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MANNED TESTING OF TWO CLOSED-CIRCUIT  
OXYGEN UNDERWATER BREATHING APPARATUS:  
U.S. NAVY EMERSON RIG AND FENZY P0.68

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The breathing characteristics of two types of closed circuit oxygen self-contained underwater breathing apparatus at a pressure equivalent to 30 feet of sea water were studied in the Ocean Simulation Facility of the Navy Experimental Diving Unit. Breath-by-breath curves of inhaled and exhaled oxygen and carbon dioxide levels and inspiratory/expiratory pressure curves were recorded. For the first type, the U.S. Navy Recirculating Underwater Breathing Apparatus, Closed-Circuit, Oxygen (Emerson Rig), the carbon dioxide		

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absorbent canister duration at 70°F (21°C) exceeded the arbitrary cutoff of 240 minutes with diver-subjects doing moderate work; at 40°F (4°C) the canister duration was 199 minutes. For the second type, the Fenzy P0.68, the canister duration at 70°F (21°C) was 95 minutes, and no studies were done at 40°F (4°C). Both types were able to support divers doing hard work. Five cases of oxygen toxicity were seen, including three divers with mild symptoms, one with a near-convulsion, and one with a convulsion.

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## ABSTRACT

The breathing characteristics of two types of closed circuit oxygen self-contained underwater breathing apparatus at a pressure equivalent to 30 feet of sea water were studied in the Ocean Simulation Facility of the Navy Experimental Diving Unit. Breath-by-breath curves of inhaled and exhaled oxygen and carbon dioxide levels and inspiratory/expiratory pressure curves were recorded. For the first type, the U.S. Navy Recirculating Underwater Breathing Apparatus, Closed-Circuit, Oxygen (Emerson Rig), the carbon dioxide absorbent canister duration at 70°F (21°C) exceeded the arbitrary cutoff of 240 minutes with diver-subjects doing moderate work; at 40°F (4°C) the canister duration was 199 minutes. For the second type, the Fenzy P0.68, the canister duration at 70°F (21°C) was 95 minutes, and no studies were done at 40°F (4°C). Both types were able to support divers doing hard work. Five cases of oxygen toxicity were seen, including three divers with mild symptoms, one with a near-convulsion, and one with a convulsion.

### KEY WORDS

Self-Contained Underwater Breathing Apparatus (SCUBA)

Oxygen

Carbon Dioxide

Closed-Circuit

Oxygen Toxicity

Canister Duration

Graded Exercise

Breathing Resistance

Fenzy P0.68

Emerson Rig

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Manned Testing of Two Closed-Circuit Oxygen Underwater Breathing Apparatus: U.S. Navy Emerson Rig and Fenzy P0.68

INTRODUCTION

The U.S. Navy Recirculating Underwater Breathing Apparatus, Closed Circuit, Oxygen (Emerson Rig or Emerson UBA) has been in use since 1963 and is scheduled for replacement. Several closed-circuit oxygen Underwater Breathing Apparatuses (UBA's) are being considered as the replacement for the Emerson UBA. One of the units being considered is the Fenzy P0.68 produced by La Spirotechnique I.C. Industrielle et Commerciale (06510 Carros Industries (T), France.) It offers the advantages of lighter weight, 15.5 lbs compared with 35 lbs for the Emerson UBA, and commercial availability, whereas the Emerson UBA is no longer manufactured.

Unmanned testing of the Fenzy P0.68 at the Navy Experimental Diving Unit (NEDU) in 1981 (1) showed that it had slightly better breathing characteristics than the Emerson UBA when measuring total breathing resistance and work of breathing. The canister duration was significantly shorter than the Emerson UBA.

In addition to testing the characteristics of the UBA's, a goal of the study was to evaluate diver performance at a pressure equivalent to 30 feet of sea water (FSW) breathing 100 percent oxygen. The current U.S. Navy Diving Manual (2) limits the use of oxygen UBA's to 45 minutes at 30 FSW due to central nervous system (CNS) toxicity. Some evidence suggests that such an exposure limit may be too conservative. Donald (3), in 1947, reported two convulsions in 20 exposures of resting divers to 30 FSW breathing 100 percent oxygen for up to 2 hours. The level of inspired carbon dioxide, which appears to affect oxygen toxicity, was not reported in this wartime study. In a previous NEDU study in 1953, no cases of CNS oxygen toxicity occurred at 30 FSW in 11 subjects breathing 100 percent oxygen for 57 minutes (4). The conditions which provoke symptoms of oxygen toxicity have been the subject of substantial investigation in the past several decades. Factors which are known to increase individual sensitivity to oxygen toxicity include an elevated inspired carbon dioxide, low temperature, immersion, and work. The relative contribution of each of these factors is unknown.

This report describes the results of a series of manned dives at the NEDU Ocean Simulation Facility (OSF) in November and December 1981 (NEDU Test Plan 81-53.) Graded exercise studies and canister duration studies were done with both UBA's which were instrumented to study breathing gas composition.

MATERIALS AND METHODS

The studies were carried out during 30 dives in the wet pot of the OSF. The chest level of the Diver-Subject was at a depth equivalent to 30 FSW. Standard Emerson UBA's and Fenzy P0.68's were used, but both were modified to use an external oxygen supply by means of a whip connected to a 72 cu. ft. oxygen cylinder. Divers breathed via the standard closed circuit mouthpieces. Both UBAs are described and illustrated in reference (1).

Two water temperatures were used. For the 40°F (4.4°C) studies, each diver wore a crushed foam neoprene dry suit with Thinsulate undergarments, the U. S. Navy Passive Diver Thermal Protection System. For the 70°F (21.1°C) studies, each diver wore a 1/4 inch neoprene wet suit.

#### Emerson UBA

The Emerson UBA consists of an oxygen supply bottle, an oxygen add valve which provides for a continuous flow and a manual add bypass, a double hose breathing circuit with one way valves, two breathing bags, and a canister to remove CO<sub>2</sub> containing 6 pounds (2.7 kg) HP Sodasorb.

#### Fenzy P0.68

The Fenzy P0.68 is similar in function to the Emerson UBA with several significant differences in design. The oxygen add valve is a demand type located in the single breathing bag, and the canister contains 3.7 pounds (1.7 kg) HP Sodasorb.

#### Subjects

The Diver-Subjects were seven U.S. Navy divers, ranging in age from 20 to 37 years. Each had passed a standard USN oxygen tolerance test prior to beginning diving training. The divers were well conditioned and prior to the experimental series were capable of running 8 km per day and pedalling 175 watts for 8 minutes on a dry bicycle ergometer. The Diver-Subjects were carefully instructed about oxygen toxicity and were drilled in emergency procedures in the OSF wet pot. During the training period, they made test pool dives with both the Emerson UBA and the Fenzy P0.68 for thorough familiarization.

#### Instrumentation

Gas samples from the UBA canister effluent and from the mouthpiece were obtained by capillary sample lines equipped with micrometering valves positioned as close to the sample point as possible. After passing through the micrometering valve, the gas sample left the UBA and went through an unbroken 1 mm I.D. sample line to the gas analysis station outside of the chamber. The delay time to the surface was less than 2 seconds which provided rapid response to variations in gas composition without significant mixing in the sample lines. The gas samples were analyzed for PO<sub>2</sub> and PCO<sub>2</sub> with a mass spectrometer (Chemetron Medspect 2.) Breath-by-breath curves from the mouthpiece were recorded on an 8 channel strip chart (Grass Polygraph Model 7-162-40.)

The inspiratory/expiratory pressure differential ( $\Delta P$ ) was measured at the mouthpiece of the UBA by a differential pressure transducer (Validyne DP-9 with a 5 psi diaphragm) referenced to ambient water pressure at the level of the sternal notch. The transducer was calibrated by a water manometer before each study. The  $\Delta P$  was recorded on the strip chart. Canister outlet PO<sub>2</sub> and PCO<sub>2</sub> were recorded both on the strip chart and on a computer (Hewlett Packard Model 1100.) Other recorded functions included heart rate, oxygen supply bottle pressure, and for the dives in 40°F water, rectal temperature.



Pulmonary function tests were performed on each diver immediately before and after each canister duration test.

### Experimental Procedures

The experiment was divided into two parts; the first part consisted of CO<sub>2</sub> absorbent canister duration studies, and the second part was graded exercise studies. Any given Diver-Subject did not do both parts of the study on the same day. Diver work rate was provided by a specially designed electronically braked pedal mode ergometer (Warren E. Collins, Braintree, MASS) modified for submerged use (6). During the canister duration study, the Diver-Subject pedalled the ergometer at 50 watts for 6 minutes and rested for 4 minutes, repeating the sequence until the canister effluent PCO<sub>2</sub> reached 7.6 mmHg (1% SEV), or for a maximum of four hours, whichever came first. The graded exercise study consisted of 10 minutes of rest followed by 7 cycles of 6 minutes work and 4 minutes rest. The work rates were 25, 50, 75, 75, 100, 125 and 150 watts respectively. Diver-Subjects all pedalled at 55 to 60 revolutions per minute. Previous studies using similar methods showed an estimated oxygen consumption while pedalling at 150 watts of approximately 3 liters per minute (7). The ergometer was mounted on a horizontal frame so that the Diver-Subject was approximately in a swimming position (prone or slightly head up).

Standard U.S. Navy purging procedures were done at the beginning of each dive to obtain an inspired oxygen concentration of at least 95%. The gas sample micrometering valve was adjusted to give continuous gas flows of approximately 350 to 700 cc (actual) per minute). Continuous gas sampling rapidly increased the oxygen concentration to over 98%. Divers were told to notify control immediately if any symptoms of oxygen toxicity occurred. An air breathing standby diver accompanied each Diver-Subject.

## RESULTS

### UBA Breathing Characteristics

Canister breakthrough is defined as the time at which the canister effluent PCO<sub>2</sub> reaches 3.8 mmHg (0.5% SEV). When possible each test was continued beyond canister breakthrough to a PCO<sub>2</sub> level of approximately 7.6 mmHg (1% SEV) in order to more easily measure the end point. Therefore, the time on 100 percent O<sub>2</sub> exceeds the canister breakthrough time except when canister breakthrough had not yet occurred when the study ended. At 70°F, three runs were stopped at the arbitrary 4 hour cut-off, and two runs were stopped by symptoms of oxygen toxicity. At 40°F, one run was stopped due to a symptom of oxygen toxicity, and one run was stopped by ergometer failure. Table 1 gives the results of 5 warm and 6 cold water canister duration studies on the Emerson UBA.

Table 2 gives the results of the 4 canister duration studies using the Fenzy P0.68 in 70°F water. The time on 100 per cent O<sub>2</sub> is longer in all cases than the canister breakthrough time for the reasons noted above.



Figures 1, 2 and 3 illustrate the average canister durations for the Emerson UBA at 70°F, at 40°F, and for the Fenzy P0.68 at 70°F respectively. Mean canister effluent PCO<sub>2</sub> in % SEV  $\pm$  one standard deviation is plotted at 50 minute intervals. An additional 25 minute value is plotted for the Fenzy P0.68 study.

Table 3 gives the results of the 5 graded exercise studies at 70°F using the Emerson UBA. Several data points were not recorded due to plugging of the capillary gas sample line from the mouthpiece by saliva. Table 4 is similar to Table 3 and gives the results of the 6 studies done at 40°F. Table 5 is also similar to Table 3, and gives the results of the four studies done on the Fenzy P0.68 at 70°F.

Table 6 summarizes the average time and standard deviation of the canister duration studies. The study was stopped arbitrarily at 4 hours and in that time no canister breakthrough was observed in the Emerson UBA at 70°F. In those 3 runs which were stopped arbitrarily, the average canister outlet PCO<sub>2</sub> in SEV at 4 hours was 0.36%  $\pm$  0.04%.

#### Oxygen Toxicity

The five cases of oxygen toxicity encountered during the 30 dives of this study are listed in Table 7. There were three Diver-Subjects who had minor manifestations and two who had major symptoms of oxygen toxicity. In the "near-convulsion", the subject noted dyspnea, fatigue, and tunnel vision near the end of a graded exercise. He stood up, rapidly climbed several steps of the wet pot ladder, stopped, began breathing chamber air, and appeared unable to speak for several minutes. He continued climbing out of the wet pot with help, spoke with the Medical Officer and lay in a chamber bunk. Within ten minutes he became lethargic, and remained hard to arouse for two hours. He remained amnesiac for the events from the onset of symptoms until waking in the bunk. The event had many characteristics of a convulsion, especially the post-ictal lethargy. However, there was no definite rigor, and therefore was called a "near-convulsion".

The other major symptom also occurred toward the end of a graded exercise. The Diver-Subject stopped pedalling and ascended two steps of the ladder. He then had a generalized convulsion with tonic-clonic movements of all extremities, lasting one minute. Within eighteen minutes, he was able to recall events before and after the convulsion, but had trouble releasing his right hand grip. The inspired PCO<sub>2</sub> was approximately 1% SEV at the time of the convulsion, which was the highest PCO<sub>2</sub> observed for any Diver-Subject at the time of symptoms.

No diver had any sequelae following symptoms.

## DISCUSSION

### UBA Breathing Characteristics

The Emerson UBA performed reliably, was able to support a diver doing hard work, and had long canister durations with a predictably flat curve of near zero canister outlet PCO<sub>2</sub> until near the time of canister breakthrough.

The Fenzy P0.68 had a very short canister duration and extreme variability between dives, even when the canister was packed by the same individual. Although the UBA supported a diver doing hard work, elevated inspired (canister effluent) PCO<sub>2</sub> early in the sequence of graded exercises suggested a problem with channeling in the canister. The Fenzy P0.68 canister holds only 3.7 pounds (1.7 kg) of HP Sodasorb compared with the Emerson UBA canister which holds 6.0 pounds (2.7 kg), which may explain some of the difference in performance. Other design differences such as shape and flow path which are known to affect canister performance were not evaluated. The short canister duration at 70°F resulted in a decision not to test the UBA at 40°F, since HP Sodasorb is less effective at colder temperatures.

### Oxygen Toxicity

The onset of oxygen toxicity symptoms has been shown in the past to be related to higher PO<sub>2</sub>, higher inspired PCO<sub>2</sub>, higher work rate, immersion in water, and to undefined individual susceptibility factors. These factors were examined in the present study. The effect of inspired PO<sub>2</sub> at 30 feet was compared with a previous study conducted using a Draeger LAR V 100% O<sub>2</sub> rebreather which used very similar methods to the present study except for the shallower depth of 25 FSW (5). In the previous study, 12 canister duration dives were performed with mean durations of 226 ± 23 minutes at 70°F, and 124 ± 9 minutes at 40°F. Only one Diver-Subject had symptoms of tinnitus, and that case was not regarded as a true oxygen toxicity symptom. Twelve graded exercise dives were performed, with no symptoms noted.

No clear trend regarding inspired PCO<sub>2</sub> was seen in the present study. During the graded exercise studies with the Fenzy P0.68, one subject had a convulsion; his inspired CO<sub>2</sub> was 8.1 mmHg which compared with the three other subjects who did not convulse and had inspired CO<sub>2</sub> levels of 9.12 mmHg, 1.5 mmHg, and 3.8 mmHg.

Higher work rate appeared to be related to earlier onset of oxygen toxicity symptoms in the present study. The two cases of the most serious symptoms occurred during graded exercises at work rates of 100 watts and 150 watts, and times of 59 minutes and 83 minutes respectively. The three other cases of symptoms occurred during 50 watt canister duration studies at 152 minutes, 165 minutes, and 220 minutes, and all three were milder symptoms. The wide range of times to symptoms and the lack of symptoms during most dives tends to confirm the wide individual susceptibility to oxygen exposure that others have noted.

The present limit in the U.S. Navy Diving Manual for oxygen diving at 30 FSW is 45 minutes. This limit appears appropriate for divers doing hard work since the earliest symptom in the present study, a convulsion, occurred at 59 minutes during a high work rate. At moderate work rates the earliest symptom occurred at 152 minutes, suggesting that at moderate work rates the present limit is conservative and could be extended.

#### SUMMARY

In summary, both the Emerson UBA and the Fenzy P0.68 were able to support working divers at 30 FSW. The Emerson UBA had a canister duration of approximately 2 1/2 hours at 40°F (4°C) and in excess of 4 hours at 70°F (21°C). The Fenzy P0.68 had a very short and inconsistent canister duration time.

Five cases of oxygen toxicity symptoms were observed including one convulsion and one near convulsion.

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TABLE 1. SUMMARY OF CANISTER DURATION STUDIES  
AT 30 FSW

EMERSON UBA

Diver (*Note)	Time On 100% O <sub>2</sub> (Min)	Canister Breakthrough Time (Min to 0.5% PCO <sub>2</sub> SEV)	Canister Effluent PCO <sub>2</sub> (%SEV) at Completion
70°F (21°C)			
A (1)	250	>250	0.345%
C (1)	254	>254	0.405%
D (1)	244	>244	0.345%
E (2)	153	>153	0.045%
F (2)	227	>227	0.250%
Mean	226±42	No Breakthrough Noted	
40°F (4°C)			
A	205	166	1.05%
D	196	143	1.34%
E	201	170	1.04%
F (3)	215		0.28%
G	205	181	1.32%
H (2)	174	143	0.78%
Mean	199 ± 14	161 ± 17	

\*Note: (1) Stopped at arbitrary limit of 4 hours at work.  
 (2) Stopped due to O<sub>2</sub> toxicity symptom.  
 (3) Stopped work due to ergometer failure; diver then  
 remained at rest for 37 minutes; canister breakthrough  
 did not occur.

TABLE 2. SUMMARY OF CANISTER DURATION STUDIES  
AT 30 FSW

FENZY PO.68

Diver	Time On 100% O <sub>2</sub> (Min)	Canister Breakthrough Time (Min to 0.5% PCO <sub>2</sub> SEV)	Canister Effluent PCO <sub>2</sub> (%SEV) at Completion
70°F (21°C)			
D First Run	145	102	1.00%
D Second Run	89	22	1.05%
E	37	14	1.10%
F	104	35	1.28%
Mean	95 ± 45	43 ± 40	

TABLE 3. SUMMARY OF GRADED EXERCISE STUDIES AT 30 FSW

EMERSON UBA

Water Temperature: 70°F (21°C)

Peak End Tidal CO <sub>2</sub> mmHg	Diver						150 Watts
	Rest	25	50	75	100	125	
A	37.2	41.0	41.0	41.0	38.0	37.2	41.0
B	26.6	49.4	49.4	49.4	42.6	42.6	38.0
D	36.5	47.1	45.6	45.6	*	*	*
E	28.9	30.4	28.9	28.9	*	*	*
F	*	*	*	*	*	*	*
Inspired CO <sub>2</sub> mmHg	A	0.5	0.5	0.5	0.5	0.5	0.5
B	0.2	0.2	0.2	0.2	0.2	0.2	0.3
D	0.2	0.2	0.2	0.2	0.2	0.2	0.2
E	1.0	0.9	0.9	0.9	0.9	1.0	1.0
F	0.9	1.0	0.9	0.9	0.9	1.0	1.0
Delta P cm H <sub>2</sub> O	A	13	25	25	28	33	41
B	20	39	33	49	38	40	58
D	18	29	24	26	31	30	30
E	10	19	15	33	13	25	21
F	9	19	15	15	16	18	23

\* Data Not Obtained  
Diver B had symptoms of O<sub>2</sub> toxicity at 150 watts.



TABLE 4. SUMMARY OF GRADED EXERCISE STUDIES AT 30 FSW  
EMERSON UBA

Water Temperature: 40°F (4°C)

		Diver	Rest	25	50	75	100	125	150 Watts
Peak End Tidal CO <sub>2</sub> mmHg	A	42.6	45.6	36.5	39.5	38.0	38.8	36.5	
	D First Run	35.7	*	*	*	*	*	*	
	D Second Run	39.5	48.6	*	*	44.8	41.0	41.0	
	E	30.4	41.0	42.6	44.1	44.1	39.5	42.6	
	F	38.0	*	*	43.3	44.9	44.1	44.8	
	G	41.0	48.6	47.9	47.1	48.6	45.6	42.6	
	A	0.5	0.4	0.5	0.4	0.4	0.5	0.8	
	D First Run	0.3	0.3	0.3	0.3	0.3	0.3	0.4	
	D Second Run	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
Inspired CO <sub>2</sub> mmHg	E	0.3	0.3	0.3	0.3	0.3	0.3	0.4	
	F	0.4	0.4	0.4	0.4	0.5	0.5	0.8	
	G	0.4	0.4	0.4	0.4	0.4	0.5	0.8	
	A	28	21	15	25	18	20	23	
	D First Run	16	21	25	34	31	40	40	
	D Second Run	8	14	14	21	18	14	14	
	E	25	18	23	23	25	24	25	
	F	10	14	11	18	18	18	24	
	G	13	25	23	25	33	45	40	
Delta P cm H <sub>2</sub> O									

\* Data Not Obtained

TABLE 5. SUMMARY OF GRADED EXERCISE STUDIES AT 30 FSW

FENZY P0.68

Water Temperature: 70°F (21°C)

		Diver	Rest	25	50	75	100	125	150 Watts
Peak End Tidal CO <sub>2</sub> mmHg	A	First Run	*	*	*	33.4	*	*	*
	A	Second Run	28.9	30.4	*	33.4	30.4	35.7	39.5
	C		44.8	42.5	53.2	53.2	*		
Inspired CO <sub>2</sub> mmHg	E		34.4	37.2	38.0	39.5	40.3	41.8	44.8
	A	First Run	2.66	4.1	4.7	5.1	6.5	7.7	9.12
	A	Second Run	0.4	0.4	0.5	0.5	0.9	1.4	1.5
	C		1.5	2.4	4.4	6.4	8.1		
	E		0.7	0.9	1.2	1.6	2.3	2.7	3.8
	A	First Run	10	11	13	16	15	15	*
Delta P cm H <sub>2</sub> O	A	Second Run	11	13	15	30	24	38	24
	C		9	13	13	19	18		
	E		10	13	15	16	20	20	20

\*Data not obtained.

Diver A - First Run - was stopped before completion of 150 watts due to canister breakthrough.  
 Diver C had symptoms of O<sub>2</sub> toxicity at 100 watts.

TABLE 6. AVERAGE CANISTER DURATION TIME TO 0.5% SEV

	<u>EMERSON RIG</u>	<u>FENZY P0.68</u>
70°F (21°C)	>240 Min	43 $\pm$ 40 Min
40°F (2°C)	161 $\pm$ 17 Min	

TABLE 7. OXYGEN TOXICITY

Depth 30 FSW

Diver	Rig	Water Temperature	Type of Exercise	Time On Oxygen	Signs/Symptoms
F	Emerson	70°F	50 Watts	220 Min	Nausea, visual
E	Emerson	70°F	50 Watts	152 Min	Dizzy, tired
H	Emerson	40°F	50 Watts	165 Min	Nausea, lips twitching, confused
B	Emerson	70°F	Graded Exercise at 150 watts	83 Min	Confused, amnesia, near-convulsion
C	Fenzy P0.68	70°F	Graded Exercise at 100 watts	59 Min	Convulsion

# EMERSON UBA CANISTER DURATION 70 DEGREES F

SOLID LINE IS CANISTER OUTLET PCO2  
EACH DOTTED LINE IS ONE STANDARD DEVIATION FROM MEAN  
BROKEN LINE DEFINES CANISTER BREAKTHROUGH  
PCO2 IN %SEV

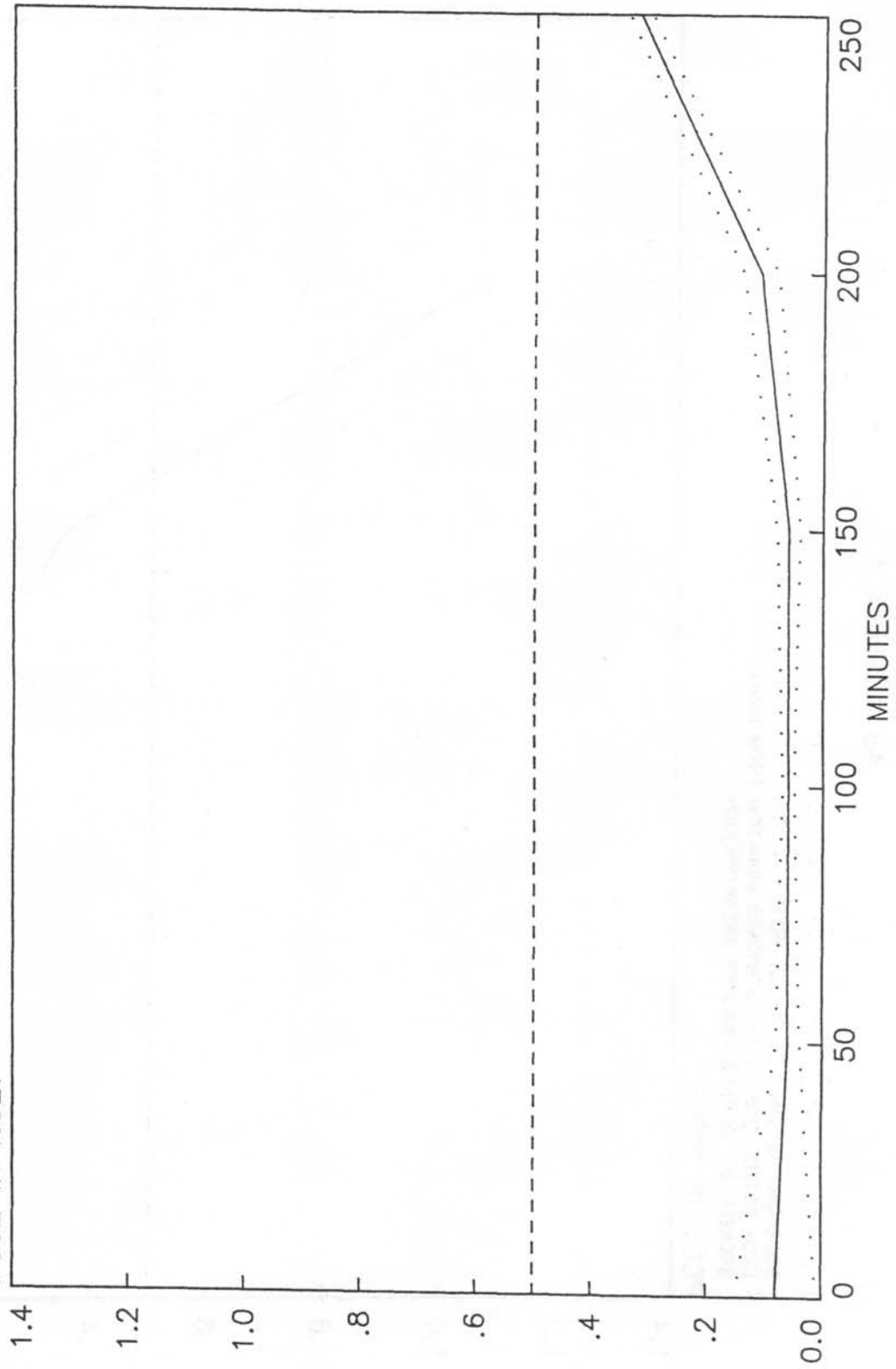


FIGURE 1.

# EMERSON UBA CANISTER DURATION 40 DEGREES F

SOLID LINE IS CANISTER OUTLET PCO2  
EACH DOTTED LINE IS ONE STANDARD DEVIATION FROM MEAN  
BROKEN LINE DEFINES CANISTER BREAKTHROUGH

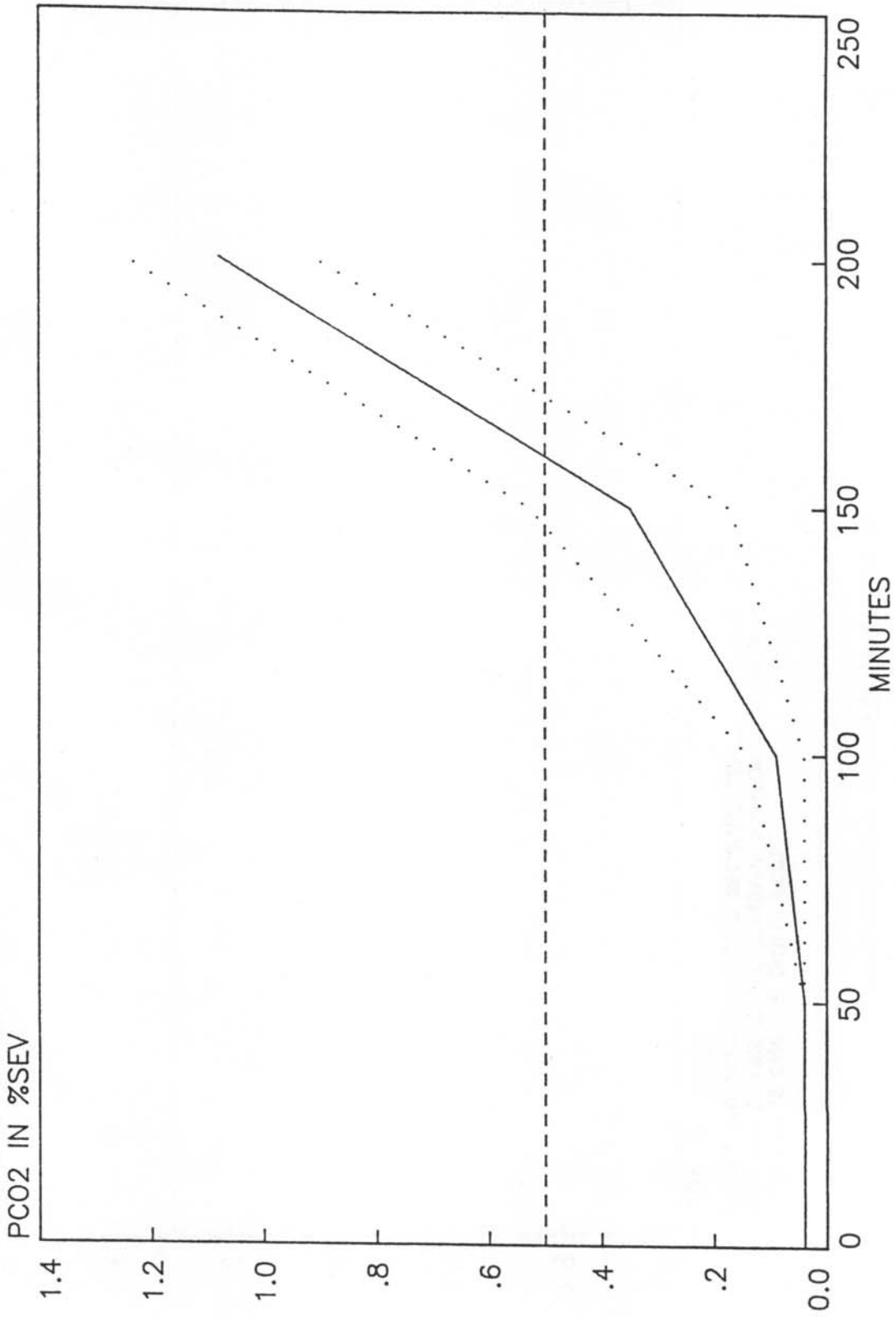


FIGURE 2.

# FENZY PO.68 CANISTER DURATION 70 DEGREES F

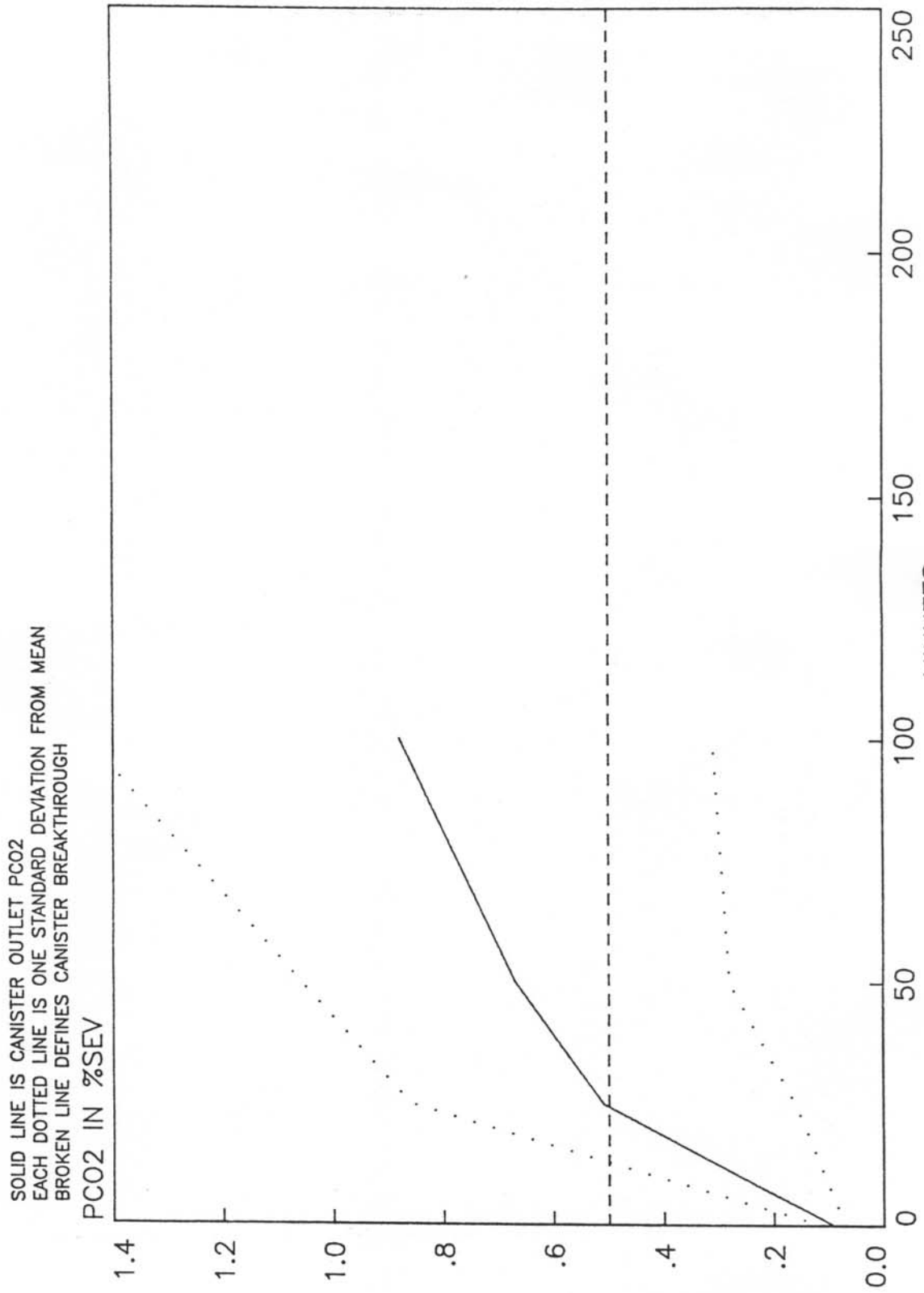


FIGURE 3.



