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PARTIAL AND FULL LIFT HYPOLIMNETIC AERATION OF MEDICAL LAKE, WA TO IMPROVE WATER QUALITY

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Abstract—Hypolimnetic aeration of Medical Lake, WA using partial lift and full lift aerator designs resulted in enhanced water quality. The partial lift system significantly reduced hypolimnetic ammonia (NH_3) and total phosphorus (TP) concentrations and increased hypolimnetic temperature. The system had no statistically significant effect on chlorophyll *a* (Chl *a*) concentration, phytoplankton biovolume, hypolimnetic nitrate (NO_3^-) and dissolved oxygen (DO) concentrations. The full lift system also significantly reduced hypolimnetic TP and NH_3 concentrations, but increased hypolimnetic DO and temperature. This system likewise had no effect on Chl *a* concentrations. Although anoxia persisted with the partial lift system, it was viewed as effective because phosphorus was not released from the lake's bottom, demonstrating that measurable concentrations of DO were not required to hold phosphorus in the sediments. Further research is required on (1) the effect of hypolimnetic aeration on stimulating DO depletion rates and (2) long term effects on phytoplankton biovolumes and Chl *a* concentrations. Continued operation of the full lift system should further reduce *in situ* oxygen demands and eventually a new equilibrium and higher hypolimnetic oxygen concentrations can be attained.

Key words—Hypolimnetic aeration, in-lake treatment, internal phosphorus loading, lake restoration, nitrogen concentration, nutrient cycling, oxygen depletion, phosphorus concentration, chlorophyll *a* concentration, phytoplankton and water quality

INTRODUCTION

Medical Lake, WA, once popular with native Americans as a medicine water lake, has become increasingly eutrophic since the turn of the century. In 1912, Kemmerer *et al.* (1924) noted large numbers of rotifers and cyanobacteria (blue-green algae), low concentrations of dissolved oxygen and an absence of fish. Low oxygen concentrations and a lack of fish were again noted in 1964 (Wolcott, 1973). Kettelle and Uttormark (1971) classified Medical Lake as highly eutrophic due to cyanobacteria blooms and high organic loading from its primary production. In 1974, it was determined that 60% of the lake's volume was anaerobic at the height of summer stratification, and a whole-lake application of aluminum sulfate (alum) and hypolimnetic aeration were recommended to improve the lake's water quality (Bauman and Soltero, 1978).

A lake restoration project involving the application of 936 metric tons of liquid alum [150 mg/l $AL_2(SO_4)_3 \cdot 18H_2O$] was initiated at Medical Lake in the summer of 1977 (Gasperino *et al.*, 1980). Following treatment, water column total phosphorus concentrations decreased about five fold (from 450 to 83 μg/l) and soluble reactive phosphorus concentrations decreased over 30 fold (from 340 to 10 μg/l; Bauman and Soltero, 1978; Soltero *et al.*, 1978). Water column sulfate concentrations increased over two-fold (from 0.65 to 1.48 me/l) due to the alum introduction. Water clarity improved by 51%. Phytoplankton standing crop decreased significantly (from 11.79 to 0.98 mm^3/l) and community composition shifted from primarily cyanophytes to mostly chlorophytes and cryptophytes (Soltero *et al.*, 1981). The zooplankton community was also altered with an increase in cladoceran and copepod numbers, while rotifer density declined (Mires *et al.*, 1981).

Medical Lake continued to show improved water quality for the next several years, with the exception of dissolved oxygen, as the lake remained in a mesotrophic state (McKee, 1983). However, more recent data showed a trend toward increased mean hypolimnetic (8 m to bottom) total phosphorus concentrations during the growing season (Table 1) indicating a return to eutrophic conditions (Soltero *et al.*, 1985, 1986, 1989; unpublished data). Several hypotheses have been formulated to account for the increase in hypolimnetic phosphorus concentrations including: (1) disruption and saturation of the alum layer with phosphorus; (2) sediment build-up over the alum layer allowing for nutrient release at the anoxic mud-water interface; and/or (3) past fisheries management practices that caused severe top-down impacts on the entire food web (McKee, 1983; Knapp and Soltero, 1983; Scholz *et al.*, 1985).

In keeping with the recommendations of Bauman and Soltero (1978), hypolimnetic aeration was initiated in an attempt to increase hypolimnetic oxygen concentrations and further reduce internal phosphorus cycling. Hypolimnetic aeration was considered to be less expensive than re-treatment with alum and another alum treatment may only introduce more of a potentially toxic substance under acidified conditions (Cooke *et al.*, 1993). Destratification during the growing season was ruled out as it would mix nutrient rich hypolimnetic waters with surface waters, enhance algal growth, significantly warm the hypolimnion and possibly preclude good development of a cold water fishery (Overholtz *et al.*, 1977; Cooke *et al.*, 1986). However, hypolimnetic aeration is not without potential problems. It may cause hypolimnetic warming, increase the volume of the hypolimnion via thermocline "sharpening" and increase hypolimnetic turbidity (Lorenzen and Fast, 1977). It is quite possible to under-estimate hypolimnetic oxygen depletion and over-estimate the oxygen output of an aerator resulting in an undersized system with minimal (Ashley *et al.*, 1987) or no discernible effect on hypolimnetic oxygen concentrations (Taggart, 1984). The purpose of this manuscript is to review the operation of two different hypolimnetic aeration systems in Medical Lake, WA and document the response of selected physical, chemical and biological parameters under varying oxygen concentrations.

DESCRIPTION OF THE STUDY AREA

Medical Lake is located within the city limits of Medical Lake, WA at latitude 47° 33′ 48″and longitude 117° 41′ 21″. The lake lies in a closed basin formed by glacial floods occurring 15,000–20,000 years ago and is primarily surrounded by igneous rock (U.S. Geologic Survey, 1973). Medical Lake has a surface area of $6.3 \times 10^5\,m^2$, a volume of $6.2 \times 10^6\,m^3$ and is 730 m above mean sea level. It has a maximum length of 1698 m, a maximum width of 370 m and a maximum depth of 18 m. The watershed is quite small at 3.5 km^2. Land use in the drainage basin is predominately residential (51%) and forest (31%) with the lake's surface amounting to 18% of the watershed area (Dion *et al.*, 1976).

Table 1. Mean hypolimnetic total phosphorus (TP) concentrations during the growing season (June–October), Medical Lake, WA

Year	TP (μg/l)
1978	89
1979	63
1980	42
1981	72
1982	118
1983	97
1984	149
1985	116
1986	127

METHODS AND MATERIALS

Previous investigations of Medical Lake have shown that the North and South sampling stations (both 10 m deep) had similar water quality to that observed at the deepest point in the lake for all parameters measured (Gasperino *et al.*, 1980; Sexton, 1989). Sampling for this work took place at the deepest point in the lake (Fig. 1). The years 1984, 1985 and 1986 formed the data base for the pre-aeration period. Partial lift hypolimnetic aeration effects are represented by 1987 data, while 1990, 1991 and 1992 data represent the full lift hypolimnetic aeration years. Sampling in 1988 was infrequent due to lack of funding and was not included in the data analysis. Sampling during 1989 was not representative of either a pre-aeration or aeration year due to system failure (see below) and was, therefore, excluded from this paper.

Physical and chemical parameters

Water samples and field measurements were conducted at monthly intervals. Temperature and dissolved oxygen (DO) profiles were determined with a Hydrolab® (System 8000 or Surveyor II) at 2 m intervals. Vertical light transmission profiles were made using a Protomatic® underwater photometer (designed after Rich and Wetzel, 1969) at 1 m intervals to a depth of one percent of surface light intensity, thus establishing the lower limit of the euphotic zone (Verduin, 1964). Water samples were collected at 2 m intervals with a 2 l acrylic Kemmerer bottle. Laboratory analyses included: nitrate nitrogen (NO_3^-–N; chromotropic acid method), nitrite nitrogen (NO_2^-–N; diazotization method), ammonia–nitrogen (NH_3–N; phenate method), soluble reactive phosphorus (SRP; stannous chloride method) and total phosphorus (TP; persulfate digestion—stannous chloride method) as described by the American Public Health Association (APHA, 1985, 1989).

Phytoplankton standing crop and chlorophyll a concentration

Equal volumes of water were collected at 2 m intervals from the surface to the lower limit of the euphotic zone and composited. Sub-samples for phytoplankton enumeration and chlorophyll *a* (Chl *a*) determinations were taken from the composites. Phytoplankton biovolumes were determined using the sedimentation method (Schwoerbel, 1970). Phytoplankton were identified to species, whenever possible, with the aid of the taxonomic keys of Hustedt (1930), Smith (1950), Prescott (1962; 1978), Patrick and Reimer (1966; 1975) and Weber (1971). Euphotic zone Chl *a* concentrations were determined using acetone extraction and the trichromatic method (APHA 1985; 1989). A Beckman DU-8® or Shimadzu® spectrophotometer was used to measure optical densities with a 1 cm cuvette and a 0.5 nm slit width. Concentrations of pheophytin *a* were not determined.

Hypolimnetic aeration

Hypolimnetic aeration can be accomplished by injection of air through partial or full lift designs (Cooke *et al.*, 1986, 1993). A partial lift system is where hypolimnetic water is aerated in place, while a full lift aerator brings hypolimnetic water to the surface for aeration then returns it to the bottom. In the fall of 1986, a flexible partial lift hypolimnetic aerator (LIMNO™, Model 20 55 100) was installed at the Deep station approximately 1 m off the bottom (Fig. 1). This unit consisted of two interconnected concentric tubes of vinyl with the outer tube sealed at the top incorporating a vent tube to purge excess gases (Verner, 1984). Aeration was achieved by injection of compressed air at the bottom of the inner chamber allowing for the air–water mixture to rise partially through the column before it was returned to

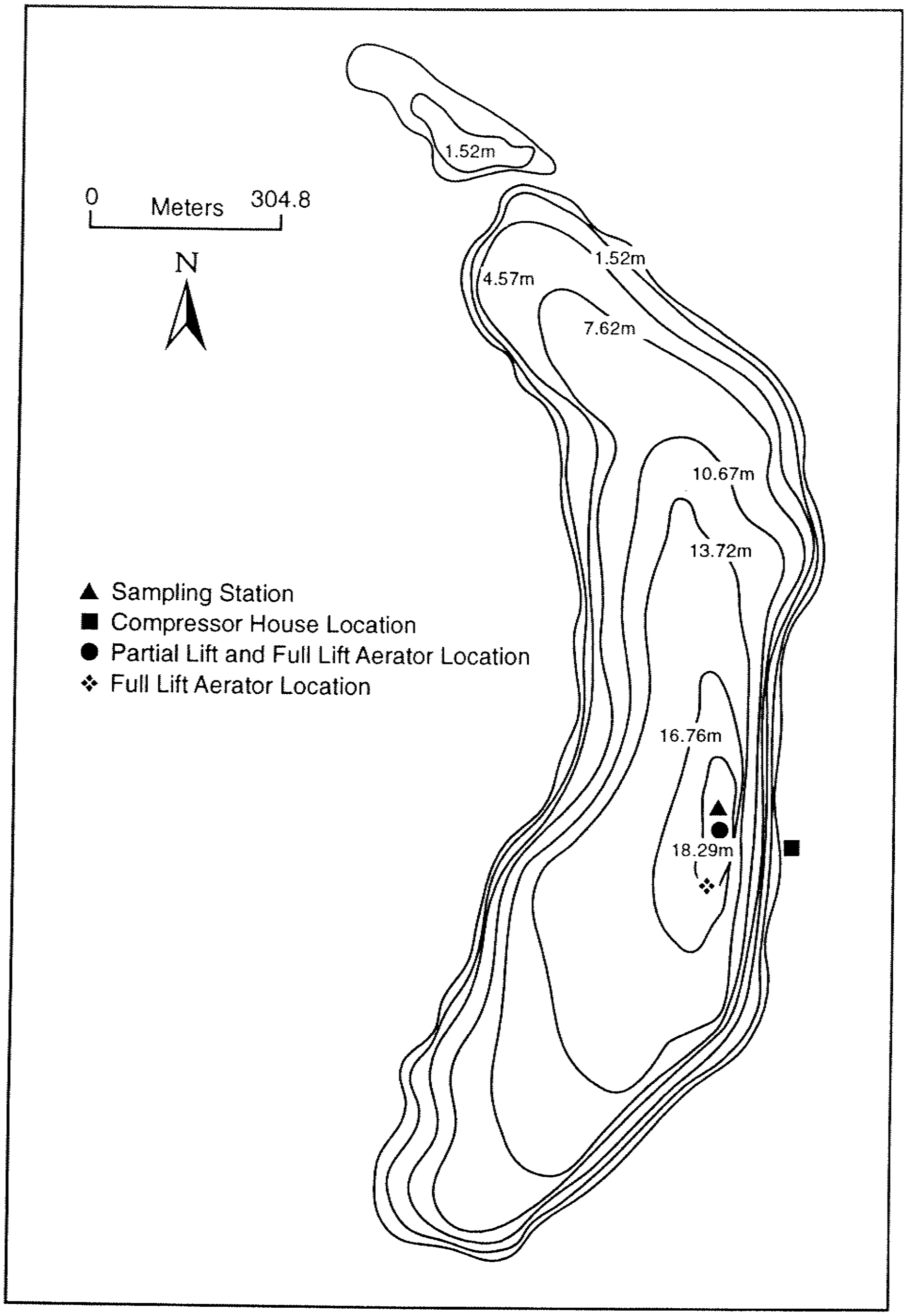

Fig. 1. Bathymetry of Medical Lake, WA showing aerator locations and sampling station.

the hypolimnion via the outer chamber and discharge arms (Fig. 2). The unit was approximately 7 m in height and 5 m in diameter. A compressor station was built on the lake shore about 100 m southeast of the aerator location (Fig. 1). A weighted air supply line (5 cm dia by 183 m long) was laid along the lake's bottom to connect the compressor and aerator.

Maximum hypolimnetic oxygen depletion rates observed in the spring were determined for each year by plotting total hypolimnetic oxygen content against time. A regression line through selected points which gave rise to the greatest slope was chosen to represent the maximum depletion rate. The average depletion rate for the hypolimnion of Medical Lake from 1980 through 1986 was 280 kg O_2/day (McKee, 1983; Sexton, 1989). The claimed oxygenation capacity of the LIMNO^{TM} system was 475 kg O_2/day.

Hypolimnetic aeration of Medical Lake began 31 March 1987 and continued through that fall (31 October; Table 2). Aeration was initiated on 1 April 1988; however, it was terminated prematurely in September 1988 because of compressor failure. At this time, it was apparent that the air supply (11.2 kW (15 h.p.) reciprocating compressor) to the LIMNO^{TM} was not sufficient to oxygenate the hypolimnion. In the spring of 1989, the original 11.2 kW compressor was

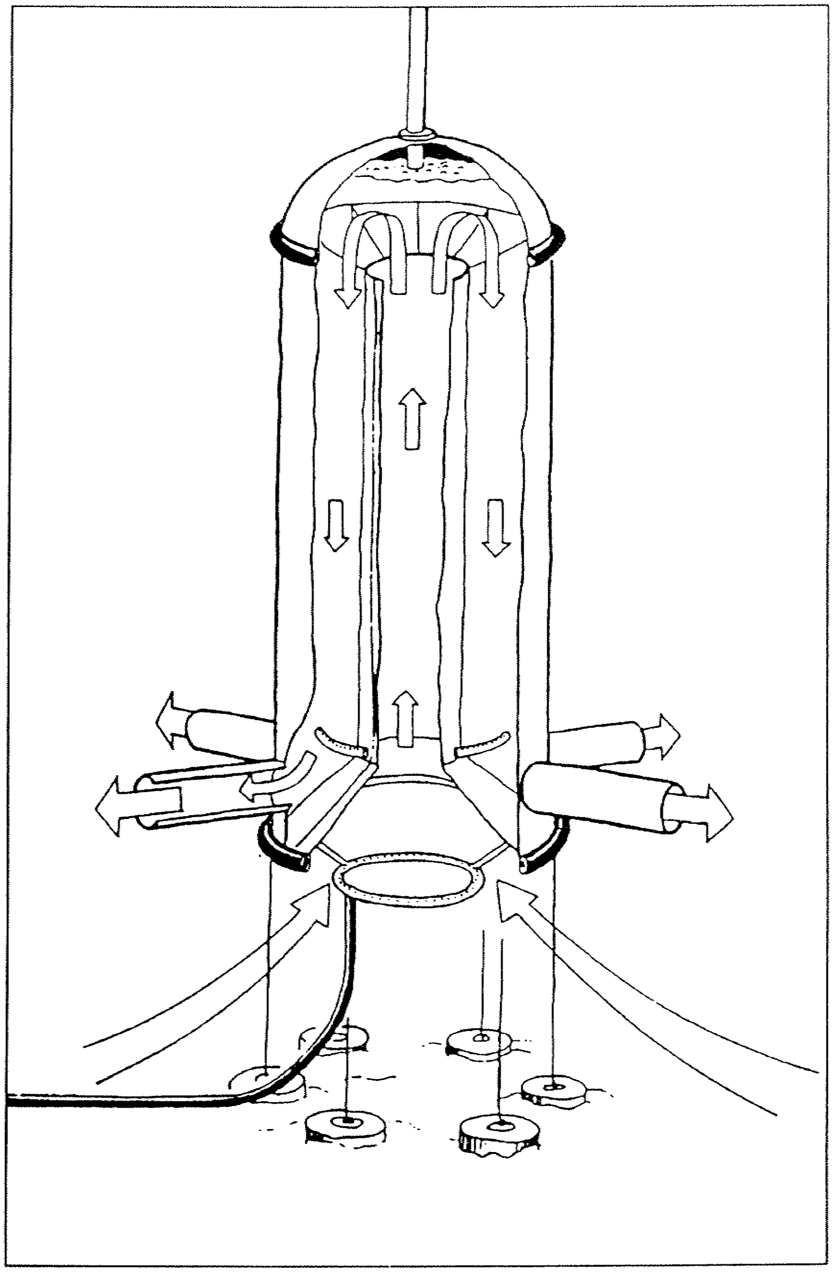

Fig. 2. Schematic diagram of the flexible LIMNO™ hypolimnetic partial lift aerator.

replaced with a 30 kW (40 h.p.) oil injected rotary screw compressor in an attempt to meet hypolimnetic oxygen demand. A diffuser with smaller orifices (0.6 mm diameter) was also installed at this time. The retrofitted system began operation in late April and continued to 25 May when the LIMNO™ broke loose from its anchors and floated to the surface. The system was removed from the lake and was out of service for the rest of 1989. Deoxygenation occurred and

Table 2. System design and operation dates for Medical Lake, WA aeration systems

System design	Compressor (kW)	Start date	End date
Partial lift	11.2	31 March 1987	31 October 1987
Partial lift	11.2	1 April 1988	Early September 1988
Partial lift	30.0	Late April 1989	25 May 1989
Full lift	30.0	27 June 1990	22 October 1990
Full lift	30.0	27 March 1991	5 November 1991
Full lift	30.0	31 March 1992	22 October 1992

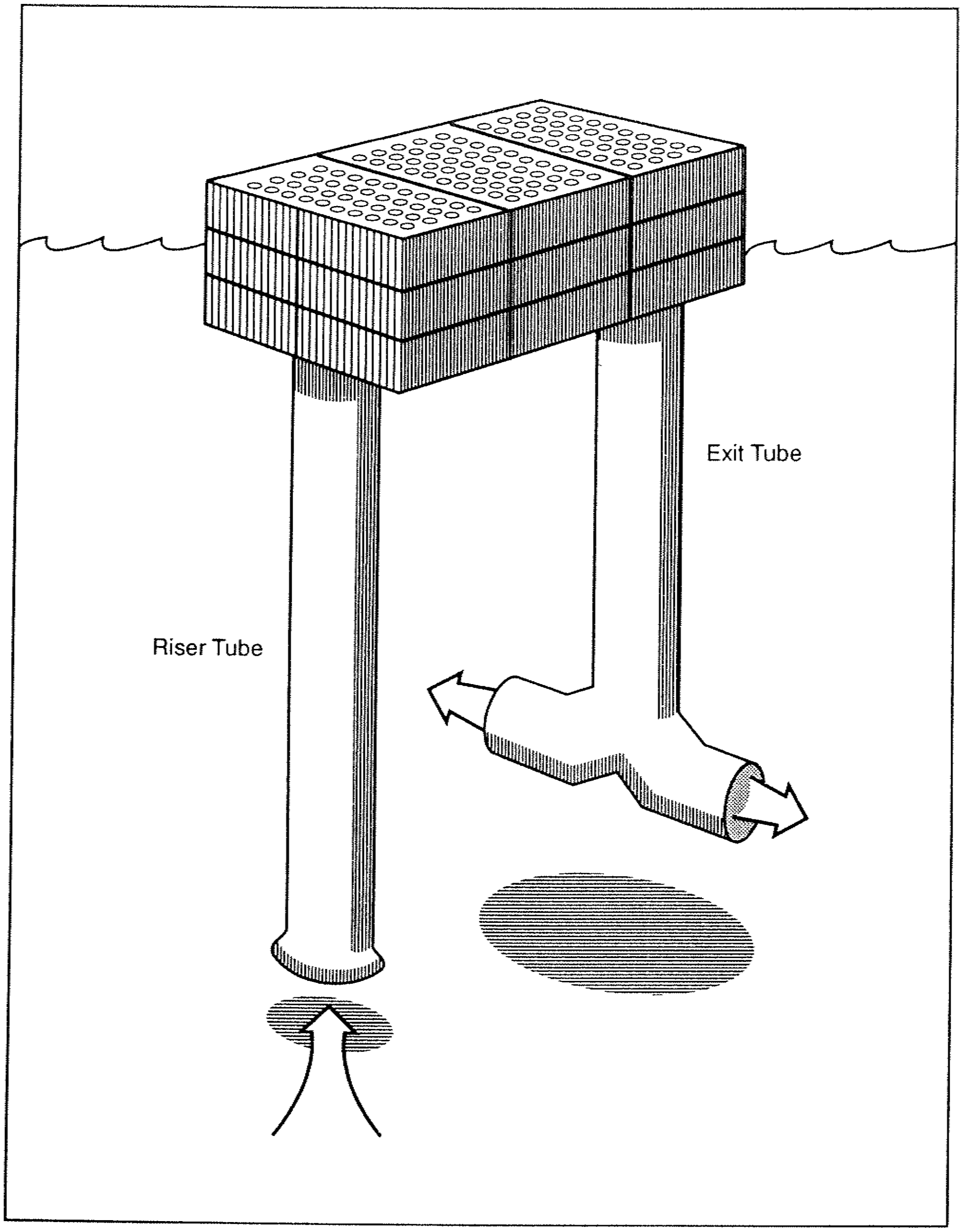

Fig. 3. Schematic diagram of a Bernhardt full lift hypolimnetic aerator.

the hypolimnion was anoxic from mid-June through the end of September. Upon inspection of the LIMNO™, the inner chamber was found to be shredded. It is not known if this was a design fault and/or a function of additional air flow supplied by the larger compressor.

In the spring of 1990, the LIMNO™ was replaced with two Bernhardt (1974) hypolimnetic aerators built to full lift design specifications (Ashley, 1985). These units consisted of insulated inflow (1.5 m dia × 12.5 m) and outflow (1.5 m dia × 10.7 m) tubes suspended vertically in the water column from an insulated (approx. 6.4 m L × 3.5 m W × 2.1 m H) fiberglass separator box (Fig. 3). A circular fine pore diffuser (140 μ dia pore size) was placed approximately 0.5 m in from the bottom of the inlet tube. The existing 30 kW compressor was fitted with separate valves so that air flow to each aerator could be regulated.

The aerators were positioned in the lake within the 16 m contour (Fig. 1) and the aeration periods were as shown in Table 2. Winter storage was accomplished by submerging the units just below the surface using an innovative water filled ballast tank system.

Statistics

Analysis of variance using monthly means for the growing season (June through October) was used to examine changes in selected water quality parameters between pre-aeration and aeration years. When a significant difference ($P \leqslant 0.05$) was found, a multiple comparison technique (least significant difference) was used to determine between which year(s) it occurred (Snedecor and Cochran, 1967). The variables selected for analysis included: hypolimnetic temperature, DO concentrations, NH_3-N and NO_3^--N concentrations, SRP and TP concentrations, euphotic zone Chl *a* concentration and phytoplankton biovolume.

RESULTS

Temperature

Medical Lake was stratified by April 1986 (Fig. 4). Rapid warming of surface waters occurred until mid-June and a well defined metalimnion existed between 4 and 8 m from late June through September. Stratification began to breakdown in October and the lake was isothermal by November. In general, the thermal properties described for 1986 are representative of those observed in 1984 and 1985.

In 1987, thermal stratification was well established by May and hypolimnetic temperatures were elevated by 2–3°C over pre-aeration years (Fig. 4). The temperature regimes of 1990, 1991 and 1992 followed similar trends except for additional hypolimnetic warming. The mean temperature of the hypolimnion during the growing seasons for the pre-aeration years ranged from 7.4 to 8.9°C. During 1987, partial lift aeration elevated mean hypolimnetic temperature to 10.2°C and mean hypolimnetic temperatures varied from 10.3 to 12.3°C with full lift operation. Monthly mean hypolimnetic temperatures during the growing season for all aeration years were found to be significantly higher ($P \leqslant 0.05$) than for the pre-aeration years. Differences in temperature between the pre-aeration years were not statistically significant. Temperatures in 1990 and 1991 did not differ from those observed in 1987, but mean 1992 temperatures (12.34°C) were significantly higher than those monitored for 1987 (10.18°C).

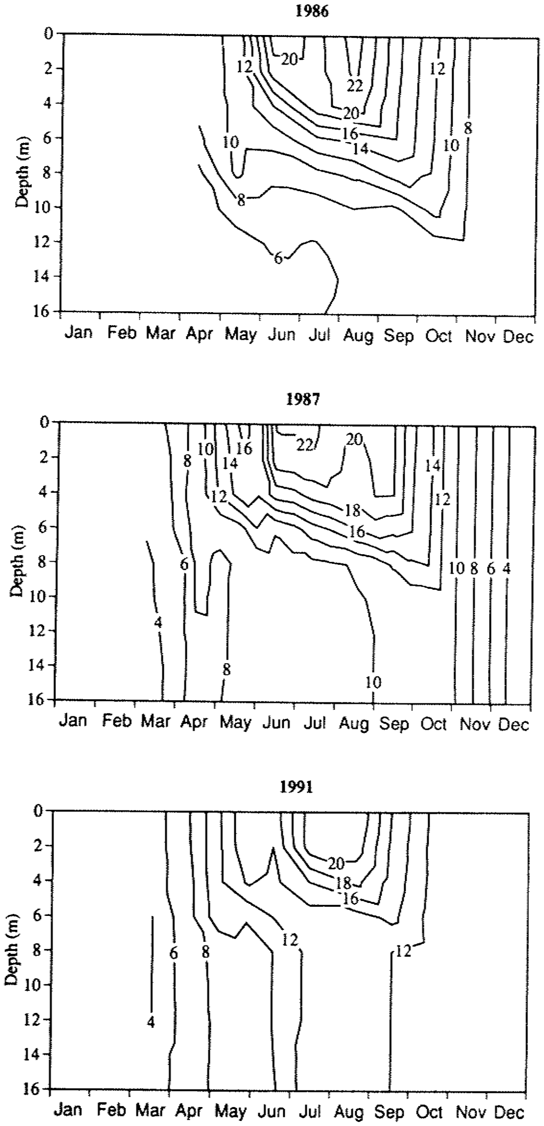

Fig. 4. The 1986, 1987 and 1991 isotherms (°C), Medical Lake, WA.

Dissolved oxygen

In 1986, DO in the hypolimnion was already depleted with the onset of thermal stratification (Fig. 5). Anoxia was evident in the hypolimnion until mid-October. Oxygen concentrations increased during fall overturn and by mid-November were greater than 4 mg/l throughout the lake. On 1 April 1987, just following the start of the partial lift system, concentrations near the bottom exceeded 9 mg/l. Dissolved oxygen then declined and hypolimnetic concentrations were less than 2 mg/l by 30 June 1987. Anoxia developed by mid-July and persisted into mid-October. Oxygen concentrations increased to 8 mg/l in early November following fall turnover. The full lift aeration system increased DO concentrations to over 10 mg/l through April, 1991. Oxygen depletion was again evident by May, but hypolimnetic concentrations were greater than 2 mg/l until mid-July. Hypolimnetic DO concentrations then remained at or above 1 mg/l until fall turnover.

The mean hypolimnetic DO concentration for the pre-aeration years during the growing season (June through October) was 1 mg/l. Mean concentrations for the partial lift and full lift aeration periods were 1.6 and 2.5 mg/l, respectively. Hypolimnetic DO concentrations were higher during aeration years; however, the 1987 levels were not statistically different from those measured in the pre-aeration years. Measures of DO content with the full lift system were statistically higher ($P \leqslant 0.05$) than those observed in the pre-aeration years, but did not differ significantly from the partial lift values.

Phosphorus

Water column TP concentrations were approximately 50 μg/l during April 1986. Concentrations in the hypolimnion increased over summer and reached a maximum of 398 μg/l in July 1986 (Fig. 6). After fall turnover, concentrations again approximated 50 μg/l throughout the water column. In 1987, with aeration, water column TP concentrations were about 30 μg/l through April and increased to a hypolimnetic maximum of 56 μg/l in late June. The

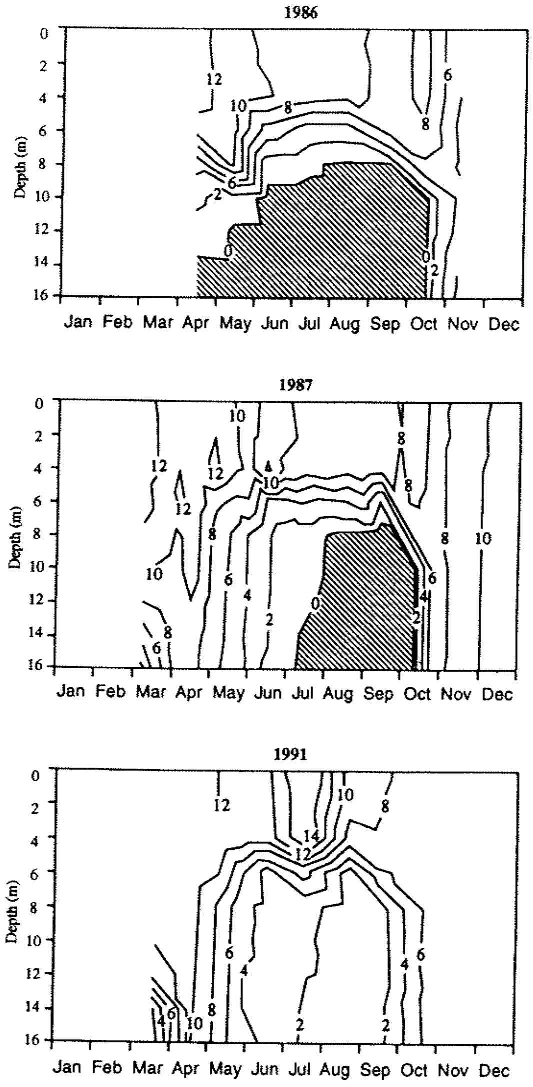

Fig. 5. The 1986, 1987 and 1991 isopleths of dissolved oxygen (mg/l), Medical Lake, WA.

entire water column again had concentrations of less than 30 μg/l by mid-October. Water column concentrations approximated 30 μg/l following the start of aeration in April 1991. Hypolimnetic TP concentrations increased to about 50 μg/l below the 6 m depth during the growing season, then declined to near 30 μg/l by mid-September.

Mean hypolimnetic TP concentrations during the 1984, 1985 and 1986 growing seasons were 149, 116 and 127 μg/l, respectively. Partial lift aeration in 1987 reduced mean hypolimnetic TP levels to 38 μg/l. The overall mean hypolimnetic TP level for full lift aeration years was 51 μg/l. The mean hypolimnetic TP concentrations for the partial and full lift aeration years were significantly lower ($P \leq 0.05$) than the pre-aeration period, but there was not a significant difference in TP between partial lift and full lift aeration. Soluble reactive phosphorus concentrations in the hypolimnion were similar to TP. Before aeration, concentrations increased in the hypolimnion during anoxia; however, hypolimnetic SRP concentrations declined significantly with both types of aeration systems (1986, 51.2 μg/l; 1987, 4.2 μg/l; 1991, 5.9 μg/l).

Nitrogen

Ammonia and nitrate nitrogen concentrations were observed through 1987. Ammonia nitrogen concentrations for the pre-aeration years averaged about 0.9 mg/l during the growing season (Fig. 7). Concentrations in 1987 for the same time period approximated 0.4 mg/l. Mean monthly concentrations of NH_3–N during the growing season were significantly lower ($P \leq 0.05$) with partial lift aeration. Mean hypolimnetic NO_3^-–N concentrations during the

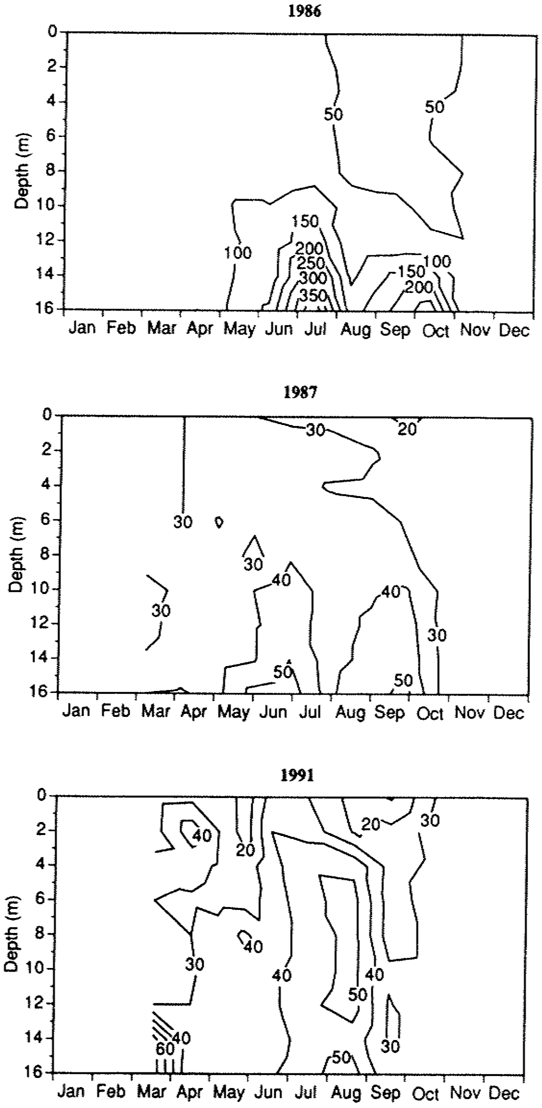

Fig. 6. The 1986, 1987 and 1991 isopleths of total phosphorus (μg/l), Medical Lake, WA.

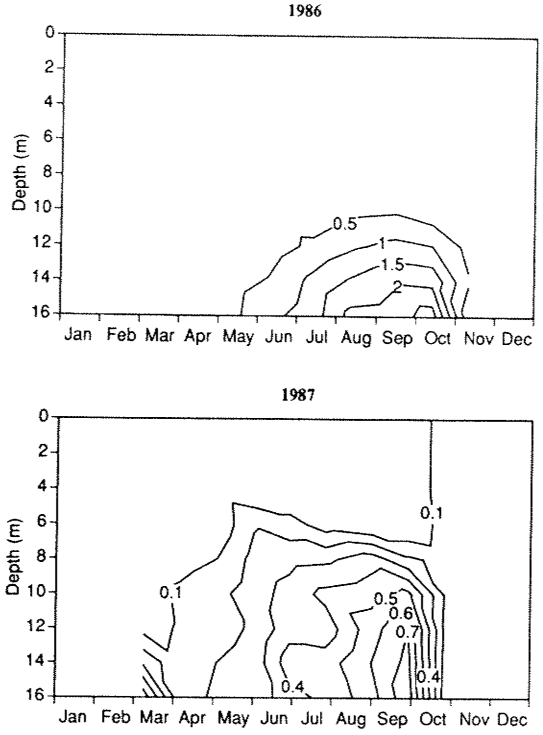

Fig. 7. The 1986 and 1987 isopleths of ammonia nitrogen (mg/l), Medical Lake, WA.

1984, 1985 and 1986 growing seasons were 0.15, 0.20 and 0.22 mg/l, respectively. The mean concentration for 1987 (0.19 mg/l NO_3^-–N) was not significantly different from the pre-aeration years.

Phytoplankton standing crop and chlorophyll a concentration

Phytoplankton biovolumes were only determined through 1987; however, Chl *a* concentrations were measured for all years of study (Fig. 8). Pre-aeration growing season means of phytoplankton biovolumes were 1.02 (1984), 1.25 (1985) and 1.29 (1986) mm^3/l. Pre-aeration biovolumes were larger; however, the means were not significantly different from the 1987 mean (0.74 mm^3/l) during partial-lift aeration.

Chlorophyll *a* concentrations usually followed biovolumes (Fig. 8). The overall mean Chl *a* concentration for the growing season of the pre-aeration years (1984–1986) was 5.13 mg/m^3. The mean Chl *a* value for the 1987 growing season was 4.91 mg/m^3, while the mean concentration for 1990–1992 was 5.87 mg/m^3. Mean monthly Chl *a* concentrations during aeration periods were not significantly different from pre-aeration values.

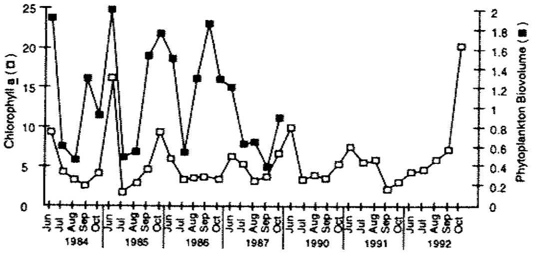

Fig. 8. Growing season phytoplankton standing crop (mm^3/l; 1984–1987) and chlorophyll *a* concentrations (mg/m^3; 1984–1987, 1990–1992), Medical Lake, WA.

DISCUSSION

Hypolimnetic aeration of Medical Lake has been recommended as the long term approach for water quality improvement as it would be less expensive than re-treatment with alum. The cost of the current full lift system to manufacture and install was $86,000. The 30 kW compressor was approximately $40,000 and annual operation and maintenance costs for the entire aeration system amounts to approximately $18,000. Assuming the lake would need an alum application every 8 to 10 years at $350,000 per treatment, aeration was considered as the less expensive restoration alternative. A discussion of specific water quality responses now follows.

Temperature

Hypolimnetic aeration can result in a minor (e.g. 2–4°C) increase in hypolimnetic temperature (Lorenzen and Fast, 1977; Ashley, 1983). A similar degree of warming was noted at Medical Lake as the mean hypolimnetic temperature during pre-aeration was approximately 8°C as compared to 10°C during partial lift aeration (1987) and about 11.5°C during full lift aeration (1990, 1991 and 1992). Elevated hypolimnetic temperatures in 1987 were attributable to an "averaging" of normal temperatures due to hypolimnetic mixing induced by the LIMNO™ system. In addition, the aerator extended to within 6 m of the surface, and some heat transfer from the epilimnion and metalimnion to water entrained in the tube undoubtedly occurred. Full lift aeration can also cause additional warming as the air-water mixture is transported to the surface where it is routed through a separator box and back into the outlet tube.

The temperature differences between aeration treatments were not statistically significant and illustrates the importance of insulating the inlet/outlet tubes and separator box in full lift systems. In addition, the proper design, installation and operation of such systems are paramount for the maintenance of hypolimnetic temperatures as close to pre-aeration conditions as possible. Respiration rates typically double with a 10°C rise in temperature, and given the inherent error in estimating hypolimnetic oxygen depletion rates, unintentional hypolimnetic warming could become a significant factor in underestimating hypolimnetic oxygen consumption.

Dissolved oxygen

Growing season mean hypolimnetic oxygen concentrations for pre-aeration, partial lift and full lift aeration periods were 1.0, 1.6 and 2.5 mg/l, respectively, with only the full lift increase being statistically significant. The LIMNO™ system was unable to meet the 1987 oxygen demand and hypolimnetic anoxia developed in July and persisted until mid-October. The continued anoxia suggests that the partial lift system was undersized. The oxygenation capacity of the LIMNO™ system was claimed to be 475 kg/day; however, the average calculated oxygen depletion rate for Medical Lake from 1980 through 1986 was only 280 kg O_2/day (McKee, 1983; Sexton, 1989).

In early May of 1987, before the onset of hypolimnetic anoxia, the maximum oxygen depletion rate was estimated to be 390 kg O_2/day. Consequently, SCUBA divers were employed to take inlet/outlet oxygen and outlet water velocity measurements in an attempt to determine the oxygenation capacity of the LIMNO™ system. The velocity of the water (mean of three outlet ports) through the aerator outlet ports (radius = 0.71 m) was determined to be 0.17 m/s and 0.15 m/s in July and August of 1987, respectively. These measurements were most likely over-estimated as the diver taking the measurements positioned the current meter near the center of the outlet arms to obtain a maximum velocity. The oxygen differential measurements between inlet and outlet ports were 1.68 mg/l in July and 1.71 mg/l in August. The oxygen input to the lake was then calculated to be 238 kg O_2/day (July) and 217 kg O_2/day (August). Therefore, Medical Lake's oxygen demand in May to August, 1987 was approximately 600 kg O_2/day (mean of 238 + 390 kg O_2/day and 217 + 390 kg O_2/day). This demand was about twice the estimated pre-aeration demand (280 kg O_2/day) and suggests the average (1980 through 1986) oxygen depletion rate estimates for Medical Lake were too low, and the LIMNO™ system was undersized, not meeting its design input specification of 475 kg O_2/day.

Two of the most common errors associated with hypolimnetic aeration are underestimating hypolimnetic oxygen depletion rates and overestimating aerator input rates (Ashley and Hall, 1990). Other investigators have found that hypolimnetic oxygen demand can temporarily increase three or four times with hypolimnetic aeration (Smith *et al.*, 1975; Lorenzen and Fast, 1977; Ashley, 1983). McQueen *et al.* (1984) investigated this phenomenon and were unable to statistically link increased oxygen demand with higher bacterial numbers, despite observing that total bacterial density was four times higher in their aerated enclosure. They identified several factors that could contribute to this situation including increased inorganic oxygen demand (i.e. iron and manganese oxidation), and the possibility that their INT-formazan reduction technique was unable to detect an increase in respiring bacteria. An additional factor may be attributed to greater turbulence in the hypolimnion which could resuspend fine sediments and increase hypolimnetic oxygen demand. Once again we are reminded that aerator sizing procedures are still somewhat of an "art", and further research is required on the two aforementioned subject areas (Taggart and McQueen, 1982; Ashley, 1985).

Since the LIMNO™ was unable to oxygenate the hypolimnion, approaches to retrofit the system began in 1988. The 1987 field assessment of aerator system efficiency pointed to the need for "hardware" changes. In 1989, the original compressor was replaced with a 30 kW compressor and the LIMNO™ was upgraded with a diffuser ring having a pore size of 0.6 mm orifice diameter. Bubble size is important for obtaining maximum oxygen transfer efficiency and fine pore diffusers are recommended as they produce smaller bubbles yielding a higher surface area to volume ratio which increases oxygen transfer efficiency (Ashley *et al.*, 1990; Ashley *et al.*, 1991). These design modifications probably increased the velocity of the water moving through the aerator and may have increased the transfer efficiency of oxygen to hypolimnetic water. However, failure of the LIMNO™ after only 30 days of operation resulted in deterioration of water quality to a level similar to that observed in the pre-aeration years.

Full lift hypolimnetic aeration resulted in minimum and mean (June through October) hypolimnetic oxygen concentrations of 1.0 and 2.5 mg/l, respectively. The full lift design was selected to replace the failed partial lift unit as full lift systems are accessible from the surface for monitoring and have a high performance rating in terms of oxygen transfer efficiency, oxygenation capacity and water:air ratio (i.e. induced water flow per unit air volume; Lorenzen and Fast, 1977). The design oxygen input specification for the two full lift units was 500 kg O_2/day using the existing 30 kW compressor (Ashley, 1990).

Based on the seasonal oxygen isopleths for 1991 (Fig. 5), hypolimnetic oxygen demand initially exceeded the aerator's input rate as oxygen concentrations declined to mid-July. However, oxygen concentrations then stabilized until mid-September before increasing again, suggesting that the aerator was meeting hypolimnetic oxygen demand. Unfortunately, a more detailed analysis of daily hypolimnetic depletion rates and aerator input rates is not possible due to the frequency and nature of the sampling program. It is possible that the full lift system may also have been unable to meet the hypolimnetic oxygen demand in the first year (i.e. 1987) of hypolimnetic aeration. The sequential nature of the experimental design does not allow clear separation of different aeration system effects vs natural time series changes in hypolimnetic oxygen concentrations. It is also possible that the observed increase in hypolimnetic DO in 1991 is simply a reflection of lowered hypolimnetic oxygen demand. Hypolimnetic oxygen depletion rates would be expected to decline over time due to gradual oxidation of accumulated organic and inorganic sediments (McQueen *et al.*, 1984); however, this effect has not been clearly demonstrated to date in the hypolimnetic aeration literature.

Phosphorus

Hypolimnetic aeration with the LIMNO™ and full lift aeration systems significantly reduced hypolimnetic SRP and TP concentrations in Medical Lake during the 1987 and 1990–1992 growing seasons. In 1987, even with anoxic conditions in the hypolimnion, sufficient oxygen was added to the hypolimnion that oxidation-reduction potentials were apparently maintained at elevated levels such that phosphorus was not released from the sediments. This is a particularly significant result as it demonstrates that (1) measurable concentrations of DO were not required to prevent phosphorus release from lake sediments and (2) a significant reduction in hypolimnetic phosphorus was demonstrated for the years of aeration.

The effect of hypolimnetic aeration on phosphorus concentrations has not been unequivocally demonstrated due to the nature of the experimental design (i.e. no external control), and the possibility of unrelated external events confounding or masking the response in question. For example, phosphorus concentrations increased one summer at Lake Waccabuck, and decreased the next, presumably in response to increased watershed loading (Garrell *et al.*, 1977). At Mirror Lake, phosphorus concentrations increased following hypolimnetic aeration, apparently due to storm water input (Smith *et al.*, 1975). The phosphorus response at Tory Lake was confounded by aerator leakage and poor farming practices within the watershed (Taggart and McQueen, 1981). At Black Lake, SRP concentrations were initially so high (700–800 μg/l) that the water quality implications of the 50% reduction were minimal (Ashley, 1983). The consistent nature of the Medical Lake response, even though 1987 DO concentrations were below desired hypolimnetic concentrations (e.g. 4–5 mg/l), suggests this was not a transient response, but a significant alteration in phosphorus flux at the sediment–water interface.

Nitrogen

Partial lift aeration in 1987 significantly reduced hypolimnetic NH_3–N levels over that observed in 1984, 1985 and 1986; however, NO_3^-–N concentrations remained essentially unchanged. One possible explanation for this response is that nitrate assimilation and denitrification exceeded nitrification. Other hypotheses to explain the apparent absence of NO_3^-–N included: (1) the hypolimnion did not contain sufficient populations of nitrifying bacteria (e.g. *Nitrosomas* sp. and *Nitrobacter* sp.); and (2) anoxic conditions in the hypolimnion minimized any potential nitrification. Given the ubiquitous nature of nitrifying bacteria in lakes, and since the overall nitrification reaction requires a minimum oxygen concentration of 0.3 mg/l (Wetzel, 1983), the cooler (<12°C) hypolimnion of Medical Lake had DO concentrations that were probably too low for the nitrification process to occur.

Possibly a more plausible deduction of no change in NO_3^-–N levels, is that volatilization of the NH_3 took place inside the aeration chamber with the subsequent discharge to the atmosphere. At the ambient pH of Medical Lake (range 7.4–9.3; McKee, 1983), the equilibrium status of NH_3 is shifted towards the gaseous form which is more easily volatilized than the ionized form (NH_4^+; Murphy and Brownlee, 1981). Volatilization of NH_3 was also suspected during hypolimnetic aeration of Black Lake, a eutrophic hardwater lake with pH values near 7.5–8.0 (Ashley, 1983).

Phytoplankton standing crop and chlorophyll a concentration

Mean growing season phytoplankton biovolumes and monthly Chl *a* concentrations during aeration periods were not significantly different from pre-aeration values. Following the successful oxygenation of the hypolimnion and subsequent reduction in internal phosphorus loading, long term reductions in phytoplankton biomass should follow as Medical Lake shifts to a less productive state. The fact that this has not been unequivocally demonstrated in the hypolimnetic aeration literature is probably due to the short time periods that hypolimnetic aeration experiments are typically conducted, the occurrence of uncontrolled nutrient loading during experimental periods, a lack of adequate controls and/or minimal pre-aeration data (McQueen and Lean, 1984).

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