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RICHARD B. RUSSELL LAKE WATER QUALITY INVESTIGATION

Hydraulic Model Investigation

by

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The thermal and dissolved oxygen regimes of the proposed Trotters Shoals (Richard B. Russell) Reservoir were simulated using a combination of physical and mathematical models. The effects of the Trotters Shoals Reservoir upon the thermal and dissolved oxygen regimes of a downstream impoundment, Clark Hill, were also evaluated. Both conventional power generation and pumped-storage power operations at Trotters Shoals Reservoir were studied. Three physical models were used to describe the expected hydrodynamics in Trotters

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20. ABSTRACT (Continued)

Shoals and Clark Hill Reservoirs. The withdrawal characteristics of the intakes and the entrainment, dilution, placement, and travel time of the inflow and pumpback density currents were determined. The results of the physical model tests were incorporated into a mathematical model capable of simulating the physical and chemical characteristics of an impoundment. This mathematical model was further modified to include a routine to predict the dissolved oxygen structure of an impoundment. The mathematical model was calibrated with observed thermal and dissolved oxygen data on the existing Hartwell and Clark Hill impoundments, which are immediately upstream and downstream, respectively, of the proposed Trotters Shoals Reservoir. The model was then used to simulate the thermal and dissolved oxygen regimes of Trotters Shoals Reservoir.

PREFACE

The water quality investigation reported herein was authorized by the U. S. Army Engineer District, Savannah, and conducted during the period June 1973-February 1974 in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Structures Division. The physical model studies and mathematical simulations were conducted by SP4 T. L. Gloriod and D. G. Fontane, respectively, under the direct supervision of Mr. J. P. Bohan, Chief of the Spillways and Channels Branch. Mr. B. Loftis assisted in the development and application of the mathematical model. This report was prepared by Messrs. Fontane and Bohan.

During the conduct of this investigation and the drafting of the report, the project under study was named the Trotters Shoals Dam and Lake. Since that time, the name of the project has been officially changed to the Richard B. Russell Dam and Lake. All references in this report to the Trotters Shoals project should now be more properly referred to as the Richard B. Russell project.

During the course of the study, meetings were held in Atlanta and at WES to discuss various phases of the study. The meeting at WES in October 1973 was attended by the following personnel: Messrs. J. Crockford and L. Kirkland, Georgia Game and Fish Division; Messrs. R. A. Herwig and L. A. Neal, Georgia Environmental Protection Division (Water Quality Control); Dr. J. M. Lawrence, Auburn University and Consultant to Savannah District; Mr. C. J. Turner, Auburn University; Mr. M. A. Churchill, Consultant to Savannah District; Messrs. D. L. Robey and G. R. Drummond, Ohio River Division; Messrs. J. J. Raynes, R. L. Tinsley, and Dr. A. G. Holler, Jr., South Atlantic Division; and Messrs. J. G. Higgs, J. W. DeWitt, C. Carter, F. H. Posey, Jr., and H. T. DeRigo, Savannah District.

Directors of WES during the conduct of this study and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U. S. statute)	1.609344	kilometers
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

RICHARD B. RUSSELL LAKE WATER QUALITY INVESTIGATION

Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. The proposed Trotters Shoals (Richard B. Russell) project will impound the Savannah River between the headwaters of Clark Hill Reservoir and the Hartwell Dam (Figure 1). The project will provide peaking

Figure 1. Vicinity map

power capability through conventional generation. In addition, consideration is being given to providing pumped-storage power facilities in the Trotters Shoals project.

Purpose of Study

2. The purpose of this study was to determine the temperature and dissolved oxygen regimes of the Trotters Shoals Reservoir as well as the effect of Trotters Shoals Reservoir on the temperature and dissolved

oxygen regimes of Clark Hill Reservoir. Both conventional and pumped-storage power operations were considered. The above task was accomplished through the use of physical and mathematical models.

PART II: APPROACH

Physical Models

3. A physical modeling approach was used for this analysis because of the extremely dynamic nature of the three hydropower plants in the Hartwell, Trotters Shoals, Clark Hill system. The operation required to provide peaking power through conventional generation at the three plants and possibly through pumped-storage power generation at Trotters Shoals will create hydrodynamic effects that could not be described without investigation of the physical phenomenon. Physical models were used to provide guidance for modifying the mathematical model that would be used to simulate the entire system.

4. A flume containing an undistorted 1:80-scale model of the Trotters Shoals intake and penstock was used to determine whether the selective withdrawal characteristics of the intake could be predicted using the generalized U. S. Army Engineer Waterways Experiment Station (WES) selective withdrawal technique.[1] These penstocks and those at Hartwell and Clark Hill are unusual because the intake openings are approximately one-third the depth of the normal operating pool, the top and bottom intake geometries are unsymmetrical, and the penstocks are inclined at an angle of approximately 45 degrees. The test facility (Figure 2) was stratified using fresh and saline water.

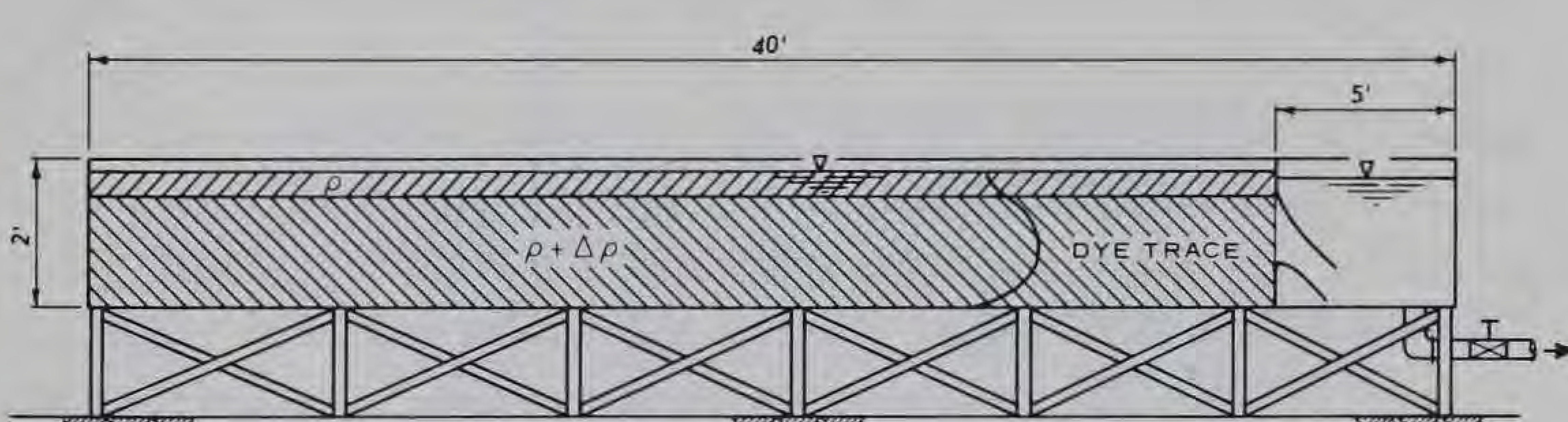

Figure 2. Selective withdrawal test facility

Flow was then initiated through the penstock, and flow patterns in the stratified flume were observed using dye streaks. These observations were then compared with flow patterns predicted based on the generalized WES selective withdrawal technique. The comparison of the predicted and observed flow patterns was unsatisfactory, and the development of a revised technique was required. This revised technique involved using two reference elevations, as shown in Figure 3, for predicting the withdrawal limits and assuming that 40 percent of the total flow passed

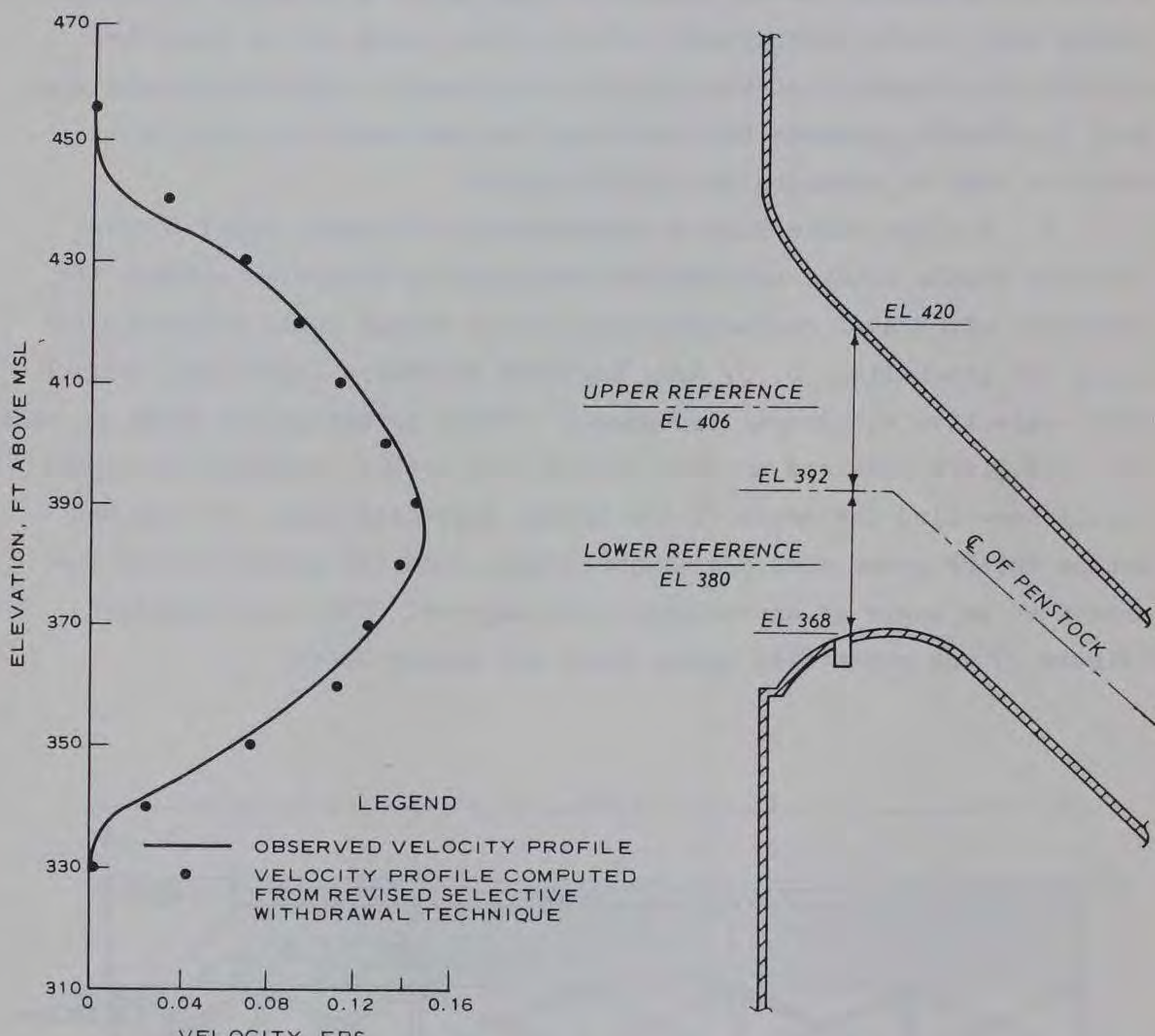

Figure 3. Typical comparison of observed and predicted velocity profiles for flow through inclined penstock from a stratified reservoir

through the upper portion of the intake and 60 percent passed through the lower portion. The flow patterns for the two reference elevations were then predicted based on the techniques described in reference 1, and the predicted patterns were superimposed and added to obtain the composite flow distribution. This procedure was incorporated into the mathematical model.

5. The second model was an undistorted 1:80-scale model of the Trotters Shoals spillway and powerhouse reproducing approximately 1/2 mile* of both the approach and exit channels. This model, which existed at WES from a previous study of the spillway hydraulics, was used to investigate the near-field dilution and areal spread of the generation and pumpback currents at Trotters Shoals. Fresh and saline waters were used to stratify the Trotters Shoals pool. During the pumping operation, the pumpback jet extended up to the water surface and remained near the surface for some distance upstream before dropping below the surface and seeking its density level. The physical boundaries of the model prevented determination of the actual expected areal spread of the pumpback plume. The generation tests in this model were conducted with several different discharges up to the maximum of 60,000 cfs. Again the physical boundaries of the model interfered with the areal spread observations and with the determination of the plunge point location in the downstream channel. However, dilution measurements were made and used to verify the third physical model.

6. The third model was a distorted scale model (1:8000 vertical length and 1:200 horizontal length) of the Trotters Shoals and Clark Hill impoundments. This model was used to study the response of the stratified reservoirs induced by the unsteady operation of the three powerhouses. With conventional power generation at Trotters Shoals, the releases from Hartwell, Trotters Shoals, and Clark Hill powerhouses will range from 0 to 35,000 cfs during a period of less than one day. Pumped storage at Trotters Shoals will increase the releases from

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

Trotters Shoals to 60,000 cfs. Pumpback rates from the Clark Hill headwaters to the Trotters Shoals pool will be 20,000 cfs. The model was constructed of plastic and reproduced the elevation-volume relationships for the two impoundments. Saline and fresh waters were used to reproduce the density variations that would exist in the prototype due primarily to temperature differences. The expected unsteady operation of the powerhouses was reproduced using a timing device and a piping system with pumps, solenoid valves, needle valves, and rotameters to control the direction and quantity of flow. A schematic representation of the model is shown in Figure 4. Various initial stratification conditions were reproduced in order to simulate different seasons of the year. The physical model was run for periods simulating one to three months in the prototype. Visual observations were recorded with movie cameras, and dilution measurements were made with conductivity and temperature sensors. The results of the model tests, which will be described in more detail in subsequent paragraphs, include the determination of travel times for flows to pass through the two model impoundments, levels and thicknesses of inflow, entrainment and pumpback currents, locations of plunge points, and magnitudes of entrainment and resulting dilution.

Mathematical Model

7. The mathematical model used for this study was based on an extention of the work by Clay and Fruh.[2] This model, referred to as "WESTEX," is a reservoir water quality parameter budget model. The model is one-dimensional in that it allows variation only in the vertical direction and assumes uniformity in the other two spatial directions. WESTEX has four basic components. The function of the first component is to add the quantity and quality of the inflow and determine the state and total budget of the reservoir. The second component accounts for external sources and sinks of the system such as the heat transfer at the air/water interface. The third component applies a vertical diffusion analogy, based on thermal

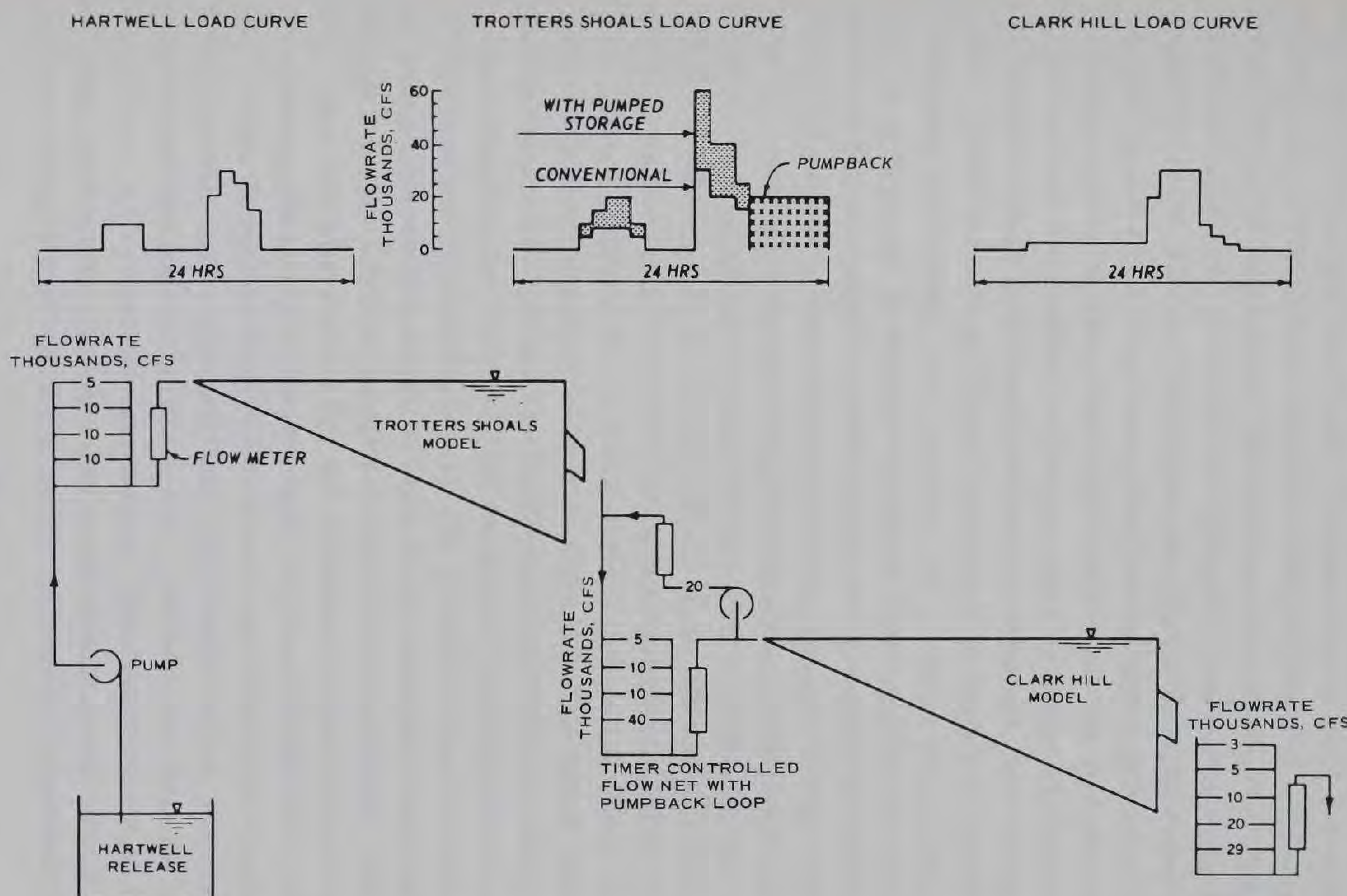


Figure 4. Reservoir models and corresponding load curves

diffusion, to the gradients of each water quality parameter and computes the new state of the reservoir. The final component selectively withdraws flow from the reservoir, computes the quality of the release, subtracts the quantity and quality of the outflow, and determines the resulting state and total budget of the reservoir. The model considers these four components during each computation interval, which for this study was one day. WES has previously used this modified model to predict the thermal and conservative chemical regimes of an impoundment.[3] Since dissolved oxygen is a nonconservative parameter, a routine was incorporated into the model to perform the dissolved oxygen computations. This routine was based on the work of Bella[4] and Fruh and Davis.[5] The upper, well-mixed layers in the reservoir were assumed to be saturated with dissolved oxygen. This saturation extended to the depth at which a temperature difference of 1°C from the surface temperature existed. The selection of this temperature difference was based on an analysis of observed temperature and dissolved oxygen profiles in Hartwell and Clark Hill Reservoirs. Since the hydrodynamic mechanisms for vertical transport of dissolved oxygen are not present in the one-dimensional model, a diffusion analogy similar to that for thermal diffusion was used to obtain the desired downward transport of dissolved oxygen. A dissolved oxygen depletion term was applied to each layer in the reservoir. This dissolved oxygen depletion term was based on a temperature-dependent deoxygenation coefficient and a constant oxygen demand term. The values of these parameters were determined based on the work of Fruh and Davis[5] and calibrations based on observed dissolved oxygen profiles. Additionally, the dissolved oxygen depletion term was applied to the dissolved oxygen content of the inflow for a period of time equal to that required for the inflow current to travel through the reservoir. This travel time was obtained from the physical model studies. The inflow, with its depleted dissolved oxygen content, was then placed into the reservoir. The resulting in-reservoir dissolved oxygen predictions were those expected near the dam.

8. The mathematical model contains certain coefficients, such as the coefficient of vertical diffusion and the oxygen demand

coefficient, which must be evaluated for the specific project. The model was verified on the basis of two years of observed temperature and dissolved oxygen data obtained from both Hartwell and Clark Hill Reservoirs. During the verification runs, the values of the coefficients were adjusted until acceptable comparisons were obtained between the predicted and observed temperature and dissolved oxygen profiles. The coefficients finally used were found to be the same for the Hartwell and Clark Hill Reservoirs. Some representative results from these verifications are shown in Figures 5 and 6. These coefficients were then used to simulate Trotters Shoals Reservoir because the three impoundments are similar in size and are subject to similar meteorological and hydrological conditions.

9. The method frequently used for selecting study years to conduct a reservoir thermal budget investigation was not used for this project. Generally, some combination of wet, dry, and average years, based on meteorological and hydrological records, is selected for study. However, other factors influenced the selection of study years for this investigation. Since the development of a dissolved oxygen prediction routine was a primary objective, only years during which sufficient dissolved oxygen data were available at Hartwell and Clark Hill were considered. In addition, the flows into Trotters Shoals and Clark Hill will probably remain reasonably constant in quantity and quality year after year because they are fixed, single-level releases from upstream impoundments. The release levels are well below the water surface so that changes in meteorological conditions will have a minor effect on the quality of the water released. For this case, the inflow and outflow are the primary factors controlling the quality structure of the hypolimnion of these impoundments. Since the Trotters Shoals and Clark Hill inflow and outflow quantities and qualities will remain fairly constant, the temperature and dissolved oxygen conditions in the reservoirs and of the releases should not vary considerably for other years investigated. The results of the Hartwell Reservoir simulation will affect the simulations of the Trotters Shoals and Clark Hill Reservoirs because the Hartwell Reservoir is the farthest

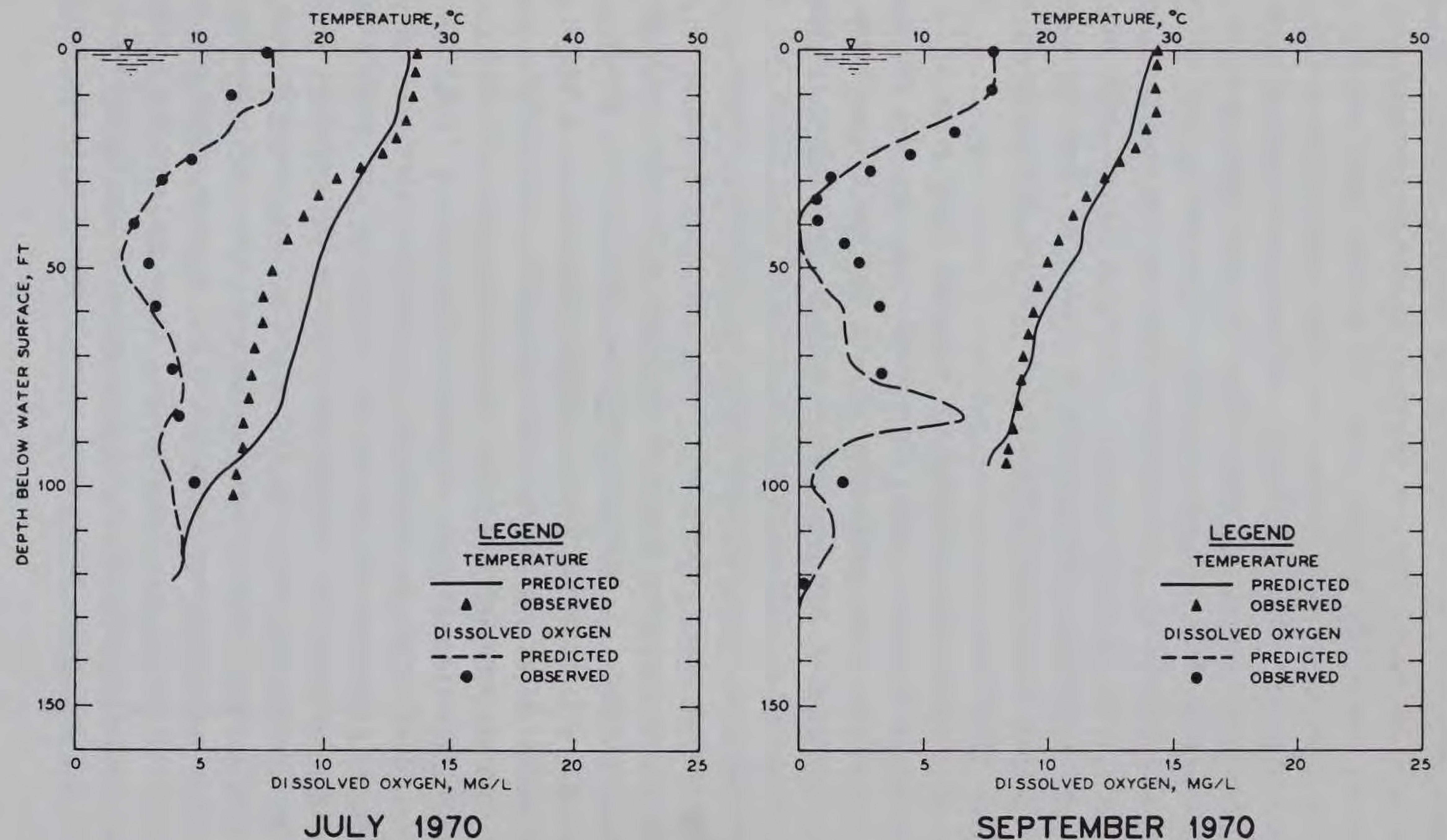


Figure 5. Clark Hill verification test results

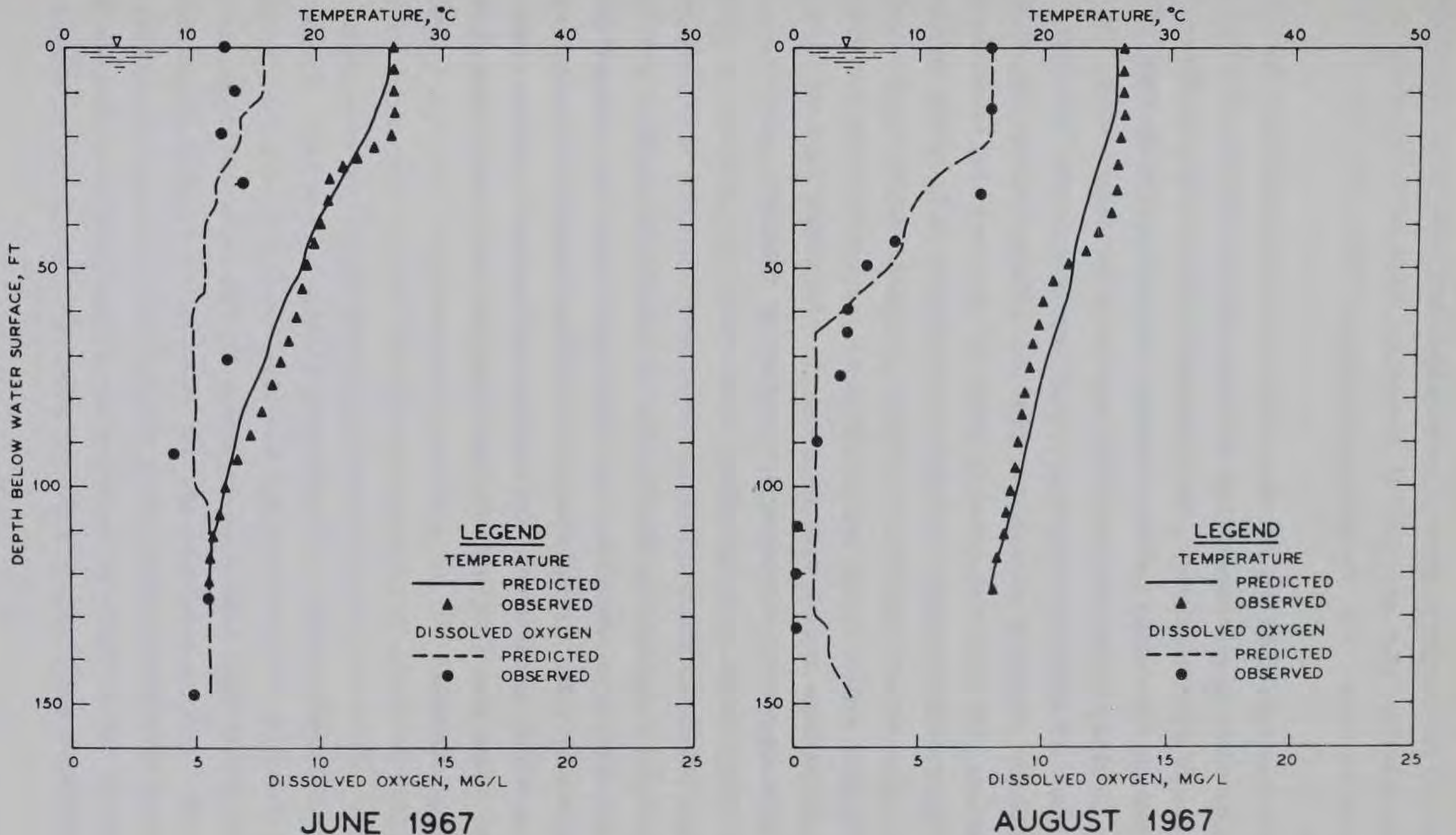


Figure 6. Hartwell verification test results

upstream. Since complete sets of temperature and dissolved oxygen data were available for 1966 and 1967 at Hartwell, these were selected as the years to be studied. For the period of record, these are years of average flow.

10. Another modification was made to the mathematical model in order to simulate the dissolved oxygen structure of Trotters Shoals Reservoir. It is anticipated that approximately 1000 feet of free-flowing stream will exist between Hartwell Dam and the headwaters of Trotters Shoals. Using observed flow and dissolved oxygen data, the oxygen uptake of Hartwell releases through the powerhouse, tailrace, and a 1000-foot reach of stream was computed. This computed uptake was then added to the dissolved oxygen content of the Hartwell release and used as the dissolved oxygen content of the inflow to Trotters Shoals.

11. The results of the mathematical simulations represent conditions that will exist in the impoundments in the vicinity of the dam because the maximum travel time required for the inflow to reach the dam was used in the dissolved oxygen prediction routine. Additional analyses were conducted to determine dissolved oxygen profiles at various longitudinal locations along the impoundments. The dissolved oxygen content of the flow entering the impoundments was depleted and the resulting values one-quarter and one-half way through the impoundments were determined. The thicknesses of the inflow currents, the magnitudes of surface water entrainment, the resulting dilution of inflows, and the travel times for flow through the reservoirs were determined from the physical models.

PART III: MATHEMATICAL SIMULATIONS

Conventional Power

12. Hartwell, Trotters Shoals, and Clark Hill Reservoirs were simulated for study years 1966 and 1967 with conventional power generation at Trotters Shoals. First the simulations were conducted using the computed dissolved oxygen of the Hartwell release plus the computed uptake in the 1000-ft reach of free-flowing stream as the inflow dissolved oxygen to Trotters Shoals. Similarly, the dissolved oxygen of the Trotters Shoals release was used as the inflow dissolved oxygen to Clark Hill. Simulations were then made assuming that oxygen could be added at both Hartwell and Trotters Shoals Dams such that the minimum release dissolved oxygen could be kept to 6 mg/ℓ. As a basis for comparison, Clark Hill Reservoir was simulated without the Trotters Shoals project for study years 1966 and 1967. These simulation results are representative of existing conditions. The simulation results are presented as isogram plots representing the reservoirs' temperatures and dissolved oxygen structures and as plots of release temperature and dissolved oxygen.

13. Prior to analysis of these results, several points should be noted about the plots. Temperature and dissolved oxygen profiles obtained from the isogram plots may be slightly different from those actually computed because the isogram plots were developed from twelve computed end-of-month profiles. Some smoothing between these twelve profiles may have occurred during plotting of the isograms. Also, it can be noted that on some of the isogram plots a slight stratification of temperature and dissolved oxygen exists during the winter months. In nature, wind mixing usually overcomes the slight stratification indicated during this time of year and the reservoir is uniformly mixed. The mathematical model has no mechanism to handle wind mixing and induces mixing only if an unstable density condition occurs. The slight stratification shown on the isogram plots during the winter months is a mathematical condition and is not expected to exist in the prototype. In regard to the plots of release dissolved oxygen, the mathematical

model computes the quality of the release as it enters the penstock. It was realized that as water passed through the intake and out into the tailrace, air could be entrained and the dissolved oxygen content would be increased. Measurements of turbine aeration conducted at both Hartwell and Clark Hill Reservoirs indicated that, on a daily average, a dissolved oxygen uptake of up to 1 mg/ℓ could be expected, depending on the dissolved oxygen content of the water entering the penstock, the water temperature, and the discharge. To obtain the release dissolved oxygen content from Hartwell and Clark Hill, the following algorithm was employed. If the release dissolved oxygen content entering the penstock was 0 mg/ℓ, then 1 mg/ℓ was added to obtain the predicted release dissolved oxygen content. If the release dissolved oxygen content entering the penstock was 10 mg/ℓ or greater, no uptake was added. For dissolved oxygen contents between 0 and 10 mg/ℓ, linear interpolation was applied to compute the amount of uptake that should be added to obtain the predicted release dissolved oxygen content. This algorithm was not applied to the Trotters Shoals releases since the draft tubes at Trotters Shoals will be submerged in approximately 30 ft of water.

14. Since Hartwell Reservoir will not be affected by the Trotters Shoals project, only one set of simulations for Hartwell was required. The results of these simulations are shown in Plates 1 and 2. The results of the simulations of Clark Hill without Trotters Shoals are shown in Plates 3 and 4.

15. The results of the simulations of Trotters Shoals Reservoir with and without oxygen added to the Hartwell release in order to maintain a minimum dissolved oxygen content of 6 mg/ℓ are shown in Plates 5-8. The results of the Clark Hill simulations with and without oxygen added to the Hartwell and Trotters Shoals releases are shown in Plates 9-12.

Pumped Storage

16. The mathematical model was modified to analyze the proposed pumped-storage operation. From the physical models, it was noted that

releases from Trotters Shoals mixed with a portion of the Clark Hill headwaters and created an underflow that resulted in a two-layer stratification in the Trotters Shoals tailrace. The mathematical model was modified such that the releases during power generation entrained 20 percent by volume of Clark Hill surface water to create the lower layer in the tailrace, and the quality of the upper layer was determined from the previous Clark Hill simulations. The temperature and dissolved oxygen content of the pumpback were then determined by selective withdrawal through the Trotters Shoals draft tubes from the two-layered stratification in the tailrace.

17. From the physical models, it was also determined that the pumpback jet was directed up to the surface of the Trotters Shoals pool. As the jet moved upward from the penstock, it entrained an amount of hypolimnial water approximately equal to the volume of pumpback and an amount of epilimnial water approximately equal to one-half the volume of the pumpback. The pumpback current then plunged and became an intermediate density current moving upstream. The advantage of the unsteady operation of the model was illustrated in determining the level of the hypolimnion from which the entrained water was drawn during pumpback. The dynamic effect of stopping the turbines and beginning the pumps is to limit the level of entrainment to a layer near the invert of the intakes and not to the bottom layers of the reservoir. The result of this effect, which was not observed during steady operation of the model, was to maintain a supply of cold water in the bottom of the reservoir during the summer months. Several different percentages of epilimnion and hypolimnion entrainment were investigated to determine the sensitivity of the reservoir thermal and dissolved oxygen structures to these entrainments. As the percentages of entrainment were increased, the surface temperatures decreased, the distinct two-layer stratification became more linear from top to bottom, and the dissolved oxygen content of the intermediate layers increased. The entrainment percentages used in the simulations were determined from the physical model. The mathematical model was modified to account for pumpback flow and its associated entrainment and dilution. Figure 7 illustrates the

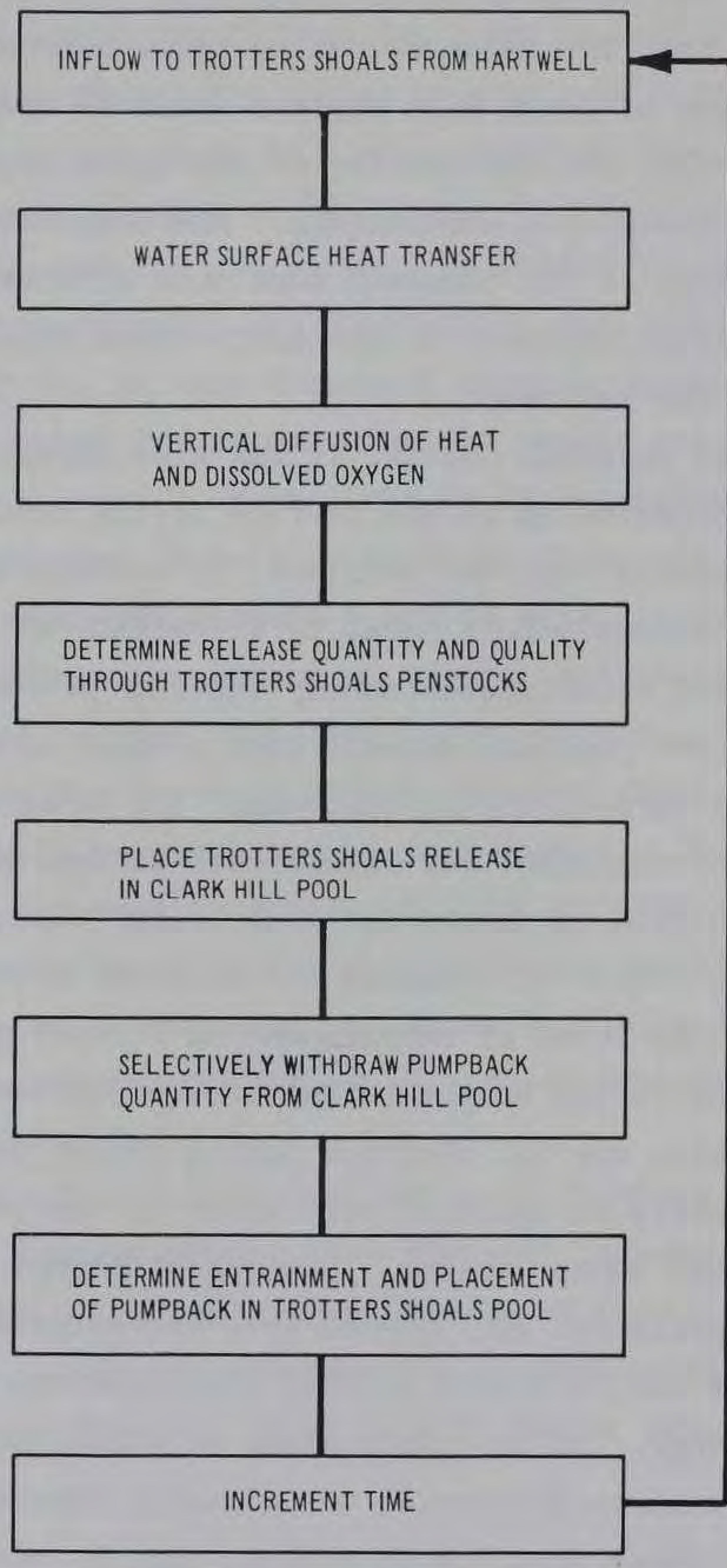


Figure 7. Flow diagram of Trotters Shoals Lake simulation with pumped storage

procedure used to account for pumpback.

18. The system was simulated with the pumped-storage operation at Trotters Shoals for study years 1966 and 1967. The results of the simulations of the Trotters Shoals Reservoir with and without oxygen added to the Hartwell release in order to maintain a minimum dissolved oxygen content of 6 mg/ℓ are shown in Plates 13-16. The results of the Clark Hill simulations with and without oxygen added to the Hartwell and Trotters Shoals releases are shown in Plates 17-20.

Additional Results

19. Temperature and dissolved oxygen profiles at various longitudinal locations along the impoundment were developed for both Trotters Shoals and Clark Hill Reservoirs. October 1 was selected for plotting, as this is the most critical period for dissolved oxygen at the dam and shows the greatest variation of dissolved oxygen in the longitudinal direction. For conventional power generation at Trotters Shoals, the results of the calculations for Trotters Shoals Reservoir with and without oxygen added to the Hartwell release in order to maintain a minimum dissolved oxygen content of 6 mg/ℓ are shown in Plate 21. The results of the Clark Hill calculations with and without oxygen added to the Hartwell and Trotters Shoals releases are shown in Plate 22.

20. For pumped-storage operation at Trotters Shoals, the results of the calculations for Trotters Shoals with and without oxygen added to the Hartwell release to maintain a minimum dissolved oxygen content of 6 mg/ℓ are shown in Plate 23. The results of the calculations for Clark Hill with and without oxygen added to the Hartwell and Trotters Shoals releases are shown in Plate 24. Additionally, plots of the longitudinal profiles for Clark Hill Reservoir without the Trotters Shoals project are shown in Plate 25.

PART IV: DISCUSSION OF RESULTS

Temperature

21. The results of the Trotters Shoals Reservoir simulations with conventional power generation yielded a thermal stratification pattern in the Trotters Shoals pool (Plates 5 and 7) similar in shape to that of Hartwell (Plate 1), but generally 2°C cooler throughout the upper 120 ft of the pool and about 3°C warmer in the bottom 40 ft from August through October. This was expected because the cool releases from Hartwell are the major inflow source to Trotters Shoals. Similarly, since Trotters Shoals releases discharge into Clark Hill, the simulation of Clark Hill with conventional power generation at Trotters Shoals (Plates 9 and 11) yielded a slightly cooler thermal structure than that which existed without Trotters Shoals (Plate 3). The temperatures at the surface and bottom of Clark Hill with conventional power generation at Trotters Shoals were essentially the same as those in Clark Hill without Trotters Shoals. However, throughout a 60-ft-deep zone corresponding to the elevation of the opening of the intake in Clark Hill, the temperatures in Clark Hill with conventional power generation at Trotters Shoals were about 4°C cooler during August through October than those at the same location in Clark Hill without Trotters Shoals.

22. The simulations of Trotters Shoals Reservoir with pumped-storage operation (Plates 13 and 15) indicated that the reservoir remained stratified although the thermocline was depressed and the well mixed epilimnion extended approximately 30 ft deeper into the pool during August through October than it did with conventional power generation (Plates 5 and 7). As a result of pumped-storage operation at Trotters Shoals, hypolimnial water was released during generation and pumped back about 1°C or 2°C warmer due to entrainment in the tailrace. The pumped-storage operation also caused entrainment of Trotters Shoals hypolimnion and epilimnion waters by the pumpback jet. As a result of these mechanisms, the epilimnion was about 1°C cooler and the hypolimnion 2°C warmer, during August through October, than they were for

conventional power generation. The predicted temperatures of the releases from Trotters Shoals with pumped storage (Plates 14 and 16) were about 2°C warmer during August through October than they were with conventional power generation (Plates 6 and 8). However, the upper 100 ft of the thermal structure of Clark Hill with pumped storage at Trotters Shoals (Plates 17 and 19) was still approximately 2°C cooler than it was without the Trotters Shoals project (Plate 3). For all cases simulated with conventional and pumped-storage operation at Trotters Shoals, the predicted release temperatures of both Trotters Shoals and Clark Hill Reservoirs did not exceed 70°F (21.1°C), which is the established upper limit for a cold water fishery in the State of Georgia.

Dissolved Oxygen

23. Analysis of the predicted dissolved oxygen structure for Trotters Shoals Reservoir indicates that a 1 mg/ℓ to 2 mg/ℓ higher dissolved oxygen content will be available throughout the pool during August through October with the pumped-storage operation (Plates 13 and 15) than with conventional power generation (Plates 5 and 7). This was attributed to the increased depth of the well mixed epilimnion bringing dissolved oxygen from the surface layers down into the pool. The simulations also indicate that about 2 mg/ℓ more dissolved oxygen will be available in the lower half of the pool during August through October for both conventional power (Plates 5 and 7) and pumped-storage operation (Plates 13 and 15) when oxygen is added to the Hartwell releases. The addition of oxygen to the Hartwell releases increases the dissolved oxygen available in the upper reaches of Trotters Shoals by about 2 mg/ℓ (Plates 21 and 23). During August through October, the level of dissolved oxygen in Trotters Shoals and the computed release dissolved oxygen content for pumped-storage operation (Plates 13-16) are approximately the same as the dissolved oxygen conditions for conventional power operation with oxygen added to the Hartwell releases (Plates 5-8). However, in the longitudinal direction, approximately 2 mg/ℓ more dissolved oxygen is available during August through October with the

addition of oxygen (Plates 21 and 23). The results of calculations of the depletion of dissolved oxygen in an inflow current indicate that an inflow current entering Trotters Shoals with a dissolved oxygen content of 7 mg/ℓ will travel approximately 10-12 miles below Hartwell Dam before the dissolved oxygen content drops to 6 mg/ℓ and will travel approximately 25-28 miles below Hartwell Dam before the dissolved oxygen drops to 3 mg/ℓ.

24. At present, approximately 30 miles of free-flowing stream exists between Hartwell and Clark Hill Reservoirs. As a result, the dissolved oxygen content of the inflow to Clark Hill is generally at saturation. The construction of the Trotters Shoals project will eliminate this free-flowing reach and, even with the addition of oxygen to the Trotters Shoals releases, generally less dissolved oxygen (i.e., the difference between the saturation level and 6 mg/ℓ) will be entering Clark Hill than is presently entering. However, a comparison of Clark Hill's dissolved oxygen content for all simulations, conventional and pumped-storage operations at Trotters Shoals with and without oxygen added to the Hartwell and Trotters Shoals releases (Plates 9, 11, 17, and 19), indicates a dissolved oxygen content in the area of the dam during August through October of only 1 to 2 mg/ℓ less than with existing conditions (Plate 3). This is a result of the relatively long (six to eight weeks) travel time through Clark Hill Reservoir.

25. Although the predicted dissolved oxygen situation at the Clark Hill Dam is similar for all simulations, about 3 mg/ℓ more dissolved oxygen is available in the reservoir's upper reaches during August through October if oxygen is added to the Trotters Shoals releases. Calculations of the depletion of the dissolved oxygen content of an inflow current indicate that an inflow with dissolved oxygen equal to 6 mg/ℓ will travel approximately 20-25 miles below Trotters Shoals Dam before the dissolved oxygen content is reduced to 3 mg/ℓ.

26. In conclusion, the simulations indicate that pumped-storage operation at Trotters Shoals will provide 1 to 2 mg/ℓ more dissolved oxygen in Trotters Shoals Reservoir and in its releases to Clark Hill than will conventional power generation alone. The oxygenation of the

Hartwell and Trotters Shoals releases will provide more favorable dissolved oxygen conditions in the upper reaches of Trotters Shoals and Clark Hill Reservoirs. Finally, in regard to the dissolved oxygen content of the releases, the results of all simulations, including those for existing conditions at Hartwell and Clark Hill, indicate that for some period in the late summer or early fall the predicted dissolved oxygen content of the releases was less than 6 mg/ℓ.

REFERENCES

1. Bohan, J. P. and Grace, J. L., Jr., "Selective Withdrawal from Man-Made Lakes; Hydraulic Laboratory Investigation," Technical Report H-73-4, Mar 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

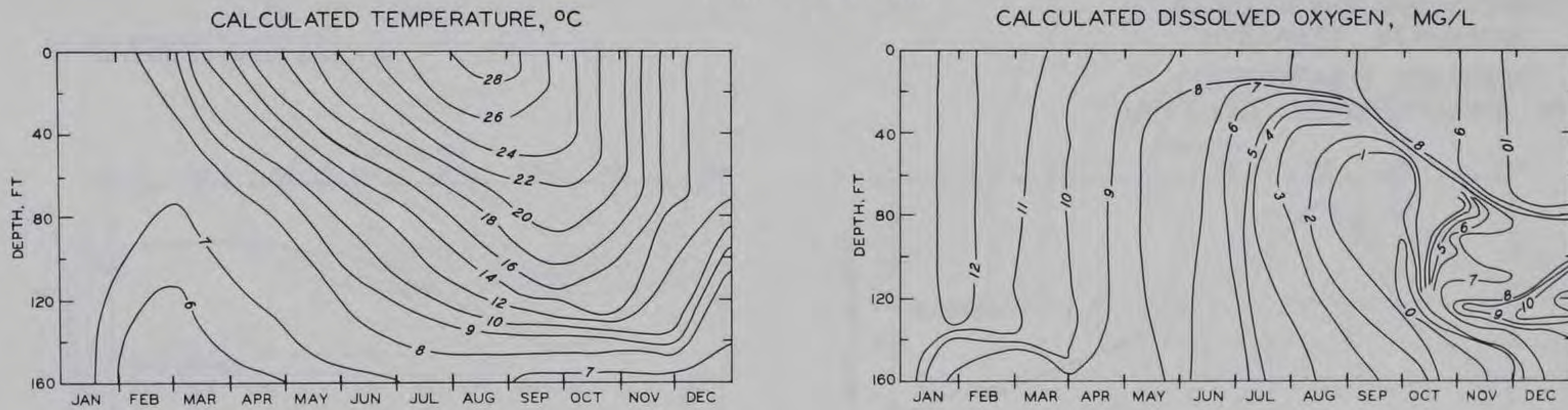
2. Clay, H. M., Jr., and Fruh, E. G., "Selective Withdrawal at Lake Livingston; An Impoundment Water Quality Model Emphasizing Selective Withdrawal," Progress Report EHE 70-18 (CRWR 66), Nov 1970, Environmental Health Engineering Research Laboratory, University of Texas, Austin, Tex.

3. Fontane, D. G., Bohan, J. P., and Grace, J. L., Jr., "Mathematical Simulation of the Turbidity Structure Within an Impoundment; Hydraulic Laboratory Investigation," Research Report H-73-2, Mar 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

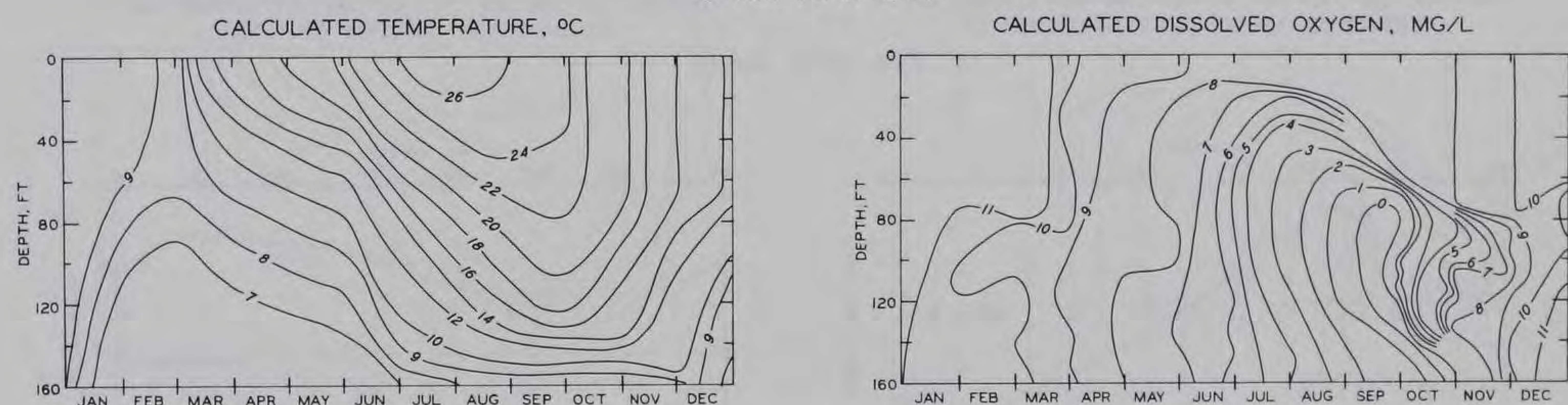
4. Bella, D. A., "Dissolved Oxygen Variations in Stratified Lakes," <u>Journal of the Sanitary Engineering Division, American Society of Civil Engineers,</u> Vol 96, No. SA5, Paper No. 7628, Oct 1970, pp 1129-1146.

5. Fruh, E. G. and Davis, E. M., "Limnological Investigations of Texas Impoundments for Water Quality Management Purposes," Final Report EHE 72-6 (CRWR 87), Feb 1972, Environmental Health Engineering Research Laboratory, University of Texas, Austin, Tex.

STUDY YEAR 1966

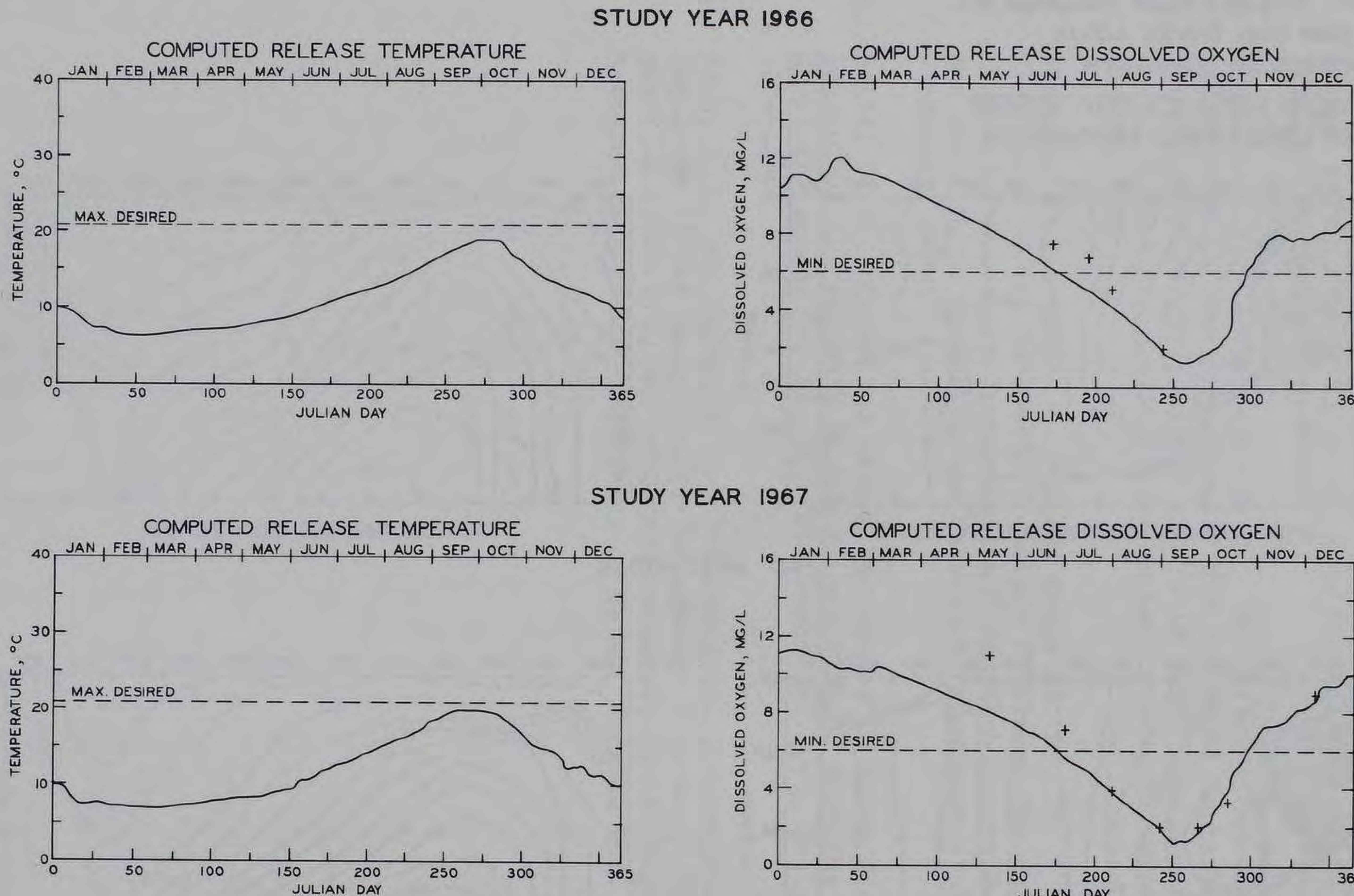


STUDY YEAR 1967



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

HARTWELL RESERVOIR
STUDY YEARS 1966 AND 1967
CALIBRATION WITH EXISTING CONDITIONS



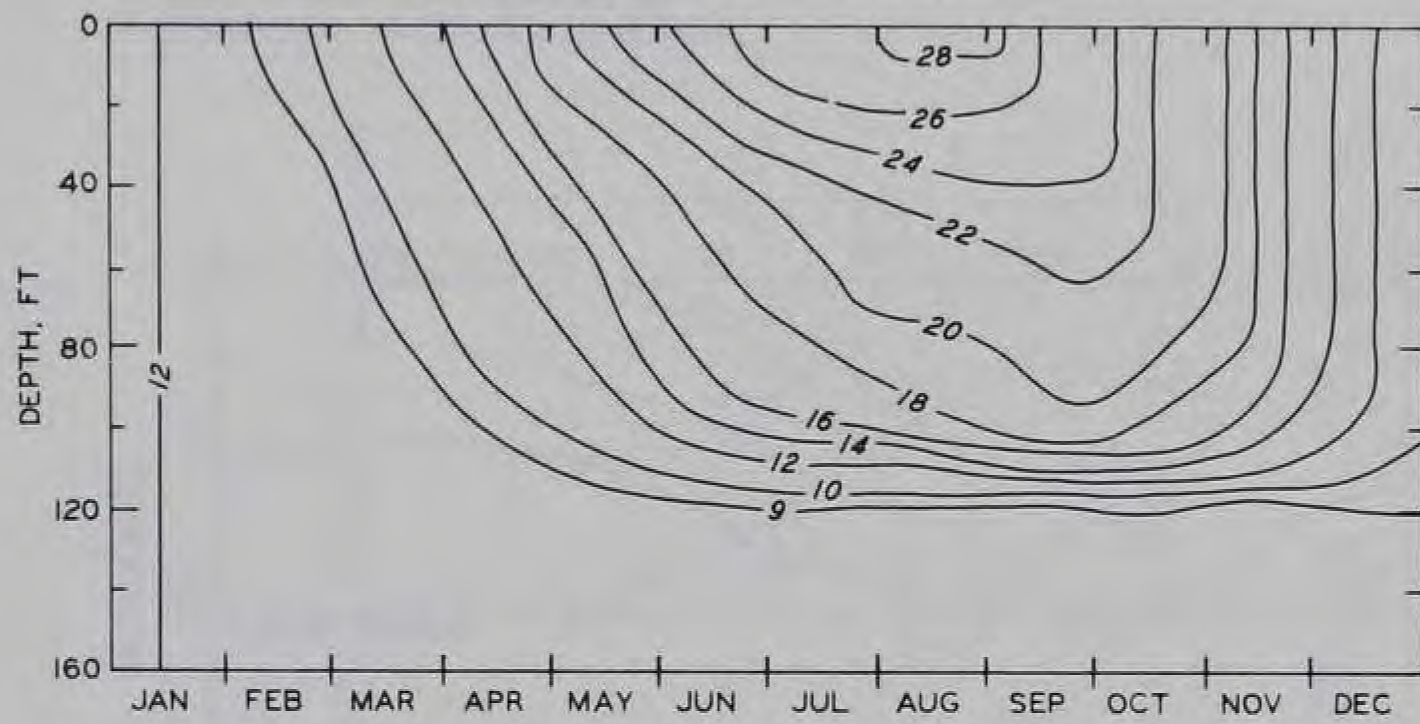
+ OBSERVED DISSOLVED OXYGEN IN THE HARTWELL TAILRACE

RELEASE TEMPERATURE AND DISSOLVED OXYGEN

HARTWELL RESERVOIR
STUDY YEARS 1966 AND 1967
CALIBRATION WITH EXISTING CONDITIONS

STUDY YEAR 1966

CALCULATED TEMPERATURE, °C



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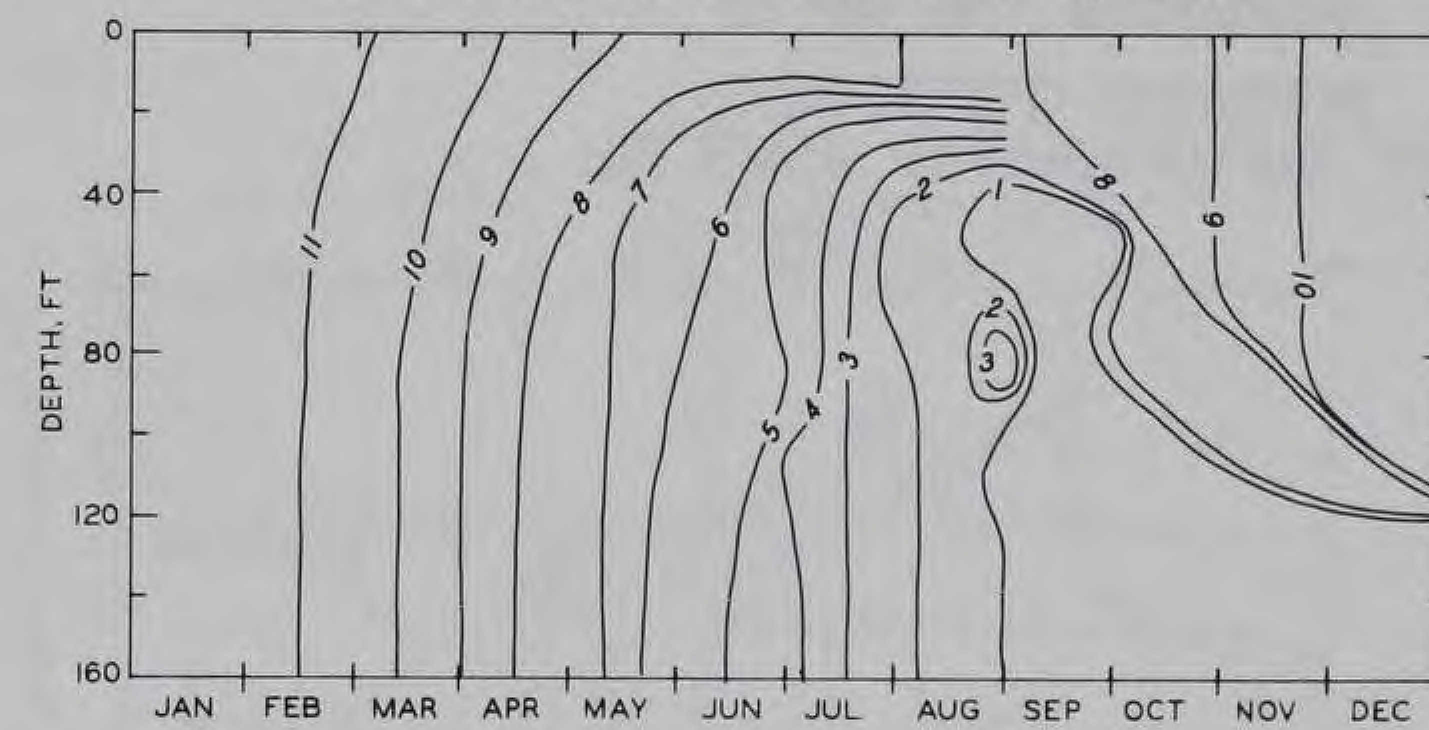

STUDY YEAR 1967

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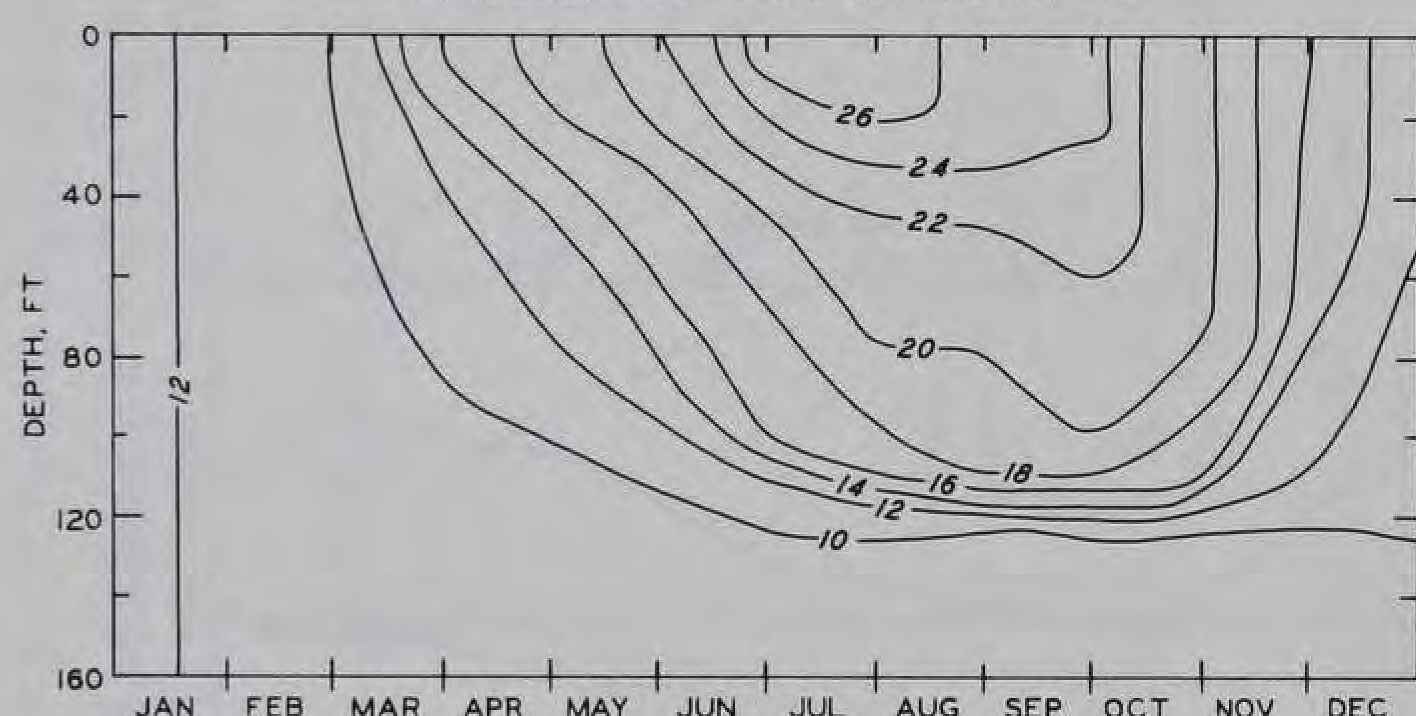

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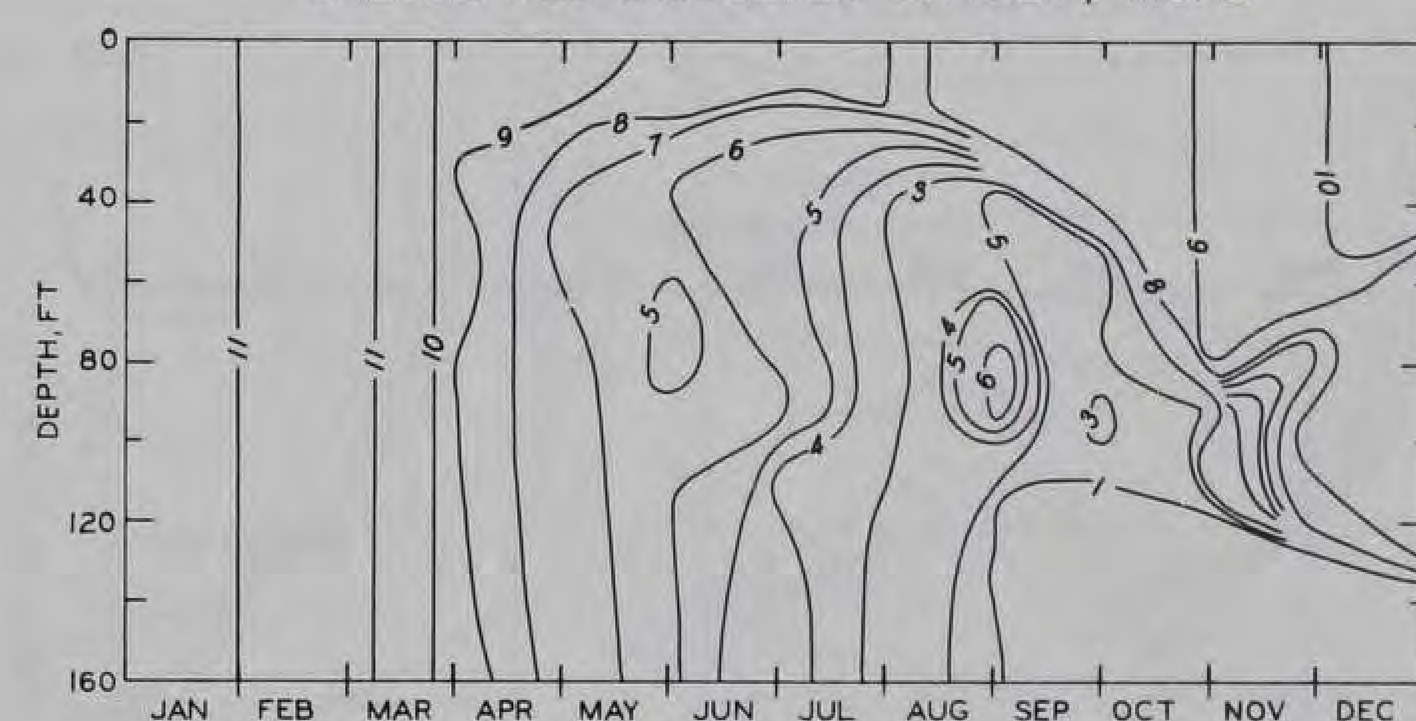


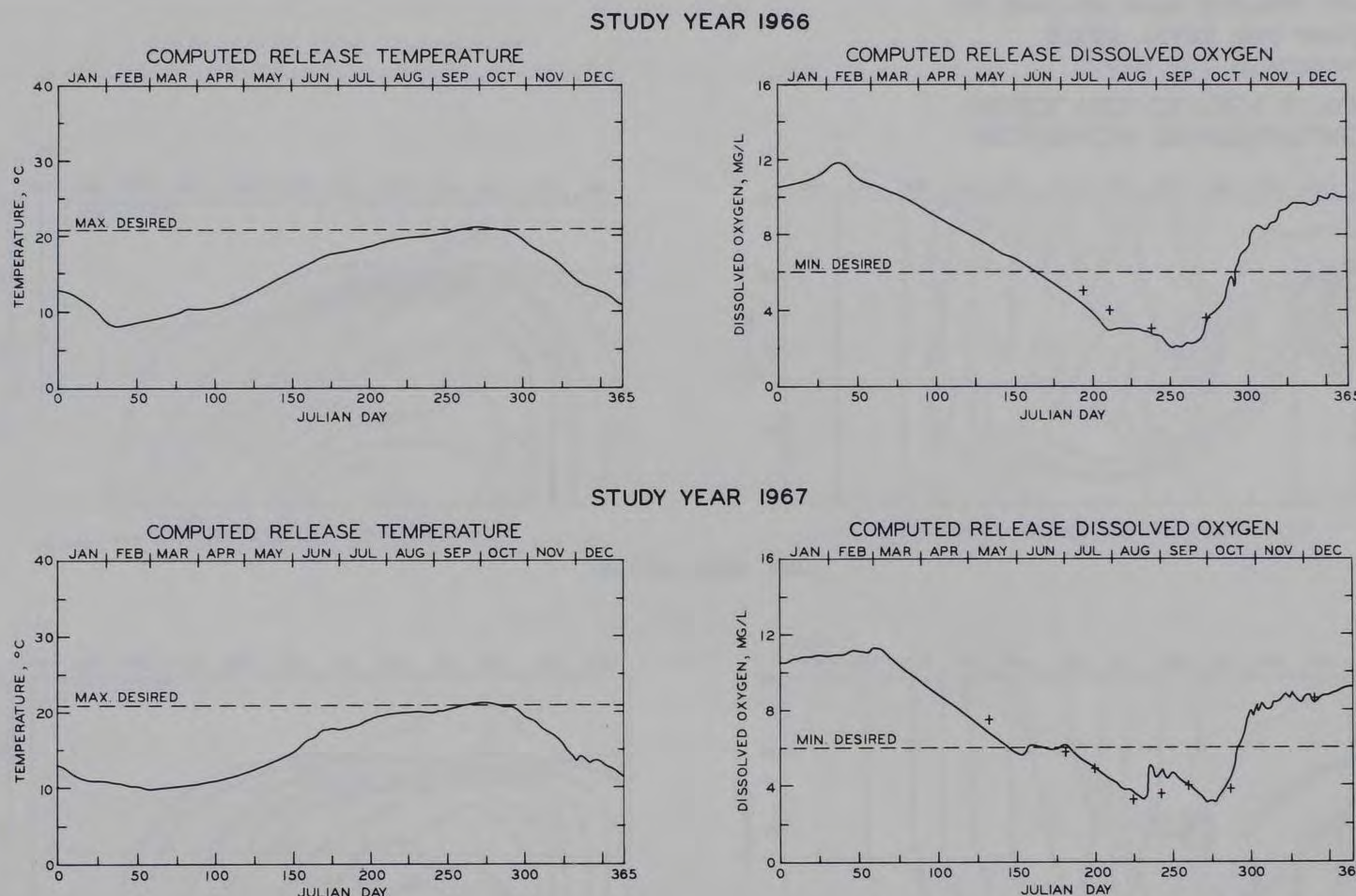
RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR

STUDY YEARS 1966 AND 1967

CALIBRATION WITH EXISTING CONDITIONS

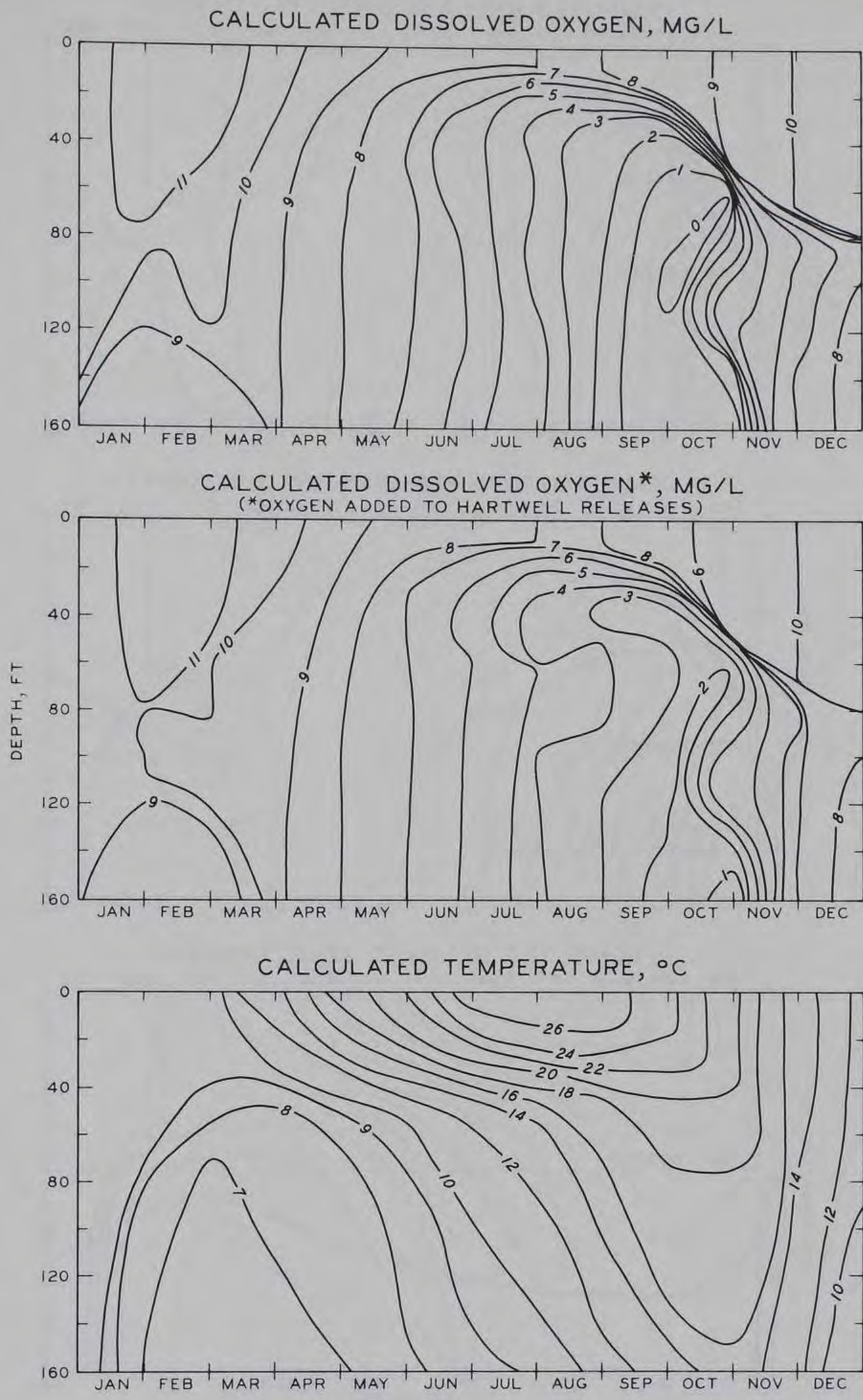
PLATE 3



+ OBSERVED DISSOLVED OXYGEN IN THE CLARK HILL TAILRACE

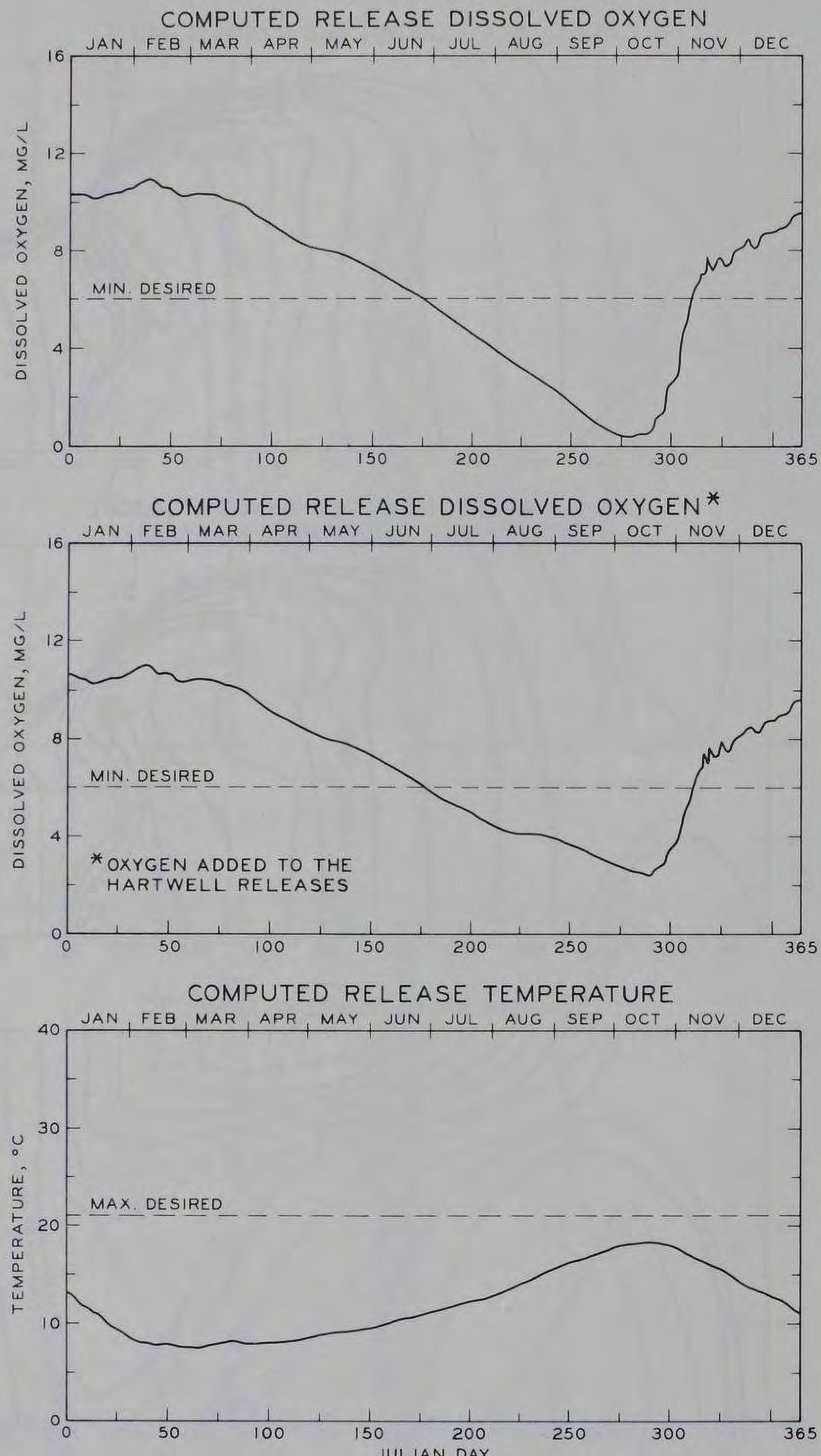
RELEASE TEMPERATURE AND DISSOLVED OXYGEN

CLARK HILL RESERVOIR
STUDY YEARS 1966 AND 1967
CALIBRATION WITH EXISTING CONDITIONS



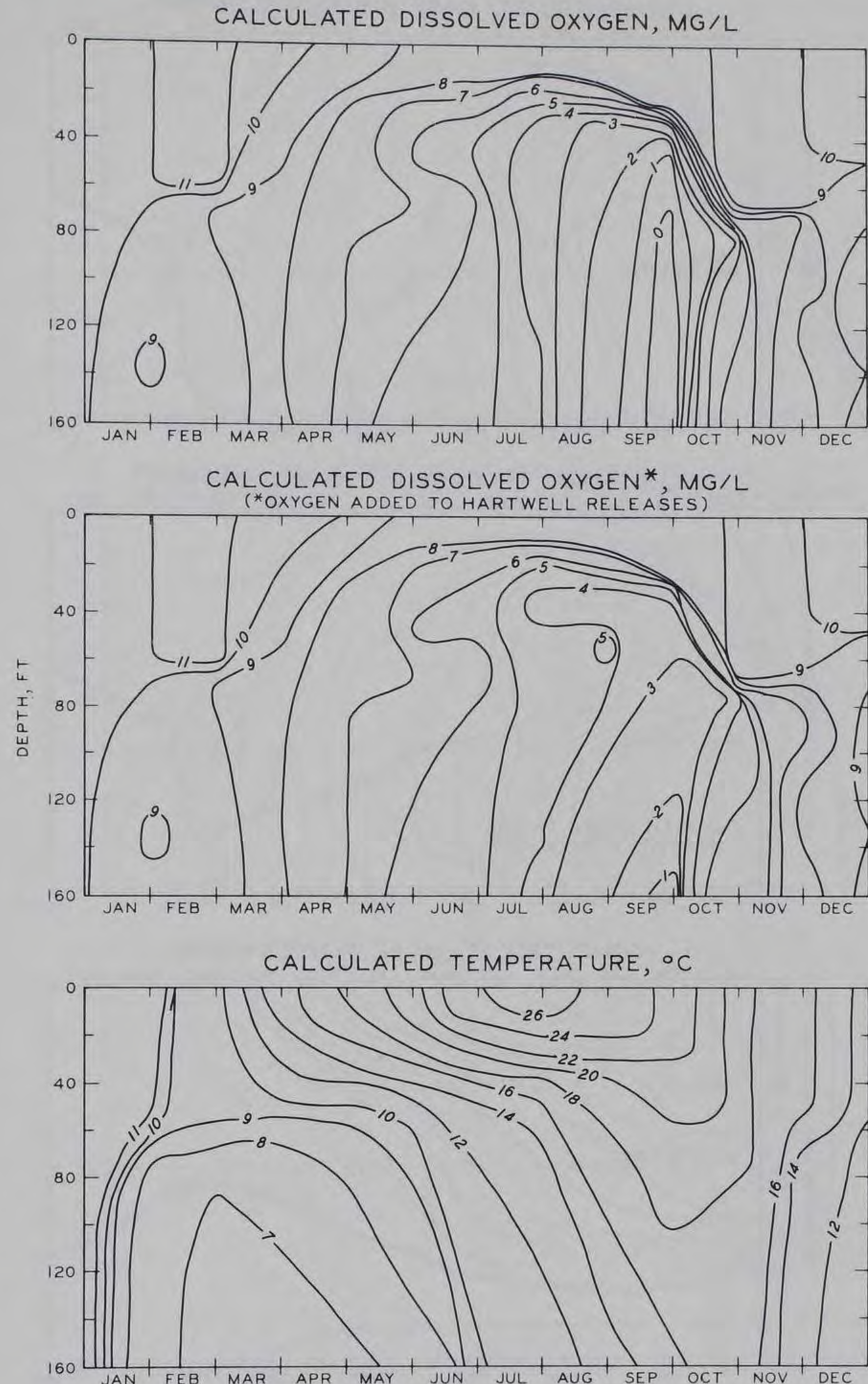
RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



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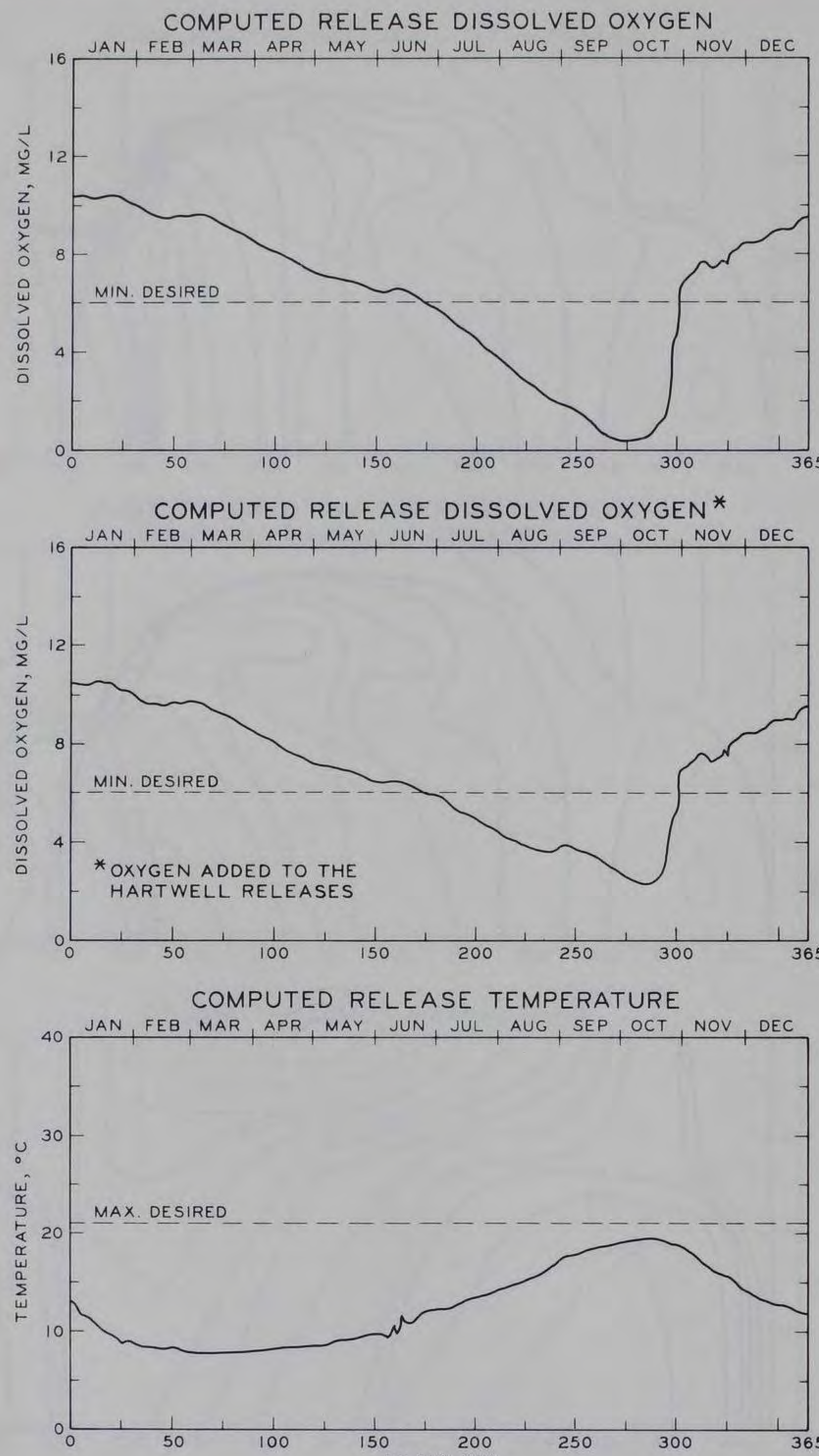
STUDY YEAR 1967
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

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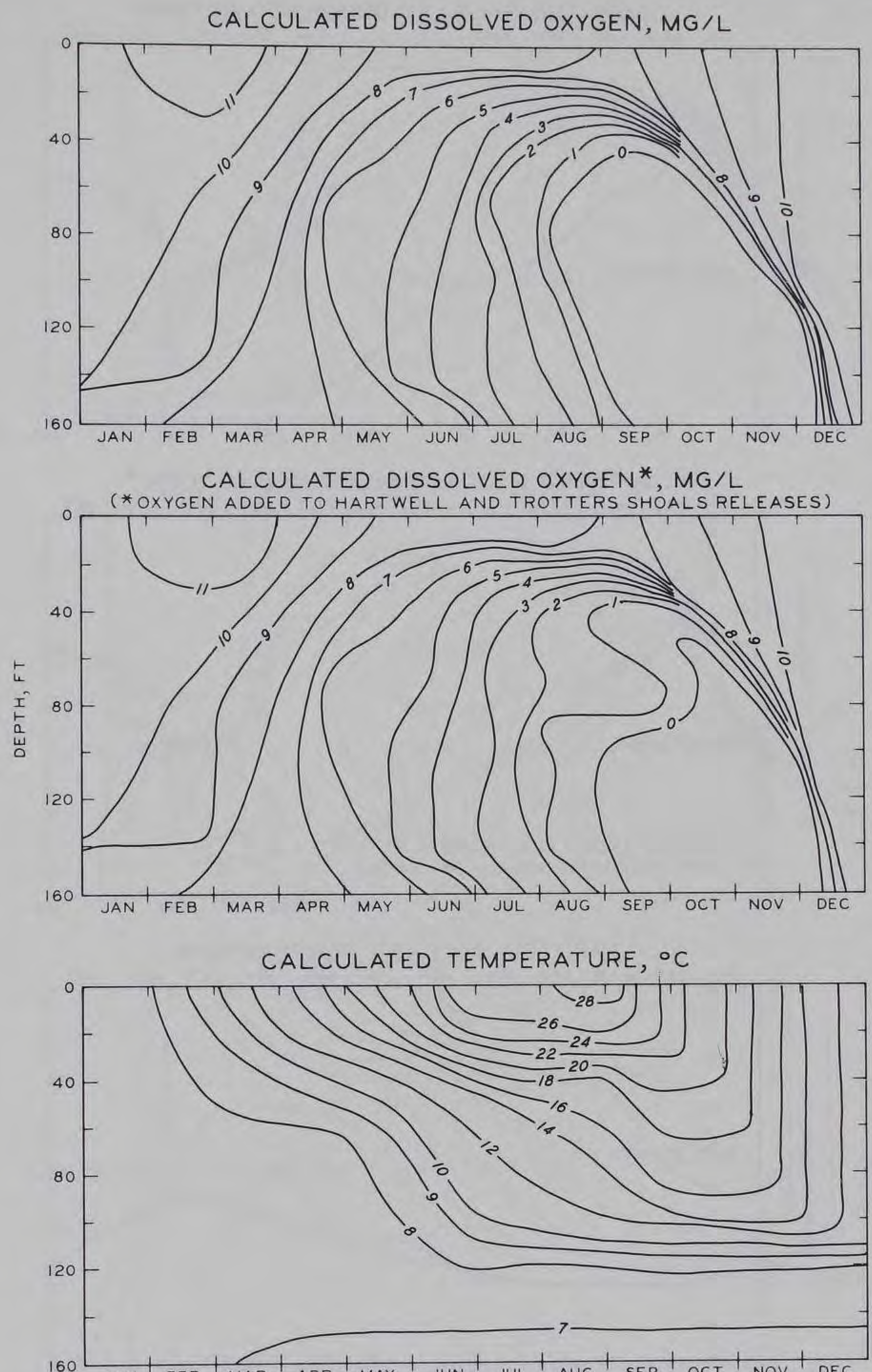
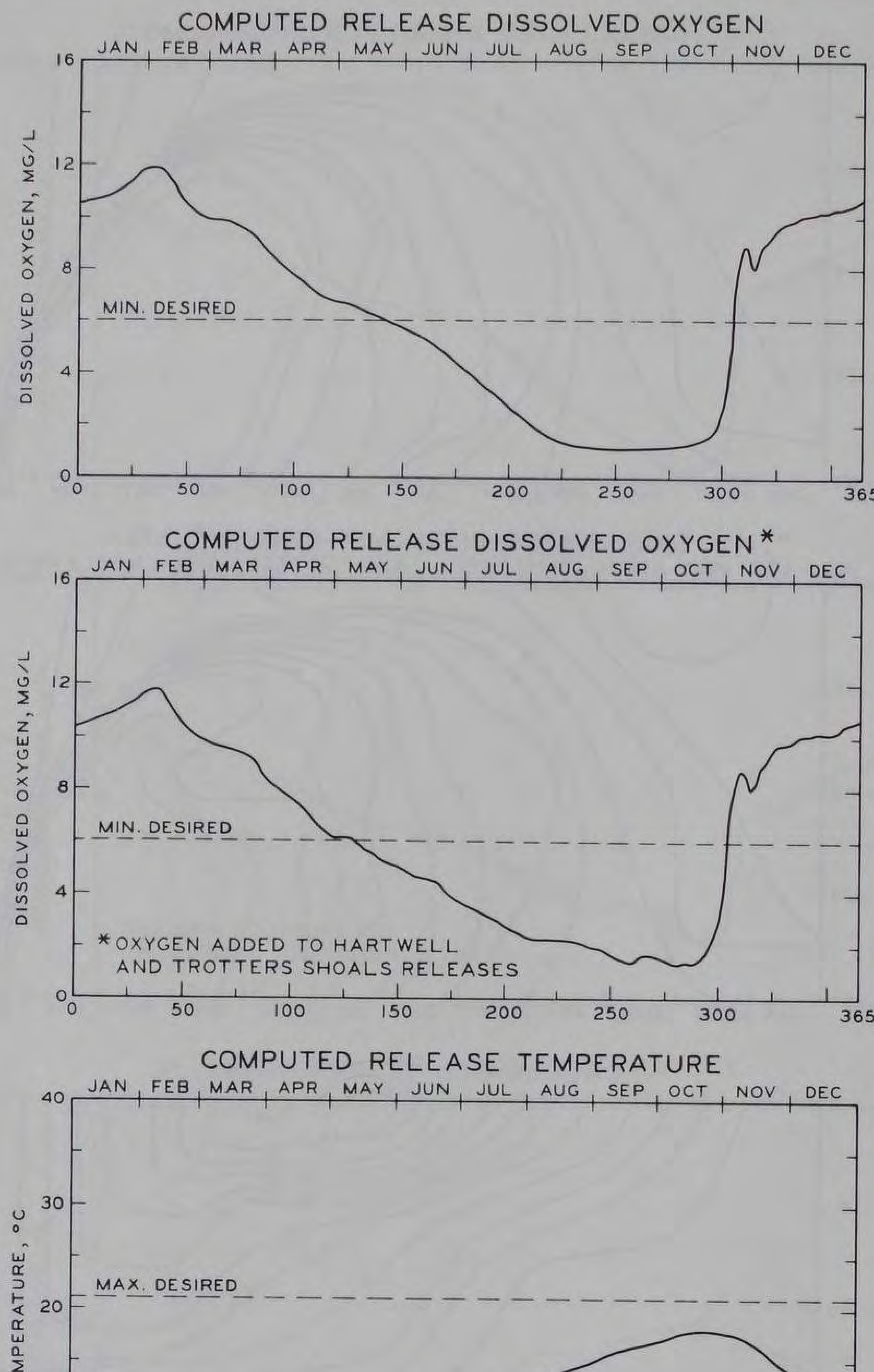
STUDY YEAR 1967
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1966

CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

CLARK HILL RESERVOIR
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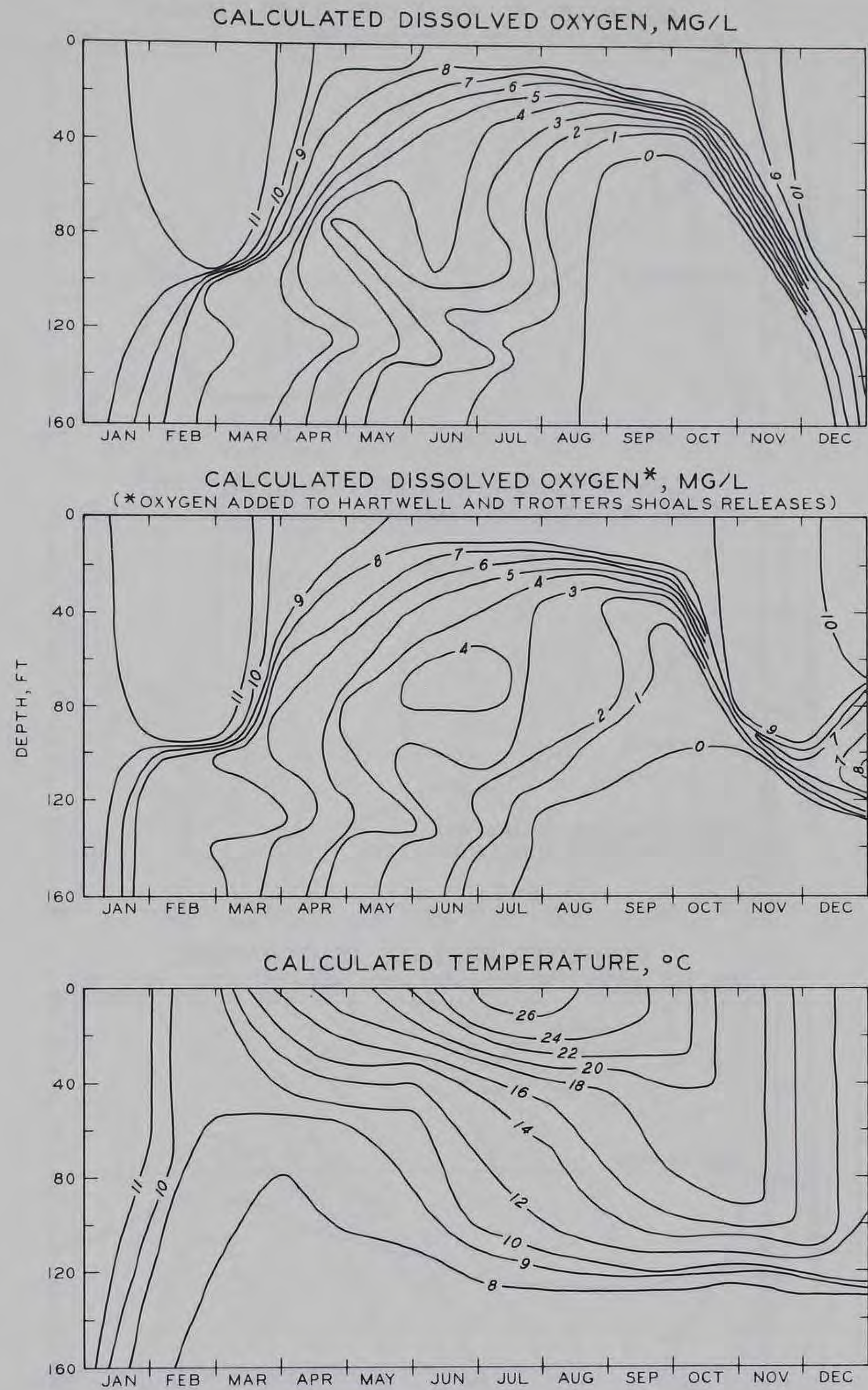
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

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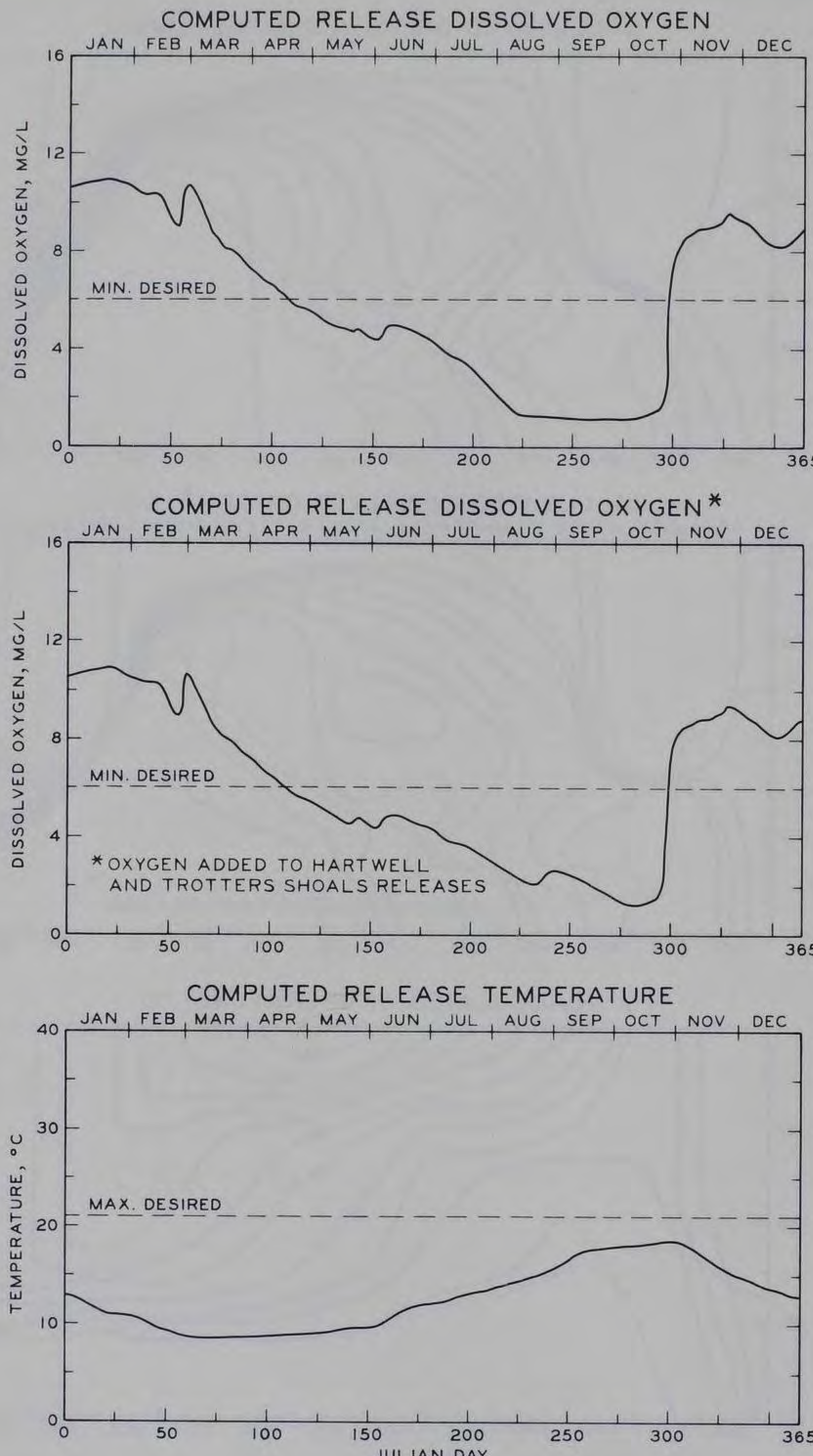
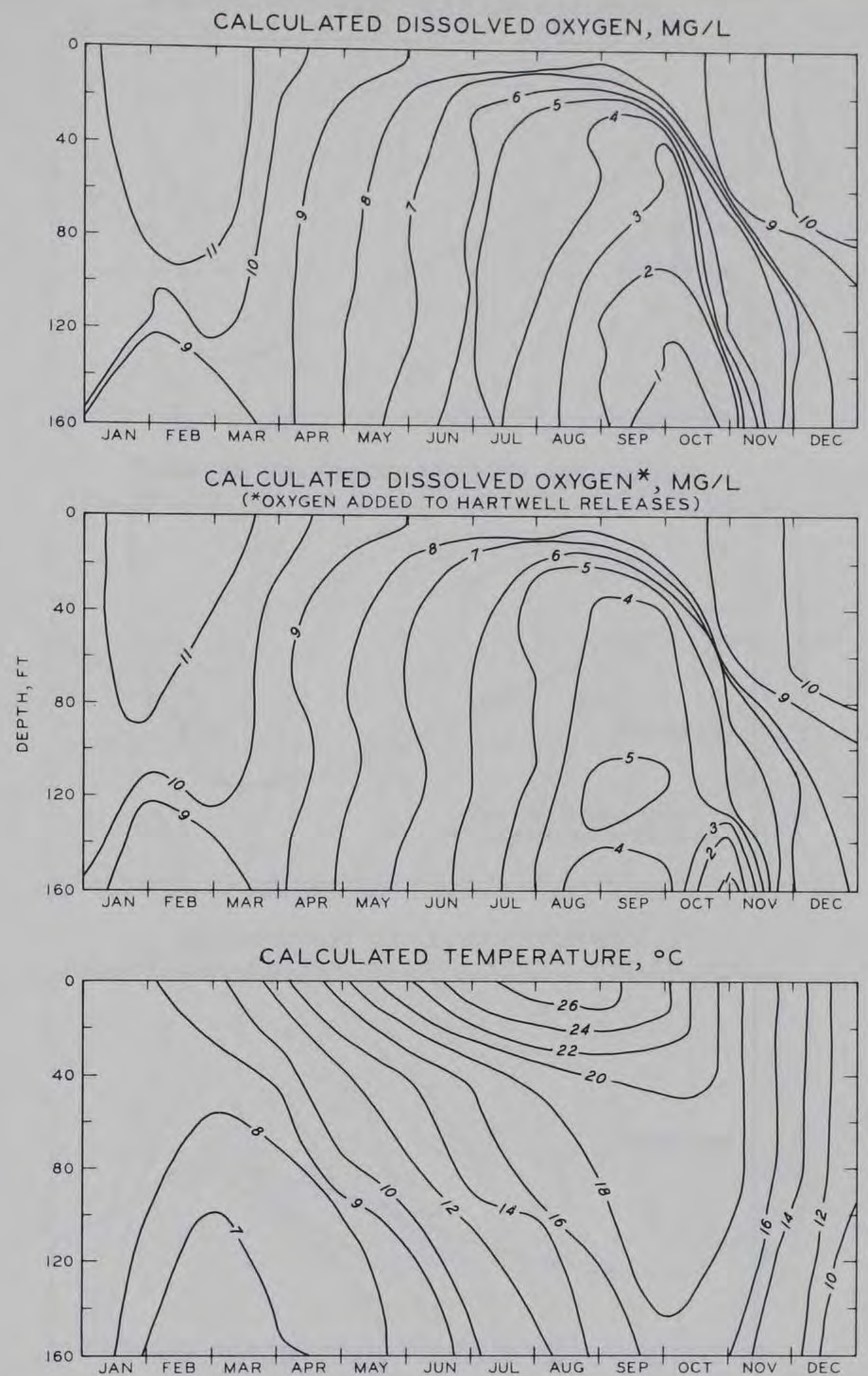
STUDY YEAR 1967
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

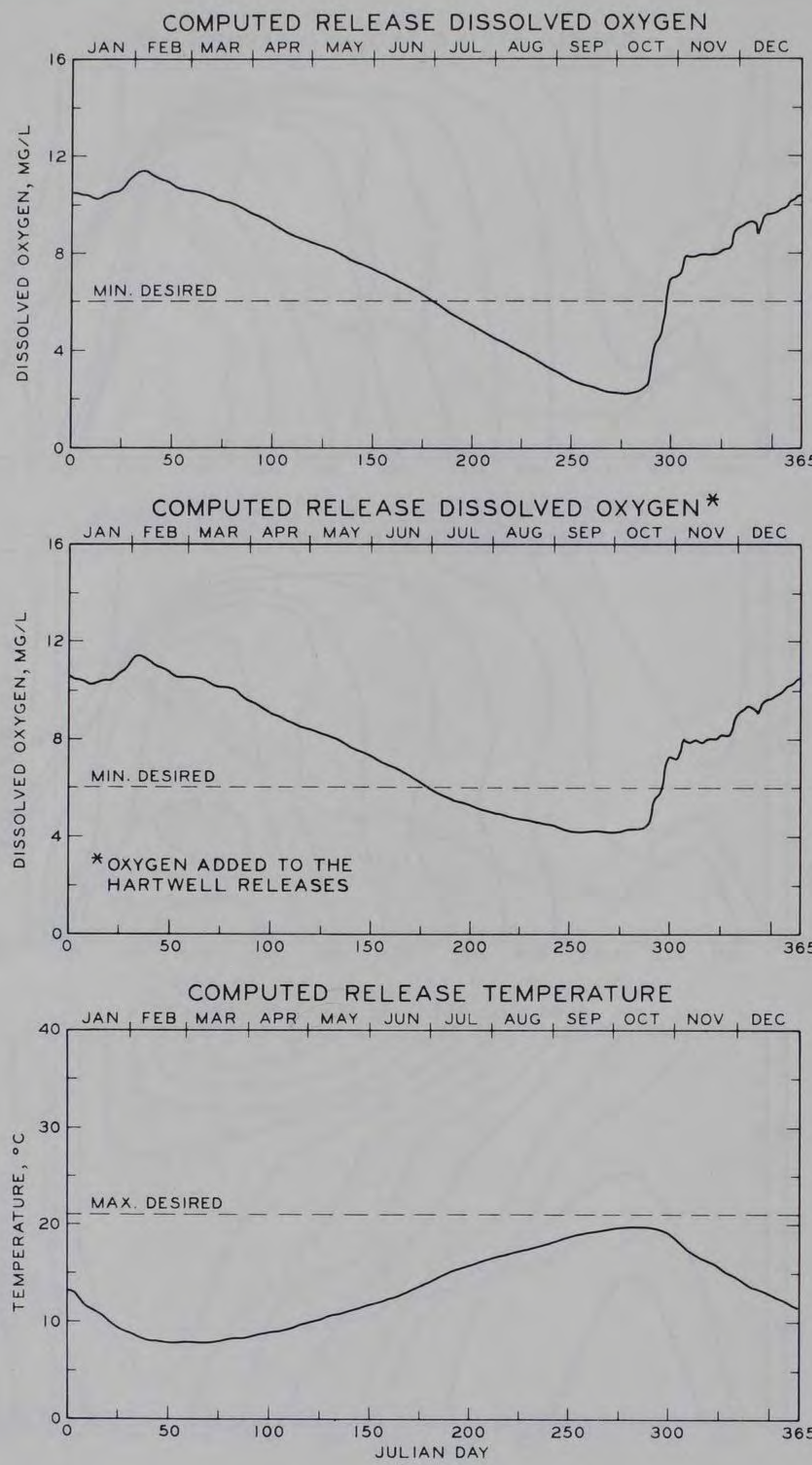
CLARK HILL RESERVOIR
STUDY YEAR 1967
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966

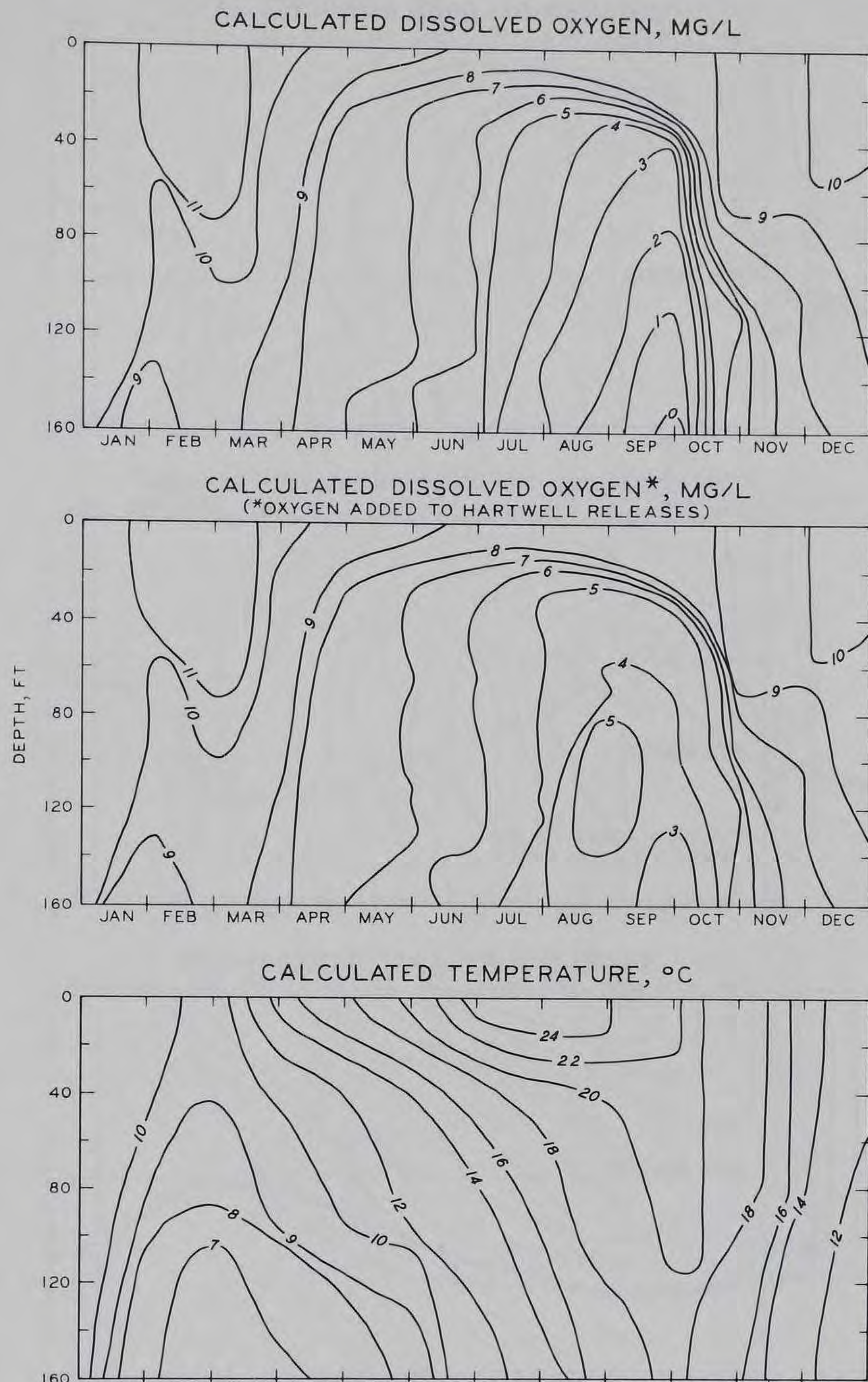
PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966

PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

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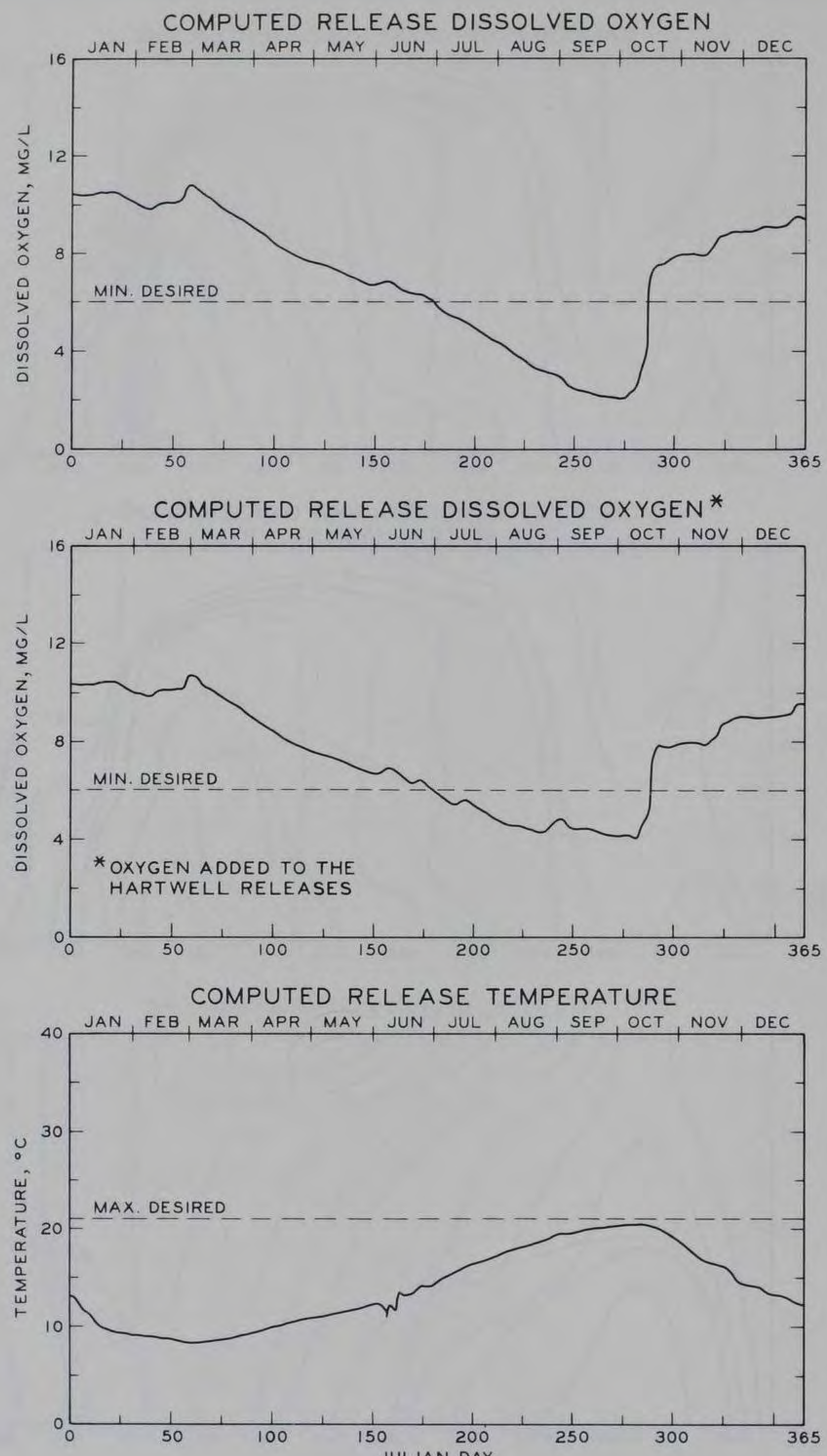
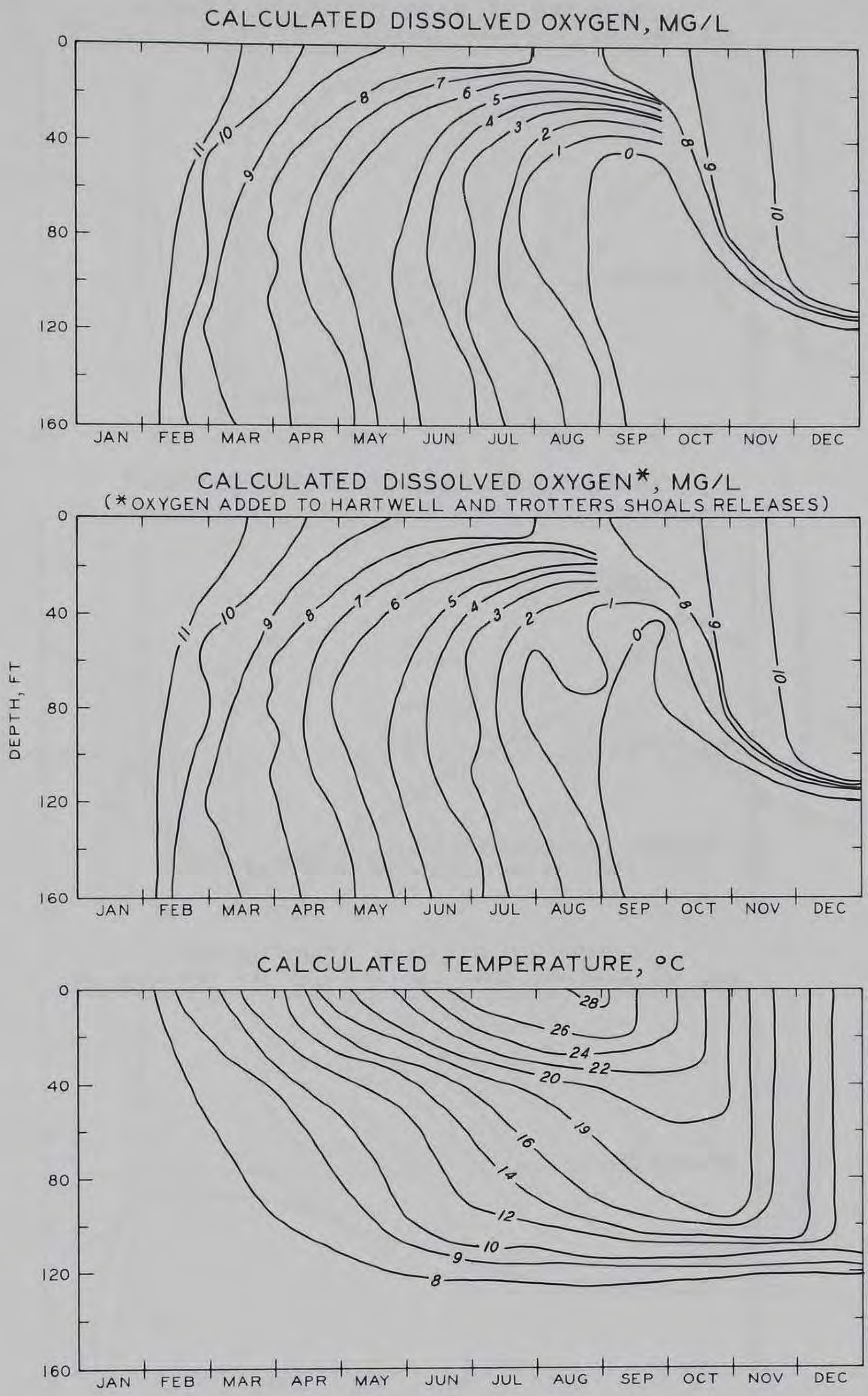
STUDY YEAR 1967

PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

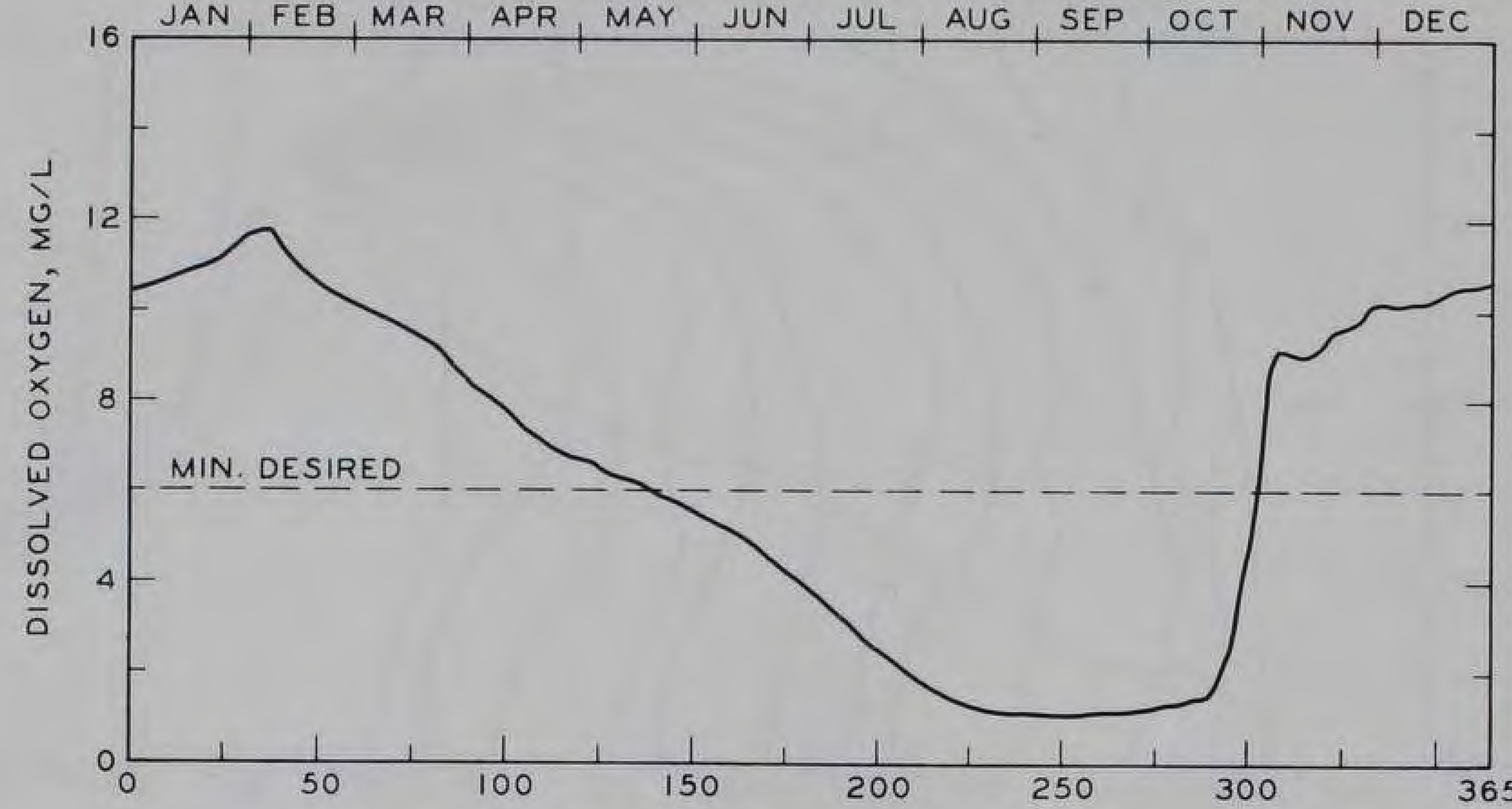
TROTTERS SHOALS RESERVOIR
STUDY YEAR 1967
PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



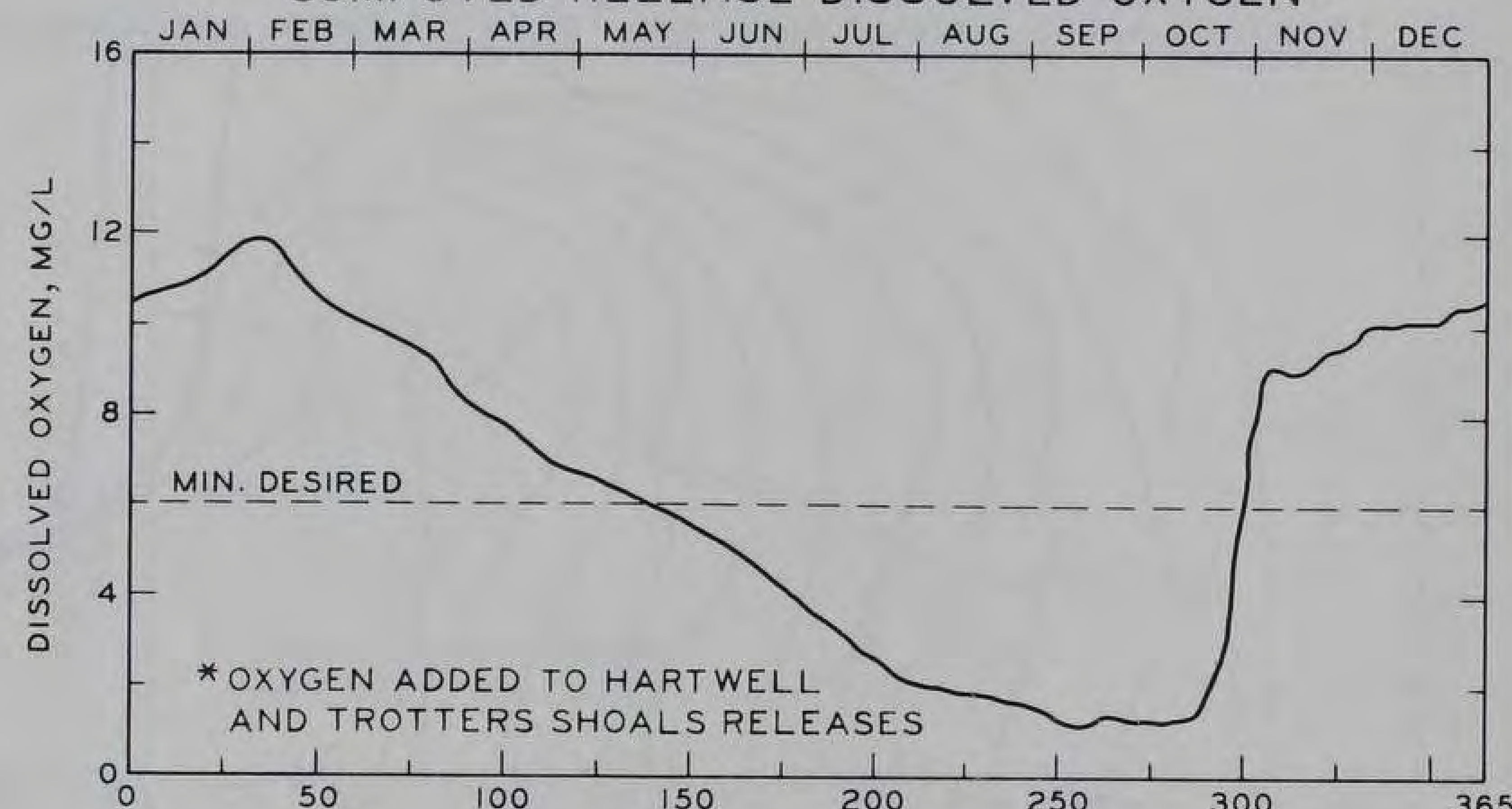
RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1966
PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS

COMPUTED RELEASE DISSOLVED OXYGEN



COMPUTED RELEASE DISSOLVED OXYGEN*



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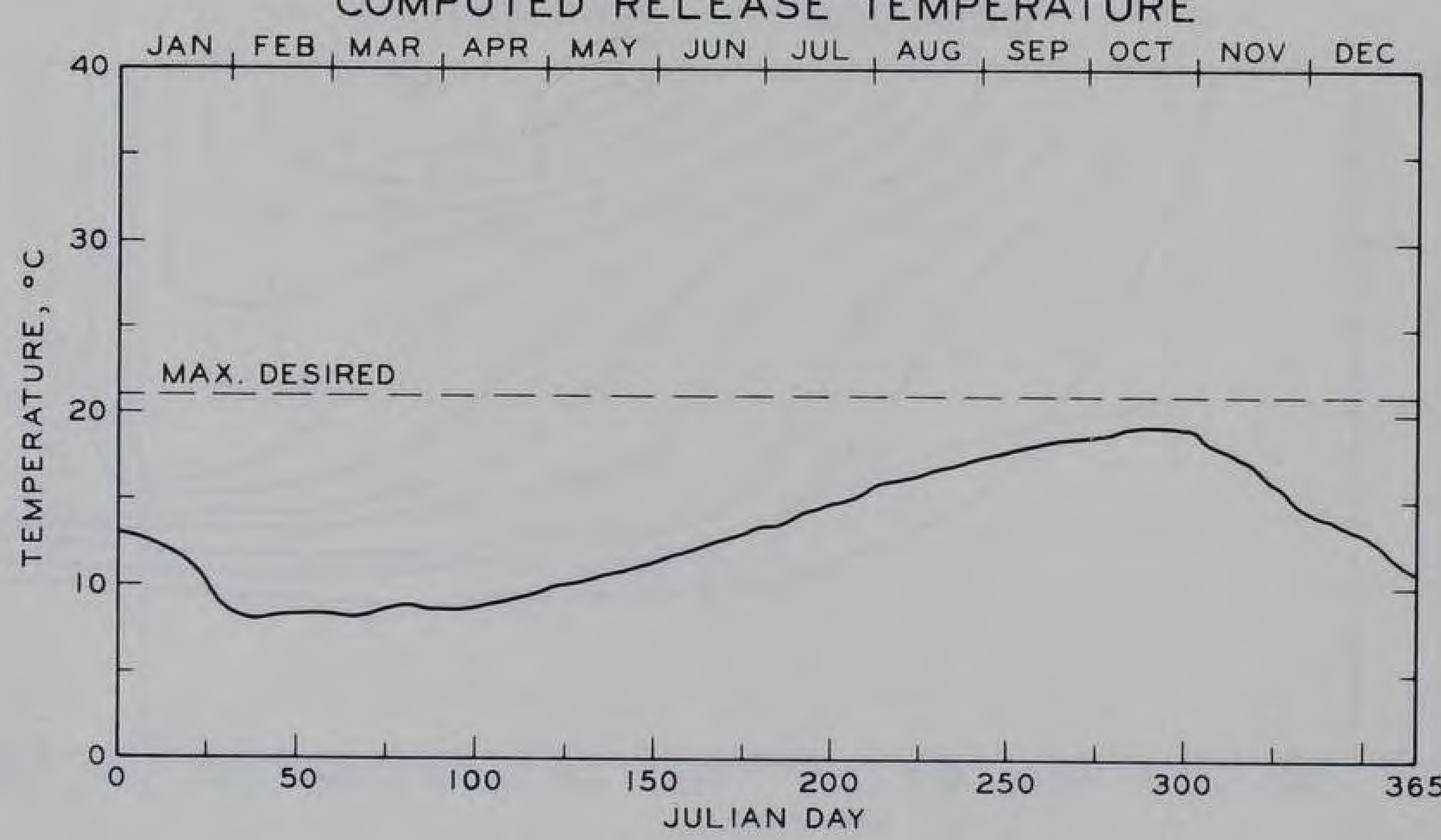
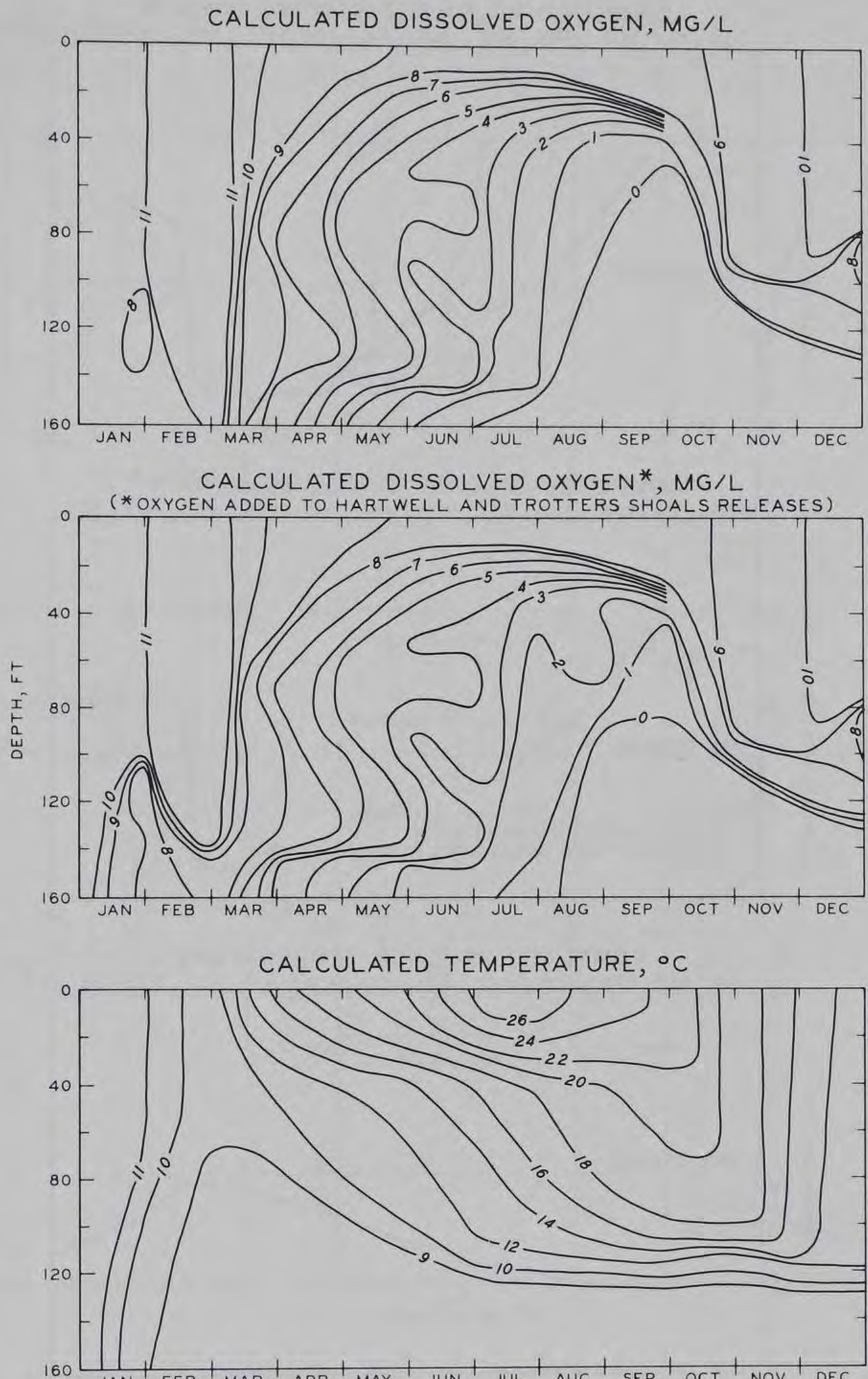


RELEASE TEMPERATURE AND DISSOLVED OXYGEN

CLARK HILL RESERVOIR
STUDY YEAR 1966

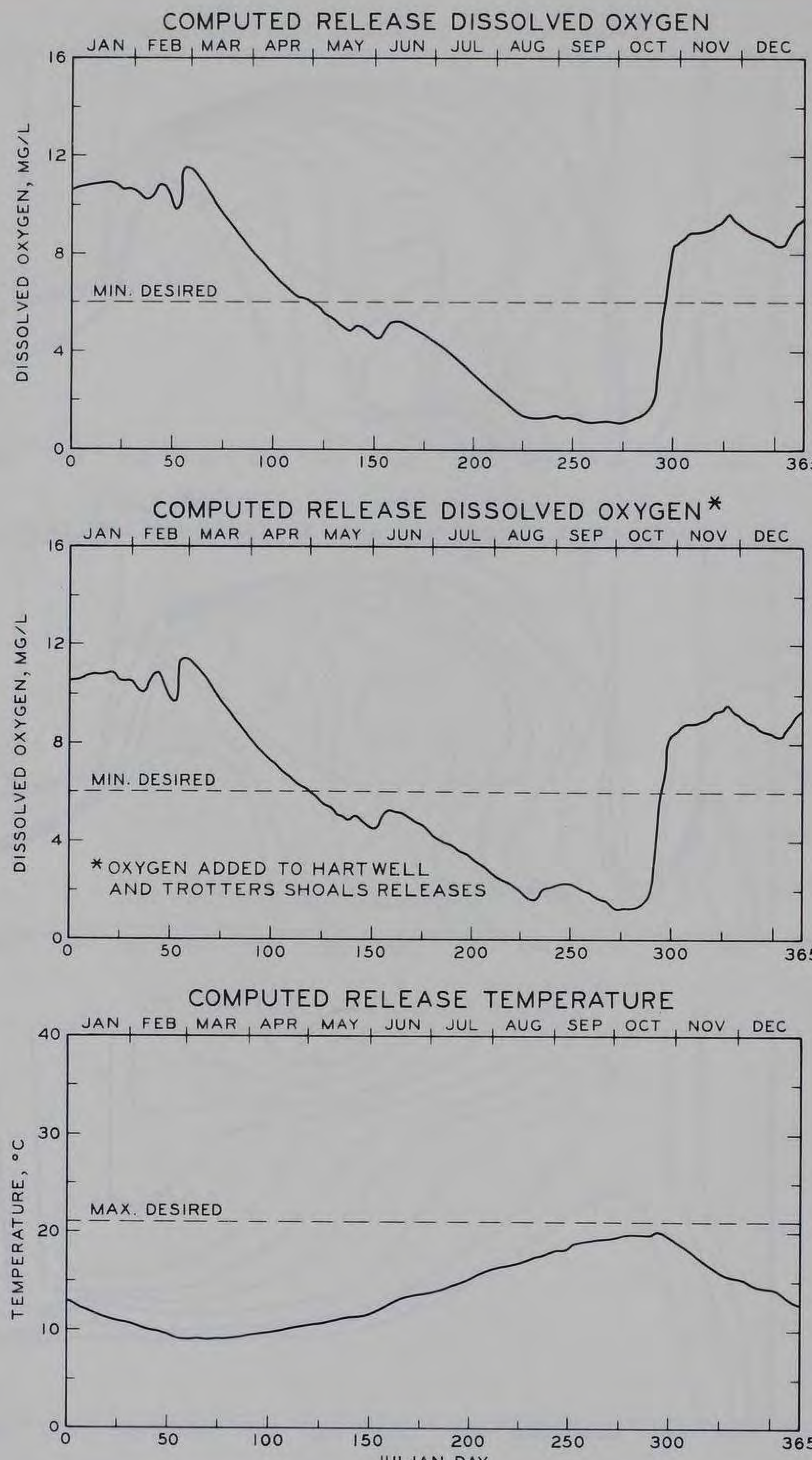
PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1967

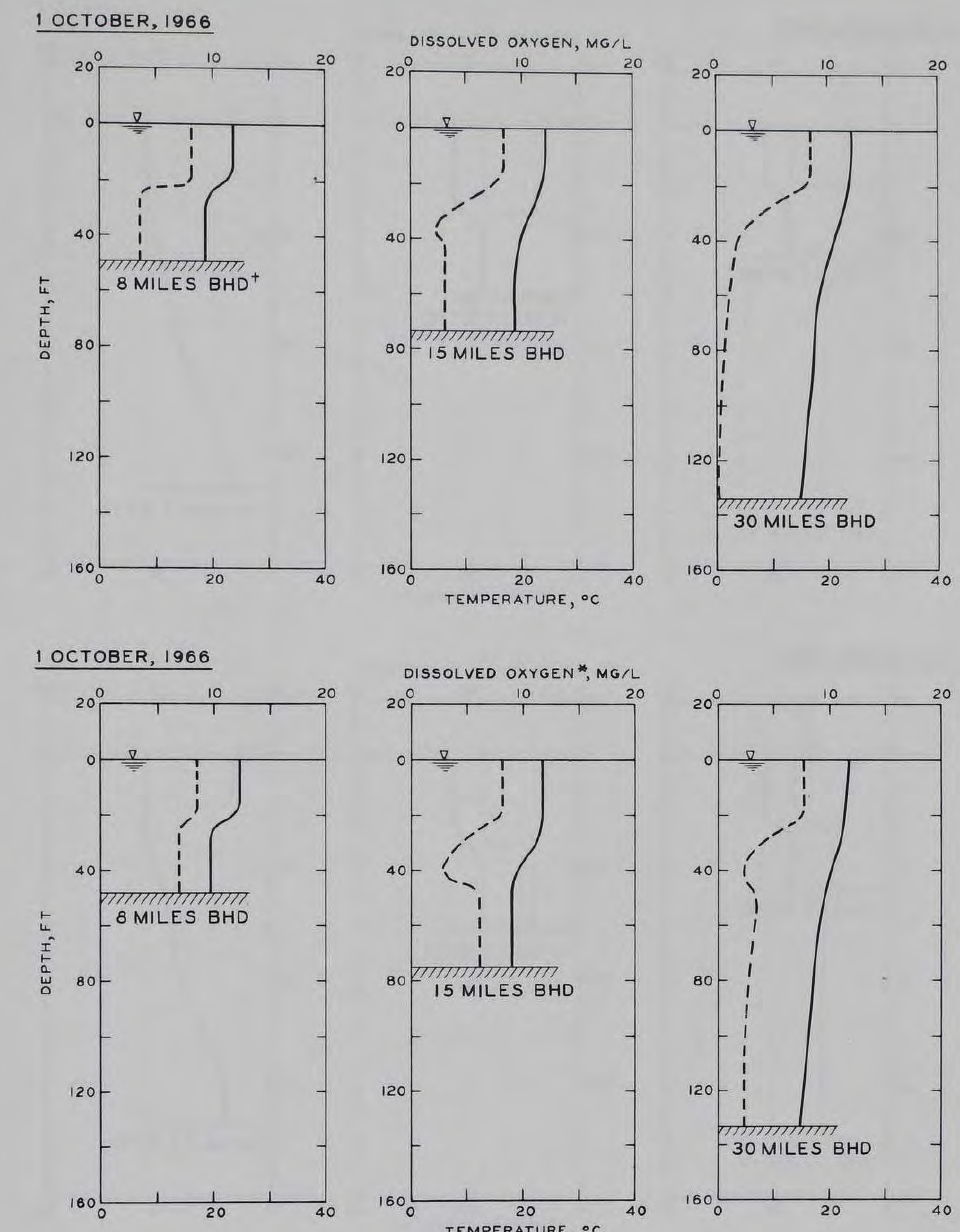
PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



RELEASE TEMPERATURE AND DISSOLVED OXYGEN

CLARK HILL RESERVOIR
STUDY YEAR 1967

PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



LEGEND

——— TEMPERATURE

- - - - DISSOLVED OXYGEN

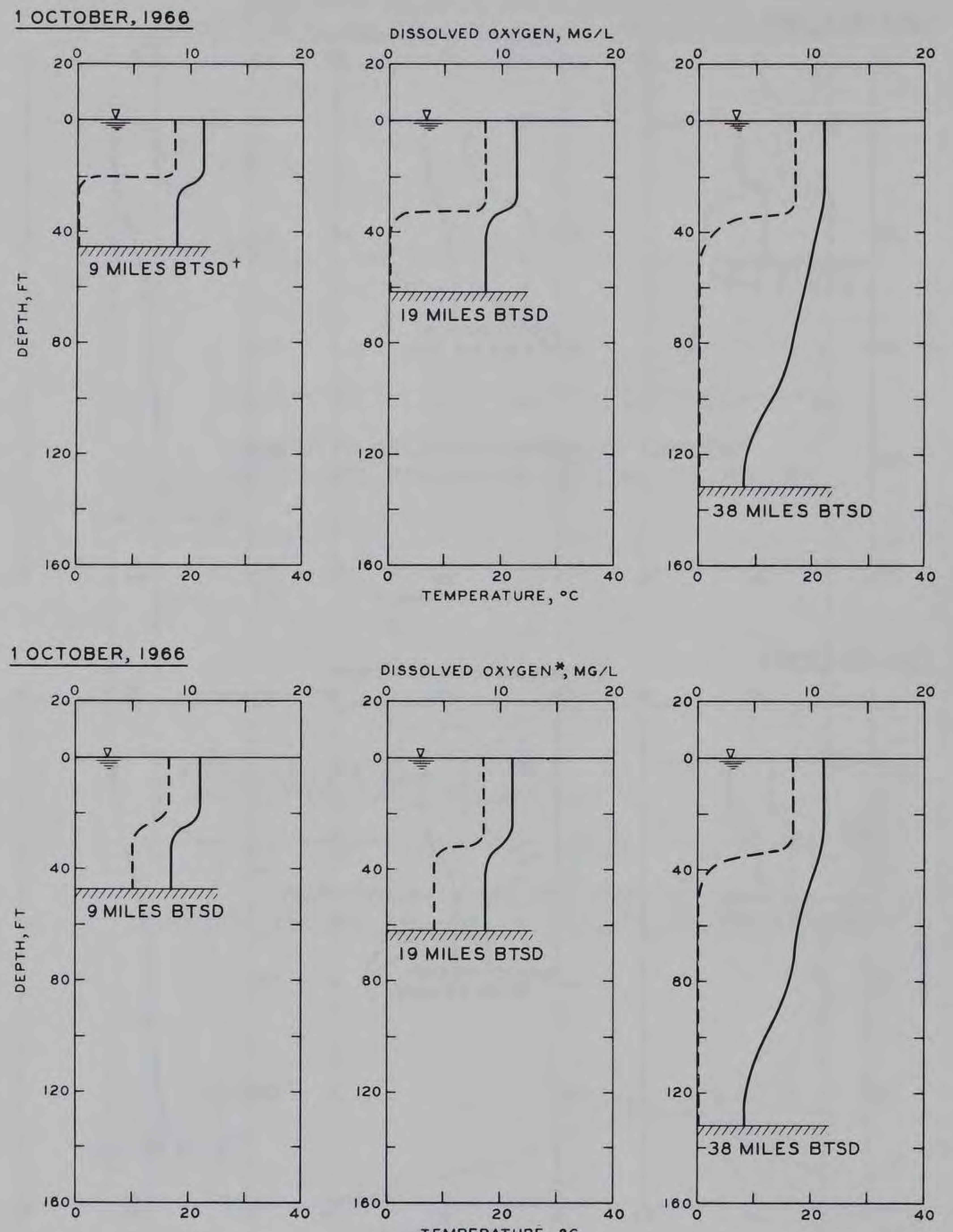
NOTE: *OXYGEN ADDED TO HARTWELL RELEASES

†BELOW HARTWELL DAM

LONGITUDINAL VARIATIONS IN THE TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966

CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



LEGEND

——— TEMPERATURE

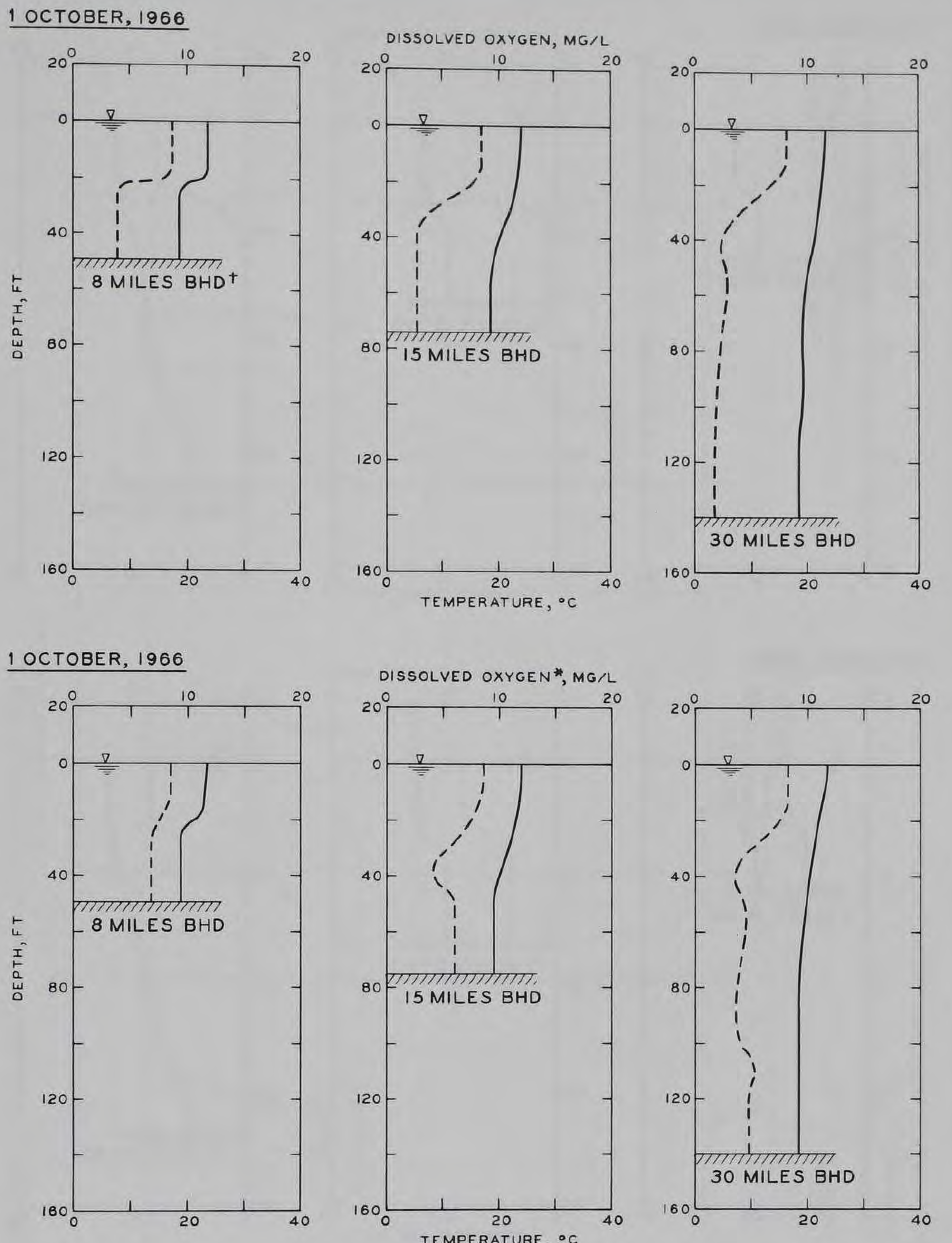
- - - - DISSOLVED OXYGEN

NOTE: *OXYGEN ADDED TO HARTWELL AND TROTTERS SHOALS RELEASES

†BELOW TROTTERS SHOALS DAM

LONGITUDINAL VARIATIONS IN THE TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1966
CONVENTIONAL POWER GENERATION AT TROTTERS SHOALS



LEGEND

——— TEMPERATURE
- - - - - DISSOLVED OXYGEN

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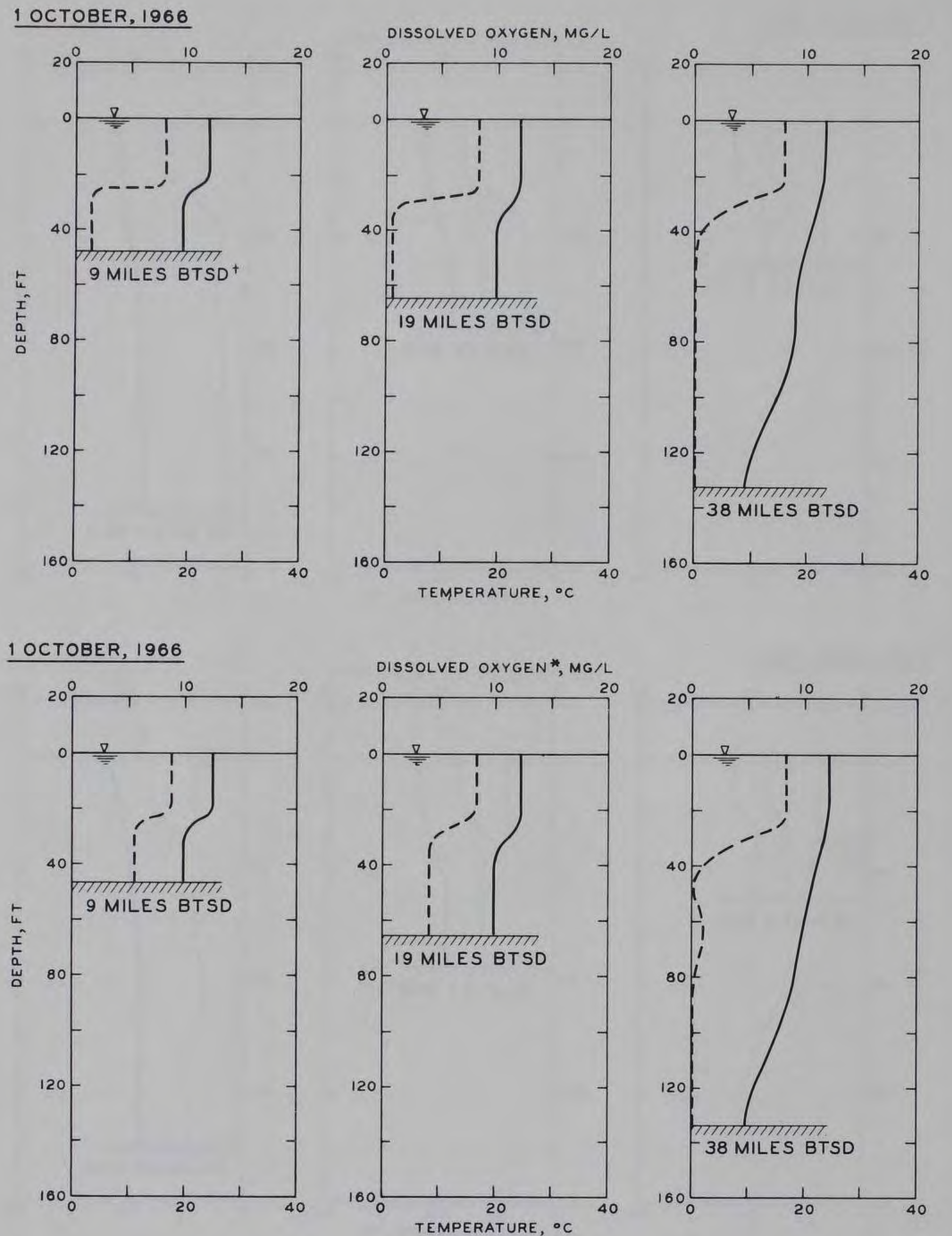
LONGITUDINAL VARIATIONS IN THE TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

TROTTERS SHOALS RESERVOIR
STUDY YEAR 1966

PUMPED STORAGE POWER
GENERATION AT TROTTERS SHOALS



LEGEND

——— TEMPERATURE
– – – – DISSOLVED OXYGEN

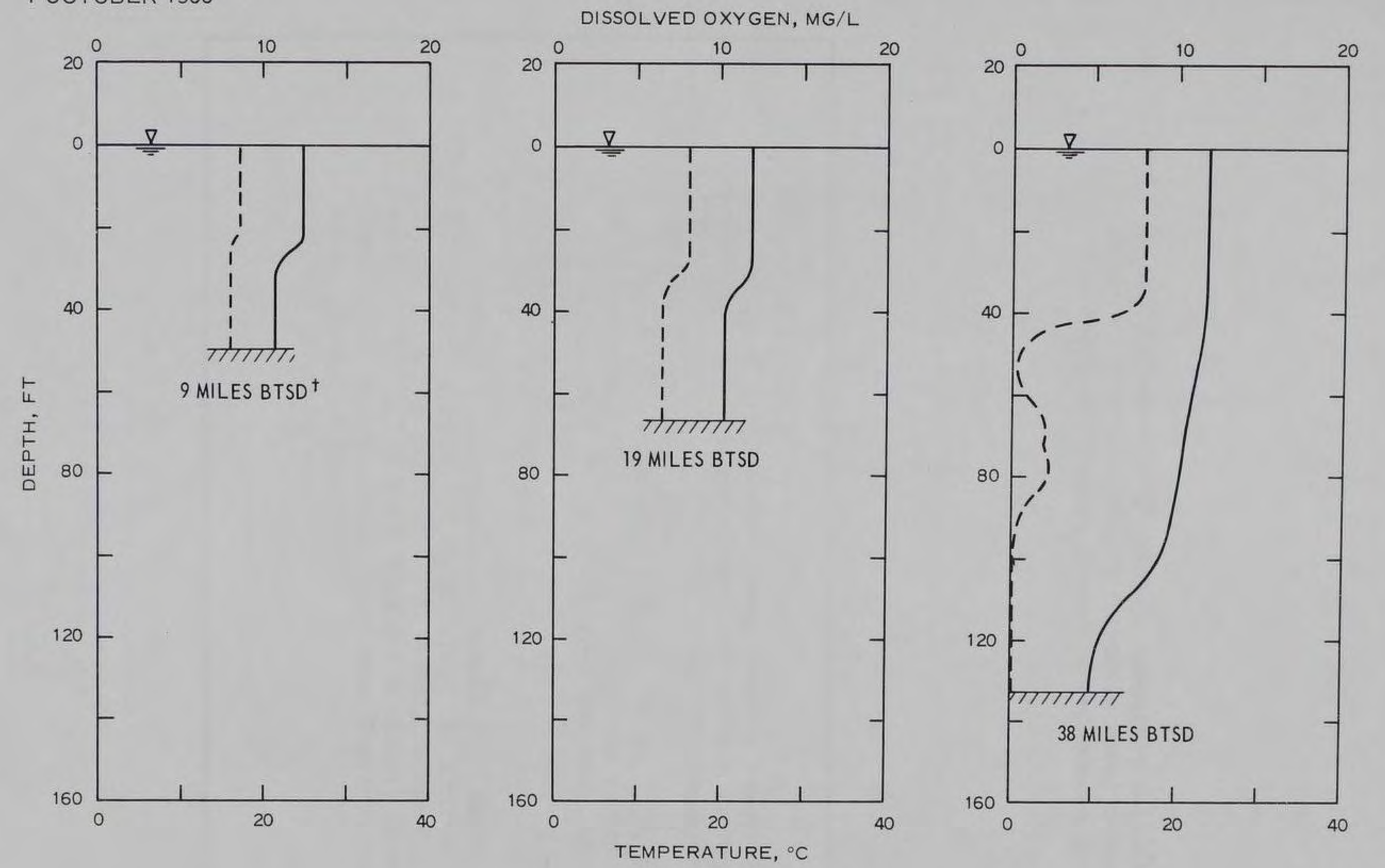
NOTE: *OXYGEN ADDED TO HARTWELL AND TROTTERS SHOALS RELEASES
†BELOW TROTTERS SHOALS DAM

LONGITUDINAL VARIATIONS IN THE TEMPERATURE AND DISSOLVED OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1966

PUMPED STORAGE POWER GENERATION AT TROTTERS SHOALS

1 OCTOBER 1966



LEGEND

——— TEMPERATURE

- - - - DISSOLVED OXYGEN

NOTE: † BELOW TROTTERS SHOALS DAM.

LONGITUDINAL VARIATIONS IN
THE TEMPERATURE AND DISSOLVED
OXYGEN STRUCTURE

CLARK HILL RESERVOIR
STUDY YEAR 1966

VERIFICATION WITH EXISTING CONDITIONS