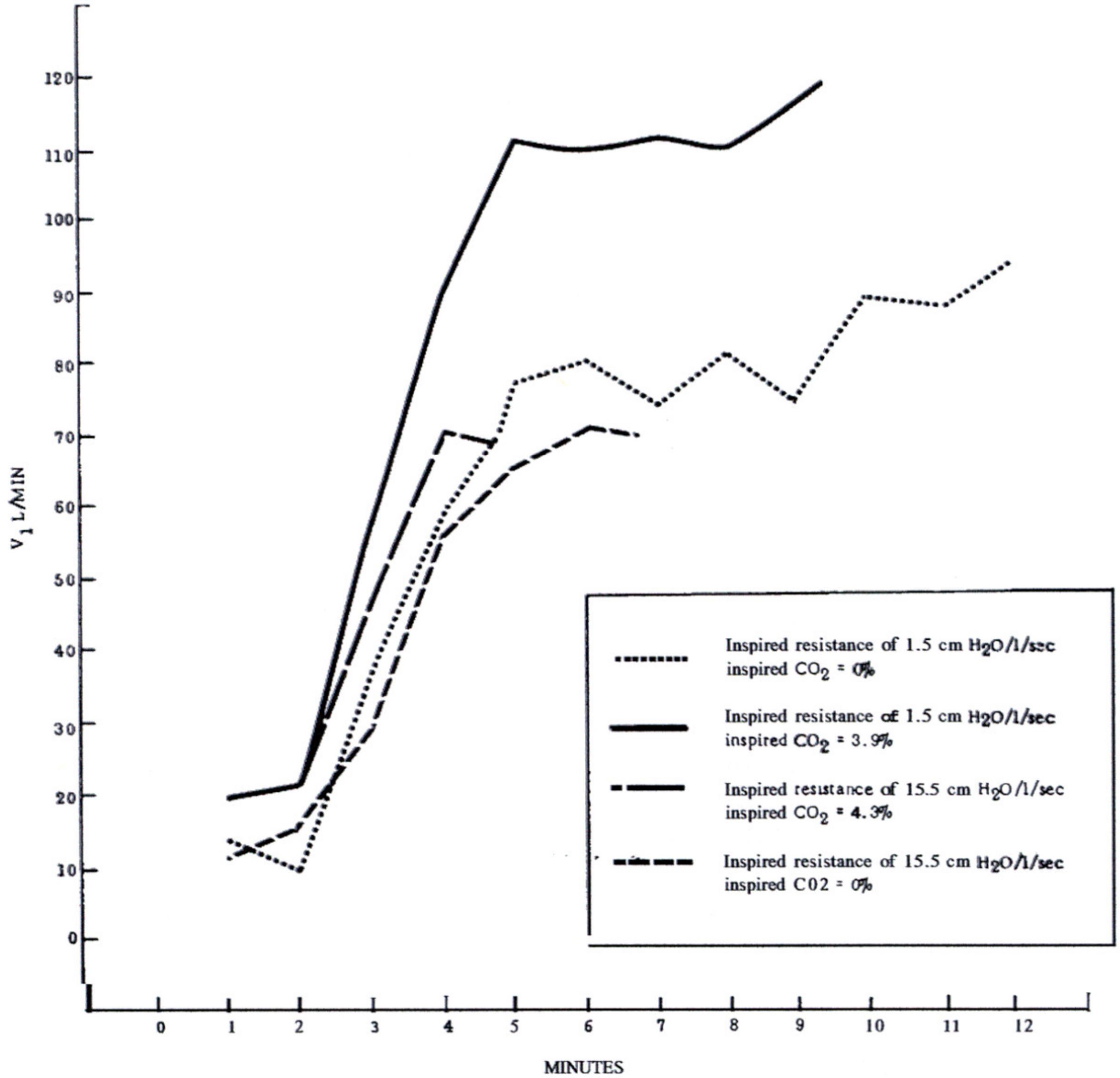

Figure 3 – Respiratory minute volumes during walks under varying conditions of inspiratory resistance and levels of inhaled carbon dioxide.*

Hence, a possible means of damping the oscillations is by increasing the inertance of the system, i.e., by increasing the diameter of the inspired tubing.

increased respiratory dead space

It has been accepted that the addition of an artificial dead space at the mouth led to an increase in the alveolar carbon dioxide tension (PCO_2) and in ventilation at rest[32,33] and at work.[34,35] Jones *et al.*[34] demonstrated that the increases in ventilatory and alveolar PCO_2 were dependent on the workload and the volume of added dead space, but that the magnitude of response was related to the ventilatory response of the subject to CO_2 measured at rest. Work by Craig *et al.*[11] and Love *et al.*^ documented the changes occurring with respirator use, i.e., operator response to inhaled CO_2 while influenced by an increased respiratory resistance. Craig *et al.*[11] investigated levels of inspiratory resistance ranging from 1.5 to 15.5 cm H_2O/L/sec and expiratory resistances of **2.0** and 3.9 cm **H_2O/L/sec** along with levels of inspired CO_2 (F_ICO_2) ranging from 1.1 to 4.5 percent. If CO_2 was present above the level of 3 percent, a consistent reduction in exercise endurance was noted; and significant

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Communication with Dr. D.C.F. Muir at Safety in Mines Research Establishment, Department of Trade and Industry, Sheffield, England. Data were obtained from an article in preparation by Love, B.G., D.C.F. Muir, K.F. Sweetland, R.A. Bentley, and O.G. Griffin: *Ventilatory Response to Inhaled CO_2 During Exercise in the Presence of an Inspiratory Resistance.

hyperventilation was observed at low inspiratory resistance. In contrast, only minor alterations in exercise ventilation were noted at the highest inspiratory resistance although endurance time was reduced; see Figure 3. As the inhalation of 3.1 to 3.9 percent of CO_2 at the low inspiratory resistance was tolerated better than inhalation of air at the highest inspiratory resistance, it appeared that inspiratory resistance played a more predominant part in the reduction of endurance time. However, when F_ICO_2 was greater than 4 percent, the effect of inspired resistance did not predominate, which suggested that the level of inspired CO_2 and resistance acted interdependently.

Love et *al.*[A] reported the effect of 2 to 5 percent inspired CO_2 on 80 miners working for 30 min at 2 L O_2/min oxygen uptake while breathing through an inspiratory resistance of 10 cm H_2O at 100 L/min. Several subjects were unable to finish the workload if the inspired CO_2 was 4 percent or greater. Reasons for stopping included headache and dyspnea. Inspired levels of CO_2 ranging from 2 to 5 percent caused a relative hyperpnea of 30 to 70 percent with a primary increase in respiratory rate and only a slight increase in tidal volume. If alveolar CO_2 tension was above 40 mmHg, headache and dyspnea were prevalent. Older subjects were more prone to stop with inhalation of 5 percent CO_2. Similar to the report of Jones et *al.*,(34) described earlier, the sensitivity of ventilation to inspired CO_2 increased; i.e., at 2 percent F_ICO_2, the average increased ventilation was 7.79 L/mmHg P_ACO_2 and at 5 percent F_ICO_2, 1.27 L/mmHg P_ACO_2. Thus, with the increased respiratory resistance, inhaled CO_2 was not well tolerated during work when its concentration was raised above 3 percent.

Other aspects of the increased dead space of breathing while wearing a respirator required the modification of equation models of protection(36) as well as those models that predicted energy requirements of respirator wearing.(29,30) Thomas(36) corrected those equations that predicted respiratory tract deposition of aerosols to allow for the additional effects of rebreathing aerosol from the previous breath. Johnson,(29,30) on the other hand, modified these equations predicting respiratory period by Yamashiro and Grodins(37) to take into account the added mask dead volume and its effect on alveolar ventilation.

cardiovascular and metabolic adjustments

The cardiovascular and metabolic alterations occurring while wearing a respirator during work have received only minor attention. This oversight has been unfortunate, for many workers using these devices might be under a prescribed pharmocologic regimen for the correction of hypertension, myocardial insufficiency and irritability, diabetes, and other metabolic and cardiovascular involved hormone disorders. The early data reported by Silverman et *al.*(24) indicated that if heavy work was performed with an inspiratory resistance of 6.4 cm H_2O and an expiratory resistance of 4.1 cm H_2O, oxygen uptake was reduced, oxygen debt was increased, and minute volume declined 20 percent. Some later work(27,28) confirmed these findings, but the results from other test protocols disagreed.(18,35) In general, the primary effect appeared to involve respiratory control and work output rather than metabolic shifts. For example, alterations in measured respiratory exchange ratios(18,27,28) might be explained by the increased respiratory resistance forcing conservation of respiratory energy by increasing respiratory rate and reducing tidal volume, thereby, favoring retention of carbon dioxide. Development of a true anaerobic shift during work has not been confirmed either by blood lactate levels or an increased oxygen debt.(16) The increased 3-min recovery oxygen values reported by Thompson and Sharkey(19) might reflect the increased respiratory energy cost during work. In short, metabolic alterations during work have not been isolated and evaluated sufficiently to answer clinically important questions concerning the use of respirators by workers with drug-controlled metabolic disorders.

Shephard(26) investigated the suggestion that the negative pressure phase of inspiration increased cardiac work because as intrathoracic pressure was decreased during inspiration, the left ventricle developed a greater tension to maintain the level of the systemic blood pressure. Two groups of subjects at rest inspired against moderate and large inspiratory resistances of 6.6 cm H_2O and 23.0 cm H_2O at 20

TABLE V
Electrocardiographic Findings for All Conditions and Both Groups of Subjects*

	ECG Comments	Conditions 1	2	3	4
Nonsmokers- (N=8)	Junctional S-T segment depression	5	4	3	2
	Increase in S-wave depth	1	-	1	-
	W C	-	1	-	1
	Increase in P-wave amplitude		-	1	-
Smokers- (N=7)	Junctional S-T segment depression	3	5	3	3
	Increase in S-wave depth	1	-	1	-
	WC	1	1	-	

'The number in each block represents the number of changes within each condition for a specific group of subjects, e.g., 5 nonsmokers out of 8 had Junctional S-T segment depression. Taken from reference no. 16.

L/min. After 15 min, systolic and diastolic pressure increased slightly and pulse rate and cardiac output decreased as would occur normally with subjects in a supine position. Unfortunately, this work was not continued with subjects exercising in the upright position which would require greater venous return. However, Van Huss *et al.*[9] reported reduced exercise pulse rates in direct relation to the magnitude of the respiratory resistance. This result might indicate an augmented venous return although times to exhaustion were significantly reduced. Chatterjee[21] and Raven et *al.*[16] reported no significant differences in exercise heart rates or ECG responses (see Table V) while wearing a respirator, but others have reported increases.[18,20]

Alifanov *et al.*[38] indicated that as inspiratory resistances increased, intrapulmonic pressures increased during the respiratory cycle and thereby reduced ventilation and produced a decrease in arterial saturation which was magnified above see level. This result may explain earlier findings at sea level by Martire *et al.*[20] who reported decreased arterial oxygen saturation while exercising at the highest inspiratory resistance (5.5 mm H_2O) for 1 hour. From a Harvard Step Test study, Spioch *et al.*[18] reported a 24 percent (151 to 188 mmHg) increase in recovery systolic blood pressure when wearing a respirator compared to not wearing a respirator. This multitude of reported responses raises serious questions concerning the effect of a respirator on the cardiovascular system. Unfortunately only further investigation of the problem can provide more definitive results.

thermoregulatory responses

Heat stress has been a primary factor in the use of respirators in numerous working situations, e.g., mine rescue, fire fighting, and reactor repair. Therefore, it has been important to understand the effect of different types of respirators on the thermoregulatory responses and work capacities of the human. **Lind**[39] noted that subjects resting in cool conditions and breathing hot, moist air had no discomfort until the wet-bulb temperature **(WB)** of the inspired air reached 54.5 to 63°C and found breathing tolerable at **WB** temperatures of 59 to 65°C. These **WB** temperatures were reduced to 51.5 to 54.5°C during exercise. Also, if the humidity of the inspired air was very low, men could breathe in comfort at temperatures of $\leqslant$**104.5°C** during

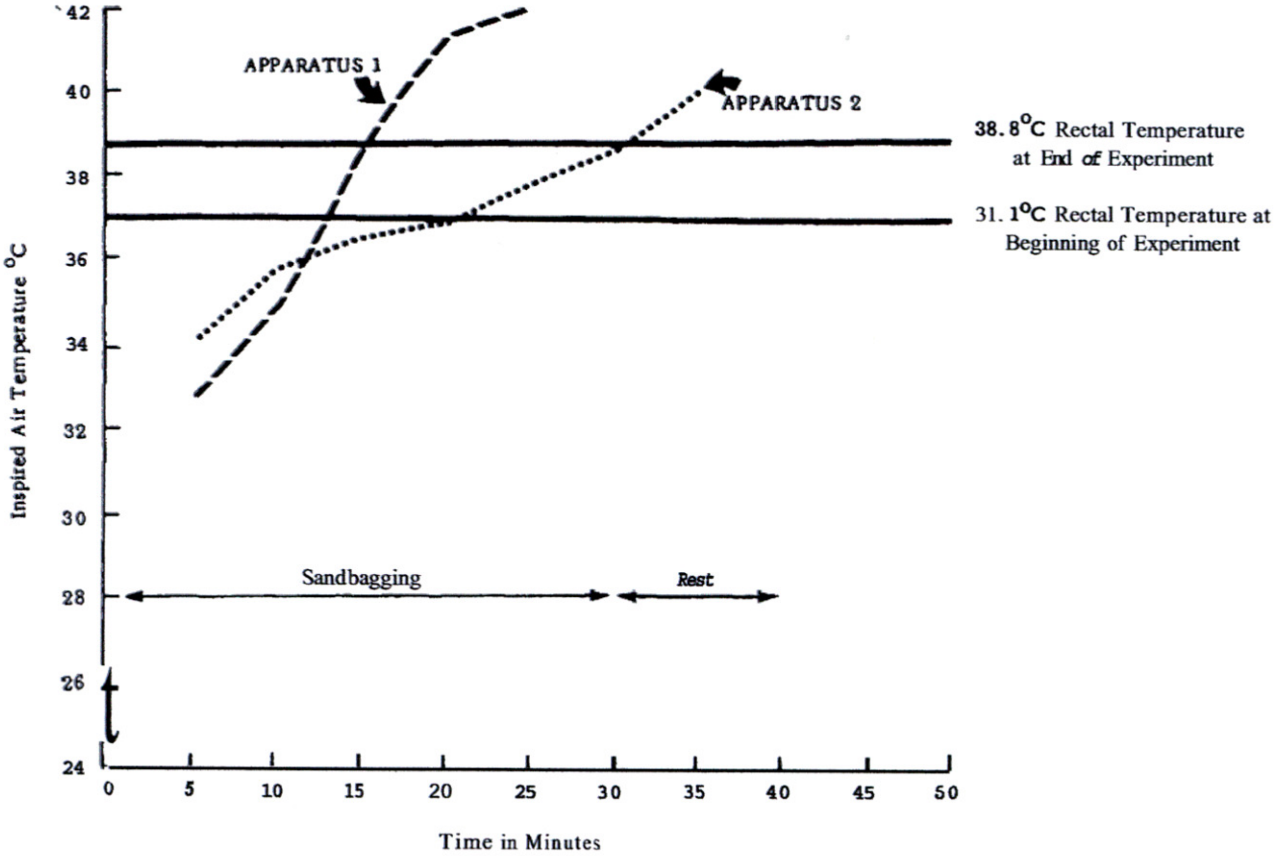
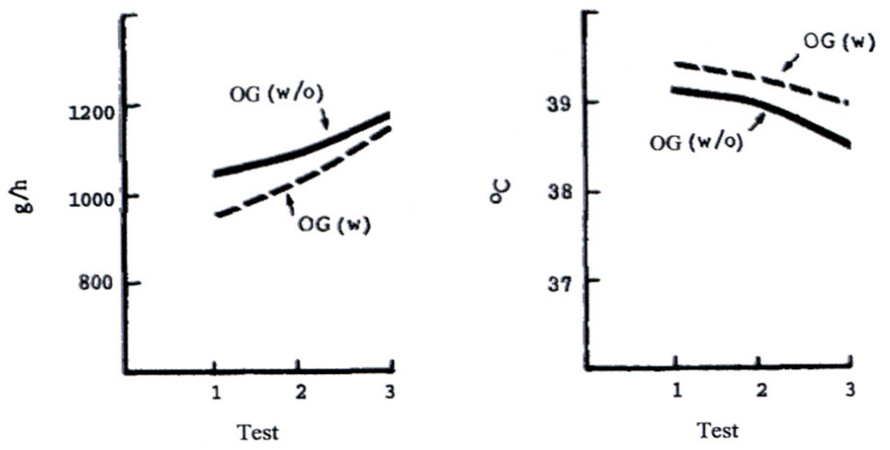


Figure 4 – Inspired air temperature and performance time for two different types of respirator while subjects performed a standard task.(39)

exercise. However, the **Lind**(39) experiments indicated that if the inspired air temperature became greater than the body temperature (T_{re}), the heat loss via the lungs was eliminated and, in fact, heat gain occurred. In these cases where the mass of the respirator was large, evaporative cooling from the trunk was diminished and, hence, the normally unimportant role of cooling by evaporation via the lungs became critical. Consequently, the tolerance time of a person wearing a respirator was significantly reduced when inspired air temperature was above body temperature; see Figure **4**. Laverne and **Leyh**(40) later confirmed the Lind findings in their comparison of open-circuit and closed-circuit respirators (Draeger, Arencheon, Fenzy and Air Magic). The apparatus that subjects preferred under heavy workloads and heat stress was that which provided the lowest inspired air temperature and subsequently reduced body temperature.

De V Martin and Callaway(41) evaluated the effect of wearing a full-face mask type respirator (the **UK** NBCS6) and found that the heat stress **(DB/WB 34/25.5°C)** on the subject was significantly elevated regardless of the degree of heat acclimatization; see Figure **5**. The heat stress was indicated by an increase in sweating rate, rectal temperature, heart rate, and skin temperature during a light workload **(200-300** Kcal min). Recent investigations(14,15,42) concerning the energy cost and heart rate response to working in protective clothing and wearing breathing apparatus indicated that both responses to a given submaximal workload increased; these increases were directly related to the weight of the apparatus. Hence, maximal workloads would be significantly reduced. Significant increases in body temperature were noted for the same workload performed without the apparatus and protective **clothing.**(15)

The modern-day, open-circuit SCBA produced a significant surface cooling of the **face.**(16) As the workload increased, inspired ventilation volumes increased and, consequently, the temperature of the air supplied from the air bottle decreased. As the inspired air was


(a) Sweat Rate

(b) Rectal Temperature

(c) Epigastric Skin Temperature

(d) Heart Rate

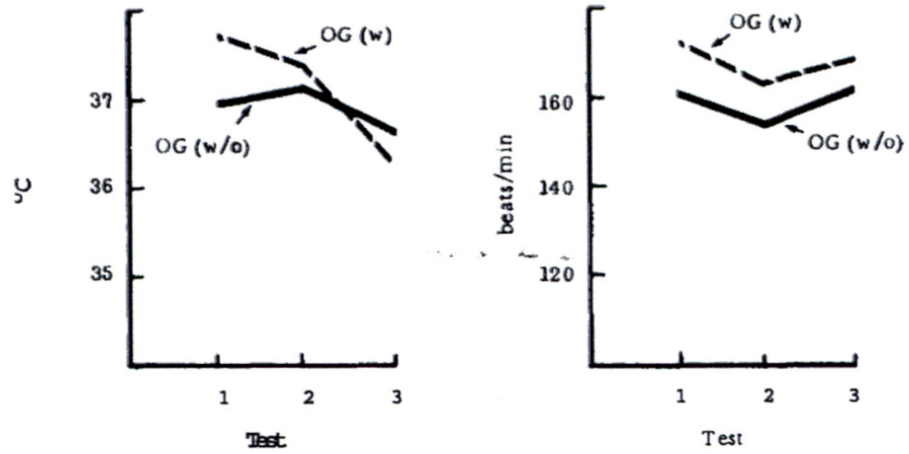


Figure 5 – Progressive heat acclimation responses within 3 weeks of testing (tests 1-3). OG (w) = Chemical overgarment plus NBC S6 respirator (----) and OG (w/o) = Chemical overgarment without NBC S6 respirator (—)— Modified from reference no. 41.

circulated within the face mask, the cooler air, a maximum of 19° C cooler than the forehead, caused a 2.5° C drop in forehead temperature. Thus, it seemed as if the increased body temperatures reported earlier(15) were a consequence of wearing the protective clothing, and not the type of respirator. Emerson *et al.*(43) also demonstrated that certain surgical masks caused as much as a 5° C rise in face temperature along with a 16 percent increase in relative humidity. Such conditions have been related to subjective fatique and an increased number of mental errors. Hence, it would appear that keeping the head and face cool during work with a respirator would prove beneficial both physically and psychologically.

psychological considerations

Physical and physiological measurements have been related to a wide variety of subjective psychological assessments of operator tolerance to increased respiratory resistance. **Cooper**(23) succinctly outlined one of the major problems of this form of subjective rating: ". . . a man who knows that he will not see his wife and family again unless he wears a respirator will tolerate much more resistance than, say, a miner who is told that if he wears a dust filter on every shift for the next 10 or 20 years, his chances of developing pneumoconiosis will be reduced." **Cotes**(25) observed on the 1953 British Mount Everest Expedition that the inspired valve opening pressure produced a large degree of subjective discomfort, especially if the valve was wet. **Shephard**(26) noted that all physiological problems were relatively minor compared to the summed psychological response to a feeling of "claustrophobia" and a variety of discomforts such as sweat accumulation and skin surface pressure.

Senneck(44) was primarily the leader in attempting to quantify the physiological effect of increased respiratory work in an objective manner. Reviewing earlier **data**,(39) he suggested a four-point rating of the subjective feelings: 1. unnoticed, 2. light, 3. moderate, and **4.** heavy with further subqualification. In reviewing Silverman's **work**,(2–4) **Sennek**(44) showed that from a plot of external respiratory work rate against minute volume, the point of little effect on the ability of man to work hard was satisfied when the respiratory work was below a curve which:

1. Divided the unnoticed from the noticed responses
2. Passed through 6.0 kg·m/min at 50 L (a point at which Silverman said that a large majority of his subjects thought the conditions were satisfactory)
3. Passed below Silverman's other points (13.3 kg·m/min at **64.4** L and 28 kg·m/min at 90.3 L)

This curve had the empirical formula:

$$W = 0.14\,M/10 + (M/10)^2 + 1.0\,(M/10)^3 \text{ kg·m/min}$$

Where W = total external respiratory work rate

M = minute volume in liters.

Generalized, this formula becomes:

$$W = 0.14\,(M)$$

Further **deductions**(44) from the data derived by Silverman, who observed that expiratory resistance was less well tolerated than inspiratory and should always be smaller, led to the conclusion that neither the inspiratory nor the expiratory work performed by the wearer should exceed:

$$W = 0.07\,(M/10) + (M/10)^2 + 0.1\,(M/10)^3 \text{ kg·m/min}$$

TABLE VI
Values for n and k for Experimental Resistances*

Inhalation Resistance No.	n	k	Airflow Range (Liters/min)
1	1.64	2.0×10^{-3}	40-200
2	1.43	1.4×10^{-2}	35-200
3	1.36	2.5×10^{-2}	40-200
4	1.36	3.2×10^{-2}	40-200
5	1.26	6.0×10^{-2}	40-200
6	1.31	5.7×10^{-2}	40-200
7	1.35	5.2×10^{-2}	40-200
8	1.32	6.2×10^{-2}	35-200
9	1.20	1.2×10^{-1}	35-200
10	1.33	7.6×10^{-2}	40-200
	1.00	2.0×10^{-2}	10- 60
Exhalation	1.63	1.5×10^{-3}	60-100
Value	1.88	4.3×10^{-4}	100-200

*Data from reference no. 24

Psychophysiological evaluations have been used to determine areas of the face more sensitive to the **force**(45) from a respirator mask as well as to determine the influence of the respirator on some functions of the central nervous system.(18) During rest wearing the respirator produced an increase in the number of operator errors and the length of time needed to perform a simple task (the bourdon test). During recovery from exercise the number of operator errors and length of performance time increased above those observed at rest while wearing a respirator.

More recently, Bentley et *al.*,(24) using a "probit" analysis, evaluated the subjective responses of 158 mine rescue workers, aged 21 to **45** years, while respiring through 10 variable resistances (**4.0** to 35 cm H20 at 100 L/min flow) during 30 min exercise on a treadmill; see Table VI. During the exercise, minute volume, respiratory rate, and instantaneous pressure across the breathing resistance were obtained each minute. Mathematical derivations allowed the investigators to determine external respiratory work rate from measurements of peak pressure, minute volume, and time of inspiration and expiration for sinusoidal, triangular and rectangular respiratory waveforms. Each man was asked to number rate his sensation from the apparatus on his breathing as: 1 = not noticeable; 2 = noticeable, but not difficult; 3 = difficult; **4** = very difficult. Intermediate answers were also rated as 1/2 or 2/3, etc. The investigators concluded that excessive inspiratory pressure was a major factor in determining subjective tolerance. They also

TABLE VII
Subjective Comments Reported as Reasons for Termination of Exercise.

Comments	Conditions			
	1	2	3	4
Leg pain	11	14	8	7
General fatigue	4	1	2	4
Lack of air			8	
Claustrophobia			4	4
Hot mask			1	1
Expired resistance high				1
Dry throat				1
Total	15	15	23	18

'Data from reference no. 16

suggested that 90 percent of a population breathing through apparatus with low-resistance expiratory values should experience no discomfort if the pressure across the apparatus did not exceed 17cm H_2O, which was equivalent to an inspiratory work rate of **0.14** kg·m/L. This value also has been confirmed for men over the age of **45.**[*]

Raven ***et al.***(16) have documented subjective responses of 15 subjects working to maximal capacity on a treadmill while using a SCBA. The subjects exercised without the SCBA (condition 1), with the weight of the SCBA (condition 2), with the weight plus the SCBA in "demand" breathing mode (condition 3), and with the SCBA in "pressure demand" breathing mode (condition **4).** Table VII summarizes the results from this investigation. In conditions 1 and 2, leg pains and general fatigue were the reasons for ending work. However, in conditions 3 and **4,** additional complaints were: lack of air, claustrophobia, and excessive heat.

Hence, it is apparent that subject comfort is an important factor in wearing a respirator, and it is important that psychological correlates (i.e., anxiety, depression, compulsion) are evaluated in relation to the ability of a person to wear a respirator under stress. **As** yet, the physician is unable to discern the psychological traits bes suited to the use of a respirator in critica situations. Without such screening, person psychologically unsuited to wearing respirator may be in situations in which they become . danger to themselves and others.

conclusion

It becomes readily apparent from the foregoin review that specific areas of physiologica concern have received a major proportion of th investigative effort. For example, the ventilator adaptations as a consequence of breathin against an increased inspiratory and/o expiratory resistance have been investigate repeatedly in terms of **mechanism.**(1-4,11-13,18-2 24,27-30,34-37) While other concerns o psychophysiological effects,(16,18,24,43-4 thermoregulatory changes,(39-41) and cardic vascular adjustments(16,21,26) have received onl moderate attention, undoubtedly thi concentration of effort is a consequence of th realization that the primary load of a respiratc is placed on the human respiratory system. Th sum total of these investigations is the fact that man is challenged by an inhibition to respirator air flow (the increase in resistance to breathing he attempts to reduce the total respirator workload by reducing exhalation time to minimum.(12,29) The result of this behavior is tha lung ventilation is impaired; and during heav work, exhaustion occurs earlier, i.e., at the poir of minimum efficient exhalation time (≃ 0.6 sec). These recent findings are not i contradiction with those of Silverman ***et al.***(2- or of **Cooper;**(7,8) they are only a refinement. Th work of Bentley ***et al.,***(24) reported in 197 suggests that 90 percent of a normal populatio will not be affected subjectively if the tots expiratory work permissible is less than **0.1** kg·m/L. This value is somewhat higher tha those of **Silverman**(3) and **Sennek,**(44) but lowe than that of **Cooper.**(5,23)

The primary problem encountered in definin the acceptable resistance for the assessment c respiratory work is related to the use of a fixe flow calibration and the waveform of the outpu airflow through the pump. Both Bentley ***et al.***(2 and Johnson ***et al.***(12,29) have provide sophisticated calculations of waveform and hav confirmed the work of Silverman ***et al.***(4) an

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[*] **Communication with Dr. D.C.F. Muir at Safety in Mines Research Establishment, Department of Trade and Industry, Sheffield, England. Data obtained from an article in preparation by Love, R.G., C.D.F. Muir, K.F. Sweetland, R.A. Bentley, and O.G. Griffin: *Acceptable Levels for the Breathing Resistance of Respiratory Apparatus: Results for Men Over the Age of 45.***

Cooper.(5) Cooper(5) in particular has reported that the respiratory waveform during work tends toward rectangularity, which he describes as a flattened sine-wave. Bentley et *al.*(24) calculated an average shape factor (peak inspiratory flow per minute) of 2.7, a value similar to that reported by Silverman et *al.*(4)

The regulatory standard using a fixed flow of 85 L/min (based on the assumption that 85 L/min represents the maximum average flow rate into or out of the lung during 30 minutes of sustained work) with an average minute volume of 42.5 L/min calculates to a mean shape factor of 2.0. This factor is 35 percent different than that reported elsewhere.(4,5,12,24,29) In addition, the standard test assumes linearity of the resistance to flow relationship; yet, it is obvious that this relationship is not valid for either the uninhibited human respiratory system,(26,31) nor for the many individual types of respirators.(24) Hence, a primary challenge to the respirator engineer is to develop a dynamic calibration system capable of producing a flattened sine-wave flow with a shape factor of 2.7 for peak flow rates between a minimum of 30 L/min and a maximum of 400 L/min. Throughout this range the respiratory work rate should not exceed 0.17 kg·m/L.

The physiological challenge is to determine the airflow shape factor of various man-respirator interfaces during the course of heavy work. Previous investigations(2-4,24) have documented only the airflow wave-form for relatively low minute volumes of ventilation (40 to 60 L/min). The shape factor related to high minute volumes (80 to 120 L/min) and peak inspiratory flows (720 L/min) of heavy work needs to be evaluated. If significant changes in shape occur, then the suggested pump design will require modification to include calibrated determinations at those levels of respiratory work.

During the course of previous investigations reviewed herein, various physiological responses have been suggested as important in the determination of work efficiency during respirator wearing. These responses include increased oxygen debt and deficit which suggest a shift to anaerobic metabolism(4,18,19) and increased cardiovascular stress as measured by recovery blood pressure and heart rate."")

However, cardiovascular responses during recent investigations(16,21) have not realized any moments of distress in relatively fit normal subjects, while investigations into the metabolic alterations have been limited to measurements of lactate.(16) In terms of physiological interest the idea of increased anaerobic metabolism needs to be investigated. In addition, the quantification of cardiac load by measurement of cardiac output and thereby cardiac work in relation to changes in intrapulmonic pressure would prove of value to the investigations concerning cardiovascularly impaired workers.

Of prime importance to the industrial physician is the need to evaluate subjects with pulmonary and cardiovascular disorders which may prove detrimental to their health and safety or to that of other workers if they are required to wear a respirator. Many questions about such disorders have not been evaluated at this time; yet, many cardiopulmonary diseased persons wear a respirator while working. The gradation of pulmonary impairment throughout the national work force ranges from mild extrinsic asthma through chronic emphysema and stage 2 pneumoconiosis. Only one investigation, unpublished as yet,' has attempted to evaluate the effects of respirator use on a pulmonary-impaired subject. While wearing a respirator, arterial desaturation at the same workload was greater in one subject with stage 2 pneumoconiosis than in a subject with stage 1 pneumoconiosis and/or when he himself was working without a respirator. The subject with stage, 1 pneumoconiosis was unaffected by respirator use. This example points out the needed shift in emphasis for future investigations. Assuming that manufacturers maintain design criteria and standards, a large-scale effort is required to determine the effects that various respirators produce on those subjects affected with various gradations of pulmonary disorders. Such impairments may not be debilitating in themselves, but may prove to be critical if in a worst-case situation. In addition, it would be beneficial to devise a simple screening test or tests of cardiopulmonary disorders which would determine individual capability to wear a specific respirator for a specific job.

Finally, a major area of concern is the subjective effect that each specific respirator has on each individual, but has received only cursory investigation.(24,43-45) In addition, the psychological correlates of an individual with respect to his ability to wear a respirator under stress' has received no attention. Hence, the industrial physician is faced with a dearth of information concerning the psychological make-up required for efficient performance in a respirator. Subjective comfort, in terms of respiratory work rate, provides the most used criteria for establishing standards(5,24,44) to be met by design engineers, but a more systematic scientific investigation of the psychophysiology of respirator wearing is required.

These conclusions are outlined in priority order.

1. The development of a physiologically sound, medical-screening examination for the industrial physician to use in determining the capability of a worker to use a respirator. This examination should emphasize both the pulmonary and the cardiovascular aspects of respirator use. Implicit within these recommendations is the understanding that subclassifications for specific respirators are required for those individuals with slight impairments who may never be asked to perform critically stressful work with a respirator.
2. The development of a simple psychological inventory for determining individual suitability to wearing a respirator. Critical questions are:
    a. What psychological correlates (anxiety, depression, etc.) relate to successful wearing of a respirator?
    b. Will training in the use and wearing of a respirator affect the attitude of the individual? If so, how much training is required?
    c. What psychophysiological parameters are involved in the subjective assessment of comfort?
3. Further investigations into respirator use and its effect on blood pressure and cardiac work. Specifically, populations of labile hypertense, essential hypertense, and borderline hypertense individuals (both medicated and nonmedicated) need to be evaluated with respect to various levels of respiratory work rate.
4. The development of a dynamic flow-resistance calibration device as outlined. In addition, the respiratory flow pattern of the human during high intensity work needs to be documented as a basis for possible modification of the existing standards and for the calibration pump.
5. Further investigation of the shifts in metabolic pathways for energy production, i.e., from aerobic to anaerobic. If metabolic process changes are involved, then investigations into nondebilitating metabolic diseases, such as diabetes mellitus, needs to be continued.
6. An evaluation of all respiratory devices for aspects of thermal comfort, especially if utilized in hot environments. This effort may result in the establishment of a standard concerning the temperature of the inspired air during prolonged use.

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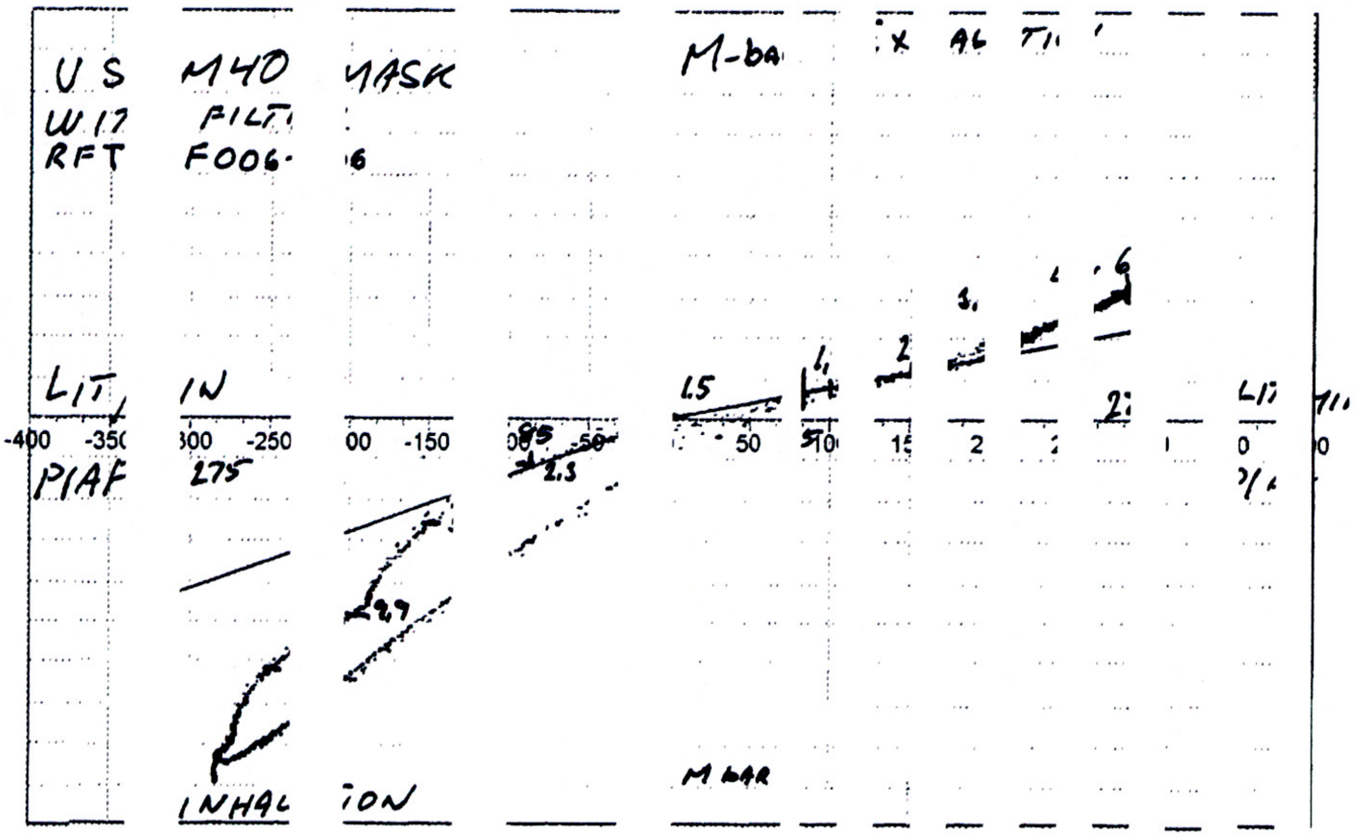
Breath Curve



Physiological Criteria for the Valid Selection of Workers Who Must Perform Physical Tasks While Wearing Protective Equipment

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The study of human physiological responses to work and environmental stresses represents a scientific discipline that has achieved a remarkable level of maturity since the pioneering days of the Harvard Fatigue Laboratory[1]. The scientists gathered there during the years from 1928 through 1945 established many of the principles which continue to guide physiologists in accurately describing physiological requirements imposed by increasing levels of physical activity or work, and those principles are inviolate. The laws of physics which describe the exact amount of energy required to lift a given weight to a given height are the same as those used to calculate the metabolic cost of performing a specific amount of muscular work. It is possible, but very technically demanding, to determine the amount of calories expended by man during varying levels of physical activity. On the other hand, it is relatively easy to measure caloric expenditure indirectly by measuring the amount of oxygen consumed during the performance of that task. The rationale being that since fuel must be oxidized to liberate the energy required to perform physical work, measuring the oxygen uptake during a task is tantamount to measuring the calories of energy liberated by the oxidative process. For example, in the human organism there are only two fuel sources for the liberation of energy: carbohydrate and fat. It has been clearly determined that every liter of oxygen consumed liberates 4.69 to 5.05 kilocalories of energy when burning fat or carbohydrate, respectively.

Therefore, from a measure of the oxygen consumed by an individual engaged in a steady bout of exercise, the caloric requirement of that work can be calculated and it is generally described as kcal./hr. This measurement of the energy requirement of an individual performing a given task is called "indirect calorimetry" and it is achieved by collecting his/her expired air for a given period of time and measuring and analyzing that air for O_2 and CO_2. Since the composition of fresh outside air is exactly 20.93% O_2 and 0.03% CO_2. and the balance predominantly N_2, knowledge of their concentrations in the expired air is all that is required to determine both the volume of O_2 consumed and the volume of CO_2 produced. Accompanying these important measures of O_2 consumption are measures of minute ventilation (V_E) and tidal volume (TV), both of which are particularly useful to the engineer designing a respiratory protection device for a particular task or career field. However, problems can result when the engineer accepts the

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[1] Horvath, S.M and E.C. Horvath. The Harvard Fatigue Laboratory, Its History and Contributions. Englewood Cliffs. Prentice-Hall, 1973.

physiologist's report on face value and then proceeds with equipment designs that consider most, but not all of the important physiological variables that may significantly impact user acceptability.

The energy and the ventilatory costs of a given activity are not only important to the engineer in the design of protective equipment, but also to the employer in the selection of personnel who are physically capable of performing the task. The physiological principles which are most helpful in describing human responses to work and environmental stresses include the following the relationships between:

1. Energy cost and oxygen consumption (VO_2).
2. VO_2 required for the task and an individual's maximum capacity for consuming oxygen (VO_2 max).
3. VO_2 and heart rate (HR).
4. VO_2 and ventilation ($V_{E)}$.
4. V_E and peak inspiratory flow rate.

Although these physiological relationships were well-established by the end of the 1930's, their contribution to the proper design of protective equipment was less than a complete success by the time World War I1 required the issuance of a gas mask for all personnel subject to combat. Dr. Steve Horvath' recalls his experiences in North Africa where he **said** that one could follow American troop movements by the gas masks that they had discarded along the way. Problem: a combination of heat stress and inspiratory resistance. A considerable effort was undertaken to improve the human acceptability of military respiratory protective devices, and this occurred along with the growing awareness of the need to protect the civilian worker from certain hostile environments as well. Silverman <u>et</u> **<u>al</u>**.[3] were among the first to systematically study the physiological parameters that needed to be considered in the design of respirators. Summarizing their work several years later in 1951 these investigators explained: "This investigation was made during the recent war in order to determine the air flow characteristics of human subjects."[4]

During this period between 1944 and 1951, Silverman <u>et</u> **<u>al</u>**.[4] reported the results of a series of experiments in which they determined a variety of physiological responses to graded intensities of physical exercise. Their findings that both oxygen consumption and heart rate increased in almost direct proportion to the increase in physical work load were not new since this had been well established by Harvard Fatigue Laboratory scientists as early as 1928. However, Silverman's group added a critically important

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[2] Horvath, S.M.,(Personal Communications).

[3] Silverman, L., *G.* Lee, T. Plotkin, L. Amory, and A.R. Yancey. Fundamental factors in design of protective equipment. <u>O.S.R.D. Report No. 5732</u>, April 1945.

[4] Silverman, L., *G.* Lee. T. Plotkin, L.A. Sawyers, and A.R. Yancey. Air flow measurements on human subjects with and without respiratory resistance at several work rates. <u>A.M.A. Arch. Indust. Hye. and Occup. Med.</u> 3:461-478. 1951.

measurement to their experiments -- peak inspiratory flow rate. Utilizing technology described by Fleisch[5] in 1925, these investigators were among the first to point out the importance of considering peak inspiratory flow rate as opposed to simply minute ventilation requirements when evaluating respirators intended for use by man during a variety of working conditions. The respirator engineer can devise a filter or a seal that will absolutely protect one from airborne hazards, but the end product must also support selected physiological parameters if it is to be tolerated by the wearer. Silverman's data showing the relationship between peak flow rates and minute volume have become classic in the field, and they continue to serve as an authoritative reference for those responsible for the certification of specific respiratory protection devices for specific applications. However, valuable as they may be, these early papers by Silverman et al. are not without controversy. It seems likely that these investigators may have made some errors in their original measurements, and it is certainly evident that others have made errors in interpreting their data. Nevertheless, those errors have been incorporated in the guides utilized by both industry and government regulating agencies in the U.S., and they have been manifest in the development of what may be called "questionable" criteria for the certification of respiratory protection devices since the 1970's. To summarize this important work, Silverman et al.[4] measured respiratory responses of normal and athletic men to graded exercise, with and without imposed respiratory resistance. They correctly measured both minute volume and peak flow rates, and reported them as follows:

		Cycle Exercise, Kg meters/min							
	Rest	0	208	415	622	830	1107	1384	1660
VO_2, ml/min	306	496	800	1176	1545	2075	2723	3114	3413
V_E l/min 10.3	14.2	20.8	29.9	37.3	54.7	75.3	104.0	113.8	
Peak Flow. l/min	40	49	63	84	100	149	194	254	286

These investigators also measured the pressure drop required to draw air through a military mask (filter) at a steady rate of 85 l/min which they reported as 2.5" H_2O and 1.6" H20 for inspiratory and expiratory resistance, respectively. The reason for the decision to select 85 l/min as the flow rate for measuring resistance in these experiments remains obscure, but it may have represented what was thought to be the typical or average air flow exhibited by man at work. For example, these investigators noted that previous researched reported that subjects could not maintain a steady state in cycle exercise requiring an oxygen consumption of more than 2000 ml/min. However, Silverman et al.[4] reasoned that this limitation could only apply to subjects in poor condition because the majority of their subjects were able to achieve a steady state at a work rate of 1107 kgm/min (VO_2 = 2723 ml/min), although few of their subjects could perform at rates above 1107 kgm/ min. Since men normally will not work at a pace exceeding 45% of their capacity for an 8-hour shift, the selection of 85 l/min flow rate describes work at what may have been thought to be

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[5] **Fleisch, A. Der Pneumotachograph: Ein Apparat zur Geschwindigkeitsregistrierungder Atemluft. Arch. ges. Physiol. 209:713-722, 1925.**

[6] **Bock. A.V., C. Vancaulaert, D.B. Dill, A. Folling, and L. M Hurxthal. Studies in muscular activity: IV. The "steady state" and the respiratory quotient during work. J. Physiol. 66:162-174. 1928.**

adequate for the average man performing an occupational (physical) task. In any case, whatever the reason, the selection a steady flow rate of 85 l/min for testing respirator resistance was unfortunate. It conveniently filled the requirement for government agencies who were struggling to determine valid criteria for testing and certifying respiratory devices, and it provided industry with a goal that would assure government certification. It did not adequately represent the respiratory needs of many of the workers who might prefer the risk imposed by the toxicants rather than wear the protective device and try to work against a seemingly suffocating resistance to respiration.

It is also interesting to note that this seemingly gross underestimate of the respiratory requirements of working man was supported by the work of later researchers, examples of which are the following:

1. An activity requiring a ventilatory rate of 40 l/min is classified as "heavy work"[7].
2. Typical peak flow rate for "hard work" would be 129.6 l/min[8]

It is particularly discouraging to note that the latter paper was published in 1997!

In the United States, every commercially available 30-minute self-contained breathing apparatus (SCBA) must be approved by the Mine Safety and Health Administration (MSHA) and by the National Institute for Occupational Health (NIOSH). Standards selected as criteria for certification include the following:

Mine Safety and Health Administration
Title 30 - Mineral Resources

Part 11 - Respiratory Protective Devices; Tests for Permissibility; Fees

Subpart H - Self-contained Breathing Apparatus

11.85-3 Breathing bag test.

(c) A breathing machine cam with a work rate of 622 kg.-m/min will be used.

11.85-5 Breathing resistance test; inhalation.

(a) Resistance to inhalation air flow will be measured in the facepiece...with 24 respirations per minute and a minute-volume of 40 liters.

(b) The inhalation resistance of open-circuit apparatus shall not exceed 32 mm (1.25 inch) water column height (at a flow rate of 120 liters per minute).

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[7] Pritchard, J.S. A Guide to Industrial Respiratory Protection. Dept. of Health, Education and Welfare. DHEW (NIOSH) Publication No. 76.189.

[8] Crutchfield, C.D. and D.L. Park. Effect of leak location on measured respirator tit. Am. Indust. Hyg. Assoc. J. 58:413-417, 1997.

11.85-10 Service time test; open-circuit apparatus.

(b) "...according to the length of time it supplies air or oxygen to the breathing machine.

11.85-12 Test for carbon dioxide in inspired gas; open- and closed-circuit apparatus; maximum allowable limits.

Service Time	Maximum Allowable CO_2
< 30 minutes	2.5%
1 hour	2.0%
2 hours	1.5%
3 hours	1.0%
4 hours	1.0%

It is obvious that the work of Silverman et al.[4] has had a major impact on the decision making process of U.S. government regulating agencies. Valuable as the work of these investigators has been to the field of respiratory protection, the apparent misinterpretation of this work in the U.S. has been the source of critical errors in establishing certification criteria for respirators. Examples include the following:

1. Resistance to inspiration observed when tested at a constant flow rate of 85-120 l/min may be used to approve an SCBA that was destined for use by a postman carrying a bag while walking to deliver mail, but it severely underestimates the respiratory distress imposed on the fire fighter who must be expected to work at levels requiring inspiratory flow rates higher than 300 l/min[9].

2. Certification of a 30-minute SCBA based on the criterion of timed air supply tested at a flow rate of 40 l/min (i.e., supposedly representing "hard physical work") can be seriously misleading for the firefighter who may be expected to work at levels requiring a ventilation rate exceeding 100 l/min[9,10].

3. The selection 27 l/min as an adequate air supply into an escape capsule has been found to underestimate by more than 140% the actual physiological requirements during a simulated escape activity".

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[9] Myhre. L.G., R.D. Holden. F.W. Baumgardner, and D. Tucker. Physiological Limits of Firefighters U.S. Air Force Technical Report ESL-TR-79-06, June, 1979.

[10] Myhre. L.G., D.M. Tucker, D.H. Bauer, J.R. Fischer, W.H. Grimm, C.R. Tattersfield, W.T. Wells. Study of the Relationship Between Selected Measures of Physical Fitness and Performance of a Simulated Fire Fighting Emergency Task. U.S. Air Force Technical Report AL/CF-TR-1996-0143, January, 1997.

"Myhre, L.G. Field Study Determinations of Ventilatory Requirements of Men Rapidly Evacuating a Space Launch Complex. U.S. Air Force Technical Report TR-80-43, November, 1980.

4. An escape capsule which meets certification requirements for the quality of inspired air (i.e., % O_2 and CO_2) may prove to be dangerously inadequate in a real-world situation".

5. The development of certification criteria based on statistical data from human experimentation, but approved for use in the general work force, cannot be justified[9,10,11].

To be sure, the responsibility for safety in the work place cannot be laid solely on the provision of adequate protective equipment. The individual worker represents what is perhaps the greatest single factor in the safe and successful performance of an occupational task. The employment of valid selection criteria for entry-level hiring must remain the responsibility of industry and government regulating agencies alike. However, the responsibility for the maintenance of health and physical capability to perform must at least be shared by the worker. It is now possible to safely and cost-effectively determine each worker's physical capacity for work[12,13], and to utilize that information in the selection/retention of those employed in a wide variety of physically demanding occupations. Indeed, the payoff in requiring appropriate physical qualifications for the worker is often more than double that which can be provided by protective equipment. Information obtained from such practical physical assessments not only assures the optimal selection of individuals for specific career fields, but even more importantly, the information provided to the worker -- at regular intervals throughout his/her career -- can become the most powerful tool in motivating appropriate changes in lifestyle that will offer the greatest potential for both safe and successful employment.

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[12] **Myhre, L.G., G.R.Van Kirk, and W. Grimm. Physical fitness status of USAF fire fighters. U.S. Air Force Technical Report ESL-TR-86-05, September 1986.**

[13] **Myhre, L.G. Validity of sub-maximal cycle ergometry for estimating aerobic capacity. (In press).**

Am. Ind. Hyg. Assoc. J. 44(5):336-340 (1983)

Do Pressure-Demand Breathing Systems Safeguard Against Inward Leakage?

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Rescue operations conducted in toxic atmospheres require respiratory protective equipment capable of providing a very high degree of protection. A slight positive pressure in the facepiece throughout the breathing cycle is used in the **pressure-demand**, compressed-air **breathing** apparatus to eliminate any inward leakage. In the present work an inward leakage test with sulphur **hexafluoride** (SF_6) was used to measure facepiece penetration in a pressure-demand system at different work loads. During the test, **inspiratory-flow** pressure variations within the facepiece and heart rate **were also** measured. Tests were performed on a dummy head and on two subjects. In some tests a poor face **seal** was introduced by putting an **open** tubing with an inner diameter of 2 mm **and** outer diameter of 3 mm under the sealing edge of the mask. It was found that inward leakage was less than 0.0001% under **all** conditions **as** long **as** facepiece pressure **was** positive. When facepiece pressure fell below zero, which occurred at inhalation peak flows about *300* **L/min,** an inward **leakage** was detected. One subject achieved, at extreme work **load,** an inhalation peak flow around **450 L/min. These** results show that pressure-demand systems should be tested with a breathing machine giving peak flows of at least *300* **L/min** to ascertain the capability of these systems to maintain positive pressure in the facepiece during hard rescue work.

Introduction

The modern world is full of situations in which workers run the risk of being exposed to a hazardous environment. Sudden outbursts of toxic gases in a fire, at a chemical plant, from a leaking tank or a hidden depot of used chemicals necessitate immediate action. The protective equipment which the men or women performing the job use, must be thoroughly reliable. One of the main requirements is that any toxic materials in the air breathed by the wearer, must be kept well below their TLVs® (threshold limit values). Thus the supplied air must be free from toxic materials and the inward leakage must be minimized.

In a breathing apparatus with an ordinary demand valve, nhalation creates a slight negative pressure in the facepiece. If at the same time, a leak occurs between face and facepiece, some ambient air is also inhaled unfiltered. **A** negative pressure in the facepiece and an inadequate seal are the two factors which are necessary to induce an inward leakage in an otherwise properly functioning apparatus.

Pressuredemand systems are based on the theory that no inward leakage can occur even in the event of a leak at the sealing edge. provided the system keeps the pressure within the facepiece positive throughout the breathing cycle. The main question is: is positive pressure in the facepiece sufficient to safeguard against inward leakage? (**No** inward leakage = a leakage rate below the minimal detectable with present technique).

The positive pressure within the facepiece of a pressure-demand system may be reduced when inhalation flow

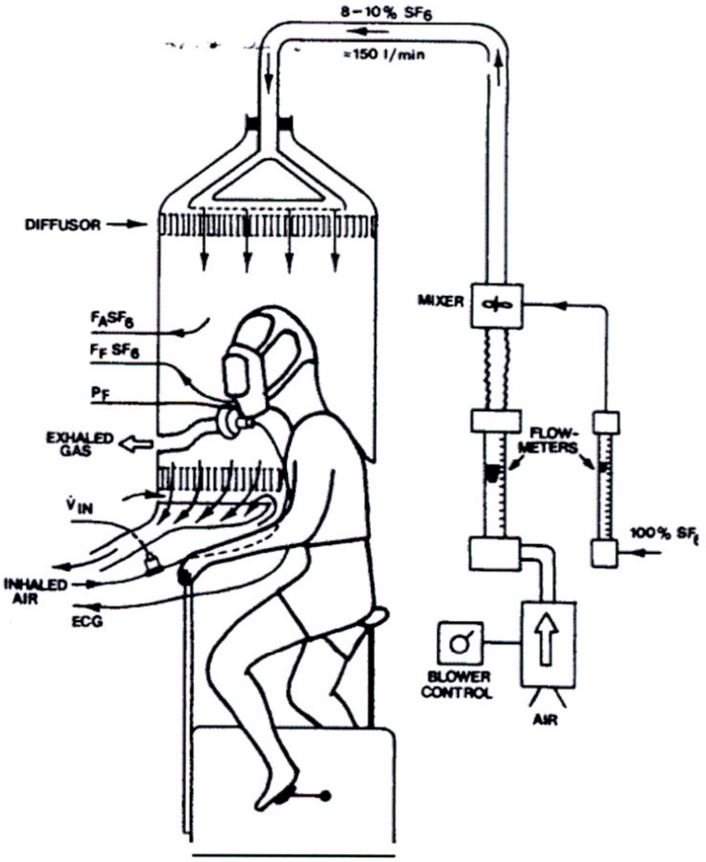

Figure 1 — Experimental set-up for inward leakage test with SF_6. For details see text, (F_ASF_6 = concentration of SF_6 in ambient air, F_FSF_6 = concentration of SF_6 in the facepiece during inhalation, P_F = pressure variations in the facepiece, $\dot{V}_{IN}$ = inhalation flow).

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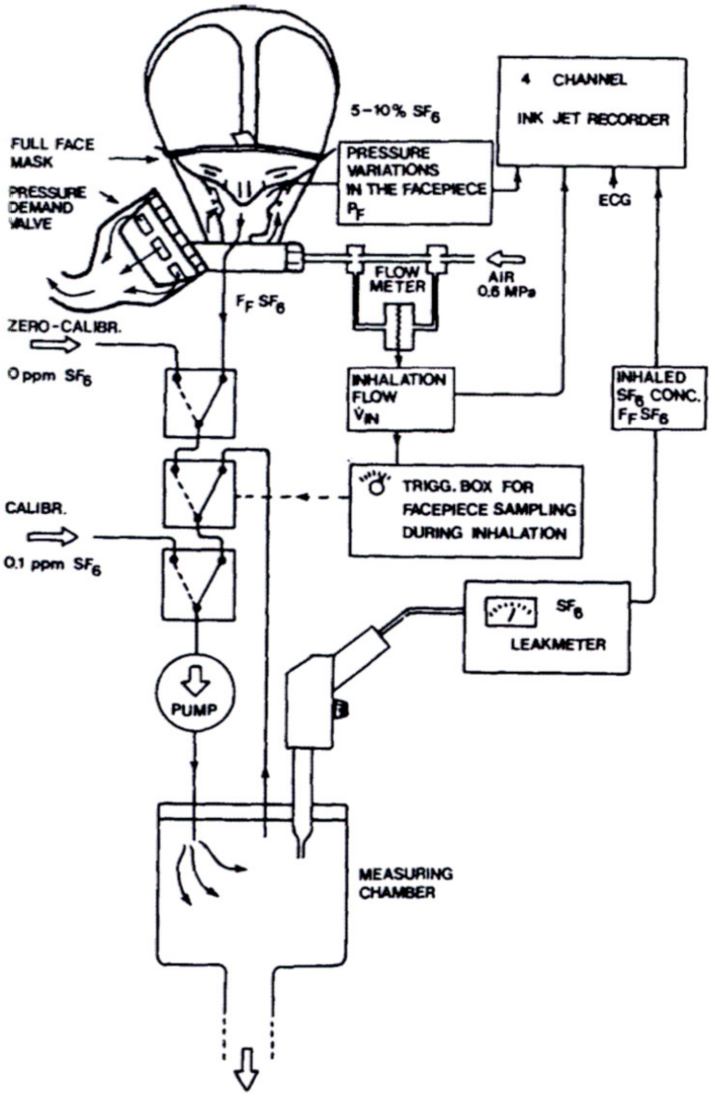

Figure 2 — Schematic drawing of leak detection system and the data sampling. For details see text.

increases due to the user's increased ventilation requirement during hard work. A second important question then is: what peak inhalation flows are required during hard work? Positive pressure must be sustained at a flow rate equal to or greater than the flow rate demanded by the user.

Materials and Methods

One frequently used method for measuring inward leakage is the DOP (dioctylphthalate) test. With this technique it is normally possible to detect leakage rates as low as 0.01%. Persson(1) has, however, presented a report in which leakage rates below 0.001% were measured with the DOP method. (Face seal leakage is defined(2) as the "inward leakage of ambient atmosphere, during inhalation, between the face and the facepiece, normally expressed as a percentage of total inhaled air". For a comprehensive review of inward leakage tests, see Balieu(3)).

In a gas cloud from a leaking chlorine tank, for example, the concentration of chlorine can exceed 10%. With a TLV for chlorine of 1 ppm, the respiratory protective equipment used in such an atmosphere must have a leakage rate less than 0.001%. In order to measure such a low inward leakage in this study, we used a sensitive gas, inward-leakage test. The gas used was sulphur hexafluoride (SF_6), which is an inert gas not present in ordinary air.

The Haupstelle fur Grubenrettungswesen in Hohenpeissenberg, Germany, has developed a practical technique for the SF_6 method, using a very sensitive leak detector, a so-called electron capture instrument.(4) We have modified this method somewhat, especially with regard to the removal of used gas and the sampling technique. Figure 1 shows the general experimental set-up.

The subject's head was surrounded by a plastic hood. At the top of the hood was a plastic foam diffusor which distributed the 10% SF_6 in an air mixture over the subject's head. In the lower portion of the hood, in front of the subject, there was also a plastic foam diffusor that kept the flow around the mask as uniform as possible. The rest of the hood was sealed to the subject's shoulders and back. Under the hood there was a nozzle through which the gas leaving the hood was aspirated and exhausted outside to keep the SF_6 level low in the laboratory. The flow rate of the suction device was about 500 L/min, which is well above the 150 L/min leaving the hood. The air supplied from the ambient atmosphere via a blower, and the SF_6 taken from the cylinder, were mixed after the flowmeters by rotating the gas with a small fan. The SF_6 concentration in the hood (F_ISF_6) was measured by taking several samples during the test. The exhaled gas was exhausted outside the hood via a hose.

During the test, four parameters were continuously recorded on an ink-jet recorder (Mingograph, Siemens-Elema, Solna, Sweden) as shown in Figure 2.

1. Inhalation flow ($\dot{V}_{IN}$) was measured via the static pressure drop over a distance of 10 cm, caused by the gas friction in the supply hose connected to the breathing valve, with a differential pressure transducer (Validyne DP9, Northridge, CA). This pressure drop was calibrated before each test to give inhalation flow by aspirating the breathing gas at different flows from the breathing valve through a mechanical flowmeter (Fischer & Porter GMBH, Goettingen, Germany).
2. Pressure variation in the facepiece (P_F) was measured with a differential pressure transducer (Validyne DP 103).
3. The ECG was recorded for calculating heart rate (HR), which was used as an indicator of the physical work performed by the subjects.
4. SF_6 was measured in the facepiece (F_FSF_6) with an electron capture instrument (AI leakmeter, AI Industrial, Cambridge, England). The leakmeter's concentration sensitivity is 1 in 10^9 and the response time is less than 1 sec. Since the probe is sensitive to pressure variations and because it was needed in order to check the calibration at any desired time during the test, a special sampling system was designed (see Figure 2). Three magnetic valves in series with a pump and a

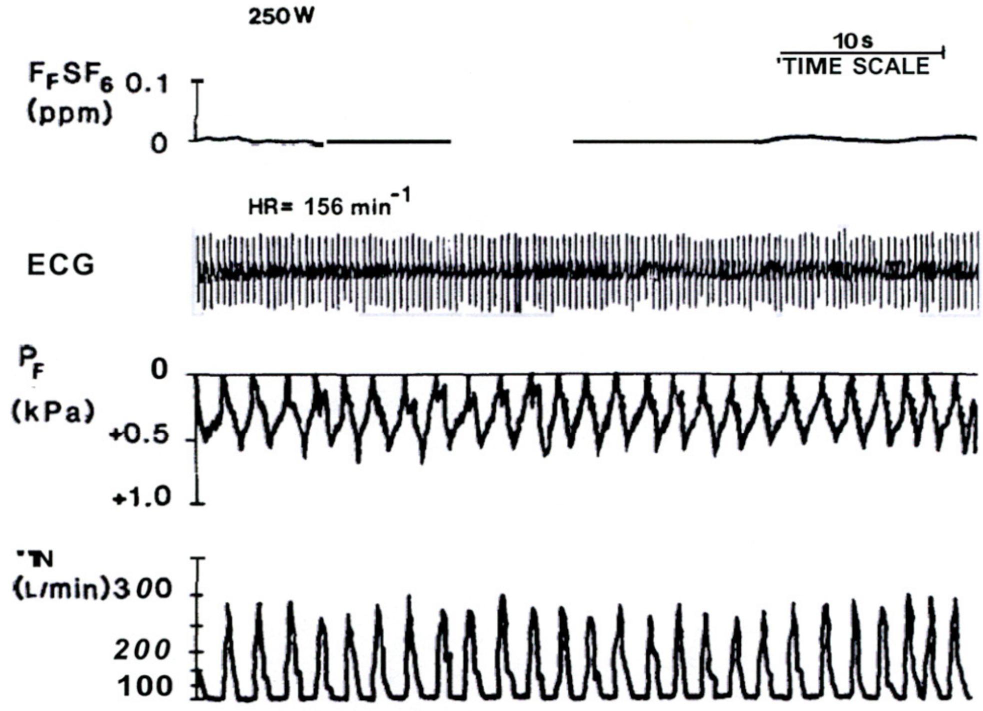

Figure 3 — Recording for subject **P.S.** at **250 W** (F_FSF_6 = concentration of SF_6 in the facepiece during inhalation, P_F = pressure variations in the facepiece, $\dot{V}_{IN}$ = inhalation **flow).**

measuring chamber were used. The first valve was used to connect the measuring chamber to clean air with zero ppm SF_6 and the third to connect a calibration gas containing **0.1** ppm SF_6 **to** the system. The middle valve was triggered via a control box by the inhalation **flow** so that the pump drew a sample from the facepiece only during the inhalation phase. Thus the recorded SF_6 concentration was the average facepiece concentration during inhalation. During the exhalation phase, the pump worked in a closed system, which improved the mixing of the sample taken during the inhalation phase.

The calibration was checked several times during the test. The **0.1** ppm SF_6 gas **(AGA** Specialgas, Lidingö, Sweden)

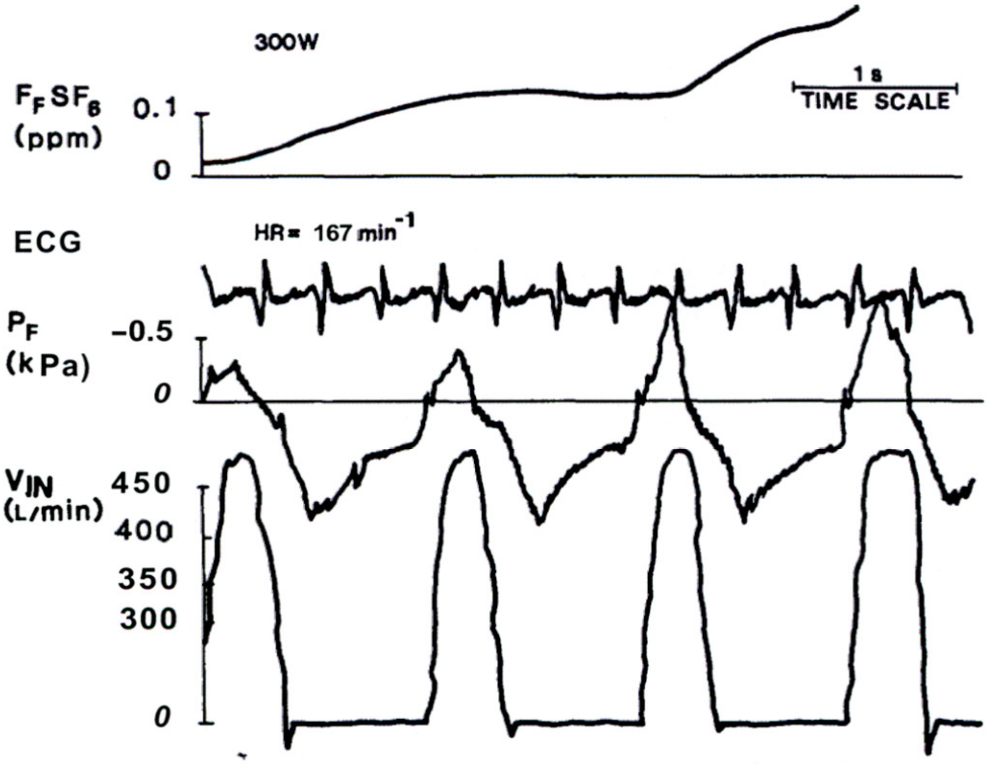

Figure **4** — Recording for subject **P.S.** at 300 **W** (For explanations of abbreviations, see Figure 3).

as an accuracy of ± 0.01 ppm. The resolution and accuracy f the ink-jet recorder allowed recordings of ± 0.01 ppm F_6, *i.e.* ± 10% of the concentration of the calibration gas. he ambient SF_6 concentration was measured with an absoute accuracy of ± 0.1% with a gas chromatograph. Thus n error analysis will show that if a concentration in the acepiece of 0.05 ppm SF_6 was recorded on the ink-jet ecorder, and the ambient SF_6 concentration was **10%**, the eakage rate would be 0.000 **05%** ± 0.000 01%. Thus it is ossible with this measuring technique to determine whether he leakage rate in less than **0.0001%**.

The first tests were done with a dummy head and a breahing machine. The ventilation was increased from 30 L/min o about 120 L/min. Since the volume changes of the breathng machine were almost sinusoidal, this corresponded to eak flows of 90 to 360 L/min.

The physiological testing was done using two well-trained ubjects, BS and PS, exercising on the bicycle ergometer (see igure 1). Their ages were 38 and 34 years, weights 86 and 77 g and heights were 1.93 and 1.84 m, respectively. The load n the ergometer was increased from 0.0 W (Watt) up to xhaustion in steps of **50** W with **4** min at each load (Watt W) is the metric-unit for power; 1 W □ 6.1 kpm/min). Two xperimental situations were tested; the first in which the nask was worn in the normal manner and the second in vhich a plastic tube (inner diameter 2 mm and outer liameter 3 mm) was placed under the chin to simulate a poor ace seal.

esults

our breathing machine tests were done. There was no neasurable inward leakage as long as facepiece pressure was bove ambient pressure, indicating a leakage rate less than **.0001%**. Above inhalation flows of 300 L/min, a slight egative pressure was created, which resulted in a facepiece oncentration of **SF_6** above 0.3 ppm (beyond the recorder's neasuring range).

Seven physiological tests were performed. Some typical ecordings for one subject with a plastic tubing under the hin at a heavy work load (250 W) and very heavy work load 300 W) are shown in Figures 3 and 4. As can be seen in igure 3, pressure in the facepiece (P_F) never dropped below ero and no inward leakage (**F_PSF_6**) was detected. Thus, ccording to the previous discussion, the leakage rate was ss than 0.0001%. Peak inhalation flow ($\dot{V}_{IN}$) was about 300 /min and heart rate (HR) was 156/min indicating that the ubject was performing heavy work.

With a 300 W load on the bicycle ergometer (Figure 4), the ubject worked very hard (**HR =** 167/min) and reached eak flows of about 450 L/min. These high inhalation flows esulted in negative pressures in the facepiece of about - 1 Pa. As a result of the negative pressure, there was an inward akage of SF_6 so that facepiece concentration rose above 0.3 pm (beyond measuring range).

In similar fashion in all seven tests, pressure in the faceiece during inhalation was reduced for both subjects from bout +40 Pa at rest to 0.0 Pa at inhalation flows around 300 L/min, which was achieved at a work load of **250** W. Within this pressure range, no inward leakage was detected, not even in the experiments in which the plastic tubing was placed under the chin.

As soon as negative pressure was created, which occurred at loads above 250 W, there was inward leakage greater than 0.3 ppm in the tests with an induced face seal leak. Without this experimental leak, the face seal was sometimes able to withstand inward leakage during negative facepiece pressure, believed to be due to heavy facial sweating.

Discussion

It has been shown in several laboratory reports that a mask with an ordinary demand valve without positive pressure will have an inward leakage rate around 0.1% to 0.01%. Balieu and Spindler''' tested the inward leakage of a mask without positive pressure on fire fighters of a fire brigade in Denmark. They found that before any attempt was made to improve poor mask fit, the maximal leakage rate for 49 men tested was 1% to **0.5%.** Of the 49 men, 16 showed leakage rates of more than 0.05%. After improvements in mask fit, the maximal leakage rate was 0.05% except for one man with a rate of 0.07%.

Persson(1) measured the inward leakage of a pressure demand set during rest and at a moderate work load of 100 W by the DOP method. At this moderate load he could not detect any leakage, which means that the inward leakage was at least less than 0.001%, depending on the sensitivity of his measuring equipment.

In the U.S.A., two **reports**(6,7) have recently presented data showing that negative pressure does occur in the facepiece of pressure-demand apparatuses and that the leakage rate is about 0.01% to 0.005%. The results in the present study, with the SF_6 method, show that if the pressure in the facepiece is positive, there is no detectable inward leakage.

One problem with using SF_6 is that owing to the manufacturing process, SF_6 may contain toxic impurities. Sulphur tetrafluoride (SF_4) and sulphur pentafluoride **(S_2F_{10})** are considered possible contaminants that may be present in commercially available **SF_6**.(8) In the present experiment, high-quality SF_6 (electrical grade, supplied by AGA Specialgas, Lidingö, Sweden) was used in which the maximal content of these impurities was well below their TLVs.

It can be seen from our data that young, physically fit men will reach peak flow values up to and above **400** L/min at the point of exhaustion, and that heavy work (250 W) gives a peak flow of 300 L/min. Thus peak flow of 300 L/min must be considered as a minimum requirement when testing pressure-demand systems. Also, in certification testing, a breathing machine must be used instead of constant flow in order to reveal any negative pressure which may be produced by inertia and friction in the breathing valve.

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