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Why is PIAF so important that we need to change the way we test APRs?

Already in January 1943 did Leslie Silverman, Robert C. Lee, George Lee, Dr Katherine R. Drinker and Dr Thorne M. Carpenter from the Department of Physiology and of Industrial Hygiene, Harvard School of Public Health, and the Nutrition Laboratory of the Carnegie Institution of Washington, publish a report:

FUNDAMENTAL FACTORS IN THE DESIGN OF PROTECTIVE RESPIRATORY EQUIPMENT
INSPIRATORY AIR FLOW MEASUREMENTS ON HUMAN SUBJECTS WITH AND WITHOUT RESISTANCE.

In the introduction to this report it was identified that:

The successful design of protective respiratory device, such as canister masks for chemical warfare, depends upon a number of physical and physiological factors. Two of the most important of these are the maximum rate at which air flows, during each inspiration, through a particular canister or filter and the length of time during which this maximum flow continues.

The opening statement of their CONCLUSION reads:

The result shows that the present flow rate for evaluating the efficiency of protective canisters is inadequate. Etc.

Already then, they measured PIAF of 294 litre per minute. This was before the technology of computers with high-frequency microprocessors was available.

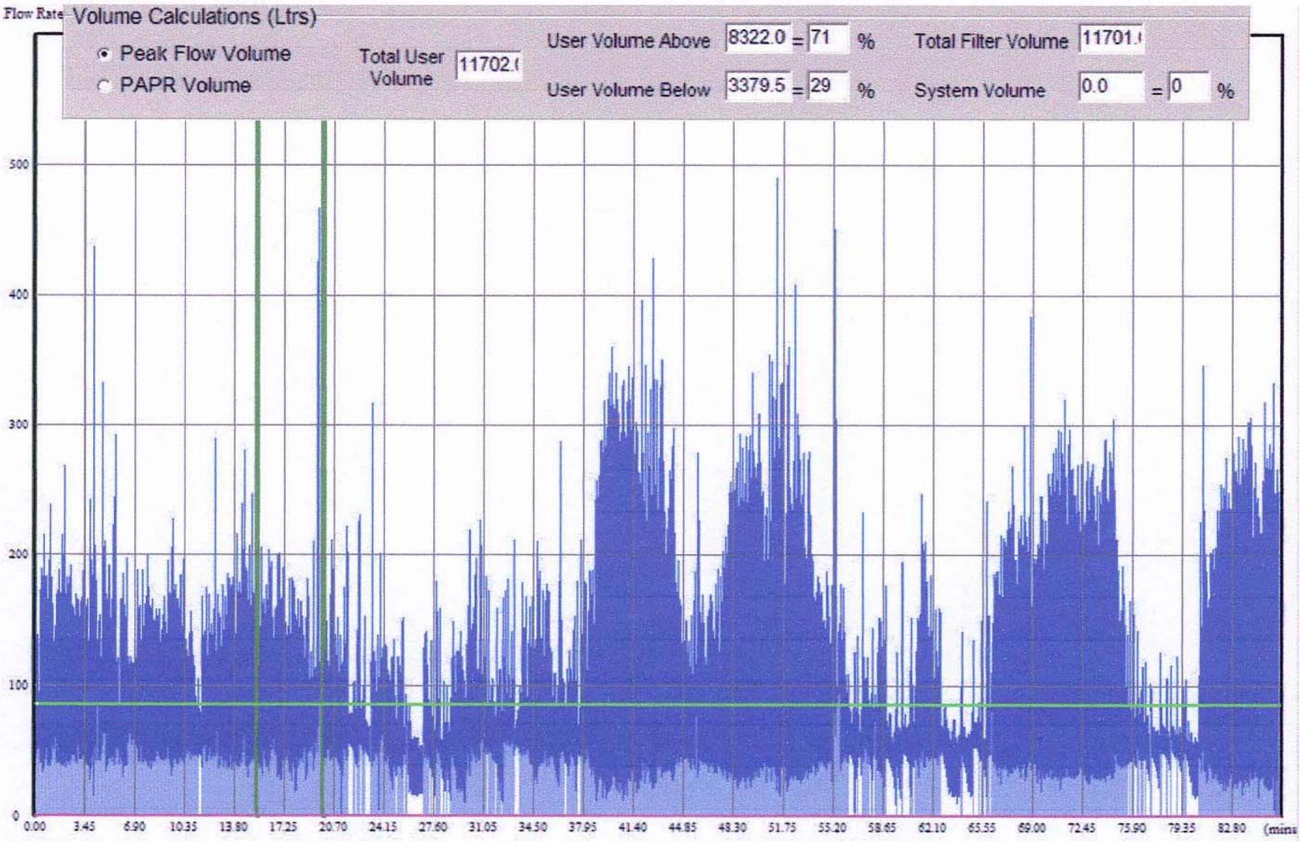
At SEA we started to look in to PIAF in the early 1990s. We did this in the alumina smelting industry in Australia and New Zealand. We built an air flowmeter which was attached in front of the regular filters used in the smelters. We then collected PIAF, volumes and heart rate of people performing their ordinary work.
The collected information led to concerns about both physiological and heat stress.
Over the years we refined our measuring and collection techniques. Today we can measure PIAF of up to 500 litre a minute with an accuracy of +-10%, as well as the total volume used.

Following are some graphs of a worker in a lead smelter in South Australia, we data-logged him for 90 minutes when he was doing manual labour including jack hammering.

This type of work is possibly well representing of the work preformed by First Responders and recovery workers.

The data loggers we are using have the capability to record on tree channels at 50 HZ for approximately 90 minutes, and the software can display the total period as well as a small part of the data. We are also capable of calculating both the percentage as well as the volume which either flows faster than a certain flow rate or above a certain level. For example, particular filters are tested at a constant flow of 85 litres, and as they are velocity dependent, they will perform differently at different flows. Therefore we need to know, as the report referred to above, both the flow rate and time (which equals the percentage or volume of total flow) which are over 85 litres per minute.

We also need to know how long the person can sustain a PIAF above the flow we now test at. There has been argument in the academic papers that PIAF of levels exceeding test levels can't be sustained for more than a few minutes. With the data, we will show that that is not true. We can also show that almost every person fit enough to wear an APR can sustain breathing rates two to tree times the flow rate used for testing.


Volume Calculations (Ltrs)
● Peak Flow Volume
○ PAPR Volume
Total User Volume 11702.
User Volume Above 8322.0 = 71 %
User Volume Below 3379.5 = 29 %
Total Filter Volume 11701.
System Volume 0.0 = 0 %

What we see here is just under 90 minutes of PIAF data squeezed in to one small graph, it just looks like different blue-coloured fields. Up in the right corner we find the number 11701.1 which is the total volume of air that was breathed trough the system. As this is a Positive Pressure Demand APR, the person breathes as freely as if not using a APR, but it is not forcing more air to the user than he actually requires. So this number of litres of air is what he would be breathing if using a Negative pressure APR with low enough pressure drop over the filter as well as over the exhalation valve/s. As I described earlier in this document we started to do this data collection with Negative Pressure APRs and surprisingly, we recorded PIAF just 10-15% lower than of the values we are recording today.

We find many examples in the literature, for instance ***Textbook of Work Physiology*** by Per-Olof Åstrand and Kaare Rodahl. In their book they say :

"*Pulmonary ventilation during exercise (VE) from resting values of 6.0 liter per minute to 100-150 liter per minute and in extreme cases 200 liter per minute* (page 229). *Maximum Volunteer Ventilation (MVV) has been* *measured up to 211 liters Minute Volume. Well-trained and fit athletes can utilize some 95% of MVV during exercise, but less fit subjects normally, only attain 60 to 70% of their MVV* (page 237).

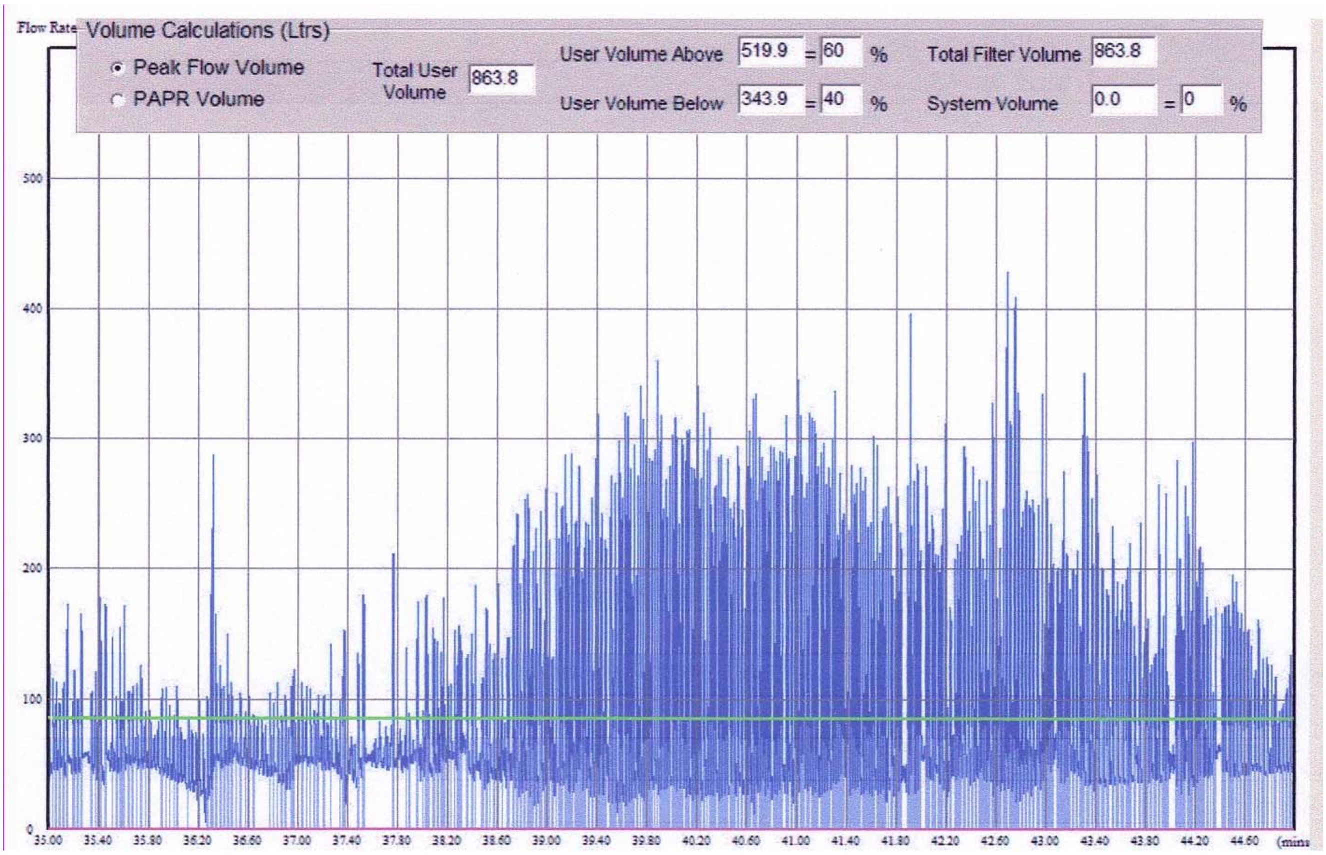
Åstrand and Rodahl also say that "*Moderately well trained individuals may walk or run for about one hour with an oxygen uptake up to about 50% of there Vo2 max, maintaining the oxygen uptake, heart rate, and cardiac output at approximately the same level as attained after about 5 minutes of exercise. Well-trained athletes, including marathon runners, can exercise for hours with an oxygen uptake around 70-80% of their maximum.*" (page 308).

Another text book, **NUNN'S APPLIED RESPIRATORY PHYSIOLOGY 4th Edition,** by J. F. Nunn, quotes the following ; *"The average fit young male adult should have an MBC (maximum breathing capacity) of about 170 l/min but normal values depend upon body size, age and sex, the range being 47-253 l/min for men and 55-139 l/min for women" (Cotes 1975)* Page 133.

Nunn also claims on Page 83 in regards to PIAF the following: *In the more usual types of breathing the peak flow/minute volume ratios tend to be in the range 3.5:1 — 5:1.*

Then we might think that those people are sportspeople and motivated by winning glory, but the person with the data from the Lead Smelter used 11701 liters of air in just 90 minutes = 130 liter per minute which, if we overstated the data by 15%, still is 110 liters per minute. The only motivating this worker has is a pay envelop every Thursday. Of course he was not breathing at this flow rate all the time, and as we can see when we look closer, he did not keep the respirator on all the time. When talking with the spotter who followed the person to record what tasks he was performing, the spotter confirmed to us that from old habit, from time to time the respirator/data logger was lifted from the face to talk (unfortunately this is common practice when APR are worn and the need of communication is required). So the APR/Data logger free-flowed and thereby lost some air. So we need to look in more detail on the data and break it down into shorter pieces.

Lets look at the data representing the 35th to the 45th minute:



Volume Calculations (Ltrs)

● Peak Flow Volume

○ PAPR Volume

Total User Volume: 863.8

User Volume Above: 519.9 = 60 %

User Volume Below: 343.9 = 40 %

Total Filter Volume: 863.8

System Volume: 0.0 = 0 %

In this period, as we can see in the upper right corner, 863.8 liters were breathed. With this software, we can also calculate how much of this had a higher velocity or flowed through the filter faster that the flow we test with, that is, 85 liters per minute.

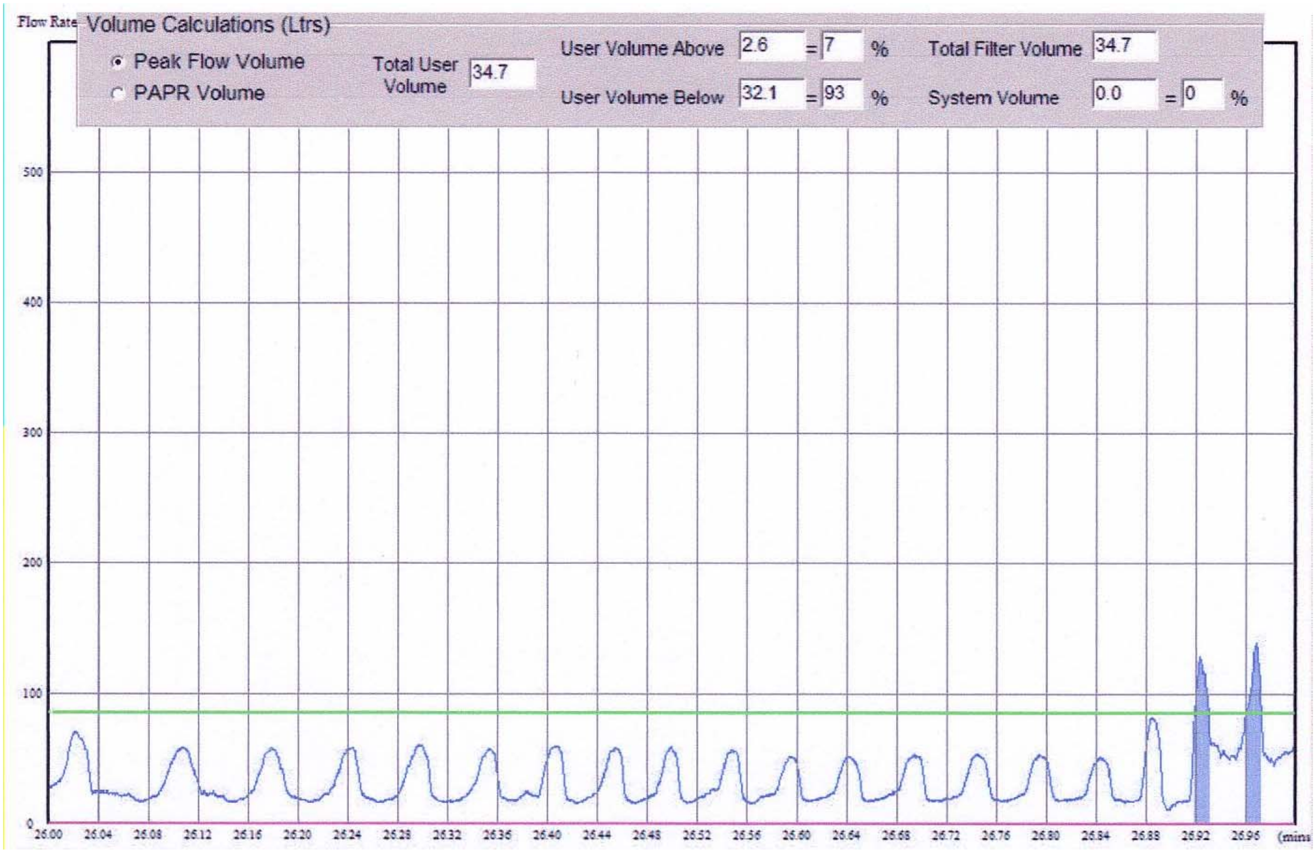
The green line in the lower part of the graph represent 85 liters, as the horizontal axis represents time and the vertical axis flow rate. All air above the 85-litre line is flowing faster than 85 liters per minute, and all air below the line is flowing slower than 85 liters per min.

In this instance the volume of air flowing faster is 519.9 liters of air or 60% percent of the total volume breathed.

How much faster? Some of the air goes just a bit faster but surprisingly, a whole 332.2 liter per minute or 38% flows faster than 170 liter per minute or *twice* the testing flow rate and 101.8 liter per minute or 12% flows faster than 255 liter per minute or *three* times the testing flow rate.

Let’s have a look at another section where the worker is not working, between the 26th to the 27th minute. The total volume of air during this minute is 34.7 liter. Still there are two breaths where the air is flowing faster than 85 liter. The volume in this sample is 2.6 liter or 7%.

His breathing frequency is 19 breaths per minute (the limit is in the range of 50-60 breaths per minute), so this is comfortable, normal breathing at rest.


Volume Calculations (Ltrs)

● Peak Flow Volume
○ PAPR Volume

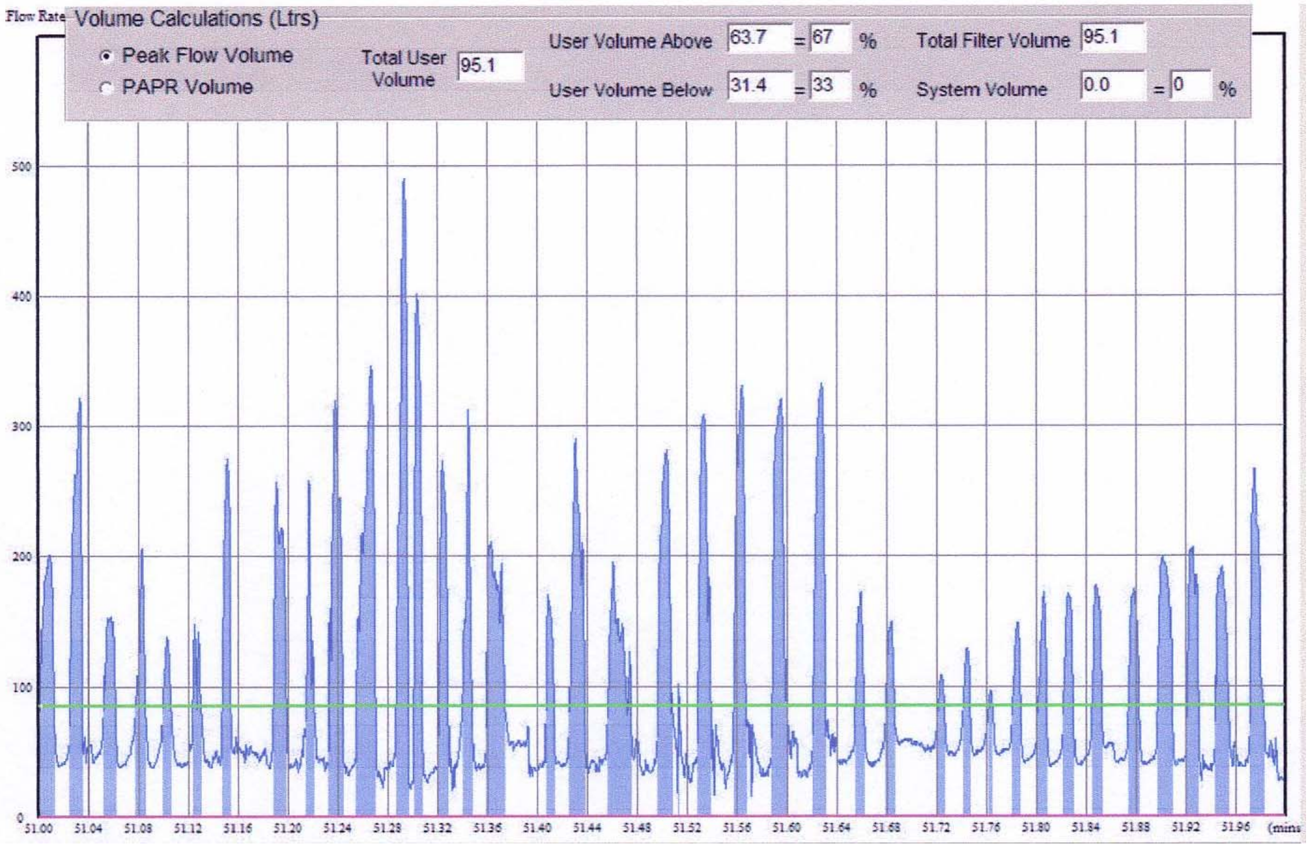
Total User Volume: 34.7

User Volume Above: 2.6 = 7 %
User Volume Below: 32.1 = 93 %

Total Filter Volume: 34.7
System Volume: 0.0 = 0 %

One more sample: Here the person breathes at a frequency of 38 breaths per minute.

The reason I think this sample is important is the difference in peak flows within one minute, the smallest one being just over 100 liters per minute and the highest just under 500 liters. It is very difficult to argue that there is some kind of average PIAF rate. This is very representative of the data we have collected over the years.
In this sample, 63.7 liters per minute or 67% of the air is flowing faster than 85 liter per minute.



Volume Calculations (Ltrs)

● Peak Flow Volume
○ PAPR Volume

Total User Volume: 95.1

User Volume Above: 63.7 = 67 %
User Volume Below: 31.4 = 33 %

Total Filter Volume: 95.1
System Volume: 0.0 = 0 %

What does this mean to the user of APR?

If we don’t test APRs at higher, more representative flow rates, it is likely that the filtering capacity is not what the user would expect. Equally important, he or she may not even be able to breathe through the respirator, as the pressure drop would prevent him or her from getting the air trough the filter.

Below we have a graph where we have measured a few different manufacturers’ P100 filters purchased on the market here in the USA.

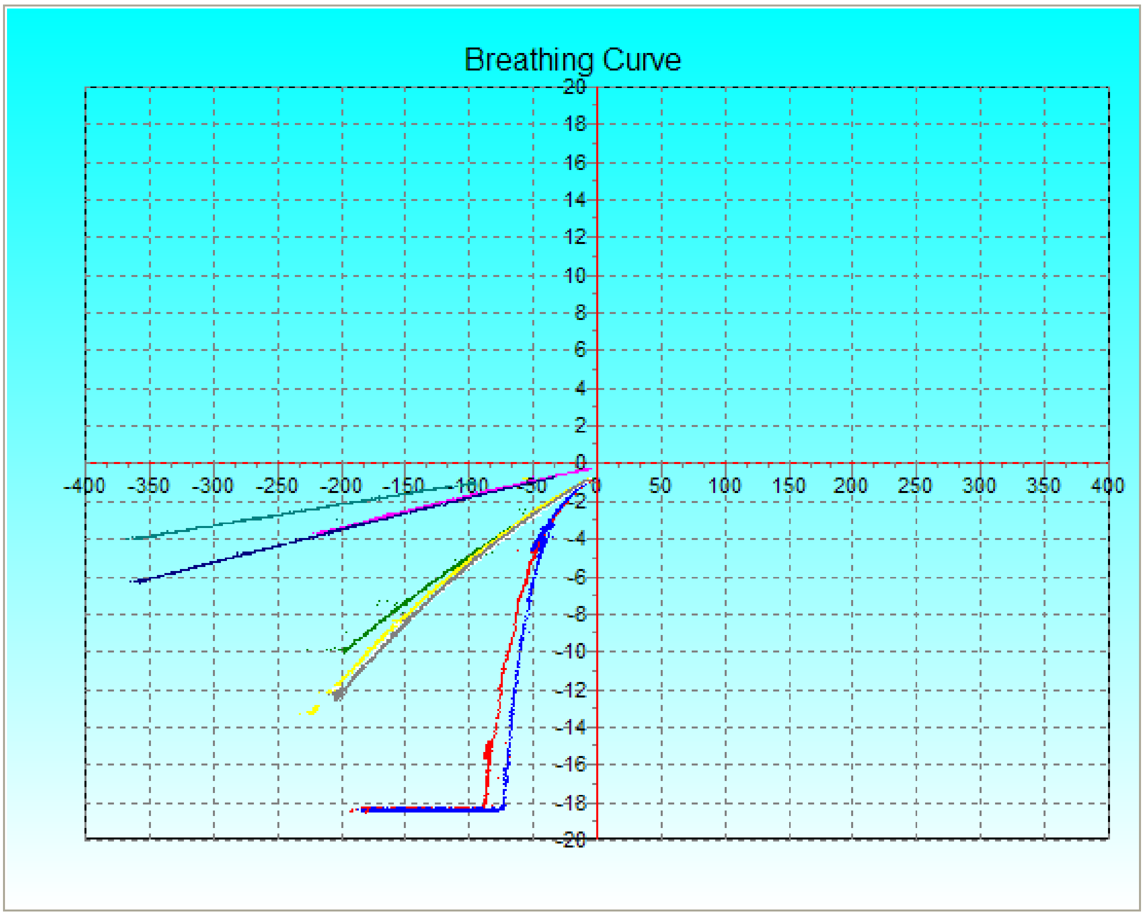
We used a calibrated test bench, and in this test we used a constant air flow. The horizontal axis is calibrated for the air flow and the vertical axis shows the pressure drop in millibar.

Three of the filters were large single filters (Euro standard thread). All the others were for two-filter APRs.

To compare the pressure drop we need to separate how we interpret the results. The three single filters are the ones where the curves go all the way to 360-370 liter. With all the others we have to double the flow rate to compare with the pressure drop of the single filters.

For example, where the yellow line crosses the horizontal number -50, this is at approximately -2.5 millibar, as we only tested one filter attached to the test head trough an adapter. We need to read the pressure drop -2.5 millibar representing a 100 liter flow.

As we expected, there is not a lot of difference at 100 liter flow. However, this changes as we increase the flow; for example already at flows of 150 liter per minute the blue and the red filters are outside the range of the transducer. Those two filters are the new type of filter (some call them pancake filters), round discs, very light in weight but very hard to breathe through.



If we don’t believe this is relevant to First Responders, lets have a look at some exercises we performed together with New South Wales Fire Services on May 8, 2002.

We hired the escape stairwell of a high-rise building in Sydney, Australia.

With six fire fighters and seven SEA employees as test objects, we used 25 floors of the 45 floor high building for our exercise.

The aim was to establish how much air was used and what PIAF would be when First Responders got to action. Before the exercise we carefully told the Fire Fighters that they should not exhaust themselves, as they had a job to do when reaching the top.

The exercise was performed using the ordinary turnout clothing and rescue equipment including a fully charged fire extinguisher. The breathing apparatus used was the SE400AT with Data Logger, and the heart rates were recorded with a POLAR 610 heart rate monitor.

The collected data is as follows:

Subject	Age	Gender	Start Heart rate	Average Heart rate	Max Heart Rate	Starting PIAF	Max PIAF	Total Air used	Average Min/Liter	Time
Fire Fighter 1	35	M	105	151	167	100	400	967	173	5.60
Fire Fighter 2	43	M	90	166	184	90	420	1152	136	8.45
Fire Fighter 3	28	M	102	164	179	115	390	923	148	6.25
Fire Fighter 4	29	F	115	168	180	80	315	1217	148	8.25
Fire Fighter 5		M	105	164	179	100	410	1049	150	7.00
Fire Fighter 6		M	100	160	179	140	490	1176	168	7.00
SEA GB	51	M	80	141	164	150	430	840	163	5.15
SEA KB	22	M	105	160	177	115	380	1116	178	6.25
SEA GP	49	M	120	154	170	150	400	1254	191	6.55
SEA JB	25	M	95	154	167	170	390	813	161	5.05
SEA SK	32	F	120	164	175	95	395	1069	156	6.85
SEA TS	25	M	105	168	186	150	430	1048	172	6.10
SEA SJ	22	F	120	183	195	95	305	1141	163	7.00
Average	33	All	105	161	177	119	397	1059	162	6.58
S/D	10	All	12	10	9	29	48	139	15	1.03
Average	28	M	101	158	175	128	414	1034	164	6.21
S/D	18	M	11	8	8	27	32	146	16	1.01
Average	28	F	118	172	183	90	338	1143	156	7.13
S/D	5	F	3	10	10	9	49	74	8	0.91
Average Fire Fighter	34		103	162	178	104	404	1081	154	7.09
S/D	7		8	6	6	21	56	120	14	1.11
Average Civilian	32		106	161	176	132	390	1040	169	6.14
S/D	13		15	13	11	30	42	160	12	0.77

What this indicates is that there is little if any difference between the civilian group we used (both this time and at another event earlier in the year) and the Fire Fighters/First Responders:

- With no exception, all tried to reach the top as efficiently as possible to be able to perform their task.
- Within one minute, all reached their max PIAF (Average 397 liters per minute).
- All would run out of air very quickly if using SCBA's.

This also indicates that we need to sooner rather than later look at the Positive Pressure requirements of SCBA's, as well as what is required to protect First Responders in the warm zone, such as PAPR's capability to maintain Positive Pressure within the enclosure.

Of course, if a piece of equipment is designed to supply only 115-200 liters per minute constant flow (this is with newly charged batteries or as some institutions test them running from transformers, so the airflow would not be jeopardized during the test), it would be imposable to maintain the protection required for this type of work.

As we can see in the table below, 39% of the air required for this exercise was above the 115-liter requirement for PAPR's with Full Face Mask, 18.5% above 200 liters/min, and 4% above 300 liters/min.

Subject	Age	Gender	Max PIAF	Total Air used	Average Min/Litre	Time		Percentage over litre flow	
							115 Litre	200 Litre	300 Litre
Fire Fighter 1	35	M	400	967	173	5.60	37	15	3
Fire Fighter 2	43	M	420	1152	136	8.45	36	17	4
Fire Fighter 3	28	M	390	923	148	6.25	40	19	3
Fire Fighter 4	29	F	315	1217	148	8.25	30	9	0
Fire Fighter 5		M	410	1049	150	7.00	42	22	6
Fire Fighter 6		M	490	1176	168	7.00	50	33	16
SEA GB	51	M	430	840	163	5.15	42	23	7
SEA KB	22	M	380	1116	178	6.25	39	18	3
SEA GP	49	M	400	1254	191	6.55	40	15	3
SEA JB	25	M	390	813	161	5.05	41	20	3
SEA SK	32	F	395	1069	156	6.85	37	18	2
SEA TS	25	M	430	1048	172	6.10	44	23	6
SEA SJ	22	F	305	1141	163	7.00	32	8	0
Average	33	All	397	1059	162	6.58	39.23	18.46	4.31
S/D	10	All	48	139	15	1.03	5.13	6.41	4.09

Conclusion:

In regards to Full Face Mask requirements for First Responders, we need to test filters or complete assemblies for not only filter performance but also pressure drop at more than one flow rate. Compulsory minimum performance should include pressure drop at 100 liters, 200 liters, and a voluntary test to meet a 300 liter requirement for high work rate approval. It is equally important to establish an acceptable exhalation resistance for those flow rates.

If those levels are too high, the user will risk getting into oxygen debt, resulting in an increase in the lactate level in the muscles, which in turn leads to fatigue. As we experienced from the WTC event, the rescue workers were more concerned about helping their work mates that keeping the respirator snugly on the face, mainly because it was too hard to breathe and talk through.

In regards to PAPR's for First Responders, we need to ensure that we require air flows high enough to maintain Positive Pressure inside the face cover when performing typical tasks, including working in the open, overcoming not only the contaminant in calm weather but also when the wind is blowing. Those requirements have sometimes been overlooked when arguing that performance for RPE does not require a snug fitting mask.

Göran Berndtsson

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