OXYGEN CONSUMPTION IN SEA WATER OVER LONG PERIODS[1]

By

NORRIS W. RAKESTRAW[2]

Woods Hole Oceanographic Institution

The rate and extent of oxygen consumption in sea water have been studied and measured under a variety of conditions and for a variety of purposes. Such studies, of what is often called the "biological oxygen demand," have either been involved in the estimation of the total content of organic matter or have contributed to the understanding of the processes of organic decomposition in the sea. They have usually consisted of bottling samples of the water and storing them for varying periods, generally at controlled temperatures, determining the oxygen content of the samples and comparing it with the content of the original water. The incubation time has seldom exceeded a few days, or at most a few weeks.

It has generally been supposed that oxygen consumption will continue, perhaps indefinitely, at a diminishing rate. But no one has apparently determined how long it will take for the process to become entirely imperceptible.

As would be expected, the rate and extent of oxygen consumption depend upon the temperature, the time of storage, and the source of the water, which determines the amount and character of the organic matter present.

Oxygen consumption is one of the factors concerned in the distribution of oxygen in the sea, and especially the occurrence and significance of the "oxygen minimum." Sverdrup (1938) has shown the mathematical consequences of the various possible assumptions concerning the rate of oxygen consumption and the distribution of oxidizable organic matter. Seiwell (1937) determined the oxygen consumption in sea water samples from various depths, incubated for ten days at two temperatures, 11° and 25° C. Extrapolating the time, he calculated the annual consumption at temperatures *in situ*. His results were many times in excess of values which he had calculated from the

[1] Contribution No. 375 from the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

[2] Present address: Scripps Institution of Oceanography, La Jolla, California.

study of the oxygen distribution in the sea, and his conclusion was that in the ocean there are restrictive influences which limit oxygen consumption.

While it is to be expected that experimental laboratory conditions will yield results very different from those in the ocean, it seems that the closest approximation to the natural process would be to take sea water samples from various depths and to incubate them for as long a time as possible at the temperature which the water had *in situ*, removing samples for analysis periodically.

Water was obtained from two stations, "B" and "C," located respectively at 39° 05′ N., 70° 40′ W. and at 35° 30′ N., 67° 30′ W. The most significant part of the water column is the oxygen minimum layer. Samples were accordingly taken from this level (230–250 m. at Station B and 900–920 m. at Station C), as well as from the surface and from a depth well below the minimum (1240 m. at Station B and 1725 m. at Station C). The "minimum" samples were immediately placed in glass-stoppered bottles of about 250 ml. capacity and incubated in a water bath in the dark at 8° to 9° C., their original temperature. The deep samples were similarly stored at a temperature of 4° to 5° C. The surface samples were distributed, some of them at 8°, some at 4°, and some at the uncontrolled laboratory temperature, about 25° C. Bottles were removed for analysis periodically over a period of nearly two years (713 days).

All analyses were made in duplicate (from a single bottle in storage) by the routine Winkler method. A single solution of sodium thiosulfate was used for the whole period and its concentration determined before each analysis by titration against standard KIO_3 and $K_2Cr_2O_7$. Several standards were prepared during the experiment and cross-checked against each other.

Due to misunderstanding, different solutions were used in the original determinations of oxygen content, made on shipboard, so that the first two analyses for each sample were considered unreliable and are not included in the results given. However, since the object of the experiment was to follow the long-term changes, rather than those which took place in the first few days, this is not considered a serious gap in the data.

The results are shown in Table I. It will be seen that the surface samples, from both stations, were erratic, especially those incubated at 25°. The surface samples incubated at each of the lower temperatures were more regular and came to a constant level (depending on the temperature) after about 100 days of incubation. Significantly greater consumption resulted at the higher temperature, even after two years.

TABLE I. Consumption of Oxygen (0_2 ml./L) in Water from Three Different Levels at Two Stations. Water Was Stored in the Dark at Temperatures (C.) Close to Those *in situ*, in Small Individual Bottles, One of Which Was Used for Each Analysis. Time Is Measured from the Day the Water Was Sampled

Time (*days*)	*Station B*					*Station C*				
	Surface			*"Minimum" (230–250 m.)*	*Deep (1240 m.)*	*Surface*			*"Minimum" (900–920 m.)*	*Deep (1725 m.)*
	25°	*8–9°*	*4–5°*	*8–9°*	*4–5°*	*25°*	*8–9°*	*4–5°*	*8–9°*	*4–5°*
18	4.11	4.50	4.68	3.55	6.38	3.62	4.05	4.15	3.54	6.18
42	4.18	4.28	4.15	3.50*	6.13	1.49	3.40	4.10	3.43*	6.07
66	3.83	4.16	4.08	3.34	6.06	3.25	3.92	3.95	3.43	5.99
85	3.93	4.22	3.96	3.26	6.02	1.21	3.44	3.79	3.43	5.98
113	3.85	3.78	3.85	3.27	6.14	3.09	3.76	3.77	3.40	5.95
148	—	—	—	3.31	6.12	—	—	—	3.43	6.04
200	—	4.06	—	3.21	6.13	—	3.43	—	3.41	5.98
260	3.51	—	3.76	3.32	6.23	2.60	3.06	—	3.44	5.97
323	—	—	—	3.48	6.05	—	—	—	3.40	6.06
412	—	3.99	3.75	3.47	6.12	—	3.15	3.80	3.42	6.03
583	—	4.11	3.66	—	6.14	1.74	3.14	—	3.44	6.02
713	—	4.15	3.53	3.46	6.11	2.89	—	3.77	3.39	6.01

* At this point samples of this water were raised to room temperature (25° C.); results are shown in Table II.

The most striking fact observed is that within the limits of the analyses there is no net oxygen consumption in either the "minimum" or the "deep" samples after the first 50 days. They remained without change for nearly two years at their temperatures *in situ*. The deep samples were particularly regular in behavior.

The apparent rise in oxygen content in the minimum samples from Station B, after the initial drop, is very likely the result of the conditions of the experiment, and the abnormally large oxygen consumption in some of the surface samples incubated at 25° is presumably due to the accidental inclusion of plankton material or other easily oxidizable substances.

In order to determine the relative importance of the temperature, some of the "minimum" samples were removed after 42 days and incubated thereafter at 25°. The results, shown in Table II, indicate consistently greater oxygen consumption in these samples.

A second series of experiments was begun, primarily to study the

TABLE II. Consumption of Oxygen (0_2 ml./L) at Room Temperature (25° C.) in Water from the Oxygen Minimum Layer at Two Stations. Water Had Previously Stood for 42 Days at 8–9° C. (See Note to Table I)

Time (*days*)	*Station B*	*Station C*
0	3.50	3.43
6	3.34	3.34
20	3.27	3.33
39	3.13	3.40
69	3.10	—
212	2.96	3.27

TABLE III. Consumption of Oxygen (0_2 ml./L) in Water Sampled and Stored Under Conditions Similar to Those in Table I. Time Measured from the Day the Water Was Sampled

Time (*days*)	*Surface*	*"Minimum"* (*400 m.*)	*Deep* (*1200 m.*)
	25°	*8–9°*	*4–5°*
0	5.11	3.89	6.28
2	5.11	3.84	6.21
20	4.97	3.76	6.17
40	4.80	3.75	—
82	4.41	3.76	6.13
172	4.65	3.81	6.10
305	4.50	—	6.14

consumption in the first few days. Samples were taken from three levels, as before: surface, 400 m. (the oxygen minimum level), and 1200 m. They were incubated at the same temperatures as in the first series (which were the temperatures *in situ*). The results are shown in Table III. The surface samples again behaved erratically, with oxygen consumption continuing for about 80 days. In each of the other sets of samples, oxygen consumption ceased after the first few days.

These experiments do not, of course, give us a clear picture of the process of oxygen consumption *in situ*. One wonders whether the true, natural rate of consumption is the maximum rate noted in the first few days of laboratory incubation or the minimum rate integrated over the whole period. The former assumption leads to the anomaly obtained by Seiwell and already referred to—more oxygen apparently consumed than can conceivably be available. Rather than to attempt to reconcile the situation by assuming *retarding* agencies in the sea, it is more in keeping with known facts to assume that the laboratory

conditions *hasten* the normal rate of consumption. Zobell and Anderson (1936), and others, have found bacterial action to be stimulated in bottled samples, because of surface effects. It is impossible to tell to what extent the observed initial rate of consumption is due to such surface concentration of bacteria, but it is probably not entirely due to this.

One also wonders why oxygen consumption ceases after a comparatively short period. It is evidently not the result of complete decomposition of organic matter. Among others, Waksman and Carey (1935) have pointed out that bacteria do not attack and oxidize all the organic matter in the water. Further, they discuss the "dynamic equilibrium" in sea water, involving the organic matter and its decomposition products, the oxygen tension, the temperature, the bacterial population, etc. The unknown condition of the equilibrium must be responsible for the fact that in water which has come to a steady state at low temperature additional oxygen is consumed when the temperature is raised.

It may be significant to observe that the surface samples which were incubated at the lower temperatures eventually reached a level of oxygen concentration similar to that in the "minimum" samples. This lends some support to the view that the organic matter in a vertical water column (at least down to the oxygen minimum layer) is principally derived from the local surface.

Until we know more about the nature and distribution of the dissolved organic matter in the sea, we cannot safely translate such laboratory experiments as these into natural processes. Nevertheless, there is reason to suspect that the natural process of exygen consumption in the sea is slower than we may previously have assumed.

REFERENCES

Seiwell, H. R.

1937. Consumption of oxygen in sea water under controlled laboratory conditions. Nature, Lond., *140:* 506–507.

Sverdrup, H. U.

1938. On the explanation of the oxygen minima and maxima in the oceans. J. Cons. int. Explor. Mer, *13* (2): 163–172.

Waksman, S. A. and C. L. Carey

1935. Decomposition of organic matter in sea water by bacteria. II. Influence of addition of organic substances upon bacterial activity. J. Bact., *29* (5): 545–561.

Zobell, C. E. and D. Q. Anderson

1936. Observations on the multiplication of bacteria in different volumes of stored sea water and the influence of oxygen tension and solid surfaces. Biol. Bull. Woods Hole, *71:* 324–342.