PHONETIC DISTORTION IN THE HeO_2 ENVIRONMENT*

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Whatever the purpose of an underwater expedition, there is the need for voice communication among individuals comprising the diving teams — as well as for the support groups on the surface. As man dives deeper and deeper, he encounters greater and greater problems of communication. And dive deeper he must, in order to benefit from the richness of the continental shelves.

The communication problems that exist in shallow water are present at greater depths and are magnified by intense cold, great ambient pressures and especially by the use of helium as an inert gas in life support. Substitution of the lighter gas, helium, for ordinary breathing gases results in problems of speech intelligibility. Acoustically, these problems are due to the increase in sound velocity through the supra-glottal resonators. This relationship results in the modification of the acoustic characteristics of the system to create a situation where it is as though the speaker's head was functionally reduced to the size of a golf ball. Obviously, the resonators within the head also are modified in their operational characterisitics and the final product of these changes is severely distorted speech — speech which is often characterized as having a simulated 'Donald Duck' quality.

In order to investigate the speech distortions created by high ambient pressures and helium/oxygen breathing mixtures, we are conducting a four-part research program. The first area of inquiry concentrates on the individual who SPEAKS in the HeO_2 environment — the studies being carried out in this area are the major focus of this paper. However, the three other programs of research in HeO_2 speech include: (1) the evaluation of electronic aids (HeO_2 speech unscramblers or processors) designed to improve the intelligibility of HeO_2 speech; (2) the ability of listeners to decode HeO_2 speech and (3) development of a special diver lexicon for use in the HeO_2 milieu.

In order to improve the speech intelligibility of the individual who must speak in helium, it is necessary to discover the exact nature of the disorder that his environment has created. Hence, our investigations of the speech of the diver/talker in HeO_2

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include studies of (1) speaker intelligibility, (2) analysis of the talker's speech errors (3) adaptation — or spontaneous speech improvement — by the diver over time, (4) changes in the fundamental frequency of speech caused by helium, (5) changes in the vowel formants caused by variation of helium and pressure and (6) the ways in which the talker can improve the intelligibility of his speech in the high ambient pressure and HeO_2 situation.

Very special environments and equipment are necessary in order that research of the nature described may be carried out. Of fundamental importance is the hyperbaric chamber or habitat. Figure 1 provides a view of such a chamber — one of several at the U.S. Navy's Experimental Diving Unit, Washington, D.C. It is two stories high and consists of four rooms: sleeping and eating, dry work, wet work and emergency lock-in. Although structurally large, once the divers and their life support systems are inside, these chambers are very crowded. Figure 2 is a schematic of the hyperbaric complex at the Westinghouse Corporation's Ocean Simulation Facility, Annapolis, Maryland. Figure 3 shows the complexity of the life support control; Figure 4, the scientific/engineering and medical team necessary to support such research; Figure 5, several of the Communication Sciences Laboratory divers inside the chamber (at 300 feet) conducting speech experiments. It is of interest to note that we use both male and female divers in order to obtain a wider spectrum of information on diver's speech in helium. Further, it must be remembered that deep diving still is very hazardous and in saturation diving, it takes days and even weeks to get divers back to the surface even after only a few hours work on the bottom. Finally, (1) all of the research reported has been carried out in partially acoustically controlled environments (enclosures constructed of fiberglass mattresses), (2) all of our recording equipment has been calibrated at depth and (3) (when speech intelligibility is under study) all word lists read were scored by at least 10-15 listeners.

The data presented in Table 1 took us almost a year and a half to collect; the research was conducted at the Experimental Diving Unit on the aquanauts in-training for Seal ab-3. A total of 46 divers were subjects; 28 at sea level and 200 feet; 22 at zero

TABLE 1

Overall means of diver intelligibility in Helium Oxygen. All recordings were made during Sealab - 3 Training at the Experimental Diving Unit. Means corrected for unequal N's.

Depth	Number of Diver/Talkers	Number of Listeners	Percent Intelligibility
0	46	487	90.9
200	28	304	50.4
450	22	242	20.7
600	9	142	9.5

The four means are based on a total of 29,375 iudged stimuli (words).

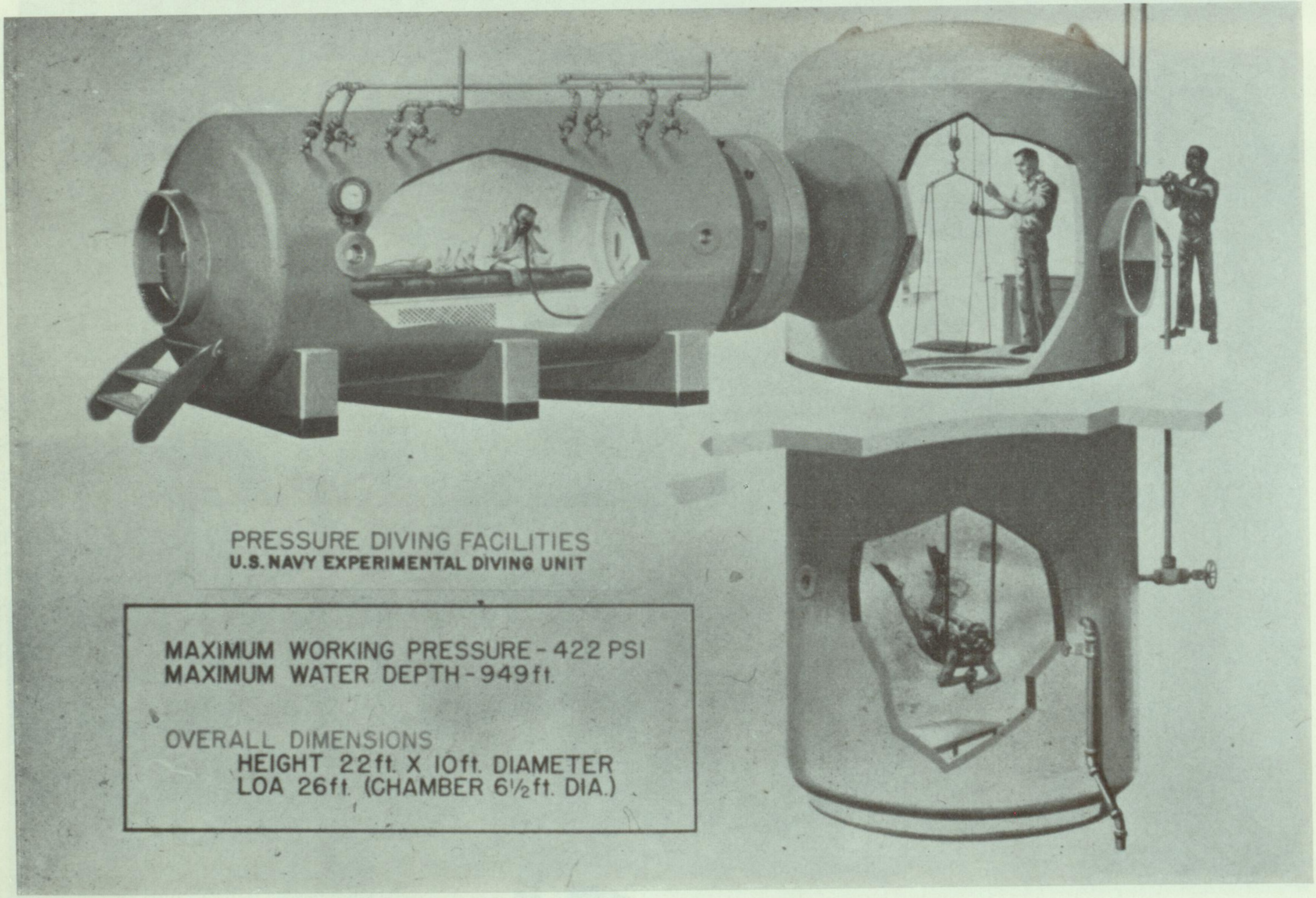

Fig. 1. View of the hyperbaric chamber at the U. S. Navy's Experimental Diving Unit, Washington, D.C.

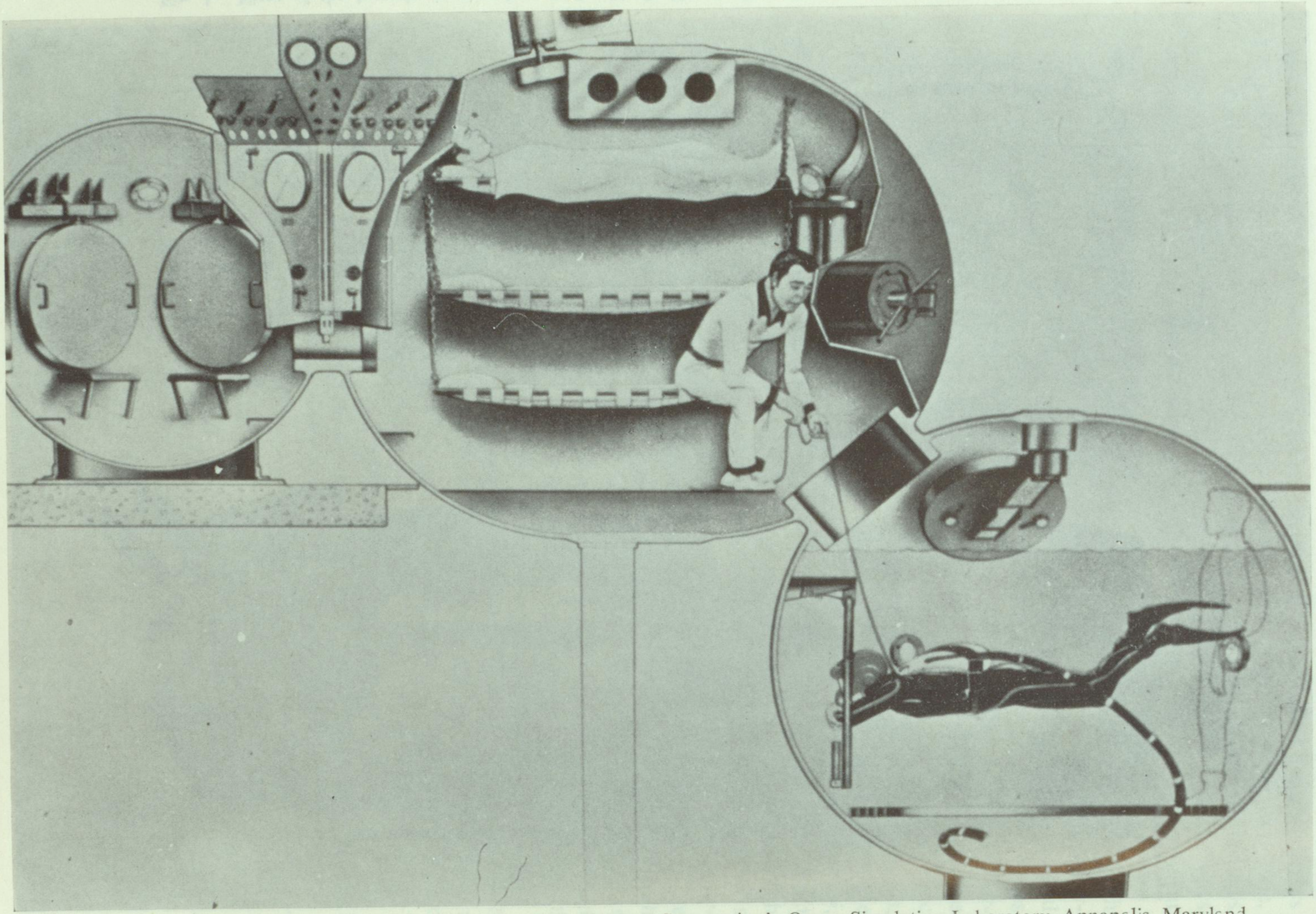

Fig. 2. Drawing of the hyperbaric facility at the Westinghouse Corporation's Ocean Simulation Laboratory, Annapolis, Maryland.

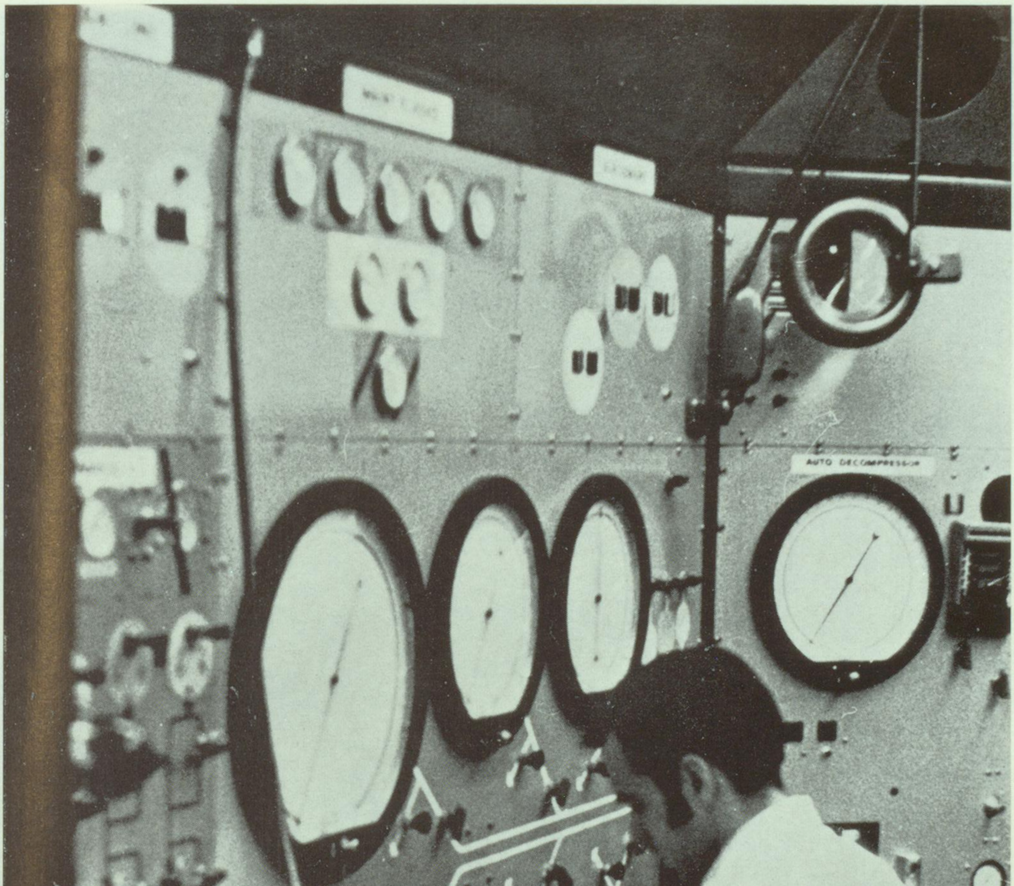

Fig. 3. Control panel for the Westinghouse chamber.

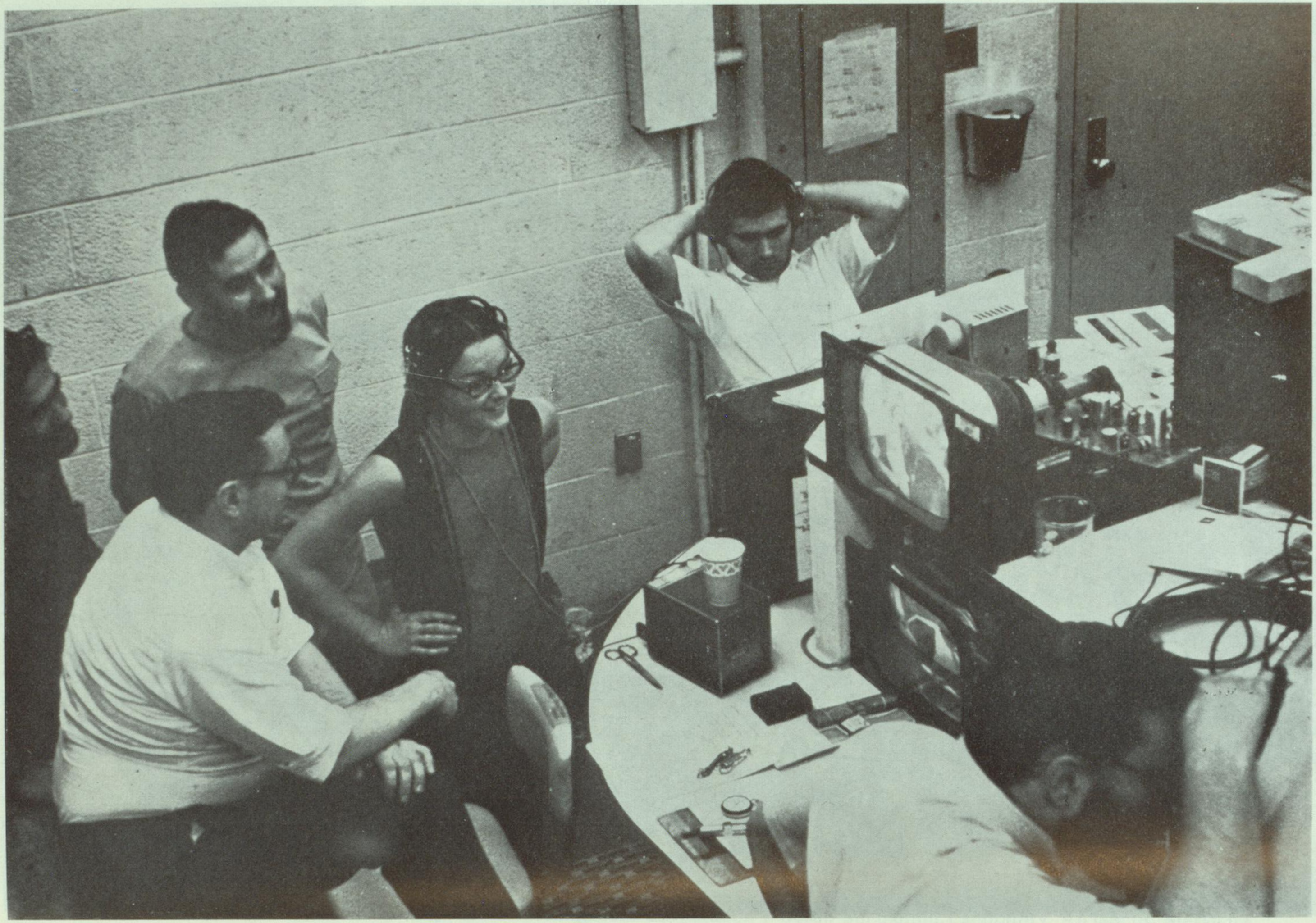

Fig. 4. The Communication Sciences Laboratory Westinghouse research support team.

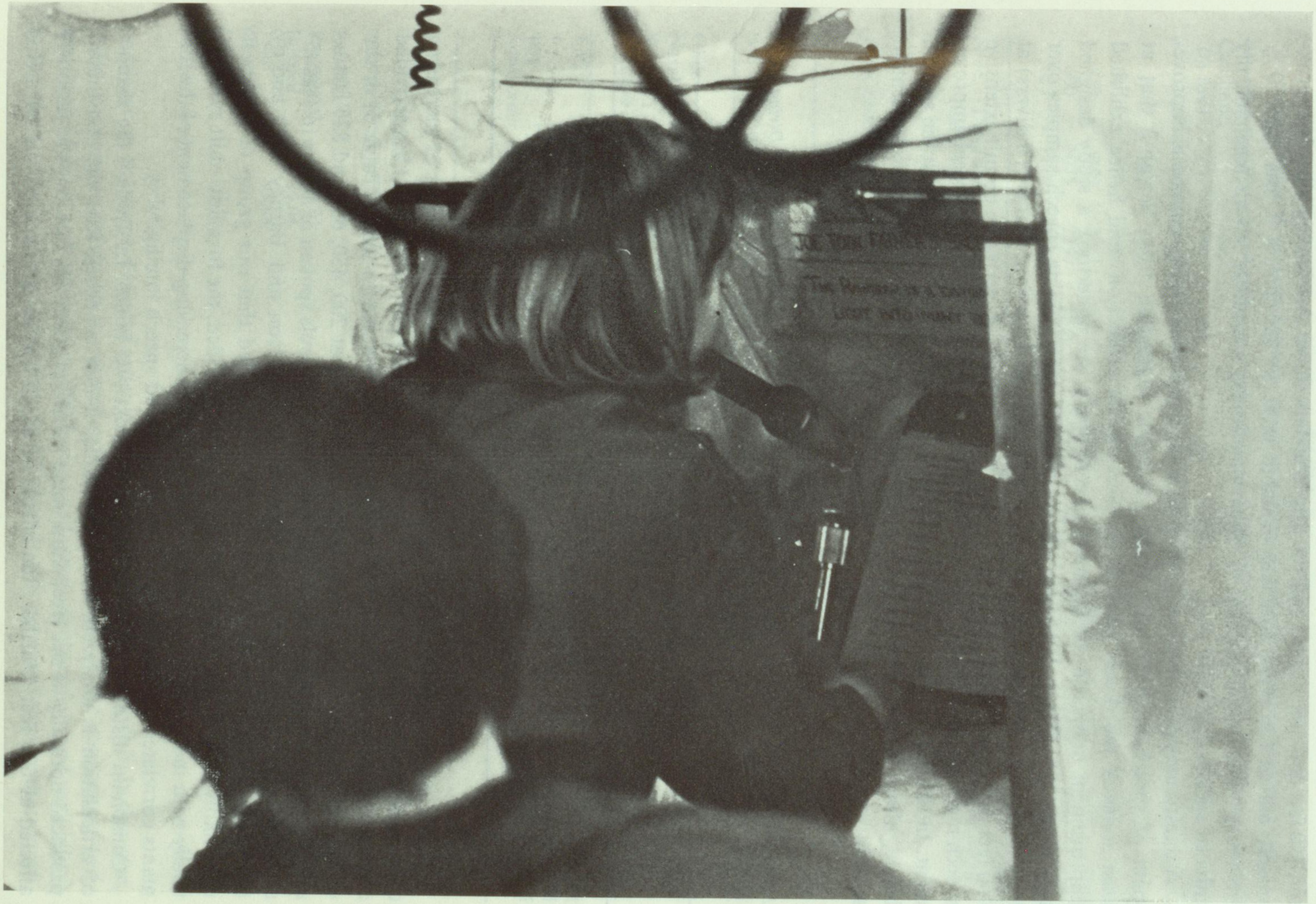

Fig. 5. Communication Sciences Laboratory divers conducting an experiment at 300'. An "acoustically isolated chamber" is formed by using fiberglass filled mattresses; the talker acts as his own baffle.

and 450 feet and nine at zero and 600 feet. The data shows that intelligibility is approximately halved for every doubling of depth until, at 600 feet, it is less than 10%. Obviously, intelligibility levels of these magnitudes constitute severe mechanically induced speech distortion.

A question of great interest is: do aquanauts experience any spontaneous improvement of speech intelligibility? There was some suggestion from Sealab-2 that at least some of the divers gave themselves 'speech correction' and hence exhibited improvement in speech intelligibility. Accordingly, we undertook a study designed to evaluate this factor. However, due to difficulty of obtaining speech samples over long periods of time, we were only able to collect data on four teams (16 divers) at 450 feet over a period of two days — hardly a long enough period to permit extensive speech modification. Table 2 reveals that there was some trend toward speech improvement. In this, as in all of our studies, there was considerable variability in the scores; hence, about half of the speakers accounted for nearly all of the improvement in speech.

TABLE 2

Mean intelligibility scores of divers at 450' in HeO_2 *in the chamber at the Experimental Diving Unit. The '0' time represents the first readings immediately upon reaching depth. Subsequent times are hours elapsed from first reading at depth.*

	Cumulative Time Between Readings (Hours)							
	0	10	15	20	25	35	45	60
Mean	18.5	18.6	15.6	22.2	14.0	23.6	26.0	29.3
Number of lists read	16	8	12	16	7	16	15	4
Number of listeners	216	196	277	357	160	374	327	100

Theory would predict an upward shift of vowel formants as a result of increasing concentrations of helium in breathing mixtures — and Fant, *et al.* (1971) has provided a model detailing these shifts. In this regard, we conducted a study (Table 3) of the vowels /u/, /a/ and /æ/ spoken by five or more divers at 200, 450, 600 and 825 feet — and, as a control, at sea level. The formants of the vowels spoken in air are in reasonably good agreement with those provided by Peterson and Barney 1952 and by Fairbanks and Grubb (1961), so it can be concluded that our group of talkers is reasonably normal. As may be seen by the data provided, the formants shift systematically with increases in helium and pressure. The increasing displacement of the formants correlates with the 'severity' of the reduced speech intelligibility.

Consonant distortion may be seen in the next two tables. In Table 4 the manner of articulation is analyzed. From the table, it can be noted that the consonants produced normally at sea level show some involvement at 200 feet and are seriously affected at 600 feet. Further, the effects of depth appear greatest on the fricatives

TABLE 3

Mean formant frequencies for three vowels as a function of depth and helium concentration.

Condition (in feet)	/u/ *F1*	/u/ *F2*	/u/ *F3*	/ɑ/ *F1*	/ɑ/ *F2*	/ɑ/ *F3*	/æ/ *F1*	/æ/ *F2*	/æ/ *F3*
0	439	1262	2386	641	1174	2215	607	1975	2762
200	820	1526	2259	1145	2013	4548	1024	2629	4672
450	950	2261	4335	1440	2420	5770	1188	3123	5648
600	1075	2257	3856	1586	2311	3350	1481	2711	5176
825	1278	2588	4125	1762	2650	4240	1687	3751	5032

Note. These data are from a preliminary study and are in the process of being replicated for validity. Later reports will provide the verified data.

TABLE 4

Rank order of the intelligibility (percent correct) for the phoneme categories grouped according to their manner of articulation at 0, 200 *and* 600 *feet.*

Manner of Articulation					
Surface		200 feet		600 feet	
Glide	99.75	Glide	93.25	Stop	31.30
Nasal	99.69	Nasal	88.66	Nasal	22.05
Stop	99.31	Stop	87.11	Glide	19.97
Fricative	98.96	Fricative	85.38	Fricative	15.97

TABLE 5

Rank order of the intelligibility (percent correct) for the phoneme categories grouped according to their place of articulation at 0, 200 *and* 600 *feet.*

Place of Articulation					
Surface		200 feet		600 feet	
Palatal	99.72	Glottal	90.64	Glottal	46.62
Pre-palatal	99.24	Pre-palatal	87.39	Velar	26.43
Bilabial	99.01	Palatal	83.20	Pre-palatal	24.76
Velar	98.84	Velar	73.77	Bilabial	21.47
Glottal	98.71	Dental	68.33	Dental	9.09
Dental	98.36	Bilabial	62.84	Palatal	5.97

and least on the stops. Place of articulation errors are detailed in Table 5. In this case, there is a serious reduction in correct production of certain of the consonants (primarily the dentals and bilabials) at 200 feet — and great involvement (and variability) in the place of articulation categories at 600 feet. It will be noted that at that depth, the dental and palatal consonants exhibit substantially reduced intelligibility (the palatals were the most intelligible at sea level) and that the glottals are the least affected. These findings — relating to the manner and place of consonant errors, coupled with the data on vowel distortion, have considerable implication for our work on the development of a training program designed to improve the speech of aquanauts in the deep diving situation.

Our research in this area continues. Especially important is an extensive study we are now completing, where our own divers systematically varied specific speech parameters (that is, F_0, rate, intensity, etc.) while keeping the others constant in order that we can discover just which speaking characteristics can be varied in order to reduce the speech distorting effects of pressure and HeO_2 breathing mixtures in saturation diving.

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DISCUSSION

BALIGAND (Toronto)
Did you notice in your experiments a lowering of the fundamental in the voice of your subjects?

ROTHMAN
Fundamental frequency is not affected by pressure or the breathing of helium. Changes in fundamental frequency occur, in an upward direction, due to tension or increased vocal effort.

KROLL (London, Ontario)
Have you found any changes in the articulatory proficiency of the divers over time?

ROTHMAN
Indications point to the improvement of a diver/talker's speech over time. This has not been adequately studied yet. Some data shows improvement due to some 'self-correction' by the diver. We feel that pre-training may enhance this.