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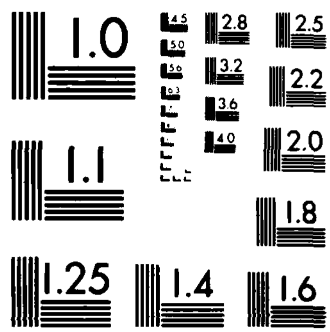

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David C. Ramsey
Captain USAF

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MICROPROCESSOR CONTROL DESIGN
FOR A LOW-HEAD CROSSFLOW TURBINE

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
David C. Ramsey, B.S.
Captain USAF
Graduate Electrical Engineering

March 1985

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Preface

This thesis presents a design of a microprocessor based controller for a low-head crossflow turbine. My intent was to provide enough information so that a follow-on project could construct the controller exclusively from this thesis. However, the turbine was being modified at the same time this thesis was written. Therefore, some of the turbine information required for the design could not be included. The follow-on project should find only a small amount of design work is necessary before starting construction of the of the controller.

I offer special thanks to Mr. Roger Ely for building the turbine and allowing us to create a project with it. My appreciation also goes to Dr. Constantine Houpis, Lt. Col. Hal Carter, and Dr. Dennis Quinn for their guidance and draft reviews.

David C. Ramsey

Table of Contents

List of Figures

List of Tables

Abstract

A microprocessor based controller is designed for use on a low-head crossflow turbine. The design contains a model of the turbine, an algorithm for maximizing output power, software design, and software testing. Modelling of the turbine is performed using tabular data in order to avoid the complexity of deriving an equation model. Linear interpolation of the tabular data is used to obtain a continuous model of the turbine.

Based upon turbine hardware, turbine characteristics, and economic feasibility, a search design is selected as most appropriate for the crossflow turbine. Specifically, a gradient search algorithm is chosen to maximize the turbine's output power. Software is designed for the gradient search and other modes of the controller. The software design contains flow diagrams, psuedo-code, and a data dictionary. Testing the software with the linear interpolation model, shows the gradient search adequately maximizes the output power of the modelled crossflow turbine.

MICROPROCESSOR CONTROL DESIGN FOR A LOW-HEAD CROSSFLOW TURBINE

I. Introduction

Background

A major problem which has prevented widespread development of small scale low-head hydroelectric power is the high cost of building the systems. For example, a 25 kilowatt hydroturbine built and installed by Bell Hydroelectric would cost approximately $20,000 in 1978 (6:49). The most expensive hardware component for this system will be a high-efficiency commercial turbine (Francis or Kaplan design) priced around $8000 (6:50).

To counter high commercial cost, several mechanically minded individuals have designed and built their own low-head turbines. Most home built designs utilize the crossflow turbine (see Figure I-1). The cost of a crossflow turbine is at least 50% less (6) than a comparable commercially available Francis or Kaplan designed turbine. However, unlike many commercial turbines, the crossflow turbine lacks efficiency throughout the range of possible water conditions (ie. change of head height). Commercially available crossflow turbines have fixed turbine blades; therefore, there is only one set of water conditions where the crossflow turbine is at maximum efficiency (6:44).

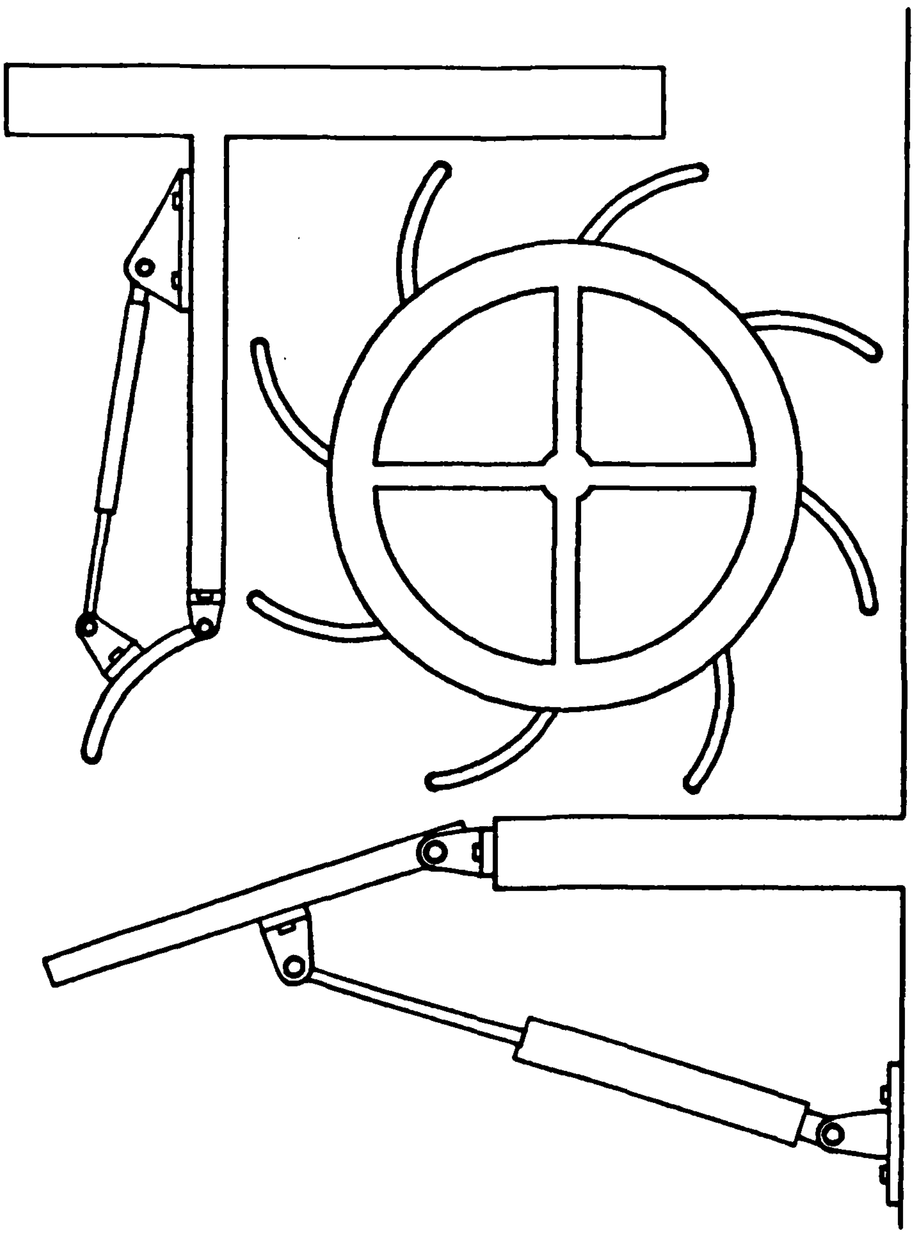


Fig. 1 Profile of Crossflow Turbine

In Sydney, Ohio, Mr. Roger Ely has constructed a crossflow turbine system with adjustable turbine blade pitch and adjustable water inlet guides. By adding these control capabilities to the turbine, Mr. Ely hopes to achieve maximum output power from the turbine over a wide range of water conditions. A typical crossflow turbine's efficiency throughout the range of typical annual water conditions is about 65% average and as high as 80% peak (6:43-53). By keeping the control parameters optimally adjusted Mr. Ely's turbine can operate near the 80% efficiency in all water conditions.

Although not complete, Mr. Ely estimates his turbine can average 2 to 8 kilowatts for an initial cost under $1000 (2). Averaging 4 kilowatts, of output power, at 4¢ per kilowatt-hour, is worth $1400 per annum. The Air Force Institute of Technology (AFIT) is interested in Mr. Ely's turbine design because if successful, the low cost of his turbine can make low-head power economically feasible as a deployable power source for tactical situations or environments at numerous military installations (1).

In order to control the turbine parameters to produce maximum output power, there are three possible methods. First is manual control which involves periodically adjusting the control parameters to optimal positions. Although this is cheapest in terms of hardware, there are two disadvantages. First, typical low head water systems have highly variable naturally-occurring head heights. Therefore, without frequent adjustments to the control parameters, the turbine will not remain at the peak efficiency. If the the average output at maximum efficiency is 4 KW, then operating at 70% of maximum efficiency equates to a loss of $420 per year (calculated at 4¢ per KW). The second disadvantage is the tedious task of monitoring the system 24 hours a day. Employing an operator is impractical, since the operator would cost more than the system is worth. Consequently, manual control is not the most efficient or least expensive means of controlling the turbine.

A second method of control is to implement a mechanical control system. Mechanical controllers use the mechanical energy of the rotating turbine to continually adjust the parameters to the optimal settings (3:2477). These controllers require an elaborate scheme of expensive parts to operate. Also, mechanical controllers are not commercially available for systems less than 500 kilowatts, therefore the controller would have to be fabricated (3:2476). Again this is impractical since the cost of fabricating a mechanical controller (approx. $8000) exceeds the net worth of the system.

To minimize cost and to maintain high efficiency, the third choice for controlling the turbine is a microprocessor-base controller, controlling hydraulic actuators. Such a controller does not require monitoring and can be relatively inexpensive. A microprocessor controller including design costs is estimated to cost \$600-1000 using AFIT resources (1). The low cost and automatic control features of the microprocessor controller make it the practical choice for controlling the turbine (see Figure I-2).

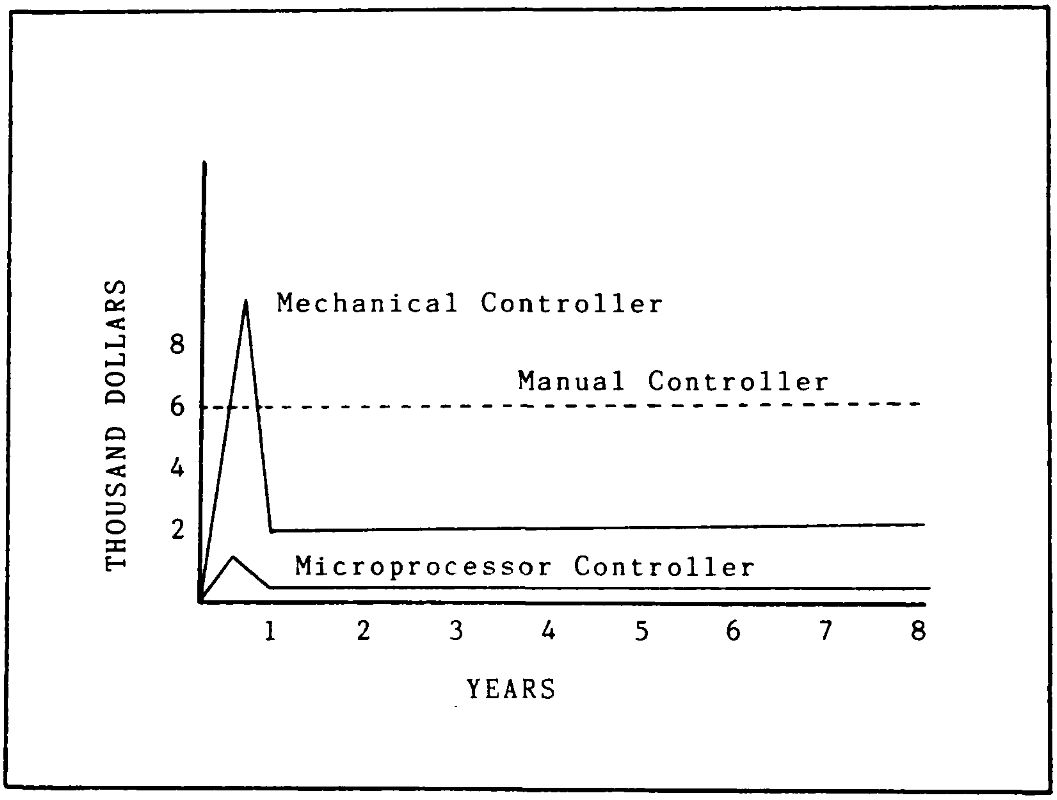


Fig. I-2 Comparative Costs of Controllers For a Typical 10 KW Hydroturbine

Problem

The crossflow turbine requires an inexpensive, automatic controller in order to operate at maximum efficiency. The practical solution to this problem is to design and implement a microprocessor-based controller (hereafter just called the "controller"). The purpose of this thesis project is to design (at the systems level) and simulate a microprocessor-base controller for a low-head hydroelectric generation system. The design of the microprocessor is such that control parameters are continuously adjusted to maintain maximum output from the turbine.

Scope

The primary objective of this design thesis is to provide the information required for a follow-on project to perform the detailed design and implement the controller. Some of the required information that is provided in this thesis is a description and block diagram of the turbine (plant), and all interfaces to the plant. The actual quantitative model of the plant was empirically derived from tabular data obtained from experimental testing of the turbine. This approach appears viable for this project. A rigorous mathematical model, while theoretically interesting, would have been a laborious undertaking and therefore was not done.

An analysis of the system requirements is performed. This includes functional requirements, environmental requirements, power supply, limitations, reliability, maintenance, and performance.

Three different controls methods are analyzed; open loop, feedback, and maximization search. Based upon the requirements, the appropriate control method is selected. Using this control method an algorithm is designed to maximize the power output. Based upon the control algorithm, the software for the entire controller is designed. The controller software consists of numerous modules which either perform secondary functions, such as hydraulic pump turn on, or directly perform a process of the control algorithm. These modules will eventually be implemented in an actual controller. This thesis presents a design which consists of psuedo-code and flow diagrams for the software modules within the controller. Actual programming will be accomplished by the builders of the controller.

To test the control algorithm, a simulation is performed using a Cyber computer. The algorithm is evaluated using a Fortran program operating on a model of the plant obtained from empirical data. The results and evaluation of this test is contained in Chapter VII. Concluding this thesis is recommendations and suggestions to the implementers of the controller.

During the tests that were performed to acquire empirical data, the turbine was found to have a faulty control surface design. The faulty control surface requires extensive modification to the turbine. Due to time constraints, the data required for modelling the turbine was only acquired for the pre-modified turbine. The controller designed and tested in this thesis is primarily based upon the model of the pre-modified turbine. However, the software design of the controller is written as general as possible. Changes to the software which will make the software applicable to the modified turbine are pointed out in the text as much as possible. Recommendations on applying the controller design to the modified turbine are contained in the final chapter.

Assumptions

Several assumption are made while designing the controller. First, the controller is designed to maintain maximum output power for all conditions. Frequency and voltage regulation are controlled by other hardware. Second, the change in water height is the only input required to show changes in water conditions. Although water flow rate changes measurably, the flow rate is a function of the actual water height. Therefore, for a given water height the flow rate is expected to be a constant. Finally, the user does not need, and will thus have no means, of on-line programming. All programming of the microprocessor will be completed in the AFIT laboratory.

Approach

The first step in designing the controller is to determine what needs to be controlled. Therefore a block diagram and general model of the system is developed. Data was taken of actual turbine output versus changing inputs. From the data, a tabular model of the turbine (plant) was constructed. After a complete characterization of the plant is completed, the requirements for the controller is determined. The derived requirements establish the desired specifications for the controller design.

Once the requirements are established, the actual design of the controller is performed. The design consists of comparing different control methods and selecting the most appropriate method based upon these requirements. The next step of the design is to develop an algorithm based upon the selected design method which achieves the control performance required. The algorithm is tested by computer simulation. From the results of the simulation the control algorithm is evaluated and modified as required.

Sequence of Presentation

Chapter II explains the modelling of the turbine. A description is given of each component of the turbine which is used in the model. This is followed by a block diagram showing the inputs and outputs of the model. The turbine section of the block diagram is modelled by empirical data. This chapter contains the procedure used to obtain the data and a discussion of the observed turbine characteristics.

Chapter III defines the requirements for the controller. The general requirements presented are; 1) interfacing with the turbine hardware, 2) user interfacing, 3) calibration and maintenance, 4) performance, 5) reliability, 6) power supply, 7) limitations, and 8) environmental.

Chapter IV presents an analysis of three controller configuration designs. The search design is selected as the most feasible for the turbine system described in this thesis. This chapter also contains a hardware diagram and component description for a possible search controller.

Chapter V presents the four modes of operation of the search controller. The basic software design for three of the four modes of the controller was completed by Lt. Mark Walker as a class project at AFIT. His software design for three of the modes is contained in Appendix J. The software design of the control cycle mode is presented in Chapter VI.

Chapter VI contains a detailed design of the control cycle mode of the controller. The control cycle mode contains the search algorithm. Therefore, this chapter describes the selection of a suitable algorithm and analyzes the procedure in which to apply this algorithm to the controller and turbine system. The application procedure is then used to develop software for the entire control cycle.

Chapter VII presents the test and evaluation of the search algorithm used in the control cycle mode.

Chapter VIII contains the conclusion to the thesis. Recommendations and suggestions for implementing the controller design to the modified turbine are included.

II. Plant Model

II-1. Introduction

In order to design and test a controller for the turbine, a suitable model of the turbine system must be developed. This chapter presents the development of a model. First the controllable sections of the turbine are described followed by a block diagram of the plant P. The plant can be broken up into two sections; the control surface actuator section ($\underline{G}$) and the turbine section (W). W is an unknown nonlinear function of water power and the control surface's positions. Therefore, to avoid the laborious exercise of mathematically solving for the overall transfer function P, this chapter contains the method of approximating W by empirical data tables. From the data tables the characteristics of the plant are determined.

II-2. Turbine Description

The turbine has six hydraulically or self-controllable sections each of which can be controlled with a small electrical signal. The controllable sections are the upper table, three upper inlet guides, lower inlet guide, and the turbine blade pitch (Figure II-1). The upper table is moved by two hydraulic pistons operating in tandem, each mounted with one end attached to the top of the upper table and the other end attached to the respective side of the turbine. The upper table can only move in a horizontal direction (up

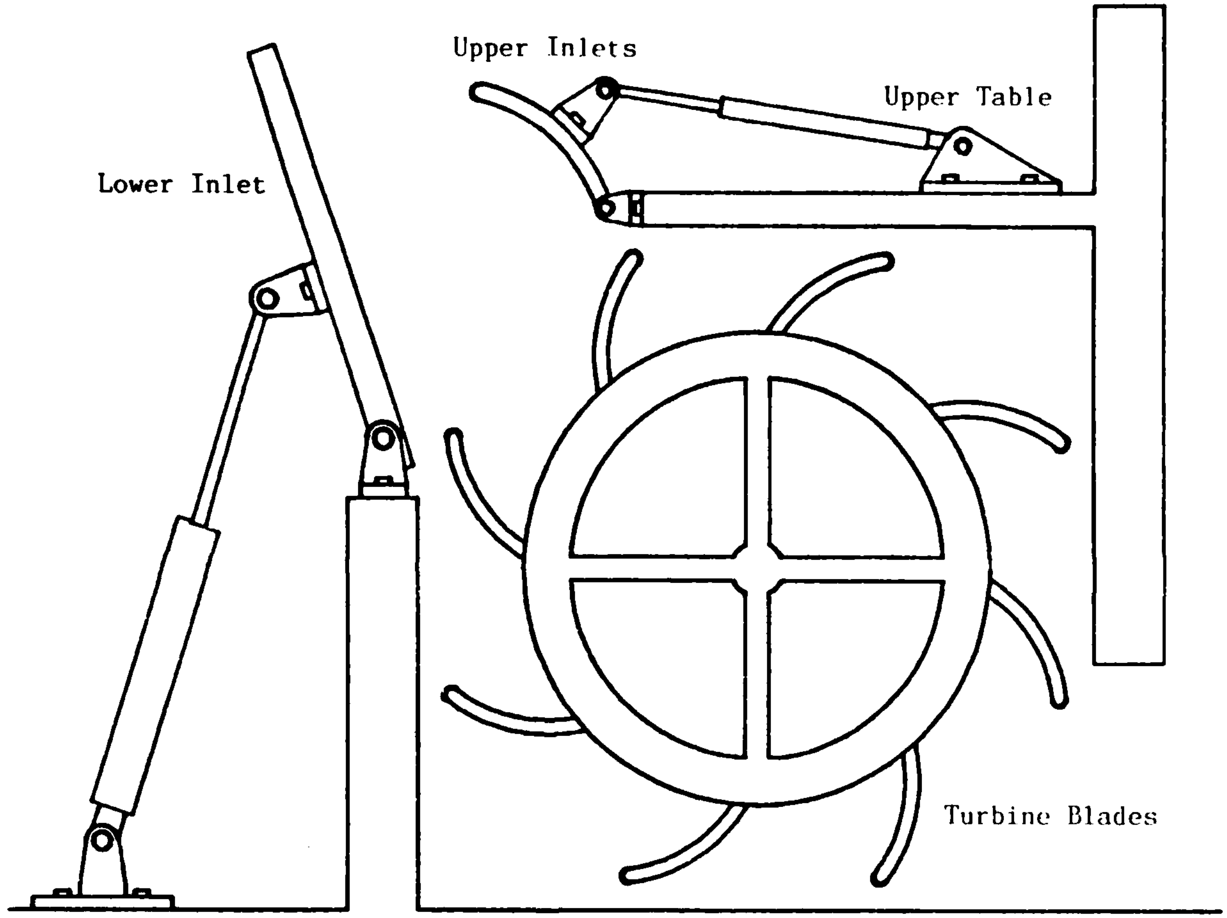


Fig. II-1 Ely's Crossflow Turbine

and down stream) parallel to the water surface. The function of the upper table is to increase or decrease the area of the water inlet to the turbine.

Mounted on top of the upper table are three inlet guides. The three guides have curved surfaces which direct the water flow into the turbine (Figure II-1). The bottom edge of the inlet guides is hinged to the edge of the upper table. Therefore, the pitch of the upper inlet guides can be changed by extension and retraction of a hydraulic piston mounted to the back side of the curved surface. Not only do the upper inlet guides direct the water into the turbine but they can also be used to decrease the water inlet area. The water inlet guides are normally moved uniformly, but during low volume water conditions (very low head) one or more of the inlet guides can be moved to a fully closed position decreasing the water inlet area to 1/3 or 2/3 the normal size.

The turbine blades (Figure II-1) can be adjusted through 60° of pitch. The blades pivot on their inside edge, therefore whenever the pitch changes the actual diameter of the turbine changes. The adjustable turbine blade pitch allows the turbine blades to be adjusted to the optimum angle to achieve maximum power transfer from the available water power.

The lower inlet guide (Figure II-1) is a steel plate hinged midway up the turbine front. The lower inlet can be moved from 90° (straight up position) to 10° (10° above horizontal). The guide is moved via an electric motor driven linkage. The purpose of the lower inlet guide is to direct the water at the optimum angle before the water strikes the turbine blades. The water entering the turbine flows over the top edge of the lower inlet. The water then flows down the surface of the lower inlet at an angle established by the position of the lower inlet. Changing the position of the lower inlet not only changes the angle of the water flow but also changes the head height. Moving the lower inlet from 10° to 90° causes a six inch increase in head height.

II-3. Available Water Power

Although the turbine has six controllable sections which can effect the power output of the turbine, no power is produced without available water power. The theoretical power which can be produced for falling water has been simplified to the following formula (5:7)

$$P_a = \frac{Q \text{ X } h}{708} = \text{Theoretical Output (KW)}$$

where Q is flow in cubic feet per minute, h is head height in feet, and 708 is a constant factor. The maximum output power that can be expected from a well designed small low-head turbine is 80% of P_a.

Due to the dam and turbine design as described in this thesis, the water flow rate and head height are not independent. Consequently, for the remainder of this thesis it is assumed that increases or decreases in head will cause respective changes in both available water power and flow rate.

II-4. Modelling the Turbine

The turbine's basic process, as shown in Figure II-2, is to convert available water power to rotational mechanical power. Output power as discussed in the remainder of this paper is the brake power measured from the drive shaft used to drive a generator. Actual electrical power output is a function of the rotational mechanical power and the efficiency of the generator.

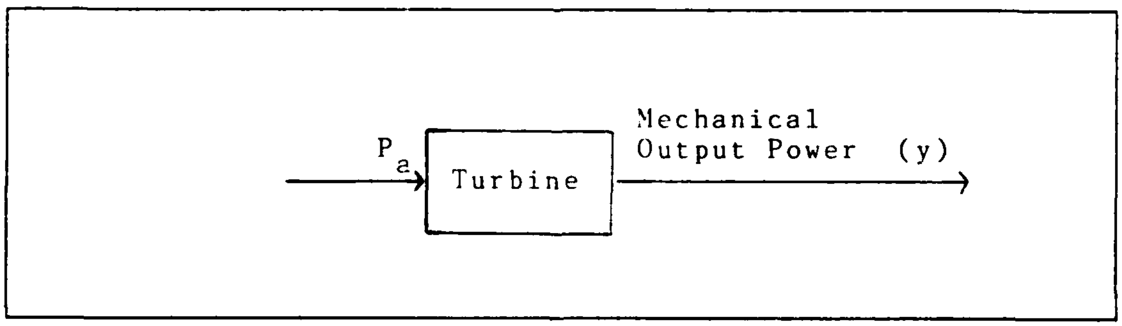


Fig. II-2 Basic Turbine

As mentioned in the description of the turbine all controllable sections of the turbine effect the water flow into and through the turbine, thus effecting the power output of the turbine. Therefore, as shown in Figure II-3, the turbine output power is actually a function of seven variables. The input variables are the six elements of the vector $\underline{x}$ and the available water power (P_a).

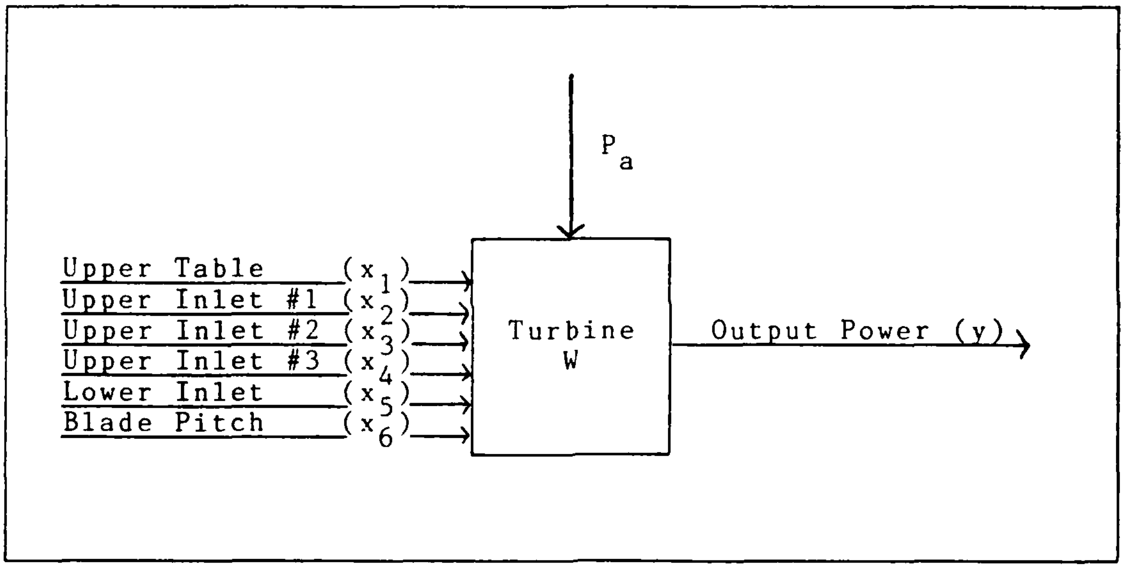


Fig. II-3 Turbine With Adjustable Control Surfaces

W is the function that relates the seven inputs to the output power y

where $$y = W(\underline{x}, P_a).$$

As shown in Figure II-4, the control surface positions are changed by applying electrical inputs (u_i's) to the control surface actuators. Each control surface moves independent of the other control surfaces, therefore each control surface has a different transfer function relating the electrical input signal (u_i) to the actual surface position (x_i). For convenience, the individual transfer functions for each control surface is written as an element on the principle diagonal of the transfer matrix $\underline{G}$. Where $x_i = u_i G_{ii}$ therefore $\underline{x} = \underline{u}^T \underline{G}$.

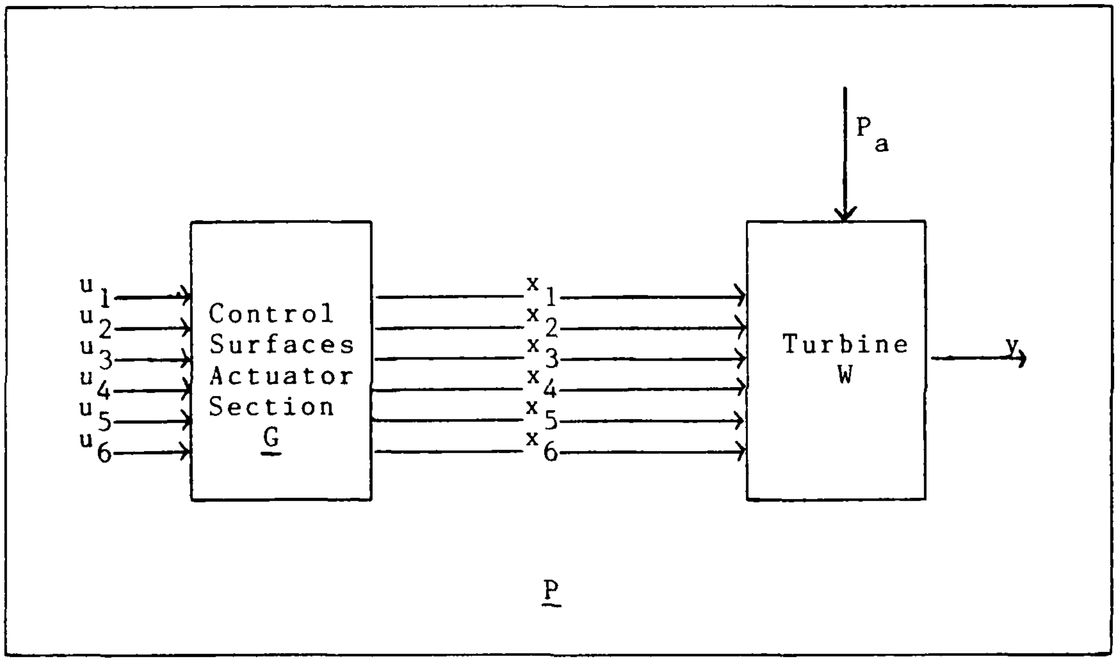


Fig. II-4 Block Diagram of Plant $\underline{P}$

In order to completely model the plant P, models must be made of both the control surface actuator section ($\underline{G}$) and the turbine section (W). The individual transfer functions (the principle diagonal elements of $\underline{G}$) can be determined from information known about the actuators and from experimental data. All of the control surface actuators were designed and tested to move at a constant rate. Therefore, as long as a control surface is not at a physical boundary the control surface position is approximated as

$$x_i = x_{io} + a_i t \qquad (1)$$

where x_{io} is the control surface position prior to movement and a_i is the rate of control surface movement. Actually, for each control surface there are two different rates, one rate for moving in the open direction (a_i) and one rate for moving in the closed direction (b_i). The electrical control inputs u_i have only three possible values $+u_{imax}$, zero, and $-u_{imax}$, where $+u_{imax}$ represents an input to move the control surface toward the open position, $-u_{imax}$ represents an input to move the control surface toward the closed position, and the zero input is for no control surface movement. Consequently, each diagonal element of the transfer matrix $\underline{G}$ has three equations. Table II-1 summarizes the equations of each element $\underline{G}$ with respect to the input values and surface positions. The rates of control surface movements (the a_i's and b_i's) for each control surface were determined experimentally and are listed in Table III-1.

Table II-1

Control Surface Position (x_i) vs Electrical Input (u_i)

u_i	x_i
u_{max}	$x_o + a_i t$
0	x_o
$-u_{max}$	$x_o - b_i t$

Finding the transfer function W for the turbine in terms of a mathematical equation is beyond the scope of this thesis. Fortunately, as is shown in chapter 4, such as equation is not required for the design of the microprocessor controller. Rather, the transfer function W is modelled by use of empirical data tables (Appendices A and B).

The empirical data tables were produced from many experimental power measurements using different input vectors <u>x</u>. The modelling of W is achieved by loading the data from Appendices A and B in a computer linear interpolation program (Appendix D). The linear interpolation program finds an approximation of the output power y for any input vector <u>x</u> (within the bounds of each element).

II-5. Data Acquisition

Data was acquired to model the turbine represented by the function W in Figure II-5. To obtain the data, measurements of the output power were obtained for numerous variations of inputs (control surface positions and water height). Sufficient data points were obtained so that linear interpolation is used to find the output power for inputs other than those that were measured.

Equipment and Measuring Technique

A pony brake was used to measure the turbines output power. The pony brake was attached to a drive shaft which was disconnected from the generators drive shaft. This shaft was geared to turn approximately nine times greater than the turbine. The speed of this shaft ranged from 0 to 1100 revolutions per minute (RPM) during the tests.

The power measured from the pony brake is a function of the measured braking torque and drive shaft speed (RPM). For each power measurement, the recorded power was the highest which could be obtained by varying the braking torque and RPM.

Position measurements of the upper table and the three upper inlet guides were made by measuring the length of the actuator shaft which extended from the hydraulic actuators of the respective control surface. The upper table actuator shaft extension ranged from 0 inches which is the table's full open position to 8.25 inches which is the full closed position. All three upper inlet guides' actuator shafts extended from 0 inches (full open) to 9.0 inches (full closed).

The lower inlet position was measured as an angle using a line parallel to the water surface as a reference for 0°. The lower inlet position is adjustable from 10° (nearly horizontal) to 90° (vertical). As is described in the next section, the turbine blade pitch is not required to be measured.

Procedure

Since water height is not a controllable input to the turbine, data tests were conducted over a period of several weeks in order to obtain data at different water heights. Data for four water heights was accumulated. These water heights are 12.125, 13.125, 14.0, and 19.875 inches. A river water height of 12.125 inches is considered low and corresponds to 103.5 cubic feet per minute of water flow. While a river height of 19.875 inches is above the average height (approximately 18.0 inches). At a water height equal to 19.875 inches, the water flow rate is 783 cubic feet per minute.

The procedure to obtain data at the different water levels was to move one input (control surface) in increments while fixing the other inputs. After each movement of a control surface, power measurements were made and recorded with the control surfaces' positions. Appendix C contains example forms used to record the raw data. The increments that control surfaces were moved were chosen so that power measurements were made at points where the power either started to increase or started to level off. Also, measurements were made where the power peaked and at the lowest point between peaks if there was more than one peak. If the control surface being moved was the upper table or one of the three upper inlet guides then power measurements were also made at the full open and full closed position of that control surface. Figure II-5 shows an example of the points chosen to measure power while incrementing the upper table position at a water height of 14 inches.

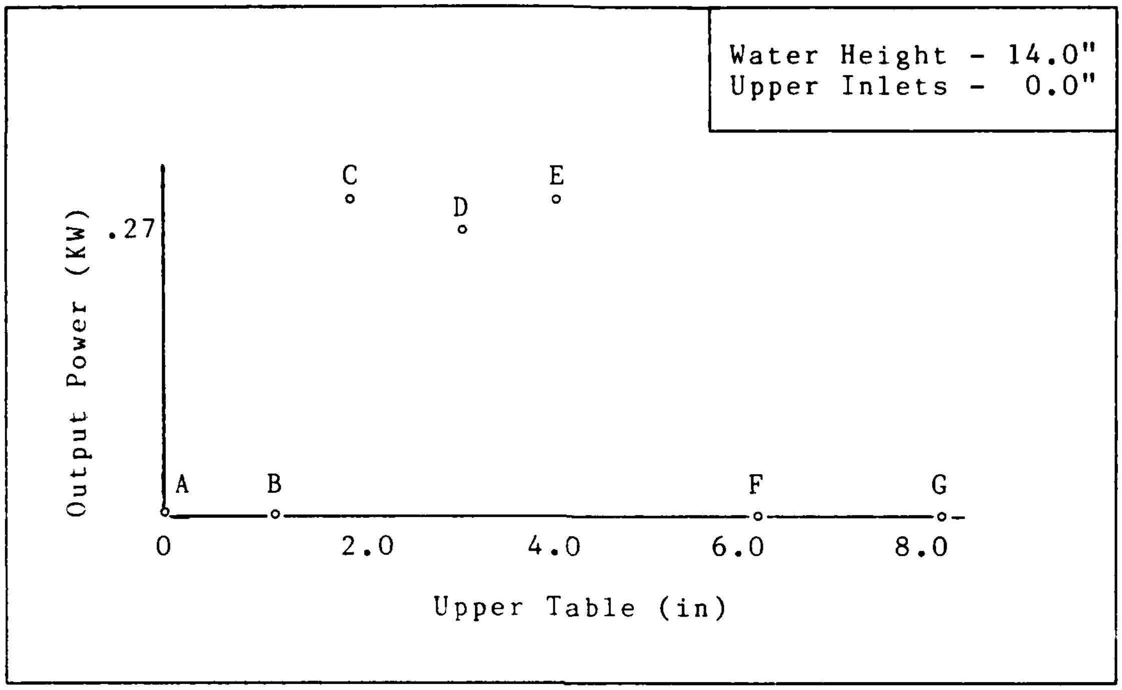


Fig. II-5. Upper Table vs Output Power

Point A in Fig. II-5 represents the power measurement where the upper table position is full open and point G corresponds to full closed. Point B represents the table position where power started to increase from zero while point F is where the power leveled at zero again. Points C and E represent the upper table positions where the power peaked and point D is the position where the power reached the lowest value between the peaks. Power measurements were made at similar points for the other control surfaces. Appendices A and B contain the data acquired for the four water heights.

Discussion

Data was not recorded for water heights above 19.875 inches however the optimum control surface positions at water heights above 19.875 were the same as the optimum positions at 19.875 inches. The reason the optimum control surface positions do not change above 19.875 inches is the river flow rate at water heights above 19.875 inches exceeds the flow rate that can pass through the turbine. Therefore, once the water height reaches 19.875 inches the control surfaces are set for maximum water flow and remain in this position for water heights greater than 19.875 inches.

Linear Interpolation

To examine the turbine characteristics and test the controller design a continuous model of the turbine is required. A continous model can be achieved by using linear interpolation with the turbine data in Appendices A and B. Appendix D contains a Fortran program which uses linear interpolation to determine the output power when the water height, upper table position, and the three upper inlet positions are input. The lower inlet position is assumed to be set at the optimum position at each input water height.

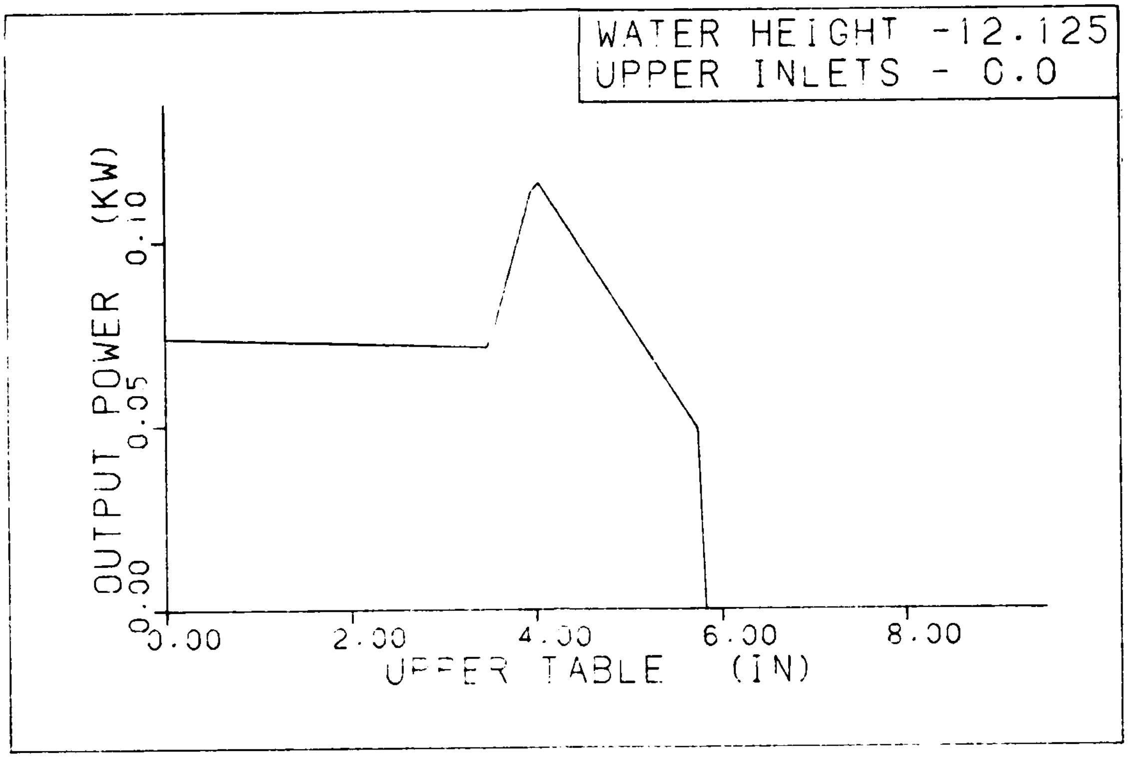


Fig. II-6 Linear Interpolated Output Power

When plotting the output power versus a control surface's position, linear interpolation results in sharp points where the output power reaches a peak (Figure II-6). Based upon the author's experience in testing the turbine, the power always changed in a smooth fashion, therefore the power versus control surface position plots should actually have a smooth curve at the peaks. However, the positions and output power of the peaks plotted by interpolation are the 'absolute' peaks and are not interpolated.

A quadratic interpolation was tried in order to smooth out the the sharp points. But as can be expected from any interpolation, the interpolated curves may contain segments which are extremely different from the actual characteristics of the turbine. For example Figure II-7 shows a quadratic fit for the same data in Figure II-6. Although the peaks are rounded, the output power at the peak is in error by over 300%. Extra logic could have resulted in the quadratic having the same peak as the linear, but this approach was not adopted because of the extra computational complexity. Consequently, the linear interpolation was considered adequate and best suited for the data in this thesis.

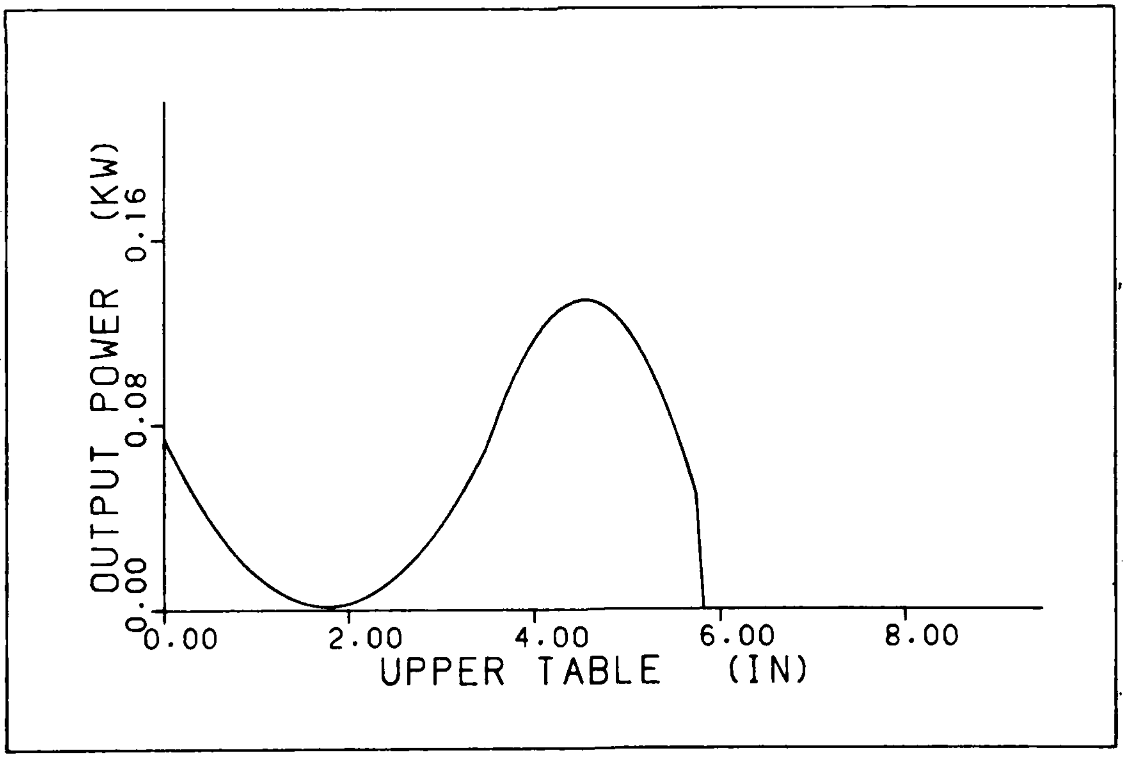


Fig. II-7 Quadratic Fit for Output Power vs Upper Table

II-6. Turbine Characteristics

During the test to acquire data, position changes of the lower inlet were found to also cause a change in the water height. Since the height of the lower inlet can be raised and lowered approximately six inches, the water height can also vary the same amount. However, once the lower inlet was positioned the water height would not stabilize to a new height immediately. The water would have to fill or drain to the new height established by the lower inlet. This draining or filling time could be as long as 30 minutes depending upon the flow rate of the river at the time.

To handle this large time delay while taking data and later when designing the controller, it was determined that the lower inlet must be set to an optimum position prior to data acquistion for the other control surfaces. Tests were performed to find the optimum setting of the lower inlet for several water heights and flow rates of the river. Appendix A contains the test data and resulting optimum positions of the lower inlet for several water heights. Throughout the remaining data acquistion tests, the lower inlet was set at the optimum position prior to recording power measurements based upon the other control surface movements.

Initial tests found that the output power remained constant regardless of the turbine blade pitch. The turbine builder and the author determined that due to a faulty lower inlet design the turbine never obtained the 'Banki effect' for which the turbine was designed (see Appendix L). Without the 'Banki effect' the turbine was much the same as a water wheel and turbine blade pitch had no affect on output power. Therefore, based upon these initial tests the turbine blade pitch was ignored as an input to the turbine.

The upper table was found to have the most influence on output power. For example, with the upper table and upper inlets at the full open positions, these control surfaces are completely out of the water flow into the turbine. Moving the upper table from the full open position to the optimum position increases output power as much as 30% at 12.125 inches of water height (Figure II-6). However, moving all three upper inlet guides from the full open to the optimum positions only increases output power approximately 1% at the same water height. Therefore the upper table is the most dominant control surface.

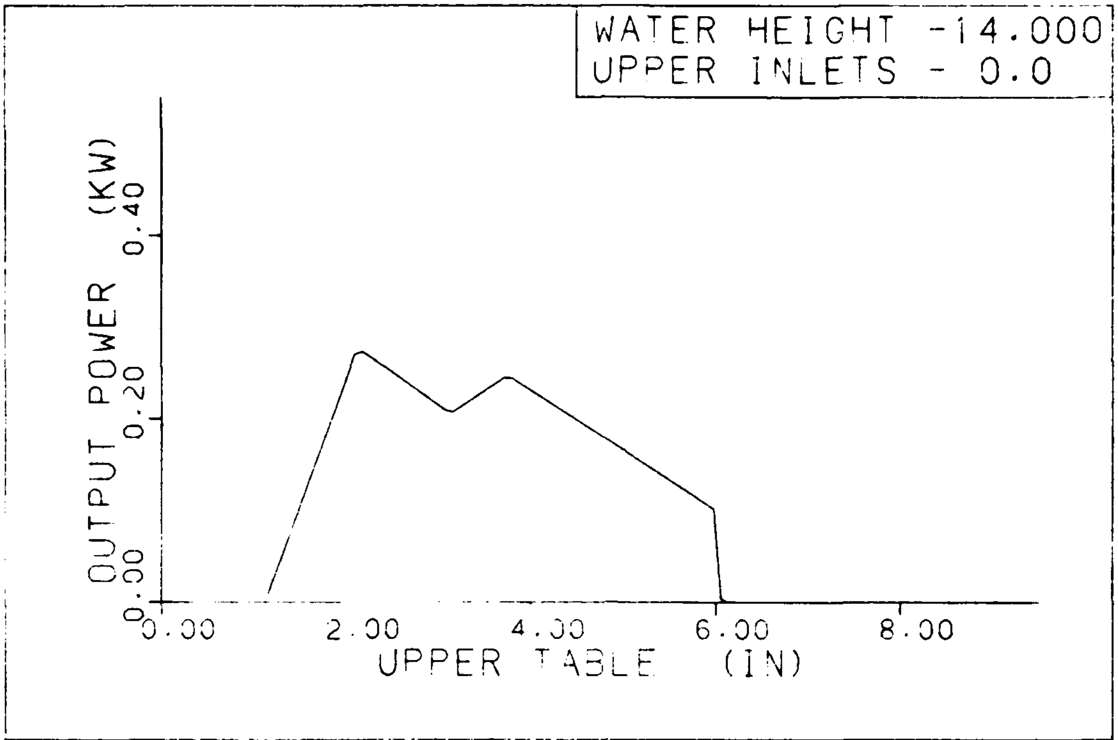


Fig. II-8 Multiple Peaked Output Power

Another characteristic of the upper table is that at various water heights the output power peaks twice with respect to upper table positions (Figure II-8). The double peak characteristic has to be taken into consideration when using a maximizing search algorithm in the microprocessor controller. Appendix E contains plots of the output power versus upper table positions. Linear interpolation was used to obtain these plots for 20 different water heights. These plots are required for the design of the controller.

As mentioned in the turbine description the three lower inlets under normal operation act as one control surface. Also, they were designed so that under very low volume water conditions one or two of the upper inlets could be moved to the full closed position. This decreasing of the water inlet area under low volume water conditions theoretically increases the turbines efficiency (see Ref. 8). However, due to the faulty lower inlet design the upper inlets could not completely close off a sector of the turbine. Therefore regardless of the water volume, optimum power was achieved when all three upper inlets were aligned and operating as one control surface. Consequently, moving one or two of the upper inlets to the closed position always obtained a lower output power than the maximum obtainable with the lower inlets aligned. Figure II-9 is an output power contour plot. The contour lines show constant power vs changes of the upper inlets. The water height in Figure II-9 is 12.125 inches (the lowest height tested) and the upper table is set at the optimum position for this water height.

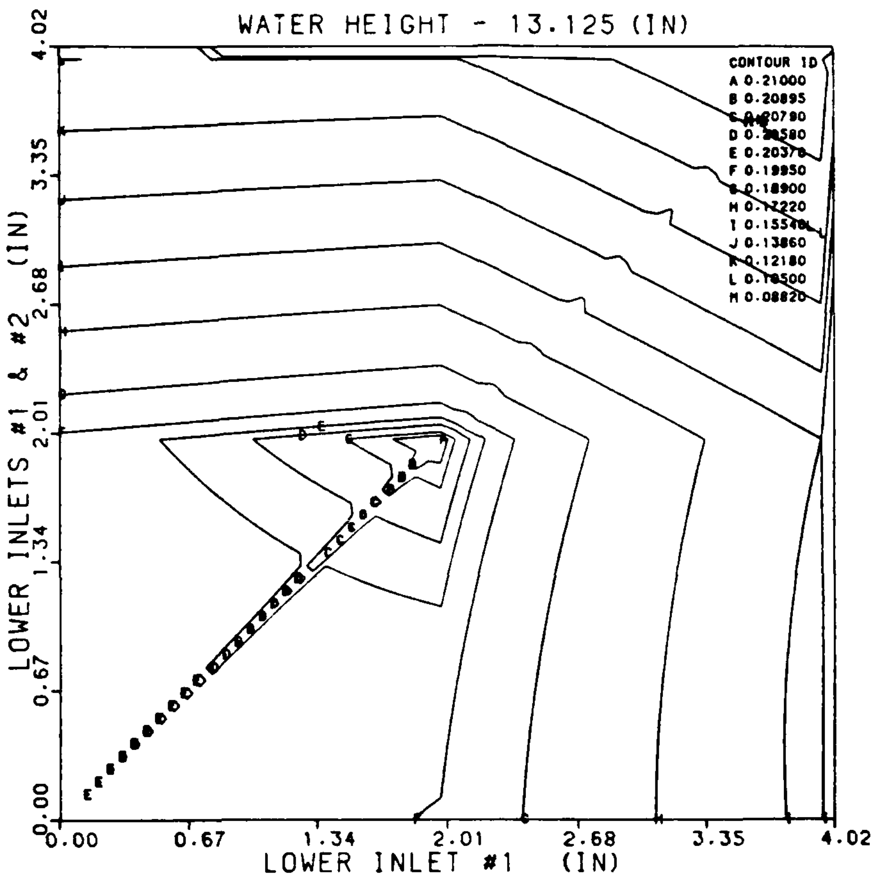


Fig. II-9 Contour Plot of Constant Output Power (KW)

Figure II-9 shows the contour lines with the highest values lie on or around a 45 degree diagonal line extending from the origin. The 45 degree diagonal corresponds to the upper inlet positions being equal. Similar results are shown for 20 other water heights in Appendix G. These results indicate that the upper inlets should always be aligned together and at their optimum positions.

II-7. Proposed Turbine Modification

As pointed out in the previous sections a faulty lower inlet design was found during initial testing. The maximum efficiency of the tested turbine at water heights close to the river's average water height was 55%. A properly designed Banki crossflow has an 80% efficiency. Therefore, the turbine builder plans to modify the turbine in order to achieve closer to the 80% efficiency. Appendix L contains the planned modifications for the turbine. These modifications are based upon the Banki Design presented in an Oregon State University's paper which interprets Dr. Banki's work (Ref. 7). The turbine modifications include a fixed position lower inlet and fixed turbine blade pitch leaving only the upper table and upper inlets as movable control surfaces. Due to time constraints the controller design in this thesis is based upon the turbine prior to the modifications. However, the controller design presented in this thesis will only require a few changes to conform to the modified turbine. These required changes are pointed out in the design sections of this thesis.

II-8. Summary

In this chapter a model of the turbine has been described for use in designing a controller. In order to develop the model a description of the inputs and outputs of the turbine was required. Since the mathematical equations relating the inputs to the outputs of turbine section are unknown, empirical data was gathered to model this section of the entire turbine system. A Fortran program (Appendix D) was written which uses linear interpolation of the empirical data to model the turbine section.

From the model, the characteristics of the control surfaces versus output power can be observed. These characteristics were described for each control surface. The upper table and upper inlets characteristics are shown, graphically, in Appendices E, F, and G.

III. Requirements

III-1. Introduction

This chapter presents the requirements established for the controller based upon experimental testing of the turbine and the turbine characteristics determined in Chapter 2. The following requirements are discussed; functional, interfacing with the turbine hardware, user interfacing, calibration and maintenance, reliability, power supply, limitations, performance, and environmental.

III-2. Controller Functions

1. The primary function of the controller is to find and maintain maximum power output from the turbine by controlling the control surface actuators.
2. A secondary function of the controller is to open and close a flood gate in order to prevent static water height from exceeding the height of the dam.
3. The controller must turn a hydraulic pump on and off in order to actuate the control surfaces. The pump should only be operated as needed in order to save energy and mechanical wear of the pump.
4. The controller is required to operate 24 hours a day with no human interaction.
5. The controller is required to check for for manual input errors and turbine failures. If an error exists then the controller will go to an idle mode.

6. The controller will notify the user of a malfunction via a LED display on the controller console.

7. A means of changing system constants (such as smallest increment a control surface can move, or control surface velocities) must exist through a numeric keyboard on the controller console.

8. The controller will have the capability to input voltage levels from sensors on the turbine output, a water height measuring device, and a flood gate position indicator.

9. The controller must be able to output control signals to the control surfaces, flood gate, and hydraulic pump.

III-3. Interfacing with the Turbine Hardware

In order to perform the functions listed in the previous section, the controller must interface with the turbine through inputs and outputs. Figure III-1 shows the turbine system interfaces which can be used by the controller. The numeric keyboard and LED display are considered components of the controller, therefore the interface of the microprocessor and other controller related hardware is discussed in the controller design sections. The following paragraphs discuss the inputs and outputs that are available from the microprocessor controller.

Controller Outputs

The controller output electrical signals to the control surface actuators or hydraulic pump are applied voltages

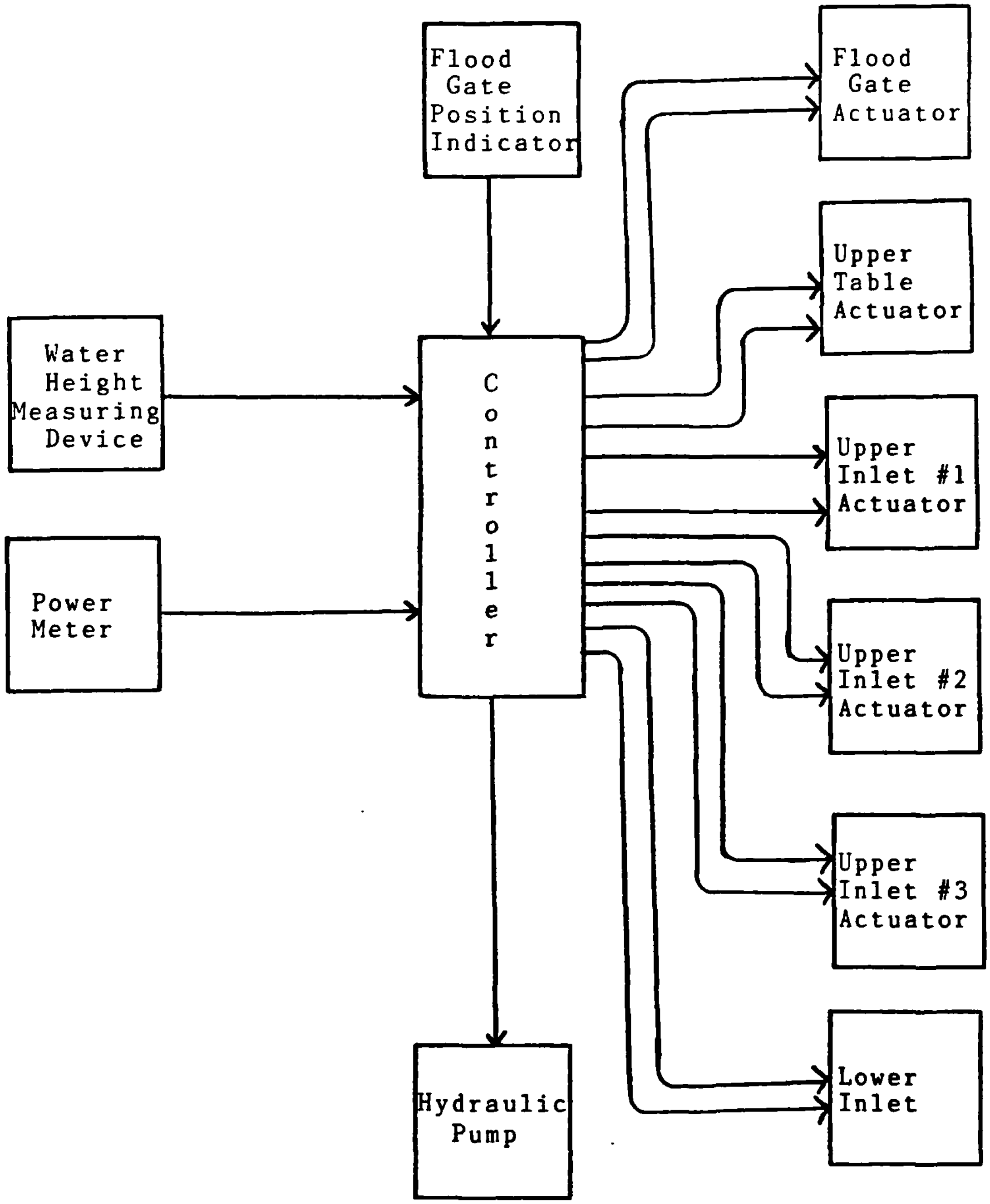


Fig. III-1. Turbine System Inferfaces

which engage a solenoid or relay. As Figure III-2 illustrates, when input of a signal. When the voltage V is applied, the solenoid or relay remains engaged or closed until the voltage is removed by the controller.

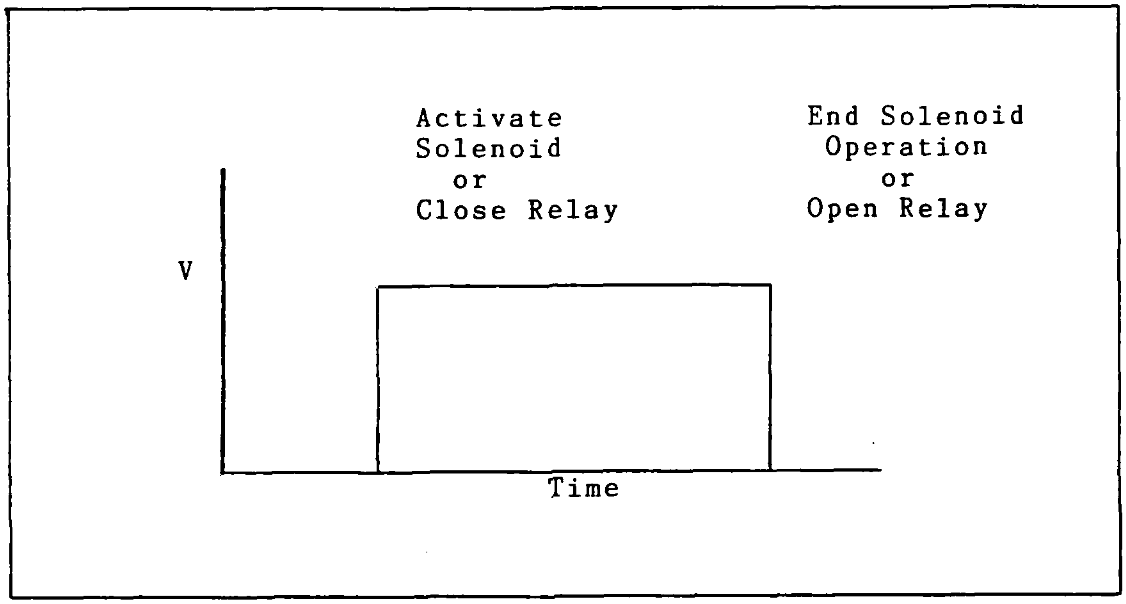


Fig. III-2 Example of Input Signal

The upper table and all three upper inlet guides are each controlled by outputs (Figure III-1). One output results in movement of the control surface in the open direction and the other output results in movement of the control surface in the closed direction. Therefore, a continuous output signal will result in continuous control surface movement provided that the mechanical limits are not reached.

The lower inlet drive was never installed on the pre-modified turbine and is not required after modification. However, initial plans were to make the outputs to the lower inlet similar to the upper table and upper inlets. Thus outputs would be required to move the lower inlet in both directions.

Only one output to the hydraulic pump is required. This output closes a relay switch which turns on the pump. The pump is turned off by removing the output to the relay. Note: the pump must be turned on approximately 10 seconds prior to control surface movement in order to support normal hydraulic pressures.

The flood gate (not yet installed) is to have two outputs. Similar to the upper table and inlet guides, the controller will output one signal to open the gate and the other signal to close the gate.

Controller Inputs

1. Water Height

A water height measuring device provides an input signal to the controller. The controller is required to initiate a control cycle after every significant change in water height. A control cycle consists of turning on the hydraulic pump, positioning the control surfaces in the positions which provide maximum turbine power, and then turning off the hydraulic pump. Also, the controller compares the water height input to a pre-programmed maximum allowable water height and opens or closes the flood gate accordingly.

2. Generated Power

A power meter will be connected to the output of the generator. The output of the power meter will provide an input to the controller for it to determine maximum power.

3. Flood Gate Position

A position indicator will be installed on the flood gate at a later date. The input of the flood gate position will provide necessary information to the controller so that the flood gate can be opened or closed to any position which will result in the highest head height without water overflowing the dam or turbine.

III-4. User Interface

The user requires an on/off switch on the controller. In the off position the controller should not output any signals causing control surface movement. In the on position the controller is required to start a control cycle regardless of the positions of the control surfaces.

The controller requires a numeric keyboard or equivalent hardware to allow the user to change values of system constants that are used by the control algorithm.

The data dictionary in Appendix H contains a list of global parameter constants that are used in the controller software. These parameter constants can be varied to fine tune the performance of the controller whenever the turbine characteristics change. For example, if a control surface actuator is replaced with a different one, the velocity of the new actuator can be updated in the controller software by the user.

The controller also requires a LED display or equivalent hardware to display malfunctions and parameter constants as discussed above. The LED display also shows the average output power for given water height when requested by the user.

III-5. Calibration and Maintenance

The user requires a means to change or calibrate the parameter constants as discussed in the previous section. Therefore, the controller is required to have a calibration mode. During this off-line mode, the controller displays the value of a selected parameter on the LED display and accepts a manual change from the numeric keypad. The controller is required to allow the user to start a control cycle after calibration has been performed. The controller is designed so that no other maintenance is required by the user.

III-6. Reliability

The controller is required to provide operational status to the user. Averaged output power values will be stored in the controller for numerous head heights. During the calibration mode, the user can inspect these average values via the LED display. The user then can compare these values against those found using manual control in order to determine if the controller is operating properly.

The controller is required to display appropriate error signals and automatically goes into an idle mode, whenever any of the inputs or outputs become open circuits (ie. breaks in leads or indicators).

III-7. Power Supply

The controller is to be powered by a 12 volt DC auto battery. The battery is charged by a low wattage battery charger which is powered by 120 volt AC power. The battery is also the power source for all actuator solenoids, hydraulic pump relay switch, flood gate position indicator, and the power meter.

III-8. Limitations

The controller's output signals (the turbine's inputs) are limited by the mechanical limits of the turbine and flood gate. The following information describes the mechanical range, position versus time formula, velocity, and smallest increments of movement for each controllable section.

Upper Table

The upper table has a range of movement from 0 (completely open) to 8-1/4 (completely closed) inches. Moving from 0 to 8-1/4 inches takes 20 seconds. Assuming linear movement

$$\%close = 100t/20$$

$$\text{Close Velocity} = 8.25/20 = .4125 \text{ in/sec}$$

where t is the time in seconds that the input signal is applied to the upper table actuator. The upper table requires 17 seconds to move from completely closed to completely open, similarly

$$\%open = 100t/17$$

$$\text{Open Velocity} = 8.25/17 = .485 \text{ in/sec}$$

The largest increments the controller can attempt to move the upper table is 20 seconds while moving in the open direction and 17 seconds while moving in the closed direction.

The upper table and upper inlets were constructed without position indicators or limit switches. However, to protect the control surfaces from excessive wear due to contact against the physical stops, the turbine builder plans to install limit switches on each control surface. A limit switch (positioned at the physical limits of the control surfaces) would electrically deactivate the control surface actuator when the switch becomes engaged. Limit switches are a necessity on the upper table and upper inlet of the modified turbine to prevent damage to the control surfaces.

Upper Inlet Guides

The upper inlet guides range from 0 to 7-3/4 inches. The signal application times for complete travel from open to close and complete travel in the opposite direction is 25 and 24 seconds respectively.

$$\%open = 100t/25$$

$$\text{Open Velocity} = 7.75/25 = .31 \text{ in/sec}$$

and

$$\%close = 100t/24$$

$$\text{Close Velocity} = 7.75/24 = .323 \text{ in/sec}$$

The largest incremental movements of the upper inlet guides which can be commanded by the controller are 25 seconds of signal in the open direction and 24 seconds of signal in the closed direction.

The smallest incremental movement that was measured for both the upper table and upper inlets was approximately 1/32 of an inch.

Lower Inlet Guide

Limits to the lower inlet guide were not obtained since no drive assembly was ever installed for this control surface. Also, an adjustable lower inlet is not required for the modified turbine.

The following table summarizes the limits for the upper table and upper inlets.

Table III-1

Control Surface Limits

Control Surface	Range (in)	Smallest Increment (in)	Open Velocity (in/sec)	Close Velocity (in/sec)
Upper Table	0-8.25	.03125	.485	.4125
Upper Inlets (All)	0-7.75	.03125	.31	.323

III-9. Performance

Significant changes in control surface position is required to maintain maximum power when water height changes by small increments. Therefore, the controller is required to initiate a new control cycle whenever water height changes by approximately 1/2 inch. Also, to prevent control surface drift due to hydraulic pressure bleed off, the controller initiates the control cycle in hour increments, regardless of water height. The controller should complete each control cycle within a reasonable time limit (approximately 10 minutes). If the control cycle is not completed after this time limit has expired, then the controller is required to go into an idle mode and notify the user of a malfunction via the LED display.

III-10. Environmental Requirements

The controller is located in a small aluminum chassis along with the generator and hydraulic pump. Temperatures in the structure can reach as high as 110°F in the summer and -20°F in the winter. Although the controller is protected from precipitation, humidity can reach 90% even at peak temperatures. The aluminum chassis contains no air conditioning or heating. Therefore, the controller must be designed for this temperature and humidity range.

III-11. Conclusion

This chapter presented the controller requirements based upon on plant characteristics and user needs. These requirements are the basis for the controller design found in the following chapters.

IV. System Design

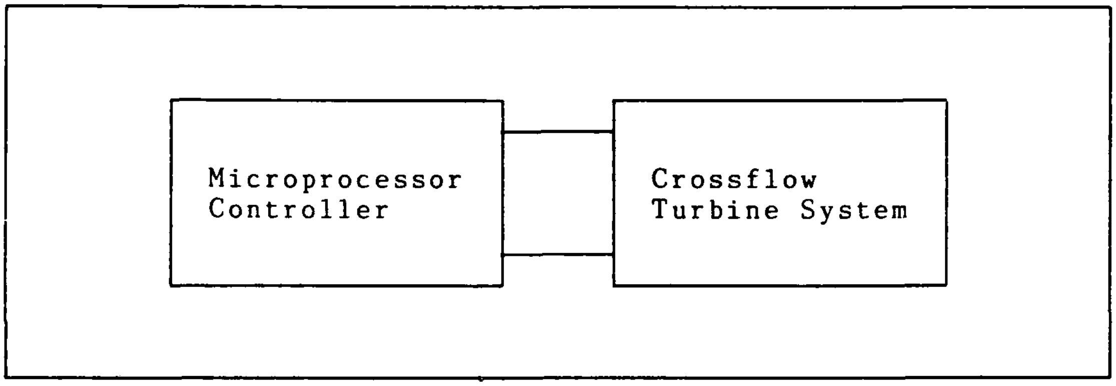


Fig. IV-1. The Hydro-turbine system with controller

IV. 1. Introduction

This chapter is divided into two sections. While Chapter 2 presented the crossflow turbine system configuration without the controller, the first section of this chapter discusses various configurations of the entire system including the controller (Figure IV-1). The configuration depends upon the control technique used within the controller. Three control techniques and configurations are discussed in this chapter including the open-loop design, the feedback design, and the search design. The search design is determined best for the crossflow turbine system. Therefore, the remainder of this chapter contains a hardware design for the search design controller.

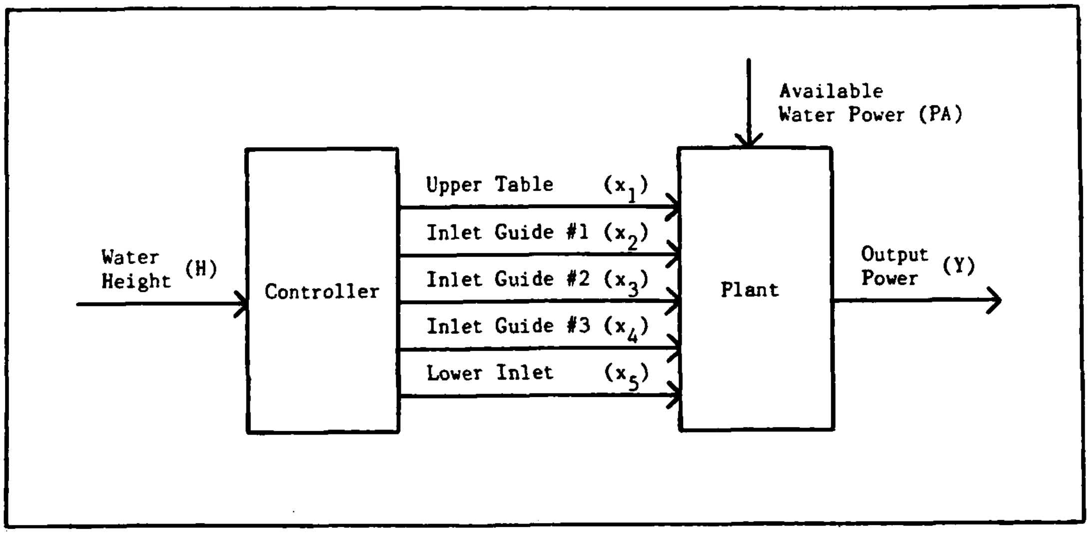


Fig. IV-2. Open-Loop Design

IV.-2. Open-Loop Design

An open-loop controller is programmed to maximize the power output of the turbine for a series of water heights. This requires the controller to be programmed with a specific optimum position for each control surface at a specific water height. Therefore, test data must be previously acquired (see Chapter II-5) to determine the optimum positions of the control surfaces. Also, the controller is programmed with closed-form equations describing the amount of travel as a function of time for each control surface (see Table III-1).

Table IV-1

Optimum Control Surface Positions vs. Water Height

Water Height: $H = 14.0$ (in)

Control Surface		Optimum Position
Upper Table	(x_1)	2.125 (in)
Upper Inlet #1	(x_2)	1.875 (in)
Upper Inlet #2	(x_3)	1.875 (in)
Upper Inlet #3	(x_4)	1.875 (in)
Lower Inlet	(x_5)	80.0 (deg)

For a specific water height, H, the controller is programmed to set each control surface at the optimum position (see Table IV-1). The controller initially moves all control surfaces to their mechanical stops in the full open position (or closed position). This procedure is required to obtain a reference position (full open is 0 inches). After the controller computes the time required to move each control surface to the optimum position, the controller then moves each control surface in the closed direction for the period of time . Hence, each control surface is moved to the optimum position to obtain maximum power from the turbine. Ideally, subsequent control surface movements can be made without moving to the full open (or full closed position) since the controller will store and use the current position as the new reference position.

Advantages of the open-loop design are simplicity and low cost. As shown in Figure IV-2, the design is simple and easy to implement. Also, the turbine builder is not required to add any extra hardware to accommodate the controller other than an electrical water height measuring device therefore eliminating additional costs to the builder.

However, the open-loop design will not satisfy all of the requirements established in Chapter 3, such as maintaining the maximum power output. The hydraulic actuators which move the control surfaces present two problems. First, the hydraulic actuator inherently will not maintain a fixed position for extended periods of time. Second, the actuators velocity may change after several weeks of wear and debris accumulation around the control surfaces. Therefore the amount of travel will be in error. Both of these problems cause the control surfaces to be positioned at a non-optimum location which will produce less than maximum power output.

IV-3. The Unity Feedback Control System Design

The design of the unity feedback control system is divided into two sections (see Figure IV-3). The first section, the optimum reference selector, operates similar to the open-loop design. This section is programmed with the optimum positions of the control surfaces for a series of water heights. This section then generates an optimum reference position r_i for each control surface. The second section, a conventional unity feedback control system, adjusts the control surfaces to the optimum reference position by a properly designed controller (algorithm).

This design allows the controller to precisely set and maintain the control surfaces at their respective optimum positions. The feedback design eliminates the inaccuracy of the open-loop design, and allows the controller to seek steady state optimum positions in minimum time.

The greatest disadvantage of using the feedback design is the number of sensors needed to provide required feedback signals. The turbine builder would be required to add costly and complex position indicators to each of the control surfaces. Also, the controller algorithm would require determining the exact transfer functions for each of the control surfaces. As described in Chapter II-4, determining these transfer functions is beyond the scope of this paper.

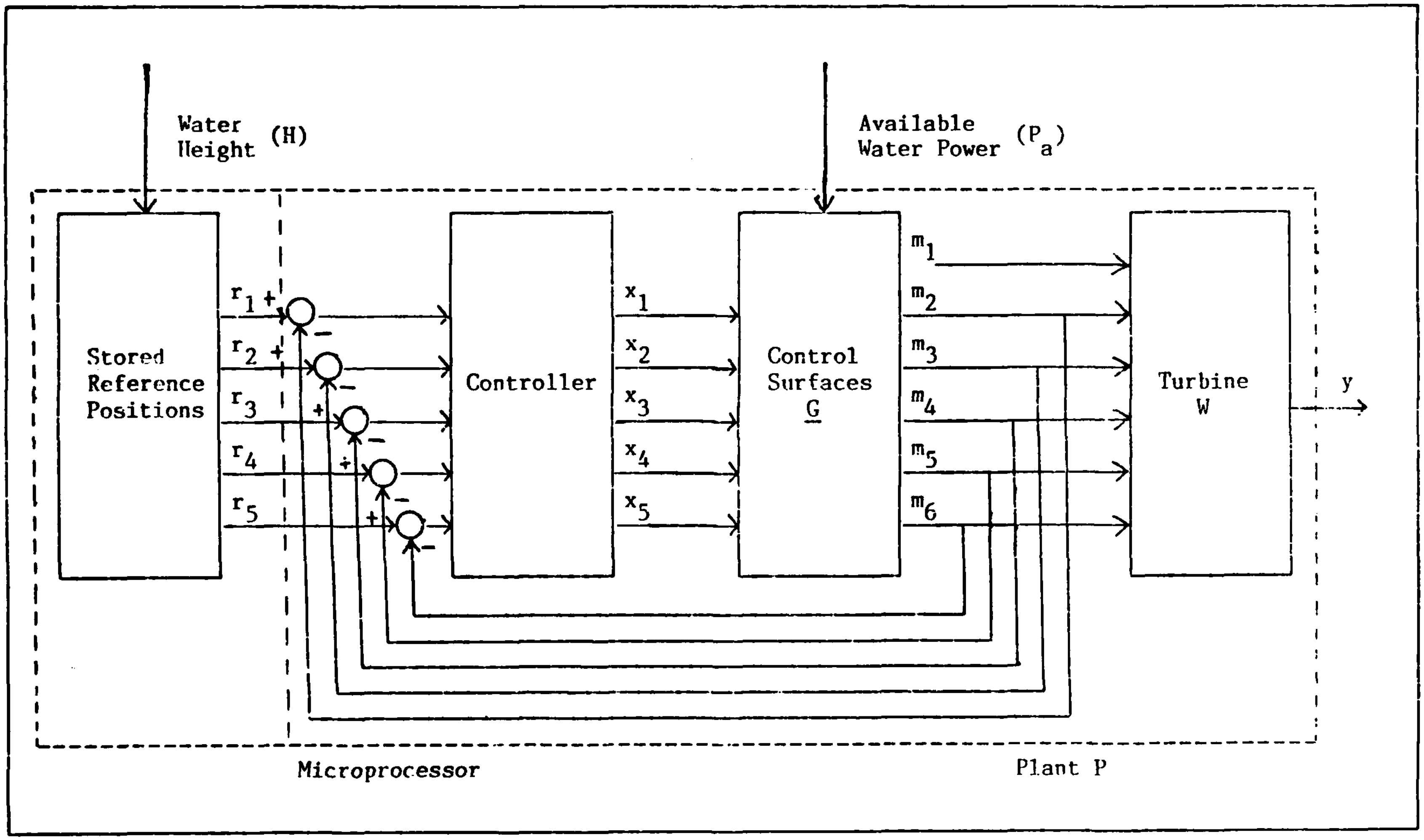
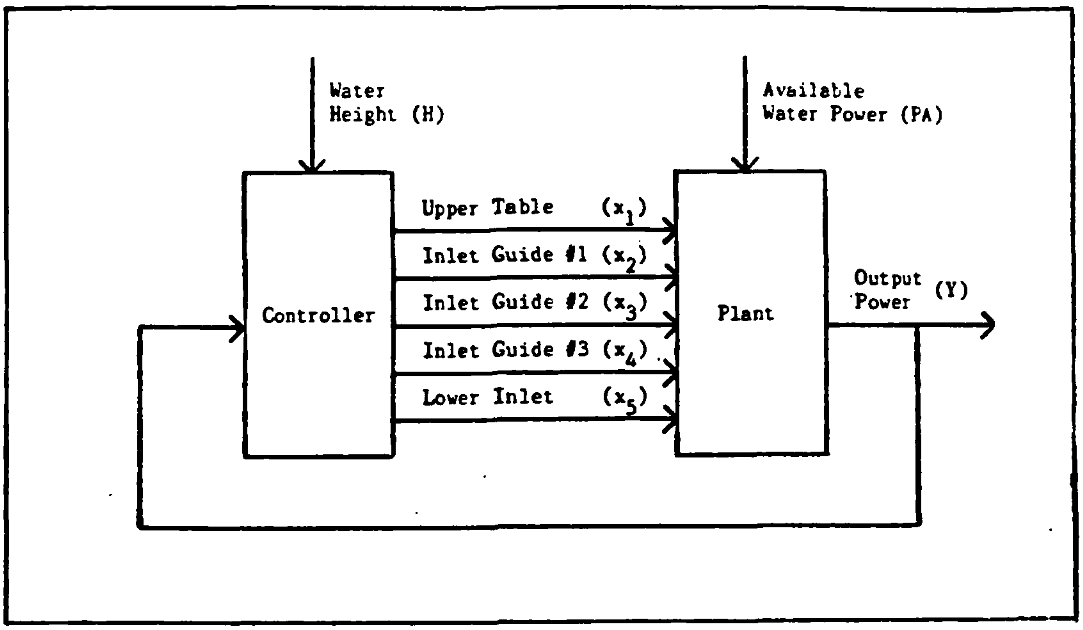


Fig. IV-3. Unity Feedback Design



IV-4. Search Design

A search design cascade controller (Figure IV-4) uses only the measured output power as a single feedback signal to search for the maximum power. The search is conducted by moving the control surfaces in a logical sequence to new positions and then testing the output power. Once the maximum power is achieved the search stops. To maintain the maximum output power, this design uses a time interval or water height change to initiate a new search. Several standard search techniques are presented Kuester and Mize (4), and two of these techniques are analysed in Chapter 5 of this thesis.

The search design is simple and inexpensive. The turbine builder is only required to add a feedback circuit from a power meter which is connected to the generator output, and a water height measuring device. Both of these additions are simple and low cost compared to adding feedback to each control surface.

There are two disadvantages of the search design controller: speed and transient response. Since the controller is searching for the maximum power throughout the entire ranges of the control surfaces, the search cycle can take several minutes to complete as compared to several seconds when using the open-loop or feedback design. Also, because of the search method the output power oscillates while the controller is seeking the maximum power. Fortunately, neither of these performance limitations is important to the turbine control presented in this thesis.

IV.-5 Selection of the Search Design

The search design does not require positioning the control surfaces to exact predetermined locations. Therefore, the problems inhere with the open-loop design are not present. Also, the search design requires fewer and less expensive hardware additions to accommodate the controller as compared to the feedback design. Control of transient responses are not critical in this crossflow turbine system, therefore the advantages of the feedback design are not necessary. Also, the search design does not require a large memory to store the optimum control surface positions which are required in the open-loop and feedback designs. The open- loop or feedback design requires reprogramming of the large memory with new optimum positions any time river dynamics change or minor modifications are made to the turbine, while the search design can operate without modifications to the controller. Therefore, after comparison, the search design seems the best for the crossflow turbine system.

IV-6. Search Controller Hardware

The previous sections discuss the selection of the search design and the additional hardware required outside the controller. This section discusses the hardware components required the controller. The necessity of each component in Figure IV-5 is based upon the controller requirements established in Chapter 3. The following summarizes the purpose of each component.

The microprocessor - is the brain of the controller. The microprocessor is a general purpose microprocessor which will fetch instructions from the PROM. Also, the microprocessor reads and writes data from the RAM and utilizes the remaining components to send and receive data while executing instructions.

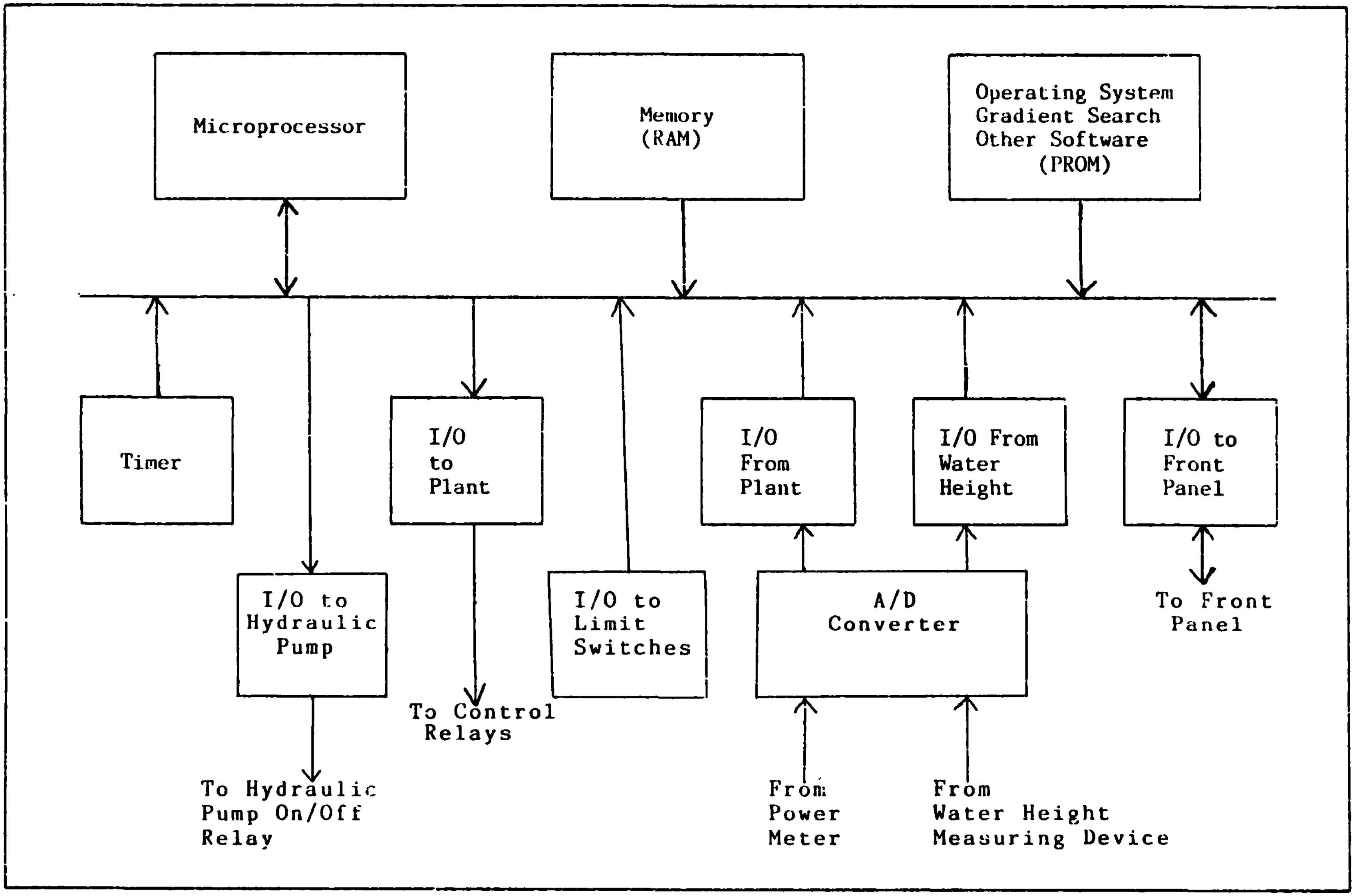


Fig. IV-5. Search Controller Hardware

The PROM - contains the necessary software instructions for the microprocessor. The software routines stored in PROM are discussed in Chapters 6 and 7.

The RAM - stores past and present output power data, water height data, control surface positions, and other data required by software execution.

The timer - provides time interval information to the microprocessor. As previously discussed (III-9 and IV-2), the control surfaces are repositioned at least once every hour to maintain maximum power output. The timer is used by the microprocessor to determine the elapsed time after a control cycle. Also, one of the requirements discussed in Chapter 3 is there must be a 30 second interval between control surface movements to allow stabilization of the water flow through the crossflow turbine. Therefore, the timer is used to determine the elapsed time after a control surface is moved.

Control relays - As discussed in Chapter 2, each control surface has two inputs (one for the open direction and one for the closed direction). Relays are required to interface the higher voltage and current of the control surface's electrical inputs to lower voltage and current of the controller's outputs. Therefore, relays are required per control surface.

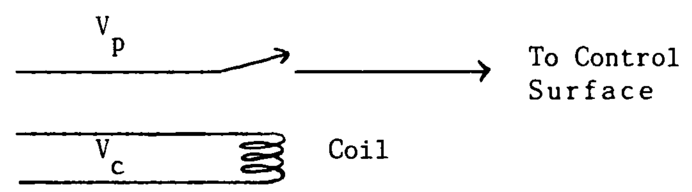


Fig. IV-6. Controller Relays

Figure IV-6 illustrates, a relay for one of the control surface inputs. V_p is the electrical power source to the control surface actuator and V_c is the voltage applied to the relay coil by the controller. When V_c is larger than the relay threshold voltage, then the relay is closed creating a path from the power source to the control surface actuator. When V_c is less than the relay coil threshold voltage then the relay is opened creating an open path to the control surface actuator.

The I/O to plant - is the interface from the controller to the plant. The purpose of this component is to output the voltage V_c to the appropriate control relay for the duration time τ (Figure IV-7). This I/O determines the correct control relay and time τ from the data received from the microprocessor.

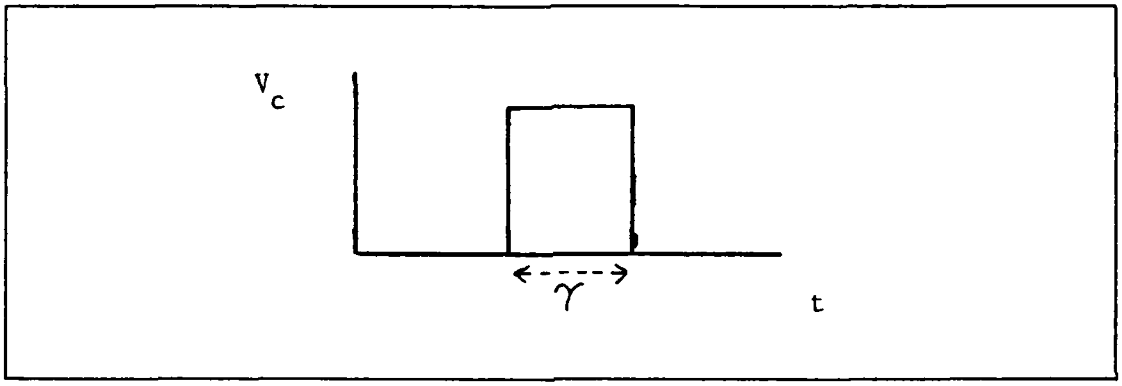


Fig. IV-7. I/O Output to Control Relay

The A/D Converter - shown in Figure IV-5 converts the analog power meter and water height measuring device outputs to usable digital inputs used by the appropriate I/O devices.

I/O from plant - interfaces the output power data to the microprocessor. As discussed earlier in this chapter, the power data is required with the search technique and design.

I/O from water height - interfaces the water height data to the microprocessor. Water height data is required in order for the controller to fulfill two of the requirements established in Chapter 3. First, the controller needs the water height data to initiate control cycles whenever water height changes by one inch or more. Second, water height data is required when comparing power outputs versus water height. This comparison is required when executing error check software (see Chapter III-6). Also, as is explained in Chapter 5, the search software design requires water height data.

I/O to front panel - interfaces the user's front panel to the microprocessor. This device receives water height, output power, and error data from the microprocessor which is then displayed on the user's front panel. Also, this I/O inputs data to the microprocessor which stops, starts, or resets a control cycle according to the users input to the front panel. The functions of this I/O are required when performing calibration and maintenance as discussed in Chapter III-5.

I/O to hydraulic pump - interfaces the hydraulic pump off/on relay to the microprocessor. As discussed in Section III-2, one of the controller's required functions is to turn on the hydraulic pump at the beginning of a control cycle and turn off the pump at the end of the control cycle. Therefore, the microprocessor sends data to this I/O will powers or depowers an off/on relay similar to the control relays. The off/on relay then provides or removes power to/from hydraulic pump.

IV-7. Summary

This chapter presented three different configurations of the crossflow turbine system with controller. The open-loop control system design, although simple and low cost, does not maintain maximum power as required. The unity feedback control system design, which is a workable solution to the open loop design, requires expensive and complex hardware additions to the turbine system. Also, the unity feedback design would require further research of the turbine to find the transfer functions of the system. On the other hand, the search design would not require expensive hardware additions or the system transfer functions. Therefore, the search design is determined best for the crossflow turbine system.

The remainder of this chapter discussed a hardware design for the search controller. The necessity of each hardware component is based upon the requirements established in Chapter 3. The hardware design presented is only a guide the controller builders can use when actually constructing the controller.

V. Controller Design

V-1. Introduction

The scope of this thesis is to design a search algorithm for the controller. However, the overall plan for implementing the controller was designed by Lt. Mark Walker for a class project at the Air Force Institute of Technology. Based upon the requirements and hardware configuration presented in Chapters III and IV, Lt. Walker designed the controller to operate in four modes; the monitor mode, control cycle mode, calibrate mode, and the major malfunction mode (Figure V-2). This chapter presents a scenario of the four modes of operation. Modifications to Lt. Walker's original design were made by this author in order to incorporate changes to the turbine that occured after Lt. Walker's design was completed. Lt. Walker's detailed software design for the major subsystems (except the control cycle mode) is contained in Appendix J. The detailed design of the control cycle mode which includes the search process is presented in Chapter VI. Note: the turbine modifications presented in Appendix L only affect the search process of the controller, therefore the design presented in this chapter and Appendix J remain valid for the revised turbine control.

Figure V-1 is a hardware interface diagram courtesy of Lt. Walker. This diagram is referenced in the following descriptions of the controller operation.

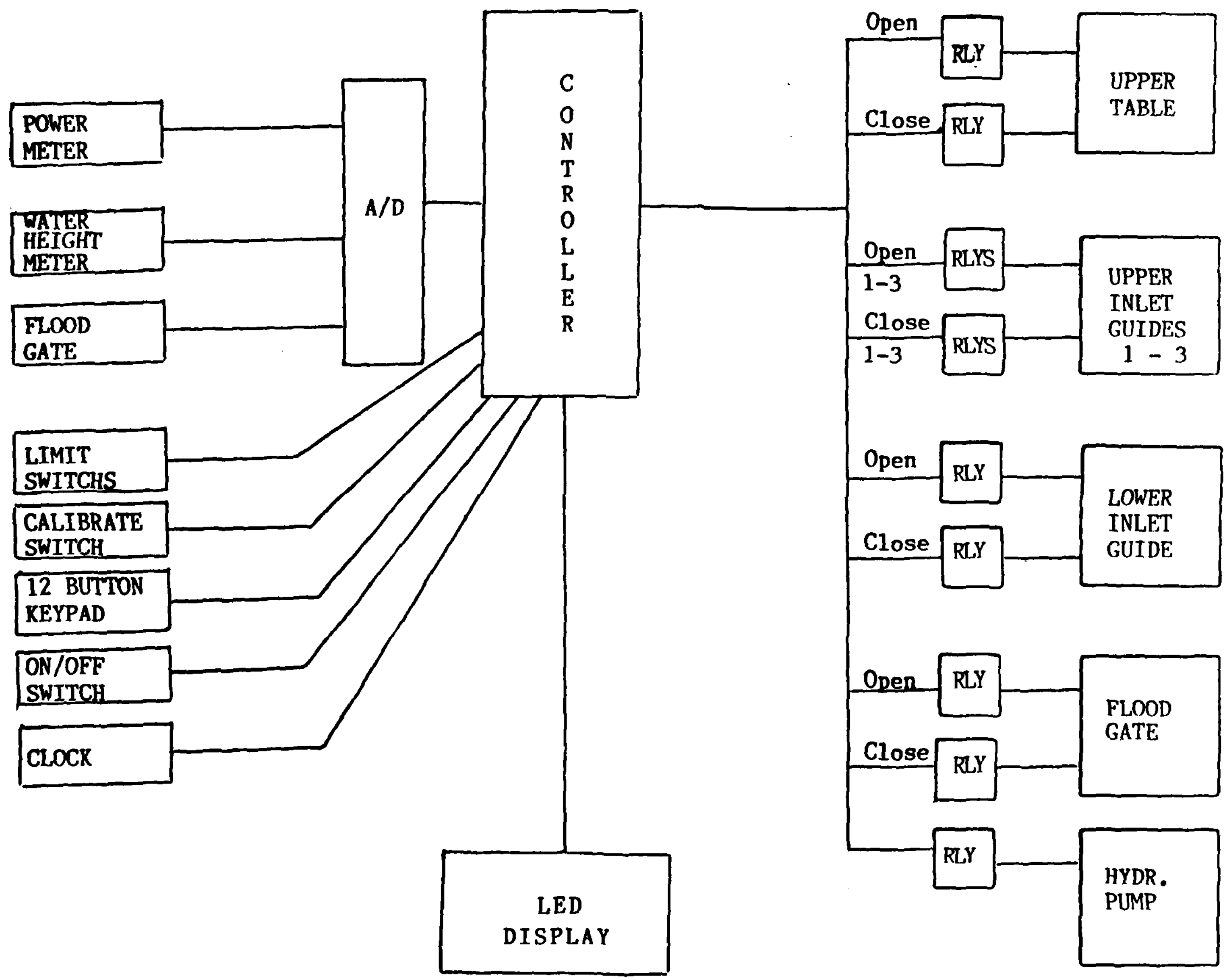


Fig. V-1 Hardware Interfaces

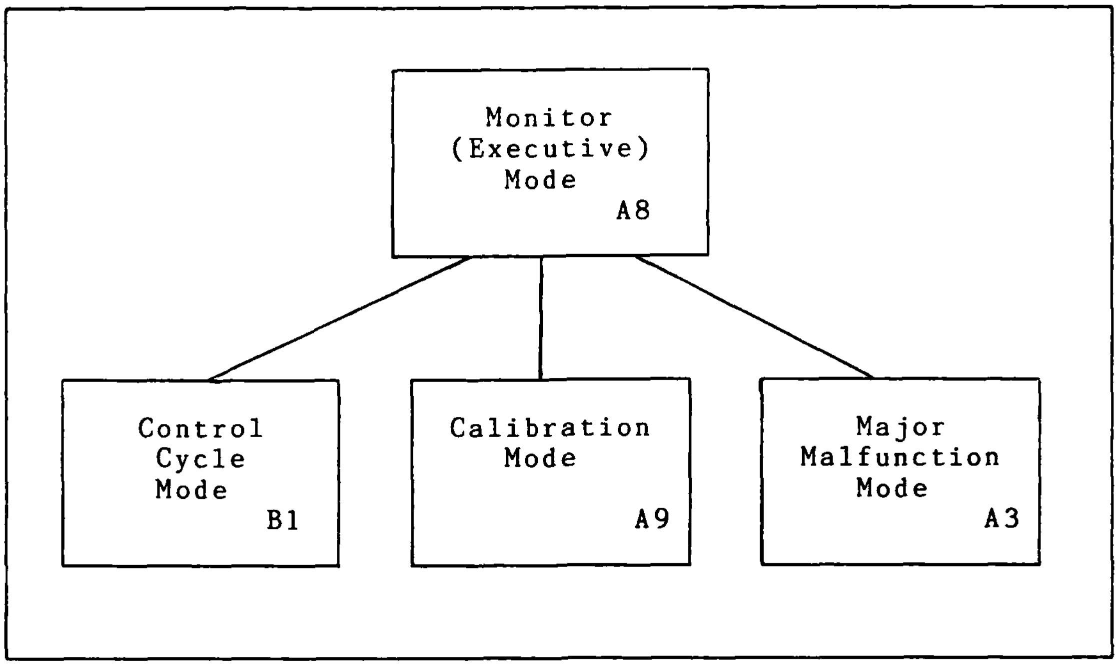


Fig. V-2 Controller Operating Modes

V-2. The Monitor Mode

As shown in Figure V-2 the monitor mode is the "executive" mode for the control system. The control system reads the input signals from the A/D (Figure V-1) and decides if it is necessary to go into one of the other three modes. If another mode is necessary, the control system enters the mode and performs the actions for that mode. If the mode entered is not the major malfunction mode then the control system returns to the monitor mode on the next computer cycle. If the mode is the major malfunction mode then the control system goes to an idle state. The monitor mode requires no human interaction. In summary, the monitor mode begins when the control system is started, decides when to go into the other modes, and is the mode the control system returns to if there is no malfunction.

V-3. The Control Cycle Mode

The controller is set in the control cycle mode if one of four conditions are true, The four conditions are:

1. Turbine output power falls below a minimum value established for the current water height. (The minimum value is based upon a percentage of the theoretical power calculated at the current water height. If the power has not increased above the minimum after the control cycle returns to the monitor mode then the controller automatically enters the major malfunction mode).

2. Water height changes by 1/2 inch or more since the last control cycle.

3. More than one hour elapses since the last control cycle.

4. The control cycle is entered from within the calibrate mode.

In the control cycle mode the control system performs a control cycle and then returns to the monitor mode. A control cycle involves turning the hydraulic pump on, move the control surfaces to the optimum positions, and then turning the hydraulic pump off. If the control cycle lasts longer than a predetermined maximum control cycle time (e.g. 10 minutes) then the system enters the major malfunction mode. The length of time allowed for the maximum control cycle can be changed depending upon operational experience.

The search process is a subsystem of the control cycle. The control cycle determines which mode of the search process that is to be performed. The two search process modes are:

1. Initial start up. This mode occurs anytime the controller is powered up, or after the calibration mode has been entered and the system is returned to the monitor mode, or when the control cycle mode is entered due to power below minimum.

2. Water height change. This mode is selected whenever the control cycle mode is entered due to a change in water height or when the maximum allowable time interval between control cycles is exceeded.

V-4. The Calibration Mode

The controller is set in the calibration cycle if the user switches the calibrate switch on. The switch is on the operator's console (Figure V-1). The user can input new scaling factors for the input and output signals, new values into the software tables, and new values for constants, via the twelve button keypad on the operator's console.

The user can also display the current values of controller inputs, outputs, software table elements, and system constants.

Finally the user can perform tests on the control surfaces, the flood gate (when installed), and the control cycle logic. The test and display capabilities mentioned above are selected via the 12 button keypad. The computer returns to the monitor mode when the calibrate switch is flipped to the off position. The buzzer on the operator's console rings if the calibrate switch is left on for 10 minutes after the last keypad input. The 10 minute time limit is one of the constants that can be changed while in this mode. The system switches back to the monitor mode if the user does not enter any data on the keypad or switch the calibrate switch off within 5 minutes of the ringing of the buzzer. The control surfaces may not be at the optimum positions to obtain maximum power during the calibrate mode, therefore the system should be in this mode only when the user is at the console or testing the system hardware.

V-5. The Major Malfunction Mode

The control system is set in the major malfunction mode if a serious error occurs that the controller cannot compensate for. In this case, the flood gate is fully opened, a warning buzzer is sound, and the control system goes to an idle mode. The buzzer shuts off after 10 minutes.

No further actions occurs until the user turns the control system on again. The three conditions that send the control system into the major malfunction mode are:

1. Hardware failure in A/D inputs to the controller (i.e. 0 volts).

2. Water height below minimum level.

3. Power remains below minimum after subsequent control cycle.

V-6. Summary

In order to fulfill the requirements established in Chapter III and to conform to the hardware configuration presented in Chapter IV, the controller operates in four modes; the monitor (executive) mode, control cycle mode, calibration mode, and the major malfunction mode. The detailed design for all subsystems except the search process is contained in Appendix J. The detailed design of the control cycle and search process are presented in the following chapters.

VI. Controller Subsystem Design
The Control Cycle Mode

VI-1. Introduction

This chapter presents a detailed design of the control cycle mode of the controller. Since the most important subsystem of the control cycle is the search subsystem, this chapter focuses on selecting an appropriate search algorithm and then analyzes the application of this algorithm to the physical turbine. This analysis is then incorporated into developing software for the complete control cycle mode.

Overview

Section VI-2 explains why the gradient search is considered the best search technique for the controller designed in this thesis. Section VI-3 presents the theory behind a general gradient search algorithm. Section VI-4 then presents an analysis of how to apply the general gradient search to the crossflow turbine described and modelled in this thesis. Finally, Section VI-5 presents the detailed software design of the entire control cycle. The software in Section VI-5 is applicable to the crossflow turbine described in Chapter 2 and the modified turbine shown in Appendix G. The psuedo code and data dictionary for the software is contained in Appendix L.

VI-2. Selection of the Gradient Search Technique

As shown in Chapter 2, the output power of the hydroturbine depends upon the head height and positions of the control surfaces. Therefore, the output power is a multivariable nonlinear function with the variables constrained by physical limits. For example, at a constant water height, the output power y is a function of four variables

$$y = W(x_1, x_2, x_3, x_4)$$

where $a_n < x_n < b_n \qquad n=1,2,3,4$

a_n and b_n are constants; and each control surface is represented by x_n.

The goal of the search process is to maximize the multivariable function W using a minimum number of iterations. Texts, such as Kuester and Mize (4), show several different computer techniques to maximize constrained multivariable functions. The major differences in these techniques are the number of derivatives of the objective function which are required. Since the mathematical equation which describes the function W is not known, all partial derivatives of W must be determined by numerical approximation. The numerical approximation is accomplished with finite differences (ie. dividing the change in output power by a small change in control surface position). This requires 2^j evaluations of W for each control surface (variable), where j is the order of the partial derivative. Therefore, to minimize the number of control surface movements required to calculate partial derivatives, only search techniques that require first order partial derivatives (called gradient search in the remainder of this report) or no partial derivatives appear useful.

Generally, search techniques that require no partial derivatives (often called random search) involve choosing test points within the constraints of each variable. Other test points are then chosen based on the information gained from the evaluation of the function at previous test points. This technique requires movement of the control surfaces to these exact test point positions. As discussed in Section IV-2, without feedback, the control surfaces exact positions are not known. Therefore, the random search, like the open loop design, requires the control surfaces to be fully opened (or closed) to obtain a reference position prior to each control cycle. This would cause excessive control surface movement which is extremely inefficient. Thus, the random search techniques are unsuitable due to inefficiency.

On the other hand, a gradient search does not require the exact position of each variable and can continue to function without repositioning to a reference point every control cycle. Therefore, the gradient search technique was selected as the better of the two methods to maximize the output power y.

VI-3. Gradient Search Theory

The gradient search method involves calculating the gradient of the objective function at a point within the limits of the variables. The function is then evaluated at points along the gradient vector in a direction which results in an increasing of the output power y this method is often referred to as the steepest descent method. When the output power stops increasing, then at this point a new gradient is computed. This process is iterated until the gradient vector becomes zero (or very close to zero). The zero gradient vector indicates either a maximum, minimum, or inflection point. As long as the search is begun sufficiently close to the global maximum (highest attainable output power if it exists, and if the function W is smooth) the gradient search converges to the global maximum.

The following expresses the gradient search technique mathematically.

$$y = W(x_1, x_2, x_3, x_4). \qquad (1)$$

Let

$$D_1 W = \frac{\partial W}{\partial x_1}$$
$$\vdots$$
$$D_4 W = \frac{\partial W}{\partial x_4}$$

Then

$$\nabla y = D_1 W \hat{x}_1 + \cdots D_4 W \hat{x}_4 \qquad (2)$$

$$\underline{m} = \nabla y/(\Sigma (D_n W)^2)^{1/2} \quad (3)$$

where $\underline{m}$ is the normalized gradient vector and the $\hat{x}_n$'s are unit direction vectors.

If the search starts at a position $\underline{x}_i$

$$\underline{x}_i = \begin{bmatrix} x_{1i} \\ x_{2i} \\ x_{3i} \\ x_{4i} \end{bmatrix} \quad (4)$$

the output power can be expressed as

$$y_i = W(x_{1i}, x_{2i}, x_{3i}, x_{4i}). \quad (5)$$

A new position vector $\underline{x}_{i+1}$ and output power y_{i+1} is then evaluated along the gradient direction

$$\underline{x}_{i+1} = \underline{x}_i + s\underline{m}_j \qquad i,j = 0,1,2,3,\ldots \quad (6)$$

where s = step size,

thus $y_{i+1} = W(\underline{x}_{i+1}).$ (7)

If the output power y_{i+1} is greater than y_i then the position vector $\underline{x}_{i+1}$ becomes the new x_i and a new $\underline{x}_{i+1}$ is computed from equation (6). This process is repeated until y_i is greater than or equal to y_{i+1}. A new normalized gradient m_{j+1} is then computed using equation (3) and the last y_i and $\underline{x}_i$. This entire procedure is repeated until the normalized gradient vector $\underline{m}$ becomes zero (or very close to zero).

The initial step size is determined by experimental data analysis and/or trial and error. Furthermore, the initial step size should be chosen, if possible, so as not to grossly overshoot or undershoot the global maximum. Figure VI-1 and Figure VI-2 show examples of poor initial step size choices.

If the initial step size is too large (Fig. VI-1), then the resultant position vector $\underline{x}_{i+1}$ is outside the region of the global maximum. In this case, the gradient search yields the position $\underline{x}_b$ as the optimum position for output power which is less than the maximum at position $\underline{x}_{opt}$.

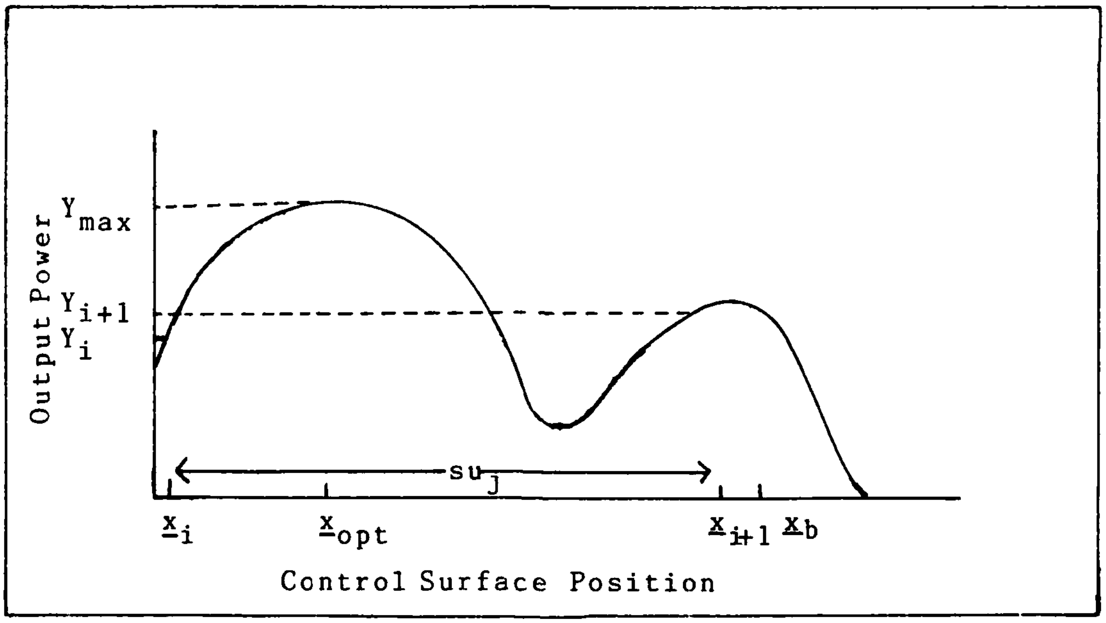


Fig. VI-1. Initial Step Size Too Large

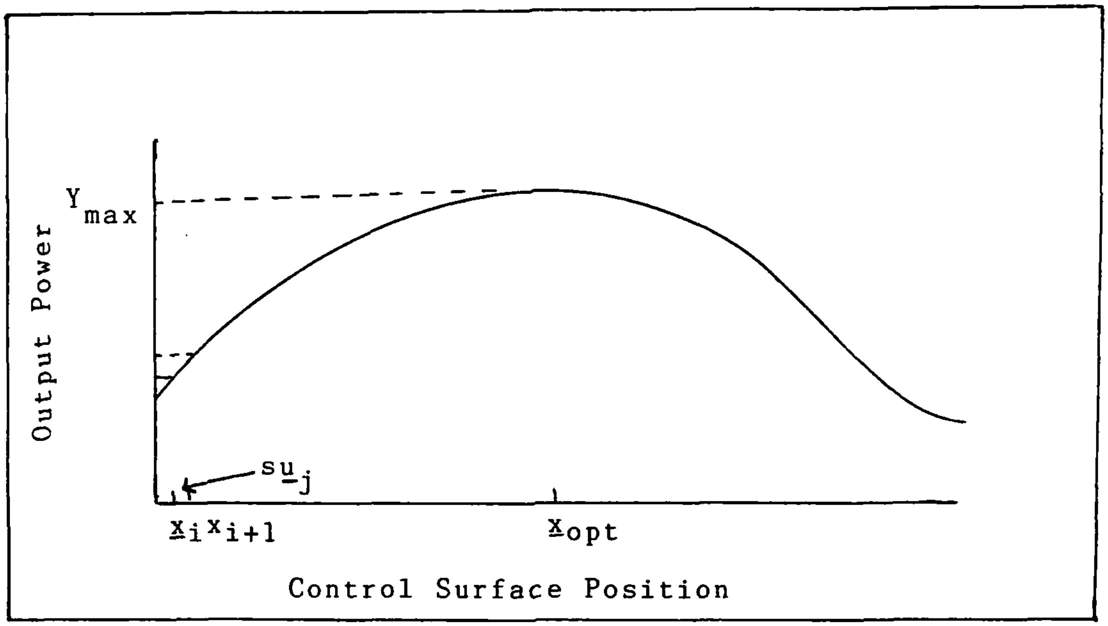


Fig. VI-2. Initial Step Size Too Small

If the initial step size is too small (Fig. VI-3), then an excessive number of steps are required to reach the maximum.

After a normalized gradient vector has been calculated, if the output power y_{i+1}, at the first position vector $\underline{x}_{i+1}$, is less than or equal to y_i (Fig. VI-3), then the step size is too large and must be reduced. After reducing the step size, a new position vector $\underline{x}_{i+1}$ is calculated. Furthermore, The step size should be reduced until the first step results in y_{i+1} greater than y_i (Fig. VI-4).

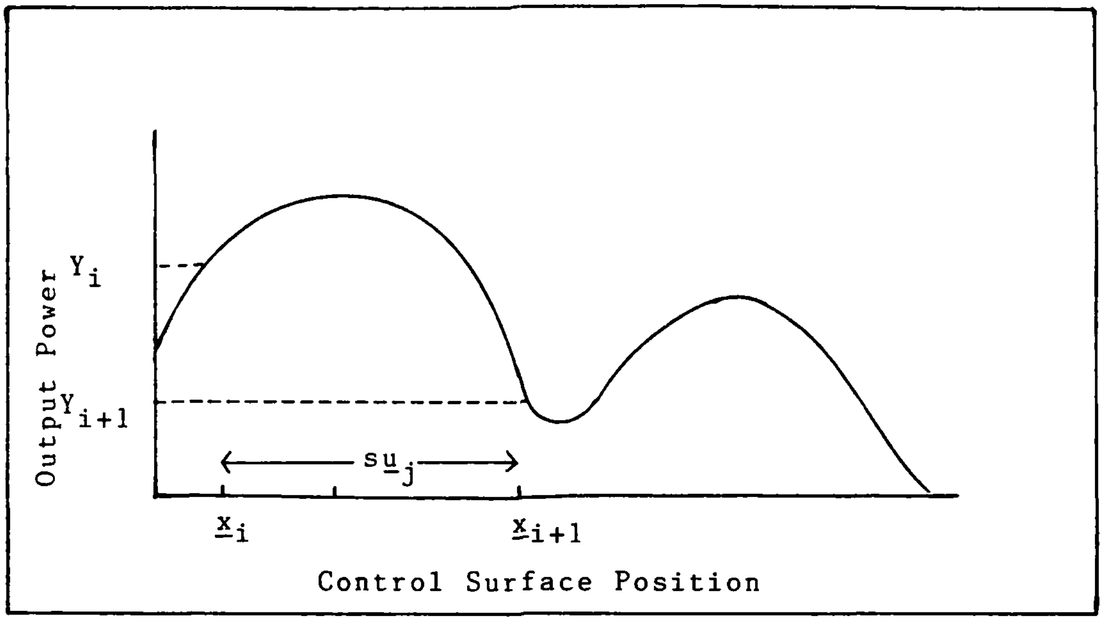


Fig. VI-3. Step Size Too Large

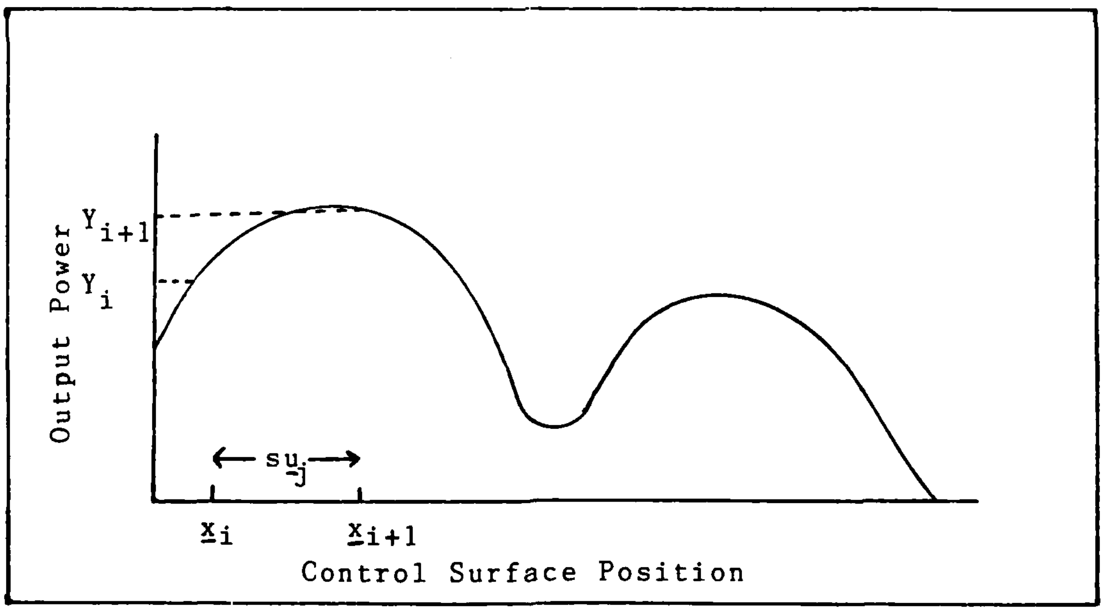


Fig. VI-4. Appropriate Step Size

VI-4. Application of the Search Technique

Writing a software program to perform the algorithm described in the previous section requires further analysis of the turbine characteristics. Consequently, several problems exist when the gradient search technique is applied to the real turbine hardware. First, due to time delays required between control surface movements, the lower inlet guide is impractical to include in the search. Therefore a separate optimization method is required to set the lower inlet at the optimum position prior to optimizing the other control surfaces. Second, output power was found to always decrease whenever the upper inlets were split from an aligned position. Therefore, in order to optimize the upper inlets all three upper inlets must first be aligned with one another. Once the upper inlets are aligned the search process becomes a function of only two variables; the upper table and the three upper inlets acting as one control surface. Finally, the search routine must be capable of optimizing the control surfaces whenever the optimum position is near or on the physical limit of the control surface. This requires additional steps in the search that will identify a control surface position at the physical limit. An analysis of these problems are presented in this section along with the recommended methods to optimize the control surfaces for both the existing turbine and the turbine after modification. The following section presents the software design based upon the recommended optimization methods presented in this section.

V-4a. Optimizing the Lower Inlet

Experimental data analysis (Section II-5) indicated that changes in the lower inlet guide position produced changes in head height. The head height can take at least 30 minutes to reach steady state after a change in the lower inlet guide. Therefore, including the lower inlet guide in the gradient search process is impractical due to this imposed time delay required between steps of the search process. To solve this problem, the lower inlet guide is positioned at a predetermined optimum position as in the open loop design prior to initiating the search algorithm.

Also, Section II-5 shows that the optimum lower inlet positions are functions of the water flow depth (d). The water flow depth is calculated from the difference of the head height and the height of the lower inlet (Fig. VI-5).

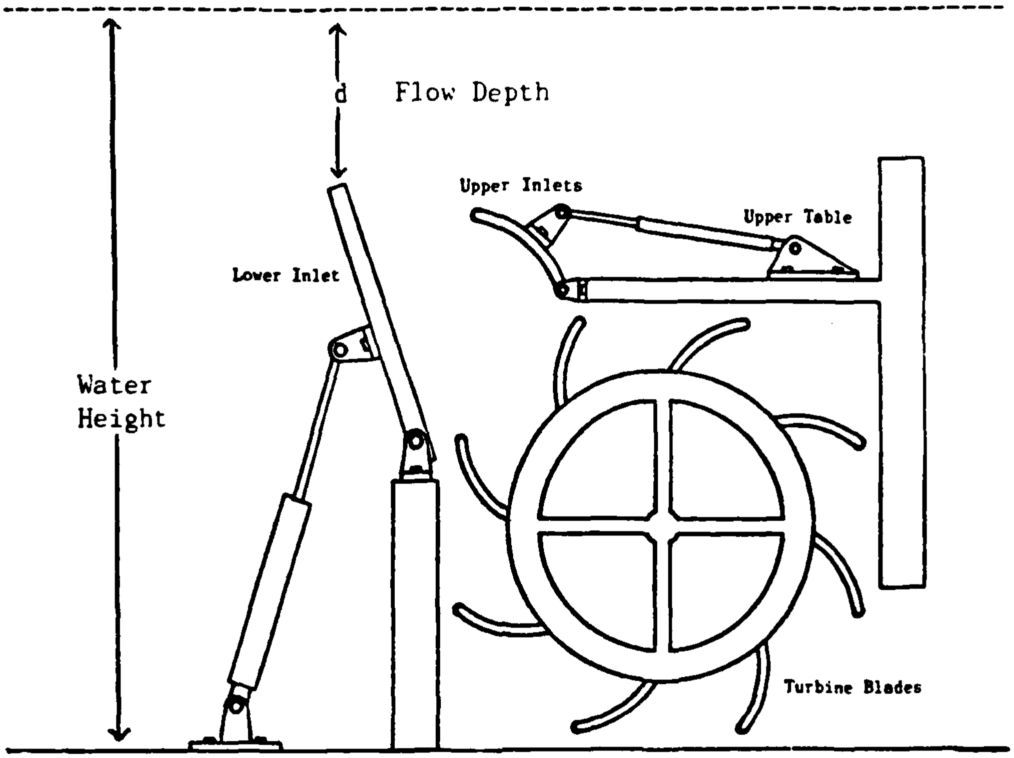


Fig. VI-5 Water Flow Depth Diagram

Several optimum lower inlet positions were determined experimentally for numerous water flow depths. These lower inlet positions are listed in Appendix A.

The procedure for optimizing the lower inlet is to first calculate the water flow depth by subtracting the current lower inlet position height from the current water height. Using the calculated water flow depth the optimum lower inlet position is determined by interpolation from the values in Appendix A. Figure VI-6 shows graphically the optimum positions versus water flow depth using linear interpolation.

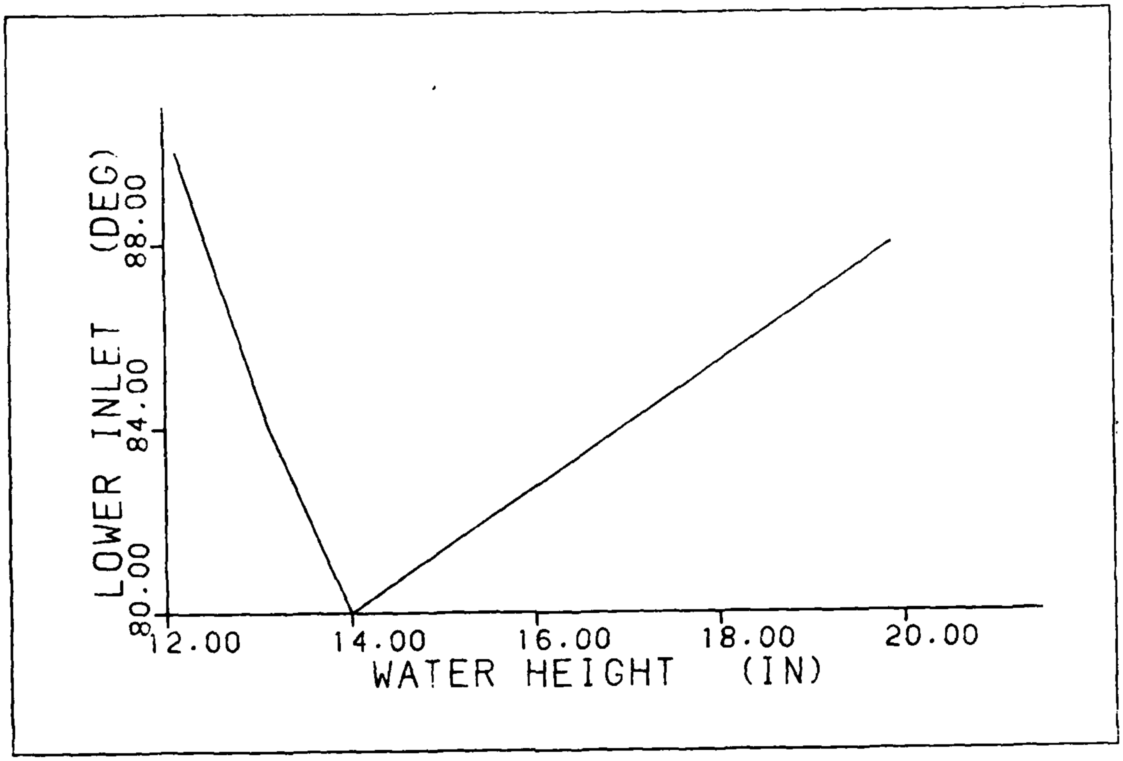


Fig. VI-6. Optimum Lower Inlet Positions

The lower inlet is then set at the interpolated optimum position. The electrical motor drive of the lower inlet guide allows precise positioning and no drift after the position is set. Setting the lower inlet guide to the optimum position prior to initiating the gradient search allows the lower inlet guide to be considered constant during the gradient search. Therefore, at a constant water height, the output power y becomes a function of only four variables.

$$y = W(x_1, x_2, x_3, x_4)$$

Once the turbine is modified as shown in Appendix G, the lower inlet and turbine blades are set at fixed positions. Therefore, the procedure to optimize the lower inlet will not be required. The output power will be function of the water height, the upper table and the upper inlets.

Optimizing the Upper Inlets

Figure VI-7 is a contour plot of constant power at a water height of 13.125 inches. Plots for other water heights are presented in Appendix J. The vertical axis represents two upper inlets aligned at the same position while the horizontal axis represents the third upper inlet.

As can be seen from this figure, the output power is highest along the 45° diagonal from the origin. This represents where the upper inlets are all at the same position. In fact, the numerical approximation for the partial derivative of the output power with respect to only one of the control surfaces at any point along this diagonal is zero. The physical reason for this behavior is that when ever the Bontrol surfaces are split, part of the water flow is directed perpendicular to the normal water flow. Therefore, the smooth flow of water into the turbine is interrupted and thus power decreases. Consequently, the gradient search as described in the previous section would stop moving the upper inlets when they become aligned with one another regardless if they are at optimum positions.

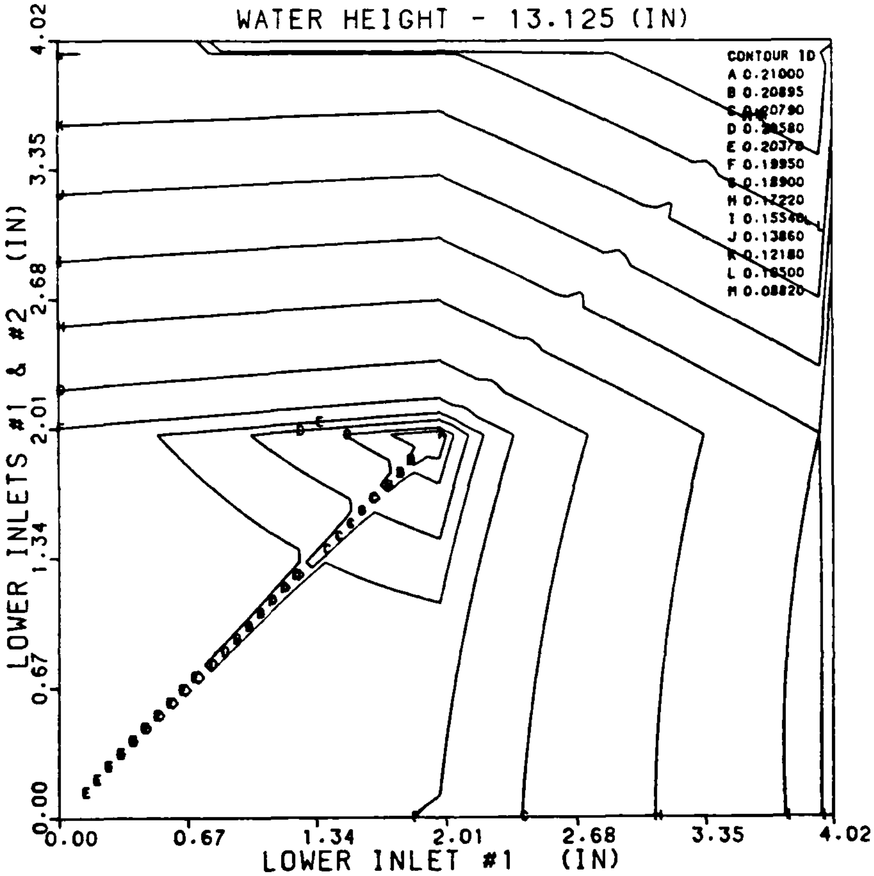


Fig. VI-7 Output Power Contours (KW)

To optimize the upper inlets, the upper inlets must first be aligned. This can be done by attempting to maximize output power by adjusting each upper inlet individually while keeping all other control surfaces fixed. As shown in Figure VI-7, optimizing the three upper inlets individually will place them on the 45° diagonal but not necessarily at the position where maximum power is output.

As long as the upper inlet positions are kept aligned, all three inlets can then be regarded as one control surface. The output power then is reduced to a function of two variables; the upper table and the three upper inlets acting as one control surface.

Optimizing the Upper Table and the Three Upper Inlets

The search section of the controller must be able to optimize the control surface positions under two different conditions. The first condition is where the control surface positions are set randomly such as initial start up, and the second condition is where the control surfaces' positions are known to be near the optimum but need to be fine tuned to maximize the power output. This latter condition occurs when there is slight change in water height or after the control surface positions drift slightly from the optimal positions.

If the control surfaces are set randomly and a gradient search is performed as described in the previous section then there is no guarantee that the control surfaces' positions will be optimized. Plots of output power versus upper table positions for 20 different water heights are presented in Appendix E. These plots show that from a water height of 12.625 inches to 18.5 inches the power peaks at two upper table positions. Figure VI-8 is example of these plots for a water height of 14.0 inches.

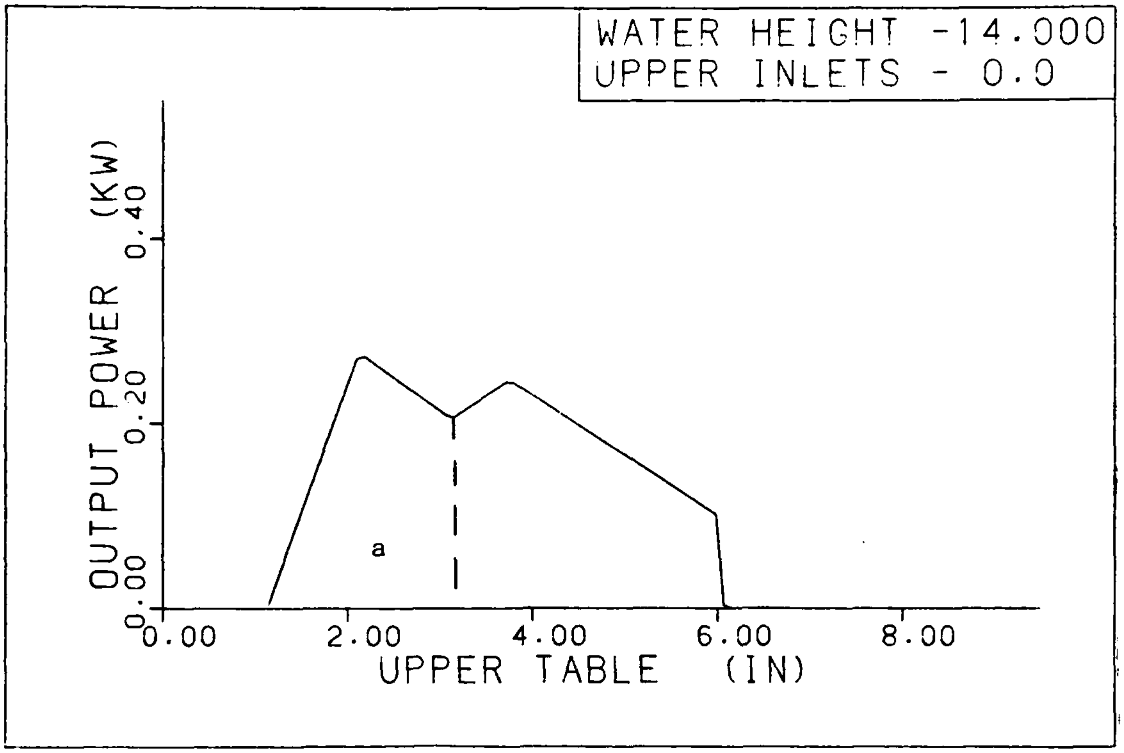


Fig. VI-8 Output Power vs Water Height

If the upper table is not in a good region (a) of Figure VI-8 when the gradient search is initiated then the search terminates with the upper table at a non optimal position. Consequently, incorporating a start up routine to position the upper table in region (a) prior to the search ensures the optimal position is found. The simplest start up routine is to position the control surfaces at the approximate optimum positions determined from modelling the turbine.

Table VI-1

Optimum Upper Table Positions vs. Water Height

Water Height		Optimum Position	
12.125	(in)	4.0	(in)
13.125	(in)	2.8125	(in)
14.0 - 17.0	(in)	2.125	(in)
17.5 -	(in)	0.0	(in)

Table VI-1 shows the approximate optimal table positions obtained from the linear interpolated plots in Appendix H. If the upper table is prepositioned to the values of Table VI-1 during a start up routine then the table position is in a good region to start the gradient search.

In order to preposition the control surfaces during the start up routine, a reference position is reqrired since the controller has no position feedback signal. Moving the control surfaces to the full open position (against the physical limits) is simple and establishes a good reference position. From the full open positions the control surfaces are then moved to the programmed positions such as those in Table VI-1 for the upper table. The user should be able to

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OH SCHOOL OF ENGINEERING D C RAMSEY MAR 85

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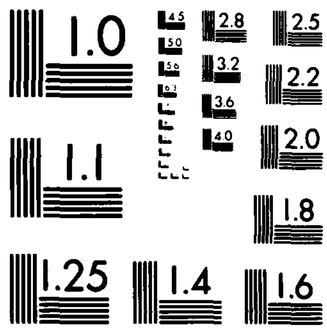

MICROCOPY RESOLUTION TEST CHART

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change both the programmed positions and water heights needed for the start up routine via the numeric keyboard.

The start-up routine will also be necessary after the modification to the turbine. However, the routine will be much simpler and not require programmed positions. As shown if Appendix L, the optimum water inlet width s can be described by the equation

$$s = Q/4.83H^{\frac{1}{2}} \qquad (8)$$

where Q is the water flow rate (CFS) and H is the head height (ft). Once the modified turbine is installed, experiments should be performed to determine a functional relationship between Q and the head height. This relationship is peculiar to this river and dam sight and cannot be determined prior to testing. Once the flow rate is approximated in terms of head height then the Q in equation (8) can be replaced by this approximation. The resulting equation is then programmed in the controller. Therefore, the controller calculates the optimum position to set the upper table based upon the current water height at the time the start up routine is initiated. The optimum inlet width s is measured from the full closed position of the upper table. Similar to the existing turbine, the modified turbine will be required to open to the full open position in order to obtain a reference position.

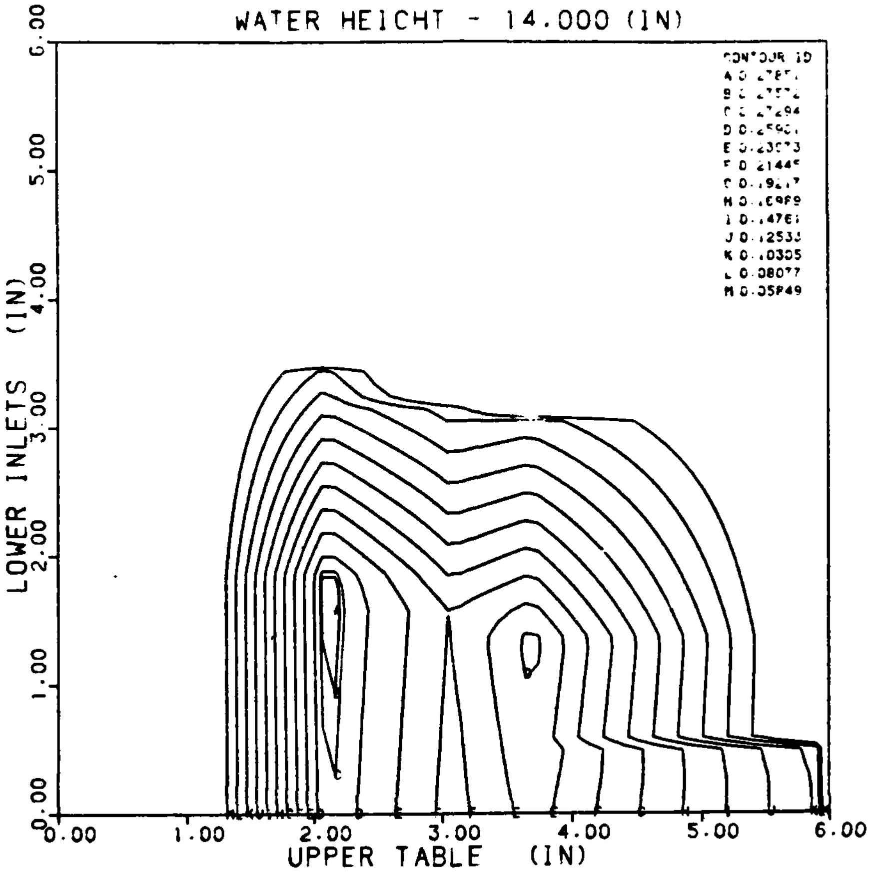


Fig. VI-9 Output Power Contour Plot (KW)

Once the control surfaces are set in a good region by a start up routine or if the control surfaces are still in a good region but must be fine tuned due to a change in water height then the gradient search can be initiated. Figure VI-10 shows a contour plot of constant power for a water height of 14 inches (contour plots for 20 different water heights are presented in Appendix J). The vertical axis represents the position of the three upper inlets and the horizontal axis is the upper table positions.

Figure VI-9 shows the upper table is the most dominate control surface. If the upper table's position is near but not at the optimal position (approximately 4 inches) and the upper inlets' positions are less than two inches then the direction of the gradient vector for the contour curves is directly horizontal. In other words, the upper table would be moved to the optimum position much faster than the upper inlets when using the gradient search. Comparing the optimal upper table positions with the upper inlets full open (Appendix H) to the optimal table positions with the upper inlets set to their respective optimal positions shows that the upper table position is the same for both cases. This is true for all water heights. Therefore, to simplify the software design for the controller that would be used on the existing turbine, the upper table and the upper inlets can be optimized separately. As long as the upper inlets' positions are less than 2.5 inches, varying the upper table position so as to find the highest power will yield the optimum position for the upper table. Once the upper table is set to the optimum position, the upper inlets can then be varied until the maximum power is found. At this point the upper table and upper inlets are optimized and the turbine is producing the maximum power.

The gradient search is extremely simplified when the control surfaces are optimized individually. This simplification is due to the behavior of the existing turbine. The behavior of the output power with respect to changes of the upper table and the upper inlet should be similar to the existing turbine. However, software design for the gradient search optimizing the upper inlet and the upper table simultaneously is presented in the next section and Appendix I. Once the modified turbine is tested, the controller builder can decide whether the upper table and upper inlets can be optimized individually and thus choose the appropriate software design.

Searching Near a Physical Limit

The only physical limit that needs to be taken into consideration is the limit at the full open position. This limit is important since the optimal position of the upper table and the upper inlets are at or near the open limit when the water height is above 17 inches (see Appendices H and I). The closed limit can be neglected since operation of the upper table or upper inlet near the closed limit results in zero output power. There is no feedback of the control surfaces positions, therefore the controller has no means of determining how close a control surface is to the open limit. This creates a problem when approximating the partial derivative during the gradient search.

The partial derivatives of the output power with respect to a control surface position is determined by a numerical approximation. The numerical approximation is performed by dividing the change of output power Δy by a small change in control surface position Δx.

$$\frac{\partial y}{\partial x} = \frac{\Delta y}{\Delta x} = \frac{y(x_2)-y(x_1)}{x_2-x_1}$$

If the numerical approximation is performed while a control surface is at the open limit and the direction of position change is attempted in the open direction then the control surface will not move and the power will not change. Therefore, the numeric approximation is zero. However, if the direction of position change is attempted in the closed direction then the numeric approximation may not be zero. Therefore, performing the numeric approximation in the open direction against the physical limit results in inaccurate information and undue wear on the control surface.

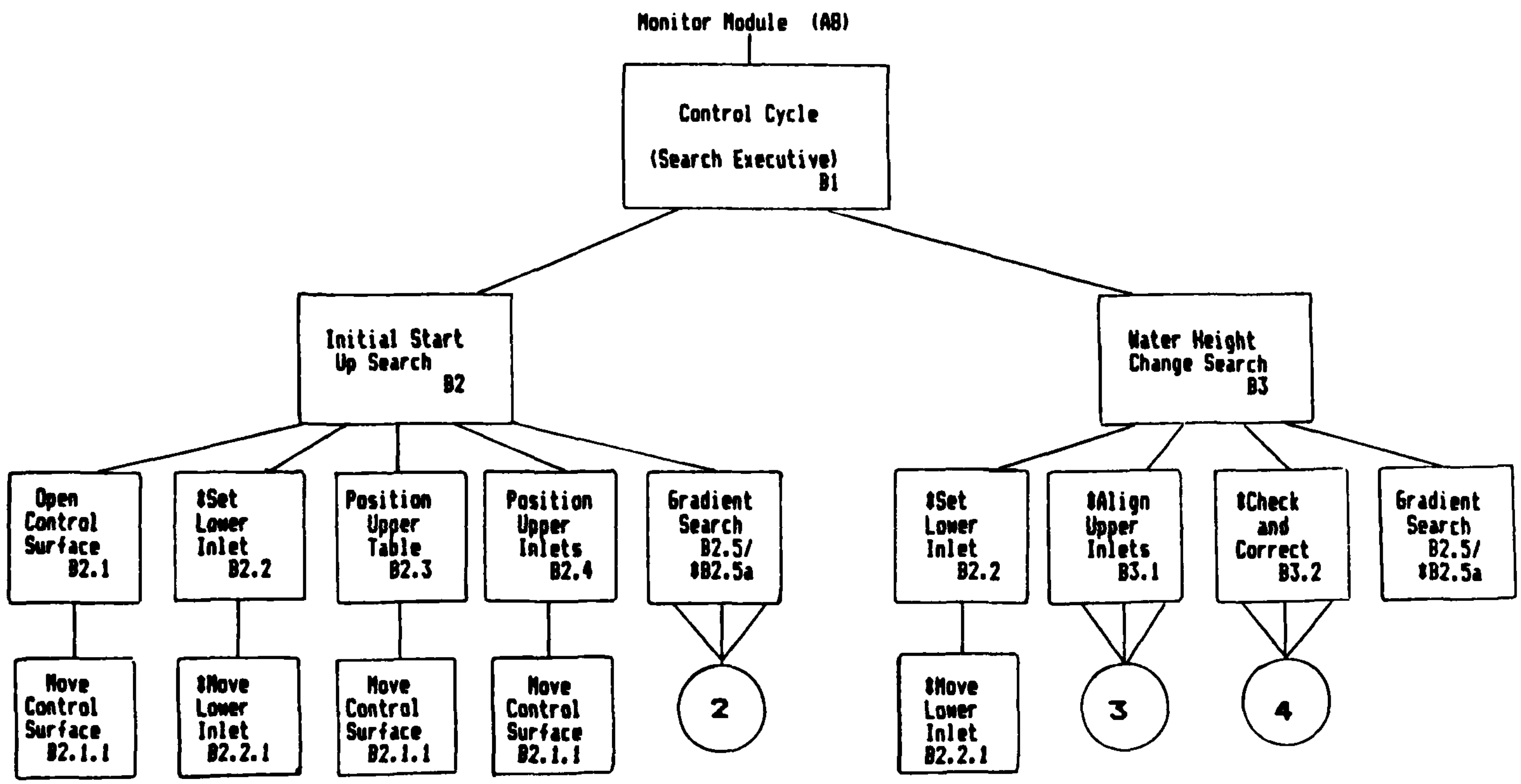
To solve this problem, the turbine builder added open limit switches on the control surfaces that input to the controller through the A/D. The software design presented in the next section makes use of the limit switches input to optimize the control surfaces.

The modified turbine will have open and closed limit switches on the upper table and upper inlet. The control surfaces will be moved via a hydraulically driven mechanical screw device. Any attempt to move the control surfaces beyond the limits will result in serious mechanical damage to the turbine. The software designed for the controller of the modified turbine must prevent attempts to move the control surfaces beyond the open or closed limits.

VI-5. Software Design

The following paragraphs focus on developing software modules that performs the necessary control cycle actions as described in the previous sections. Figures VI-10 through VI-13 provide the reader a diagram which shows the hierarchy of the software modules. These figures are followed by diagrams and descriptions of each module. The individual module diagrams show the basic processes involved in the modules. If the process requires another module to be called then this is indicated by the module number listed below the process name. The data names printed near the arrows show which data is passed to the module being called or the data required by the next process. However, much of the data used by the modules are global parameters. The use of most global parameters will either be shown in the process name or explained in the module description.

Some software modules used in the control cycle mode were developed for use with the other modes of the controller. These modules are described in Appendix J and are identified by the letter A as a prefix to the module number. All modules specific to the control cycle mode have a B prefix. To aid in reading the software modules a module index and data dictionary are provided in Appendix H. Also, psuedo-code is provided in Appendix I which shows greater detail of the modules.



$ not required after turbine modification

Fig. VI-10 Structure Chart #1

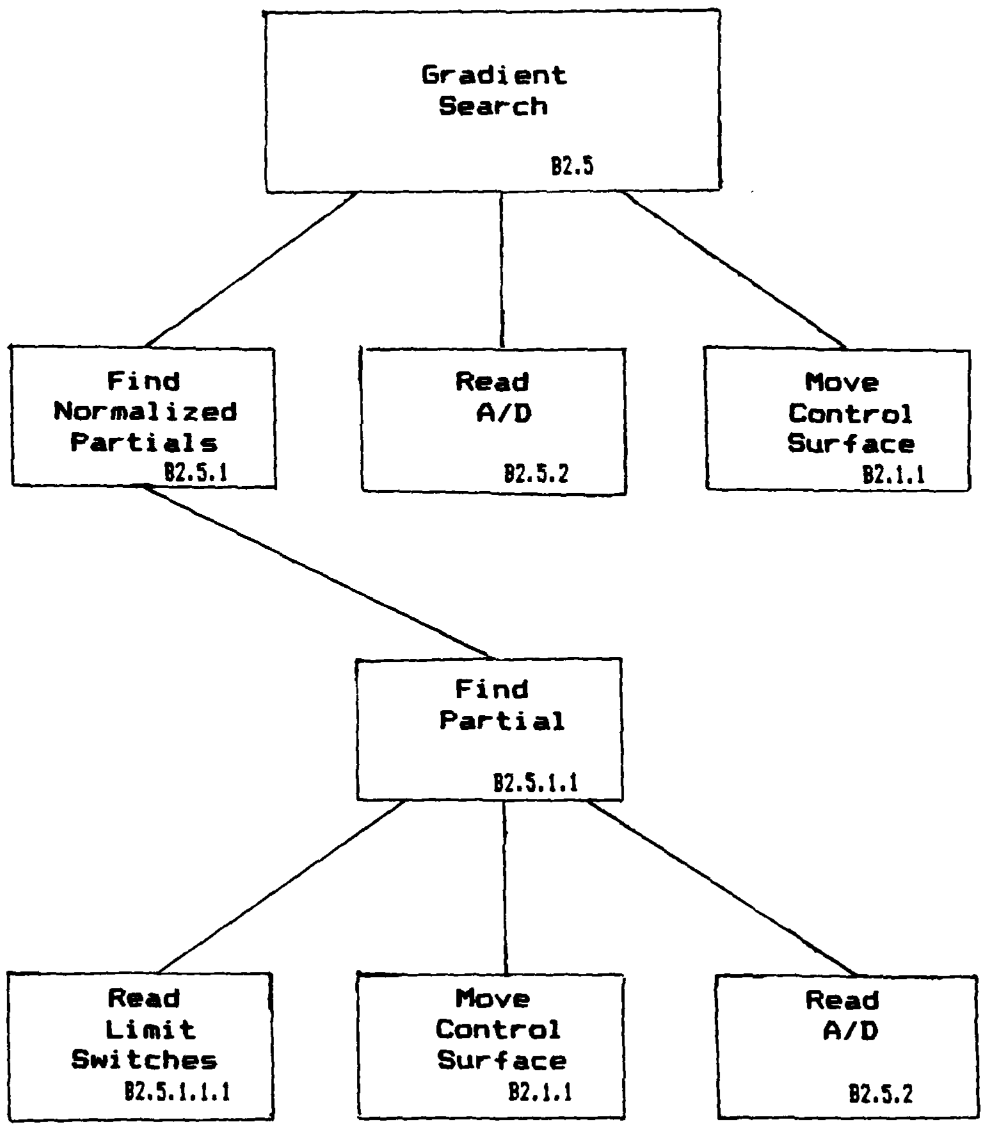


Fig. VI-11 Structure Chart #2

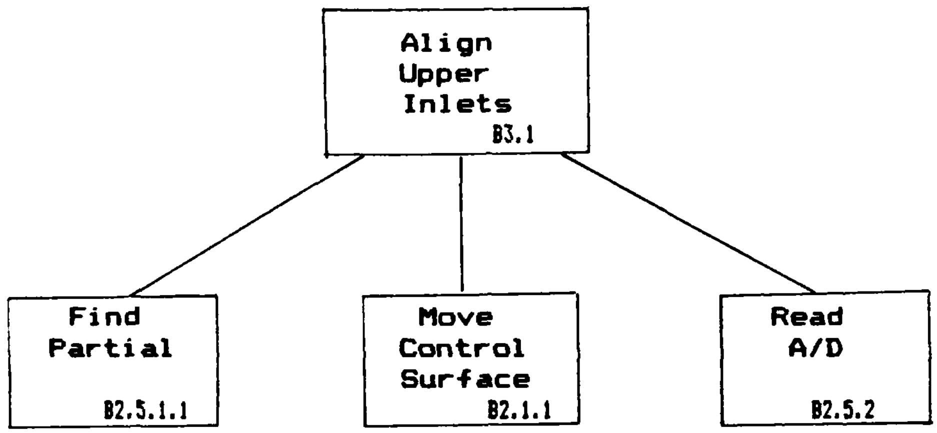


Fig. VI-12 Structure Chart #3

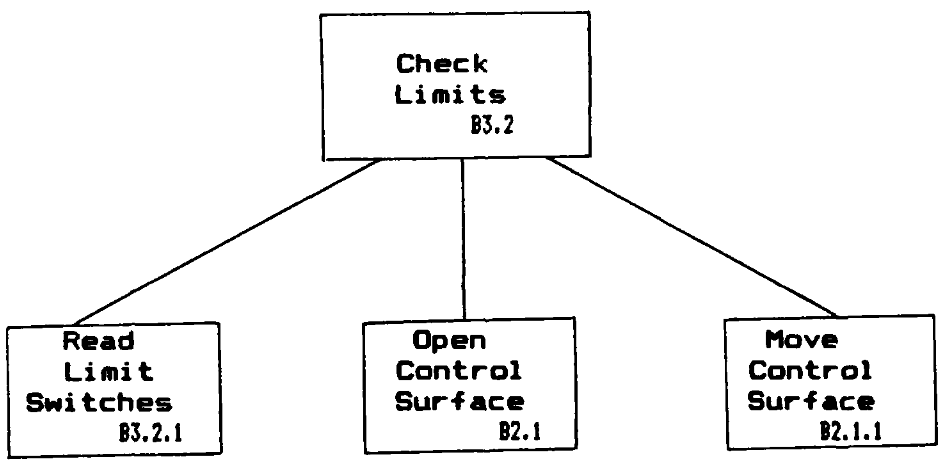


Fig. VI-13 Structure Chart #4

Control Cycle Module B1

The Control Cycle Module is one of the three modes selected by the Monitor Module and is the executive of the search process. The goal of this module is to move the control surfaces to their respective optimum position within a designated time limit (MAX_TIME). This module also computes and stores an average output power (POWER_ARRAY), and the completion time of the module (TIME_OF_LAST_CONTROL_CYCLE). These two global parameters are used by other modes of the controller.

Figure VI-14 shows the overall flow of the Control Cycle Module. The module's first task is to turn on the hydraulic pump. As explained in Chapter II, the hydraulic pump must be turned on prior to moving the control surfaces. Once the hydraulic pump is on and up to speed, the clock is read (Read Clock) in order to obtain the current time (CURRENT_TIME). Using CURRENT_TIME, the module computes the time limit for completion of this module. This time limit is stored in the global parameter MAX_TIME. MAX_TIME is checked by the Control Cycle Module. The module's first task is to turn on the hydraulic pump. As explained in Chapter II, the hydraulic pump must be turned on prior to moving the control surfaces. Once the hydraulic pump is on and up to speed, the clock is read (Read Clock) in order to obtain the current time (CURRENT_TIME). Using CURRENT_TIME, the module computes the time limit for completion of this

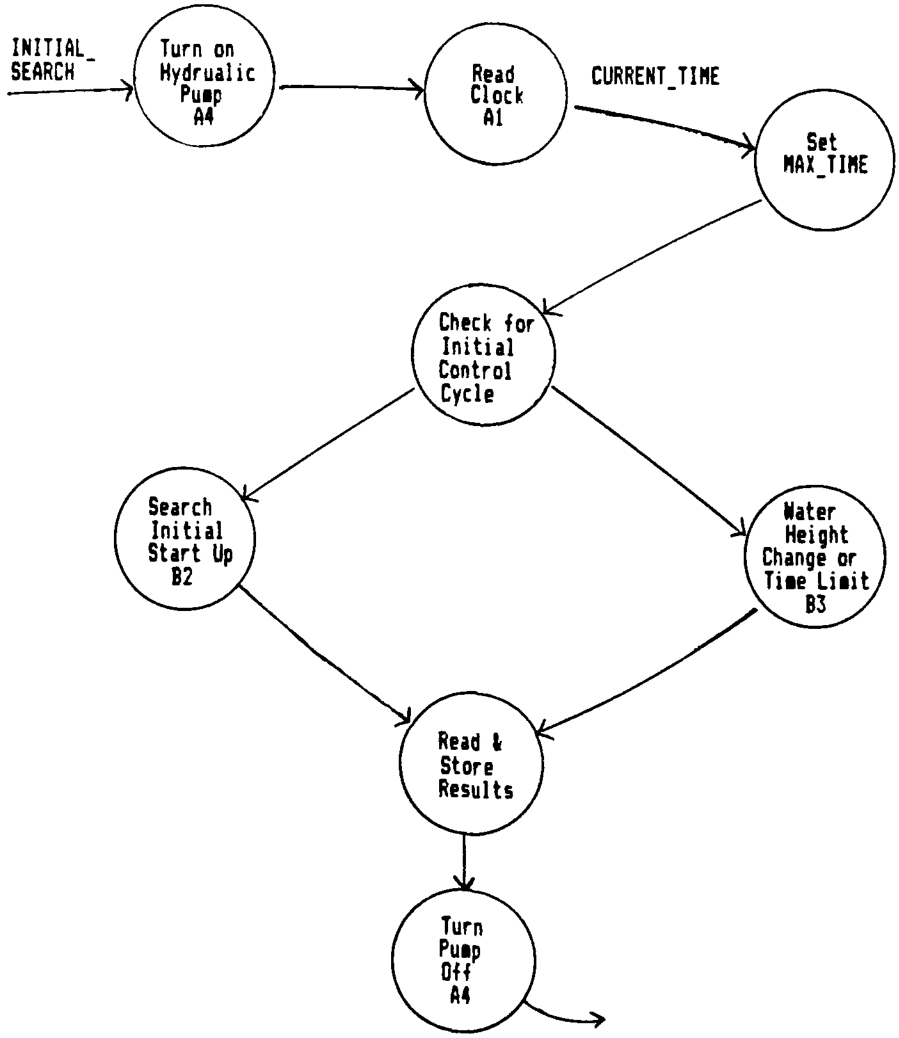


Fig. VI-14 Control Cycle Module B1 (Search Executive)

Initial Start Up Search Module B2

The purpose of this module (Fig. VI-15) is to move the control surfaces to their respective optimum positions regardless of their initial positions. As explained in Section VI-4, the control surfaces must be in a 'good' region (near the optimum position) prior to initiating the gradient search. Consequently, the first six steps of this module is to get the control surfaces in a 'good' region. The gradient search is then performed which optimizes the control surface positions .

The first two of the six steps is to open the upper table and upper inlets. The full open position of the control surfaces is now a reference point from which the control surfaces can be moved to their known approximate optimal positions. After the upper table and upper inlets are full open, a delay is required to allow the water flowing through the turbine to reach a steady flow. This time can be as long as several minutes. The delay time is a global parameter (DELAY_TIME).

After the time delay, the lower inlet, upper table, and upper inlets are set to their respective approximate optimal positions. At this point the control surfaces are in a 'good' region and the gradient search is performed. The lower inlet is not included in the gradient search for reasons explained in Section VI-4.

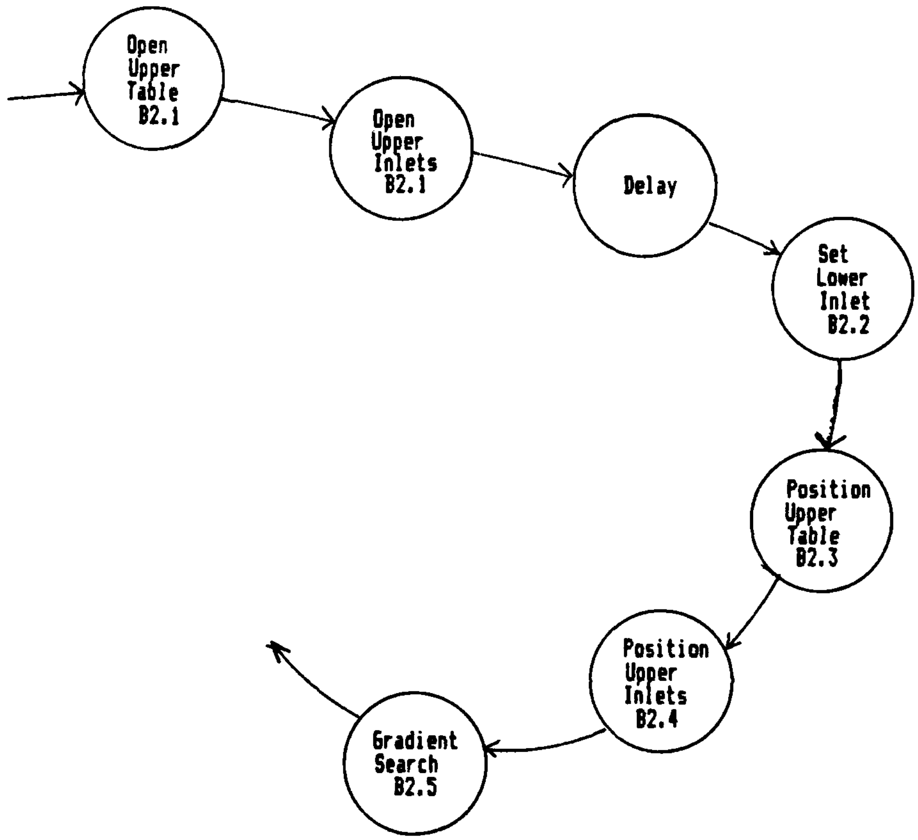


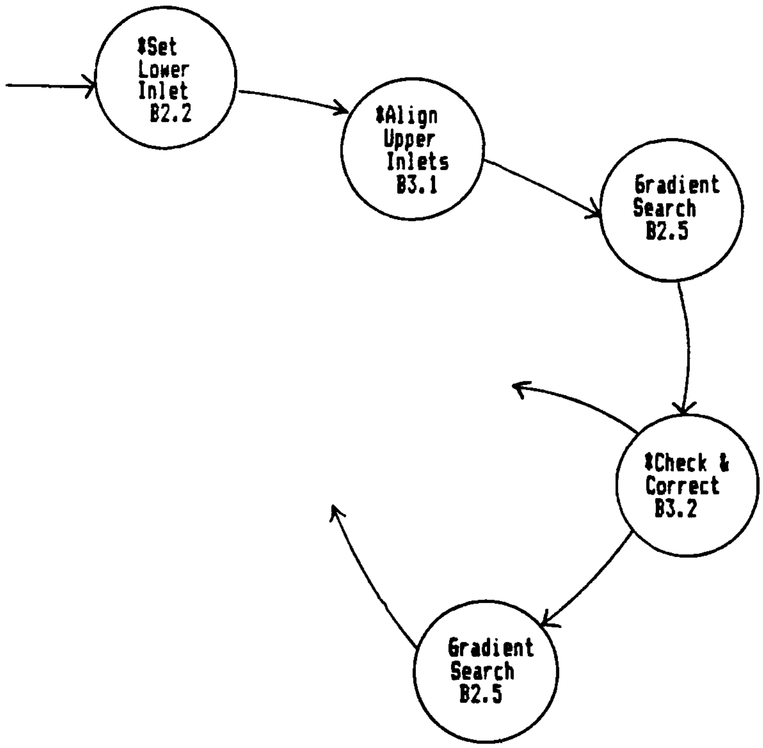
Fig. VI-15 Initial Start Up Search Module B2

Water Height or Time Limit Search Module B3

The purpose of the module shown in Figure VI-16 is to optimize the control surface positions after a change in water height or if the maximum time allowed between control cycles has been exceeded. This module assumes the control surfaces are positioned in a region near the global maximum such that the gradient search will converge to the global maximum.

This search module first sets the lower inlet to the approximate optimal position. Next the upper inlets are aligned. The gradient search only optimizes the upper table and upper inlets positions. Since the upper inlets are moved as one control surface in the gradient search, they must be aligned prior to the gradient search.

Once the gradient search has been performed this module calls the Check and Correct Module to verify and if necessary correct the positions of the control surfaces. This process is required for the existing turbine to ensure the gradient search has not moved the control surfaces to a zero gradient position which is not the global maximum. (This can happen if the control surfaces have moved out of a 'good' region). If an error is detected, the Check and Correct Module will only move the control surfaces to the approximate optimal position. Consequently, the gradient search would be performed again.



* not required after turbine modification

Fig. VI-16 Water Height Change or Time Limit Search Module B3

The turbine modification will fix the lower inlet therefore all process related to optimizing the lower inlet will not be required. Also, the upper inlets will be replaced with only one upper inlet therefore the Align Upper Inlets Module will also not be required. The modification will also change the drive mechanism of the upper table and lower inlet. This change will not allow the control surfaces to drift between control cycles eliminating the need for a Check and Correct Module.

Open Control Surfaces Module B2.1

The module in Figure VI-17 sets the control surface designated by the control surface argument (CON_SURFACE) to the full open position. If control surface argument is the upper table then the upper table is opened to full open otherwise all three upper inlets are fully opened. The control surfaces are fully opened by attempting to move them a distance equal to the distance from full closed to full open (UI-MAX or UT-MAX). If the control surfaces are located at a position other than full closed, the Move Control Surface Module (B2.1.1) will prevent the control surfaces from attempting to move beyond the physical full open limit.

Set Lower Inlet Module B2.2

The Set Lower Inlet Module positions the lower inlet to the approximate optimum position that corresponds to the current water height. Since no mechanical drive was ever installed on the lower inlet the process to move the upper inlet was not designed. Also, the lower inlet will be fixed after the turbine modification therefore this and the Move Lower Inlet Module will not be required.

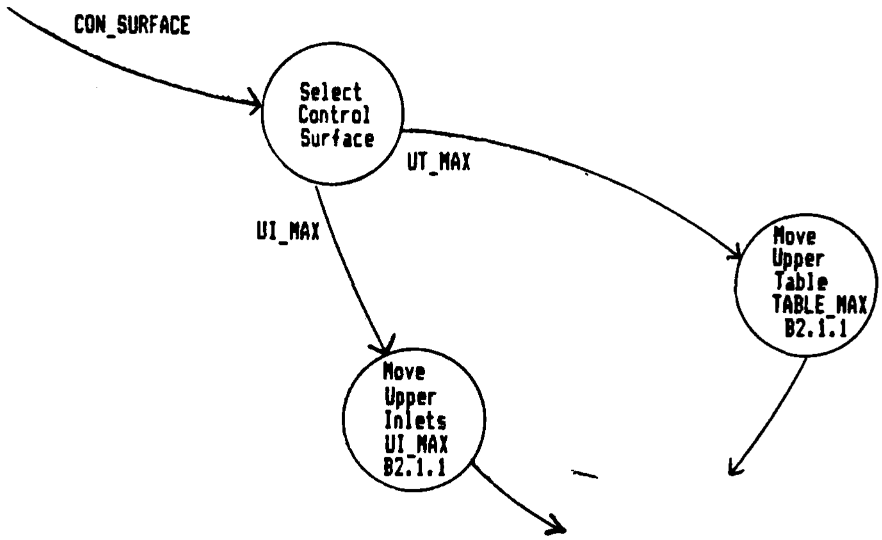


Fig. VI-17 Open Control Surfaces Module B2.1

Position Upper Table Module B2.3

The purpose of the module shown in Figure VI-18 is to move the upper table from the full open position to an approximate optimal position. The approximate optimal positions are stored in a global array UT(I). The approximate optimum positions stored in the array are determined from experimental tests. For the pre-modified turbine, the approximate optimal positions can be determined from the linear interpolated plots shown in Appendix H. As described in Section VI-4, the UT(I) array will be eliminated after the turbine modification and replaced with an equation which yields the approximate optimum position given the water height. Once the approximate optimal position has been determined the module then moves the control surface (Module B2.1) to this position.

Position Upper Inlets Module B2.4

The purpose of the Position Upper Inlets module is to move the upper inlets from the full open position to the approximate optimum position. This module is identical to the Position Upper Table Module (B2.3) except the approximate optimum upper inlet positions are stored in array UI(I) and all three upper inlets are positioned to this approximate optimum position. After turbine modification, a new array of optimum positions will have to be determined experimentally, and then programmed in the controller.

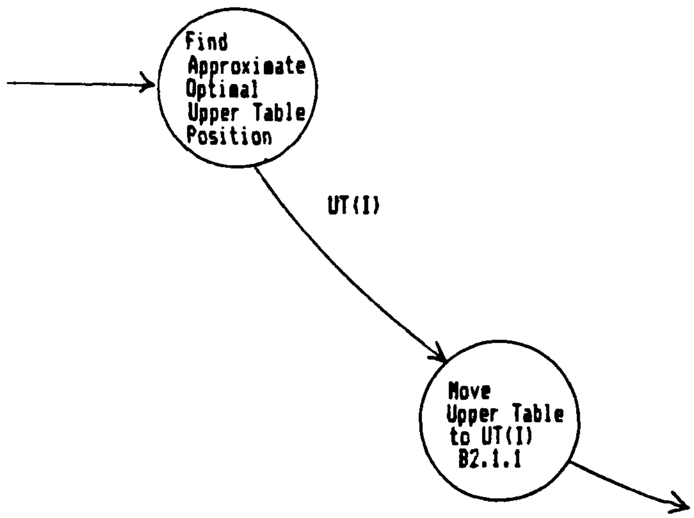


Fig. VI-18 Position Upper Table Module B2.3

B2.5 Gradient Search #1

Figure VI-19 shows the general gradient search. This module performs the gradient search as discussed in Section VI-3. This search uses two variables; the upper table and the combination of the three upper inlets moved as one control surface. The gradient search module assumes the upper inlets are aligned and all the control surfaces are in a region where the positions will converge to the global maximum. The following is a discussion of the steps shown in Figure VI-20.

Step 1. Find the normalized partial derivatives of the output power with respect to the upper table position and upper inlet positions, UT_NORMAL and UI_NORMAL (Module B2.5.1).

Step 2. If both normalized partial derivatives are zero then the control surfaces are at the optimal positions therefore terminate search.

Step 3. Initialize the step size. The step size is the combined distance (vector magnitude) that the control surfaces are moved. Initially the step size is set to the global parameter MAX_STEP which is determined experimentally.

Step 4. The power is read from the A/D in order to obtain an initial reference power (PO).

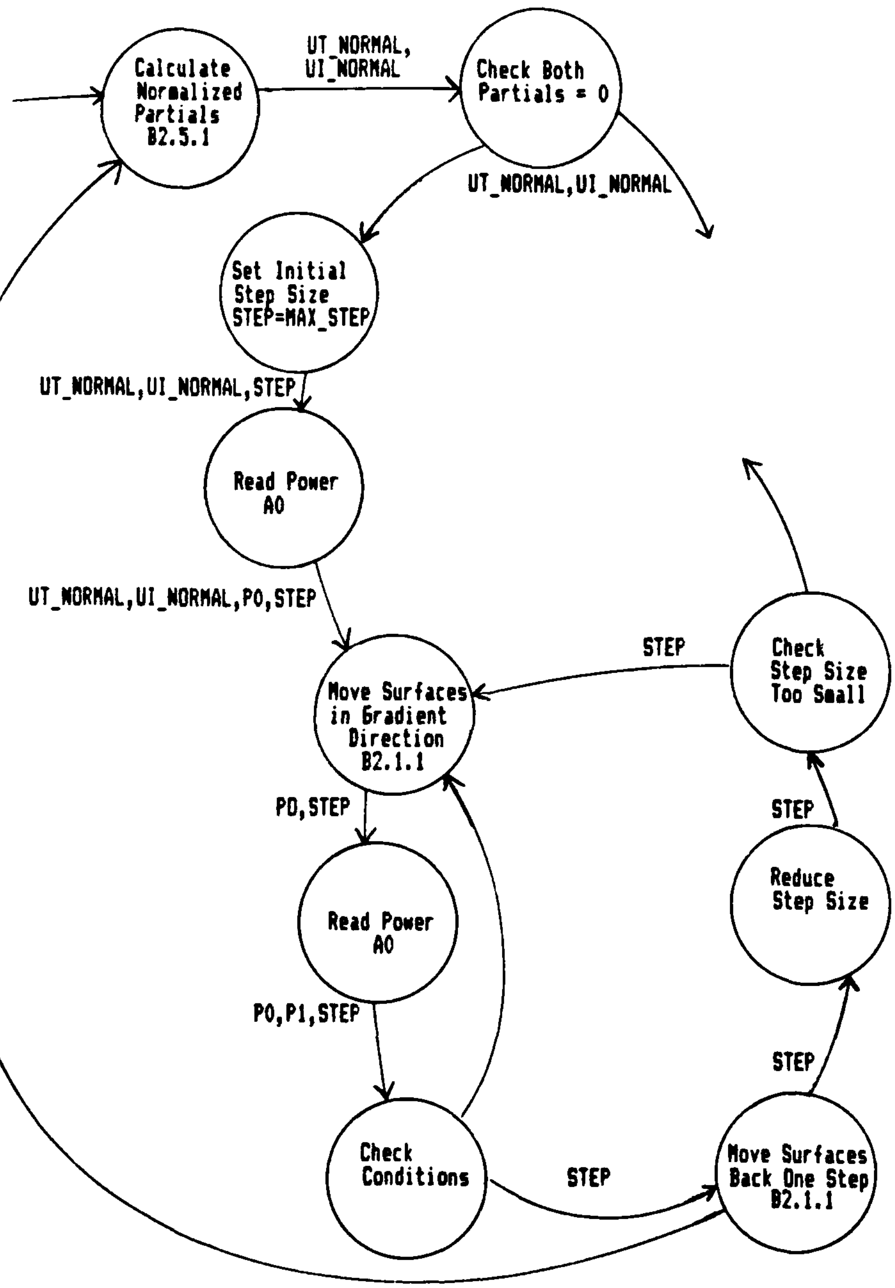


Fig. VI-19 Gradient Search #1 Module B2.5

Step 5. The control surfaces are moved the distance STEP in the gradient vector direction. This is done by moving the upper table the distance equal to STEP times UT_NORMAL and by moving all the upper inlets the distance equal to STEP times UI_NORMAL. The control surfaces are moved by calling the Move Control Surfaces Module (B2.1.1).

Step 6. A new output power (P1) is read from the A/D after the control surfaces are moved.

Step 7. If the power increases after moving in the gradient direction then the control surfaces are moved again by repeating step 5 (shown by the arrow pointing from Check Conditions to Move Surfaces in Gradient Direction). Otherwise, perform step 8 and move the control surfaces back to the last position.

Steps 8. Move the control surfaces back to the last position. If the control surfaces are back at the original position where the partial derivatives were calculated, then reduce the step size (STEP) by the factor REDUCE_STEP (a global parameter). If the step new size is greater than .707 times DELTA_X (the smallest increment the control surfaces can move), then loop to step 4 and move the control surfaces the new step distance, otherwise, terminate search. (Maintaining a STEP larger than .707 times DELTA_X will ensure all attempted movements of both control surfaces to be larger than the smallest possible incremental movement, DELTA_X). However, if after the control surfaces are moved back to the last position and this position is not the original position where the partial derivatives were calculated, then restart the search (go to step 1) at this new position.

In summary, this module computes the gradient then moves the control surfaces in the gradient direction which increases power. As the control surfaces are moved in the gradient direction, if the power stops increasing then the control surfaces are stopped, and moved back to the position of highest power along the gradient path. A new gradient direction is then computed at this new position and the process repeated until the gradient is computed as zero. Since the control surfaces can only be moved in incremental movements, the module has to adjust step sizes while moving the control surfaces. A check is made so that the module will terminate if the step size becomes too small.

Gradient Search #2 Module B2.5a

The module shown in Figure VI-20 is the simplified gradient search applicable to the pre-modified turbine. This module optimizes the two variables (the upper table and the three upper inlets) individually. Since the control surfaces are optimized individually, the partial derivatives will only provide direction. The magnitude of movement for each control surface is equal to the desired step size.

Gradient Search #2 has only a few differences with Gradient Search #1. First, the control surfaces are optimized individually, therefore the module is performed twice (once with the upper table as the variable CON_SURFACE and once with the upper inlets as the variable CON_SURFACE). Second, only the partial derivative is required (versus the normalized partials in Gradient Search #1). The last difference is that a limit switch check is incorporated in the module after every control surface movement. The limit switch check enables the controller to eliminate several unnecessary control surface movements or attempted movements. Other than the differences described above, Gradient Search #2 is the same as Gradient Search #1 (see description of Gradient Search #1).

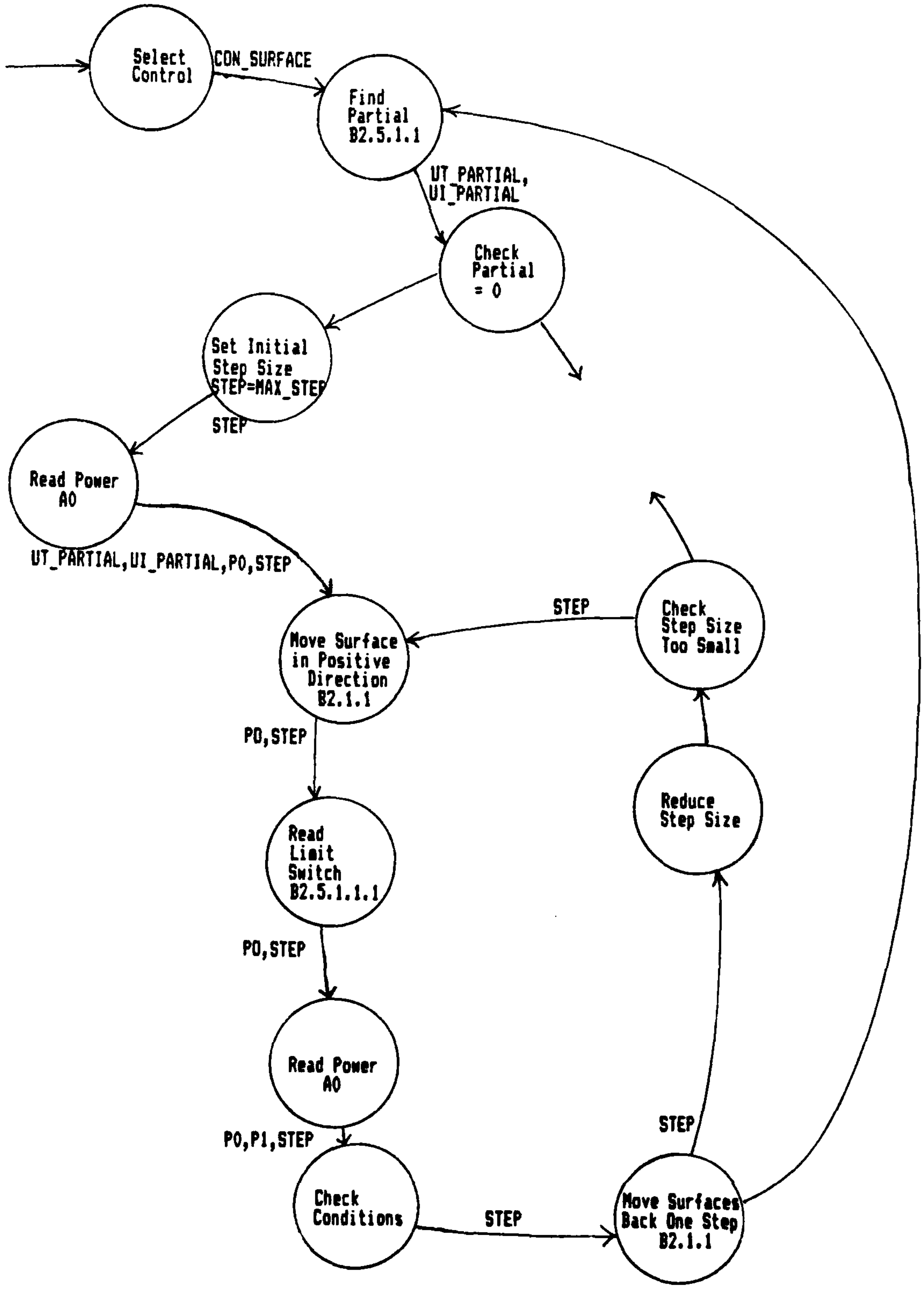


Fig. VI-20 Gradient Search #2 Module B2.5a

Align Upper Inlets Module B3.1

The purpose of the module shown in Figure VI-21 is to align the three upper inlets. As described in Section VI-4, the upper inlets must be aligned prior to initiating the gradient search. The upper inlets are aligned by moving them individually until a peak power is achieved. The resulting position of the upper inlets may not be the global optimum position (see Section VI-4).

Aligning the upper inlets is performed similar to the gradient search module for the pre-modified turbine. Each upper inlet is moved to a relative optimum position individually, therefore the module loops three times, once for each control surface. Similar to the gradient search #2 module the partial derivative of each control surface is used only to determine the direction of control surface movement. The step size used for this module is a constant DELTA_X (the smallest increment any of the control surfaces can move). Once the direction of movement is determined, the upper inlet is moved in small increments until the power stops increasing. Then the control surface is moved back one increment to the position which achieved the highest power. The module is terminated after this procedure is performed on all three upper inlets.

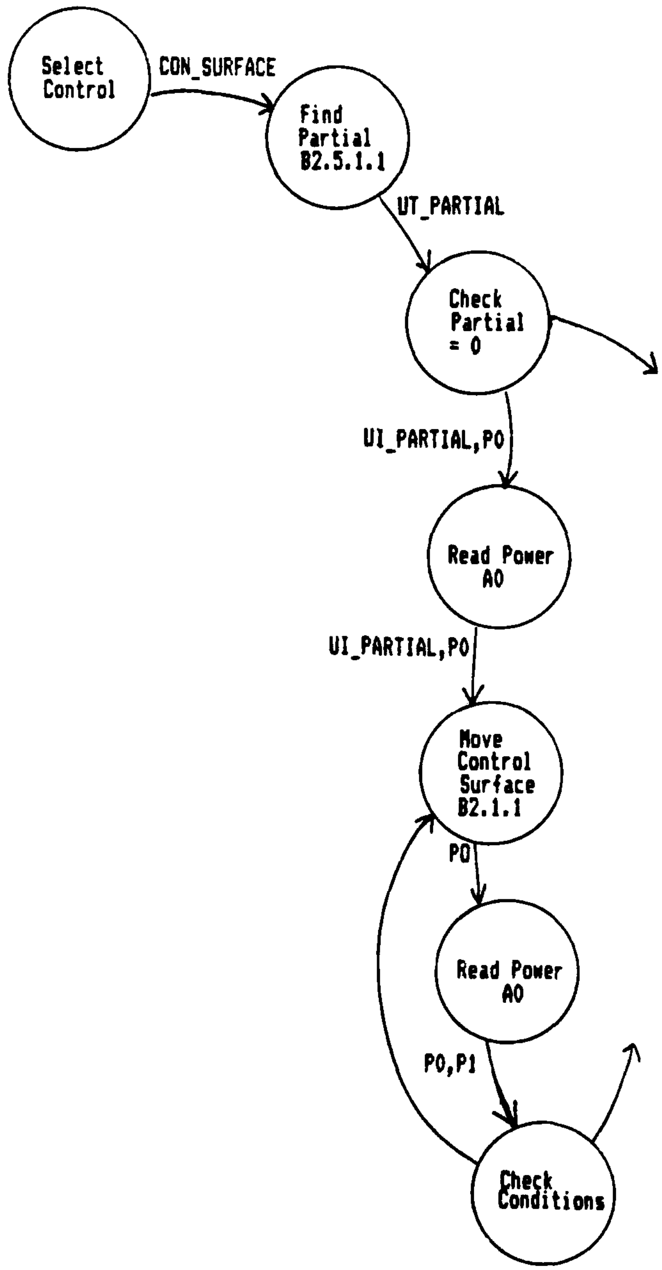


Fig. VI-21 Align Upper Inlets Module B3.1

Check and Correct Module B3.2

This module (Fig. VI-22) checks the upper table [UT(I)] and upper inlet [UI(I)] position arrays to verify whether the control surface should be at the open limit. If an error exists the control surface is moved to the approximate optimum position found in the array. For example, the limit switch for the upper table is engaged (indicating the upper table is full open), however the upper table array indicates the approximate optimum position for the upper table is four inches in the closed direction. The upper table is then moved to the approximate optimum position. On the other hand, if the upper table limit switch is not engaged, but the upper table array shows that the approximate optimum position is at full open, then the upper table is moved to the full open position. As shown in Figure VI-23, this procedure is performed first with the upper table and then with the upper inlets. This module assumes the upper inlets are aligned.

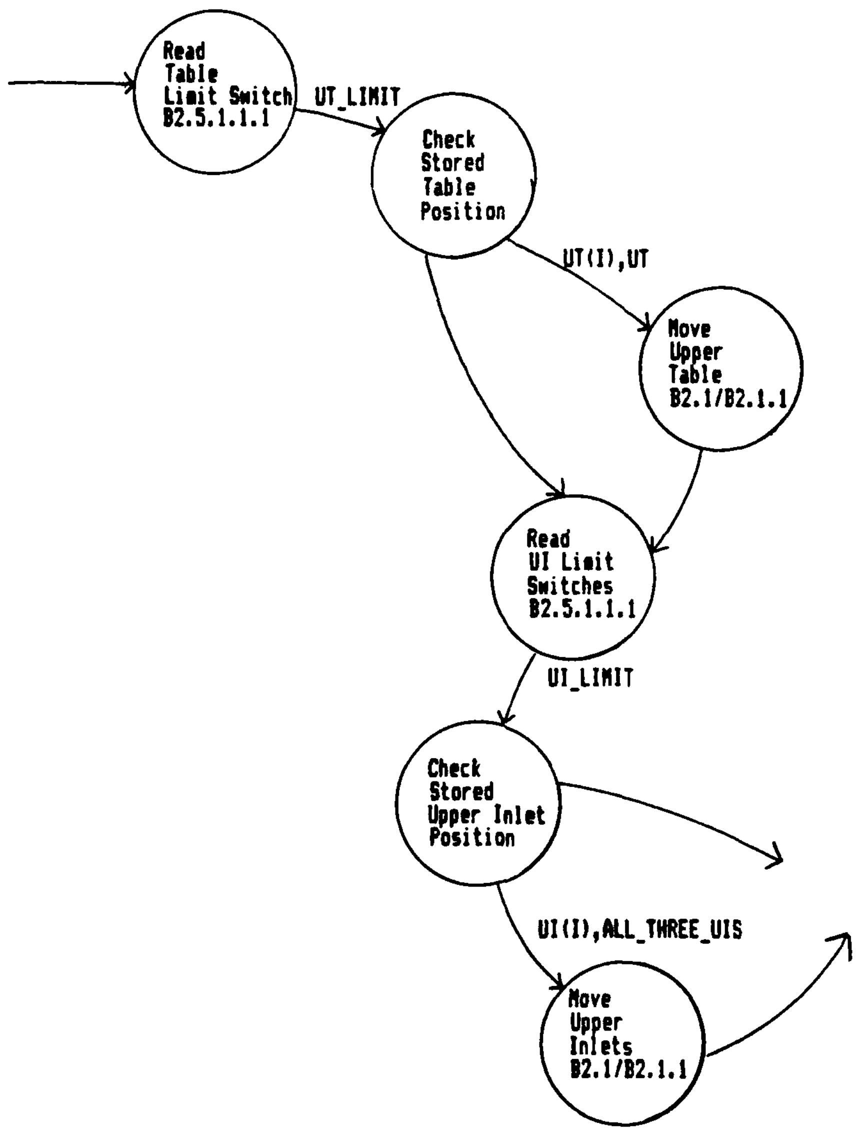


Fig. VI-22 Check and Correct Module B3.2

Move Control Surface Module B2.1.1

The purpose of the module shown in Figure VI-23 is to move a control surface a finite distance. The control surface which is to be moved and the move distance are passed from the calling modules through the variables CON_SURFACE and DISTANCE. The appropriate relay I/O code (RELAY_CODE) is determined from the CON_SURFACE variable, and then a time of movement variable (MOVE_TIME) is calculated from the DISTANCE variable and the control surface velocity. If the move distance is less than one half the smallest allowable (DELTA_X) then the module is terminated, however if the move distance is greater than or equal to one half of DELTA_X then the control surface is moved DELTA_X.

Once the move time and relay code is determined, the relay code is sent to the relay I/O which will power the appropriate relay. The current time is read from the clock and the appropriate limit switch is checked. The module then loops to the Read Clock module until the limit switch becomes engaged or if the time elapsed is equal to or greater than the MOVE_TIME. Then the relay I/O is set to neutral (all relays de-powered) and the module is terminated. Also during the condition check, if the current time is equal to or greater than the MAX_TIME, then the module calls the Major Malfunction Mode Module. This condition means the controller has exceeded the maximum time allowable for a control cycle, therefore a malfunction exists.

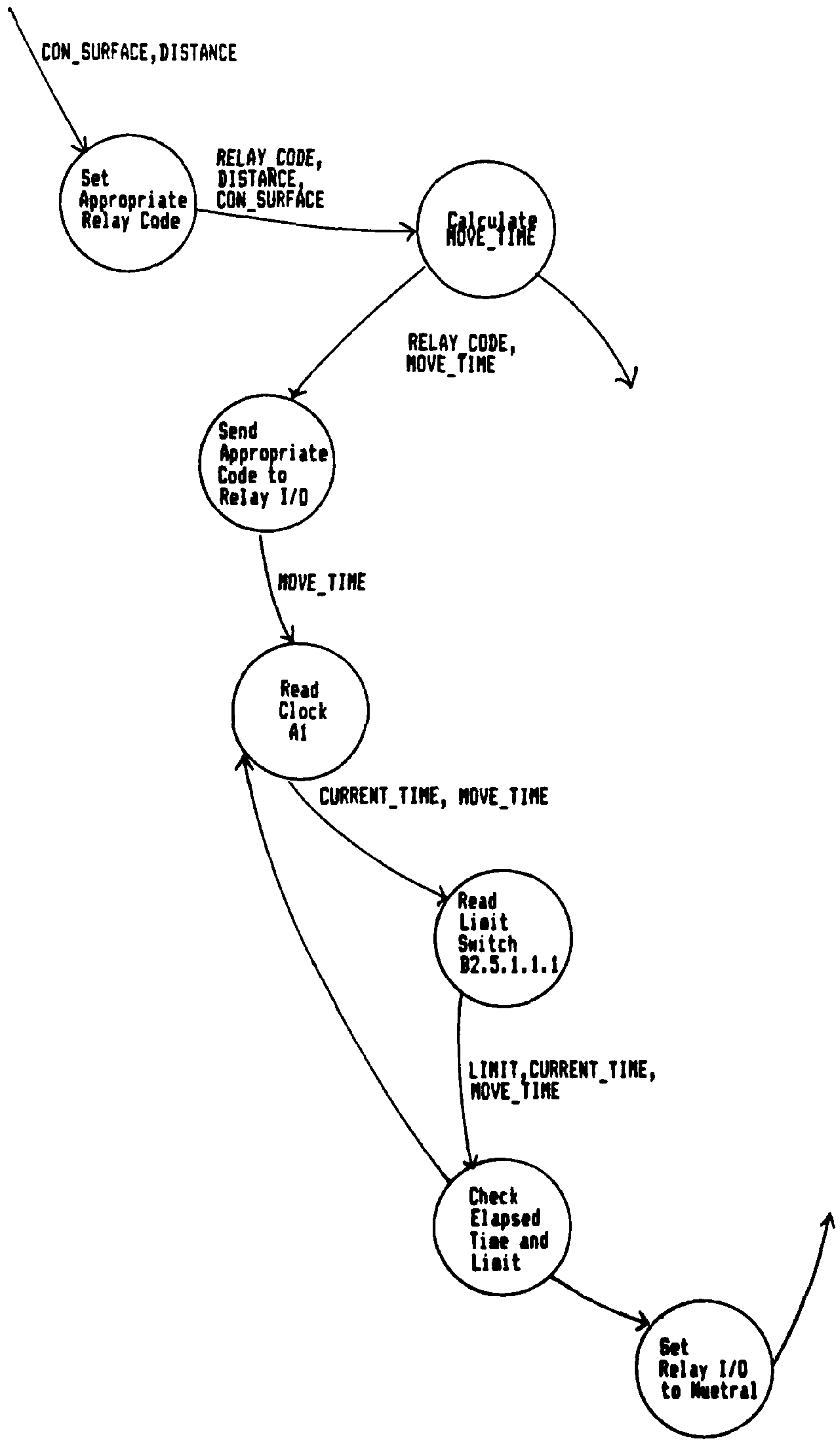


Fig. VI-23 Move Control Surface Module B2.1.1

Find Normalized Partials Module B2.5.1

The purpose of the module shown in Figure VI-24 is to calculate the normalized partial derivatives from the upper table and upper inlet partial derivatives. Using these two partial derivatives, a normalization factor is calculated (see NORMALIZATION_FACTOR in data dictionary). Then the normalized partials are calculated by dividing the respective partials by the normalization factor. The normalized partials are passed to the calling modules by the variables UT_NORMAL and UI_NORMAL.

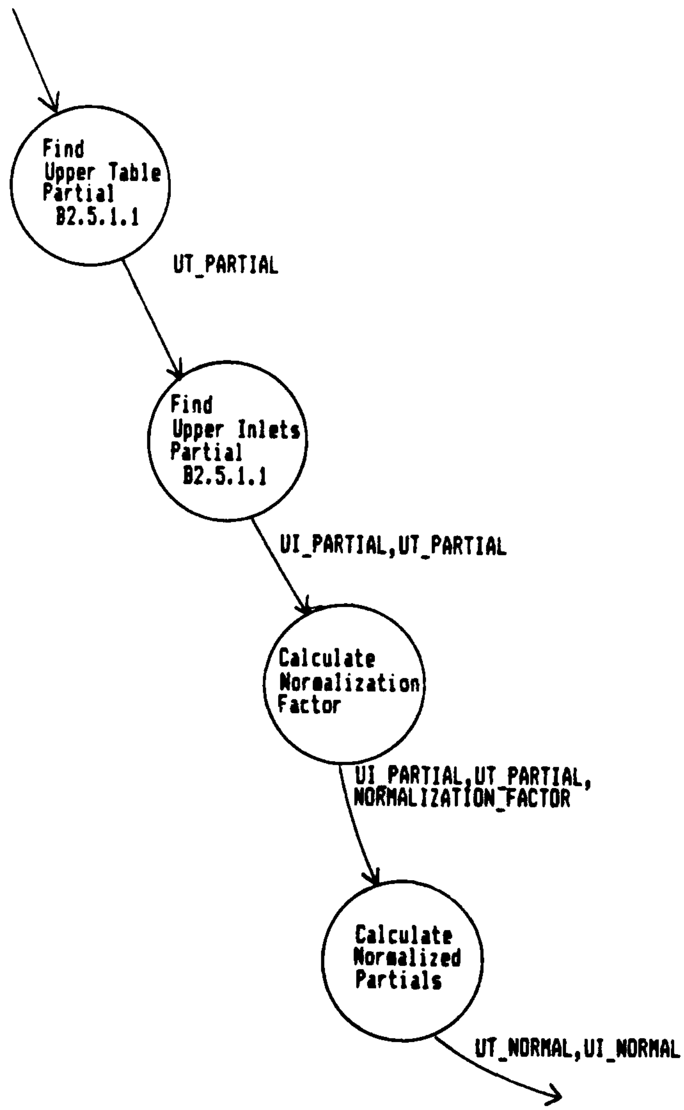


Fig. VI-24 Find Normalized Partials Module B2.5.1

Find Partial Module B2.5.1.1

The purpose of the Find Partial Module shown in Figure VI-25 is to approximate the partial derivative of the output power with respect to the control surface designated in the CON_SURFACE variable. Normally, this module determines the partial by moving the control surface a distance DELTA_X, in the closed and open direction from the initial position. The partial is then calculated from the change of power that results divided by twice DELTA_X.

The initial position of the control surface can cause variations of the normal procedure. If a control surface is at the full open limit (limit switch engaged) as shown by condition #1 of Figure VI-27, then the control surface can only be moved in the closed direction. Therefore, the partial is calculated over a distance DELTA_X from the full open position. However, if the partial calculated is negative (power decreases as the control surface is moved in the closed direction) then the partial is output as zero since the control cannot be moved in the open direction.

If the initial control surface position is near full open but not engaging the limit switch as shown by condition #2, then the control surface will not move a full DELTA_X when moved in the open direction. Therefore, once the control surface engages the limit switch, the partial will have to be re-computed as in the case of condition #1.

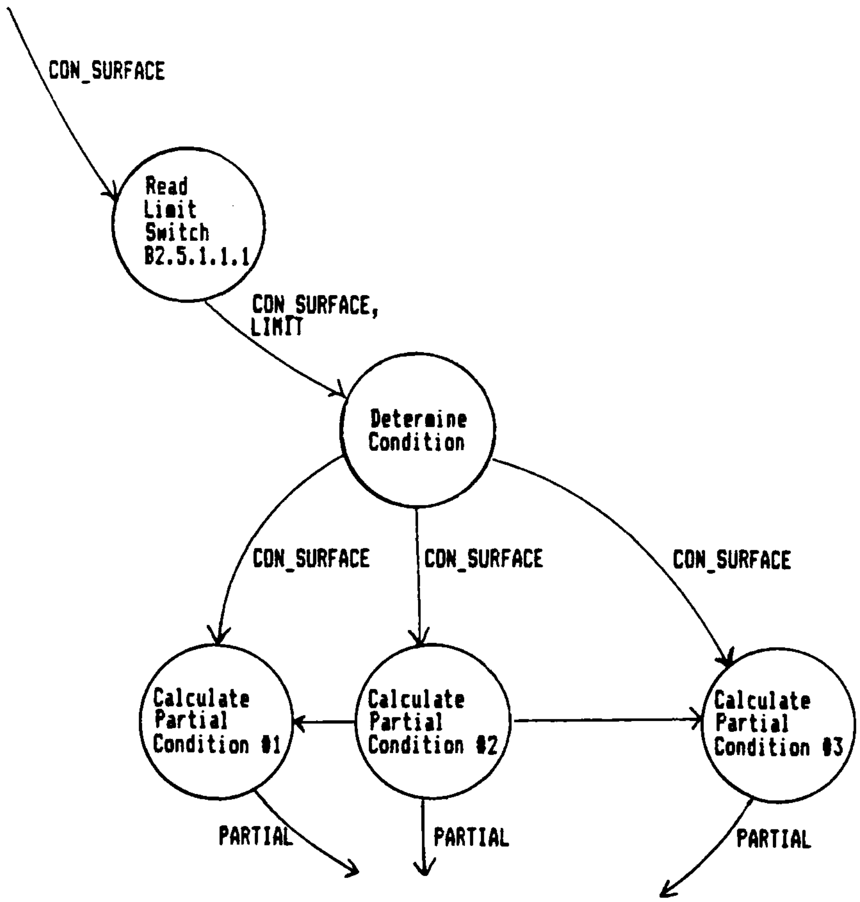


Fig. VI-25 Find Partial Module B2.5.1.1

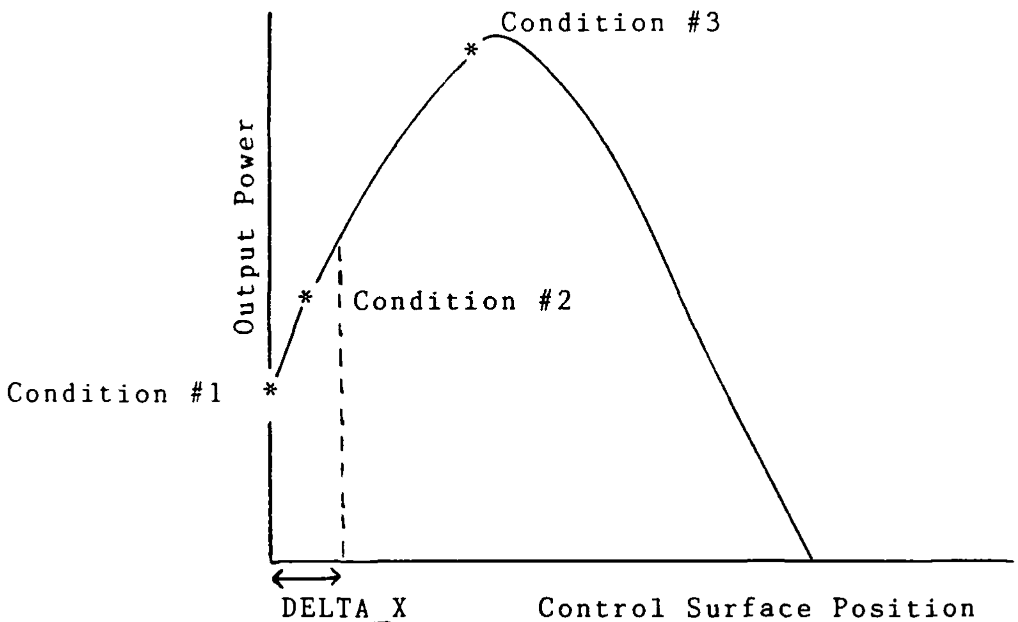


Fig. VI-26 The Three Conditions of the Find Partial Module

Condition #3 as shown in Figure VI-26 is when the initial position of the control surface is located where the output power reaches a sharp peak. In this case, the power will decrease when the control surface is moved in either direction from the initial position. When condition #3 is encountered, the module will output zero for the partial derivative indicating a maximum. Normally, the output power versus control surface position has a flat slope near the peak, therefore condition #3 may not be present and normal procedure (condition #4) is performed.

Condition #4 is when the initial control surface position is not condition #1, #2, or #3. In condition #4 the normal procedure is used to calculate the partial.

Read Limit Switch Module B2.5.1.1.1

The purpose of the module shown in Figure VI-28 is to check whether the limit switch is engaged for the control surface designated by the variable CON_SURFACE. This module simply checks the value in the appropriate limit switch I/O. The value of the output argument LIMIT is then changed to reflect a true or false condition.

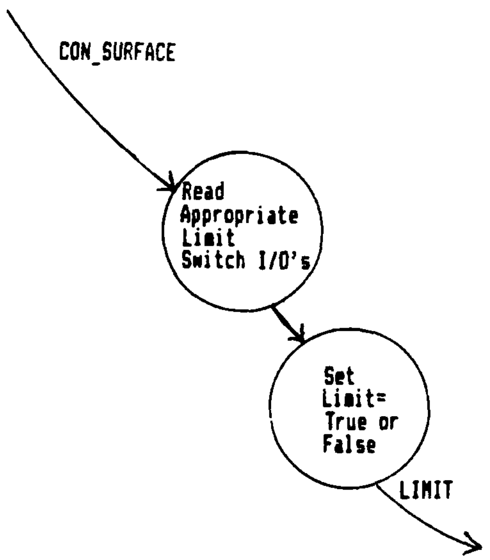


Fig. VI-27 Read Limit Switches Module B2.5.1.1.1

VI-6. Summary

This chapter provides the design of the control cycle section of the controller. However, the primary focus is on the search process. The gradient search is selected as the best search process due to its compatibility to the turbine tested in this thesis. However, in order to use the gradient search, a detailed analysis of how the gradient search can be applied in conjunction with the turbine's characteristics is required. The analysis narrowed the gradient search to two variables; the upper table and the upper inlets moved as one control surface. Also, the gradient search can only be performed when the control surfaces are initially positioned in a region where the global maximum will be the convergence position. Therefore, an initial start up routine is required in order to pre-position the control surfaces prior to initiating the gradient search. The initial start up routine is only required when the control surfaces are set at random such as controller turn on or after calibration or maintenance.

After the analysis, software modules is designed that performed the control cycle and search process. These modules fulfilled the requirements for applying the gradient search as described in the analysis. The software presented is applicable to the pre-modified and modified turbine with any differences specified. The following chapter explains the testing of this software using the computer model.

VII. Test and Evaluation

VII-I. Introduction

This chapter describes the computer simulation of the the Gradient Search #2 module. The purpose of the simuation was to evaluate the gradient search performance while varying the water height. The test program, Search, was written in Fortran (Appendix K) and run on a Cyber computer. Search, which simulates the Water Height Change module (Section VI-5), uses the linear interpolation model (IPOWER) to approximate reading the output power from an A/D. The simulation was conducted by performing the gradient search at differing water heights. The simulated water height was changed in 1/2 inch increments through the range of 12.125 to 20.0 inches. This is the same water height range that was used to obtain the turbine data from which the linear interpolation model is based. Results of the simulation confirmed the requirement for the Check and Correct module. The simulation showed that performing the Gradient Search #2 and Check and Correct modules produced control surface positions that correlated very closely to the optimum positions found in the linear interpolated model.

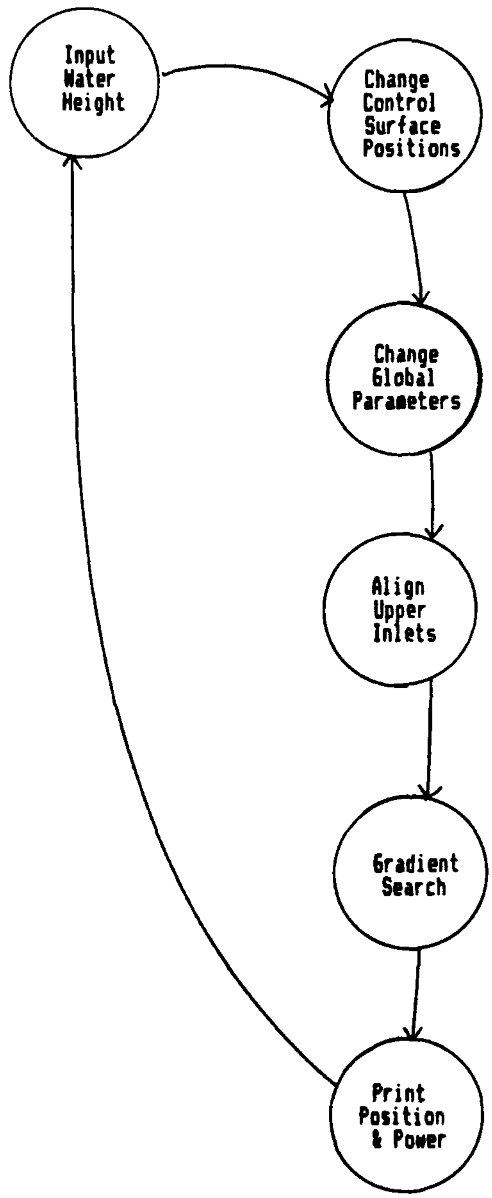


Fig. VII-1 Search Module

VII-2. Testing the Gradient Search Module

1. Main Module

The module shown in Figure VII-1, Search, is the main program (executive) of the simulation program. This module is similar to the Water Height Change module (Module 3.1) which assumes the control surface positions are near the optimum before performing the gradient search.

The user is first prompted to enter water height. The water height is stored in a global variable (WH) subsequently used by the Read A/D simulation module and the linear interpolation subroutine. As shown in Figure VII-1, the program always returns to prompting the water height after the gradient search is performed. Therefore the water height can be incremented to simulate increasing or decreasing river height. During the simulation, water height increments of 1/2 inch were used. Water height changes of 1/2 inch resulted in significant changes to optimum control surface positions at water heights below 14 inches. Smaller increments were not attempted since the measured water height of the actual system is estimated to be accurate to ± 1/2 inch.

After the water height is input, the main module prompts the user to change the control surface positions to any desired setting. The gradient search must be initiated with the control surface positions in a region near their optimum positions in order to insure convergence to the optimum position. Therefore, for the first test cycle, the user should input the control surfaces positions near the actual optimum positions of the model (Table VII-1). However, on subsequent test cycles, the user can slightly vary the control surface positions to simulate drift between control cycles or debris collection on the control surfaces.

After setting the control surface positions, the user is then prompted to change the global parameters used in the Align Upper Inlets, Gradient Search #2, Find Partial, and Move Control Surface modules. This is similar to the calibration mode of the controller described in Chapter V. The descriptions of the following global parameters which the user can change are located in the Data Dictionary in Appendix H: DELTA_X, MAX_STEP, and REDUCE_STEP.

Once the global parameters are set, the program then calls the Align Upper Inlets and the Gradient Search #2 modules. These modules simulate the functions as described in Section VI-5.

Finally, the program prints the resulting control surface positions, the number of control surface movements, and the final output power. The program then returns to the input water height prompt. Subsequent test cycles can be performed without changes to control surface positions or global parameters. The control surface positions determined from the last gradient search are used as the initial control surface positions unless changed by the user.

The Align Upper Inlets and the Gradient Search #2 modules use one or all of the following sub-modules: Find Partial, Move Control Surfaces, Read Limit Switches, and Read A/D (see Figure VI-12). The Find Partial module is performed identically as described in Section VI-5, however the other three modules are rewritten to simulate the process they would perform in the actual controller.

2. Move Control Surface Module

The simulated Move Control Surface module (Figure VII-2) uses the same inputs as the actual version described in Section VI-8. These two inputs are the control surface (CON_SURFACE) and the distance to move the control surface (DISTANCE). This module verifies the distance moved by the control surface is larger than or equal to 1/2 times the smallest allowable movement DELTA_X. If the move distance is smaller than 1/2 times DELTA_X then this module terminates without any further action. If the move distance is smaller than DELTA_X,

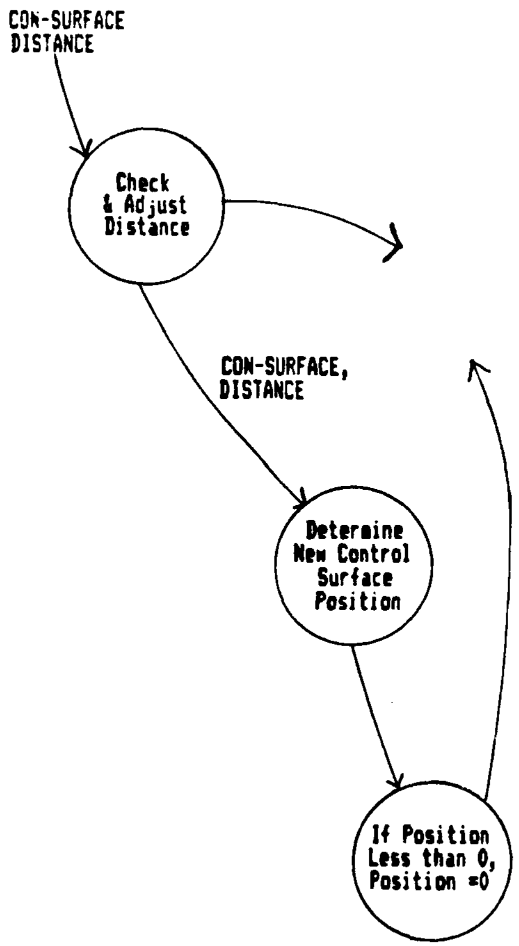


Fig. VII-2 Simulated Move Control Surface Module but greater than or equal to 1/2 times DELTA_X, then the control surface is moved the full distance DELTA_X.

The current positions of the control surfaces are stored in global variables, X1, X2, X3, X4, which represent the upper table and the three upper inlets respectively. The simulated Move Control Surface Module adds the move distance (DISTANCE) to the appropriate stored control surface position. If the sum is greater than or equal to zero, then the sum is stored as the new control surface position. If the sum is less than zero, then the new control surface position is changed to zero indicating the limit switch has been engaged or a physical limit has been reached.

3. Read Limit Switches Module

The simulated Read Limit Switches Module is very similar to the actual module described in Section VI-5. This module checks the position of the control surface designated by the input argument, CON_SURFACE. The control surface positions are the global variables, X1, X2, X3, and X4. If the control surface position is zero then a LIMIT=True otherwise LIMIT=False.

4. Read A/D Module

The simulated Read A/D module inputs the control surface positions stored in the global variables to the linear interpolation module, named Ipower. The Ipower module utilizes linear interpolation of the model data (Chapter II) to determine the approximate output power. The Read A/D module then outputs the linear interpolated output power through the argument POWER.

Table VII-4 lists the maximum power and corresponding control surface positions found from the measured data using linear interpolation. These values were compared to the power and control surface positions determined from the simulation.

VII-3. Evaluation of Gradient Search #2

Initial tests were conducted without using the Check and Correct module. Figures VII-3, VII-4, and VII-5 show the upper table positions, upper inlet positions, and the output power, respectively, for water heights from 12.125 to 20 inches. The dash lines show the actual optimum positions or maximum power found in the interpolated model data (the values in Table VII-1). The solid lines are the values determined from the simulation while varying the water height from 12.125 to 20 inches using 1/2 inch increments.

Table VII-1

Linear Interpolated Optimum Positions

	Water Height (in)	Upper Table (in)	Upper Inlets (in)	Output Power (in)
*	12.125	4.0	2.0	.131
	12.625	4.0	2.0	.142
*	13.125	2.8125	2.0	.21
	13.625	2.8125	1.625	.222
*	14.00	2.125	1.875	.285
	14.50	2.125	.75	.331
	15.00	2.125	.75	.382
	15.50	2.125	.75	.432
	16.00	2.125	.75	.483
	16.50	2.125	.75	.534
	17.00	2.125	.75	.585
	17.50	2.125	.75	.635
	18.00	0.0	.75	.689
	18.50	0.0	.75	.775
	19.00	0.0	.75	.861
	19.50	0.0	.75	.947
*	19.825	0.0	.75	1.01
	20.00	0.0	.75	1.03

* actual data

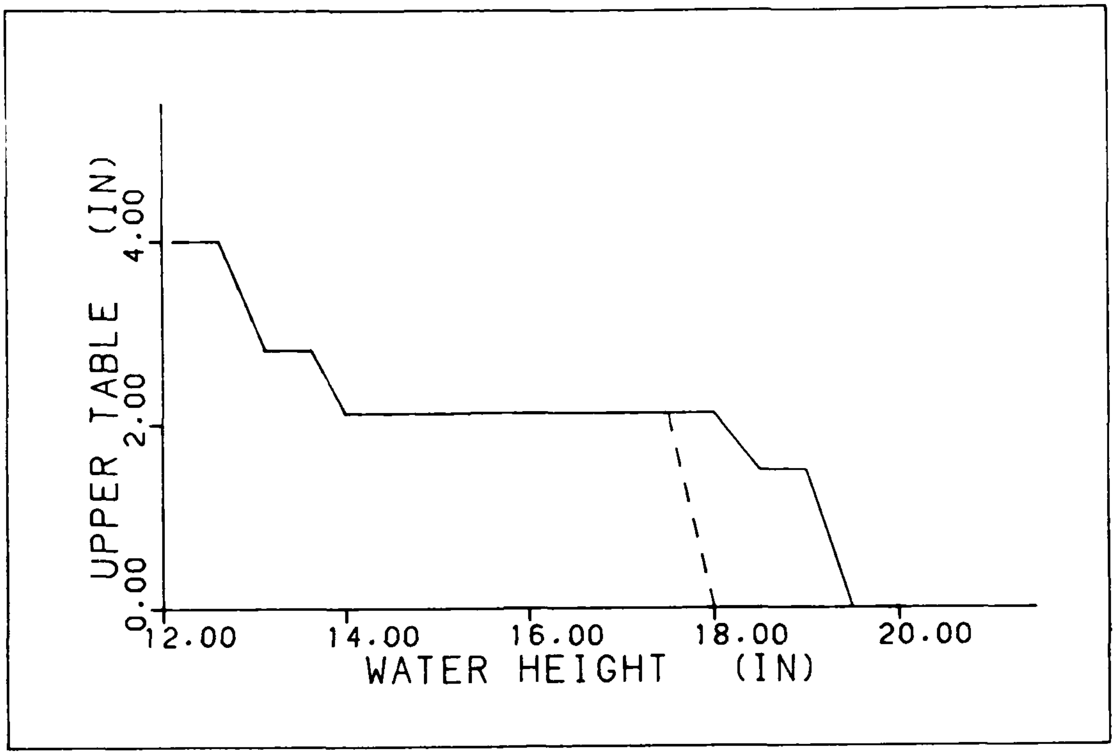


Fig. VII-3 Upper Table Positions During Simulation

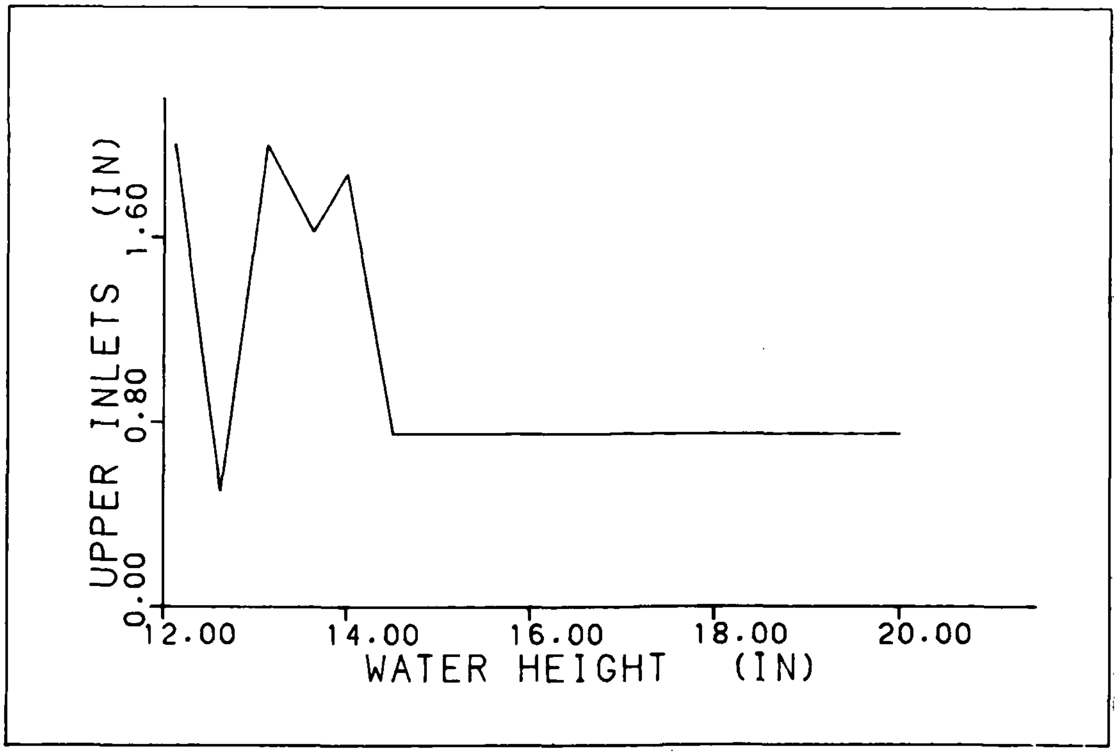


Fig. VII-4 Upper Inlets Positions During Simulation

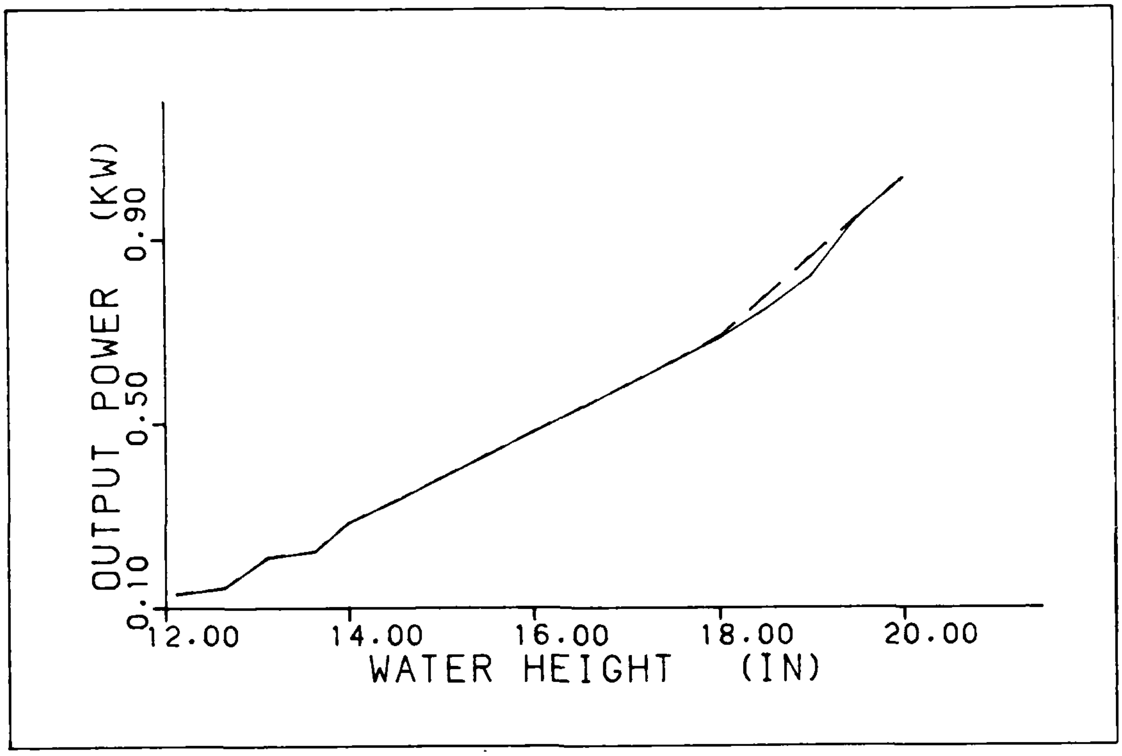


Fig. VII-5 Output Power with Increasing Water Height

The Gradient Search found and maintained the global maximum output power from 12.125 through 17.5 inches. However, at 18.0 inches the gradient search began to deviate slightly from the global maximum. The gradient search was unable to converge the upper table to the global optimum position since a local maximum had been created as the water height increased from 17.0 to 17.5 inches. Therefore, the upper table position remained at a local maximum of 2.125 inches (Figure VII-3) while the global maximum was at zero inches. Once the water height reached 19.5 inches the gradient search was again able to converge to the global maximum. The upper inlets converged to the optimum positions for all water heights.

Figure VII-5 shows that although the upper table position did not reach the global optimum position for all water heights, the output power remained within 96% of the modeled maximum power.

Figures VII-6 and VII-7 show the upper table positions and output power while the water height is varied from 20.0 to 12.125 inches using 1/2 inch increments. Again the gradient search is unable to converge the upper table when the water height reaches 18.0 inches. As the water height further decreases, the output power deviation becomes larger until a water height of 14.0.

The problem can be corrected by using the Check and Correct Module. This module checks the limit switch of each control surface. If the approximate optimum control surface position is at the full open position, then the control surface limit switch should be engaged. The Check and Correct module would then move the control surface to the full open position if the control surface was not already there. Conversely, if the approximate optimum control surface position is not the full open position and the limit switch is engaged, then the module moves the control surface from the full open position to the approximate optimum position.

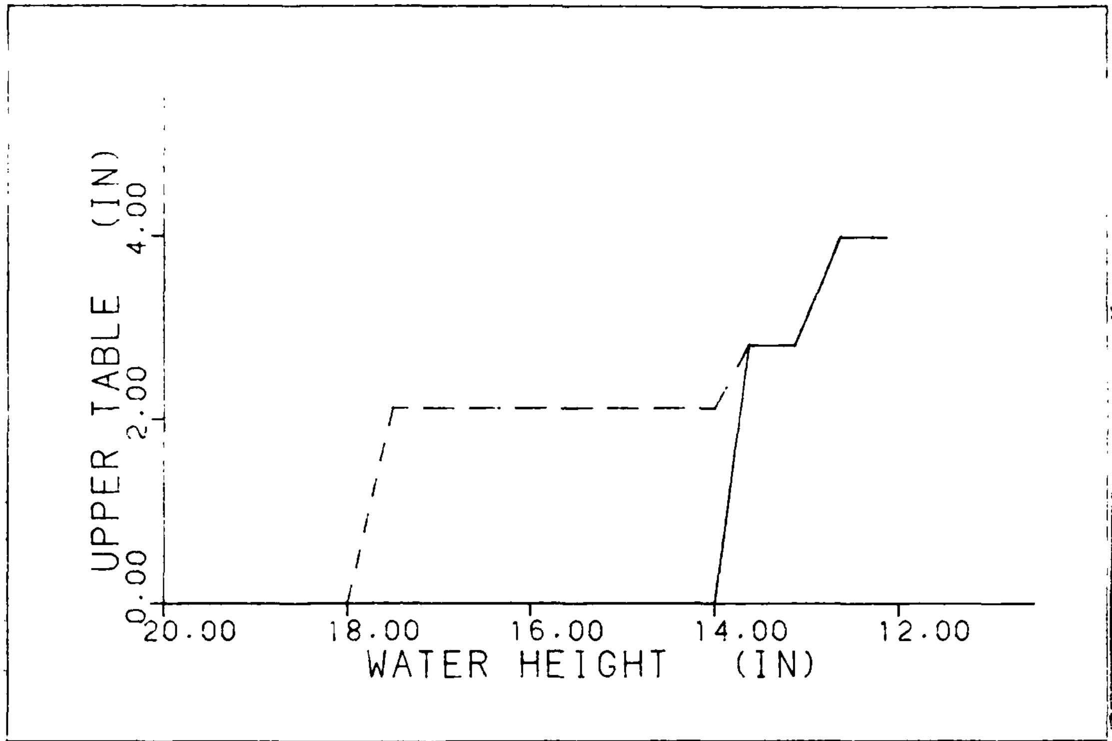


Fig. VII-6 Upper Table With Decreasing Water Height

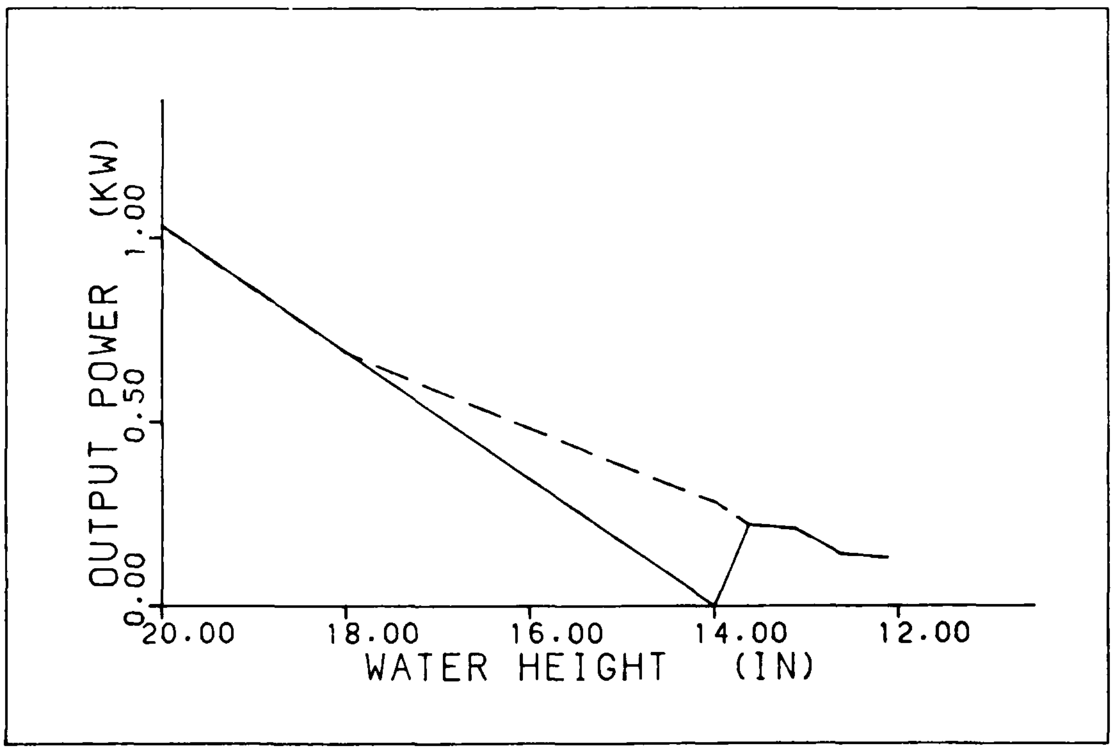


Fig. VII-7 Output Power With Decreasing Water Height

In the case where the water height increases from 12.125 to 20.0 inches, the check and correct module would find the upper table limit switch not engaged when the water height reaches 18.0 inches. Therefore, the upper table is moved to the full open position which is the optimum position for this water height. In the actual controller, a second gradient search will be performed to fine tune the control surface positions to the global maximum.

In the case where the water height decreases from 20.0 to 12.125 inches, the gradient search finds the limit switch engaged at 17.5 inches while the stored approximate optimum position is 2.125 inches. The Check and Correct Module then moves the upper table to the approximate optimum position. Again in the actual controller, a second gradient search will be performed to fine tune the optimum positions. Figure VII-8 shows that the upper table needs to be positioned at least 1.25 inches from the full open in order for the partial derivative to indicate the proper direction of the global optimum. Therefore, the stored optimum positions of the upper table are not required to be critically accurate.

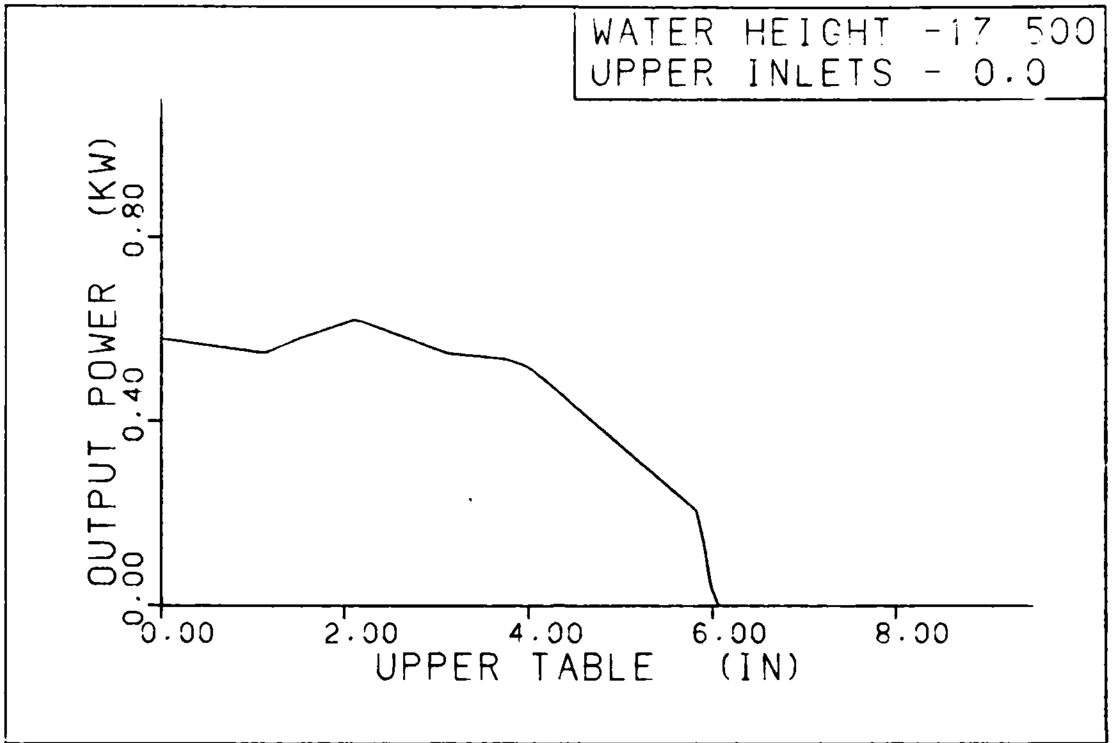


Fig. VII-8 Upper Table vs Output Power

The search simulation was performed again using a Check and Correct module. The water height again was increased 12.125 to 20.0 inches at 1/2 inch increments. At a water height of 18.0 inches the upper table position was set a zero inches prior to the gradient search. The resulting control surface positions and output power were identical to the actual optimum control surface positions and maximum output power of the modelled data (Table VII-1). Similarly, the search test was performed while decreasing the water height from 20.0 to 12.125 inches. At a water height of 17.5 inches the upper table was positioned by the user to 2.0 inches prior to the gradient search, thus simulating the Check and Correct Module. The position of 2.0 inches is less than the exact optimum position of 2.125 inches but is in the region where the gradient search can converge to the exact optimum position. Again the resulting control surface positions and output power were identical to the values found in Table VII-1.

Table VII-2

Tested Global Parameter Values

MAX_STEP	------------	.125 (in)
REDUCE_STEP	------------	.25
DELTA_X	------------	.03125 (in)

Table VII-2 shows the global parameter values used in the test. The DELTA_X value is the estimate derived experimentally of the smallest commanded control surface movement. This value will change for the modified turbine. MAX_STEP, the maximum step size used in the gradient search, was tested at values from .5 to .03125 inches. Values greater than .25 inch resulted in cases where the gradient search would move out of a good region while performing the gradient search and thus converge to a local maximum. A MAX_STEP of .125 and a reduction factor, REDUCE_STEP, of 1/4 was found to require the least amount of control surface movements in order to converge to the global maximum output power for most water heights. The MAX_STEP and REDUCE_STEP values are peculiar to the linear interpolated model. Therefore in the actual controller, the optimum MAX_STEP and REDUCE_STEP global parameters will be determined by trial and error. The values in Table VII-1, can be used for initial starting values.

VII-4. Conclusion

The Gradient Search #2, and the Align Upper Inlets modules worked as designed. The Gradient Search Module always converges to the global maximum when the control surfaces are in a region near the global maximum. However, due to the nature of the turbine, the optimum position for the upper table shifts significantly when water height changed from 17.5 to 18.0 inches or vise versa. The resulting position of the upper table is out of a 'good region', therefore the gradient search converges to a local rather than global maximum.

To alleviate the problem, the Check and Correct module was simulated as the water height passed the critical range from 17.5 to 18.0 inches. Combining this module with the gradient search resulted in the control surface positions and output power values identical to the optimum control surface positions and maximum output power found in the linear interpolated model for all water heights tested.

VIII. Conclusion and Recommendations

Conclusion

The purpose of thesis was to provide a complete controller design so that a follow on project can construct the controller . During the course of this thesis however, it was found the turbine required modification. Due to time constraints, the design presented here is based upon the pre-modified turbine. However, the proposed turbine modification is included with this thesis along with the recommended changes to the controller design. Therefore, a follow on project will only require a small degree of design work prior to constructing the actual controller for the modified turbine. Recommendations on how to complete the design for the modified turbine are included in the recommendations section of this chapter.

The search software designed in this thesis performed successfully using the linear interpolated model of the pre-modified turbine. Note, however that the design presented here is only one method of accomplishing the gradient search process. During implementation, this software may be modified to make more efficient use of the microprocessors capabilities.

Recommendations for the Design of the Modified Turbine Controller

The design of the modified turbine controller should be identical to the controller designed in this thesis with only a few exceptions. These exceptions are pointed out in Chapters II and VI, and are also listed below. Recommendations are also given on how to model the modified turbine and test the new controller design.

1. The controller for the modified turbine requires the same hardware and hardware interfaces as shown if Chapters IV and V with the following exception. The modified turbine only has two adjustable control surfaces; the upper table and the upper inlet. Therefore, the controller only needs to interface with two control surfaces instead of four as was required with the original design. The hardware interfacing will remain the same, using two controller outputs per control surface, one output to move the control surface in the open direction and one output to move the control surface in the closed direction.

2. All software changes required for the modified turbine are shown in Chapter VI. Basically, since the modified turbine has only two control surfaces, the following software modules are not required: Set Inlet, Move Lower Inlet, and Align Upper Inlets. The optimum control surface positions for the modified turbine will never be at a physical limit and the control surface's drive mechanism

will not allow drift or slippage, therefore the Check and Correct module will also not be required. The selection of the gradient search algorithm will depend upon the model and/or testing of the modified turbine.

3. Modelling and testing of the modified controller will be required in order to obtain the global parameters used in the software and to choose the appropriate gradient search algorithm (ie. Gradient Search #1 or Gradient Search #2). However, the modified turbine should be totally completed before obtaining test data. This includes all electrical inputs to the turbine system, the electrical water height measuring device, and the output generator with power meter. For this thesis, all data was taken using a pony brake to measure output power brake since an output generator was not available. In order to obtain a complete model of the turbine system, the generator output should be considered.

4. The following global parameters are utilized by the controller software and must be determined experimentally. OPEN_VELOCITY_UT and CLOSE_VELOCITY_UT are the opening and closing velocities of the upper table. OPEN_VELOCITY_UI and CLOSE_VELOCITY_UI are the respective opening and closing velocities of the upper inlet. These parameters can be determined by measuring the time of travel of the control surface from one physical limit (such as full open) to the other physical limit (full closed) and vice versa. The

respective velocity is then the distance traveled divided by the time of travel. This is the same procedure described in Chapter II.

Another global parameter that is to be determined experimentally is DELTA_X, the smallest increment that a control surface is allowed to move. To determine DELTA_X the electrical input hardware to the control surface actuators are required to be complete. Tests by trial and error must be completed in order to find the minimum time that an electrical input to the control surface actuator can be applied and result in control surface movement. This minimum time is then multiplied by the control surface velocity to determine DELTA_X. This procedure is accomplished for both control surfaces and the largest DELTA_X is used as the global parameter in the software. DELTA_X can be increased with a safety factor to insure that control surface movement will always result when the controller is implemented. However, too large of a DELTA_X will reduce the accuracy of the gradient search software.

Finally, the approximate optimum positions for the upper inlet must be determined experimentally. The approximate optimum positions are stored in the global array UI(I) and are used in the Position Upper Inlet Module described in Chapter VI. This module places the upper inlet near the optimum position prior to performing the gradient search. To find the specific optimum position using the array the module must first find the index I. The module determines I by comparing the current water height with water height ranges stored in the array WATER_HEIGHT_ARRAY (see psuedo-code for Position Upper Inlets, Appendix I). Therefore, while obtaining data for the approximate optimum upper inlet positions, the data for the WATER_HEIGHT_ARRAY must also be recorded. The data for U(I) and the WATER_HEIGHT_ARRAY can either be determined from separate experiments or by the modified turbine model.

The approximate optimum position for the upper table can be calculated using the formula shown in Section VI-4. This formula will replace the requirement for an optimum upper table position array. However, experimental tests will be required to determine the relationship between Water Height H and Flow Rate Q in order to replace Q with an expression in terms of H (see Section VI-4).

5. The primary purpose of modelling the modified turbine is to determine the appropriate gradient search and to find the optimum step parameters in the gradient search. Modelling the modified turbine can be completed similar to the procedure used in this thesis (Section II-5) via data tables. The ideal method of obtaining a good model of the turbine via data tables is to connect a microprocessor with storage device (floppy disks) to the control surface

actuators (via a D/A converter) and input to the microprocessor (via an A/D) the power meter output and water height electrical signal. Software would have to be written that would increment the control surfaces throughout their ranges and store the control surface positions, water height, and output power in the storage device. This would allow the accumulation of data points limited only by the capacity of the storage device. A linear interpolation program similar to the one used in this thesis (Appendix D) could then be written to obtain a continous model of the turbine for use in the laboratory.

6. Regardless of how the model is obtained, an appropriate gradient search algorithm must be selected. Obtaining contour plots of the upper inlet versus the upper table using lines of constant output power as was done in Appendix F will show if Gradient Search #2 can be performed. If the position of the upper table which provides the best output power is the same position regardless of the position of the upper inlet, then Gradient Search #2 is the best choice to implement in the controller. Gradient Search #2 will optimize the upper table and upper inlet individually starting with the upper table, therefore eliminating small control surface movements that would be present if both control surfaces are optimized at the same time.

If the control surfaces cannot be optimized individually, then Gradient Search #1 will be implemented in the controller. The Gradient Search #1 module described in Chapter VI was designed as a procedure of two variables and can be applied directly to the modified turbine if necessary.

7. Once the appropriate gradient search is selected then the global parameters which create the step sizes used in the search must be determined. These two global parameters are MAX_STEP which is the initial and largest step size and REDUCE_STEP which is a factor used to decrease the step size during iterations. Performing the same test as presented in Chapter 7 and using trial and error will enable the designer to select values for these two parameters which will minimize the number of control surface movements while the control surfaces are moved to their respective optimum positions . These two parameters may have to be fined tuned after the controller is installed, but the test will at least provide initial values.

8. The last step is to actually construct the controller. However if resources are available, testing the controller design using a programmable microprocessor such as the LSI-11 connected to the actual turbine system would allow on line programming changes to the software. The final software would then be proven prior to implementation with the constructed controller.

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Appendix A.

Lower Inlet Data

Table A-1 shows the data taken for the various water heights and flow depths. Table A-2 summarizes the otimum lower inlet positions used when acquiring the remaining turbine data in Appendix B. water heights at which data was taken.

Table A-1

Lower Inlet Data

Water Flow Depth (in)	Lower Inlet Position (deg)	Water Height (in)	Maximum Output Power (KW)
1.75	90	12.120	.131
	88	12.125	.128
	86	12.125	.124
	84	12.115	.118
	82	12.0	.97
	80	12.0	0.0
3.5	90	13.125	.190
	88	13.125	.198
	86	13.125	.205
	84	13.125	.21
	82	13.125	.198
	80	13.125	.182
4.5	90	14.125	.250
	88	14.0	.250
	86	14.0	.255
	84	14.0	.273
	82	14.0	.283
	80	14.0	.285
9.815	90	19.875	.975
	88	19.875	1.012
	86	19.875	.991
	84	19.875	.980
	82	19.875	.972
	80	19.875	.960

Table A-2

Summary of Optimum Lower Inlet Position

Water Flow Depth (in)	Optimum Lower Inlet Position (deg)	Water Height (in)	Maximum Output Power (KW)
1.75	90	12.120	.131
3.5	84	13.125	.21
4.5	80	14.0	.285
9.815	88	19.875	1.012

Appendix B.

Turbine Data

The turbine data is listed in four tables. These tables correspond to the water heights at which data was taken.

Legend:

H - Water Height

d - Flow Depth

PA - Power Available

LI - Lower Inlet Position

PM - Power Measured

E - Efficiency

T - Upper Table Position

UI#1 - Upper Inlet #1 Position

UI#2 - Upper Inlet #2 Position

UI#3 - Upper INlet #3 Position

$$PA = (QH)/8496 \quad (KW)$$

$$E = 100PM/PA$$

TABLE B-1

Fixed Parameters:

H (in)	d (in)	Q (CFM)	PA (KW)	LI (deg)
12.125	1.750	103.5	.148	90.0

Hydroturbine data:

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
1	.074	50.0	.000	.000	.000	.000
2	.072	48.5	.000	.000	.000	5.125
3	.058	39.0	.000	.000	.000	6.000
4	.053	36.0	.000	.000	.000	6.025
5	.047	31.8	.000	.000	.000	9.000
6	.072	48.5	.000	.000	5.125	.000
7	.072	48.5	.000	.000	5.125	5.125
8	.056	38.0	.000	.000	5.125	6.000
9	.052	35.0	.000	.000	5.125	6.025
10	.046	30.8	.000	.000	5.125	9.000
11	.058	39.0	.000	.000	6.000	.000
12	.056	38.0	.000	.000	6.000	5.125
13	.044	29.5	.000	.000	6.000	6.000
14	.038	25.5	.000	.000	6.000	6.025
15	.000	.0	.000	.000	6.000	9.000
16	.053	36.0	.000	.000	6.025	.000
17	.052	35.0	.000	.000	6.025	5.125
18	.038	25.5	.000	.000	6.025	6.000
19	.035	23.5	.000	.000	6.025	6.025
20	.000	.0	.000	.000	6.025	9.000
21	.047	31.8	.000	.000	9.000	.000
22	.046	30.8	.000	.000	9.000	5.125
23	.000	.0	.000	.000	9.000	6.000
24	.000	.0	.000	.000	9.000	6.025
25	.000	.0	.000	.000	9.000	9.000
26	.072	48.5	.000	5.125	.000	.000
27	.072	48.5	.000	5.125	.000	5.125
28	.056	38.0	.000	5.125	.000	6.000
29	.052	35.0	.000	5.125	.000	6.025
30	.046	30.8	.000	5.125	.000	9.000
31	.072	48.5	.000	5.125	5.125	.000
32	.074	50.0	.000	5.125	5.125	5.125
33	.058	39.0	.000	5.125	5.125	6.000
34	.053	36.0	.000	5.125	5.125	6.025
35	.047	31.8	.000	5.125	5.125	9.000
36	.056	38.0	.000	5.125	6.000	.000
37	.058	39.0	.000	5.125	6.000	5.125

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
38	.044	29.5	.000	5.125	6.000	6.000
39	.038	25.5	.000	5.125	6.000	6.025
40	.000	.0	.000	5.125	6.000	9.000
41	.052	35.0	.000	5.125	6.025	.000
42	.053	36.0	.000	5.125	6.025	5.125
43	.038	25.5	.000	5.125	6.025	6.000
44	.035	23.5	.000	5.125	6.025	6.025
45	.000	.0	.000	5.125	6.025	9.000
46	.046	30.8	.000	5.125	9.000	.000
47	.047	31.8	.000	5.125	9.000	5.125
48	.000	.0	.000	5.125	9.000	6.000
49	.000	.0	.000	5.125	9.000	6.025
50	.000	.0	.000	5.125	9.000	9.000
51	.058	39.0	.000	6.000	.000	.000
52	.056	38.0	.000	6.000	.000	5.125
53	.044	29.5	.000	6.000	.000	6.000
54	.038	25.5	.000	6.000	.000	6.025
55	.000	.0	.000	6.000	.000	9.000
56	.056	38.0	.000	6.000	5.125	.000
57	.058	39.0	.000	6.000	5.125	5.125
58	.044	29.5	.000	6.000	5.125	6.000
59	.038	25.5	.000	6.000	5.125	6.025
60	.000	.0	.000	6.000	5.125	9.000
61	.044	29.5	.000	6.000	6.000	.000
62	.044	29.5	.000	6.000	6.000	5.125
63	.032	21.5	.000	6.000	6.000	6.000
64	.000	.0	.000	6.000	6.000	6.025
65	.000	.0	.000	6.000	6.000	9.000
66	.038	25.5	.000	6.000	6.025	.000
67	.038	25.5	.000	6.000	6.025	5.125
68	.000	.0	.000	6.000	6.025	6.000
69	.000	.0	.000	6.000	6.025	6.025
70	.000	.0	.000	6.000	6.025	9.000
71	.000	.0	.000	6.000	9.000	.000
72	.000	.0	.000	6.000	9.000	5.125
73	.000	.0	.000	6.000	9.000	6.000
74	.000	.0	.000	6.000	9.000	6.025
75	.000	.0	.000	6.000	9.000	9.000
76	.053	36.0	.000	6.025	.000	.000
77	.052	35.0	.000	6.025	.000	5.125
78	.038	25.5	.000	6.025	.000	6.000
79	.035	23.5	.000	6.025	.000	6.025
80	.000	.0	.000	6.025	.000	9.000
81	.052	35.0	.000	6.025	5.125	.000
82	.053	36.0	.000	6.025	5.125	5.125
83	.038	25.5	.000	6.025	5.125	6.000
84	.035	23.5	.000	6.025	5.125	6.025
85	.000	.0	.000	6.025	5.125	9.000
86	.038	25.5	.000	6.025	6.000	.000
87	.038	25.5	.000	6.025	6.000	5.125

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
88	.000	.0	.000	6.025	6.000	6.000
89	.000	.0	.000	6.025	6.000	6.025
90	.000	.0	.000	6.025	6.000	9.000
91	.035	23.5	.000	6.025	6.025	.000
92	.035	23.5	.000	6.025	6.025	5.125
93	.000	.0	.000	6.025	6.025	6.000
94	.000	.0	.000	6.025	6.025	6.025
95	.000	.0	.000	6.025	6.025	9.000
96	.000	.0	.000	6.025	9.000	.000
97	.000	.0	.000	6.025	9.000	5.125
98	.000	.0	.000	6.025	9.000	6.000
99	.000	.0	.000	6.025	9.000	6.025
100	.000	.0	.000	6.025	9.000	9.000
101	.047	31.8	.000	9.000	.000	.000
102	.046	30.8	.000	9.000	.000	5.125
103	.000	.0	.000	9.000	.000	6.000
104	.000	.0	.000	9.000	.000	6.025
105	.000	.0	.000	9.000	.000	9.000
106	.046	30.8	.000	9.000	5.125	.000
107	.047	31.8	.000	9.000	5.125	5.125
108	.000	.0	.000	9.000	5.125	6.000
109	.000	.0	.000	9.000	5.125	6.025
110	.000	.0	.000	9.000	5.125	9.000
111	.000	.0	.000	9.000	6.000	.000
112	.000	.0	.000	9.000	6.000	5.125
113	.000	.0	.000	9.000	6.000	6.000
114	.000	.0	.000	9.000	6.000	6.025
115	.000	.0	.000	9.000	6.000	9.000
116	.000	.0	.000	9.000	6.025	.000
117	.000	.0	.000	9.000	6.025	5.125
118	.000	.0	.000	9.000	6.025	6.000
119	.000	.0	.000	9.000	6.025	6.025
120	.000	.0	.000	9.000	6.025	9.000
121	.000	.0	.000	9.000	9.000	.000
122	.000	.0	.000	9.000	9.000	5.125
123	.000	.0	.000	9.000	9.000	6.000
124	.000	.0	.000	9.000	9.000	6.025
125	.000	.0	.000	9.000	9.000	9.000
126	.071	48.1	3.500	.000	.000	.000
127	.069	46.6	3.500	.000	.000	1.750
128	.070	47.3	3.500	.000	.000	2.250
129	.053	35.6	3.500	.000	.000	4.875
130	.050	33.9	3.500	.000	.000	4.938
131	.069	46.6	3.500	.000	1.750	.000
132	.069	46.6	3.500	.000	1.750	1.750
133	.068	46.3	3.500	.000	1.750	2.250
134	.051	34.6	3.500	.000	1.750	4.875
135	.049	32.9	3.500	.000	1.750	4.938
136	.070	47.3	3.500	.000	2.250	.000
137	.068	46.3	3.500	.000	2.250	1.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
138	.071	47.9	3.500	.000	2.250	2.250
139	.052	35.2	3.500	.000	2.250	4.875
140	.050	33.5	3.500	.000	2.250	4.938
141	.053	35.6	3.500	.000	4.875	.000
142	.051	34.6	3.500	.000	4.875	1.750
143	.052	35.2	3.500	.000	4.875	2.250
144	.036	24.5	3.500	.000	4.875	4.875
145	.032	21.9	3.500	.000	4.875	4.938
146	.050	33.9	3.500	.000	4.938	.000
147	.049	32.9	3.500	.000	4.938	1.750
148	.050	33.5	3.500	.000	4.938	2.250
149	.032	21.9	3.500	.000	4.938	4.875
150	.031	21.2	3.500	.000	4.938	4.938
151	.069	46.6	3.500	1.750	.000	.000
152	.069	46.6	3.500	1.750	.000	1.750
153	.068	46.3	3.500	1.750	.000	2.250
154	.051	34.6	3.500	1.750	.000	4.875
155	.049	32.9	3.500	1.750	.000	4.938
156	.069	46.6	3.500	1.750	1.750	.000
157	.071	48.1	3.500	1.750	1.750	1.750
158	.070	47.3	3.500	1.750	1.750	2.250
159	.053	35.6	3.500	1.750	1.750	4.875
160	.050	33.9	3.500	1.750	1.750	4.938
161	.068	46.3	3.500	1.750	2.250	.000
162	.070	47.3	3.500	1.750	2.250	1.750
163	.071	47.9	3.500	1.750	2.250	2.250
164	.052	35.2	3.500	1.750	2.250	4.875
165	.050	33.5	3.500	1.750	2.250	4.938
166	.051	34.6	3.500	1.750	4.875	.000
167	.053	35.6	3.500	1.750	4.875	1.750
168	.052	35.2	3.500	1.750	4.875	2.250
169	.036	24.5	3.500	1.750	4.875	4.875
170	.032	21.9	3.500	1.750	4.875	4.938
171	.049	32.9	3.500	1.750	4.938	.000
172	.050	33.9	3.500	1.750	4.938	1.750
173	.050	33.5	3.500	1.750	4.938	2.250
174	.032	21.9	3.500	1.750	4.938	4.875
175	.031	21.2	3.500	1.750	4.938	4.938
176	.070	47.3	3.500	2.250	.000	.000
177	.068	46.3	3.500	2.250	.000	1.750
178	.071	47.9	3.500	2.250	.000	2.250
179	.052	35.2	3.500	2.250	.000	4.875
180	.050	33.5	3.500	2.250	.000	4.938
181	.068	46.3	3.500	2.250	1.750	.000
182	.070	47.3	3.500	2.250	1.750	1.750
183	.071	47.9	3.500	2.250	1.750	2.250
184	.052	35.2	3.500	2.250	1.750	4.875
185	.050	33.5	3.500	2.250	1.750	4.938
186	.071	47.9	3.500	2.250	2.250	.000
187	.071	47.9	3.500	2.250	2.250	1.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
188	.074	50.0	3.500	2.250	2.250	2.250
189	.054	36.8	3.500	2.250	2.250	4.875
190	.052	35.2	3.500	2.250	2.250	4.938
191	.052	35.2	3.500	2.250	4.875	.000
192	.052	35.2	3.500	2.250	4.875	1.750
193	.054	36.8	3.500	2.250	4.875	2.250
194	.037	25.2	3.500	2.250	4.875	4.875
195	.033	22.5	3.500	2.250	4.875	4.938
196	.050	33.5	3.500	2.250	4.938	.000
197	.050	33.5	3.500	2.250	4.938	1.750
198	.052	35.2	3.500	2.250	4.938	2.250
199	.033	22.5	3.500	2.250	4.938	4.875
200	.032	21.8	3.500	2.250	4.938	4.938
201	.053	35.6	3.500	4.875	.000	.000
202	.051	34.6	3.500	4.875	.000	1.750
203	.052	35.2	3.500	4.875	.000	2.250
204	.036	24.5	3.500	4.875	.000	4.875
205	.032	21.9	3.500	4.875	.000	4.938
206	.051	34.6	3.500	4.875	1.750	.000
207	.053	35.6	3.500	4.875	1.750	1.750
208	.052	35.2	3.500	4.875	1.750	2.250
209	.036	24.5	3.500	4.875	1.750	4.875
210	.032	21.9	3.500	4.875	1.750	4.938
211	.052	35.2	3.500	4.875	2.250	.000
212	.052	35.2	3.500	4.875	2.250	1.750
213	.054	36.8	3.500	4.875	2.250	2.250
214	.037	25.2	3.500	4.875	2.250	4.875
215	.033	22.5	3.500	4.875	2.250	4.938
216	.036	24.5	3.500	4.875	4.875	.000
217	.036	24.5	3.500	4.875	4.875	1.750
218	.037	25.2	3.500	4.875	4.875	2.250
219	.022	15.0	3.500	4.875	4.875	4.875
220	.000	.0	3.500	4.875	4.875	4.938
221	.032	21.9	3.500	4.875	4.938	.000
222	.032	21.9	3.500	4.875	4.938	1.750
223	.033	22.5	3.500	4.875	4.938	2.250
224	.000	.0	3.500	4.875	4.938	4.875
225	.000	.0	3.500	4.875	4.938	4.938
226	.050	33.9	3.500	4.938	.000	.000
227	.049	32.9	3.500	4.938	.000	1.750
228	.050	33.5	3.500	4.938	.000	2.250
229	.032	21.9	3.500	4.938	.000	4.875
230	.031	21.2	3.500	4.938	.000	4.938
231	.049	32.9	3.500	4.938	1.750	.000
232	.050	33.9	3.500	4.938	1.750	1.750
233	.050	33.5	3.500	4.938	1.750	2.250
234	.032	21.9	3.500	4.938	1.750	4.875
235	.031	21.2	3.500	4.938	1.750	4.938
236	.050	33.5	3.500	4.938	2.250	.000
237	.050	33.5	3.500	4.938	2.250	1.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
238	.052	35.2	3.500	4.938	2.250	2.250
239	.033	22.5	3.500	4.938	2.250	4.875
240	.032	21.8	3.500	4.938	2.250	4.938
241	.032	21.9	3.500	4.938	4.875	.000
242	.032	21.9	3.500	4.938	4.875	1.750
243	.033	22.5	3.500	4.938	4.875	2.250
244	.000	.0	3.500	4.938	4.875	4.875
245	.000	.0	3.500	4.938	4.875	4.938
246	.031	21.2	3.500	4.938	4.938	.000
247	.031	21.2	3.500	4.938	4.938	1.750
248	.032	21.8	3.500	4.938	4.938	2.250
249	.000	.0	3.500	4.938	4.938	4.875
250	.000	.0	3.500	4.938	4.938	4.938
251	.117	79.2	4.000	.000	.000	.000
252	.118	79.6	4.000	.000	.000	2.000
253	.086	58.4	4.000	.000	.000	4.500
254	.083	56.1	4.000	.000	.000	4.563
255	.074	50.2	4.000	.000	.000	9.000
256	.118	79.6	4.000	.000	2.000	.000
257	.122	82.7	4.000	.000	2.000	2.000
258	.088	59.7	4.000	.000	2.000	4.500
259	.085	57.4	4.000	.000	2.000	4.563
260	.076	51.5	4.000	.000	2.000	9.000
261	.086	58.4	4.000	.000	4.500	.000
262	.088	59.7	4.000	.000	4.500	2.000
263	.059	40.3	4.000	.000	4.500	4.500
264	.053	36.1	4.000	.000	4.500	4.563
265	.045	30.2	4.000	.000	4.500	9.000
266	.083	56.1	4.000	.000	4.563	.000
267	.085	57.4	4.000	.000	4.563	2.000
268	.053	36.1	4.000	.000	4.563	4.500
269	.053	35.5	4.000	.000	4.563	4.563
270	.041	27.9	4.000	.000	4.563	9.000
271	.074	50.2	4.000	.000	9.000	.000
272	.076	51.5	4.000	.000	9.000	2.000
273	.045	30.2	4.000	.000	9.000	4.500
274	.041	27.9	4.000	.000	9.000	4.563
275	.000	.0	4.000	.000	9.000	9.000
276	.118	79.6	4.000	2.000	.000	.000
277	.122	82.7	4.000	2.000	.000	2.000
278	.088	59.7	4.000	2.000	.000	4.500
279	.085	57.4	4.000	2.000	.000	4.563
280	.076	51.5	4.000	2.000	.000	9.000
281	.122	82.7	4.000	2.000	2.000	.000
282	.131	88.4	4.000	2.000	2.000	2.000
283	.095	64.6	4.000	2.000	2.000	4.500
284	.092	62.2	4.000	2.000	2.000	4.563
285	.083	56.3	4.000	2.000	2.000	9.000
286	.088	59.7	4.000	2.000	4.500	.000
287	.095	64.6	4.000	2.000	4.500	2.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
288	.064	43.3	4.000	2.000	4.500	4.500
289	.058	39.2	4.000	2.000	4.500	4.563
290	.049	33.3	4.000	2.000	4.500	9.000
291	.085	57.4	4.000	2.000	4.563	.000
292	.092	62.2	4.000	2.000	4.563	2.000
293	.058	39.2	4.000	2.000	4.563	4.500
294	.057	38.6	4.000	2.000	4.563	4.563
295	.046	31.0	4.000	2.000	4.563	9.000
296	.076	51.5	4.000	2.000	9.000	.000
297	.083	56.3	4.000	2.000	9.000	2.000
298	.049	33.3	4.000	2.000	9.000	4.500
299	.046	31.0	4.000	2.000	9.000	4.563
300	.040	26.8	4.000	2.000	9.000	9.000
301	.086	58.4	4.000	4.500	.000	.000
302	.088	59.7	4.000	4.500	.000	2.000
303	.059	40.3	4.000	4.500	.000	4.500
304	.053	36.1	4.000	4.500	.000	4.563
305	.045	30.2	4.000	4.500	.000	9.000
306	.088	59.7	4.000	4.500	2.000	.000
307	.095	64.6	4.000	4.500	2.000	2.000
308	.064	43.3	4.000	4.500	2.000	4.500
309	.058	39.2	4.000	4.500	2.000	4.563
310	.049	33.3	4.000	4.500	2.000	9.000
311	.059	40.3	4.000	4.500	4.500	.000
312	.064	43.3	4.000	4.500	4.500	2.000
313	.037	24.8	4.000	4.500	4.500	4.500
314	.000	.0	4.000	4.500	4.500	4.563
315	.000	.0	4.000	4.500	4.500	9.000
316	.053	36.1	4.000	4.500	4.563	.000
317	.058	39.2	4.000	4.500	4.563	2.000
318	.000	.0	4.000	4.500	4.563	4.500
319	.000	.0	4.000	4.500	4.563	4.563
320	.000	.0	4.000	4.500	4.563	9.000
321	.045	30.2	4.000	4.500	9.000	.000
322	.049	33.3	4.000	4.500	9.000	2.000
323	.000	.0	4.000	4.500	9.000	4.500
324	.000	.0	4.000	4.500	9.000	4.563
325	.000	.0	4.000	4.500	9.000	9.000
326	.083	56.1	4.000	4.563	.000	.000
327	.085	57.4	4.000	4.563	.000	2.000
328	.053	36.1	4.000	4.563	.000	4.500
329	.053	35.5	4.000	4.563	.000	4.563
330	.041	27.9	4.000	4.563	.000	9.000
331	.085	57.4	4.000	4.563	2.000	.000
332	.092	62.2	4.000	4.563	2.000	2.000
333	.058	39.2	4.000	4.563	2.000	4.500
334	.057	38.6	4.000	4.563	2.000	4.563
335	.046	31.0	4.000	4.563	2.000	9.000
336	.053	36.1	4.000	4.563	4.500	.000
337	.058	39.2	4.000	4.563	4.500	2.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
338	.000	.0	4.000	4.563	4.500	4.500
339	.000	.0	4.000	4.563	4.500	4.563
340	.000	.0	4.000	4.563	4.500	9.000
341	.053	35.5	4.000	4.563	4.563	.000
342	.057	38.6	4.000	4.563	4.563	2.000
343	.000	.0	4.000	4.563	4.563	4.500
344	.000	.0	4.000	4.563	4.563	4.563
345	.000	.0	4.000	4.563	4.563	9.000
346	.041	27.9	4.000	4.563	9.000	.000
347	.046	31.0	4.000	4.563	9.000	2.000
348	.000	.0	4.000	4.563	9.000	4.500
349	.000	.0	4.000	4.563	9.000	4.563
350	.000	.0	4.000	4.563	9.000	9.000
351	.074	50.2	4.000	9.000	.000	.000
352	.076	51.5	4.000	9.000	.000	2.000
353	.045	30.2	4.000	9.000	.000	4.500
354	.041	27.9	4.000	9.000	.000	4.563
355	.000	.0	4.000	9.000	.000	9.000
356	.076	51.5	4.000	9.000	2.000	.000
357	.083	56.3	4.000	9.000	2.000	2.000
358	.049	33.3	4.000	9.000	2.000	4.500
359	.046	31.0	4.000	9.000	2.000	4.563
360	.040	26.8	4.000	9.000	2.000	9.000
361	.045	30.2	4.000	9.000	4.500	.000
362	.049	33.3	4.000	9.000	4.500	2.000
363	.000	.0	4.000	9.000	4.500	4.500
364	.000	.0	4.000	9.000	4.500	4.563
365	.000	.0	4.000	9.000	4.500	9.000
366	.041	27.9	4.000	9.000	4.563	.000
367	.046	31.0	4.000	9.000	4.563	2.000
368	.000	.0	4.000	9.000	4.563	4.500
369	.000	.0	4.000	9.000	4.563	4.563
370	.000	.0	4.000	9.000	4.563	9.000
371	.000	.0	4.000	9.000	9.000	.000
372	.040	26.8	4.000	9.000	9.000	2.000
373	.000	.0	4.000	9.000	9.000	4.500
374	.000	.0	4.000	9.000	9.000	4.563
375	.000	.0	4.000	9.000	9.000	9.000
376	.048	32.7	5.750	.000	.000	.000
377	.046	31.2	5.750	.000	.000	.500
378	.000	.0	5.750	.000	.000	.563
379	.000	.0	5.750	.000	.000	5.000
380	.000	.0	5.750	.000	.000	9.000
381	.046	31.2	5.750	.000	.500	.000
382	.000	.0	5.750	.000	.500	.500
383	.000	.0	5.750	.000	.500	.563
384	.000	.0	5.750	.000	.500	5.000
385	.000	.0	5.750	.000	.500	9.000
386	.000	.0	5.750	.000	.563	.000
387	.000	.0	5.750	.000	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
388	.000	.0	5.750	.000	.563	.563
389	.000	.0	5.750	.000	.563	5.000
390	.000	.0	5.750	.000	.563	9.000
391	.000	.0	5.750	.000	5.000	.000
392	.000	.0	5.750	.000	5.000	.500
393	.000	.0	5.750	.000	5.000	.563
394	.000	.0	5.750	.000	5.000	5.000
395	.000	.0	5.750	.000	5.000	9.000
396	.000	.0	5.750	.000	9.000	.000
397	.000	.0	5.750	.000	9.000	.500
398	.000	.0	5.750	.000	9.000	.563
399	.000	.0	5.750	.000	9.000	5.000
400	.000	.0	5.750	.000	9.000	9.000
401	.046	31.2	5.750	.500	.000	.000
402	.000	.0	5.750	.500	.000	.500
403	.000	.0	5.750	.500	.000	.563
404	.000	.0	5.750	.500	.000	5.000
405	.000	.0	5.750	.500	.000	9.000
406	.000	.0	5.750	.500	.500	.000
407	.046	31.0	5.750	.500	.500	.500
408	.000	.0	5.750	.500	.500	.563
409	.000	.0	5.750	.500	.500	5.000
410	.000	.0	5.750	.500	.500	9.000
411	.000	.0	5.750	.500	.563	.000
412	.000	.0	5.750	.500	.563	.500
413	.000	.0	5.750	.500	.563	.563
414	.000	.0	5.750	.500	.563	5.000
415	.000	.0	5.750	.500	.563	9.000
416	.000	.0	5.750	.500	5.000	.000
417	.000	.0	5.750	.500	5.000	.500
418	.000	.0	5.750	.500	5.000	.563
419	.000	.0	5.750	.500	5.000	5.000
420	.000	.0	5.750	.500	5.000	9.000
421	.000	.0	5.750	.500	9.000	.000
422	.000	.0	5.750	.500	9.000	.500
423	.000	.0	5.750	.500	9.000	.563
424	.000	.0	5.750	.500	9.000	5.000
425	.000	.0	5.750	.500	9.000	9.000
426	.000	.0	5.750	.563	.000	.000
427	.000	.0	5.750	.563	.000	.500
428	.000	.0	5.750	.563	.000	.563
429	.000	.0	5.750	.563	.000	5.000
430	.000	.0	5.750	.563	.000	9.000
431	.000	.0	5.750	.563	.500	.000
432	.000	.0	5.750	.563	.500	.500
433	.000	.0	5.750	.563	.500	.563
434	.000	.0	5.750	.563	.500	5.000
435	.000	.0	5.750	.563	.500	9.000
436	.000	.0	5.750	.563	.563	.000
437	.000	.0	5.750	.563	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
438	.000	.0	5.750	.563	.563	.563
439	.000	.0	5.750	.563	.563	5.000
440	.000	.0	5.750	.563	.563	9.000
441	.000	.0	5.750	.563	5.000	.000
442	.000	.0	5.750	.563	5.000	.500
443	.000	.0	5.750	.563	5.000	.563
444	.000	.0	5.750	.563	5.000	5.000
445	.000	.0	5.750	.563	5.000	9.000
446	.000	.0	5.750	.563	9.000	.000
447	.000	.0	5.750	.563	9.000	.500
448	.000	.0	5.750	.563	9.000	.563
449	.000	.0	5.750	.563	9.000	5.000
450	.000	.0	5.750	.563	9.000	9.000
451	.000	.0	5.750	5.000	.000	.000
452	.000	.0	5.750	5.000	.000	.500
453	.000	.0	5.750	5.000	.000	.563
454	.000	.0	5.750	5.000	.000	5.000
455	.000	.0	5.750	5.000	.000	9.000
456	.000	.0	5.750	5.000	.500	.000
457	.000	.0	5.750	5.000	.500	.500
458	.000	.0	5.750	5.000	.500	.563
459	.000	.0	5.750	5.000	.500	5.000
460	.000	.0	5.750	5.000	.500	9.000
461	.000	.0	5.750	5.000	.563	.000
462	.000	.0	5.750	5.000	.563	.500
463	.000	.0	5.750	5.000	.563	.563
464	.000	.0	5.750	5.000	.563	5.000
465	.000	.0	5.750	5.000	.563	9.000
466	.000	.0	5.750	5.000	5.000	.000
467	.000	.0	5.750	5.000	5.000	.500
468	.000	.0	5.750	5.000	5.000	.563
469	.000	.0	5.750	5.000	5.000	5.000
470	.000	.0	5.750	5.000	5.000	9.000
471	.000	.0	5.750	5.000	9.000	.000
472	.000	.0	5.750	5.000	9.000	.500
473	.000	.0	5.750	5.000	9.000	.563
474	.000	.0	5.750	5.000	9.000	5.000
475	.000	.0	5.750	5.000	9.000	9.000
476	.000	.0	5.750	9.000	.000	.000
477	.000	.0	5.750	9.000	.000	.500
478	.000	.0	5.750	9.000	.000	.563
479	.000	.0	5.750	9.000	.000	5.000
480	.000	.0	5.750	9.000	.000	9.000
481	.000	.0	5.750	9.000	.500	.000
482	.000	.0	5.750	9.000	.500	.500
483	.000	.0	5.750	9.000	.500	.563
484	.000	.0	5.750	9.000	.500	5.000
485	.000	.0	5.750	9.000	.500	9.000
486	.000	.0	5.750	9.000	.563	.000
487	.000	.0	5.750	9.000	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
488	.000	.0	5.750	9.000	.563	.563
489	.000	.0	5.750	9.000	.563	5.000
490	.000	.0	5.750	9.000	.563	9.000
491	.000	.0	5.750	9.000	5.000	.000
492	.000	.0	5.750	9.000	5.000	.500
493	.000	.0	5.750	9.000	5.000	.563
494	.000	.0	5.750	9.000	5.000	5.000
495	.000	.0	5.750	9.000	5.000	9.000
496	.000	.0	5.750	9.000	9.000	.000
497	.000	.0	5.750	9.000	9.000	.500
498	.000	.0	5.750	9.000	9.000	.563
499	.000	.0	5.750	9.000	9.000	5.000
500	.000	.0	5.750	9.000	9.000	9.000
501	.000	.0	5.813	*****	*****	*****
502	.000	.0	8.250	*****	*****	*****

TABLE B-2

Fixed Parameters:

H (in)	d (in)	Q (CFM)	PA (KW)	LI (deg)
13.125	3.500	219.4	.339	84.0

Hydroturbine data:

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
1	.090	26.6	.000	.000	.000	.000
2	.087	25.8	.000	.000	.000	4.500
3	.086	25.2	.000	.000	.000	4.625
4	.000	.0	.000	.000	.000	4.688
5	.000	.0	.000	.000	.000	9.000
6	.087	25.8	.000	.000	4.500	.000
7	.087	25.8	.000	.000	4.500	4.500
8	.000	.0	.000	.000	4.500	4.625
9	.000	.0	.000	.000	4.500	4.688
10	.000	.0	.000	.000	4.500	9.000
11	.086	25.2	.000	.000	4.625	.000
12	.000	.0	.000	.000	4.625	4.500
13	.000	.0	.000	.000	4.625	4.625
14	.000	.0	.000	.000	4.625	4.688
15	.000	.0	.000	.000	4.625	9.000
16	.000	.0	.000	.000	4.688	.000
17	.000	.0	.000	.000	4.688	4.500
18	.000	.0	.000	.000	4.688	4.625
19	.000	.0	.000	.000	4.688	4.688
20	.000	.0	.000	.000	4.688	9.000
21	.000	.0	.000	.000	9.000	.000
22	.000	.0	.000	.000	9.000	4.500
23	.000	.0	.000	.000	9.000	4.625
24	.000	.0	.000	.000	9.000	4.688
25	.000	.0	.000	.000	9.000	9.000
26	.087	25.8	.000	4.500	.000	.000
27	.087	25.8	.000	4.500	.000	4.500
28	.000	.0	.000	4.500	.000	4.625
29	.000	.0	.000	4.500	.000	4.688
30	.000	.0	.000	4.500	.000	9.000
31	.087	25.8	.000	4.500	4.500	.000
32	.090	26.6	.000	4.500	4.500	4.500
33	.086	25.2	.000	4.500	4.500	4.625
34	.000	.0	.000	4.500	4.500	4.688
35	.000	.0	.000	4.500	4.500	9.000
36	.000	.0	.000	4.500	4.625	.000
37	.086	25.2	.000	4.500	4.625	4.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
38	.000	.0	.000	4.500	4.625	4.625
39	.000	.0	.000	4.500	4.625	4.688
40	.000	.0	.000	4.500	4.625	9.000
41	.000	.0	.000	4.500	4.688	.000
42	.000	.0	.000	4.500	4.688	4.500
43	.000	.0	.000	4.500	4.688	4.625
44	.000	.0	.000	4.500	4.688	4.688
45	.000	.0	.000	4.500	4.688	9.000
46	.000	.0	.000	4.500	9.000	.000
47	.000	.0	.000	4.500	9.000	4.500
48	.000	.0	.000	4.500	9.000	4.625
49	.000	.0	.000	4.500	9.000	4.688
50	.000	.0	.000	4.500	9.000	9.000
51	.086	25.2	.000	4.625	.000	.000
52	.000	.0	.000	4.625	.000	4.500
53	.000	.0	.000	4.625	.000	4.625
54	.000	.0	.000	4.625	.000	4.688
55	.000	.0	.000	4.625	.000	9.000
56	.000	.0	.000	4.625	4.500	.000
57	.086	25.2	.000	4.625	4.500	4.500
58	.000	.0	.000	4.625	4.500	4.625
59	.000	.0	.000	4.625	4.500	4.688
60	.000	.0	.000	4.625	4.500	9.000
61	.000	.0	.000	4.625	4.625	.000
62	.000	.0	.000	4.625	4.625	4.500
63	.085	25.0	.000	4.625	4.625	4.625
64	.000	.0	.000	4.625	4.625	4.688
65	.000	.0	.000	4.625	4.625	9.000
66	.000	.0	.000	4.625	4.688	.000
67	.000	.0	.000	4.625	4.688	4.500
68	.000	.0	.000	4.625	4.688	4.625
69	.000	.0	.000	4.625	4.688	4.688
70	.000	.0	.000	4.625	4.688	9.000
71	.000	.0	.000	4.625	9.000	.000
72	.000	.0	.000	4.625	9.000	4.500
73	.000	.0	.000	4.625	9.000	4.625
74	.000	.0	.000	4.625	9.000	4.688
75	.000	.0	.000	4.625	9.000	9.000
76	.000	.0	.000	4.688	.000	.000
77	.000	.0	.000	4.688	.000	4.500
78	.000	.0	.000	4.688	.000	4.625
79	.000	.0	.000	4.688	.000	4.688
80	.000	.0	.000	4.688	.000	9.000
81	.000	.0	.000	4.688	4.500	.000
82	.000	.0	.000	4.688	4.500	4.500
83	.000	.0	.000	4.688	4.500	4.625
84	.000	.0	.000	4.688	4.500	4.688
85	.000	.0	.000	4.688	4.500	9.000
86	.000	.0	.000	4.688	4.625	.000
87	.000	.0	.000	4.688	4.625	4.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
88	.000	.0	.000	4.688	4.625	4.625
89	.000	.0	.000	4.688	4.625	4.688
90	.000	.0	.000	4.688	4.625	9.000
91	.000	.0	.000	4.688	4.688	.000
92	.000	.0	.000	4.688	4.688	4.500
93	.000	.0	.000	4.688	4.688	4.625
94	.000	.0	.000	4.688	4.688	4.688
95	.000	.0	.000	4.688	4.688	9.000
96	.000	.0	.000	4.688	9.000	.000
97	.000	.0	.000	4.688	9.000	4.500
98	.000	.0	.000	4.688	9.000	4.625
99	.000	.0	.000	4.688	9.000	4.688
100	.000	.0	.000	4.688	9.000	9.000
101	.000	.0	.000	9.000	.000	.000
102	.000	.0	.000	9.000	.000	4.500
103	.000	.0	.000	9.000	.000	4.625
104	.000	.0	.000	9.000	.000	4.688
105	.000	.0	.000	9.000	.000	9.000
106	.000	.0	.000	9.000	4.500	.000
107	.000	.0	.000	9.000	4.500	4.500
108	.000	.0	.000	9.000	4.500	4.625
109	.000	.0	.000	9.000	4.500	4.688
110	.000	.0	.000	9.000	4.500	9.000
111	.000	.0	.000	9.000	4.625	.000
112	.000	.0	.000	9.000	4.625	4.500
113	.000	.0	.000	9.000	4.625	4.625
114	.000	.0	.000	9.000	4.625	4.688
115	.000	.0	.000	9.000	4.625	9.000
116	.000	.0	.000	9.000	4.688	.000
117	.000	.0	.000	9.000	4.688	4.500
118	.000	.0	.000	9.000	4.688	4.625
119	.000	.0	.000	9.000	4.688	4.688
120	.000	.0	.000	9.000	4.688	9.000
121	.000	.0	.000	9.000	9.000	.000
122	.000	.0	.000	9.000	9.000	4.500
123	.000	.0	.000	9.000	9.000	4.625
124	.000	.0	.000	9.000	9.000	4.688
125	.000	.0	.000	9.000	9.000	9.000
126	.090	26.6	2.000	.000	.000	.000
127	.090	26.7	2.000	.000	.000	2.500
128	.085	25.1	2.000	.000	.000	4.250
129	.000	.0	2.000	.000	.000	4.313
130	.000	.0	2.000	.000	.000	9.000
131	.090	26.7	2.000	.000	2.500	.000
132	.094	27.6	2.000	.000	2.500	2.500
133	.086	25.5	2.000	.000	2.500	4.250
134	.000	.0	2.000	.000	2.500	4.313
135	.000	.0	2.000	.000	2.500	9.000
136	.085	25.1	2.000	.000	4.250	.000
137	.086	25.5	2.000	.000	4.250	2.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
138	.000	.0	2.000	.000	4.250	4.250
139	.000	.0	2.000	.000	4.250	4.313
140	.000	.0	2.000	.000	4.250	9.000
141	.000	.0	2.000	.000	4.313	.000
142	.000	.0	2.000	.000	4.313	2.500
143	.000	.0	2.000	.000	4.313	4.250
144	.000	.0	2.000	.000	4.313	4.313
145	.000	.0	2.000	.000	4.313	9.000
146	.000	.0	2.000	.000	9.000	.000
147	.000	.0	2.000	.000	9.000	2.500
148	.000	.0	2.000	.000	9.000	4.250
149	.000	.0	2.000	.000	9.000	4.313
150	.000	.0	2.000	.000	9.000	9.000
151	.090	26.7	2.000	2.500	.000	.000
152	.094	27.6	2.000	2.500	.000	2.500
153	.086	25.5	2.000	2.500	.000	4.250
154	.000	.0	2.000	2.500	.000	4.313
155	.000	.0	2.000	2.500	.000	9.000
156	.094	27.6	2.000	2.500	2.500	.000
157	.100	29.5	2.000	2.500	2.500	2.500
158	.092	27.1	2.000	2.500	2.500	4.250
159	.090	26.5	2.000	2.500	2.500	4.313
160	.000	.0	2.000	2.500	2.500	9.000
161	.086	25.5	2.000	2.500	4.250	.000
162	.092	27.1	2.000	2.500	4.250	2.500
163	.087	25.5	2.000	2.500	4.250	4.250
164	.000	.0	2.000	2.500	4.250	4.313
165	.000	.0	2.000	2.500	4.250	9.000
166	.000	.0	2.000	2.500	4.313	.000
167	.090	26.5	2.000	2.500	4.313	2.500
168	.000	.0	2.000	2.500	4.313	4.250
169	.000	.0	2.000	2.500	4.313	4.313
170	.000	.0	2.000	2.500	4.313	9.000
171	.000	.0	2.000	2.500	9.000	.000
172	.000	.0	2.000	2.500	9.000	2.500
173	.000	.0	2.000	2.500	9.000	4.250
174	.000	.0	2.000	2.500	9.000	4.313
175	.000	.0	2.000	2.500	9.000	9.000
176	.085	25.1	2.000	4.250	.000	.000
177	.086	25.5	2.000	4.250	.000	2.500
178	.000	.0	2.000	4.250	.000	4.250
179	.000	.0	2.000	4.250	.000	4.313
180	.000	.0	2.000	4.250	.000	9.000
181	.086	25.5	2.000	4.250	2.500	.000
182	.092	27.1	2.000	4.250	2.500	2.500
183	.087	25.5	2.000	4.250	2.500	4.250
184	.000	.0	2.000	4.250	2.500	4.313
185	.000	.0	2.000	4.250	2.500	9.000
186	.000	.0	2.000	4.250	4.250	.000
187	.087	25.5	2.000	4.250	4.250	2.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
188	.084	24.9	2.000	4.250	4.250	4.250
189	.000	.0	2.000	4.250	4.250	4.313
190	.000	.0	2.000	4.250	4.250	9.000
191	.000	.0	2.000	4.250	4.313	.000
192	.000	.0	2.000	4.250	4.313	2.500
193	.000	.0	2.000	4.250	4.313	4.250
194	.000	.0	2.000	4.250	4.313	4.313
195	.000	.0	2.000	4.250	4.313	9.000
196	.000	.0	2.000	4.250	9.000	.000
197	.000	.0	2.000	4.250	9.000	2.500
198	.000	.0	2.000	4.250	9.000	4.250
199	.000	.0	2.000	4.250	9.000	4.313
200	.000	.0	2.000	4.250	9.000	9.000
201	.000	.0	2.000	4.313	.000	.000
202	.000	.0	2.000	4.313	.000	2.500
203	.000	.0	2.000	4.313	.000	4.250
204	.000	.0	2.000	4.313	.000	4.313
205	.000	.0	2.000	4.313	.000	9.000
206	.000	.0	2.000	4.313	2.500	.000
207	.090	26.5	2.000	4.313	2.500	2.500
208	.000	.0	2.000	4.313	2.500	4.250
209	.000	.0	2.000	4.313	2.500	4.313
210	.000	.0	2.000	4.313	2.500	9.000
211	.000	.0	2.000	4.313	4.250	.000
212	.000	.0	2.000	4.313	4.250	2.500
213	.000	.0	2.000	4.313	4.250	4.250
214	.000	.0	2.000	4.313	4.250	4.313
215	.000	.0	2.000	4.313	4.250	9.000
216	.000	.0	2.000	4.313	4.313	.000
217	.000	.0	2.000	4.313	4.313	2.500
218	.000	.0	2.000	4.313	4.313	4.250
219	.000	.0	2.000	4.313	4.313	4.313
220	.000	.0	2.000	4.313	4.313	9.000
221	.000	.0	2.000	4.313	9.000	.000
222	.000	.0	2.000	4.313	9.000	2.500
223	.000	.0	2.000	4.313	9.000	4.250
224	.000	.0	2.000	4.313	9.000	4.313
225	.000	.0	2.000	4.313	9.000	9.000
226	.000	.0	2.000	9.000	.000	.000
227	.000	.0	2.000	9.000	.000	2.500
228	.000	.0	2.000	9.000	.000	4.250
229	.000	.0	2.000	9.000	.000	4.313
230	.000	.0	2.000	9.000	.000	9.000
231	.000	.0	2.000	9.000	2.500	.000
232	.000	.0	2.000	9.000	2.500	2.500
233	.000	.0	2.000	9.000	2.500	4.250
234	.000	.0	2.000	9.000	2.500	4.313
235	.000	.0	2.000	9.000	2.500	9.000
236	.000	.0	2.000	9.000	4.250	.000
237	.000	.0	2.000	9.000	4.250	2.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
238	.000	.0	2.000	9.000	4.250	4.250
239	.000	.0	2.000	9.000	4.250	4.313
240	.000	.0	2.000	9.000	4.250	9.000
241	.000	.0	2.000	9.000	4.313	.000
242	.000	.0	2.000	9.000	4.313	2.500
243	.000	.0	2.000	9.000	4.313	4.250
244	.000	.0	2.000	9.000	4.313	4.313
245	.000	.0	2.000	9.000	4.313	9.000
246	.000	.0	2.000	9.000	9.000	.000
247	.000	.0	2.000	9.000	9.000	2.500
248	.000	.0	2.000	9.000	9.000	4.250
249	.000	.0	2.000	9.000	9.000	4.313
250	.000	.0	2.000	9.000	9.000	9.000
251	.203	60.0	2.813	.000	.000	.000
252	.199	58.8	2.813	.000	.000	2.000
253	.151	44.5	2.813	.000	.000	4.000
254	.143	42.1	2.813	.000	.000	4.063
255	.129	38.1	2.813	.000	.000	9.000
256	.199	58.8	2.813	.000	2.000	.000
257	.201	59.4	2.813	.000	2.000	2.000
258	.149	44.0	2.813	.000	2.000	4.000
259	.141	41.5	2.813	.000	2.000	4.063
260	.127	37.6	2.813	.000	2.000	9.000
261	.151	44.5	2.813	.000	4.000	.000
262	.149	44.0	2.813	.000	4.000	2.000
263	.105	30.9	2.813	.000	4.000	4.000
264	.092	27.2	2.813	.000	4.000	4.063
265	.079	23.3	2.813	.000	4.000	9.000
266	.143	42.1	2.813	.000	4.063	.000
267	.141	41.5	2.813	.000	4.063	2.000
268	.092	27.2	2.813	.000	4.063	4.000
269	.088	26.0	2.813	.000	4.063	4.063
270	.071	20.8	2.813	.000	4.063	9.000
271	.129	38.1	2.813	.000	9.000	.000
272	.127	37.6	2.813	.000	9.000	2.000
273	.079	23.3	2.813	.000	9.000	4.000
274	.071	20.8	2.813	.000	9.000	4.063
275	.000	.0	2.813	.000	9.000	9.000
276	.199	58.8	2.813	2.000	.000	.000
277	.201	59.4	2.813	2.000	.000	2.000
278	.149	44.0	2.813	2.000	.000	4.000
279	.141	41.5	2.813	2.000	.000	4.063
280	.127	37.6	2.813	2.000	.000	9.000
281	.201	59.4	2.813	2.000	2.000	.000
282	.210	62.0	2.813	2.000	2.000	2.000
283	.155	45.9	2.813	2.000	2.000	4.000
284	.147	43.4	2.813	2.000	2.000	4.063
285	.134	39.5	2.813	2.000	2.000	9.000
286	.149	44.0	2.813	2.000	4.000	.000
287	.155	45.9	2.813	2.000	4.000	2.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
288	.107	31.6	2.813	2.000	4.000	4.000
289	.095	27.9	2.813	2.000	4.000	4.063
290	.081	24.0	2.813	2.000	4.000	9.000
291	.141	41.5	2.813	2.000	4.063	.000
292	.147	43.4	2.813	2.000	4.063	2.000
293	.095	27.9	2.813	2.000	4.063	4.000
294	.090	26.6	2.813	2.000	4.063	4.063
295	.073	21.5	2.813	2.000	4.063	9.000
296	.127	37.6	2.813	2.000	9.000	.000
297	.134	39.5	2.813	2.000	9.000	2.000
298	.081	24.0	2.813	2.000	9.000	4.000
299	.073	21.5	2.813	2.000	9.000	4.063
300	.000	.0	2.813	2.000	9.000	9.000
301	.151	44.5	2.813	4.000	.000	.000
302	.149	44.0	2.813	4.000	.000	2.000
303	.105	30.9	2.813	4.000	.000	4.000
304	.092	27.2	2.813	4.000	.000	4.063
305	.079	23.3	2.813	4.000	.000	9.000
306	.149	44.0	2.813	4.000	2.000	.000
307	.155	45.9	2.813	4.000	2.000	2.000
308	.107	31.6	2.813	4.000	2.000	4.000
309	.095	27.9	2.813	4.000	2.000	4.063
310	.081	24.0	2.813	4.000	2.000	9.000
311	.105	30.9	2.813	4.000	4.000	.000
312	.107	31.6	2.813	4.000	4.000	2.000
313	.065	19.2	2.813	4.000	4.000	4.000
314	.000	.0	2.813	4.000	4.000	4.063
315	.000	.0	2.813	4.000	4.000	9.000
316	.092	27.2	2.813	4.000	4.063	.000
317	.095	27.9	2.813	4.000	4.063	2.000
318	.000	.0	2.813	4.000	4.063	4.000
319	.000	.0	2.813	4.000	4.063	4.063
320	.000	.0	2.813	4.000	4.063	9.000
321	.079	23.3	2.813	4.000	9.000	.000
322	.081	24.0	2.813	4.000	9.000	2.000
323	.000	.0	2.813	4.000	9.000	4.000
324	.000	.0	2.813	4.000	9.000	4.063
325	.000	.0	2.813	4.000	9.000	9.000
326	.143	42.1	2.813	4.063	.000	.000
327	.141	41.5	2.813	4.063	.000	2.000
328	.092	27.2	2.813	4.063	.000	4.000
329	.088	26.0	2.813	4.063	.000	4.063
330	.071	20.8	2.813	4.063	.000	9.000
331	.141	41.5	2.813	4.063	2.000	.000
332	.147	43.4	2.813	4.063	2.000	2.000
333	.095	27.9	2.813	4.063	2.000	4.000
334	.090	26.6	2.813	4.063	2.000	4.063
335	.073	21.5	2.813	4.063	2.000	9.000
336	.092	27.2	2.813	4.063	4.000	.000
337	.095	27.9	2.813	4.063	4.000	2.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
338	.000	.0	2.813	4.063	4.000	4.000
339	.000	.0	2.813	4.063	4.000	4.063
340	.000	.0	2.813	4.063	4.000	9.000
341	.088	26.0	2.813	4.063	4.063	.000
342	.090	26.6	2.813	4.063	4.063	2.000
343	.000	.0	2.813	4.063	4.063	4.000
344	.000	.0	2.813	4.063	4.063	4.063
345	.000	.0	2.813	4.063	4.063	9.000
346	.071	20.8	2.813	4.063	9.000	.000
347	.073	21.5	2.813	4.063	9.000	2.000
348	.000	.0	2.813	4.063	9.000	4.000
349	.000	.0	2.813	4.063	9.000	4.063
350	.000	.0	2.813	4.063	9.000	9.000
351	.129	38.1	2.813	9.000	.000	.000
352	.127	37.6	2.813	9.000	.000	2.000
353	.079	23.3	2.813	9.000	.000	4.000
354	.071	20.8	2.813	9.000	.000	4.063
355	.000	.0	2.813	9.000	.000	9.000
356	.127	37.6	2.813	9.000	2.000	.000
357	.134	39.5	2.813	9.000	2.000	2.000
358	.081	24.0	2.813	9.000	2.000	4.000
359	.073	21.5	2.813	9.000	2.000	4.063
360	.000	.0	2.813	9.000	2.000	9.000
361	.079	23.3	2.813	9.000	4.000	.000
362	.081	24.0	2.813	9.000	4.000	2.000
363	.000	.0	2.813	9.000	4.000	4.000
364	.000	.0	2.813	9.000	4.000	4.063
365	.000	.0	2.813	9.000	4.000	9.000
366	.071	20.8	2.813	9.000	4.063	.000
367	.073	21.5	2.813	9.000	4.063	2.000
368	.000	.0	2.813	9.000	4.063	4.000
369	.000	.0	2.813	9.000	4.063	4.063
370	.000	.0	2.813	9.000	4.063	9.000
371	.000	.0	2.813	9.000	9.000	.000
372	.000	.0	2.813	9.000	9.000	2.000
373	.000	.0	2.813	9.000	9.000	4.000
374	.000	.0	2.813	9.000	9.000	4.063
375	.000	.0	2.813	9.000	9.000	9.000
376	.110	32.5	5.875	.000	.000	.000
377	.104	30.7	5.875	.000	.000	.500
378	.102	30.2	5.875	.000	.000	.563
379	.000	.0	5.875	.000	.000	5.000
380	.000	.0	5.875	.000	.000	9.000
381	.104	30.7	5.875	.000	.500	.000
382	.000	.0	5.875	.000	.500	.500
383	.000	.0	5.875	.000	.500	.563
384	.000	.0	5.875	.000	.500	5.000
385	.000	.0	5.875	.000	.500	9.000
386	.102	30.2	5.875	.000	.563	.000
387	.000	.0	5.875	.000	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
388	.000	.0	5.875	.000	.563	.563
389	.000	.0	5.875	.000	.563	5.000
390	.000	.0	5.875	.000	.563	9.000
391	.000	.0	5.875	.000	5.000	.000
392	.000	.0	5.875	.000	5.000	.500
393	.000	.0	5.875	.000	5.000	.563
394	.000	.0	5.875	.000	5.000	5.000
395	.000	.0	5.875	.000	5.000	9.000
396	.000	.0	5.875	.000	9.000	.000
397	.000	.0	5.875	.000	9.000	.500
398	.000	.0	5.875	.000	9.000	.563
399	.000	.0	5.875	.000	9.000	5.000
400	.000	.0	5.875	.000	9.000	9.000
401	.104	30.7	5.875	.500	.000	.000
402	.000	.0	5.875	.500	.000	.500
403	.000	.0	5.875	.500	.000	.563
404	.000	.0	5.875	.500	.000	5.000
405	.000	.0	5.875	.500	.000	9.000
406	.000	.0	5.875	.500	.500	.000
407	.102	30.2	5.875	.500	.500	.500
408	.000	.0	5.875	.500	.500	.563
409	.000	.0	5.875	.500	.500	5.000
410	.000	.0	5.875	.500	.500	9.000
411	.000	.0	5.875	.500	.563	.000
412	.000	.0	5.875	.500	.563	.500
413	.000	.0	5.875	.500	.563	.563
414	.000	.0	5.875	.500	.563	5.000
415	.000	.0	5.875	.500	.563	9.000
416	.000	.0	5.875	.500	5.000	.000
417	.000	.0	5.875	.500	5.000	.500
418	.000	.0	5.875	.500	5.000	.563
419	.000	.0	5.875	.500	5.000	5.000
420	.000	.0	5.875	.500	5.000	9.000
421	.000	.0	5.875	.500	9.000	.000
422	.000	.0	5.875	.500	9.000	.500
423	.000	.0	5.875	.500	9.000	.563
424	.000	.0	5.875	.500	9.000	5.000
425	.000	.0	5.875	.500	9.000	9.000
426	.102	30.2	5.875	.563	.000	.000
427	.000	.0	5.875	.563	.000	.500
428	.000	.0	5.875	.563	.000	.563
429	.000	.0	5.875	.563	.000	5.000
430	.000	.0	5.875	.563	.000	9.000
431	.000	.0	5.875	.563	.500	.000
432	.000	.0	5.875	.563	.500	.500
433	.000	.0	5.875	.563	.500	.563
434	.000	.0	5.875	.563	.500	5.000
435	.000	.0	5.875	.563	.500	9.000
436	.000	.0	5.875	.563	.563	.000
437	.000	.0	5.875	.563	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
438	.000	.0	5.875	.563	.563	.563
439	.000	.0	5.875	.563	.563	5.000
440	.000	.0	5.875	.563	.563	9.000
441	.000	.0	5.875	.563	5.000	.000
442	.000	.0	5.875	.563	5.000	.500
443	.000	.0	5.875	.563	5.000	.563
444	.000	.0	5.875	.563	5.000	5.000
445	.000	.0	5.875	.563	5.000	9.000
446	.000	.0	5.875	.563	9.000	.000
447	.000	.0	5.875	.563	9.000	.500
448	.000	.0	5.875	.563	9.000	.563
449	.000	.0	5.875	.563	9.000	5.000
450	.000	.0	5.875	.563	9.000	9.000
451	.000	.0	5.875	5.000	.000	.000
452	.000	.0	5.875	5.000	.000	.500
453	.000	.0	5.875	5.000	.000	.563
454	.000	.0	5.875	5.000	.000	5.000
455	.000	.0	5.875	5.000	.000	9.000
456	.000	.0	5.875	5.000	.500	.000
457	.000	.0	5.875	5.000	.500	.500
458	.000	.0	5.875	5.000	.500	.563
459	.000	.0	5.875	5.000	.500	5.000
460	.000	.0	5.875	5.000	.500	9.000
461	.000	.0	5.875	5.000	.563	.000
462	.000	.0	5.875	5.000	.563	.500
463	.000	.0	5.875	5.000	.563	.563
464	.000	.0	5.875	5.000	.563	5.000
465	.000	.0	5.875	5.000	.563	9.000
466	.000	.0	5.875	5.000	5.000	.000
467	.000	.0	5.875	5.000	5.000	.500
468	.000	.0	5.875	5.000	5.000	.563
469	.000	.0	5.875	5.000	5.000	5.000
470	.000	.0	5.875	5.000	5.000	9.000
471	.000	.0	5.875	5.000	9.000	.000
472	.000	.0	5.875	5.000	9.000	.500
473	.000	.0	5.875	5.000	9.000	.563
474	.000	.0	5.875	5.000	9.000	5.000
475	.000	.0	5.875	5.000	9.000	9.000
476	.000	.0	5.875	9.000	.000	.000
477	.000	.0	5.875	9.000	.000	.500
478	.000	.0	5.875	9.000	.000	.563
479	.000	.0	5.875	9.000	.000	5.000
480	.000	.0	5.875	9.000	.000	9.000
481	.000	.0	5.875	9.000	.500	.000
482	.000	.0	5.875	9.000	.500	.500
483	.000	.0	5.875	9.000	.500	.563
484	.000	.0	5.875	9.000	.500	5.000
485	.000	.0	5.875	9.000	.500	9.000
486	.000	.0	5.875	9.000	.563	.000
487	.000	.0	5.875	9.000	.563	.500

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
488	.000	.0	5.875	9.000	.563	.563
489	.000	.0	5.875	9.000	.563	5.000
490	.000	.0	5.875	9.000	.563	9.000
491	.000	.0	5.875	9.000	5.000	.000
492	.000	.0	5.875	9.000	5.000	.500
493	.000	.0	5.875	9.000	5.000	.563
494	.000	.0	5.875	9.000	5.000	5.000
495	.000	.0	5.875	9.000	5.000	9.000
496	.000	.0	5.875	9.000	9.000	.000
497	.000	.0	5.875	9.000	9.000	.500
498	.000	.0	5.875	9.000	9.000	.563
499	.000	.0	5.875	9.000	9.000	5.000
500	.000	.0	5.875	9.000	9.000	9.000
501	.000	.0	5.938	*****	*****	*****
502	.000	.0	8.250	*****	*****	*****

TABLE B-3

Fixed Parameters:

H (in)	d (in)	Q (CFM)	PA (KW)	LI (deg)
14.000	4.500	291.9	.481	80.0

Hydroturbine data:

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
1	.000	.0	.000	*****	*****	*****
2	.000	.0	1.125	*****	*****	*****
3	.277	57.6	2.125	.000	.000	.000
4	.271	56.4	2.125	.000	.000	1.875
5	.205	42.5	2.125	.000	.000	3.500
6	.195	40.6	2.125	.000	.000	3.563
7	.176	36.6	2.125	.000	.000	9.000
8	.271	56.4	2.125	.000	1.875	.000
9	.274	56.9	2.125	.000	1.875	1.875
10	.202	41.9	2.125	.000	1.875	3.500
11	.192	39.9	2.125	.000	1.875	3.563
12	.173	36.0	2.125	.000	1.875	9.000
13	.205	42.5	2.125	.000	3.500	.000
14	.202	41.9	2.125	.000	3.500	1.875
15	.141	29.3	2.125	.000	3.500	3.500
16	.126	26.1	2.125	.000	3.500	3.563
17	.107	22.2	2.125	.000	3.500	9.000
18	.195	40.6	2.125	.000	3.563	.000
19	.192	39.9	2.125	.000	3.563	1.875
20	.126	26.1	2.125	.000	3.563	3.500
21	.122	25.3	2.125	.000	3.563	3.563
22	.097	20.2	2.125	.000	3.563	9.000
23	.176	36.6	2.125	.000	9.000	.000
24	.173	36.0	2.125	.000	9.000	1.875
25	.107	22.2	2.125	.000	9.000	3.500
26	.097	20.2	2.125	.000	9.000	3.563
27	.000	.0	2.125	.000	9.000	9.000
28	.271	56.4	2.125	1.875	.000	.000
29	.274	56.9	2.125	1.875	.000	1.875
30	.202	41.9	2.125	1.875	.000	3.500
31	.192	39.9	2.125	1.875	.000	3.563
32	.173	36.0	2.125	1.875	.000	9.000
33	.274	56.9	2.125	1.875	1.875	.000
34	.285	59.2	2.125	1.875	1.875	1.875
35	.210	43.6	2.125	1.875	1.875	3.500
36	.200	41.7	2.125	1.875	1.875	3.563
37	.181	37.7	2.125	1.875	1.875	9.000

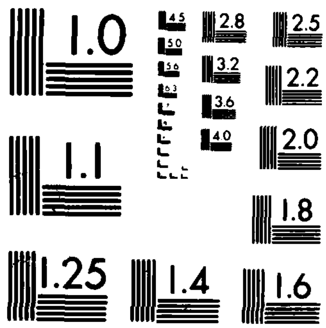
#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
38	.202	41.9	2.125	1.875	3.500	.000
39	.210	43.6	2.125	1.875	3.500	1.875
40	.143	29.8	2.125	1.875	3.500	3.500
41	.128	26.7	2.125	1.875	3.500	3.563
42	.109	22.7	2.125	1.875	3.500	9.000
43	.192	39.9	2.125	1.875	3.563	.000
44	.200	41.7	2.125	1.875	3.563	1.875
45	.128	26.7	2.125	1.875	3.563	3.500
46	.124	25.9	2.125	1.875	3.563	3.563
47	.100	20.7	2.125	1.875	3.563	9.000
48	.173	36.0	2.125	1.875	9.000	.000
49	.181	37.7	2.125	1.875	9.000	1.875
50	.109	22.7	2.125	1.875	9.000	3.500
51	.100	20.7	2.125	1.875	9.000	3.563
52	.086	18.0	2.125	1.875	9.000	9.000
53	.205	42.5	2.125	3.500	.000	.000
54	.202	41.9	2.125	3.500	.000	1.875
55	.141	29.3	2.125	3.500	.000	3.500
56	.126	26.1	2.125	3.500	.000	3.563
57	.107	22.2	2.125	3.500	.000	9.000
58	.202	41.9	2.125	3.500	1.875	.000
59	.210	43.6	2.125	3.500	1.875	1.875
60	.143	29.8	2.125	3.500	1.875	3.500
61	.128	26.7	2.125	3.500	1.875	3.563
62	.109	22.7	2.125	3.500	1.875	9.000
63	.141	29.3	2.125	3.500	3.500	.000
64	.143	29.8	2.125	3.500	3.500	1.875
65	.086	17.8	2.125	3.500	3.500	3.500
66	.000	.0	2.125	3.500	3.500	3.563
67	.000	.0	2.125	3.500	3.500	9.000
68	.126	26.1	2.125	3.500	3.563	.000
69	.128	26.7	2.125	3.500	3.563	1.875
70	.000	.0	2.125	3.500	3.563	3.500
71	.000	.0	2.125	3.500	3.563	3.563
72	.000	.0	2.125	3.500	3.563	9.000
73	.107	22.2	2.125	3.500	9.000	.000
74	.109	22.7	2.125	3.500	9.000	1.875
75	.000	.0	2.125	3.500	9.000	3.500
76	.000	.0	2.125	3.500	9.000	3.563
77	.000	.0	2.125	3.500	9.000	9.000
78	.195	40.6	2.125	3.563	.000	.000
79	.192	39.9	2.125	3.563	.000	1.875
80	.126	26.1	2.125	3.563	.000	3.500
81	.122	25.3	2.125	3.563	.000	3.563
82	.097	20.2	2.125	3.563	.000	9.000
83	.192	39.9	2.125	3.563	1.875	.000
84	.200	41.7	2.125	3.563	1.875	1.875
85	.128	26.7	2.125	3.563	1.875	3.500
86	.124	25.9	2.125	3.563	1.875	3.563
87	.100	20.7	2.125	3.563	1.875	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
88	.126	26.1	2.125	3.563	3.500	.000
89	.128	26.7	2.125	3.563	3.500	1.875
90	.000	.0	2.125	3.563	3.500	3.500
91	.000	.0	2.125	3.563	3.500	3.563
92	.000	.0	2.125	3.563	3.500	9.000
93	.122	25.3	2.125	3.563	3.563	.000
94	.124	25.9	2.125	3.563	3.563	1.875
95	.000	.0	2.125	3.563	3.563	3.500
96	.000	.0	2.125	3.563	3.563	3.563
97	.000	.0	2.125	3.563	3.563	9.000
98	.097	20.2	2.125	3.563	9.000	.000
99	.100	20.7	2.125	3.563	9.000	1.875
100	.000	.0	2.125	3.563	9.000	3.500
101	.000	.0	2.125	3.563	9.000	3.563
102	.000	.0	2.125	3.563	9.000	9.000
103	.176	36.6	2.125	9.000	.000	.000
104	.173	36.0	2.125	9.000	.000	1.875
105	.107	22.2	2.125	9.000	.000	3.500
106	.097	20.2	2.125	9.000	.000	3.563
107	.000	.0	2.125	9.000	.000	9.000
108	.173	36.0	2.125	9.000	1.875	.000
109	.181	37.7	2.125	9.000	1.875	1.875
110	.109	22.7	2.125	9.000	1.875	3.500
111	.100	20.7	2.125	9.000	1.875	3.563
112	.086	18.0	2.125	9.000	1.875	9.000
113	.107	22.2	2.125	9.000	3.500	.000
114	.109	22.7	2.125	9.000	3.500	1.875
115	.000	.0	2.125	9.000	3.500	3.500
116	.000	.0	2.125	9.000	3.500	3.563
117	.000	.0	2.125	9.000	3.500	9.000
118	.097	20.2	2.125	9.000	3.563	.000
119	.100	20.7	2.125	9.000	3.563	1.875
120	.000	.0	2.125	9.000	3.563	3.500
121	.000	.0	2.125	9.000	3.563	3.563
122	.000	.0	2.125	9.000	3.563	9.000
123	.000	.0	2.125	9.000	9.000	.000
124	.086	18.0	2.125	9.000	9.000	1.875
125	.000	.0	2.125	9.000	9.000	3.500
126	.000	.0	2.125	9.000	9.000	3.563
127	.000	.0	2.125	9.000	9.000	9.000
128	.205	42.6	3.125	.000	.000	.000
129	.201	41.8	3.125	.000	.000	1.625
130	.152	31.7	3.125	.000	.000	3.250
131	.144	29.9	3.125	.000	.000	3.313
132	.130	27.1	3.125	.000	.000	9.000
133	.201	41.8	3.125	.000	1.625	.000
134	.204	42.4	3.125	.000	1.625	1.625
135	.151	31.3	3.125	.000	1.625	3.250
136	.142	29.6	3.125	.000	1.625	3.313
137	.129	26.7	3.125	.000	1.625	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
138	.152	31.7	3.125	.000	3.250	.000
139	.151	31.3	3.125	.000	3.250	1.625
140	.106	22.0	3.125	.000	3.250	3.250
141	.093	19.4	3.125	.000	3.250	3.313
142	.080	16.6	3.125	.000	3.250	9.000
143	.144	29.9	3.125	.000	3.313	.000
144	.142	29.6	3.125	.000	3.313	1.625
145	.093	19.4	3.125	.000	3.313	3.250
146	.089	18.5	3.125	.000	3.313	3.313
147	.071	14.8	3.125	.000	3.313	9.000
148	.130	27.1	3.125	.000	9.000	.000
149	.129	26.7	3.125	.000	9.000	1.625
150	.080	16.6	3.125	.000	9.000	3.250
151	.071	14.8	3.125	.000	9.000	3.313
152	.000	.0	3.125	.000	9.000	9.000
153	.201	41.8	3.125	1.625	.000	.000
154	.204	42.4	3.125	1.625	.000	1.625
155	.151	31.3	3.125	1.625	.000	3.250
156	.142	29.6	3.125	1.625	.000	3.313
157	.129	26.7	3.125	1.625	.000	9.000
158	.204	42.4	3.125	1.625	1.625	.000
159	.213	44.3	3.125	1.625	1.625	1.625
160	.158	32.8	3.125	1.625	1.625	3.250
161	.149	31.0	3.125	1.625	1.625	3.313
162	.136	28.2	3.125	1.625	1.625	9.000
163	.151	31.3	3.125	1.625	3.250	.000
164	.158	32.8	3.125	1.625	3.250	1.625
165	.109	22.6	3.125	1.625	3.250	3.250
166	.096	19.9	3.125	1.625	3.250	3.313
167	.082	17.1	3.125	1.625	3.250	9.000
168	.142	29.6	3.125	1.625	3.313	.000
169	.149	31.0	3.125	1.625	3.313	1.625
170	.096	19.9	3.125	1.625	3.313	3.250
171	.092	19.0	3.125	1.625	3.313	3.313
172	.074	15.3	3.125	1.625	3.313	9.000
173	.129	26.7	3.125	1.625	9.000	.000
174	.136	28.2	3.125	1.625	9.000	1.625
175	.082	17.1	3.125	1.625	9.000	3.250
176	.074	15.3	3.125	1.625	9.000	3.313
177	.000	.0	3.125	1.625	9.000	9.000
178	.152	31.7	3.125	3.250	.000	.000
179	.151	31.3	3.125	3.250	.000	1.625
180	.106	22.0	3.125	3.250	.000	3.250
181	.093	19.4	3.125	3.250	.000	3.313
182	.080	16.6	3.125	3.250	.000	9.000
183	.151	31.3	3.125	3.250	1.625	.000
184	.158	32.8	3.125	3.250	1.625	1.625
185	.109	22.6	3.125	3.250	1.625	3.250
186	.096	19.9	3.125	3.250	1.625	3.313
187	.082	17.1	3.125	3.250	1.625	9.000

AD-A155 477 MICROPROCESSOR CONTROL DESIGN FOR A LOW-HEAD CROSSFLOW TURBINE(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING D C RAMSEY MAR 85 3/4

UNCLASSIFIED AFIT/GE/ENG/85M-2 F/G 9/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
188	.106	22.0	3.125	3.250	3.250	.000
189	.109	22.6	3.125	3.250	3.250	1.625
190	.066	13.7	3.125	3.250	3.250	3.250
191	.000	.0	3.125	3.250	3.250	3.313
192	.000	.0	3.125	3.250	3.250	9.000
193	.093	19.4	3.125	3.250	3.313	.000
194	.096	19.9	3.125	3.250	3.313	1.625
195	.000	.0	3.125	3.250	3.313	3.250
196	.000	.0	3.125	3.250	3.313	3.313
197	.000	.0	3.125	3.250	3.313	9.000
198	.080	16.6	3.125	3.250	9.000	.000
199	.082	17.1	3.125	3.250	9.000	1.625
200	.000	.0	3.125	3.250	9.000	3.250
201	.000	.0	3.125	3.250	9.000	3.313
202	.000	.0	3.125	3.250	9.000	9.000
203	.144	29.9	3.125	3.313	.000	.000
204	.142	29.6	3.125	3.313	.000	1.625
205	.093	19.4	3.125	3.313	.000	3.250
206	.089	18.5	3.125	3.313	.000	3.313
207	.071	14.8	3.125	3.313	.000	9.000
208	.142	29.6	3.125	3.313	1.625	.000
209	.149	31.0	3.125	3.313	1.625	1.625
210	.096	19.9	3.125	3.313	1.625	3.250
211	.092	19.0	3.125	3.313	1.625	3.313
212	.074	15.3	3.125	3.313	1.625	9.000
213	.093	19.4	3.125	3.313	3.250	.000
214	.096	19.9	3.125	3.313	3.250	1.625
215	.000	.0	3.125	3.313	3.250	3.250
216	.000	.0	3.125	3.313	3.250	3.313
217	.000	.0	3.125	3.313	3.250	9.000
218	.089	18.5	3.125	3.313	3.313	.000
219	.092	19.0	3.125	3.313	3.313	1.625
220	.000	.0	3.125	3.313	3.313	3.250
221	.000	.0	3.125	3.313	3.313	3.313
222	.000	.0	3.125	3.313	3.313	9.000
223	.071	14.8	3.125	3.313	9.000	.000
224	.074	15.3	3.125	3.313	9.000	1.625
225	.000	.0	3.125	3.313	9.000	3.250
226	.000	.0	3.125	3.313	9.000	3.313
227	.000	.0	3.125	3.313	9.000	9.000
228	.130	27.1	3.125	9.000	.000	.000
229	.129	26.7	3.125	9.000	.000	1.625
230	.080	16.6	3.125	9.000	.000	3.250
231	.071	14.8	3.125	9.000	.000	3.313
232	.000	.0	3.125	9.000	.000	9.000
233	.129	26.7	3.125	9.000	1.625	.000
234	.136	28.2	3.125	9.000	1.625	1.625
235	.082	17.1	3.125	9.000	1.625	3.250
236	.074	15.3	3.125	9.000	1.625	3.313
237	.000	.0	3.125	9.000	1.625	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
238	.080	16.6	3.125	9.000	3.250	.000
239	.082	17.1	3.125	9.000	3.250	1.625
240	.000	.0	3.125	9.000	3.250	3.250
241	.000	.0	3.125	9.000	3.250	3.313
242	.000	.0	3.125	9.000	3.250	9.000
243	.071	14.8	3.125	9.000	3.313	.000
244	.074	15.3	3.125	9.000	3.313	1.625
245	.000	.0	3.125	9.000	3.313	3.250
246	.000	.0	3.125	9.000	3.313	3.313
247	.000	.0	3.125	9.000	3.313	9.000
248	.000	.0	3.125	9.000	9.000	.000
249	.000	.0	3.125	9.000	9.000	1.625
250	.000	.0	3.125	9.000	9.000	3.250
251	.000	.0	3.125	9.000	9.000	3.313
252	.000	.0	3.125	9.000	9.000	9.000
253	.247	51.3	3.750	.000	.000	.000
254	.246	51.1	3.750	.000	.000	1.375
255	.186	38.6	3.750	.000	.000	3.125
256	.175	36.4	3.750	.000	.000	3.183
257	.156	32.5	3.750	.000	.000	9.000
258	.246	51.1	3.750	.000	1.375	.000
259	.253	52.6	3.750	.000	1.375	1.375
260	.188	39.0	3.750	.000	1.375	3.125
261	.177	36.8	3.750	.000	1.375	3.183
262	.158	32.9	3.750	.000	1.375	9.000
263	.186	38.6	3.750	.000	3.125	.000
264	.188	39.0	3.750	.000	3.125	1.375
265	.133	27.7	3.750	.000	3.125	3.125
266	.117	24.3	3.750	.000	3.125	3.183
267	.098	20.4	3.750	.000	3.125	9.000
268	.175	36.4	3.750	.000	3.183	.000
269	.177	36.8	3.750	.000	3.183	1.375
270	.117	24.3	3.750	.000	3.183	3.125
271	.112	23.2	3.750	.000	3.183	3.183
272	.000	.0	3.750	.000	3.183	9.000
273	.156	32.5	3.750	.000	9.000	.000
274	.158	32.9	3.750	.000	9.000	1.375
275	.098	20.4	3.750	.000	9.000	3.125
276	.000	.0	3.750	.000	9.000	3.183
277	.000	.0	3.750	.000	9.000	9.000
278	.246	51.1	3.750	1.375	.000	.000
279	.253	52.6	3.750	1.375	.000	1.375
280	.188	39.0	3.750	1.375	.000	3.125
281	.177	36.8	3.750	1.375	.000	3.183
282	.158	32.9	3.750	1.375	.000	9.000
283	.253	52.6	3.750	1.375	1.375	.000
284	.268	55.7	3.750	1.375	1.375	1.375
285	.200	41.6	3.750	1.375	1.375	3.125
286	.189	39.4	3.750	1.375	1.375	3.183
287	.171	35.5	3.750	1.375	1.375	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
288	.188	39.0	3.750	1.375	3.125	.000
289	.200	41.6	3.750	1.375	3.125	1.375
290	.140	29.2	3.750	1.375	3.125	3.125
291	.124	25.8	3.750	1.375	3.125	3.183
292	.105	21.9	3.750	1.375	3.125	9.000
293	.177	36.8	3.750	1.375	3.183	.000
294	.189	39.4	3.750	1.375	3.183	1.375
295	.124	25.8	3.750	1.375	3.183	3.125
296	.119	24.7	3.750	1.375	3.183	3.183
297	.095	19.7	3.750	1.375	3.183	9.000
298	.158	32.9	3.750	1.375	9.000	.000
299	.171	35.5	3.750	1.375	9.000	1.375
300	.105	21.9	3.750	1.375	9.000	3.125
301	.095	19.7	3.750	1.375	9.000	3.183
302	.000	.0	3.750	1.375	9.000	9.000
303	.186	38.6	3.750	3.125	.000	.000
304	.188	39.0	3.750	3.125	.000	1.375
305	.133	27.7	3.750	3.125	.000	3.125
306	.117	24.3	3.750	3.125	.000	3.183
307	.098	20.4	3.750	3.125	.000	9.000
308	.188	39.0	3.750	3.125	1.375	.000
309	.200	41.6	3.750	3.125	1.375	1.375
310	.140	29.2	3.750	3.125	1.375	3.125
311	.124	25.8	3.750	3.125	1.375	3.183
312	.105	21.9	3.750	3.125	1.375	9.000
313	.133	27.7	3.750	3.125	3.125	.000
314	.140	29.2	3.750	3.125	3.125	1.375
315	.088	18.4	3.750	3.125	3.125	3.125
316	.000	.0	3.750	3.125	3.125	3.183
317	.000	.0	3.750	3.125	3.125	9.000
318	.117	24.3	3.750	3.125	3.183	.000
319	.124	25.8	3.750	3.125	3.183	1.375
320	.000	.0	3.750	3.125	3.183	3.125
321	.000	.0	3.750	3.125	3.183	3.183
322	.000	.0	3.750	3.125	3.183	9.000
323	.098	20.4	3.750	3.125	9.000	.000
324	.105	21.9	3.750	3.125	9.000	1.375
325	.000	.0	3.750	3.125	9.000	3.125
326	.000	.0	3.750	3.125	9.000	3.183
327	.000	.0	3.750	3.125	9.000	9.000
328	.175	36.4	3.750	3.183	.000	.000
329	.177	36.8	3.750	3.183	.000	1.375
330	.117	24.3	3.750	3.183	.000	3.125
331	.112	23.2	3.750	3.183	.000	3.183
332	.000	.0	3.750	3.183	.000	9.000
333	.177	36.8	3.750	3.183	1.375	.000
334	.189	39.4	3.750	3.183	1.375	1.375
335	.124	25.8	3.750	3.183	1.375	3.125
336	.119	24.7	3.750	3.183	1.375	3.183
337	.095	19.7	3.750	3.183	1.375	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
338	.117	24.3	3.750	3.183	3.125	.000
339	.124	25.8	3.750	3.183	3.125	1.375
340	.000	.0	3.750	3.183	3.125	3.125
341	.000	.0	3.750	3.183	3.125	3.183
342	.000	.0	3.750	3.183	3.125	9.000
343	.112	23.2	3.750	3.183	3.183	.000
344	.119	24.7	3.750	3.183	3.183	1.375
345	.000	.0	3.750	3.183	3.183	3.125
346	.000	.0	3.750	3.183	3.183	3.183
347	.000	.0	3.750	3.183	3.183	9.000
348	.000	.0	3.750	3.183	9.000	.000
349	.095	19.7	3.750	3.183	9.000	1.375
350	.000	.0	3.750	3.183	9.000	3.125
351	.000	.0	3.750	3.183	9.000	3.183
352	.000	.0	3.750	3.183	9.000	9.000
353	.156	32.5	3.750	9.000	.000	.000
354	.158	32.9	3.750	9.000	.000	1.375
355	.098	20.4	3.750	9.000	.000	3.125
356	.000	.0	3.750	9.000	.000	3.183
357	.000	.0	3.750	9.000	.000	9.000
358	.158	32.9	3.750	9.000	1.375	.000
359	.171	35.5	3.750	9.000	1.375	1.375
360	.105	21.9	3.750	9.000	1.375	3.125
361	.095	19.7	3.750	9.000	1.375	3.183
362	.000	.0	3.750	9.000	1.375	9.000
363	.098	20.4	3.750	9.000	3.125	.000
364	.105	21.9	3.750	9.000	3.125	1.375
365	.000	.0	3.750	9.000	3.125	3.125
366	.000	.0	3.750	9.000	3.125	3.183
367	.000	.0	3.750	9.000	3.125	9.000
368	.000	.0	3.750	9.000	3.183	.000
369	.095	19.7	3.750	9.000	3.183	1.375
370	.000	.0	3.750	9.000	3.183	3.125
371	.000	.0	3.750	9.000	3.183	3.183
372	.000	.0	3.750	9.000	3.183	9.000
373	.000	.0	3.750	9.000	9.000	.000
374	.000	.0	3.750	9.000	9.000	1.375
375	.000	.0	3.750	9.000	9.000	3.125
376	.000	.0	3.750	9.000	9.000	3.183
377	.000	.0	3.750	9.000	9.000	9.000
378	.100	20.8	6.000	.000	.000	.000
379	.097	20.2	6.000	.000	.000	.250
380	.095	19.7	6.000	.000	.000	.500
381	.000	.0	6.000	.000	.000	.563
382	.000	.0	6.000	.000	.000	9.000
383	.097	20.2	6.000	.000	.250	.000
384	.097	20.2	6.000	.000	.250	.250
385	.000	.0	6.000	.000	.250	.500
386	.000	.0	6.000	.000	.250	.563
387	.000	.0	6.000	.000	.250	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
388	.095	19.7	6.000	.000	.500	.000
389	.000	.0	6.000	.000	.500	.250
390	.000	.0	6.000	.000	.500	.500
391	.000	.0	6.000	.000	.500	.563
392	.000	.0	6.000	.000	.500	9.000
393	.000	.0	6.000	.000	.563	.000
394	.000	.0	6.000	.000	.563	.250
395	.000	.0	6.000	.000	.563	.500
396	.000	.0	6.000	.000	.563	.563
397	.000	.0	6.000	.000	.563	9.000
398	.000	.0	6.000	.000	9.000	.000
399	.000	.0	6.000	.000	9.000	.250
400	.000	.0	6.000	.000	9.000	.500
401	.000	.0	6.000	.000	9.000	.563
402	.000	.0	6.000	.000	9.000	9.000
403	.097	20.2	6.000	.250	.000	.000
404	.097	20.2	6.000	.250	.000	.250
405	.000	.0	6.000	.250	.000	.500
406	.000	.0	6.000	.250	.000	.563
407	.000	.0	6.000	.250	.000	9.000
408	.097	20.2	6.000	.250	.250	.000
409	.100	20.8	6.000	.250	.250	.250
410	.095	19.7	6.000	.250	.250	.500
411	.000	.0	6.000	.250	.250	.563
412	.000	.0	6.000	.250	.250	9.000
413	.000	.0	6.000	.250	.500	.000
414	.095	19.7	6.000	.250	.500	.250
415	.000	.0	6.000	.250	.500	.500
416	.000	.0	6.000	.250	.500	.563
417	.000	.0	6.000	.250	.500	9.000
418	.000	.0	6.000	.250	.563	.000
419	.000	.0	6.000	.250	.563	.250
420	.000	.0	6.000	.250	.563	.500
421	.000	.0	6.000	.250	.563	.563
422	.000	.0	6.000	.250	.563	9.000
423	.000	.0	6.000	.250	9.000	.000
424	.000	.0	6.000	.250	9.000	.250
425	.000	.0	6.000	.250	9.000	.500
426	.000	.0	6.000	.250	9.000	.563
427	.000	.0	6.000	.250	9.000	9.000
428	.095	19.7	6.000	.500	.000	.000
429	.000	.0	6.000	.500	.000	.250
430	.000	.0	6.000	.500	.000	.500
431	.000	.0	6.000	.500	.000	.563
432	.000	.0	6.000	.500	.000	9.000
433	.000	.0	6.000	.500	.250	.000
434	.095	19.7	6.000	.500	.250	.250
435	.000	.0	6.000	.500	.250	.500
436	.000	.0	6.000	.500	.250	.563
437	.000	.0	6.000	.500	.250	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
438	.000	.0	6.000	.500	.500	.000
439	.000	.0	6.000	.500	.500	.250
440	.094	19.5	6.000	.500	.500	.500
441	.000	.0	6.000	.500	.500	.563
442	.000	.0	6.000	.500	.500	9.000
443	.000	.0	6.000	.500	.563	.000
444	.000	.0	6.000	.500	.563	.250
445	.000	.0	6.000	.500	.563	.500
446	.000	.0	6.000	.500	.563	.563
447	.000	.0	6.000	.500	.563	9.000
448	.000	.0	6.000	.500	9.000	.000
449	.000	.0	6.000	.500	9.000	.250
450	.000	.0	6.000	.500	9.000	.500
451	.000	.0	6.000	.500	9.000	.563
452	.000	.0	6.000	.500	9.000	9.000
453	.000	.0	6.000	.563	.000	.000
454	.000	.0	6.000	.563	.000	.250
455	.000	.0	6.000	.563	.000	.500
456	.000	.0	6.000	.563	.000	.563
457	.000	.0	6.000	.563	.000	9.000
458	.000	.0	6.000	.563	.250	.000
459	.000	.0	6.000	.563	.250	.250
460	.000	.0	6.000	.563	.250	.500
461	.000	.0	6.000	.563	.250	.563
462	.000	.0	6.000	.563	.250	9.000
463	.000	.0	6.000	.563	.500	.000
464	.000	.0	6.000	.563	.500	.250
465	.000	.0	6.000	.563	.500	.500
466	.000	.0	6.000	.563	.500	.563
467	.000	.0	6.000	.563	.500	9.000
468	.000	.0	6.000	.563	.563	.000
469	.000	.0	6.000	.563	.563	.250
470	.000	.0	6.000	.563	.563	.500
471	.000	.0	6.000	.563	.563	.563
472	.000	.0	6.000	.563	.563	9.000
473	.000	.0	6.000	.563	9.000	.000
474	.000	.0	6.000	.563	9.000	.250
475	.000	.0	6.000	.563	9.000	.500
476	.000	.0	6.000	.563	9.000	.563
477	.000	.0	6.000	.563	9.000	9.000
478	.000	.0	6.000	9.000	.000	.000
479	.000	.0	6.000	9.000	.000	.250
480	.000	.0	6.000	9.000	.000	.500
481	.000	.0	6.000	9.000	.000	.563
482	.000	.0	6.000	9.000	.000	9.000
483	.000	.0	6.000	9.000	.250	.000
484	.000	.0	6.000	9.000	.250	.250
485	.000	.0	6.000	9.000	.250	.500
486	.000	.0	6.000	9.000	.250	.563
487	.000	.0	6.000	9.000	.250	9.000

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
488	.000	.0	6.000	9.000	.500	.000
489	.000	.0	6.000	9.000	.500	.250
490	.000	.0	6.000	9.000	.500	.500
491	.000	.0	6.000	9.000	.500	.563
492	.000	.0	6.000	9.000	.500	9.000
493	.000	.0	6.000	9.000	.563	.000
494	.000	.0	6.000	9.000	.563	.250
495	.000	.0	6.000	9.000	.563	.500
496	.000	.0	6.000	9.000	.563	.563
497	.000	.0	6.000	9.000	.563	9.000
498	.000	.0	6.000	9.000	9.000	.000
499	.000	.0	6.000	9.000	9.000	.250
500	.000	.0	6.000	9.000	9.000	.500
501	.000	.0	6.000	9.000	9.000	.563
502	.000	.0	6.000	9.000	9.000	9.000
503	.000	.0	6.063	*****	*****	*****
504	.000	.0	8.250	*****	*****	*****

TABLE B-4

Fixed Parameters:

H (in)	d (in)	Q (CFM)	PA (KW)	LI (deg)
19.875	9.815	782.7	1.831	88.0

Hydroturbine data:

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
1	.972	53.1	.000	.000	.000	.000
2	.955	52.1	.000	.000	.000	.750
3	.722	39.4	.000	.000	.000	5.000
4	.685	37.4	.000	.000	.000	5.063
5	.617	33.7	.000	.000	.000	9.000
6	.955	52.1	.000	.000	.750	.000
7	.968	52.9	.000	.000	.750	.750
8	.715	39.1	.000	.000	.750	5.000
9	.678	37.0	.000	.000	.750	5.063
10	.611	33.3	.000	.000	.750	9.000
11	.722	39.4	.000	.000	5.000	.000
12	.715	39.1	.000	.000	5.000	.750
13	.503	27.5	.000	.000	5.000	5.000
14	.445	24.3	.000	.000	5.000	5.063
15	.378	20.6	.000	.000	5.000	9.000
16	.685	37.4	.000	.000	5.063	.000
17	.678	37.0	.000	.000	5.063	.750
18	.445	24.3	.000	.000	5.063	5.000
19	.428	23.4	.000	.000	5.063	5.063
20	.341	18.6	.000	.000	5.063	9.000
21	.617	33.7	.000	.000	9.000	.000
22	.611	33.3	.000	.000	9.000	.750
23	.378	20.6	.000	.000	9.000	5.000
24	.341	18.6	.000	.000	9.000	5.063
25	.000	.0	.000	.000	9.000	9.000
26	.955	52.1	.000	.750	.000	.000
27	.968	52.9	.000	.750	.000	.750
28	.715	39.1	.000	.750	.000	5.000
29	.678	37.0	.000	.750	.000	5.063
30	.611	33.3	.000	.750	.000	9.000
31	.968	52.9	.000	.750	.750	.000
32	1.012	55.3	.000	.750	.750	.750
33	.749	40.9	.000	.750	.750	5.000
34	.712	38.9	.000	.750	.750	5.063
35	.644	35.2	.000	.750	.750	9.000
36	.715	39.1	.000	.750	5.000	.000
37	.749	40.9	.000	.750	5.000	.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
38	.516	28.2	.000	.750	5.000	5.000
39	.459	25.1	.000	.750	5.000	5.063
40	.391	21.4	.000	.750	5.000	9.000
41	.678	37.0	.000	.750	5.063	.000
42	.712	38.9	.000	.750	5.063	.750
43	.459	25.1	.000	.750	5.063	5.000
44	.442	24.1	.000	.750	5.063	5.063
45	.354	19.3	.000	.750	5.063	9.000
46	.611	33.3	.000	.750	9.000	.000
47	.644	35.2	.000	.750	9.000	.750
48	.391	21.4	.000	.750	9.000	5.000
49	.354	19.3	.000	.750	9.000	5.063
50	.000	.0	.000	.750	9.000	9.000
51	.722	39.4	.000	5.000	.000	.000
52	.715	39.1	.000	5.000	.000	.750
53	.503	27.5	.000	5.000	.000	5.000
54	.445	24.3	.000	5.000	.000	5.063
55	.378	20.6	.000	5.000	.000	9.000
56	.715	39.1	.000	5.000	.750	.000
57	.749	40.9	.000	5.000	.750	.750
58	.516	28.2	.000	5.000	.750	5.000
59	.459	25.1	.000	5.000	.750	5.063
60	.391	21.4	.000	5.000	.750	9.000
61	.503	27.5	.000	5.000	5.000	.000
62	.516	28.2	.000	5.000	5.000	.750
63	.314	17.1	.000	5.000	5.000	5.000
64	.000	.0	.000	5.000	5.000	5.063
65	.000	.0	.000	5.000	5.000	9.000
66	.445	24.3	.000	5.000	5.063	.000
67	.459	25.1	.000	5.000	5.063	.750
68	.000	.0	.000	5.000	5.063	5.000
69	.000	.0	.000	5.000	5.063	5.063
70	.000	.0	.000	5.000	5.063	9.000
71	.378	20.6	.000	5.000	9.000	.000
72	.391	21.4	.000	5.000	9.000	.750
73	.000	.0	.000	5.000	9.000	5.000
74	.000	.0	.000	5.000	9.000	5.063
75	.000	.0	.000	5.000	9.000	9.000
76	.685	37.4	.000	5.063	.000	.000
77	.678	37.0	.000	5.063	.000	.750
78	.445	24.3	.000	5.063	.000	5.000
79	.428	23.4	.000	5.063	.000	5.063
80	.341	18.6	.000	5.063	.000	9.000
81	.678	37.0	.000	5.063	.750	.000
82	.712	38.9	.000	5.063	.750	.750
83	.459	25.1	.000	5.063	.750	5.000
84	.442	24.1	.000	5.063	.750	5.063
85	.354	19.3	.000	5.063	.750	9.000
86	.445	24.3	.000	5.063	5.000	.000
87	.459	25.1	.000	5.063	5.000	.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
88	.000	.0	.000	5.063	5.000	5.000
89	.000	.0	.000	5.063	5.000	5.063
90	.000	.0	.000	5.063	5.000	9.000
91	.428	23.4	.000	5.063	5.063	.000
92	.442	24.1	.000	5.063	5.063	.750
93	.000	.0	.000	5.063	5.063	5.000
94	.000	.0	.000	5.063	5.063	5.063
95	.000	.0	.000	5.063	5.063	9.000
96	.341	18.6	.000	5.063	9.000	.000
97	.354	19.3	.000	5.063	9.000	.750
98	.000	.0	.000	5.063	9.000	5.000
99	.000	.0	.000	5.063	9.000	5.063
100	.000	.0	.000	5.063	9.000	9.000
101	.617	33.7	.000	9.000	.000	.000
102	.611	33.3	.000	9.000	.000	.750
103	.378	20.6	.000	9.000	.000	5.000
104	.341	18.6	.000	9.000	.000	5.063
105	.000	.0	.000	9.000	.000	9.000
106	.611	33.3	.000	9.000	.750	.000
107	.644	35.2	.000	9.000	.750	.750
108	.391	21.4	.000	9.000	.750	5.000
109	.354	19.3	.000	9.000	.750	5.063
110	.000	.0	.000	9.000	.750	9.000
111	.378	20.6	.000	9.000	5.000	.000
112	.391	21.4	.000	9.000	5.000	.750
113	.000	.0	.000	9.000	5.000	5.000
114	.000	.0	.000	9.000	5.000	5.063
115	.000	.0	.000	9.000	5.000	9.000
116	.341	18.6	.000	9.000	5.063	.000
117	.354	19.3	.000	9.000	5.063	.750
118	.000	.0	.000	9.000	5.063	5.000
119	.000	.0	.000	9.000	5.063	5.063
120	.000	.0	.000	9.000	5.063	9.000
121	.000	.0	.000	9.000	9.000	.000
122	.000	.0	.000	9.000	9.000	.750
123	.000	.0	.000	9.000	9.000	5.000
124	.000	.0	.000	9.000	9.000	5.063
125	.000	.0	.000	9.000	9.000	9.000
126	.904	49.4	1.500	.000	.000	.000
127	.889	48.6	1.500	.000	.000	.750
128	.669	36.5	1.500	.000	.000	4.875
129	.634	34.6	1.500	.000	.000	4.938
130	.574	31.4	1.500	.000	.000	9.000
131	.889	48.6	1.500	.000	.750	.000
132	.903	49.3	1.500	.000	.750	.750
133	.663	36.2	1.500	.000	.750	4.875
134	.629	34.3	1.500	.000	.750	4.938
135	.569	31.1	1.500	.000	.750	9.000
136	.669	36.5	1.500	.000	4.875	.000
137	.663	36.2	1.500	.000	4.875	.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
138	.462	25.2	1.500	.000	4.875	4.875
139	.408	22.3	1.500	.000	4.875	4.938
140	.349	19.0	1.500	.000	4.875	9.000
141	.634	34.6	1.500	.000	4.938	.000
142	.629	34.3	1.500	.000	4.938	.750
143	.408	22.3	1.500	.000	4.938	4.875
144	.393	21.4	1.500	.000	4.938	4.938
145	.314	17.1	1.500	.000	4.938	9.000
146	.574	31.4	1.500	.000	9.000	.000
147	.569	31.1	1.500	.000	9.000	.750
148	.349	19.0	1.500	.000	9.000	4.875
149	.314	17.1	1.500	.000	9.000	4.938
150	.000	.0	1.500	.000	9.000	9.000
151	.889	48.6	1.500	.750	.000	.000
152	.903	49.3	1.500	.750	.000	.750
153	.663	36.2	1.500	.750	.000	4.875
154	.629	34.3	1.500	.750	.000	4.938
155	.569	31.1	1.500	.750	.000	9.000
156	.903	49.3	1.500	.750	.750	.000
157	.945	51.6	1.500	.750	.750	.750
158	.696	38.0	1.500	.750	.750	4.875
159	.661	36.1	1.500	.750	.750	4.938
160	.601	32.8	1.500	.750	.750	9.000
161	.663	36.2	1.500	.750	4.875	.000
162	.696	38.0	1.500	.750	4.875	.750
163	.475	26.0	1.500	.750	4.875	4.875
164	.422	23.0	1.500	.750	4.875	4.938
165	.362	19.8	1.500	.750	4.875	9.000
166	.629	34.3	1.500	.750	4.938	.000
167	.661	36.1	1.500	.750	4.938	.750
168	.422	23.0	1.500	.750	4.938	4.875
169	.406	22.2	1.500	.750	4.938	4.938
170	.327	17.9	1.500	.750	4.938	9.000
171	.569	31.1	1.500	.750	9.000	.000
172	.601	32.8	1.500	.750	9.000	.750
173	.362	19.8	1.500	.750	9.000	4.875
174	.327	17.9	1.500	.750	9.000	4.938
175	.287	15.6	1.500	.750	9.000	9.000
176	.669	36.5	1.500	4.875	.000	.000
177	.663	36.2	1.500	4.875	.000	.750
178	.462	25.2	1.500	4.875	.000	4.875
179	.408	22.3	1.500	4.875	.000	4.938
180	.349	19.0	1.500	4.875	.000	9.000
181	.663	36.2	1.500	4.875	.750	.000
182	.696	38.0	1.500	4.875	.750	.750
183	.475	26.0	1.500	4.875	.750	4.875
184	.422	23.0	1.500	4.875	.750	4.938
185	.362	19.8	1.500	4.875	.750	9.000
186	.462	25.2	1.500	4.875	4.875	.000
187	.475	26.0	1.500	4.875	4.875	.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
188	.283	15.5	1.500	4.875	4.875	4.875
189	.000	.0	1.500	4.875	4.875	4.938
190	.000	.0	1.500	4.875	4.875	9.000
191	.408	22.3	1.500	4.875	4.938	.000
192	.422	23.0	1.500	4.875	4.938	.750
193	.000	.0	1.500	4.875	4.938	4.875
194	.000	.0	1.500	4.875	4.938	4.938
195	.000	.0	1.500	4.875	4.938	9.000
196	.349	19.0	1.500	4.875	9.000	.000
197	.362	19.8	1.500	4.875	9.000	.750
198	.000	.0	1.500	4.875	9.000	4.875
199	.000	.0	1.500	4.875	9.000	4.938
200	.000	.0	1.500	4.875	9.000	9.000
201	.634	34.6	1.500	4.938	.000	.000
202	.629	34.3	1.500	4.938	.000	.750
203	.408	22.3	1.500	4.938	.000	4.875
204	.393	21.4	1.500	4.938	.000	4.938
205	.314	17.1	1.500	4.938	.000	9.000
206	.629	34.3	1.500	4.938	.750	.000
207	.661	36.1	1.500	4.938	.750	.750
208	.422	23.0	1.500	4.938	.750	4.875
209	.406	22.2	1.500	4.938	.750	4.938
210	.327	17.9	1.500	4.938	.750	9.000
211	.408	22.3	1.500	4.938	4.875	.000
212	.422	23.0	1.500	4.938	4.875	.750
213	.000	.0	1.500	4.938	4.875	4.875
214	.000	.0	1.500	4.938	4.875	4.938
215	.000	.0	1.500	4.938	4.875	9.000
216	.393	21.4	1.500	4.938	4.938	.000
217	.406	22.2	1.500	4.938	4.938	.750
218	.000	.0	1.500	4.938	4.938	4.875
219	.000	.0	1.500	4.938	4.938	4.938
220	.000	.0	1.500	4.938	4.938	9.000
221	.314	17.1	1.500	4.938	9.000	.000
222	.327	17.9	1.500	4.938	9.000	.750
223	.000	.0	1.500	4.938	9.000	4.875
224	.000	.0	1.500	4.938	9.000	4.938
225	.000	.0	1.500	4.938	9.000	9.000
226	.574	31.4	1.500	9.000	.000	.000
227	.569	31.1	1.500	9.000	.000	.750
228	.349	19.0	1.500	9.000	.000	4.875
229	.314	17.1	1.500	9.000	.000	4.938
230	.000	.0	1.500	9.000	.000	9.000
231	.569	31.1	1.500	9.000	.750	.000
232	.601	32.8	1.500	9.000	.750	.750
233	.362	19.8	1.500	9.000	.750	4.875
234	.327	17.9	1.500	9.000	.750	4.938
235	.287	15.6	1.500	9.000	.750	9.000
236	.349	19.0	1.500	9.000	4.875	.000
237	.362	19.8	1.500	9.000	4.875	.750

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
238	.000	.0	1.500	9.000	4.875	4.875
239	.000	.0	1.500	9.000	4.875	4.938
240	.000	.0	1.500	9.000	4.875	9.000
241	.314	17.1	1.500	9.000	4.938	.000
242	.327	17.9	1.500	9.000	4.938	.750
243	.000	.0	1.500	9.000	4.938	4.875
244	.000	.0	1.500	9.000	4.938	4.938
245	.000	.0	1.500	9.000	4.938	9.000
246	.000	.0	1.500	9.000	9.000	.000
247	.287	15.6	1.500	9.000	9.000	.750
248	.000	.0	1.500	9.000	9.000	4.875
249	.000	.0	1.500	9.000	9.000	4.938
250	.000	.0	1.500	9.000	9.000	9.000
251	.715	39.1	4.000	.000	.000	.000
252	.698	38.1	4.000	.000	.000	.250
253	.547	29.9	4.000	.000	.000	4.250
254	.516	28.2	4.000	.000	.000	4.313
255	.455	24.8	4.000	.000	.000	9.000
256	.698	38.1	4.000	.000	.250	.000
257	.702	38.4	4.000	.000	.250	.250
258	.537	29.3	4.000	.000	.250	4.250
259	.506	27.6	4.000	.000	.250	4.313
260	.445	24.3	4.000	.000	.250	9.000
261	.547	29.9	4.000	.000	4.250	.000
262	.537	29.3	4.000	.000	4.250	.250
263	.401	21.9	4.000	.000	4.250	4.250
264	.355	19.4	4.000	.000	4.250	4.313
265	.294	16.1	4.000	.000	4.250	9.000
266	.516	28.2	4.000	.000	4.313	.000
267	.506	27.6	4.000	.000	4.313	.250
268	.355	19.4	4.000	.000	4.313	4.250
269	.338	18.5	4.000	.000	4.313	4.313
270	.000	.0	4.000	.000	4.313	9.000
271	.455	24.8	4.000	.000	9.000	.000
272	.445	24.3	4.000	.000	9.000	.250
273	.294	16.1	4.000	.000	9.000	4.250
274	.000	.0	4.000	.000	9.000	4.313
275	.000	.0	4.000	.000	9.000	9.000
276	.698	38.1	4.000	.250	.000	.000
277	.702	38.4	4.000	.250	.000	.250
278	.537	29.3	4.000	.250	.000	4.250
279	.506	27.6	4.000	.250	.000	4.313
280	.445	24.3	4.000	.250	.000	9.000
281	.702	38.4	4.000	.250	.250	.000
282	.729	39.8	4.000	.250	.250	.250
283	.556	30.4	4.000	.250	.250	4.250
284	.525	28.7	4.000	.250	.250	4.313
285	.464	25.3	4.000	.250	.250	9.000
286	.537	29.3	4.000	.250	4.250	.000
287	.556	30.4	4.000	.250	4.250	.250

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
288	.406	22.2	4.000	.250	4.250	4.250
289	.359	19.6	4.000	.250	4.250	4.313
290	.299	16.3	4.000	.250	4.250	9.000
291	.506	27.6	4.000	.250	4.313	.000
292	.525	28.7	4.000	.250	4.313	.250
293	.359	19.6	4.000	.250	4.313	4.250
294	.342	18.7	4.000	.250	4.313	4.313
295	.000	.0	4.000	.250	4.313	9.000
296	.445	24.3	4.000	.250	9.000	.000
297	.464	25.3	4.000	.250	9.000	.250
298	.299	16.3	4.000	.250	9.000	4.250
299	.000	.0	4.000	.250	9.000	4.313
300	.000	.0	4.000	.250	9.000	9.000
301	.547	29.9	4.000	4.250	.000	.000
302	.537	29.3	4.000	4.250	.000	.250
303	.401	21.9	4.000	4.250	.000	4.250
304	.355	19.4	4.000	4.250	.000	4.313
305	.294	16.1	4.000	4.250	.000	9.000
306	.537	29.3	4.000	4.250	.250	.000
307	.556	30.4	4.000	4.250	.250	.250
308	.406	22.2	4.000	4.250	.250	4.250
309	.359	19.6	4.000	4.250	.250	4.313
310	.299	16.3	4.000	4.250	.250	9.000
311	.401	21.9	4.000	4.250	4.250	.000
312	.406	22.2	4.000	4.250	4.250	.250
313	.277	15.1	4.000	4.250	4.250	4.250
314	.000	.0	4.000	4.250	4.250	4.313
315	.000	.0	4.000	4.250	4.250	9.000
316	.355	19.4	4.000	4.250	4.313	.000
317	.359	19.6	4.000	4.250	4.313	.250
318	.000	.0	4.000	4.250	4.313	4.250
319	.000	.0	4.000	4.250	4.313	4.313
320	.000	.0	4.000	4.250	4.313	9.000
321	.294	16.1	4.000	4.250	9.000	.000
322	.299	16.3	4.000	4.250	9.000	.250
323	.000	.0	4.000	4.250	9.000	4.250
324	.000	.0	4.000	4.250	9.000	4.313
325	.000	.0	4.000	4.250	9.000	9.000
326	.516	28.2	4.000	4.313	.000	.000
327	.506	27.6	4.000	4.313	.000	.250
328	.355	19.4	4.000	4.313	.000	4.250
329	.338	18.5	4.000	4.313	.000	4.313
330	.000	.0	4.000	4.313	.000	9.000
331	.506	27.6	4.000	4.313	.250	.000
332	.525	28.7	4.000	4.313	.250	.250
333	.359	19.6	4.000	4.313	.250	4.250
334	.342	18.7	4.000	4.313	.250	4.313
335	.000	.0	4.000	4.313	.250	9.000
336	.355	19.4	4.000	4.313	4.250	.000
337	.359	19.6	4.000	4.313	4.250	.250

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
338	.000	.0	4.000	4.313	4.250	4.250
339	.000	.0	4.000	4.313	4.250	4.313
340	.000	.0	4.000	4.313	4.250	9.000
341	.338	18.5	4.000	4.313	4.313	.000
342	.342	18.7	4.000	4.313	4.313	.250
343	.000	.0	4.000	4.313	4.313	4.250
344	.000	.0	4.000	4.313	4.313	4.313
345	.000	.0	4.000	4.313	4.313	9.000
346	.000	.0	4.000	4.313	9.000	.000
347	.000	.0	4.000	4.313	9.000	.250
348	.000	.0	4.000	4.313	9.000	4.250
349	.000	.0	4.000	4.313	9.000	4.313
350	.000	.0	4.000	4.313	9.000	9.000
351	.455	24.8	4.000	9.000	.000	.000
352	.445	24.3	4.000	9.000	.000	.250
353	.294	16.1	4.000	9.000	.000	4.250
354	.000	.0	4.000	9.000	.000	4.313
355	.000	.0	4.000	9.000	.000	9.000
356	.445	24.3	4.000	9.000	.250	.000
357	.464	25.3	4.000	9.000	.250	.250
358	.299	16.3	4.000	9.000	.250	4.250
359	.000	.0	4.000	9.000	.250	4.313
360	.000	.0	4.000	9.000	.250	9.000
361	.294	16.1	4.000	9.000	4.250	.000
362	.299	16.3	4.000	9.000	4.250	.250
363	.000	.0	4.000	9.000	4.250	4.250
364	.000	.0	4.000	9.000	4.250	4.313
365	.000	.0	4.000	9.000	4.250	9.000
366	.000	.0	4.000	9.000	4.313	.000
367	.000	.0	4.000	9.000	4.313	.250
368	.000	.0	4.000	9.000	4.313	4.250
369	.000	.0	4.000	9.000	4.313	4.313
370	.000	.0	4.000	9.000	4.313	9.000
371	.000	.0	4.000	9.000	9.000	.000
372	.000	.0	4.000	9.000	9.000	.250
373	.000	.0	4.000	9.000	9.000	4.250
374	.000	.0	4.000	9.000	9.000	4.313
375	.000	.0	4.000	9.000	9.000	9.000
376	.256	14.0	5.875	.000	.000	.000
377	.000	.0	5.875	.000	.000	.250
378	.000	.0	5.875	.000	.000	.313
379	.000	.0	5.875	.000	.000	5.000
380	.000	.0	5.875	.000	.000	9.000
381	.000	.0	5.875	.000	.250	.000
382	.000	.0	5.875	.000	.250	.250
383	.000	.0	5.875	.000	.250	.313
384	.000	.0	5.875	.000	.250	5.000
385	.000	.0	5.875	.000	.250	9.000
386	.000	.0	5.875	.000	.313	.000
387	.000	.0	5.875	.000	.313	.250

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
388	.000	.0	5.875	.000	.313	.313
389	.000	.0	5.875	.000	.313	5.000
390	.000	.0	5.875	.000	.313	9.000
391	.000	.0	5.875	.000	5.000	.000
392	.000	.0	5.875	.000	5.000	.250
393	.000	.0	5.875	.000	5.000	.313
394	.000	.0	5.875	.000	5.000	5.000
395	.000	.0	5.875	.000	5.000	9.000
396	.000	.0	5.875	.000	9.000	.000
397	.000	.0	5.875	.000	9.000	.250
398	.000	.0	5.875	.000	9.000	.313
399	.000	.0	5.875	.000	9.000	5.000
400	.000	.0	5.875	.000	9.000	9.000
401	.000	.0	5.875	.250	.000	.000
402	.000	.0	5.875	.250	.000	.250
403	.000	.0	5.875	.250	.000	.313
404	.000	.0	5.875	.250	.000	5.000
405	.000	.0	5.875	.250	.000	9.000
406	.000	.0	5.875	.250	.250	.000
407	.246	13.4	5.875	.250	.250	.250
408	.000	.0	5.875	.250	.250	.313
409	.000	.0	5.875	.250	.250	5.000
410	.000	.0	5.875	.250	.250	9.000
411	.000	.0	5.875	.250	.313	.000
412	.000	.0	5.875	.250	.313	.250
413	.000	.0	5.875	.250	.313	.313
414	.000	.0	5.875	.250	.313	5.000
415	.000	.0	5.875	.250	.313	9.000
416	.000	.0	5.875	.250	5.000	.000
417	.000	.0	5.875	.250	5.000	.250
418	.000	.0	5.875	.250	5.000	.313
419	.000	.0	5.875	.250	5.000	5.000
420	.000	.0	5.875	.250	5.000	9.000
421	.000	.0	5.875	.250	9.000	.000
422	.000	.0	5.875	.250	9.000	.250
423	.000	.0	5.875	.250	9.000	.313
424	.000	.0	5.875	.250	9.000	5.000
425	.000	.0	5.875	.250	9.000	9.000
426	.000	.0	5.875	.313	.000	.000
427	.000	.0	5.875	.313	.000	.250
428	.000	.0	5.875	.313	.000	.313
429	.000	.0	5.875	.313	.000	5.000
430	.000	.0	5.875	.313	.000	9.000
431	.000	.0	5.875	.313	.250	.000
432	.000	.0	5.875	.313	.250	.250
433	.000	.0	5.875	.313	.250	.313
434	.000	.0	5.875	.313	.250	5.000
435	.000	.0	5.875	.313	.250	9.000
436	.000	.0	5.875	.313	.313	.000
437	.000	.0	5.875	.313	.313	.250

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
438	.000	.0	5.875	.313	.313	.313
439	.000	.0	5.875	.313	.313	5.000
440	.000	.0	5.875	.313	.313	9.000
441	.000	.0	5.875	.313	5.000	.000
442	.000	.0	5.875	.313	5.000	.250
443	.000	.0	5.875	.313	5.000	.313
444	.000	.0	5.875	.313	5.000	5.000
445	.000	.0	5.875	.313	5.000	9.000
446	.000	.0	5.875	.313	9.000	.000
447	.000	.0	5.875	.313	9.000	.250
448	.000	.0	5.875	.313	9.000	.313
449	.000	.0	5.875	.313	9.000	5.000
450	.000	.0	5.875	.313	9.000	9.000
451	.000	.0	5.875	5.000	.000	.000
452	.000	.0	5.875	5.000	.000	.250
453	.000	.0	5.875	5.000	.000	.313
454	.000	.0	5.875	5.000	.000	5.000
455	.000	.0	5.875	5.000	.000	9.000
456	.000	.0	5.875	5.000	.250	.000
457	.000	.0	5.875	5.000	.250	.250
458	.000	.0	5.875	5.000	.250	.313
459	.000	.0	5.875	5.000	.250	5.000
460	.000	.0	5.875	5.000	.250	9.000
461	.000	.0	5.875	5.000	.313	.000
462	.000	.0	5.875	5.000	.313	.250
463	.000	.0	5.875	5.000	.313	.313
464	.000	.0	5.875	5.000	.313	5.000
465	.000	.0	5.875	5.000	.313	9.000
466	.000	.0	5.875	5.000	5.000	.000
467	.000	.0	5.875	5.000	5.000	.250
468	.000	.0	5.875	5.000	5.000	.313
469	.000	.0	5.875	5.000	5.000	5.000
470	.000	.0	5.875	5.000	5.000	9.000
471	.000	.0	5.875	5.000	9.000	.000
472	.000	.0	5.875	5.000	9.000	.250
473	.000	.0	5.875	5.000	9.000	.313
474	.000	.0	5.875	5.000	9.000	5.000
475	.000	.0	5.875	5.000	9.000	9.000
476	.000	.0	5.875	9.000	.000	.000
477	.000	.0	5.875	9.000	.000	.250
478	.000	.0	5.875	9.000	.000	.313
479	.000	.0	5.875	9.000	.000	5.000
480	.000	.0	5.875	9.000	.000	9.000
481	.000	.0	5.875	9.000	.250	.000
482	.000	.0	5.875	9.000	.250	.250
483	.000	.0	5.875	9.000	.250	.313
484	.000	.0	5.875	9.000	.250	5.000
485	.000	.0	5.875	9.000	.250	9.000
486	.000	.0	5.875	9.000	.313	.000
487	.000	.0	5.875	9.000	.313	.250

#	PM (KW)	E (%)	T (in)	UI#1 (in)	UI#2 (in)	UI#3 (in)
488	.000	.0	5.875	9.000	.313	.313
489	.000	.0	5.875	9.000	.313	5.000
490	.000	.0	5.875	9.000	.313	9.000
491	.000	.0	5.875	9.000	5.000	.000
492	.000	.0	5.875	9.000	5.000	.250
493	.000	.0	5.875	9.000	5.000	.313
494	.000	.0	5.875	9.000	5.000	5.000
495	.000	.0	5.875	9.000	5.000	9.000
496	.000	.0	5.875	9.000	9.000	.000
497	.000	.0	5.875	9.000	9.000	.250
498	.000	.0	5.875	9.000	9.000	.313
499	.000	.0	5.875	9.000	9.000	5.000
500	.000	.0	5.875	9.000	9.000	9.000
501	.000	.0	5.938	*****	*****	*****
502	.000	.0	8.250	*****	*****	*****

Appendix C.

Data Acquisition Forms

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Inlet Guide #3 ______

	a	b	c	d	e
Turbine Blades					
Lower Inlet Guide					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Inlet Guide #3 ______

	a	b	c	d	e
Turbine Blades					
Lower Inlet Guide					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Inlet Guide #3 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Upper Table					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Inlet Guide #3 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Upper Table					
Power					

Turbine Data Test No. _______

Fixed:

Water Height _______

Upper Table _______

Inlet Guide #2 _______

Inlet Guide #3 _______

Lower Inlet Guide _______

Turbine Blades _______

	a	b	c	d	e
Inlet Guide #1					
Power					

Turbine Data Test No. _______

Fixed:

Water Height _______

Upper Table _______

Inlet Guide #2 _______

Inlet Guide #3 _______

Lower Inlet Guide _______

Turbine Blades _______

	a	b	c	d	e
Inlet Guide #1					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #3 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Inlet Guide #2					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #3 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Inlet Guide #2					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Inlet Guide #3					
Power					

Turbine Data Test No. ______

Fixed:

Water Height ______

Upper Table ______

Inlet Guide #1 ______

Inlet Guide #2 ______

Lower Inlet Guide ______

Turbine Blades ______

	a	b	c	d	e
Inlet Guide #3					
Power					

Appendix D.

Linear Interpolation Program

This Appendix contains the Fortran code for the linear interpolation program, IPower. IPower is written as a subroutine which can be used with other programs such as the simulation program (Search) or programs written to develop plots. A subroutine which loads the measured data (LDATA) must be performed before calling IPower. LDATA is not included with IPower to preclude loading the data each time IPower is called.

IPower determines, by linear interpolation, the output power corresponding to the water height and control surface positions input.

Figure D-1 is a diagram showing the processes utilized in IPower. After the measured data is loaded into arrays. IPower iteratively interpolates the output power between control surface positions and between water heights which are stored in the data arrays. The variables H1, H2, T1, T2, X1, X2, Y1, Y2, Z1, Z2, are the stored measured data values closest to the input water heights and control surface positions respectively.

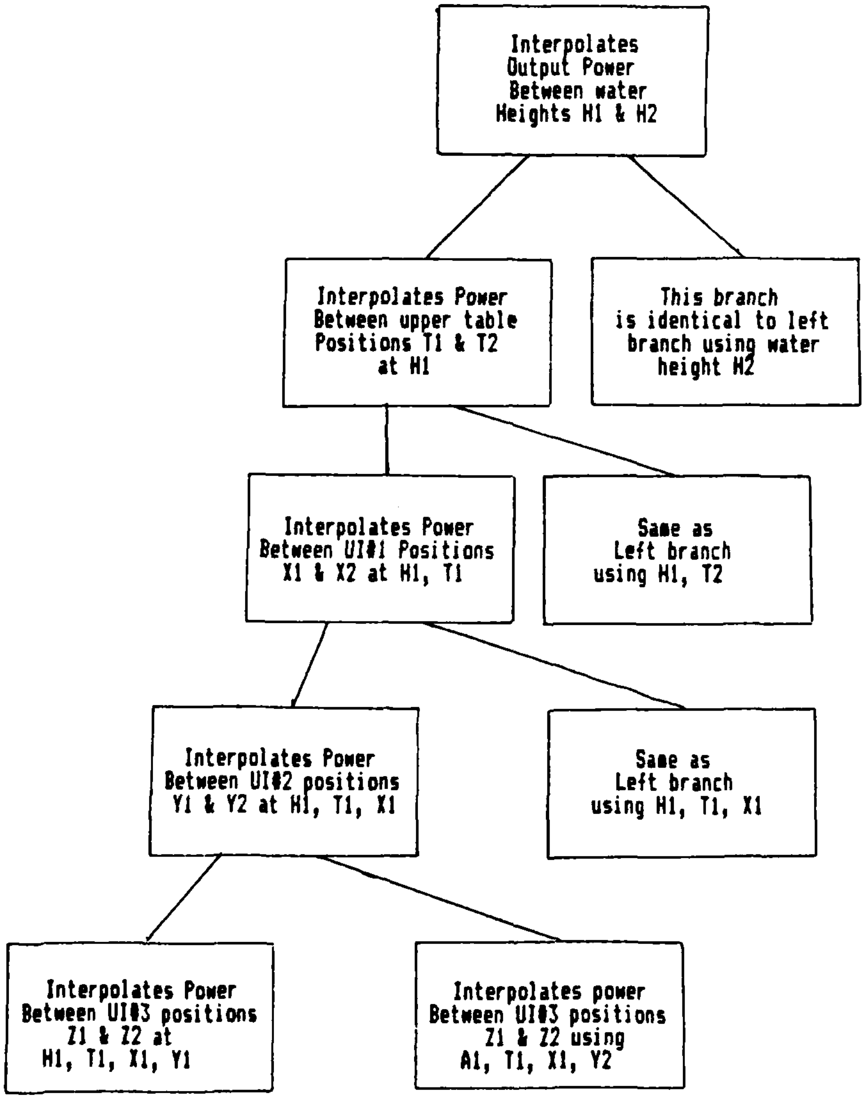


Fig. D-1 IPower

```
************************************************************
*
*     NAME:  SUBROUTINE LDATA
*     DATE:  18 OCT 84
*     MODULE NUMBER: N/A
*     FUNCTION:  THIS SUBROUTINE READS THE TURBINE DATA FROM
*                THE DATA INFO FILE DINFO.  THIS SUBROUTINE
*                MUST BE CALLED PRIOR TO CALLING IPOWER.
*     INPUTS:  NONE
*     OUTPUTS: TPS, UI
*     FILES READ:  DINFO
*     FILES WRITTEN:  NONE
*     MODULES CALLED:  NONE
*     CALLING MODULES:  CALLING PROGRAM WHICH UTILIZES
*                       SUBROUTINE IPOWER.
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************

      SUBROUTINE LDATA(TPS,UI)
      REAL TPS(4,8),UI(4,8,135)
      INTEGER J,K,L,M,N,P,R
      OPEN(UNIT=1,FILE='DINFO')
      REWIND 1
      DO 40 J=1,4
         IF (J.EQ.3) THEN
            R=8
         ELSE
            R=6
         END IF
         DO 30 K=1,R
            READ(1,100)TPS(J,K)
 30      CONTINUE
 40   CONTINUE
      DO 80 L=1,4
         IF (L.EQ.3) THEN
            R=8
         ELSE
            R=6
         ENDIF
         DO 70 M=1,R
            DO 50 N=1,6
               READ(1,100)UI(L,M,N)
 50         CONTINUE
            IF (UI(L,M,6).NE.0.0) THEN
               DO 60 P=7,131
                  READ(1,100)UI(L,M,P)
 60            CONTINUE
            END IF
 70      CONTINUE
 80   CONTINUE
 100  FORMAT(F10.5)
```

```
      END

************************************************************
*
*     NAME:  SUBROUTINE IPOWER
*     DATE:  18 OCT 84
*     MODULE NUMBER:  1
*     FUNCTION:  THIS SUBROUTINE IS OUTPUTS THE LINEAR
*                INTERPOLATED OUTPUT POWER P BASED UPON THE
*                UPPER TABLE AND UPPER INLETS POSITIONS.
*     INPUTS:  W - WATER HEIGHT
*              G - UPPER TABLE POSITION
*              A - UPPER INLET #1 POSITION
*              B - UPPER INLET #2 POSITION
*              C - UPPER INLET #3 POSITION
*              TPS - TABLE POSITION DATA ARRAY
*              UI  - UPPER INLET DATA ARRAY
*     OUTPUTS:  P - OUTPUT POWER
*     MODULES CALLED: H1H2, PWGABC, LINEAR
*     CALLING MODULES:  SEARCH (CONTROLLER TEST PROGRAM),
*                       PLOTTING PROGRAMS.
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE IPOWER(W,G,A,B,C,TPS,UI,P)
      REAL W,G,A,B,C,P,P1,P2,H1,H2
      REAL TPS(4,8),UI(4,8,135)
      CALL H1H2(W,H1,H2)
      CALL PHGABC(H1,G,A,B,C,TPS,UI,P1)
      CALL PHGABC(H2,G,A,B,C,TPS,UI,P2)
      CALL LINEAR(H1,P1,H2,P2,W,P)
      END

************************************************************
*
*     NAME:  SUBROUTINE H1H2
*     DATE:  18 OCT 84
*     MODULE NUMBER:  2
*     FUNCTION:  THIS MODULE DETERMINES FROM THE DATA TABLE
*                THE CLOSEST WATER HEIGHTS ABOVE AND BELOW
*                THE INPUT WATER HEIGHT W.
*     INPUTS:  W - CURRENT WATER HEIGHT
*     OUTPUTS:  H1 - DATA WATER HEIGHT BELOW W
*               H2 - DATA WATER HEIGHT ABOVE W
*     MODULES CALLED:  NONE
*     CALLING MODULES:  IPOWER
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE H1H2(W,H1,H2)
      REAL W,H1,H2
      IF (W.EQ.12.125) THEN
```

```
         H1=W
         H2=W
      ELSE IF (W.EQ.13.125) THEN
         H1=W
         H2=W
      ELSE IF (W.EQ.14.0) THEN
         H1=W
         H2=W
      ELSE IF (W.EQ.19.875) THEN
         H1=W
         H2=W
      ELSE IF (W.LT.13.125) THEN
         H1=12.125
         H2=13.125
      ELSE IF (W.LT.14.0) THEN
         H1=13.125
         H2=14.0
      ELSE
         H1=14.0
         H2=19.875
      END IF
      END

************************************************************
*
*     NAME:  PHGABC
*     DATE:  18 OCT 84
*     MODULE NUMBER:  3
*     FUNCTION:  FINDS THE LINEAR INTERPOLATE POWER AT A
*                WATER HEIGHT IN THE DATA TABLE H FOR ANY
*                CONTROL SURFACE POSITIONS.
*     INPUTS:  H - DATA TABLE WATER HEIGHT
*              G - UPPER TABLE POSITION
*              A - UPPER INLET #1 POSITION
*              B - UPPER INLET #2 POSITION
*              C - UPPER INLET #3 POSITION
*              TPS - TABLE POSITION DATA ARRAY
*              UI - UPPER INLET DATA ARRAY
*     OUTPUTS:  PT - INTERPOLATED OUTPUT POWER
*     MODULES CALLED:  T1T2,PHTABC,LINEAR
*     CALLING MODULES:  IPOWER
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE PHGABC(H,G,A,B,C,TPS,UI,PT)
      REAL H,G,A,B,C,T1,T2,PT,PT1,PT2
      REAL TPS(4,8),UI(4,8,135)
      CALL T1T2(H,G,TPS,T1,T2)
      CALL PHTABC(H,T1,A,B,C,UI,TPS,PT1)
      CALL PHTABC(H,T2,A,B,C,UI,TPS,PT2)
      CALL LINEAR(T1,PT1,T2,PT2,G,PT)
      END
```

```
************************************************************
*
*     NAME:  SUBROUTINE T1T2
*     DATE:  18 OCT 84
*     MODULE NUMBER: 4
*     FUNCTION:  FINDS FROM THE DATA TABLES THE CLOSEST
*                UPPER TABLE POSITIONS GREATER AND LESS THAN
*                THE INPUT TABLE POSITION G.
*     INPUTS:  H - DATA TABLE WATER HEIGHT
*              G - UPPER TABLE POSITION
*              TPS - TABLE POSITION ARRAY
*     OUTPUTS: T1 - DATA TABLE UPPER TABLE POSITION
*              T2 - DATA TABLE UPPER TABLE POSITION
*     MODULES CALLED:  NONE
*     CALLING MODULES:  PHGABC
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE T1T2(H,G,TPS,T1,T2)
      REAL H,G,T1,T2
      REAL TPS(4,8)
      INTEGER S,R,I,J,DUM
      DUM=0
      IF (H.EQ.12.125) THEN
         S=1
         R=6
      ELSE IF (H.EQ.13.125) THEN
         S=2
         R=6
      ELSE IF (H.EQ.14.0) THEN
         S=3
         R=8
      ELSE
         S=4
         R=6
      END IF
      DO 70 I=1,R
         IF (G.EQ.TPS(S,I)) THEN
            T1=TPS(S,I)
            T2=TPS(S,I)
            DUM=5
         ELSE IF (I.EQ.R) THEN
           DO 20 J=1,R-1
              IF (DUM.NE.5) THEN
                 IF (G.LT.TPS(S,J+1)) THEN
                    T1=TPS(S,J)
                    T2=TPS(S,J+1)
                    DUM=5
                 END IF
              END IF
 20        CONTINUE
          END IF
```

```
 70   CONTINUE
      END

*************************************************************
*
*     NAME:  SUBROUTINE PHTABC
*     DATE:  18 OCT 84
*     MODULE NUMBER:  5
*     FUNCTION:  FIND THE LINEAR INTERPOLATED POWER AT DATA
*                TABLE WATER HEIGHT H AND UPPER TABLE
*                POSITION T FOR ANY UPPER INLET POSITIONS.
*                IF THE UPPER INLET POSITIONS ARE WITHIN A
*                DEV DISTANCE FROM ONE ANOTHER THEN THEY ARE
*                CONSIDERED AT THE SAME POSITION (ALIGNED).
*     INPUTS:  H - DATA TABLE WATER HEIGHT
*              T - DATA TABLE UPPER TABLE POSITION
*              A - UPPER INLET POSITION #1
*              B - UPPER INLET POSITION #2
*              C - UPPER INLET POSITION #3
*              UI - UPPER INLET DATA ARRAY
*              TPS - UPPER TABLE POSITION DATA ARRAY
*     OUTPUTS:  PX - INTERPOLATED OUTPUT POWER
*     MODULES CALLED:  UIPS, PHTXY, LINEAR, PHTXBC
*     CALLING MODULES:  PHGABC
*     AUTHOR:  CAPT DAVE RAMSEY
*
*************************************************************
      SUBROUTINE PHTABC(H,T,A,B,C,UI,TPS,PX)
      REAL H,T,A,B,C,PX,X1,X2,PX1,PX2,DEV
      REAL TPS(4,8),UI(4,8,135)
      INTEGER S,I
      CALL UIPS(H,T,A,UI,TPS,X1,X2,S,I)
      DEV=.015625
      IF (B.LE.A+DEV.AND.B.GE.A-DEV.AND.C.LE.B+DEV.AND.C.GE.B-DEV) THEN
          CALL PHTXYZ(X1,X1,X1,UI,PX1,S,I)
          CALL PHTXYZ(X2,X2,X2,UI,PX2,S,I)
          CALL LINEAR(X1,PX1,X2,PX2,B,PX)
      ELSE
        CALL PHTXBC(H,T,X1,B,C,UI,TPS,PX1)
        CALL PHTXBC(H,T,X2,B,C,UI,TPS,PX2)
        CALL LINEAR(X1,PX1,X2,PX2,A,PX)
      END IF
      END

*************************************************************
*
*     NAME:  SUBROUTINE PHTXBC
*     DATE:  18 OCT 84
*     MODULE NUMBER:  6
*     FUNCTION:  DETERMINE THE INTERPOLATE POWER USING THE
*                DATA TABLE WATER HEIGHT H, UPPER TABLE
*                POSITION T, AND UPPER INLET #1 POSITION X
```

```
*                WITH ANY POSITION FOR UPPER INLETS 2 & 3.
*      INPUTS:  H - DATA TABLE WATER HEIGHT
*               T - DATA TABLE UPPER TABLE POSITION
*               X - DATA TABLE UPPER INLET #1 POSITION
*               B - UPPER INLET #2 POSITION
*               C - UPPER INLET #3 POSITION
*               UI - UPPER INLET DATA ARRAY
*               TPS - UPPER TABLE POSITION DATA ARRAY
*      OUTPUTS:  PY - INTERPOLATED OUTPUT POWER
*      MODULES CALLED:  UIPS, PHTXYC, LINEAR
*      CALLING MODULES:  PHTABC
*      AUTHOR:  CAPT DAVE RAMSEY
*
***********************************************************
       SUBROUTINE PHTXBC(H,T,X,B,C,UI,TPS,PY)
       REAL H,T,X,B,C,PY,Y1,Y2,PY1,PY2
       REAL TPS(4,8),UI(4,8,135)
       INTEGER S,I
       CALL UIPS(H,T,B,UI,TPS,Y1,Y2,S,I)
       CALL PHTXYC(H,T,X,Y1,C,UI,TPS,PY1)
       CALL PHTXYC(H,T,X,Y2,C,UI,TPS,PY2)
       CALL LINEAR(Y1,PY1,Y2,PY2,B,PY)
       END

***********************************************************
*
*      NAME:  SUBROUTINE PHTXYC
*      DATE:  18 OCT 84
*      MODULE NUMBER:  6
*      FUNCTION:  FINDS THE INTERPOLATED POWER USING THE DATA
*                 TABLE WATER HEIGHT H, UPPER TABLE POSITION
*                 T, UPPER INLET #1 POSITION X, UPPER INLET
*                 #2 POSITION Y WITH ANY POSITION FOR UPPER
*                 INLET #3.
*      INPUTS:  H - DATA TABLE WATER HEIGHT
*               T - DATA TABLE UPPER TABLE POSITION
*               X - DATA TABLE UPPER INLET #1 POSITION
*               Y - DATA TABLE UPPER INLET #2 POSITION
*               C - UPPER INLET #3 POSITION
*               UI - UPPER INLETS DATA ARRAY
*               TPS - UPPER TABLE POSITION DATA ARRAY
*      OUTPUTS:  PZ - INTEROLATED OUTPUT POWER
*      MODULES CALLED:  UIPS, PHTXYZ, LINEAR
*      CALLING MODULES:  PHTXBC
*      AUTHOR:  CAPT DAVE RAMSEY
*
***********************************************************
       SUBROUTINE PHTXYC(H,T,X,Y,C,UI,TPS,PZ)
       REAL H,T,X,Y,C,PZ,Z1,Z2,PZ1,PZ2
       REAL TPS(4,8),UI(4,8,135)
       INTEGER I,S
       CALL UIPS(H,T,C,UI,TPS,Z1,Z2,S,I)
```

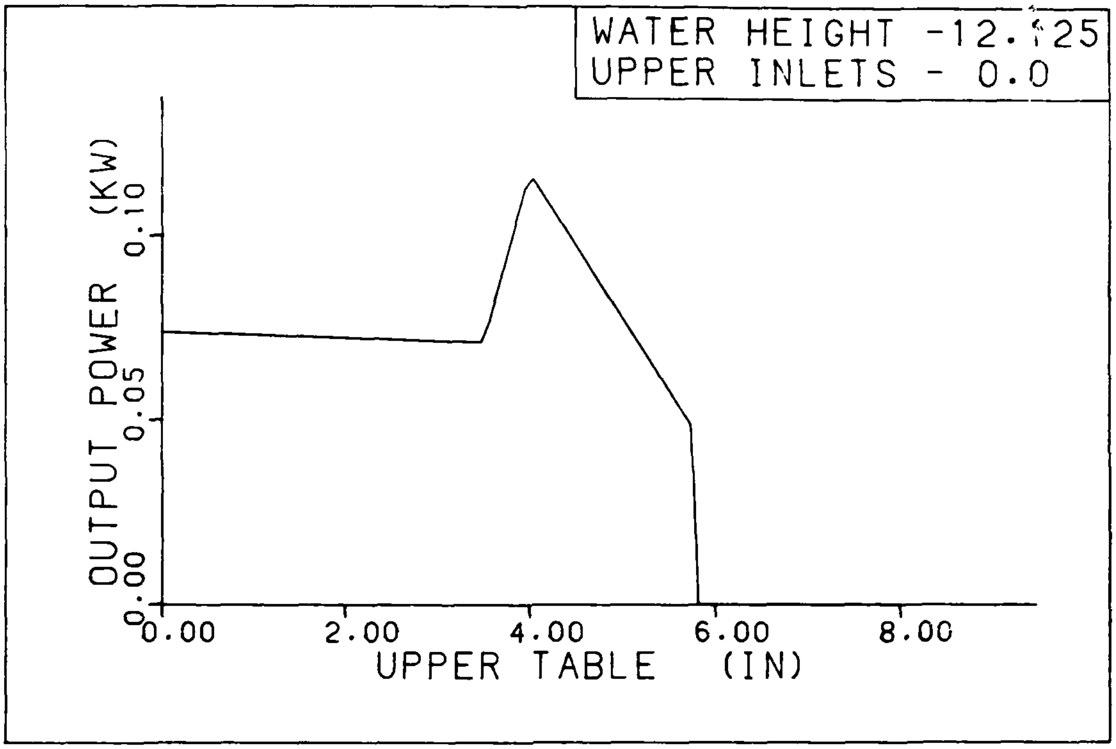
```
      CALL PHTXYZ(X,Y,Z1,UI,PZ1,S,I)
      CALL PHTXYZ(X,Y,Z2,UI,PZ2,S,I)
      CALL LINEAR(Z1,PZ1,Z2,PZ2,C,PZ)
      END

************************************************************
*
*     NAME:  SUBROUTINE UIPS
*     DATE:  18 OCT 84
*     MODULE NUMBER:  7
*     FUNCTION:  FINDS FROM THE DATA TABLE THE CLOSEST UPPER
*                INLET POSITIONS LESS THAN AND GREATER THAN
*                THE INPUT UPPER INLET POSITION XYZ.
*     INPUTS:  H - DATA TABLE WATER HEIGHT
*              T - DATA TABLE UPPER TABLE POSITION
*              XYZ - ANY UPPER INLET POSITION
*              UI - UPPER INLET DATA ARRAY
*              TPS - UPPER TABLE POSITION DATA ARRAY
*     OUTPUTS:  XYZ1 - DATA TABLE UPPER INLET POSITION
*               XYZ2 - DATA TABLE UPPER INLET POSITION
*               S - COUNTER, POSITION OF DATA IN UI ARRAY
*               Q - COUNTER, POSITION OF DATA IN UI ARRAY
*     MODULES CALLED:  NONE
*     CALLING MODULES:  PHTABC, PHTXBC, PHTXYC
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE UIPS(H,T,XYZ,UI,TPS,XYZ1,XYZ2,S,Q)
      REAL H,T,XYZ,XYZ1,XYZ2
      REAL TPS(4,8),UI(4,8,135)
      INTEGER S,I,J,W,V,Q,DUMY
      DUMY=0
      IF (H.EQ.12.125) THEN
         S=1
         J=6
      ELSE IF (H.EQ.13.125) THEN
         S=2
         J=6
      ELSE IF (H.EQ.14.0) THEN
         S=3
         J=8
      ELSE
         S=4
         J=6
      END IF
      DO 60 I=1,J
         IF (T.EQ.TPS(S,I)) THEN
            Q=I
            DO 20 W=1,5
               IF (XYZ.EQ.UI(S,I,W)) THEN
                  XYZ1=XYZ
                  XYZ2=XYZ
```

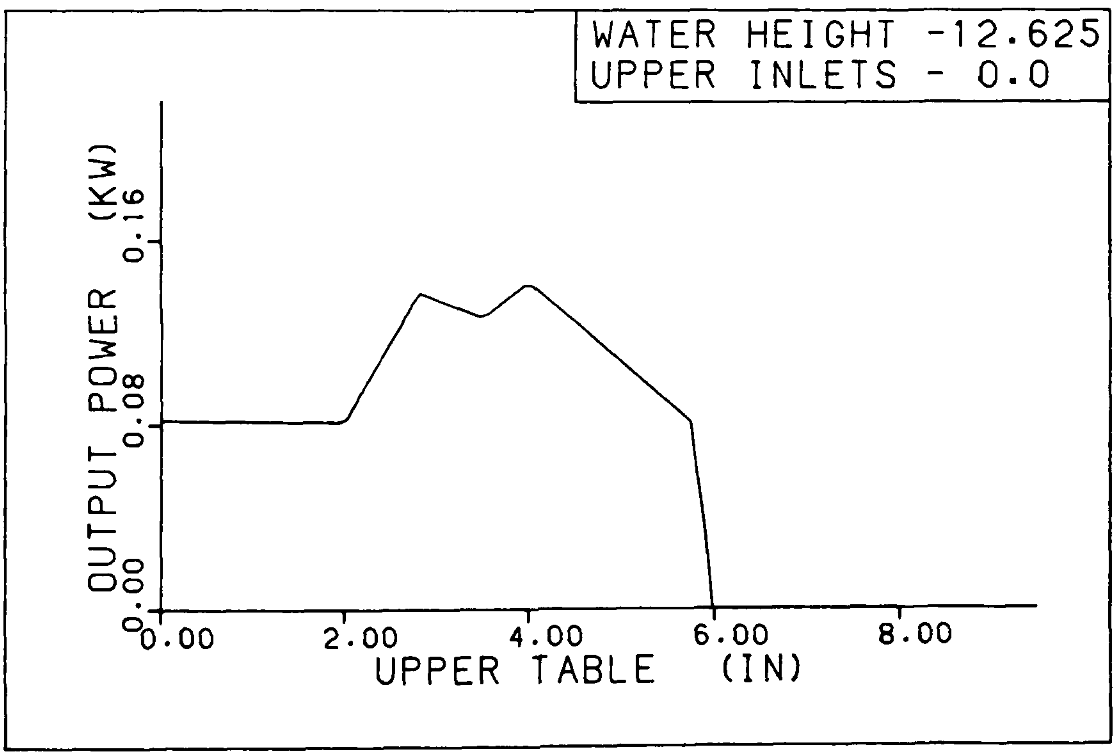
```
                DUMY=6
             END IF
 20        CONTINUE
           IF (DUMY.NE.6) THEN
             IF (XYZ.LT.UI(S,I,2)) THEN
                XYZ1=UI(S,I,1)
                XYZ2=UI(S,I,2)
             ELSE IF (XYZ.LT.UI(S,I,3)) THEN
                XYZ1=UI(S,I,2)
                XYZ2=UI(S,I,3)
             ELSE IF (XYZ.LT.UI(S,I,4)) THEN
                XYZ1=UI(S,I,3)
                 XYZ2=UI(S,I,4)
             ELSE
                XYZ1=UI(S,I,4)
                XYZ2=UI(S,I,5)
             END IF
           END IF
        END IF
 60   CONTINUE
      END

************************************************************
*
*     NAME:  SUBROUTINE PHTXYZ
*     DATE:  18 OCT 84
*     MODULE NUMBER:  8
*     FUNCTION:  FINDS THE NON-INTERPOLATED OUTPUT POWER
*                FROM THE DATA TABLE.
*     INPUTS:  X - DATA TABLE UPPER INLET #1 POSITION
*              Y - DATA TABLE UPPER INLET #2 POSITION
*              Z - DATA TABLE UPPER INLET #3 POSITION
*              UI - UPPER INLET DATA ARRAY
*              S - COUNTER, POSITION OF DATA IN UI ARRAY
*              I - COUNTER, POSITION OF DATA IN UI ARRAY
*     OUTPUTS:  PXYZ - DATA TABLE OUTPUT POWER
*     MODULES CALLED:  NONE
*     CALLING MODULES:  PHTXYC, PHTABC
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE PHTXYZ(X,Y,Z,UI,PXYZ,S,I)
      REAL H,T,X,Y,Z,PXYZ
      REAL UI(4,8,135)
      INTEGER S,I,Q,A,B,C
      IF (UI(S,I,6).EQ.0.0) THEN
         PXYZ=0
      ELSE
        Q=6
        DO 60 A=1,5
           DO 40 B=1,5
              DO 20 C=1,5
```

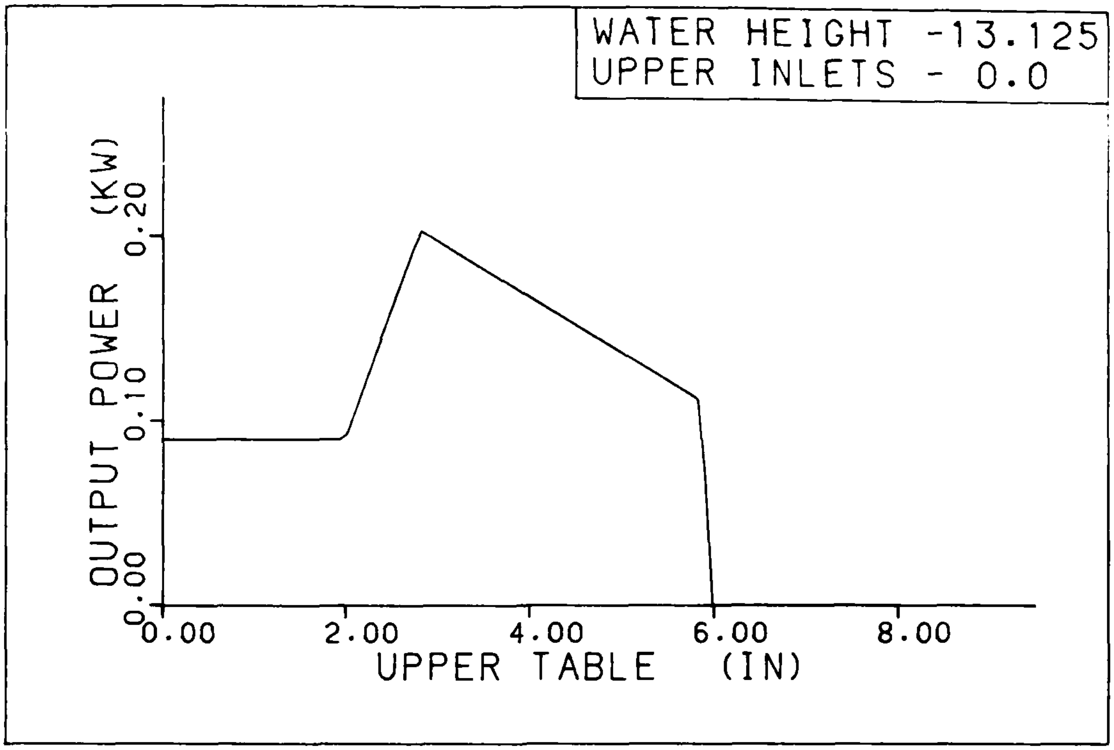
```
                  Q=Q+1
                  IF (X.EQ.UI(S,I,A)) THEN
                     IF (Y.EQ.UI(S,I,B)) THEN
                        IF (Z.EQ.UI(S,I,C)) THEN
                           PXYZ=UI(S,I,Q)
                        END IF
                     END IF
                  END IF
 20            CONTINUE
 40         CONTINUE
 60      CONTINUE
      ENDIF
      END

************************************************************
*
*     NAME:  SUBROUTINE LINEAR
*     DATE:  18 OCT 84
*     MODULE NUMBER:  9
*     FUNCTION:  THIS IS THE WORK HORSE OF THE IPOWER
*                PROGRAM.  THIS SUBROUTINE FINDS THE LINEAR
*                INTERPOLATED VALUE Y3 AT X3 GIVEN TWO OTHER
*                POINTS (X1,Y1) AND (X2,Y2).
*     INPUTS:  X1 - CONTROL SURFACE POSITION OR WATER HEIGHT
*              Y1 - POWER KNOWN AT X1
*              X2 - CONTROL SURFACE POSITION OR WATER HEIGHT
*              Y2 - POWER KNOWN AT X2
*              X3 - CONTROL SURFACE POSITION OR WATER HEIGHT
*     OUTPUTS:  Y3 - INTERPOLATED POWER AT X3
*     MODULES CALLED:  NONE
*     CALLING MODULES:  IPOWER, PHGABC, PHTABC, PHTXBC,
*                       PHTXYC
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE LINEAR (X1,Y1,X2,Y2,X3,Y3)
      REAL X1,X2,X3,Y1,Y2,Y3,A,B,C,BN,BD
      BN=Y1*(X1-X2)-X1*(Y1-Y2)
      BD=X1-X2
      IF (BD.EQ.0.0) THEN
         Y3=(Y1+Y2)/2
      ELSE
         B=BN/BD
         A=(Y1-Y2)/(X1-X2)
         Y3=A*X3+B
      END IF
      IF (Y3.LT.0.0) THEN
        Y3=0
      END IF
      END
```

Appendix E.

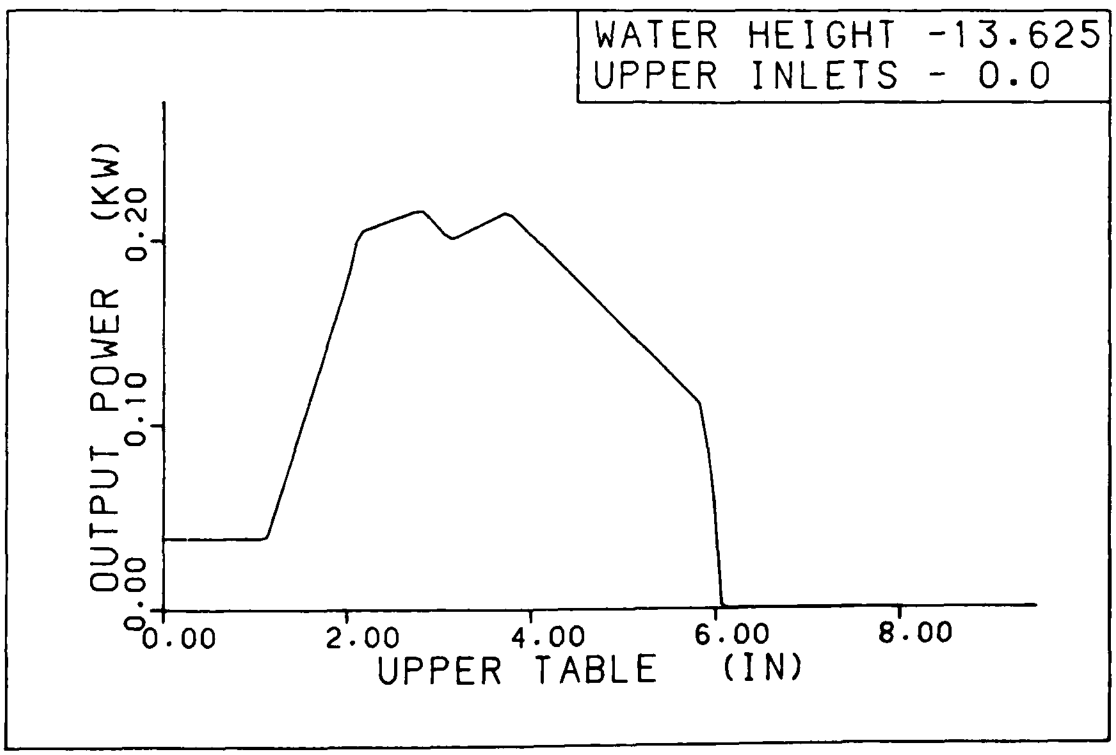
Upper Table vs Output Plots


WATER HEIGHT -12. 25
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.05
0.10
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

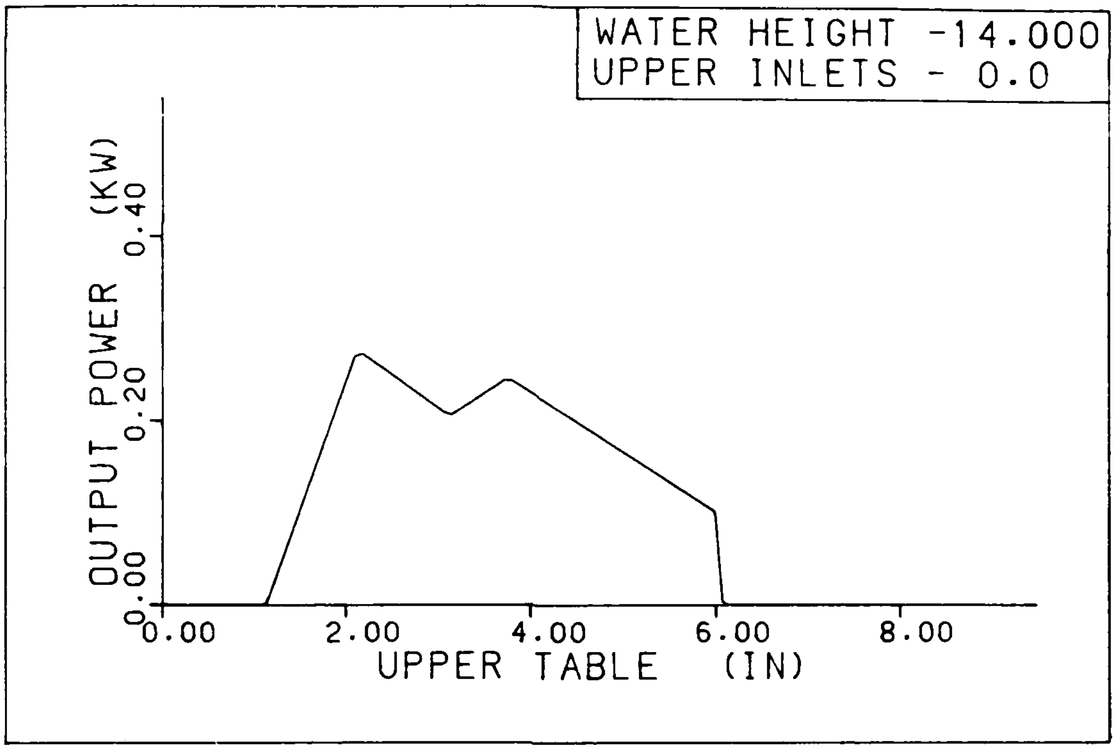

WATER HEIGHT -12.625
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.08
0.16
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)



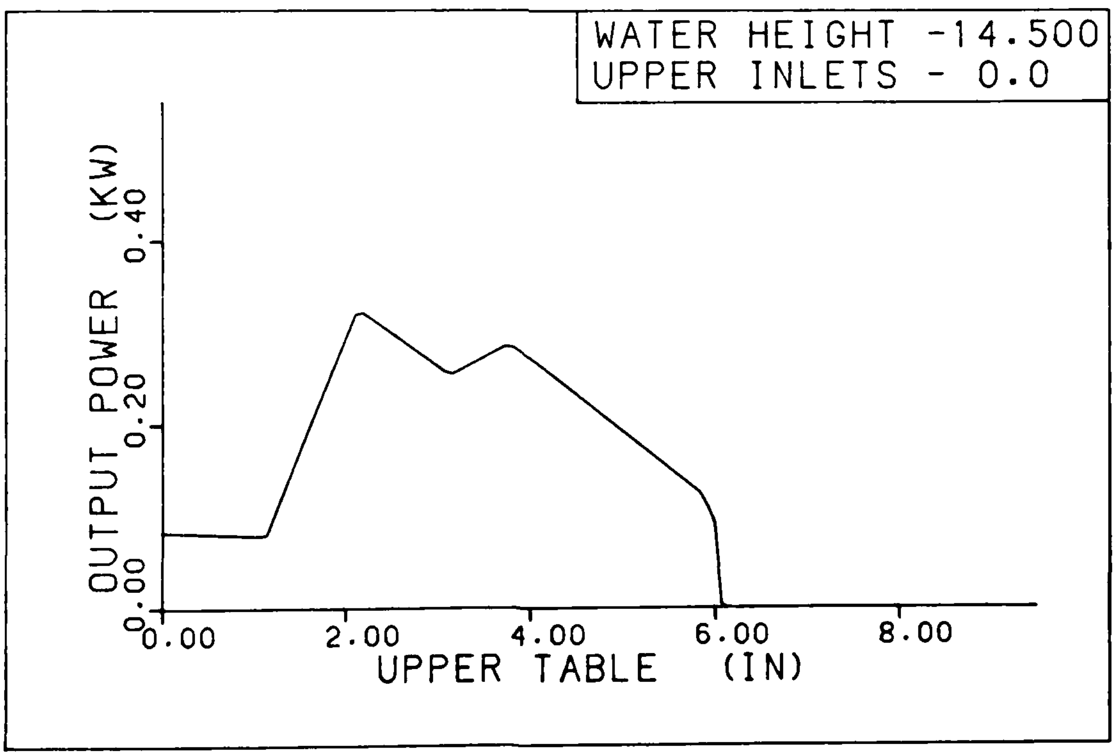
WATER HEIGHT -13.125
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.10
0.20
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)



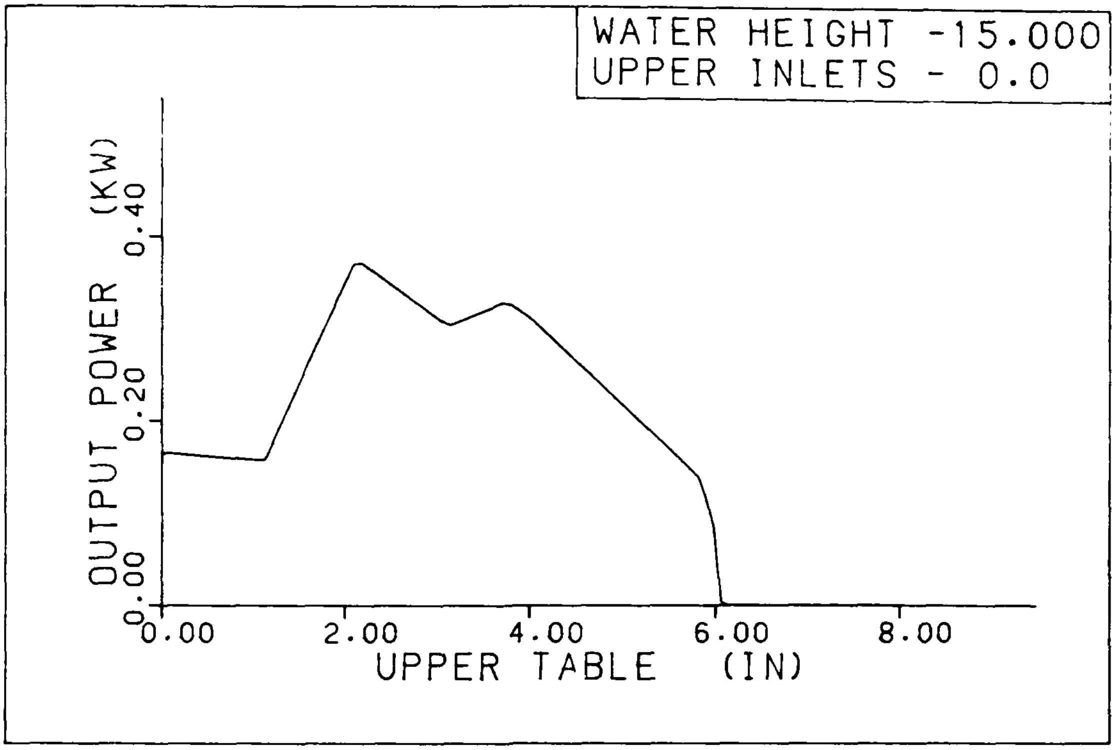
WATER HEIGHT -13.625
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.10
0.20
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)



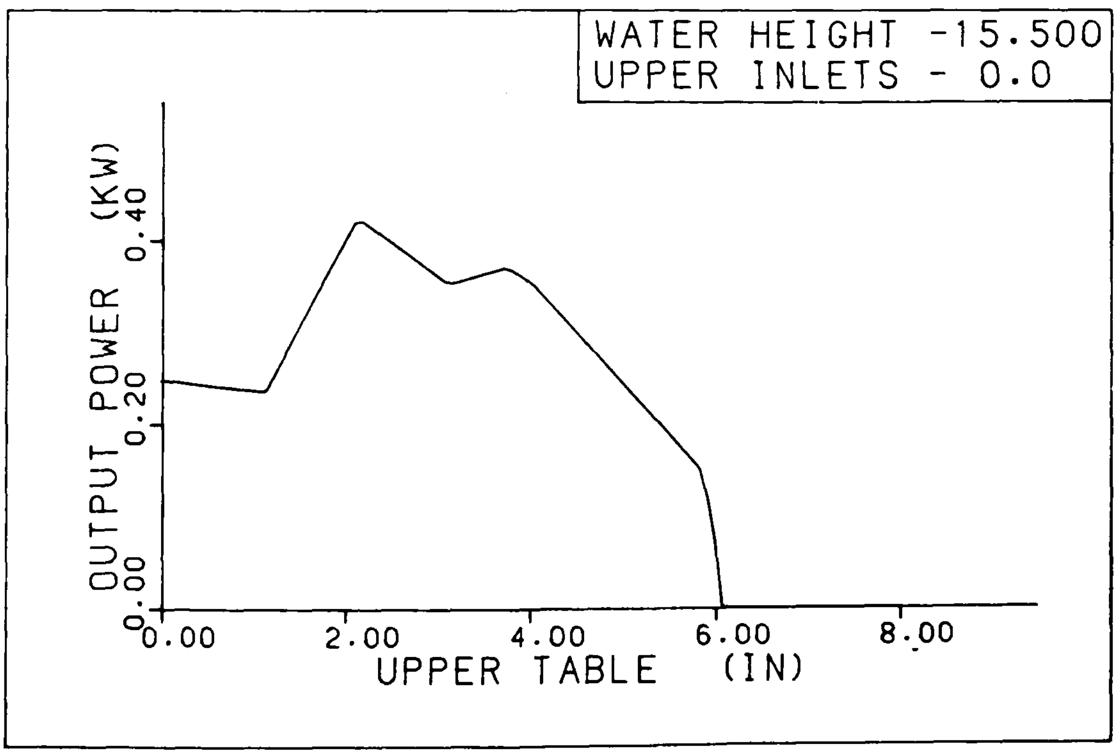
WATER HEIGHT -14.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.20
0.40
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)



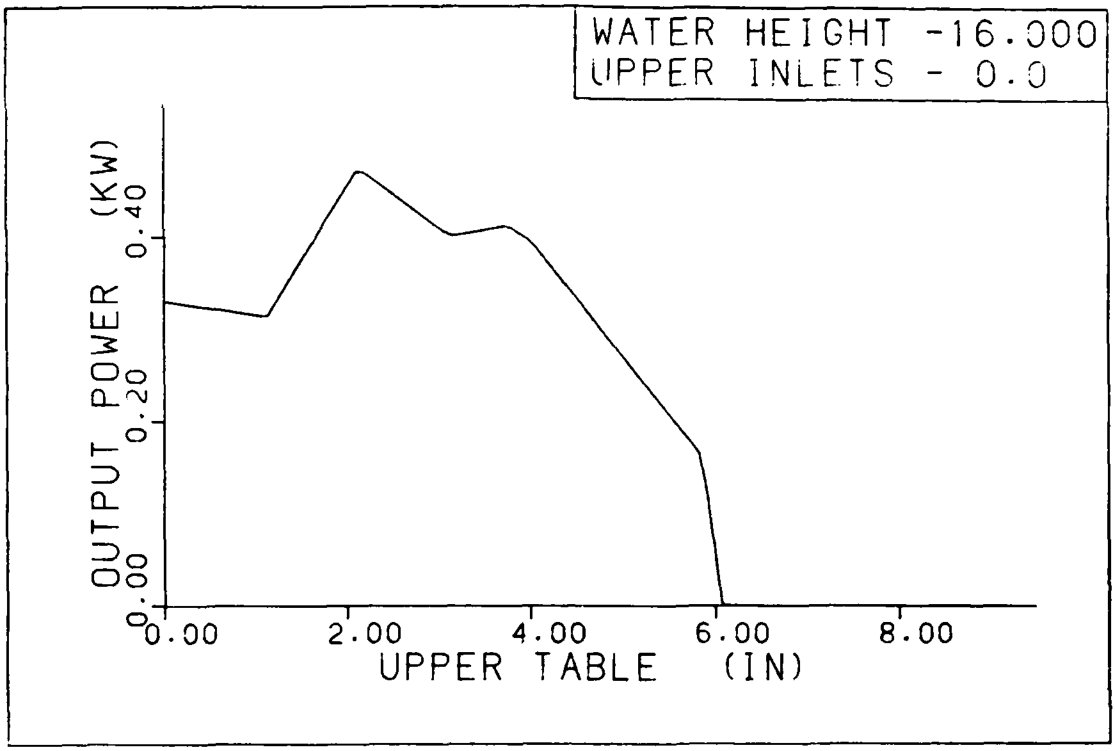
WATER HEIGHT -14.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.20
0.40
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

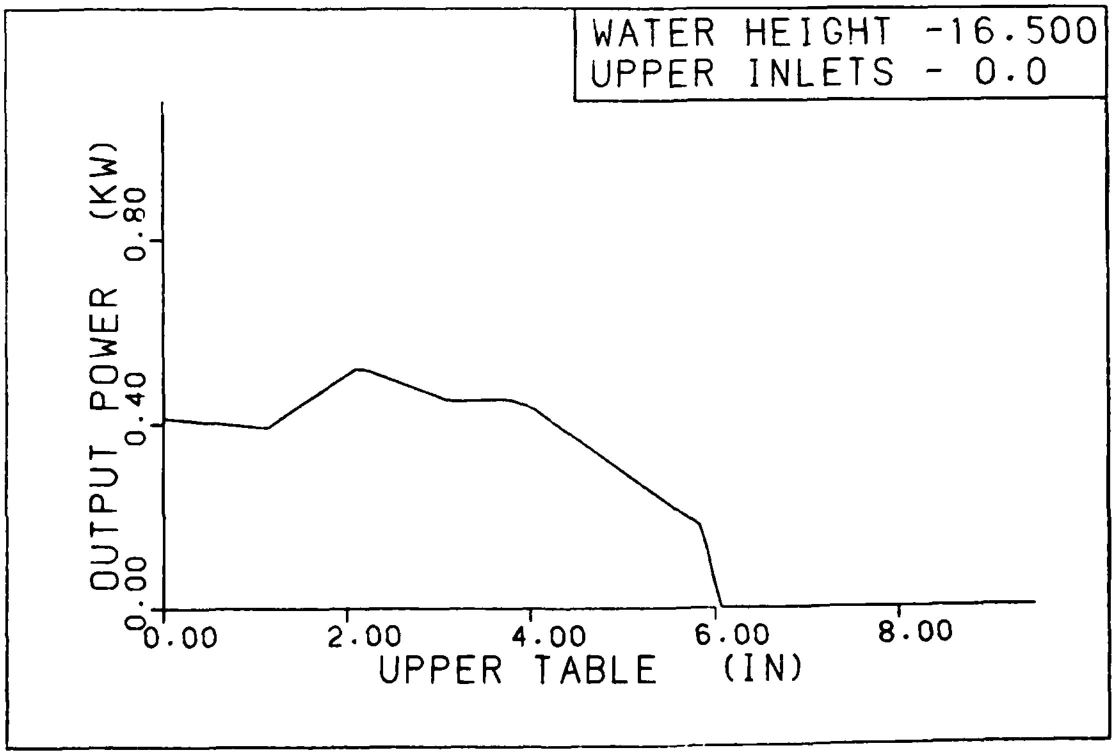


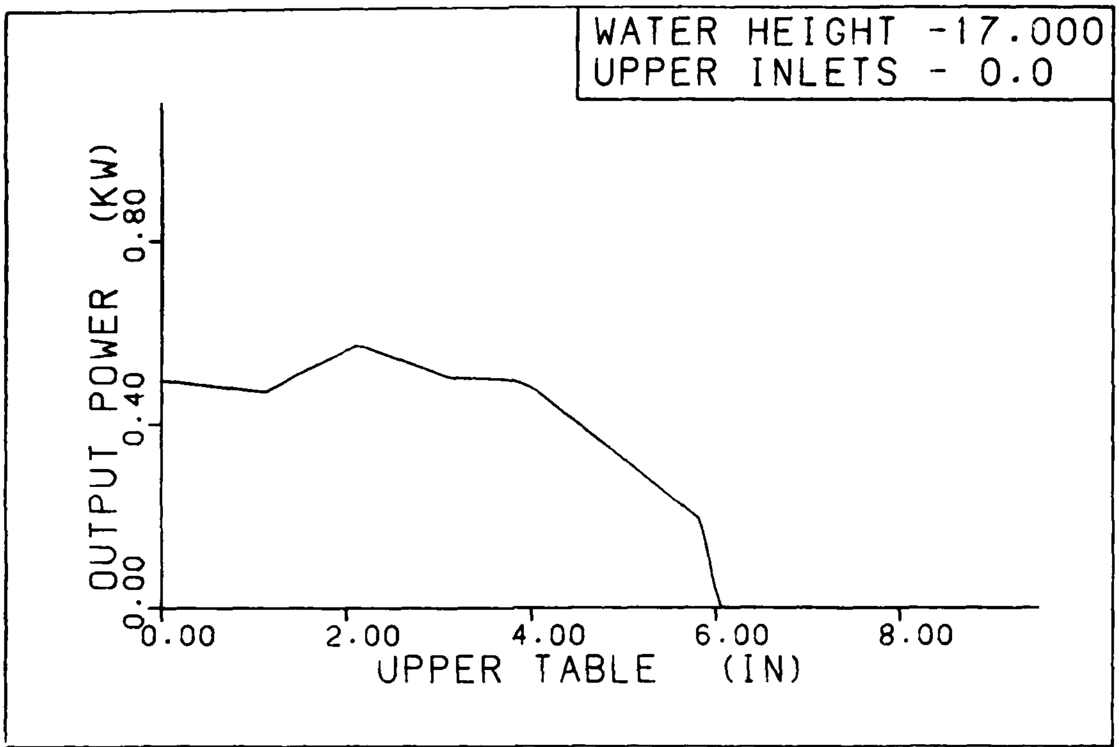
WATER HEIGHT -15.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.20
0.40
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

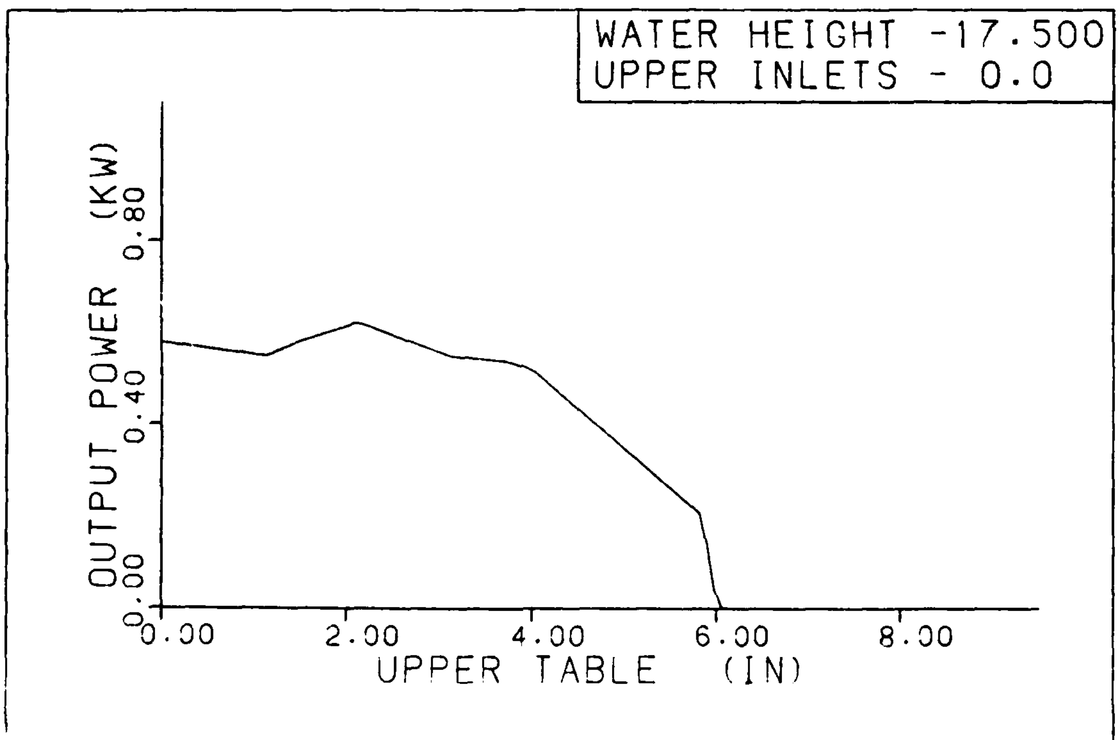


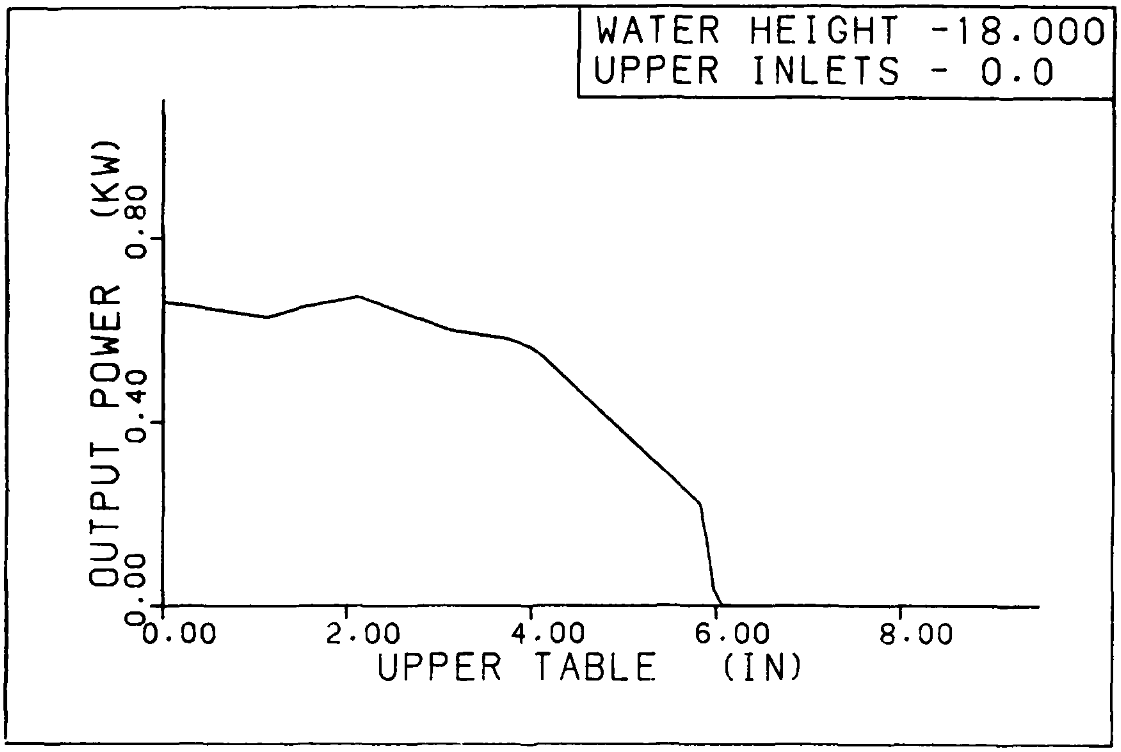
WATER HEIGHT -15.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.20
0.40
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

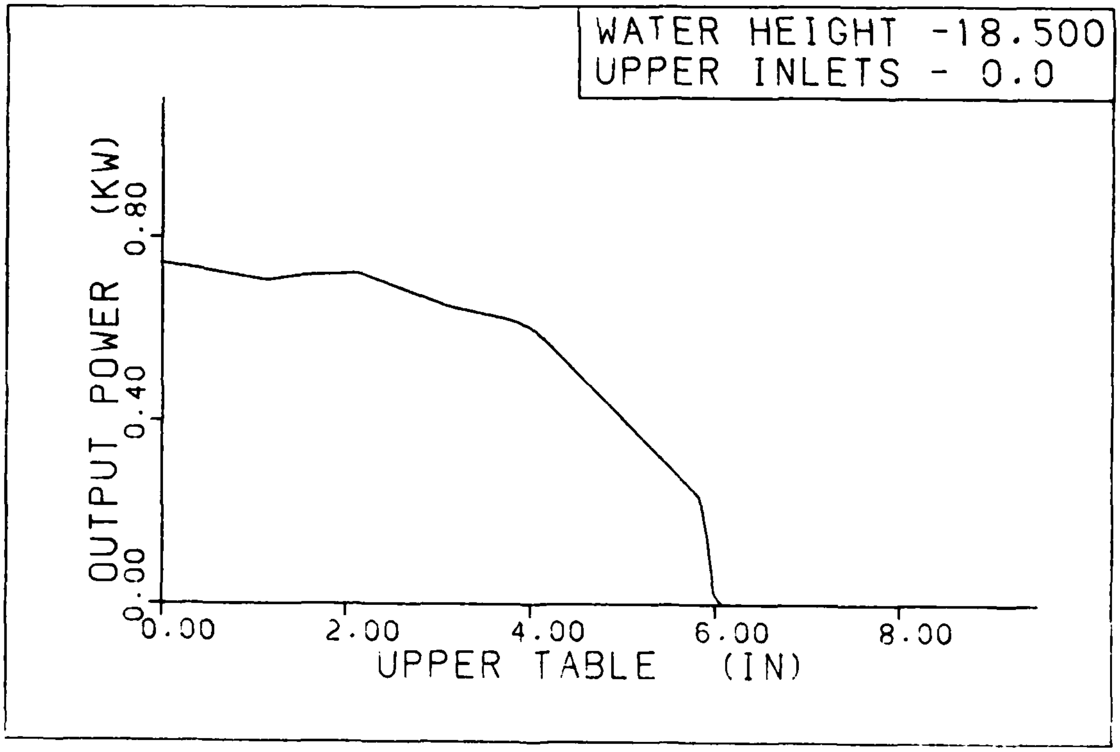

WATER HEIGHT -16.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.20
0.40
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

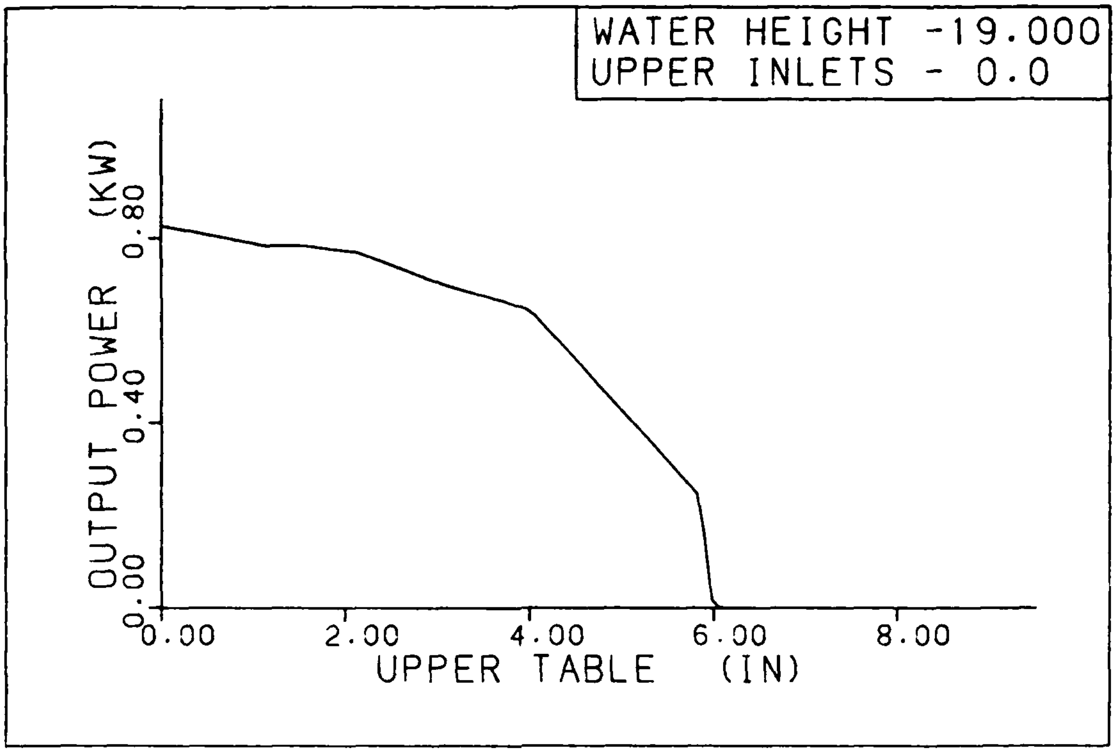

WATER HEIGHT -16.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

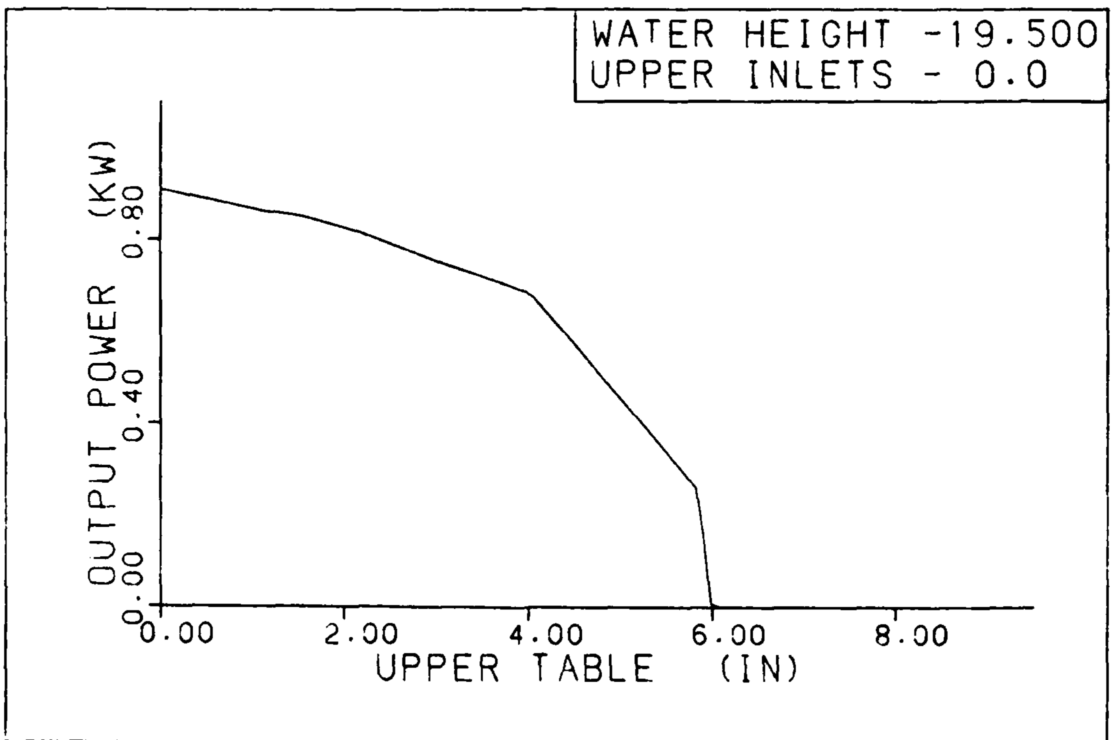

WATER HEIGHT -17.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

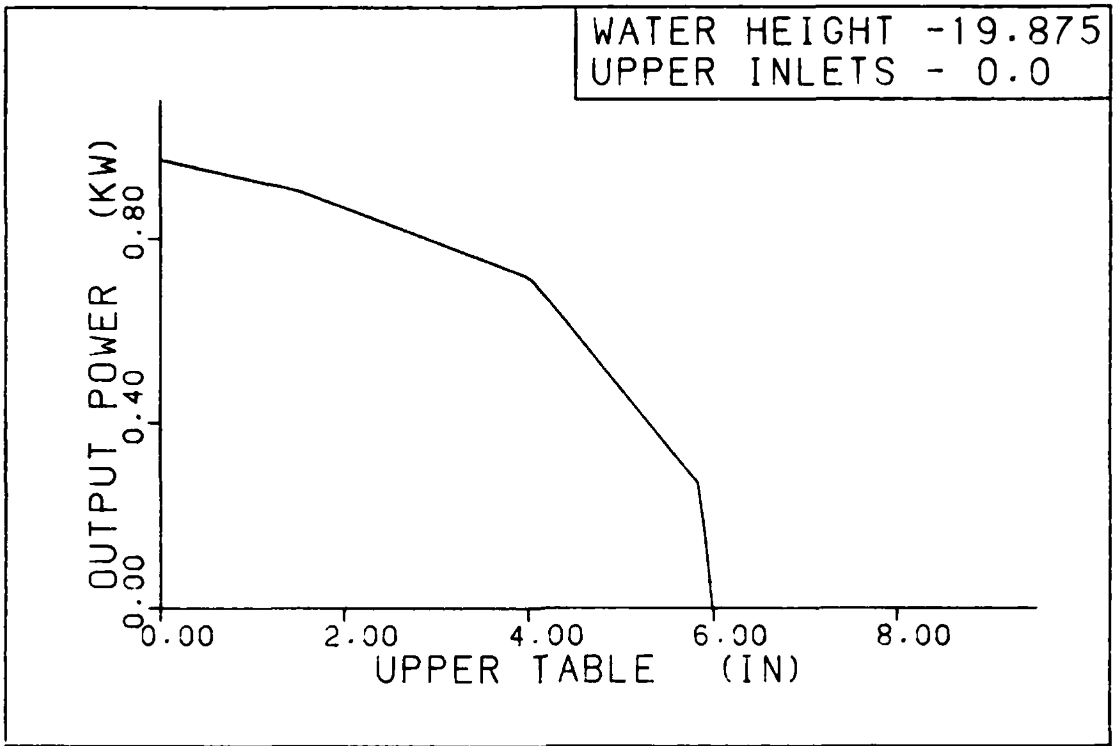

WATER HEIGHT -17.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

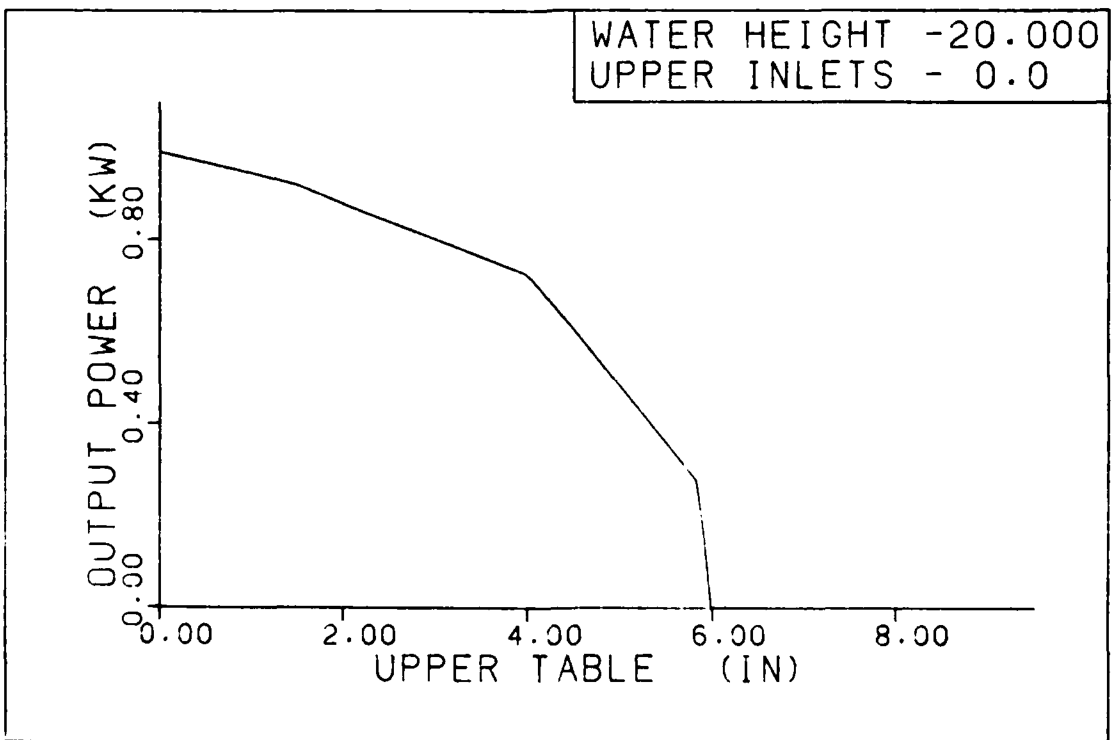

WATER HEIGHT -18.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)


WATER HEIGHT -18.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)


WATER HEIGHT -19.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

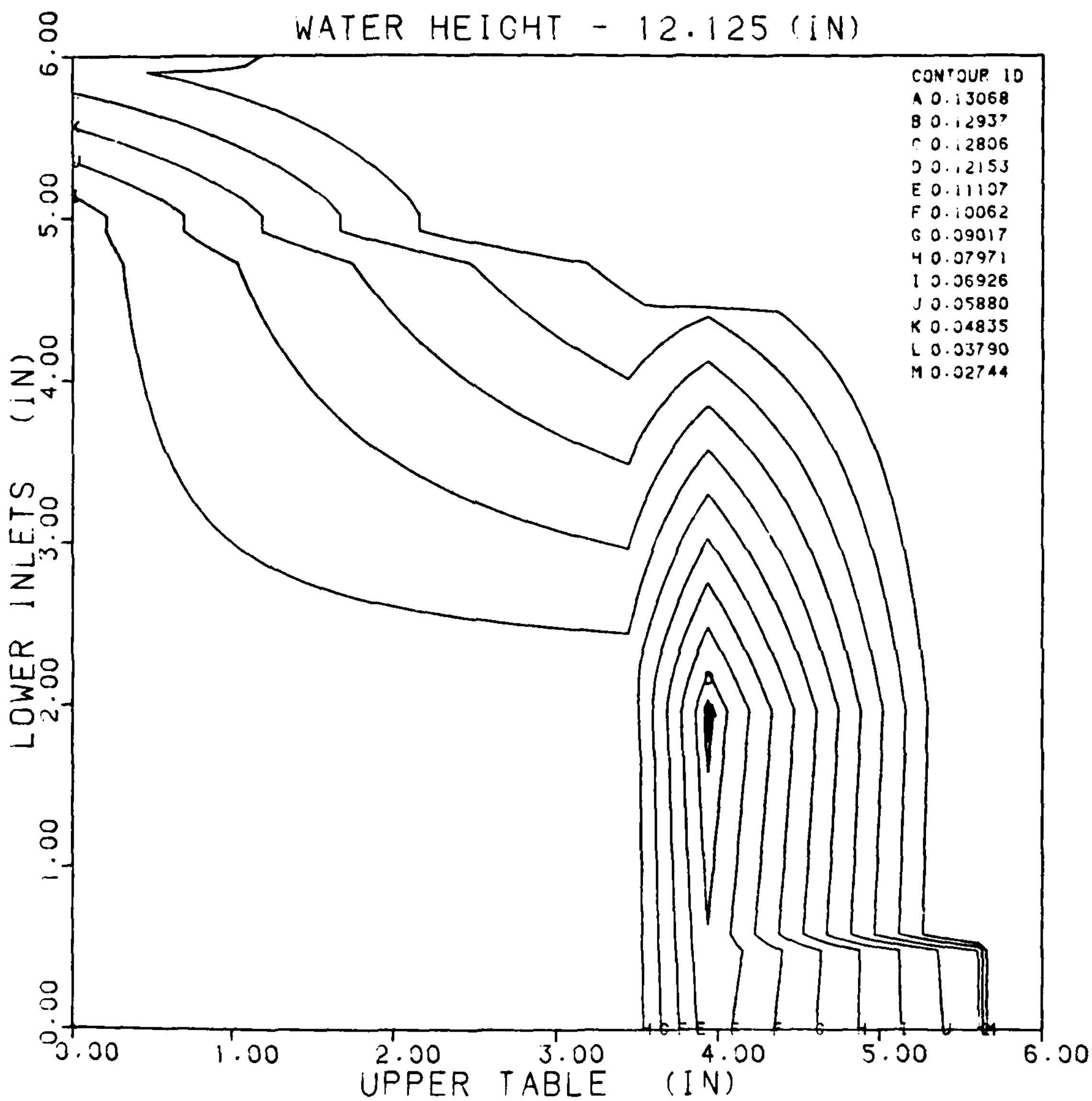

WATER HEIGHT -19.500
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

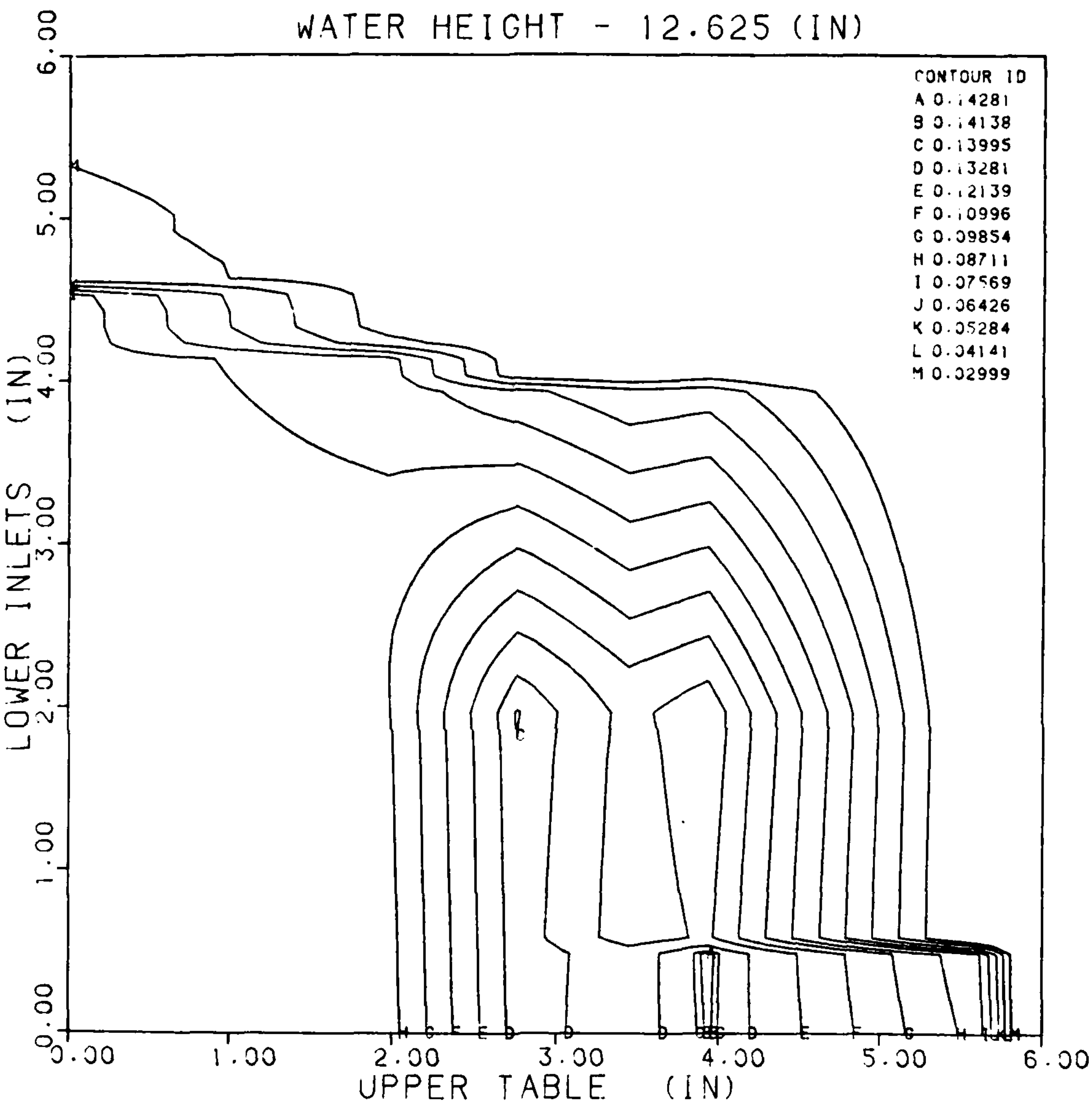

WATER HEIGHT -19.875
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

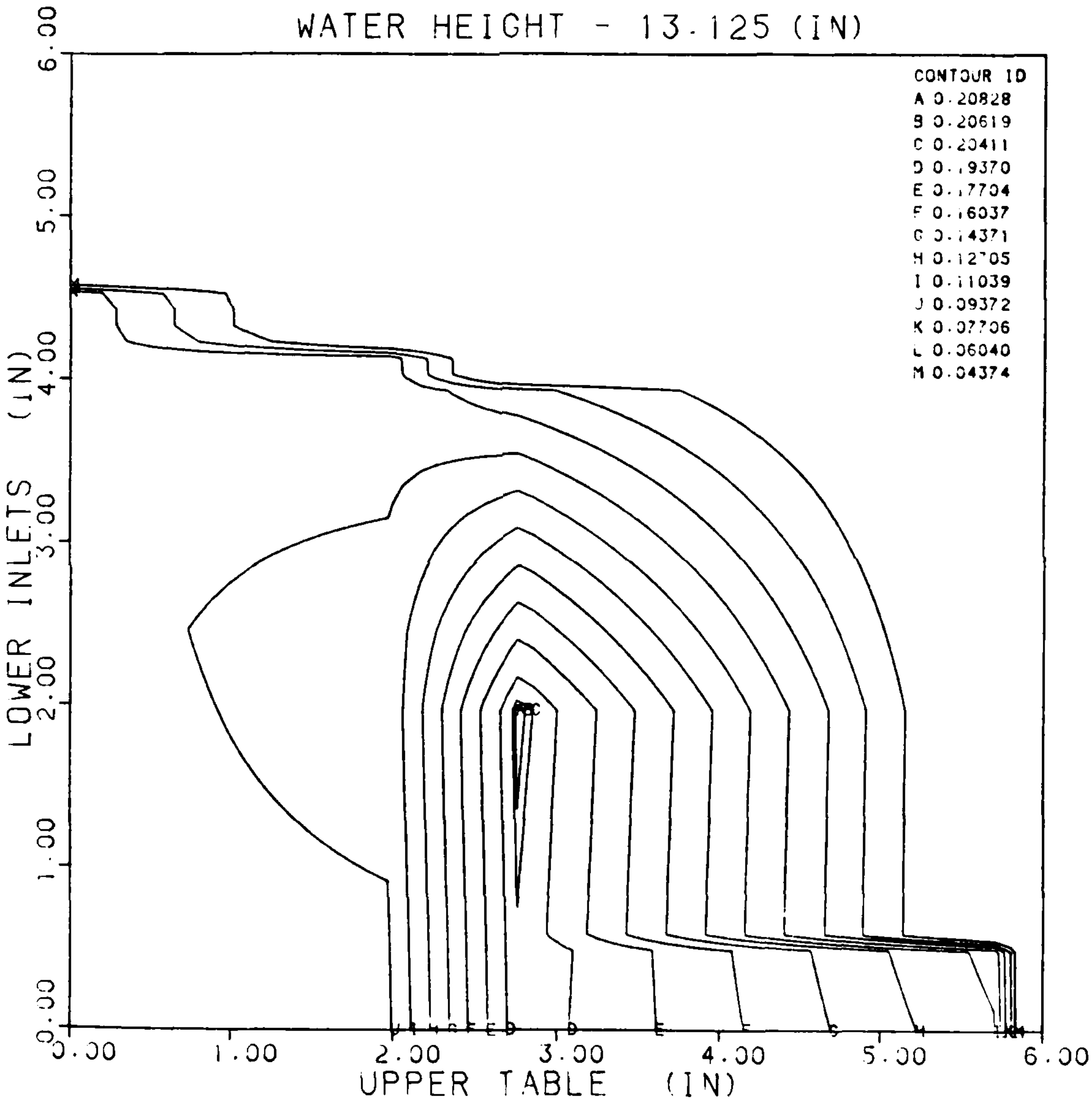

WATER HEIGHT -20.000
UPPER INLETS - 0.0
OUTPUT POWER (KW)
0.00
0.40
0.80
0.00
2.00
4.00
6.00
8.00
UPPER TABLE (IN)

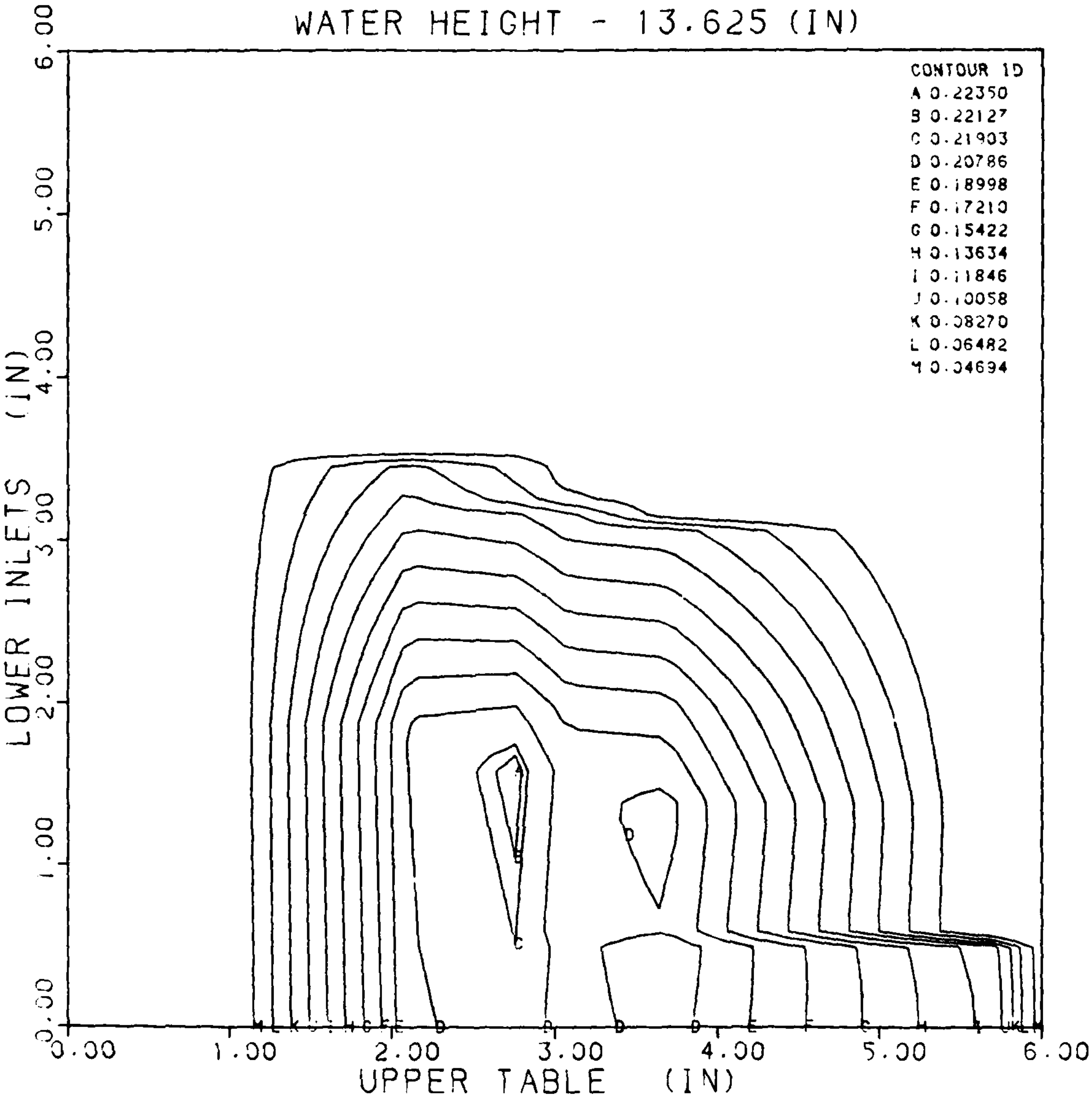
Appendix F.

Contour Plots: Upper Table vs Upper Inlets

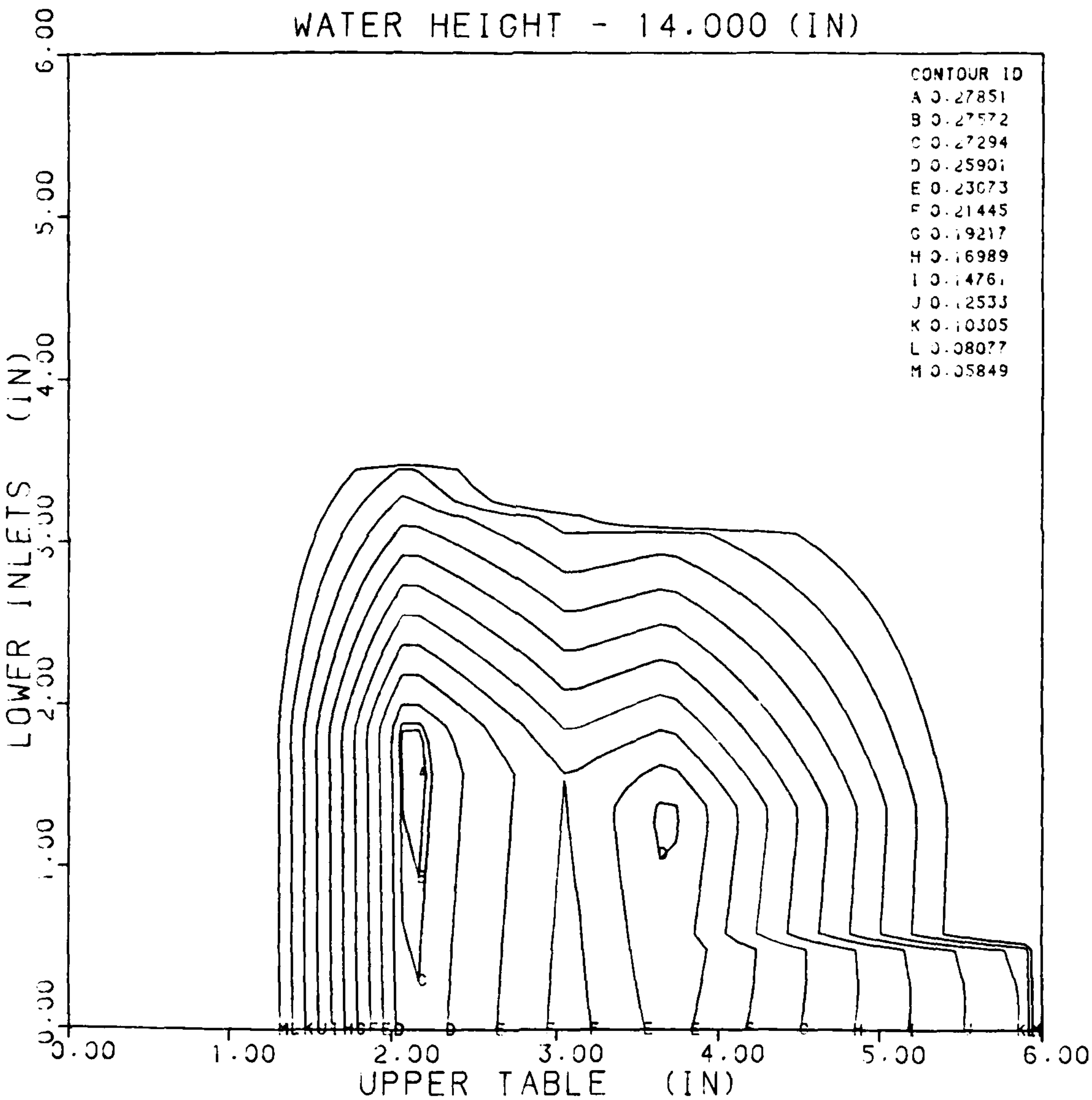

WATER HEIGHT - 12.125 (IN)
CONTOUR ID
A 0.13068
B 0.12937
C 0.12806
D 0.12153
E 0.11107
F 0.10062
G 0.09017
H 0.07971
I 0.06926
J 0.05880
K 0.04835
L 0.03790
M 0.02744
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

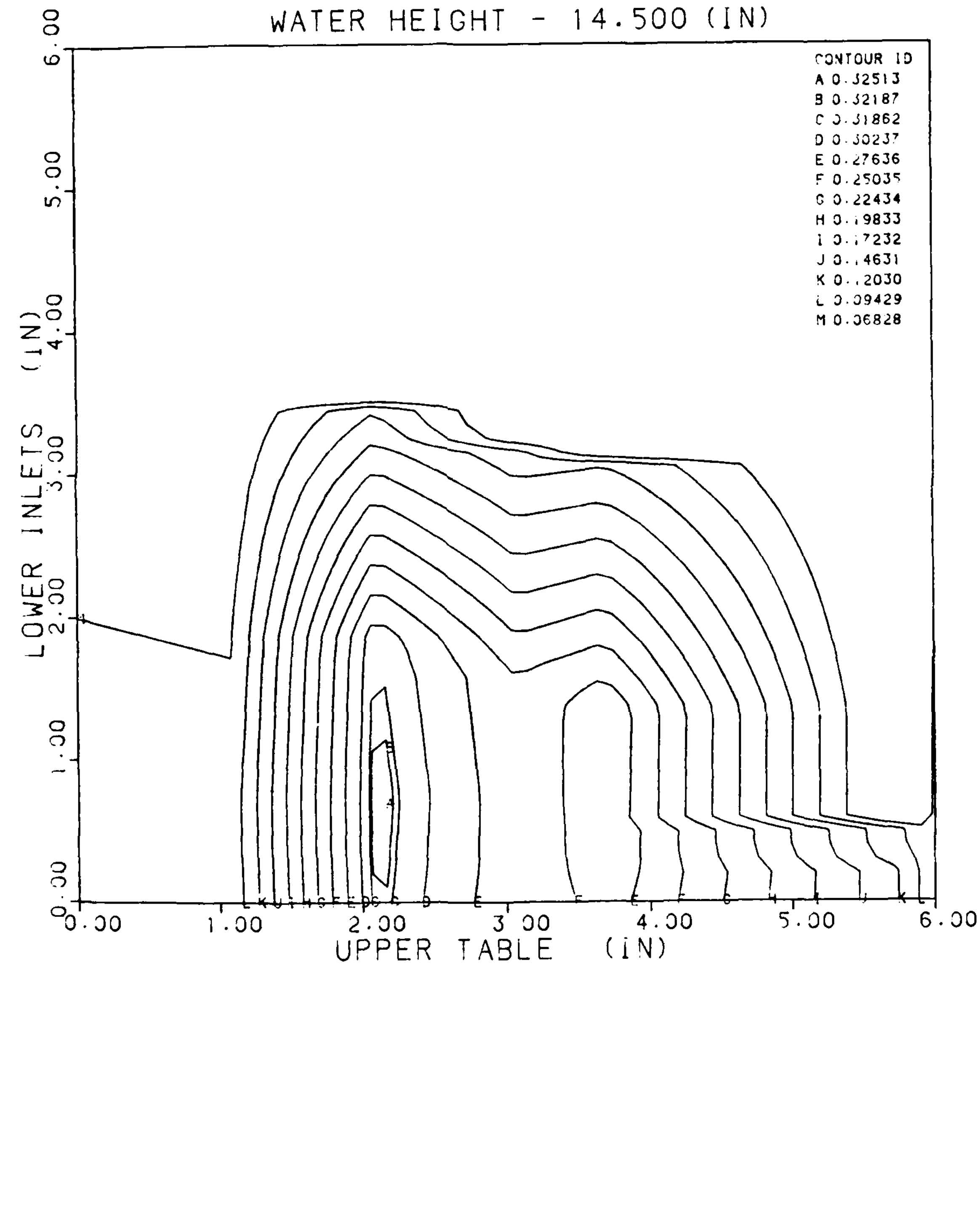

WATER HEIGHT - 12.625 (IN)
CONTOUR ID
A 0.14281
B 0.14138
C 0.13995
D 0.13281
E 0.12139
F 0.10996
G 0.09854
H 0.08711
I 0.07569
J 0.06426
K 0.05284
L 0.04141
M 0.02999
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00


WATER HEIGHT - 13.125 (IN)
CONTOUR ID
A 0.20828
B 0.20619
C 0.20411
D 0.19370
E 0.17704
F 0.16037
G 0.14371
H 0.12705
I 0.11039
J 0.09372
K 0.07706
L 0.06040
M 0.04374
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

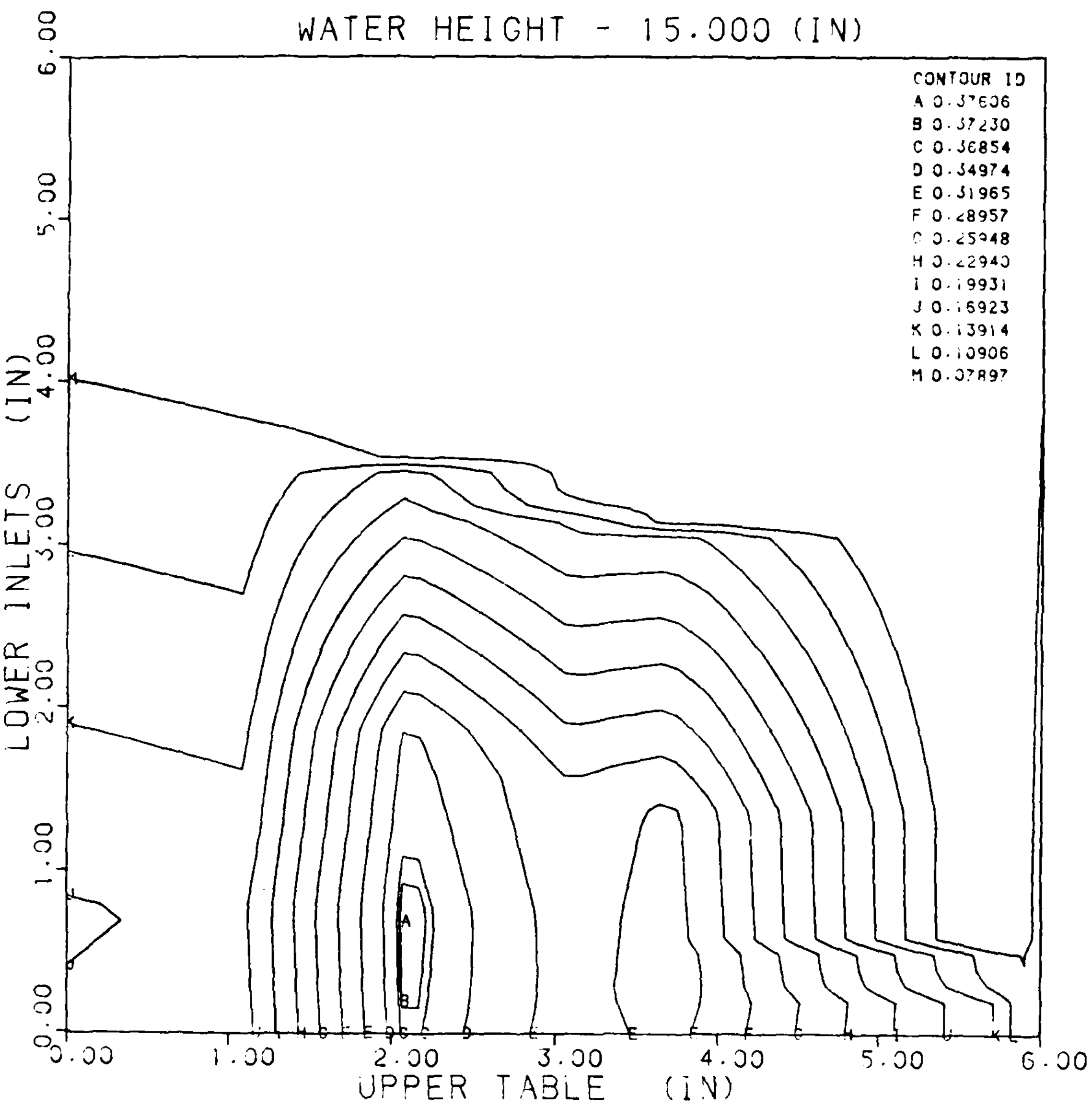


WATER HEIGHT - 13.625 (IN)
CONTOUR ID
A 0.22350
B 0.22127
C 0.21903
D 0.20786
E 0.18998
F 0.17210
G 0.15422
H 0.13634
I 0.11846
J 0.10058
K 0.08270
L 0.06482
M 0.04694
LOWER INLETS (IN)
UPPER TABLE (IN)

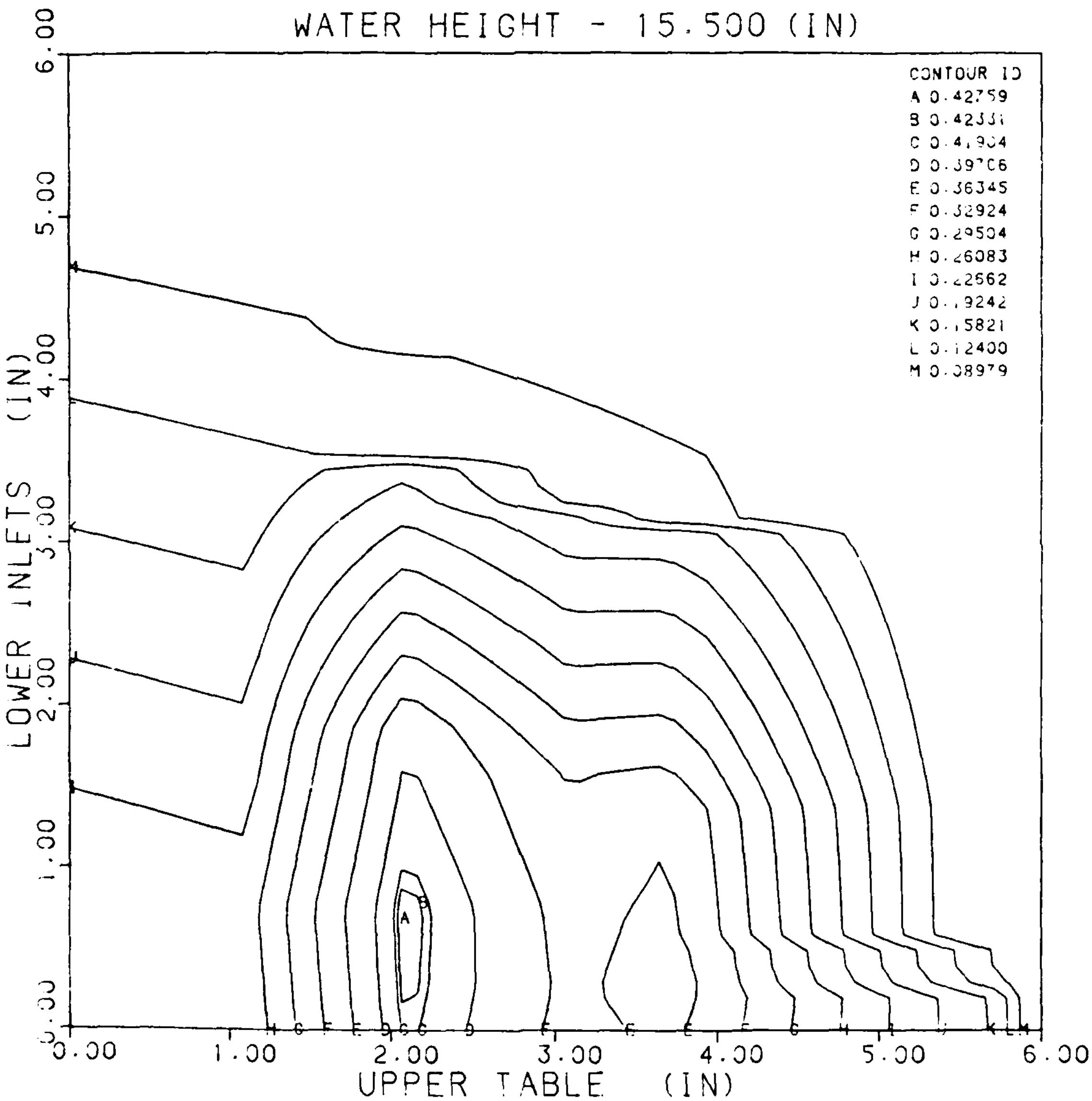

WATER HEIGHT - 14.000 (IN)
CONTOUR ID
A 0.27851
B 0.27572
C 0.27294
D 0.25901
E 0.23073
F 0.21445
G 0.19217
H 0.16989
I 0.14761
J 0.12533
K 0.10305
L 0.08077
M 0.05849
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

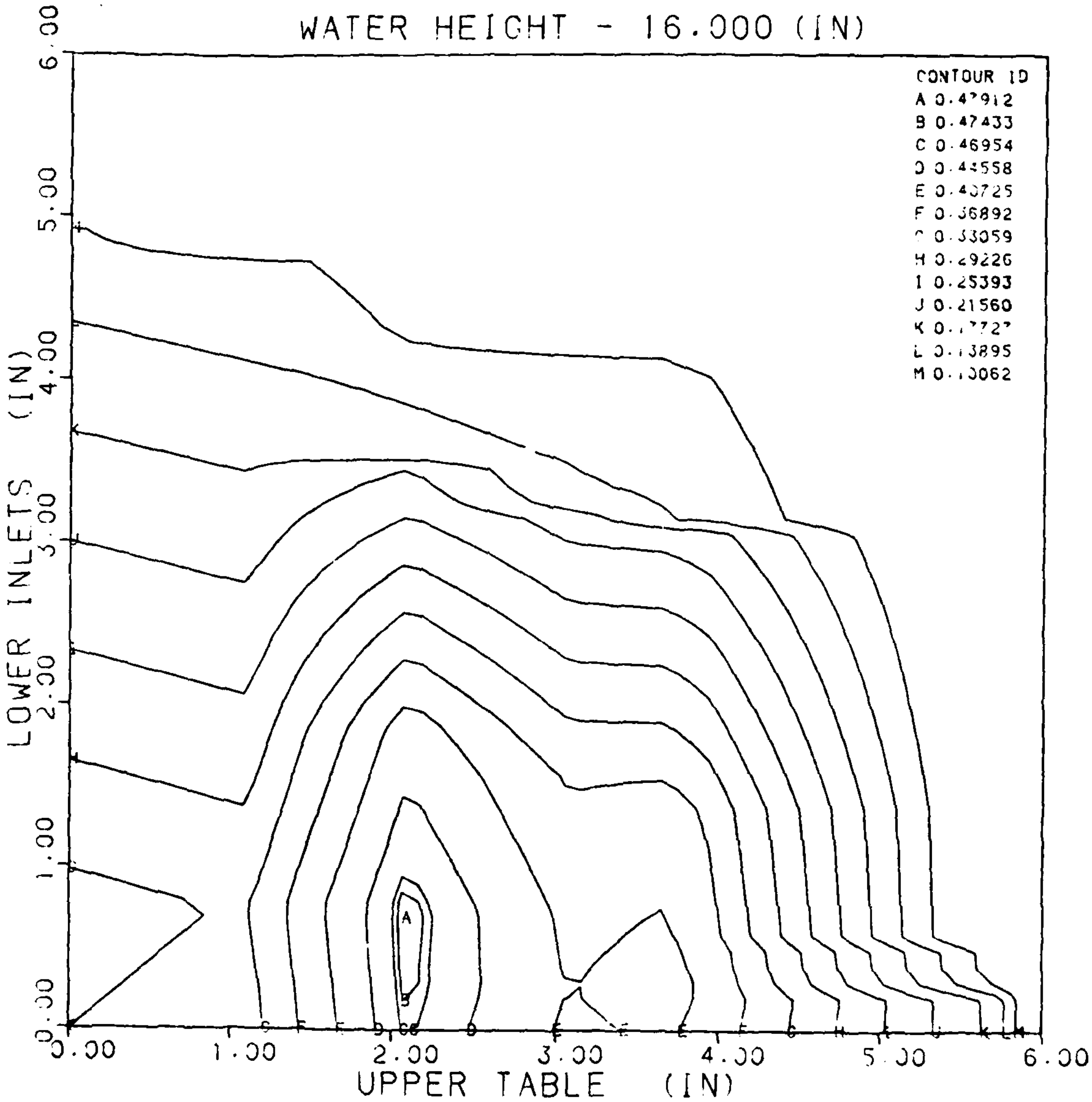


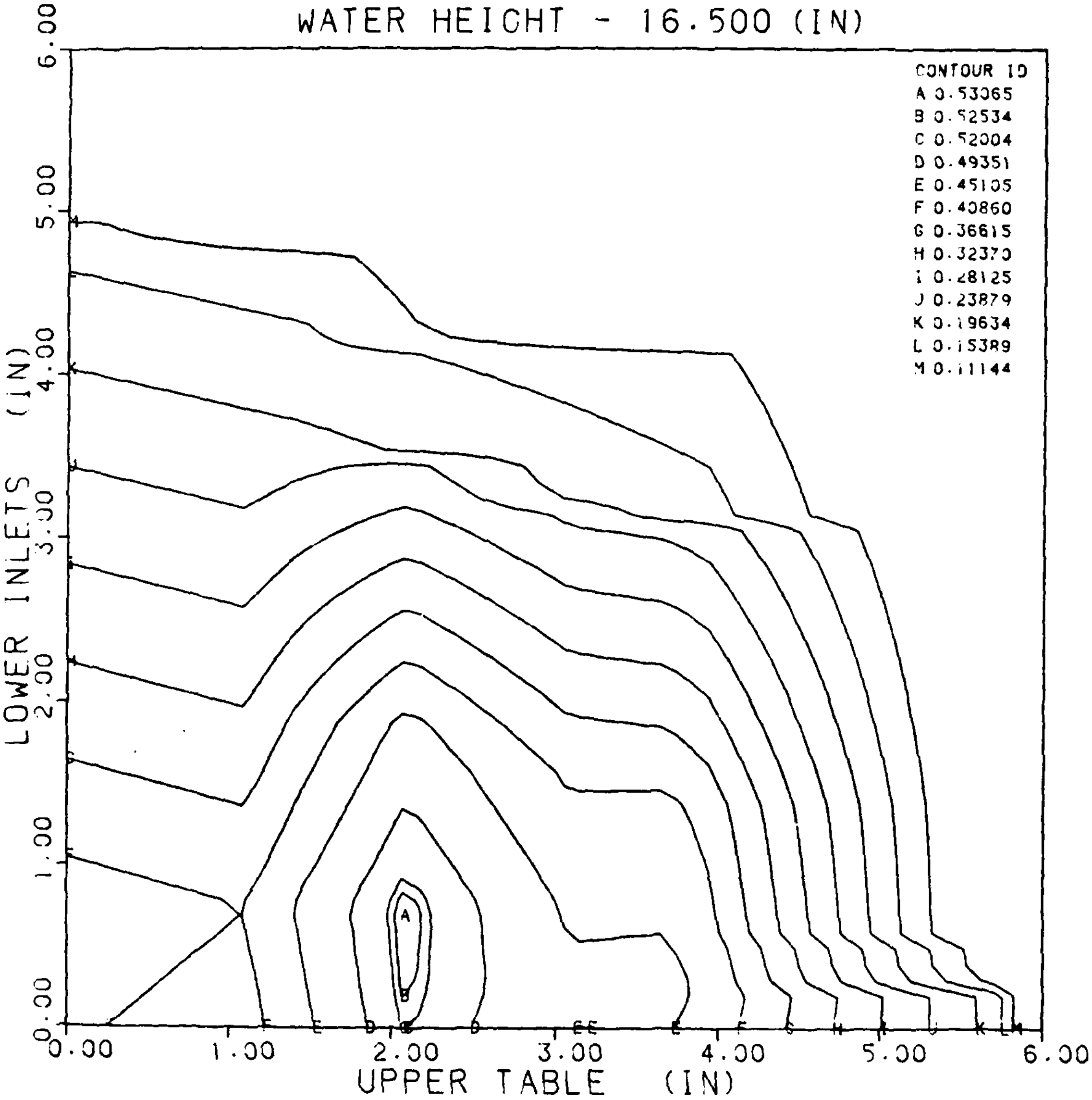
WATER HEIGHT - 14.500 (IN)
CONTOUR ID
A 0.32513
B 0.32187
C 0.31862
D 0.30237
E 0.27636
F 0.25035
G 0.22434
H 0.19833
I 0.17232
J 0.14631
K 0.12030
L 0.09429
M 0.06828
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

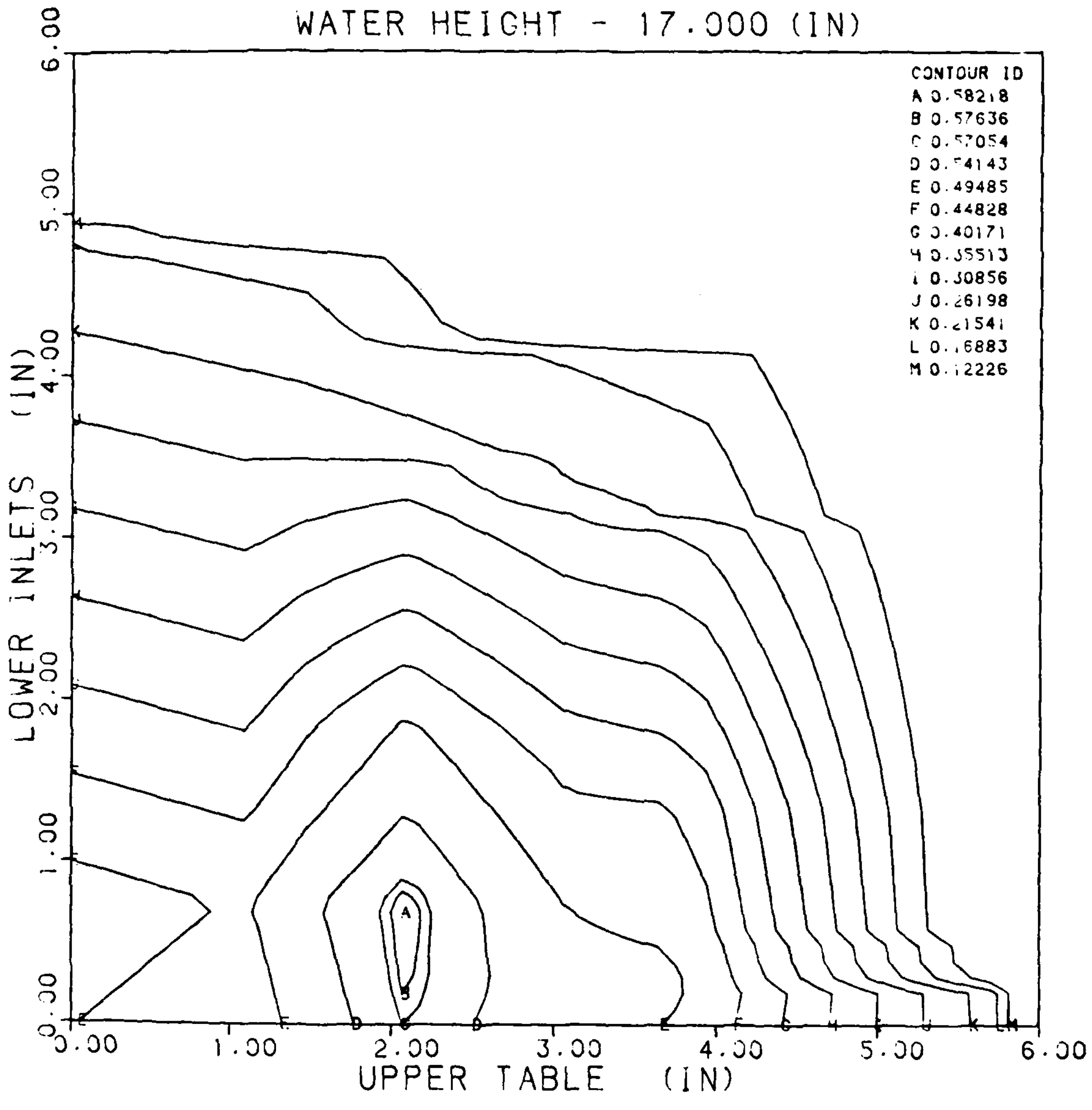


WATER HEIGHT - 15.000 (IN)
CONTOUR ID
A 0.37606
B 0.37230
C 0.36854
D 0.34974
E 0.31965
F 0.28957
G 0.25948
H 0.22940
I 0.19931
J 0.16923
K 0.13914
L 0.10906
M 0.07897
LOWER INLETS (IN)
UPPER TABLE (IN)


WATER HEIGHT - 15.500 (IN)
CONTOUR ID
A 0.42759
B 0.42331
C 0.41904
D 0.39706
E 0.36345
F 0.32924
G 0.29504
H 0.26083
I 0.22562
J 0.19242
K 0.15821
L 0.12400
M 0.08979
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

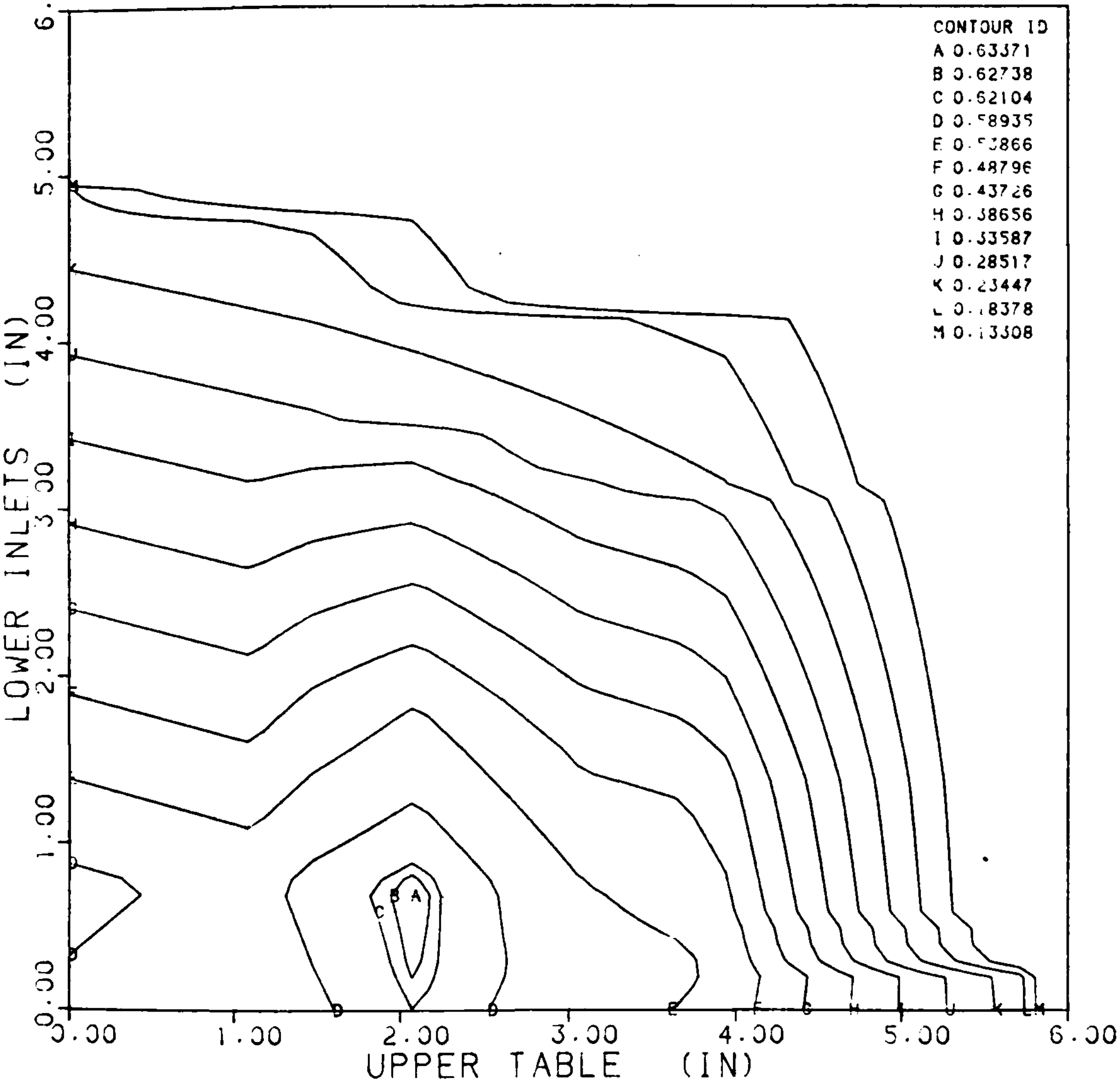

WATER HEIGHT - 16.000 (IN)
CONTOUR ID
B 0.47433
C 0.46954
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

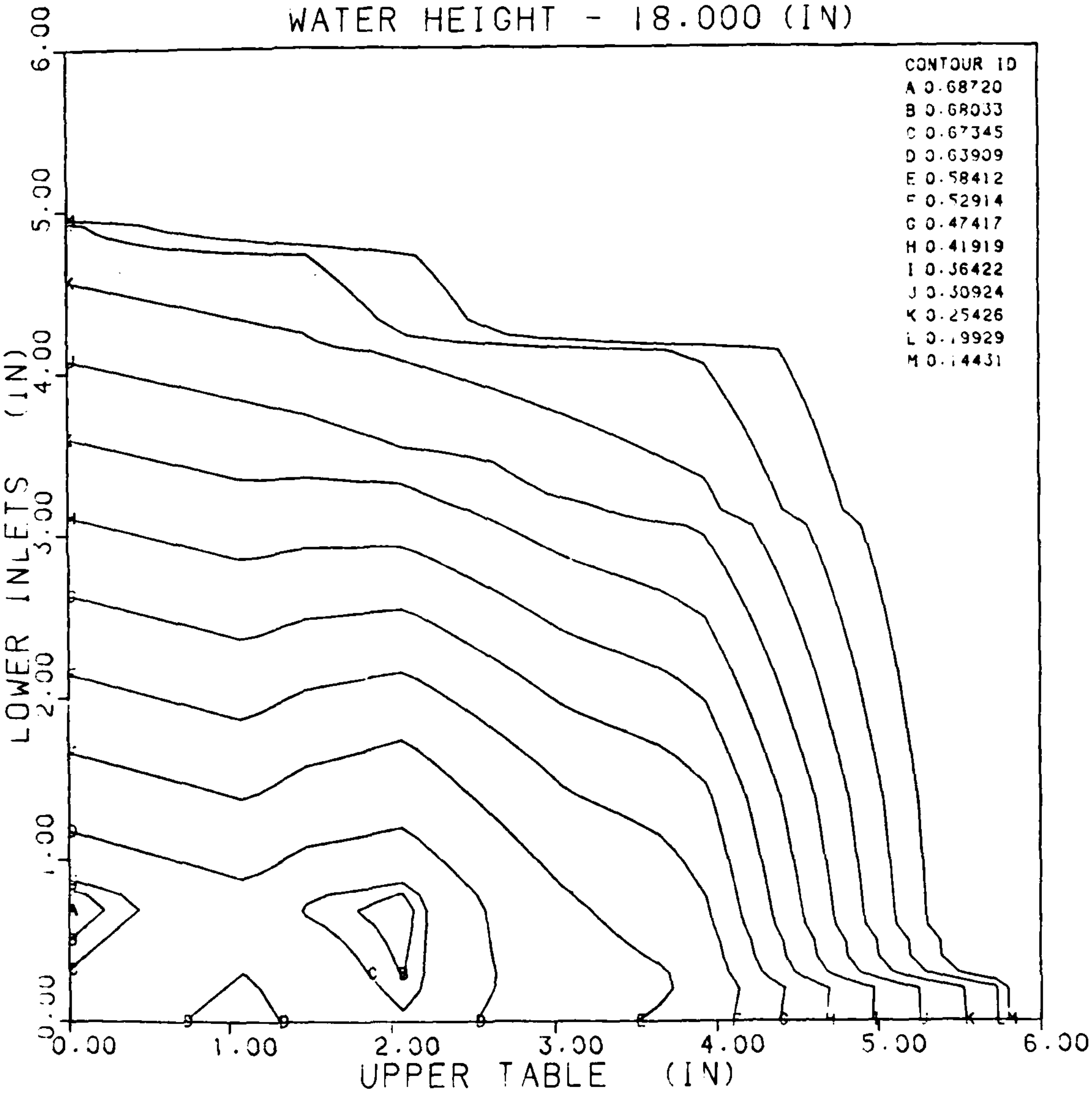

WATER HEIGHT - 16.500 (IN)
CONTOUR ID
A 0.53065
B 0.52534
C 0.52004
D 0.49351
E 0.45105
F 0.40860
G 0.36615
H 0.32370
I 0.28125
J 0.23879
K 0.19634
L 0.15389
M 0.11144
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00



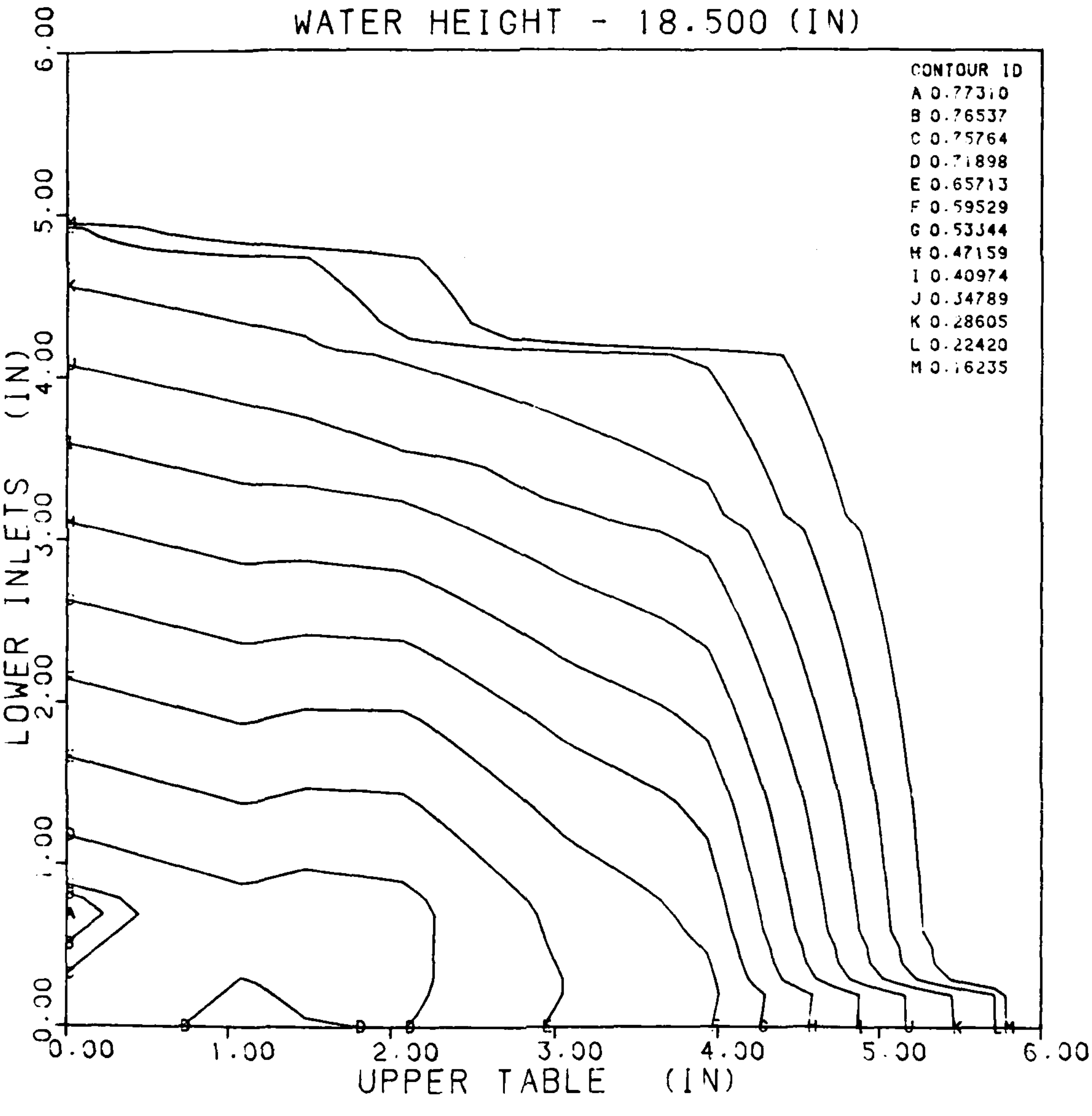
WATER HEIGHT - 17.000 (IN)
CONTOUR ID
A 0.58218
B 0.57636
C 0.57054
D 0.54143
E 0.49485
F 0.44828
G 0.40171
H 0.35513
I 0.30856
J 0.26198
K 0.21541
L 0.16883
M 0.12226
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

WATER HEIGHT - 17.500 (IN)

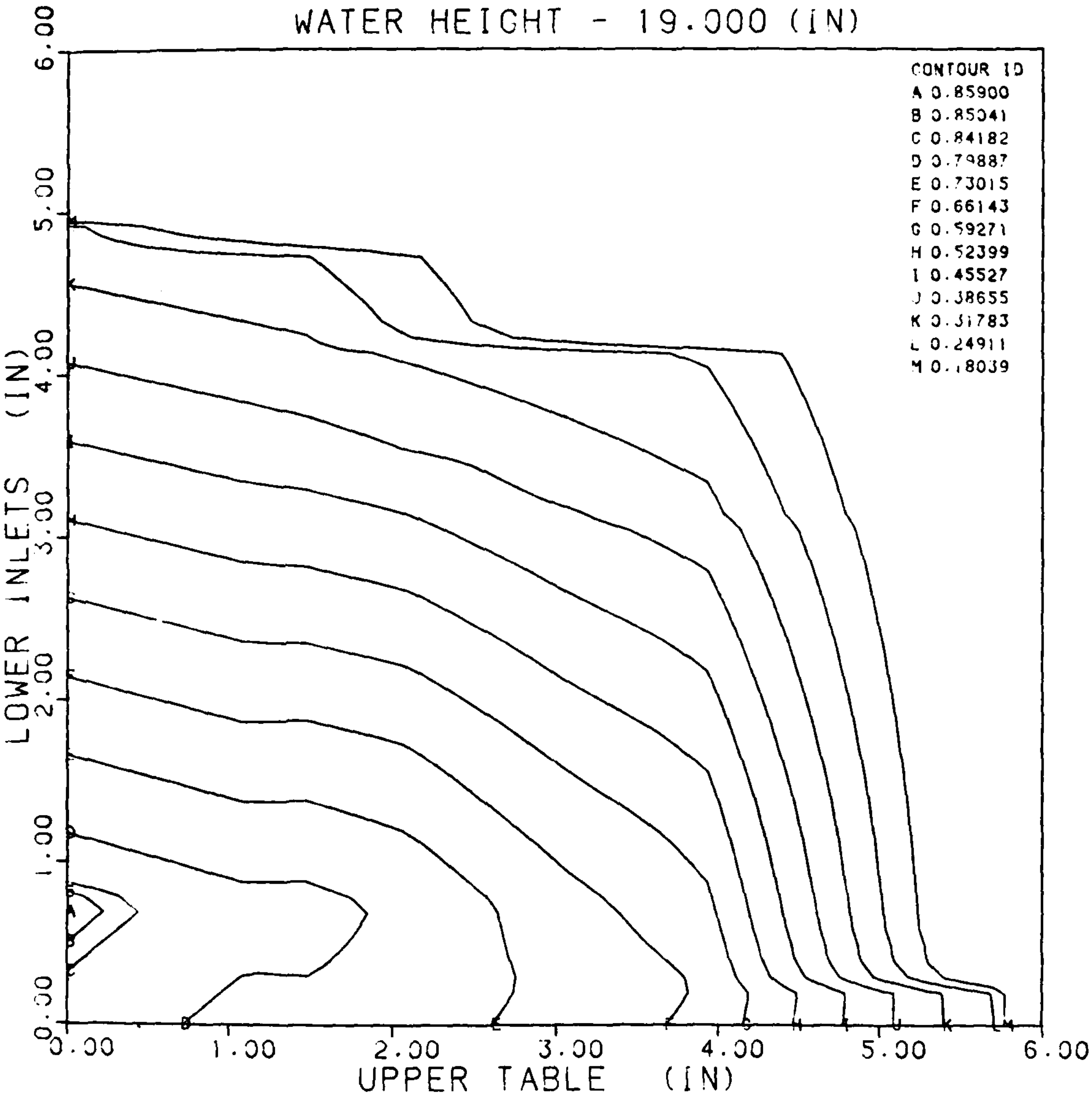




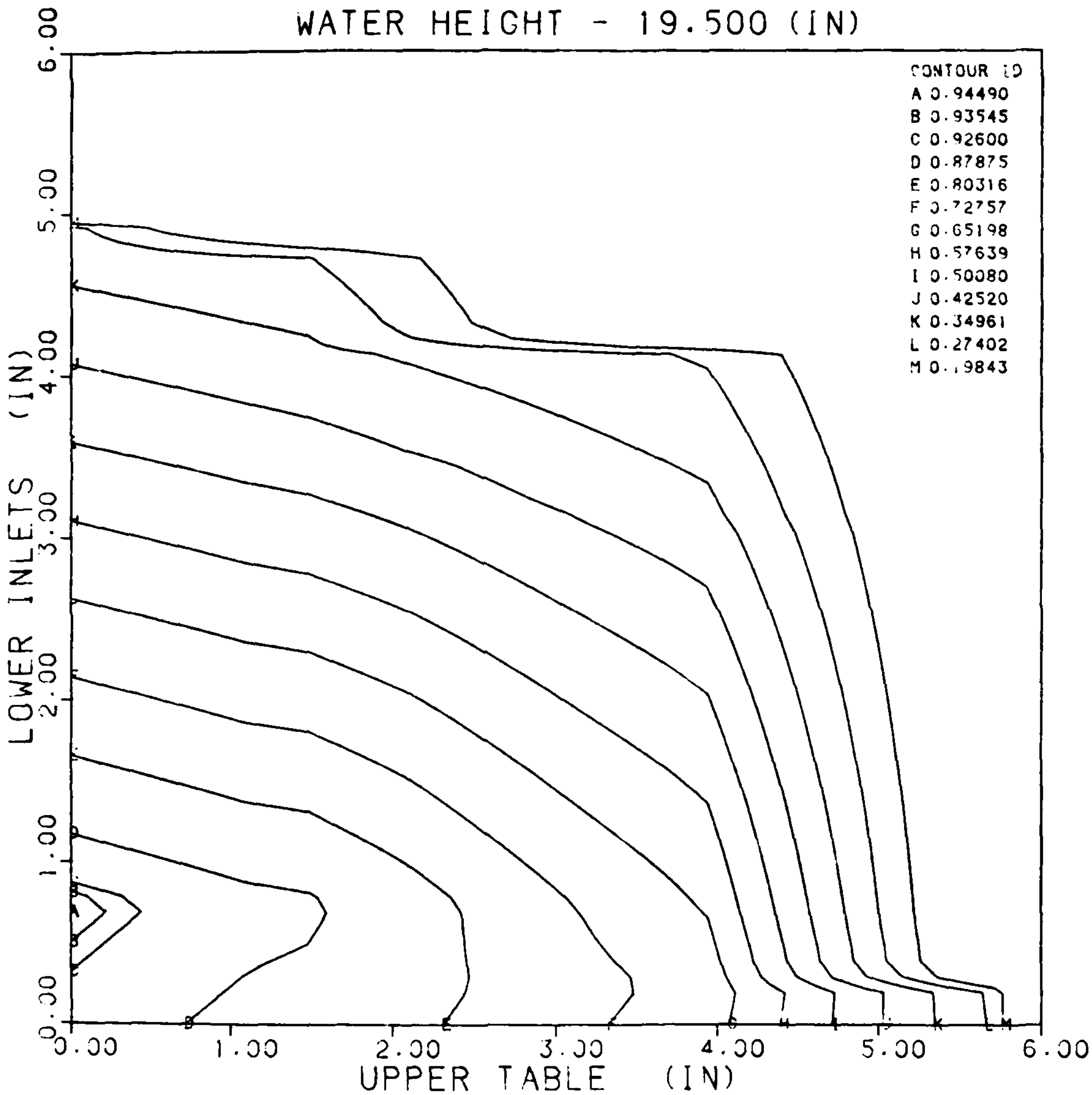
WATER HEIGHT - 18.000 (IN)
CONTOUR ID
A 0.68720
B 0.68033
C 0.67345
D 0.63909
E 0.58412
F 0.52914
G 0.47417
H 0.41919
I 0.36422
J 0.30924
K 0.25426
L 0.19929
M 0.14431
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00



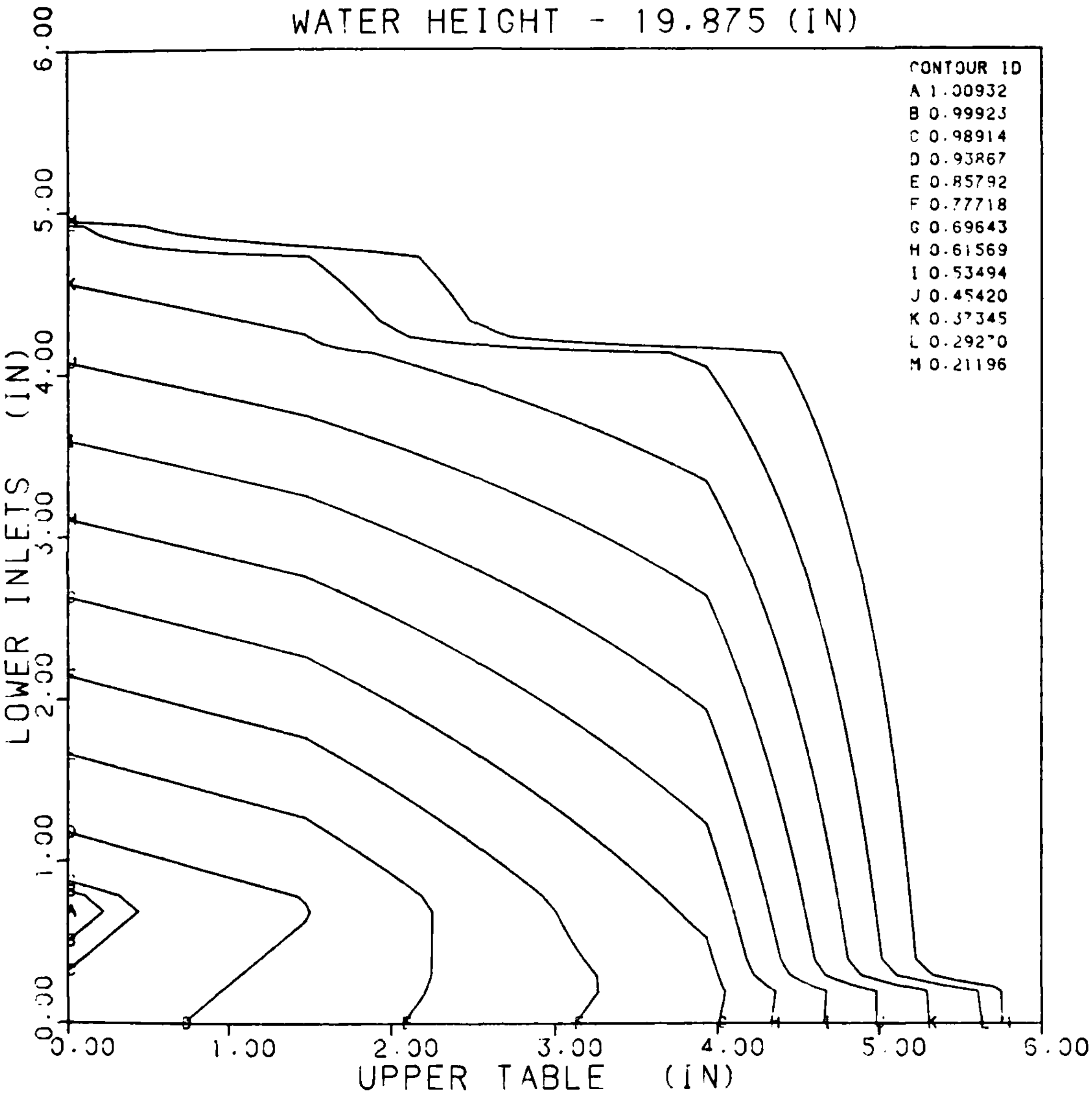
WATER HEIGHT - 18.500 (IN)
CONTOUR ID
A 0.77310
B 0.76537
C 0.75764
D 0.71898
E 0.65713
F 0.59529
G 0.53344
H 0.47159
I 0.40974
J 0.34789
K 0.28605
L 0.22420
M 0.16235
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00



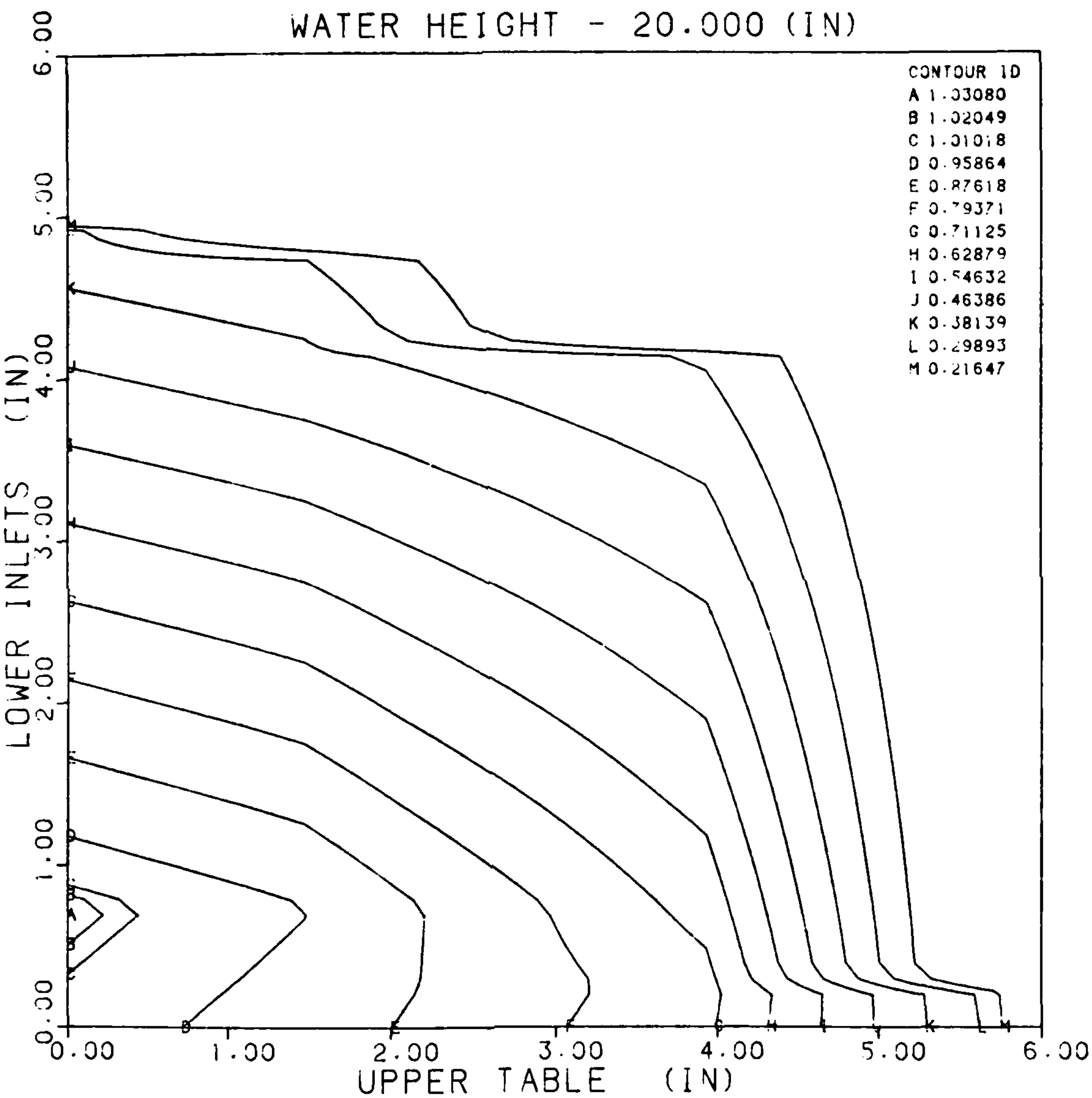
WATER HEIGHT - 19.000 (IN)
CONTOUR ID
A 0.85900
B 0.85041
C 0.84182
D 0.79887
E 0.73015
F 0.66143
G 0.59271
H 0.52399
I 0.45527
J 0.38655
K 0.31783
L 0.24911
M 0.18039
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00



WATER HEIGHT - 19.500 (IN)
CONTOUR ID
A 0.94490
B 0.93545
C 0.92600
D 0.87875
E 0.80316
F 0.72757
G 0.65198
H 0.57639
I 0.50080
J 0.42520
K 0.34961
L 0.27402
M 0.19843
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

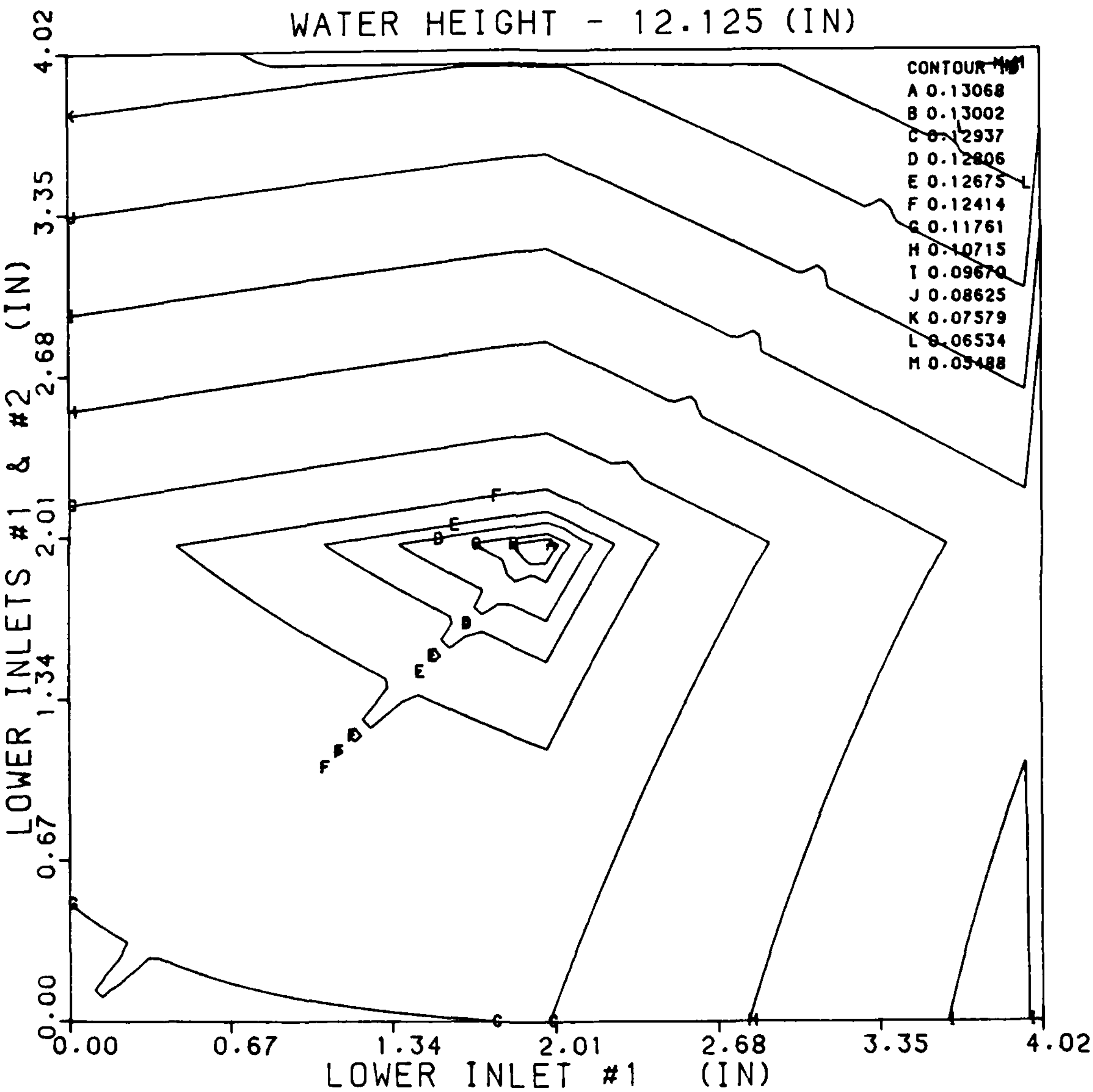


WATER HEIGHT - 19.875 (IN)
CONTOUR ID
A 1.00932
B 0.99923
C 0.98914
D 0.93867
E 0.85792
F 0.77718
G 0.69643
H 0.61569
I 0.53494
J 0.45420
K 0.37345
L 0.29270
M 0.21196
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

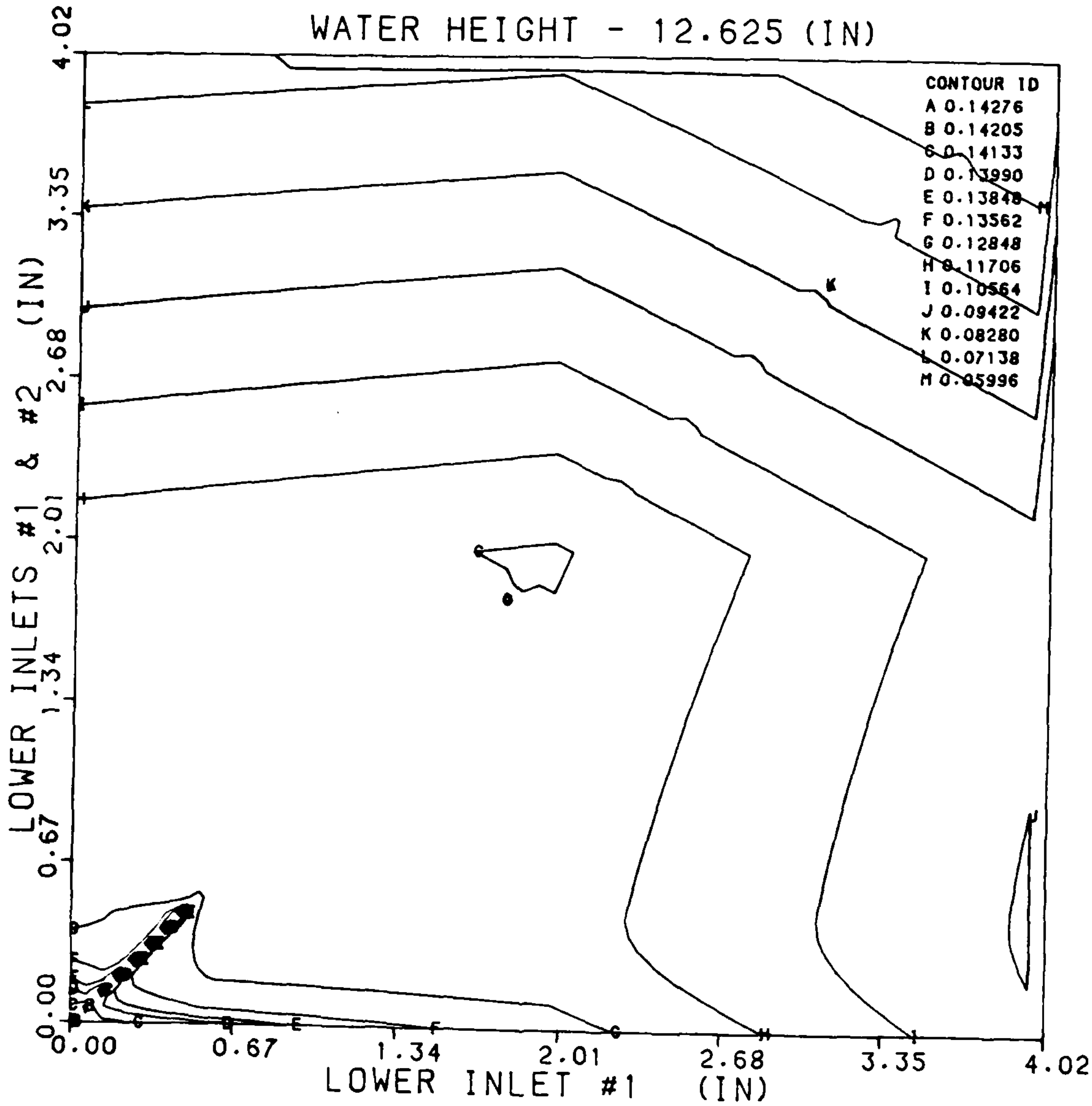

WATER HEIGHT - 20.000 (IN)
CONTOUR ID
A 1.03080
B 1.02049
C 1.01018
D 0.95864
E 0.87618
F 0.79371
G 0.71125
H 0.62879
I 0.54632
J 0.46386
K 0.38139
L 0.29893
M 0.21647
LOWER INLETS (IN)
UPPER TABLE (IN)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

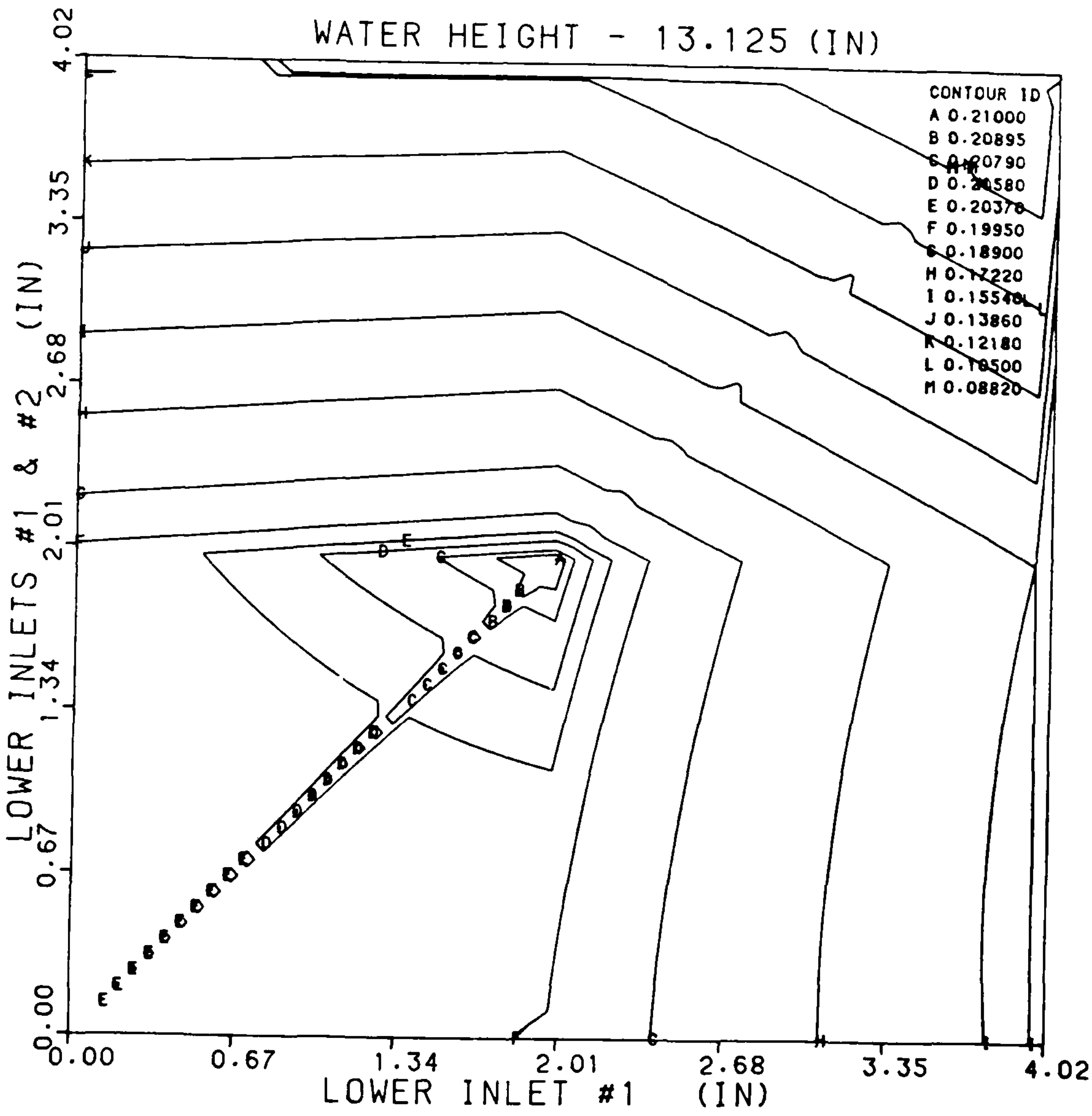
Appendix G.

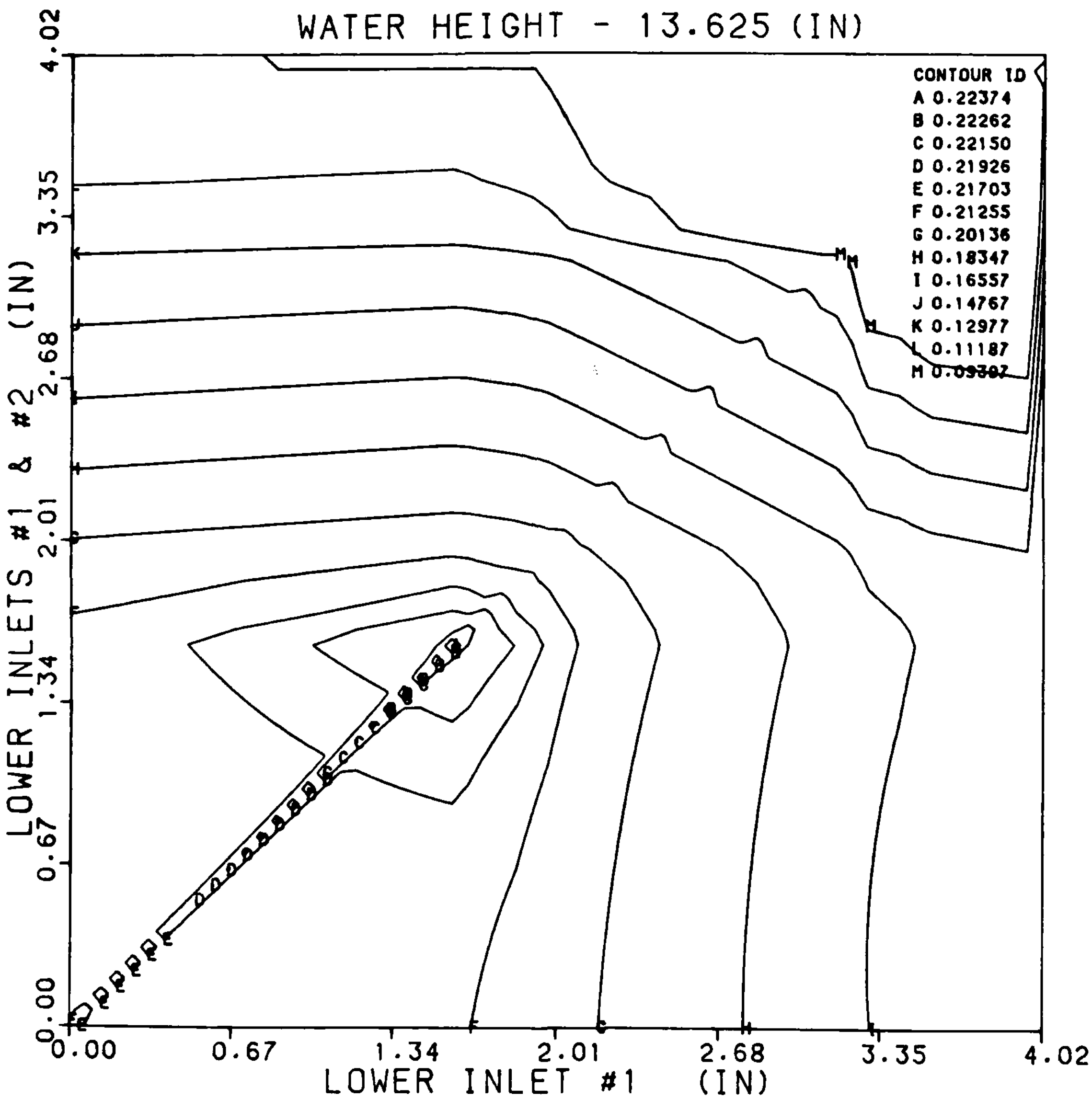
<u>Contour Plots: Upper Inlet vs Upper Inlet</u>



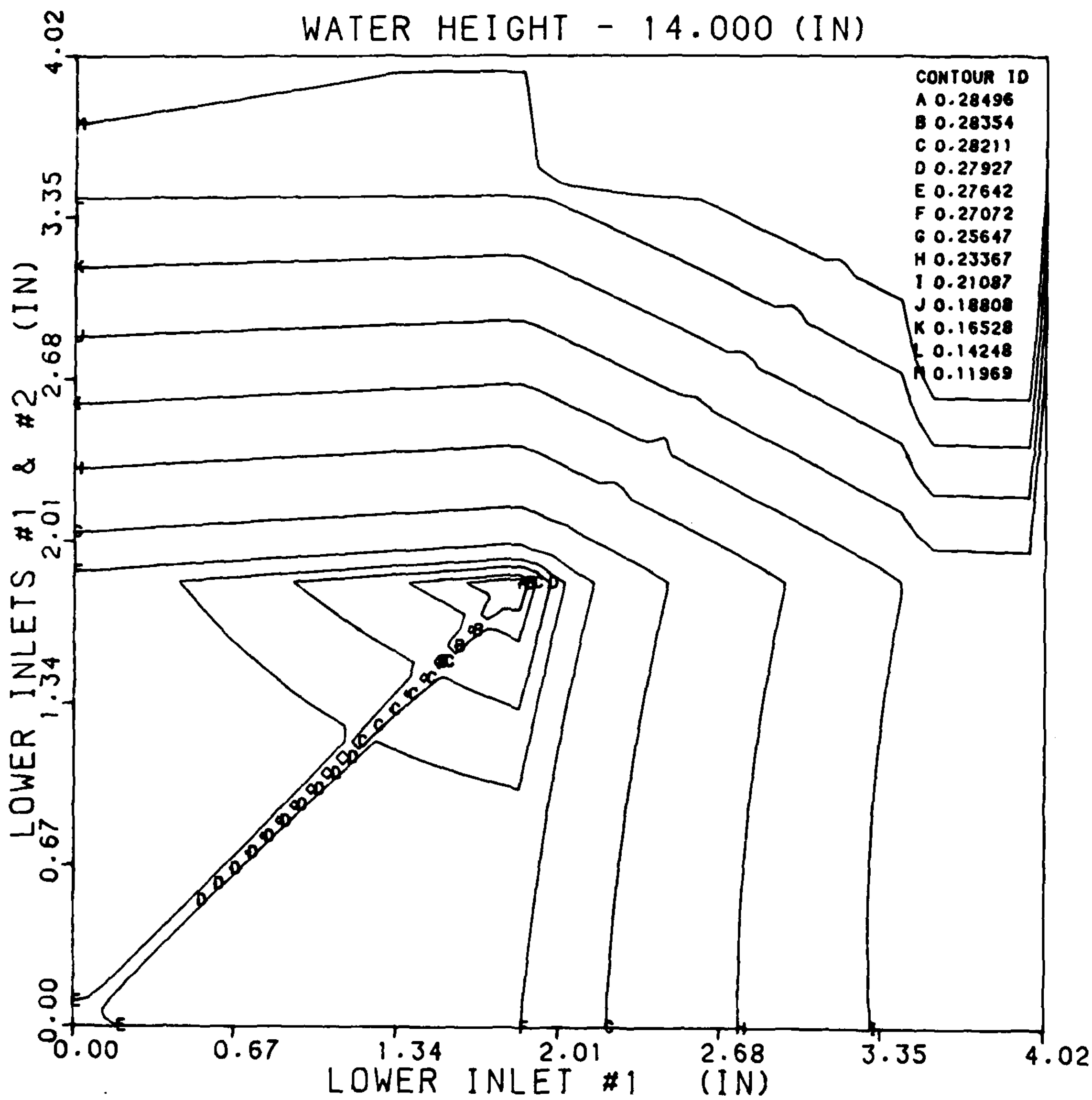
WATER HEIGHT - 12.125 (IN)
CONTOUR
A 0.13068
B 0.13002
C 0.12937
D 0.12806
E 0.12675
F 0.12414
G 0.11761
H 0.10715
I 0.09670
J 0.08625
K 0.07579
L 0.06534
M 0.05488
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

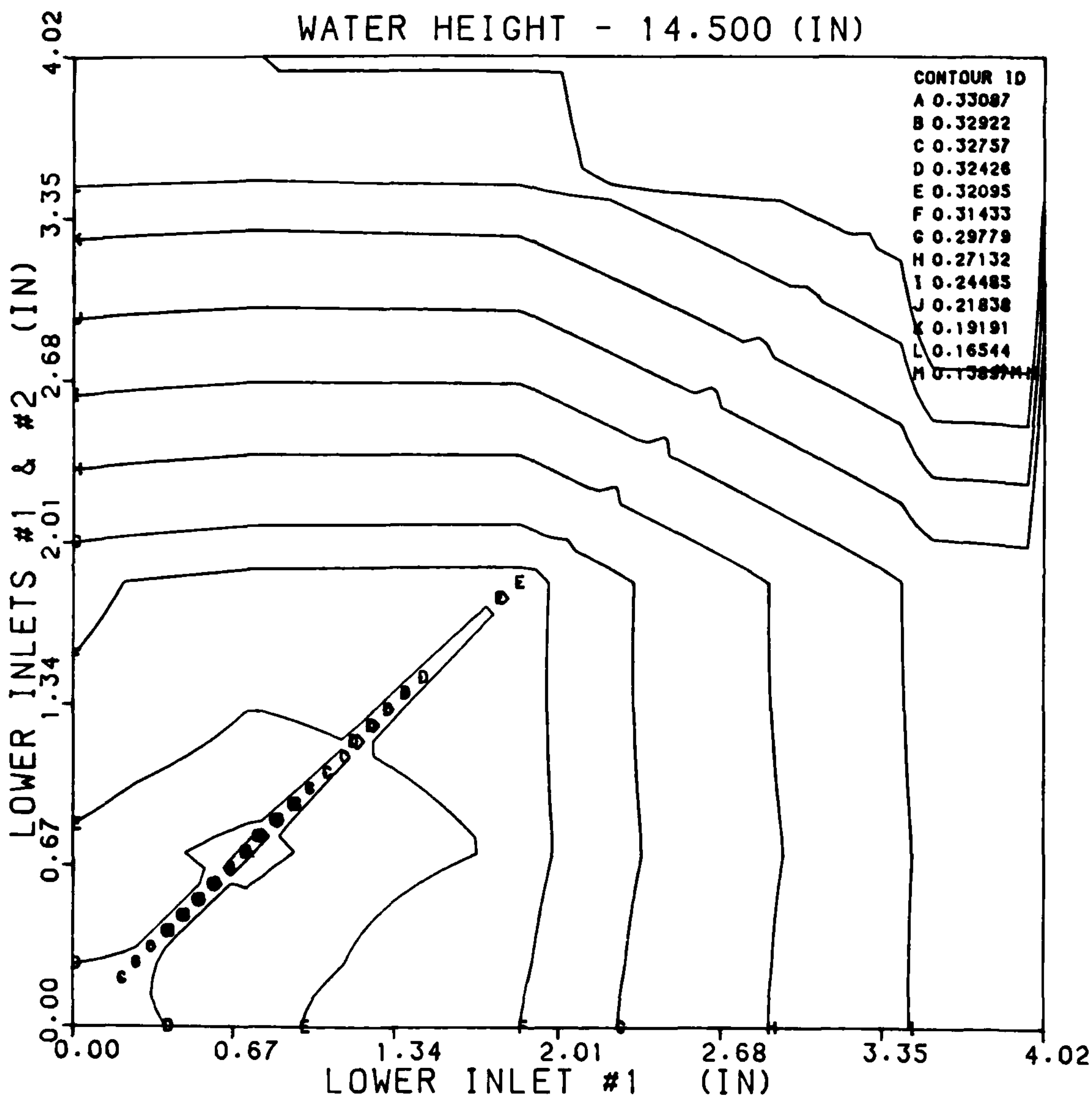

WATER HEIGHT - 12.625 (IN)
CONTOUR ID
A 0.14276
B 0.14205
C 0.14133
D 0.13990
E 0.13848
F 0.13562
G 0.12848
H 0.11706
I 0.10564
J 0.09422
K 0.08280
L 0.07138
M 0.05996
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02


WATER HEIGHT - 13.125 (IN)
CONTOUR ID
A 0.21000
B 0.20895
C 0.20790
D 0.20580
E 0.20370
F 0.19950
G 0.18900
H 0.17220
I 0.15540
J 0.13860
K 0.12180
L 0.10500
M 0.08820
LOWER INLETS #1 & #2 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02
LOWER INLET #1 (IN)

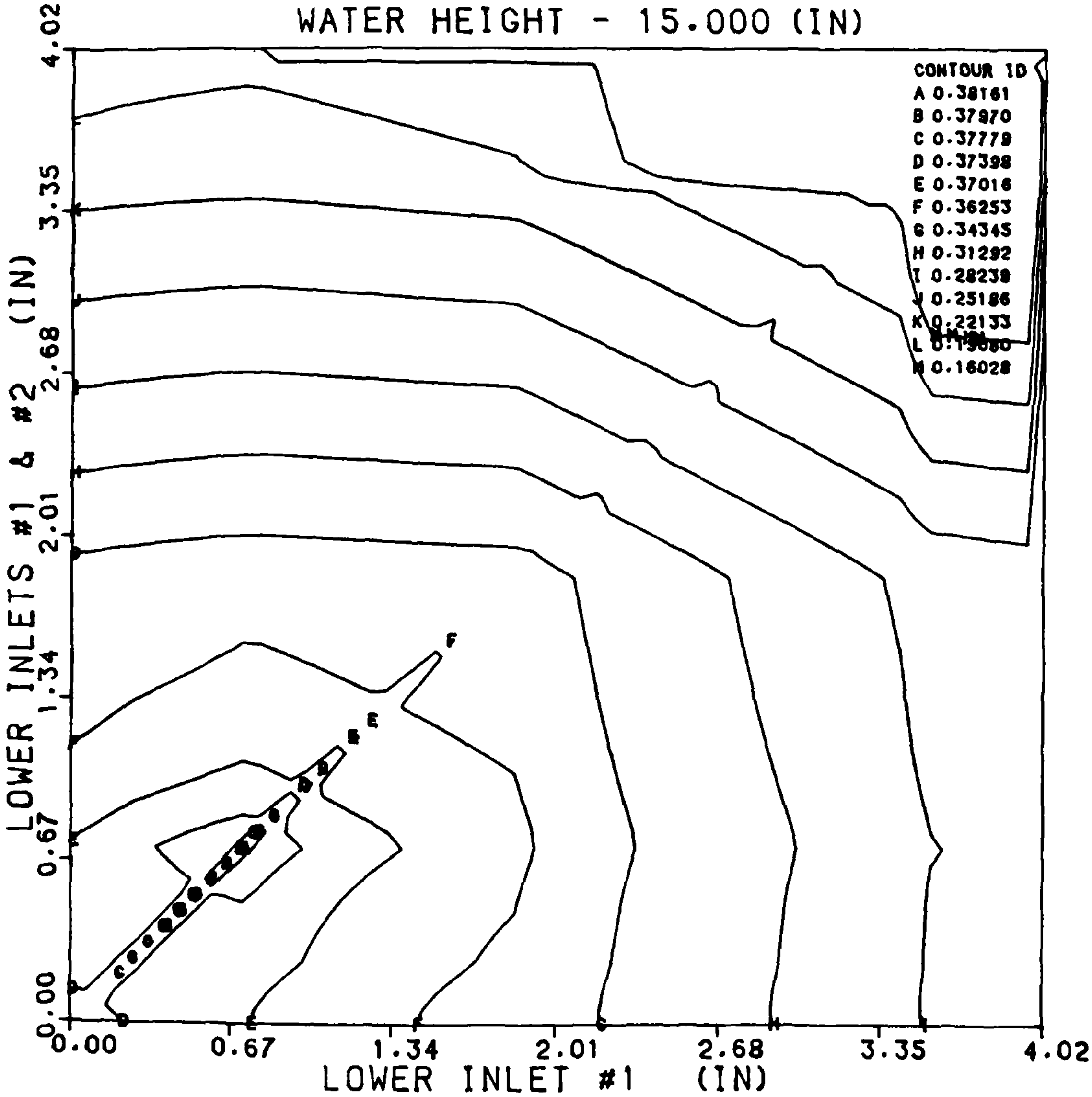


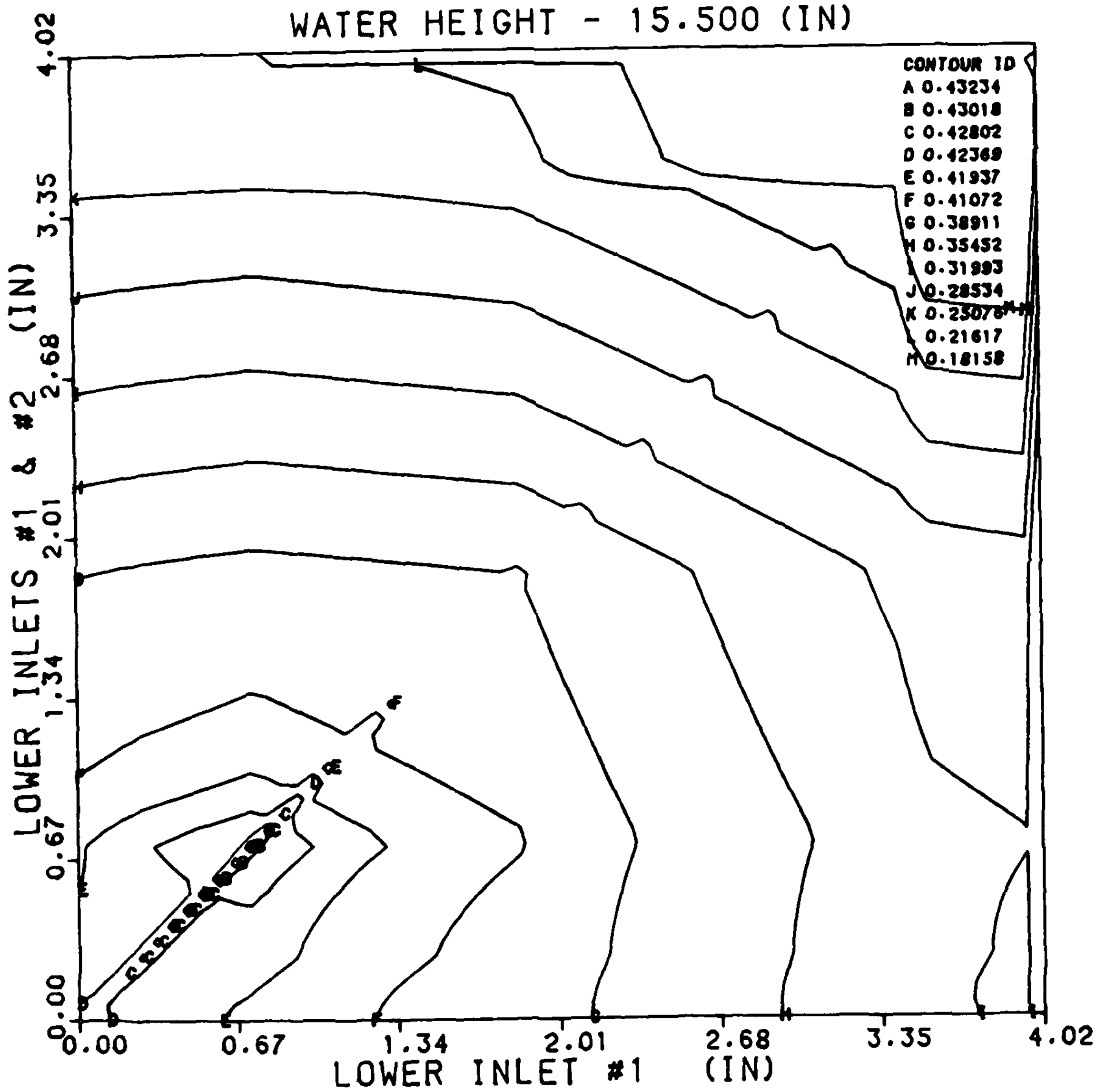
WATER HEIGHT - 13.625 (IN)
CONTOUR ID
A 0.22374
B 0.22262
C 0.22150
D 0.21926
E 0.21703
F 0.21255
G 0.20136
H 0.18347
I 0.16557
J 0.14767
K 0.12977
L 0.11187
M 0.09397
0.00
0.67
1.34
2.01
2.68
3.35
4.02
LOWER INLET #1 (IN)
LOWER INLETS #1 & #2 (IN)


WATER HEIGHT - 14.000 (IN)
CONTOUR ID
A 0.28496
B 0.28354
C 0.28211
D 0.27927
E 0.27642
F 0.27072
G 0.25647
H 0.23367
I 0.21087
J 0.18808
K 0.16528
L 0.14248
M 0.11969
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

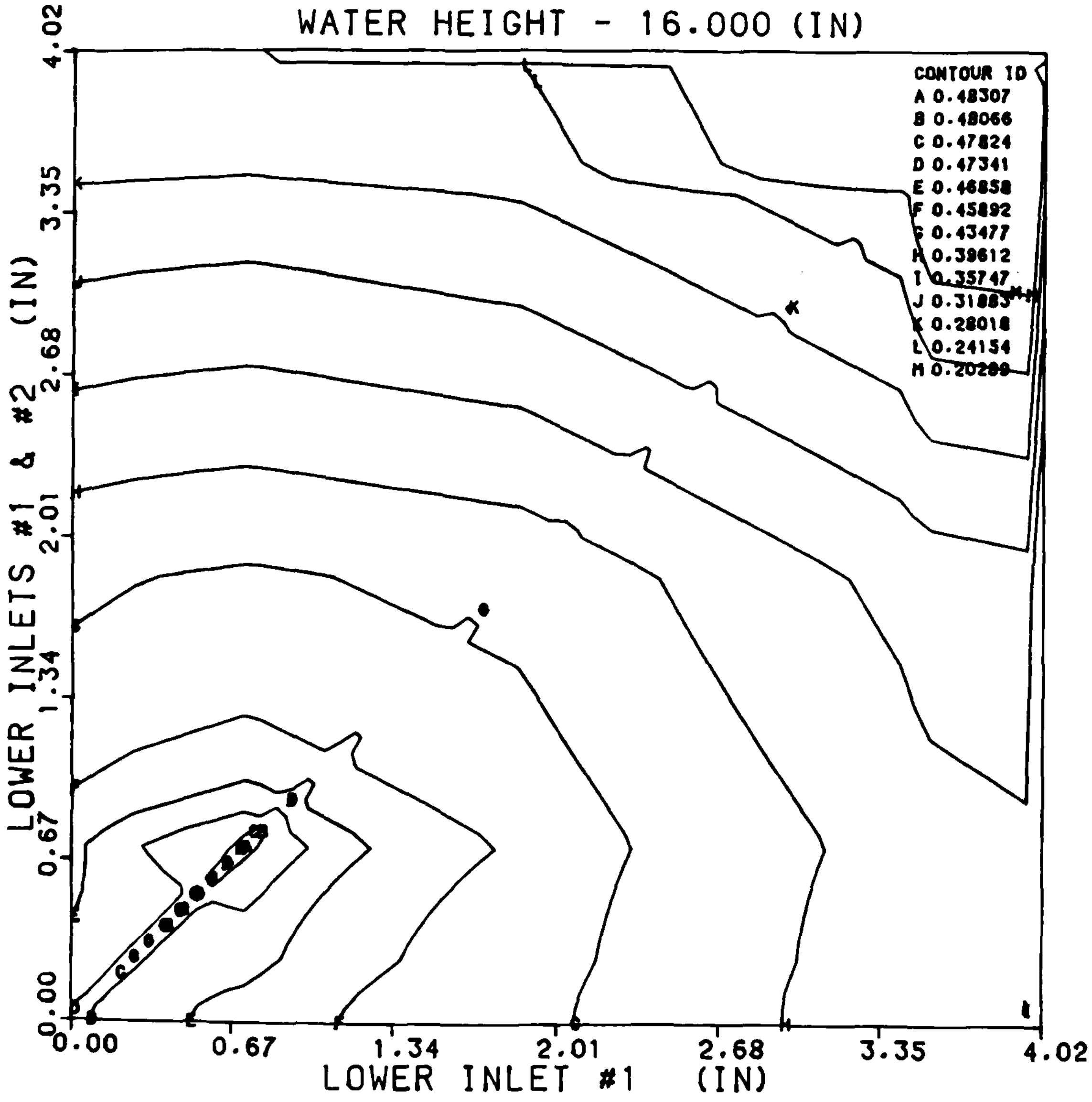


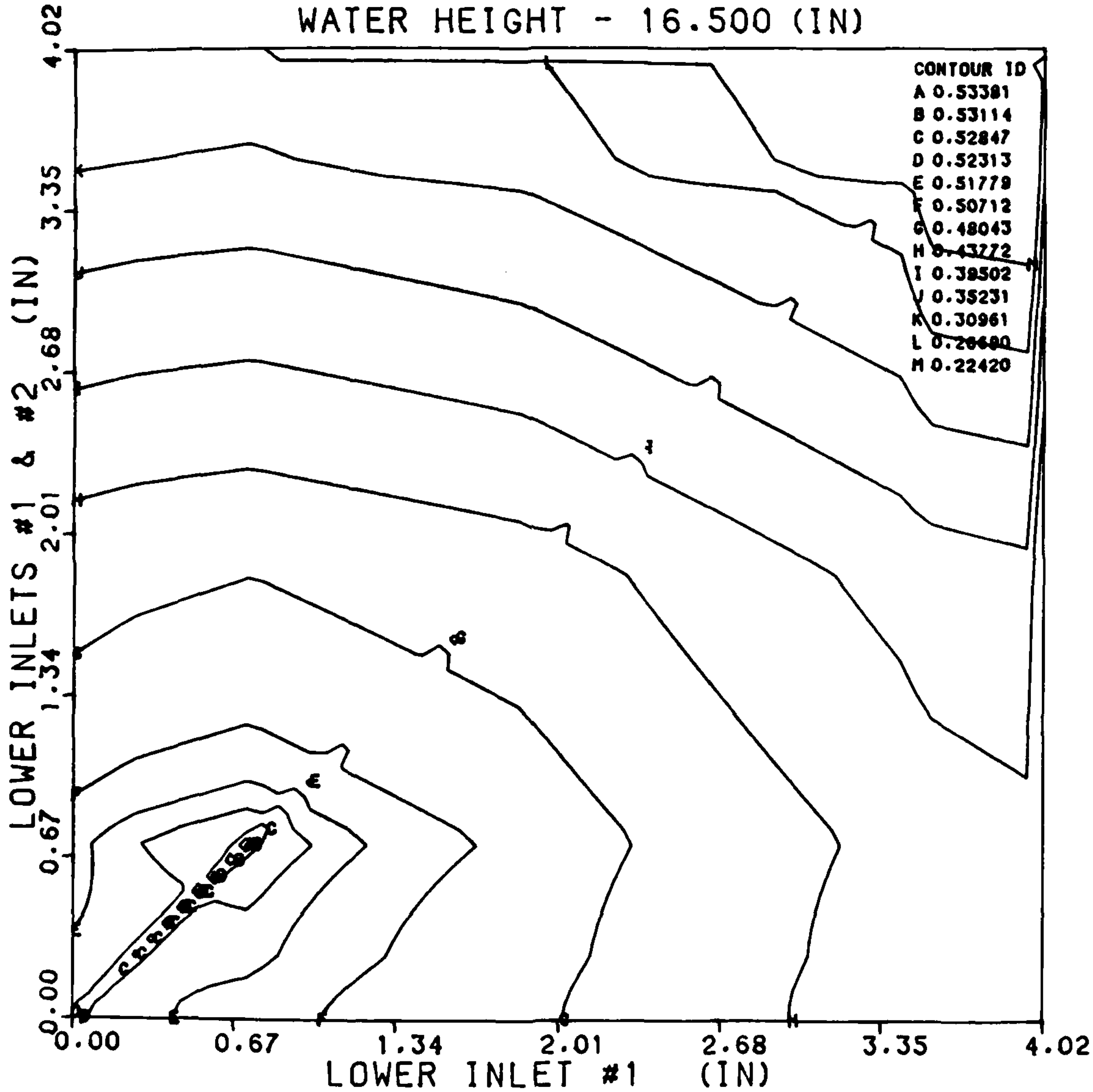
WATER HEIGHT - 14.500 (IN)
CONTOUR ID
A 0.33087
B 0.32922
C 0.32757
D 0.32426
E 0.32095
F 0.31433
G 0.29779
H 0.27132
I 0.24485
J 0.21838
K 0.19191
L 0.16544
M
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02


WATER HEIGHT - 15.000 (IN)
CONTOUR ID
A 0.38161
B 0.37970
C 0.37779
D 0.37398
E 0.37016
F 0.36253
G 0.34345
H 0.31292
I 0.28239
J 0.25186
K 0.22133
L 0.19080
M 0.16028
0.00
0.67
1.34
2.01
2.68
3.35
4.02
LOWER INLET #1 (IN)
LOWER INLETS #1 & #2 (IN)

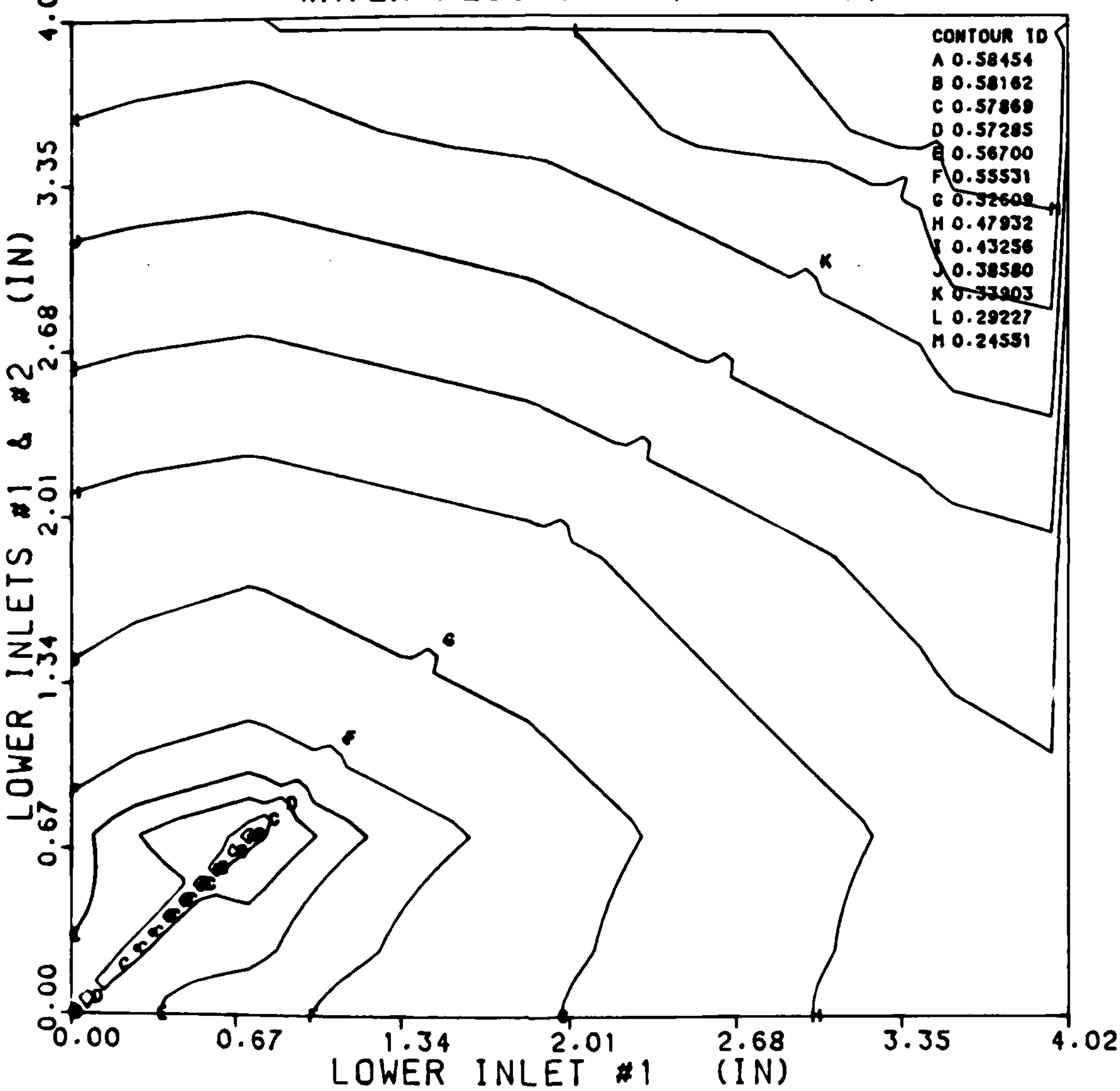


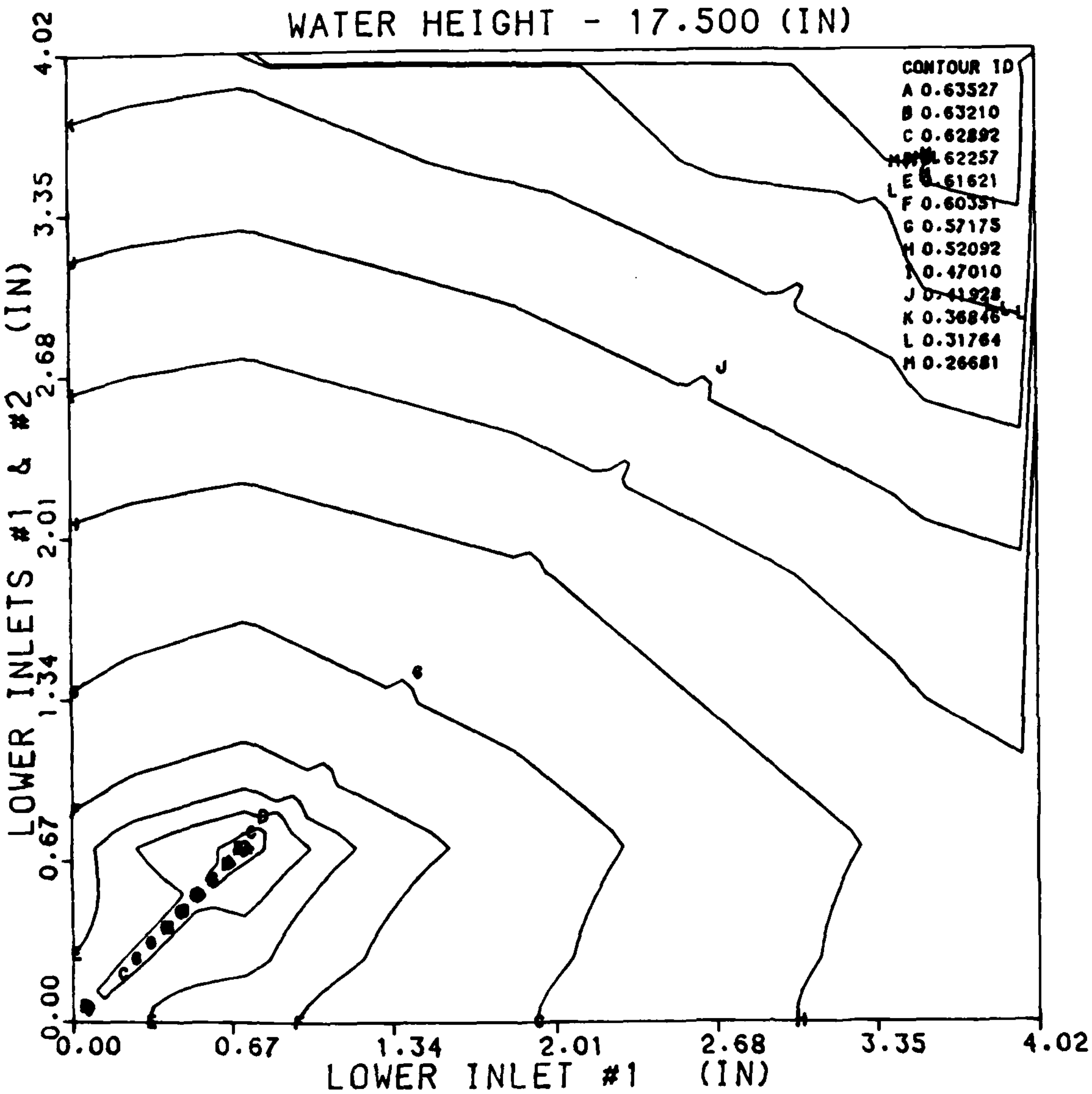
WATER HEIGHT - 15.500 (IN)
CONTOUR ID
A 0.43234
B 0.43018
C 0.42802
D 0.42369
E 0.41937
F 0.41072
G 0.38911
H 0.35452
I 0.31993
J 0.28534
K 0.25076
L 0.21617
M 0.18158
LOWER INLETS #1 & #2 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02
LOWER INLET #1 (IN)


WATER HEIGHT - 16.000 (IN)
CONTOUR ID
A 0.48307
B 0.48066
C 0.47824
D 0.47341
E 0.46858
F 0.45892
G 0.43477
H 0.39612
I 0.35747
J 0.31883
K 0.28018
L 0.24154
M 0.20289
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

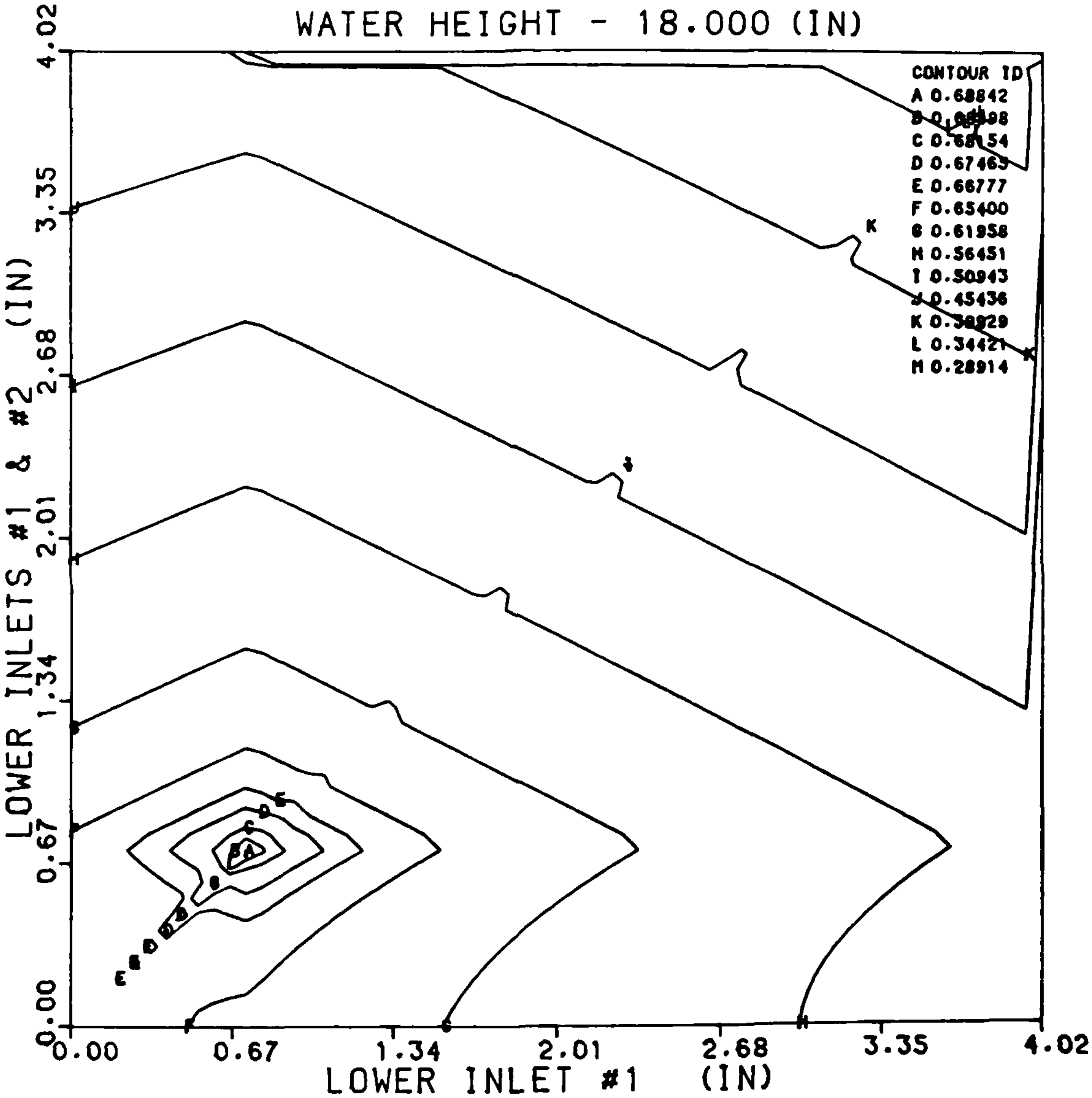

WATER HEIGHT - 16.500 (IN)
CONTOUR ID
A 0.53381
B 0.53114
C 0.52847
D 0.52313
E 0.51779
F 0.50712
G 0.48043
H 0.43772
I 0.39502
J 0.35231
K 0.30961
L 0.26690
M 0.22420
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

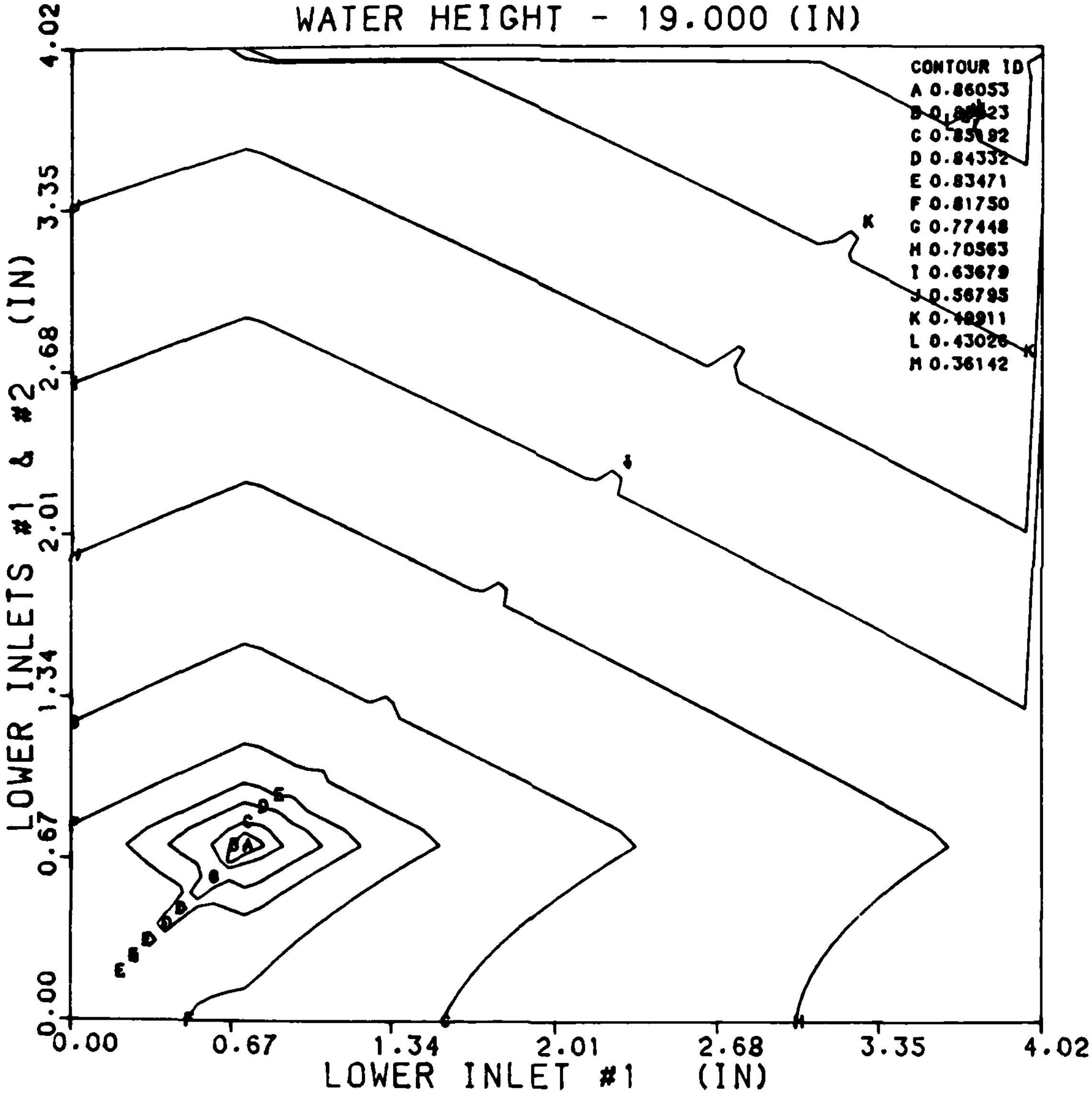
WATER HEIGHT - 17.000 (IN)



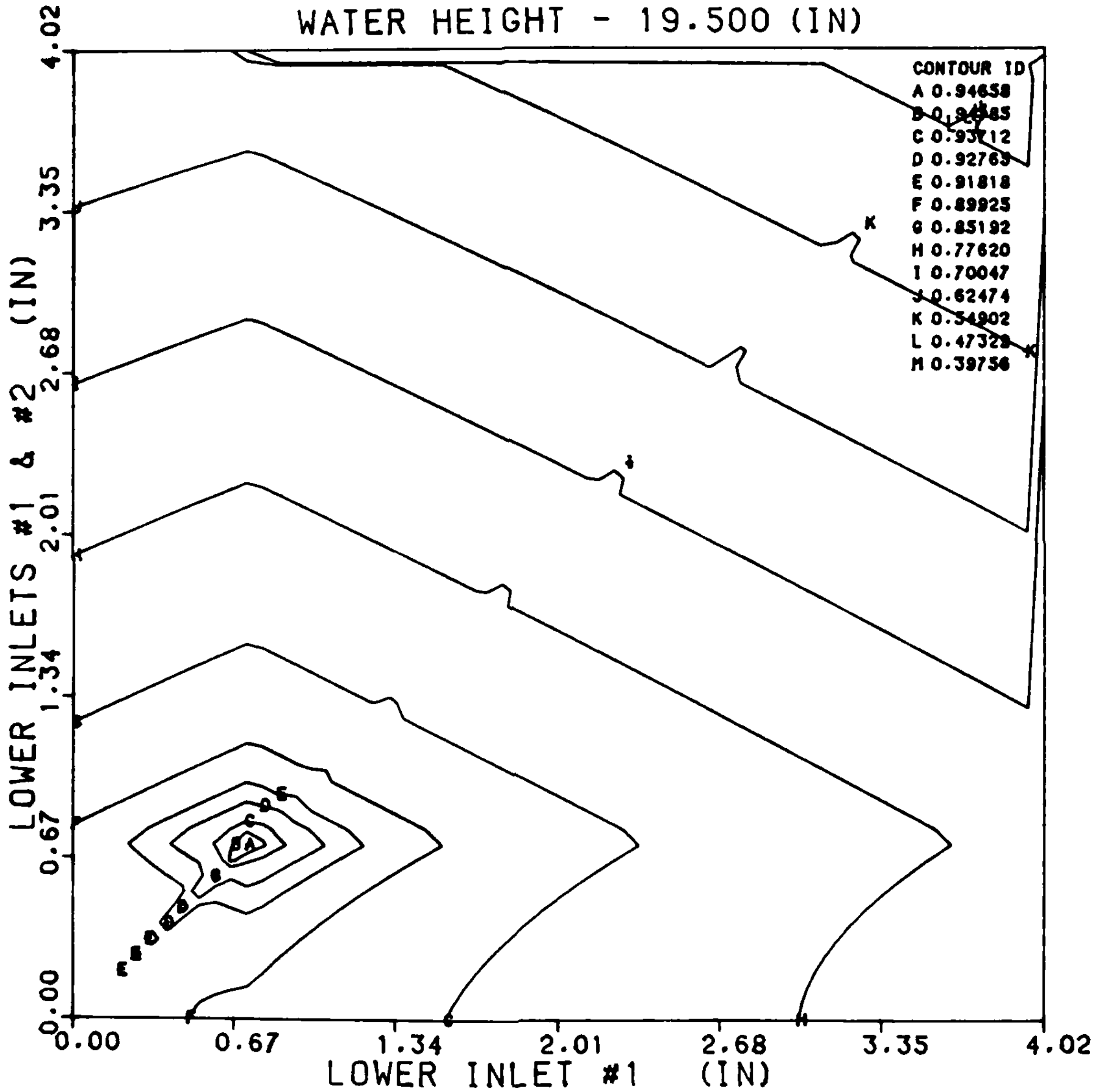


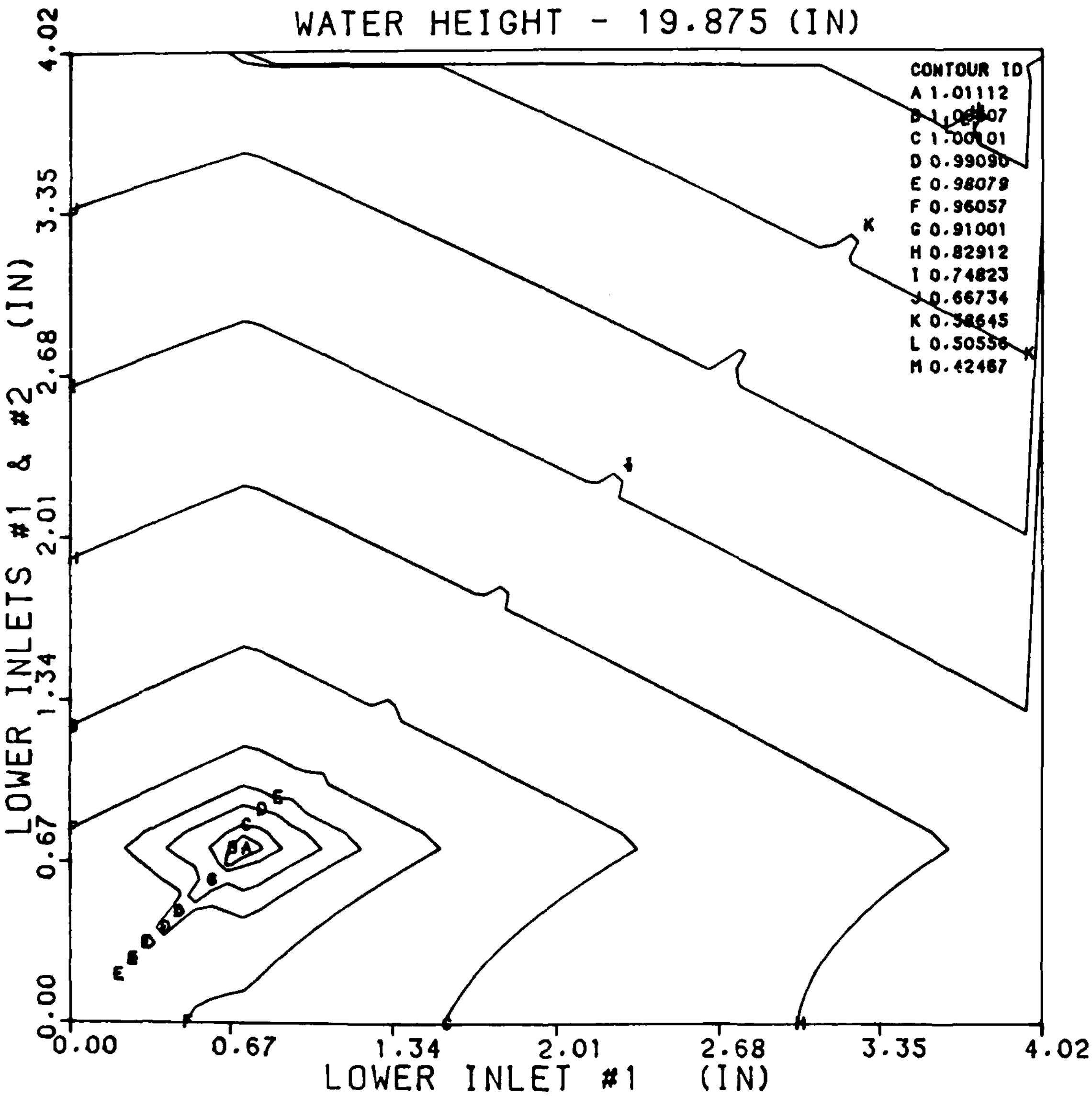
WATER HEIGHT - 17.500 (IN)
CONTOUR ID
A 0.63527
B 0.63210
C 0.62892
D 0.62257
E 0.61621
F 0.60351
G 0.57175
H 0.52092
I 0.47010
J 0.41928
K 0.36846
L 0.31764
M 0.26681
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02


WATER HEIGHT - 18.000 (IN)
CONTOUR ID
A 0.68842
B 0.68498
C 0.68154
D 0.67465
E 0.66777
F 0.65400
G 0.61958
H 0.56451
I 0.50943
J 0.45436
K 0.39929
L 0.34421
M 0.28914
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

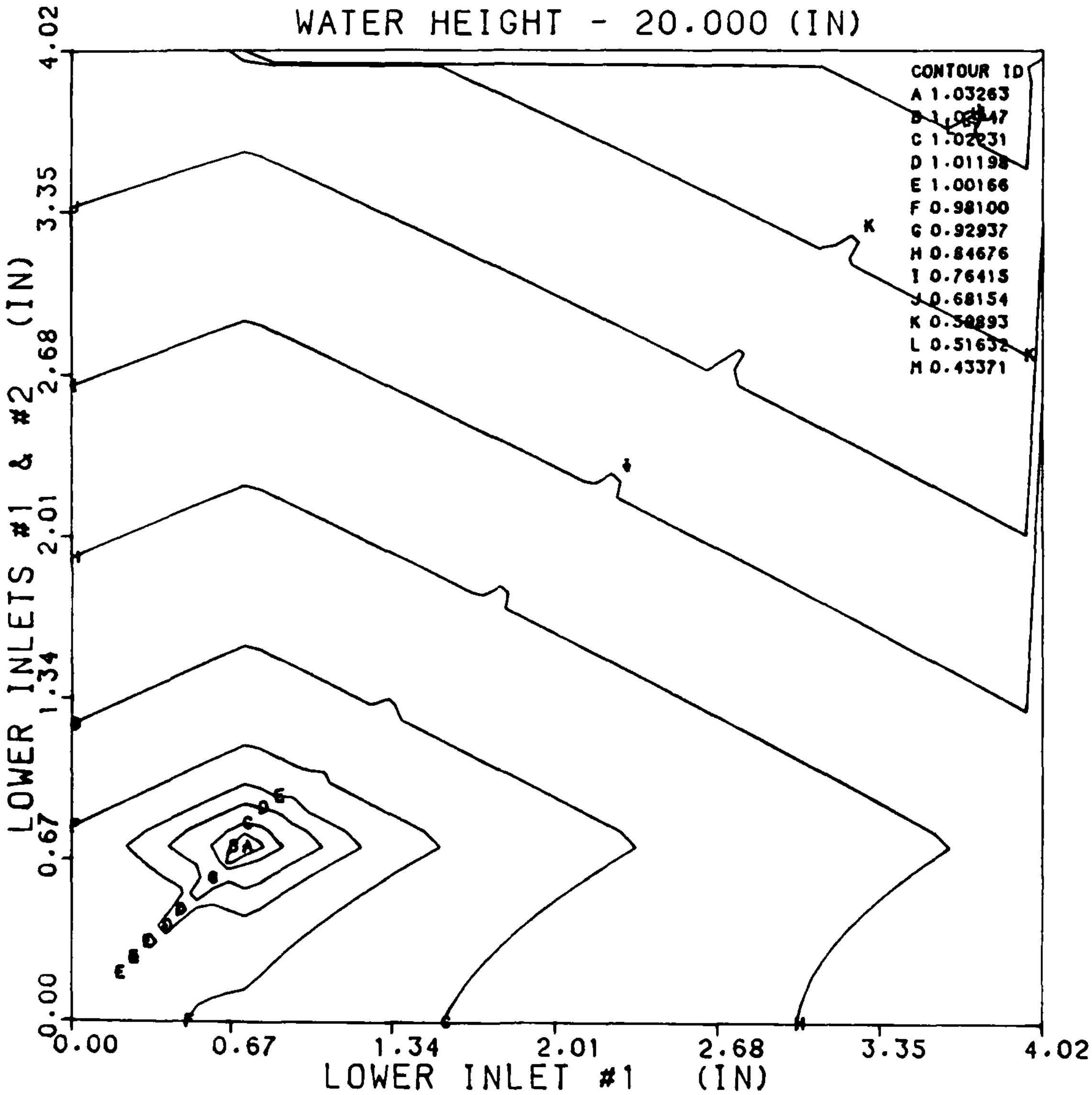


WATER HEIGHT - 19.000 (IN)
CONTOUR ID
A 0.86053
D 0.84332
E 0.83471
F 0.81750
G 0.77448
H 0.70563
I 0.63679
J 0.56795
L 0.43026
M 0.36142
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02


WATER HEIGHT - 19.500 (IN)
CONTOUR ID
A 0.94658
B 0.94185
C 0.93712
D 0.92765
E 0.91818
F 0.89925
G 0.85192
H 0.77620
I 0.70047
J 0.62474
K 0.54902
L 0.47329
M 0.39756
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02



WATER HEIGHT - 19.875 (IN)
CONTOUR ID
A 1.01112
D 0.99090
E 0.98079
F 0.96057
G 0.91001
H 0.82912
I 0.74823
J 0.66734
L 0.50556
M 0.42467
0.00
0.67
1.34
2.01
2.68
3.35
4.02
LOWER INLET #1 (IN)
LOWER INLETS #1 & #2 (IN)


WATER HEIGHT - 20.000 (IN)
CONTOUR ID
A 1.03263
E 1.00166
F 0.98100
G 0.92937
H 0.84676
I 0.76415
J 0.68154
L 0.51632
M 0.43371
LOWER INLETS #1 & #2 (IN)
LOWER INLET #1 (IN)
0.00
0.67
1.34
2.01
2.68
3.35
4.02

Appendix H

This Appendix contains a module index and data dictionary for the Control Cycle Software. The data dictionary is divided into three sections, global parameters global variables, and passed variables. Each section is divided alphabetically.

Module Index

DATA DICTIONARY

GLOBAL PARAMETERS

CLOSE_ALL3_RELAYS
CLOSE_TABLE_RELAYS
CLOSE_UI#1_RELAYS
CLOSE_UI#2_RELAYS
CLOSE_UI#3_RELAYS
CLOSE_VEL_UI
CLOSE_VEL_UI
DELAY_TIME
DELTA_X
LOWER_INLET_POS_ARRAY
MAX_CONTROL_CYCLE_TIME
MAX_STEP
OPEN_ALL_THREE_RELAYS
OPEN_TABLE_RELAYS
OPEN_UI#1_RELAYS
OPEN_UI#2_RELAYS
OPEN_UI#3_RELAYS
OPEN_VEL_UI
OPEN_VEL_UT
REDUCE_STEP
RELAY
UI#1_LIMIT
UI#2_LIMIT
UI#3_LIMIT
UI_MAX
UPPER_INLETS_POS_ARRAY [UI(I)]
UPPER_TABLE_POS_ARRAY [UT(I)]
UT_LIMIT
UT_MAX
WATER_HEIGHT_ARRAY [A(I)]

NAME: CLOSE_ALL_THREE_RELAYS
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to the Relay I/O to output a close signal to each upper inlet actuator relay.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: 2.1.1

NAME: CLOSE_UI_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to the Relay I/O to output a close signal to the upper table.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: CLOSE_UI#1_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to the Relay I/O to output a close signal to the upper table #1.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: CLOSE_UI#2 RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to the Relay I/O to output a close signal to upper inlet #2.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: CLOSE_UI#3_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to the Relay I/O to output a close signal to upper inlet #3.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: CLOSE_VEL_UI
TYPE: GLOBAL PARAMETER
DESCRIPTION: The closing velocity of the upper inlets.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1.1

NAME: CLOSE_VEL_UT
TYPE: GLOBAL PARAMETER
DESCRIPTION: The closing velocity of the upper table.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1.1

NAME: DELAY_TIME
TYPE: GLOBAL PARAMETER
DESCRIPTION: The length of time the controller delays after control surfaces are moved to the full open position. The delay allows the water flow to settle to steady state.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2

NAME: DELTA_X
TYPE: GLOBAL PARAMETER
DESCRIPTION: The smallest increment that the controller can move the control surfaces.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.5, B3.1, B2.1.1

NAME: LOWER_INLET_POS_ARRAY
TYPE: GLOBAL PARAMETER ARRAY
DESCRIPTION: The stored optimum position of the lower inlet
DATA CHARACTERISTICS: Real Array
ASSOCIATED PROCESSES: B2.2

NAME: MAX_CONTROL_CYCLE_TIME
TYPE: GLOBAL PARAMETER
DESCRIPTION: The maximum time length allowed for a control cycle.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B1

NAME: MAX_STEP
TYPE: GLOBAL PARAMETER
DESCRIPTION: The first and largest step moved during the Gradient Search Software.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.5, B2.5a

NAME: OPEN_ALL_THREE_RELAYS
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to relay I/O to output an open signal to all three upper inlets.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_TABLE_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to relay I/O to output an open signal to

the upper table.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_UI#1_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to relay I/O to output an open signal to the upper inlet #1.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_UI#2_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to relay I/O to output an open signal to the upper inlet #2.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_UI#3_RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Code to relay I/O to output an open signal to the upper inlet #3.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_VEL_UI
TYPE: GLOBAL PARAMETER
DESCRIPTION: The opening velocity of the upper inlet.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1.1

NAME: OPEN_VEL_UT
TYPE: GLOBAL PARAMETER
DESCRIPTION: The measured opening velocity of the upper table.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1.1

NAME: REDUCE_STEP
TYPE: GLOBAL PARAMETER
DESCRIPTION: REDUCE_STEP is the factor which is multiplied times the step size each time the step is considered too large in the gradient search.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.5, B2.5a, B3.1

NAME: RELAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: Address of relay I/O which interfaces the controller to the control surfaces.
DATA CHARACTERISTICS: I/O Address
ASSOCIATED PROCESSES: B2.1.1

NAME: UI#1_LIMIT
TYPE: GLOBAL PARAMETER
DESCRIPTION: Address of upper inlet #1Os limit switch I/O.
DATA CHARACTERISTICS: I/O Address
ASSOCIATED PROCESSES: B2.1.1

NAME: UI_#2_LIMIT
TYPE: GLOBAL PARAMETER
DESCRIPTION: Address of upper inlet #2's limit switch I/O.
DATA CHARACTERISTICS: I/O address
ASSOCIATED PROCESSES: B2.1.1

NAME: UI#3_LIMIT
TYPE: GLOBAL PARAMETER
DESCRIPTION: Address of upper inlet #3's limit switch I/O.
DATA CHARACTERISTICS: I/O Address
ASSOCIATED PROCESSES: B2.1.1.1

NAME: UI_MAX
TYPE: GLOBAL PARAMETER
DESCRIPTION: The distance the upper inlets tranfer from full closed to full open.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1

NAME: UPPER_INLETS_POS_ARRAY [UI(I)]
TYPE: GLOBAL PARAMETER ARRAY
DESCRIPTION: The stored measured optimum positions for the upper inlets.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.4

NAME: UPPER_TABLE_POS_ARRAY
TYPE: GLOBAL PARAMETER ARRAY
DESCRIPTION: The stored optimum positions of the upper table
DATA CHARACTERISTICS: Real Array
ASSOCIATED PROCESSES: B2.3

NAME: UT_LIMIT
TYPE: GLOBAL PARAMETER
DESCRIPTION: The upper table limit switch I/O address.
DATA CHARACTERISTICS: I/O Address
ASSOCIATED PROCESSES: B2.5.1.1.1

NAME: UT_MAX
TYPE: GLOBAL PARAMETER
DESCRIPTION: The distance the upper table will travel when moving from full closed to full open.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1

NAME: WATER_HEIGHT_ARRAY
TYPE: GLOBAL PARAMETER
DESCRIPTION: The stored ranges of water heights which are referenced in order to obtain an index number. The index # is then used to find the appropriate positions of control surfaces from their respective position arrays.
DATA CHARACTERISTICS: Real Array
ASSOCIATED PROCESSES: B2.2, B2.3, B2.4

PASSED VARIABLES

CON_SURFACE
CURRENT_TIME
DISTANCE
ERROR
INITIAL_SEARCH
LI_DISTANCE
LIMIT
PARTIAL
POWER
UI_NORMAL
UT_NORMA;
WATER_HEIGHT

NAME: CON_SURFACE
TYPE: PASSED VARIABLES
DESCRIPTION: Represents one of the four control surfaces. Upper table, UI#1, UI#2, UI#3, or ALL THREE UPPER INLETS.
DATA CHARACTERISTICS: Integer
ASSOCIATED PROCESSES: B2, B21.1, B2.5, B2.5a, B2.3, B2.4, B3.1, B3.2, B.2.5.1,B2.5.1.1

NAME: CURRENT_TIME
TYPE: PASSED VARIABLES
DESCRIPTION: The current time read from the clock.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B1, A1, B2.1.1

NAME: DISTANCE
TYPE: PASSED VARIABLES
DESCRIPTION: The distance a control surface is designed to move.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.1, B2.1.1, B2.5, B2.5a, B2.3, B2.4,B2.3.1

NAME: ERROR
TYPE: PASSED VARIABLES
DESCRIPTION: Indicates whether an error was found in the cleck and correct module.
DATA CHARACTERISTICS: Boolean
ASSOCIATED PROCESSES: B3, B3.2

NAME: INITIAL_SEARCH
TYPE: PASSED VARIABLES
DESCRIPTION: Indicates whether the control cycle is the initial control cycle.
DATA CHARACTERISTICS: Boolean
ASSOCIATED PROCESSES: B1, A8

NAME: LI_DISTANCE
TYPE: PASSED VARIABLES
DESCRIPTION: The distance the lower inlet is designated to move.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.2

NAME: LIMIT
TYPE: PASSED VARIBLES

DESCRIPTION: Indicates whether a limit switch is engaged.
DATA CHARACTERISTICS: Boolean
ASSOCIATED PROCESSES: B3.2, B2.5a, B2.1.1, B2.3

NAME: PARTIAL
TYPE: PASSED VARIABLES
DESCRIPTION: The numeric approximated partial derivative for a control surface.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B1, A0, B2.5.1, B2.5.1.1

NAME: POWER
TYPE: PASSED VARIABLES
DESCRIPTION: The power read from the AID (power meter).
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B1, A0, B2.5, B3.1, B2.1.1

NAME: UI_NORMAL
TYPE: PASSED VARIBLES
DESCRIPTION: The normalized partial derivative for the upper inlets.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.5, B2.5.1

NAME: UT_NORMAL
TYPE: PASSED VARIABLES
DESCRIPTION: The normalized partial derivative for the upper table.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.5, B2.5.1

NAME: WATER_HEIGHT
TYPE: PASSED VARIABLES
DESCRIPTION: The water height read from the AID.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B2.3, B2.4

GLOBAL VARIABLES

MAX_TIME
NUMB_OF_CC_ARRAY
POWER_ARRAY
TIME_OF_LAST_CONTROL_CYCLE

NAME: MAX_TIME
TYPE: GLOBAL VARIABLE
DESCRIPTION: MAX_TIME is calculated in the Control Cycle Module and is the time limit set for this current control cycle. MAX_TIME is compared to the current time each time a control surface is moved.
DATA CHARACTERISTICS: Real
ASSOCIATED PROCESSES: B1, B2.1.1

NAME: NUMB_OF_CC_ARRAY
TYPE: GLOBAL VARIABLES ARRAY
DESCRIPTION: The number of control cycles that have been performed at a water height range corresponding to the array index.
DATA CHARACTERISTICS: Integer Array
ASSOCIATED PROCESSES: B1, A9

NAME: POWER_ARRAY
TYPE: GLOBAL VARIABLES ARRAY
DESCRIPTION: The averaged power for each water height range corresponding to the array index.
DATA CHARACTERISTICS: Real Array
ASSOCIATED PROCESSES: B1, A9

Appendix I

Psuedo-code for Control Cycle Software

MODULE NAME: Control Cycle (B1)

Module Description:

This module selects the mode in which the search will be performed based upon the start code sent from the monitor module.

Calling Modules:	Arguments:
Monitor Mode (A8)	INITIAL_SEARCH

Modules Called:	Arguments:
Search Initial Start Up (B2)	
Water Height Change (B3)	
Read Clock (A1)	CURRENT_TIME
Read A/D (A0)	Power
Turn Pump on/off (A4)	

Global Parameters:

MAX_CONTROL_CYCLE_TIME

Global Variables:

TIME_OF_LAST_CONTROL_CYCLE, MAX_TIME, NUMB_OF_CC

Passed Variables:

CURRENT_TIME, POWER, INITIAL_SEARCH

Psuedocode:

```
Turn on Hydraulic Pump (A4)
Read Clock (A1)
MAX_TIME = CURRENT_TIME + MAX_CONTROL_CYCLE_TIME
```

AD-A155 477 MICROPROCESSOR CONTROL DESIGN FOR A LOW-HEAD CROSSFLOW TURBINE(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING D C RAMSEY MAR 85 4/4

UNCLASSIFIED AFIT/GE/ENG/85M-2 F/G 9/2 NL

END

FILMED

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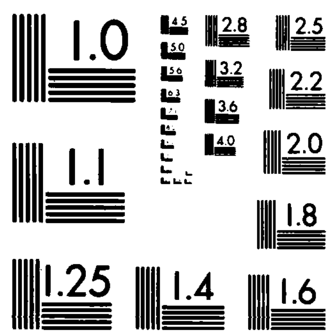


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
If INITIAL_SEARCH = TRUE  Then
  Search Initial Start Up (B2)
Else
  Water Height Change or Time Limit (Module B3)
End If
  Read Clock  (A1)
  TIME_OF_LAST_CONTROL_CYCLE = CURRENT_TIME
  Read Aid  (A0)
  OLD_AVG = POWER_ARRAY(WATER_HEIGHT)
  POWER_ARRAY(WATER_HEIGHT)=((NUMB_OF_CC*OLD_AVG)+POWER)/NUMB_OF_CC+1
  NUMB_OF_CC = NUMB_OF_CC + 1
  Turn Off Hydraulic Pump  (A4)
```

MODULE NAME: Search Initial Start Up (B2)

Module Description:

This module will optimize the control surfaces regardless of the control surfaces' initial positions. This module fully opens the upper table and the upper inlets to obtain a reference position. Then, this module contains a delay loop to allow the water to stabilize. The lower inlet is then moved to the optimal position. This module also sets the upper table and upper inlets to approximate optimal positions stored in memory. Finally, this module calls for the gradient search to begin on the upper table and upper inlets.

Calling Modules:	Arguments:
Search Executive (B1)	

Modules Called:	Arguments:
Open Control Surfaces (B2.1)	CON_SURFACE
Set Lower Inlet (B2.2)	
Position Upper Table (B2.3)	
Position Upper Inlets (B2.4)	
Gradient Search (B2.5)	N/A

Global Parameters:

DELAY_TIME

Passed Variables:

CON_SURFACE

Psuedocode:

```
Open Upper Table  (B2.1)

Open Upper Inlets  (B2.1)

For I=1,DELAY_TIME Loop

   Kill time

End Counting Loop

Set Lower Inlet  (B2.2)

Position Upper Table  (B2.3)

Position Upper Inlets  (B2.4)

Do Gradient Search  (B2.5)

End
```

MODULE NAME: Water Height Change (B3)

Module Description:

This module optimizes the control surface positions after a change in water height or time limit exploration between control cycles. This module assumes the control surfaces are positioned in a region where the global maximum can be found. However, this module also checks whether a control surface is and should be at the open limit and vice versa. If an error exists the control surfaces are positioned near the optimum positions and another gradient search is performed.

Calling Modules:	Arguments:
Search Executive (B1)	

Modules Called:	Arguments:
Align Upper Inlets (B3.1)	N/A
Check Limits (B3.2)	ERROR

Passed Variables:

ERROR

Psuedocode:

```
Align the upper inlets  (B3.1)
Do gradient search   (B2.5)
Check and correct   (B3.2)
If (ERROR = TRUE) Then
   Do gradient search  (B2.5)
End If
End
```

MODULE NAME: Open Control Surfaces (B2.1)

Module Description:

This module sets the control surface designated by the argument to the open position. The control surface is attempted to be moved the distance from full closed to full open regardless of the initial control surface position.

Calling Modules: Arguments:

Search Initial Start Up (B2) CON_SURFACE

Modules Called: Arguments:

Move Control Surface (B2.1.1) CON_SURFACE,DISTANCE

Global Parameters:

UT_MAX, UI_MAX UPPER_TABLE

Passed Variables:

DISTANCE,CONSURFACE

Psuedocode:

```
If CON_SURFACE = UPPER_TABLE  Then

   DISTANCE = UT_MAX

   Move the upper table the distance UT_MAX
   (Module B2.1.1)

Else

   DISTANCE = UI_MAX

   Move all the upper inlets the distance UI_MAX
   (Module B2.1.1)

End If

End
```

MODULE NAME: *Set Lower Inlet (B2.2)

Module Description:

This module sets the lower inlet to the optimum position that corresponds to the current water height. This module is similar to the modules positioning the upper and lower inlets to the approximate optimal positions (Modules B2.3 and B2.4). However, since the lower inlet was never connected to a mechanical drive and since the lower inlet will be fixed after the turbine modification, no psuedocode is provided for this module.

Calling Modules:	Arguments:
Search Initial Start Up (B2)	
Water Height Change (B3)	

Modules Called:	Arguments:
Move Lower Inlet	LI_DISTANCE

Global Parameters:

WATER_HEIGHT_ARRAY, LOWER_INLET_POS_ARRAY

Passed Variables:

LI_DISTANCE

* This module not required for the modified turbine.

MODULE NAME: *Move Lower Inlet (B2.2.1)

Module Description:

This module would move the lower inlet the distance designated by the argument. This module is similar to the Move Control Surface Module (B2.1.1). No psuedocode has been developed since the mechanical drive was never installed the lower inlet. Also, the lower inlet will be fixed after the turbine modification, therefore this module will not be required.

Calling Modules:

Set Lower Inlet

Arguments:

LI_DISTANCE

* This module is not required for the modified turbine.

MODULE NAME: Position Upper Table (B2.3)

Module Description:

This module moves the upper table from the full open position to an approximate optimal position. The distance the upper table is moved is selected from the optimal table positions stored in the upper table position array. The current water height is used as the basis for for selecting the distance.

Calling Modules: | Arguments:

Search Initial Start Up (B2)

Modules Called: | Arguments:

Move Control Surfaces (B2.1.1) CON_SURFACE, DISTANCE

Global Parameters:

WATER_HEIGHT_ARRAY [H(I)],
UPPER_TABLE_POS_ARRAY [UT(I)]

Global Variables:

WATER_HEIGHT

Passed Variables:

DISTANCE,CON_SURFACE

Psuedocode:

```
I = 1
Until (H(I) < WATER_HEIGHT < H(I+1)) Loop
   I = I + 1
End Until Loop
DISTANCE = UT(I)
Move upper table to UT(I) (B2.1.1)
End
```

MODULE NAME: Position Upper Inlets (B2.4)

Calling Modules: Search Initial Start Up (B2)

Arguments:

Modules Called: Move Control Surfaces (B2.1.1)

Arguments: CON_SURFACE, DISTANCE

Global Parameters:

WATER_HEIGHT_ARRAY [H(I)],
UPPER_INLETS_POS_ARRAY [UI(I)]

Passed Variables:

CON_SURFACE, DISTANCE

GLOBAL VARIABLES:

WATER_HEIGHT

Module Description:

This module moves the upper inlets from the full open position to an approximate optimal position. The distance the upper inlets are moved is selected from the optimal inlet positions stored in the upper inlets position array. The current water height is used as the basis for selecting the distance.

Psuedocode:

```
I = 1
Until (H(I) < WATER_HEIGHT < H(I+1)) Loop
   I = I + 1
End Until Loop
DISTANCE = UI(I)
Move upper inlets to UI(I) (Module B2.1.1)
End
```

MODULE NAME: Gradient Search #1 (B2.5)

Module Description:

This module is the general gradient search algorithm as discussed is Section VI-3. This module performs a gradient search to fins the maximum power using two variables; the upper table and the combination of the three upper inlets moved as one control surface. The module assumes the upper inlets have been aligned and all the control surfaces are in a region where the global maximum will be obtained. Step sizes for the search start at the maximum step step are reduced by a factor of .5 until step size is less than or equal to .707 times the minimum increment a control surface can be moved.

Calling Modules:	Arguments:
Search Initial Start Up (B2)	
Water Height Change (B3)	

Modules Called:	Arguments:
Read A/D (AO)	POWER
Find Normalized Partials (B2.5.1)	UT_NORMAL, UI_NORMAL
Move Control Surfaces (B2.1.1)	CON_SURFACE, DISTANCE

Global Parameters:

DELTA_X, MAX_STEP, REDUCE_STEP

Passed Variables:

UT_NORMAL, UI_NORMAL, POWER, CON_SURFACE, DISTANCE

Psuedocode:

```
START: Find Normalized Partials (B2.5.1)
       If (UT_NORMAL = 0 and UI_NORMAL = 0) Then
          Return to calling module
       End If
       STEP = MAX_STEP
       While STEP > .707DELTA_X Loop
         INNER_LOOP = 0
         Read Power (P0) from A/D  (A0)
         While (Power Increases ie. P1>P0) Loop
           Move Table (DISTANCE = STEP*UT_NORMAL) (B2.1.)
           Move UI's  (DISTANCE = STEP*UI_NORMAL) (B2.1.)
           Read power (P1) from A/D (Module A0)
           INNER_LOOP = INNER_LOOP + 1
         End Inner While Loop
         DISTANCE = -STEP*UT_NORMAL
         Move table back to best position (B2.1.1)
         DISTANCE = -STEP*UI_NORMAL
         Move UI's back to best position  (B2.1.1)
         If (INNER_LOOP > 0) Then
            Go back to START and redo from this new
            position
         Else
            STEP = STEP*REDUCE FACTOR
         End If
       End Outer While Loop
       End
```

MODULE NAME: Align Upper Inlets (B3.1)

Module Description:

This module aligns the upper inlets to the same position. Each inlet is moved individually to a position which produces the highest power with all other control surfaces fixed. The highest power will always be where the control surfaces are aligned. The resulting position of the upper inlets may not be the optimal position (see Section VI-5).

Calling Modules:	Arguments:
Water Height Change (B3)	

Modules Called:	Arguments:
Find Partials (B2.5.1.1)	CON_SURFACE, PARTIAL
Move Control Surface (B2.1.1)	CON_SURFACE, DISTANCE
Read A/D (A0)	POWER

Global Parameters:

DELX

Passed Variables:

CON_SURFACE, PARTIAL, POWER, DISTANCE

Psuedocode:

```
Do (for each of the upper inlets) Loop
    Find partial with respect to control surface position
    (Module B2.5.1.1)
    Read power (P0) from A/D (Module A0)
    If (PARTIAL > 0) Then
```

```
        While (P1 > P0) Loop
           P0 = P1
           Move upper inlet DELTA_X (Module B2.1.1)
           Read power (P1) from A/D   (Module A0)
        End While Loop
        Move upper inlet -DELTA_X (Module B2.1.1)
     Else If (Partial < 0) Then
        While (P1 > P0) Then
           P0 = P1
           Move upper inlet -DELTA_X (Module B.1.1)

           Read power (P1) from A/D  (Module A0)x

        End While Loop
        Move upper inlet DELT_X
     End if
  End Do Loop
  End
```

MODULE NAME: Check and Correct (3.2)

Module Description:

This module checks the upper table and uppper inlet position arrays to verify whether the control surface should be at the open limit. If an error exists the control surface is moved to the approximate optimal position found in the array and an the error variable is set to TRUE.

Calling Modules:	Arguments:
Water Height Change (B3)	ERROR

Modules Called:	Arguments:
Read Limit Switches (B2.5.1.1.1)	CON_SURFACE, LIMIT
Open Control Surfaces (B2.1)	CON_SURFACE
Move Control Surface (B2.1.1)	CON_SURFACE, DISTANCE

Global Parameters

WATER_HEIGHT_ARRAY [H(I)], UPPER_TABLE_POS_ARRAY [UT(I)], UPPER_INLETS_POS_ARRAY [UT(I)]

Passed Variables:

ERROR, LIMIT,CON_SURFACE, DISTANCE

Psuedocode:

```
Read table limit switch (B2.5.1.1.1)
I=1
Until (H(I) < WATER_HEIGHT < H(I+1)) Loop
   I = I + 1
End Until Loop
```

MODULE NAME: Check and Correct (3.2)

Module Description:

This module checks the upper table and uppper inlet position arrays to verify whether the control surface should be at the open limit. If an error exists the control surface is moved to the approximate optimal position found in the array and an the error variable is set to TRUE.

Calling Modules:	Arguments:
Water Height Change (B3)	ERROR

Modules Called:	Arguments:
Read Limit Switches (B2.5.1.1.1)	CON_SURFACE, LIMIT
Open Control Surfaces (B2.1)	CON_SURFACE
Move Control Surface (B2.1.1)	CON_SURFACE, DISTANCE

Global Parameters

WATER_HEIGHT_ARRAY [H(I)], UPPER_TABLE_POS_ARRAY [UT(I)], UPPER_INLETS_POS_ARRAY [UT(I)]

Passed Variables:

ERROR, LIMIT,CON_SURFACE, DISTANCE

Psuedocode:

```
Read table limit switch (B2.5.1.1.1)
I=1
Until (H(I) < WATER_HEIGHT < H(I+1)) Loop
   I = I + 1
End Until Loop
```

```
If (UT(I) = 0) Then
   CHECK = TRUE
Else
   CHECK = FALSE
End if
If (LIMIT ≠ CHECK) Then
   ERROR = TRUE
   If (UT(I) = 0) Then
      Open Upper Table  (Module B2.1)
   Else
      Move Upper Table to UT(I)  (Module B2.1.1)
   End If
End IF
Read the upper inlets' limit switches (Module B2.5.1.1.1)
If (UI(I) = 0) Then
   CHECK = TRUE
Else
   CHECK = FALSE
End If
If (CHECK ≠ LIMIT) Then
   ERROR = TRUE
   If (UI(I) = 0) Then
      Open Upper Inlets  (Module B2.1)
   Else
      Move upper inlets to UI(I)  (Module B2.1.1)
   End If
End If
```

MODULE NAME: Move Control Surface (B2.1.1)

Module Description:

This module moves the appropriate control surface or surfaces the distance specified in the argurment. The sign of the distance argument determines the direction. If the distance designated to move is less than one half the smallest allowable then the control surface is not moved. If the distance designated to move the control surface is less than the smallest allowable but greater than or equal to one half the smallest allowable then the control surface is moved the smallest allowable increment. This module also checks the open limit switch of each control surface and will not attempt movement in the open position while this switch is engaged. Actual movement of the actuator is accomplished by setting the relay I/O address to the appropriate value. The value will correspond to the control surface to move and the direction of movement. The relay I/O is then set back to nuetral (ie all zeros) after the amount of time required to move the control surface has elapsed. The elapsed time equals the distance to move the control surface divided by the velocity of the control surface.

Calling Modules: | Arguments:

Calling Modules:	Arguments:	
Open Control Surfaces (B2.1)	CON_SURFACE,DISTANCE	
Position Upper Table (B2.3)	"	"
Positon Upper Inlets (B2.4)	"	"
Gradient Search (B2.5)	"	"
Find Partials (B2.5.1.1)	"	"

Modules Called:	Arguments:
Read Clock (A1)	CURRENT_TIME
Read Limit Switches (B2.5.1.1.1)	CON_SURFACE,LIMIT

Global Parameters:

DELTA_X, OPEN_VEL_UT, OPEN_VEL_UI, CLOSE_VEL_UI, CLOSE_UI, OPEN_TABLE_RELAY, CLOSE_TABLE_RELAY

Passed Variables:

CON_SURFACE, DISTANCE, LIMIT, CURRENT_TIME

Psuedocode:

```
If (DIST ≥ .5DELTA_X  or  DIST ≤ -.5DELTA_X) Then
   If (.5DELTA_X < DIST < DELTA_X) Then
      DIST = DELTA _X
   End If
   If (-.5DELTA_X > DIST > -DELTA_X) Then
      DIST = -DELTA_X
   End if
   If (CON_SURFACE = UPPER_TABLE) Then
      OPEN_VELOCITY = OPEN_VEL_UT
      CLOSE_VELOCITY = CLOSE_VEL_UI
      OPEN_RELAY = OPEN_TABLE_RELAY
      CLOSE_RELAY = CLOSE_TABLE_RELAY
```

```
Else
   OPEN_VELOCITY = OPEN_VEL_UI
   CLOSE_VELOCITY = CLOSE_VEL_UI
   If (CON_SURFACE = UI#1) Then
      OPEN_RELAY = OPEN_UI#1_RELAY
      CLOSE_RELAY = CLOSE_UI#1_RELAY
   End If
   If (CON_SURFACE = UI#2) Then
      OPEN_RELAY =  OPEN_UI#2_RELAY
      CLOSE_RELAY = CLOSE_UI#2_RELAY
   End If
   If (CON_SURFACE = UI#3) Then
      OPEN_RELAY = OPEN_UI#3_RELAY
      CLOSE_RELAY = CLOSE_UI#3_RELAY
   End If
   If (CON_SURFACE = ALL_THREE_UIS) THEN
      OPEN_RELAY = OPEN_ALL3_RELAYS
      CLOSE_RELAY = CLOSE_ALL3_RELAYS
   End If
End If
```

```
        If (DISTANCE < 0) Then

           Read control surface limit switch
           (Module B2.5.1.1.1)

           If (LIMIT = True) Then

              Return to calling modules

           End If

           VELOCITY = OPEN_VELOCITY

           Read Clock (Module A1)

           RELAY = OPEN_RELAY

        Else

           VELOCITY = CLOSE_VELOCITY

           Read Clock (Module A1)

           RELAY = CLOSE_RELAY

        End If

        INITIAL_TIME = CURRENT_TIME

        Read Clock (Module A1)

        ELAPSED_TIME = CURRENT_TIME - INITIAL_TIME

        While (ELAPSED_TIME < DISTANCE/VELOCITY) Loop

           Read table limit switch (Module B2.5.1.1.1)

           If (LIMIT = True) Then

              Return to calling  modules

           End If

           Read Clock (Module A1)

           ELAPSED_TIME = CURRENT_TIME - INITIAL_TIME

        End While Loop

     End If

     End
```

MODULE NAME: Find Normalized Partials (B2.5.1)

Module Description:

This module computes the normalized parital derivatives of power with respect to the two variables; the upper table position and the upper inlets position. This module assumes the upper inlets are aligned and are moved as one control surface.

Calling Modules:

Gradient Search (B2.5)

Arguments:

UT_NORMAL, UI_NORMAL

Modules Called:

Find Partials (2.5.1.1)

Arguments:

CON_SURFACES, PARTIAL

Passed Variables:

CON_SURFACE, PARTIAL, UT_NORMAL, UI_NORMAL

Psuedocode:

```
Find Partial with respect to upper table position
(Module B2.5.1.1)

Find Partial with respect to the upper inlets postion
(Module B2.5.1.1)

NORMALIZATION_FACTOR = [(UT_PARTIAL)^2 + (UI_PARTIAL)^2]^(1/2)

UT_NORMAL = UT_PARTIAL/NORMALIZATION_FACTOR

UI_NORMAL = UI_PARTIAL/NORMALIZATION_FACTOR

End
```

MODULE NAME: Find Partials (B2.5.1.1)

Module Description:

This module approximates the partial derivative of the the output power with respect to the control surfaces by numeric approximation. The control surface used for determining the partial is based upon the control surface designated in the argument. If a control surface is against the open physical limit and the partial derivative is negative, then the partial is output as zero since the control surface cannot move any further in the open direction.

Calling Modules:	Arguments:
Find Normalized Partials (B2.5.1)	CON_SURFACE, PARTIAL
Align Upper Inlets (B3.1)	CON_SURFACE, PARTIAL

Modules Called:	Arguments:
Move Control Surfaces (B2.1.1)	CON_SURFACE, DISTANCE
Read A/D (AO)	POWER
Read Limit Switches (B2.5.1.1.1)	CON_SURFACE, LIMIT

Global Parameters:

DELTA_X

Passed VAriables:

CON_SURFACE, PARTIAL, DISTANCE, POWER, LIMIT

Psuedocode:

```
Read power (P0) from A/D  (Module A0)

Read limit switch for control surface  (Module B2.5.1.1.1)

If (LIMIT = TRUE) Then

   Move control surface the distance DELTA_X
   (Module B2.1.1)

   Read power (P1) from A/D  (Module A0)

   If (P1 < P0) Then

      Move control surface back -DELTA_X  (Module B2.1.1)

      Partial = 0

      Return to calling module

   Else

      DELTA_P = P1 - P0

      PARTIAL = DELTA_P/DELTA_X

      Return to calling module

   End If

Move control surface DELTA_X (Module B2.1.1)

Read power (P1) from A/D  (Module A0)

Move control surface back -2*DELTA_X  (Module B2.1.1)

Read power (P2) from A/D  (Module A0)

Read limit switches  (Module B2.5.1.1.1)

If (LIMIT = TRUE) Then

   If (P1 < P0 and P2 < P0) Then

      Move control surface DELTA_X, this places the
      control surface back to the original position.
      (Module B2.1.1)

      Partial = 0

      Return to calling module

   End If
```

```
    If (PO > P2) Then
       Move control surface DELTA_X (Module B2.1.1)
       Read power (PO) from A/D  <Module AO)
       DELTA_P = PO - P2
       PARTIAL = DELTA_P/DELTA_X
       Return to calling module
    Else
       PARTIAL = 0
       Return to calling module
    End If
End If
If (P1 < PO and P2 < PO) Then
    PARTIAL = 0
ELSE
    DELTA_P=P1-P2
    PARTIAL = DELTA_P/2*DELTA_X
END IF
END
```

MODULE NAME: Read Limit Switches (B2.5.1.1.1)

Module Description:

This module determines if a control surface limit switch is engaged. This module assumes that the limit switch will change the value at one of the four addresses listed as global parameters whenever the switch is engaged or disengaged. The switch that is checked is determined by the control surface input in the argument.

Calling Modules:	Arguments:
Find Partials (B2.5.1.1)	CON_SURFACE, LIMIT
Align Upper Inlets (B3.1)	CON_SURFACE, LIMIT

Modules Called:	Arguments:
N/A	

Global Parameters:

UT_LIMIT, UI#1_LIMIT, UI#2_LIMIT, UI#3_LIMIT

Passed Variables:

CON_SURFACE, LIMIT

Psuedocode:

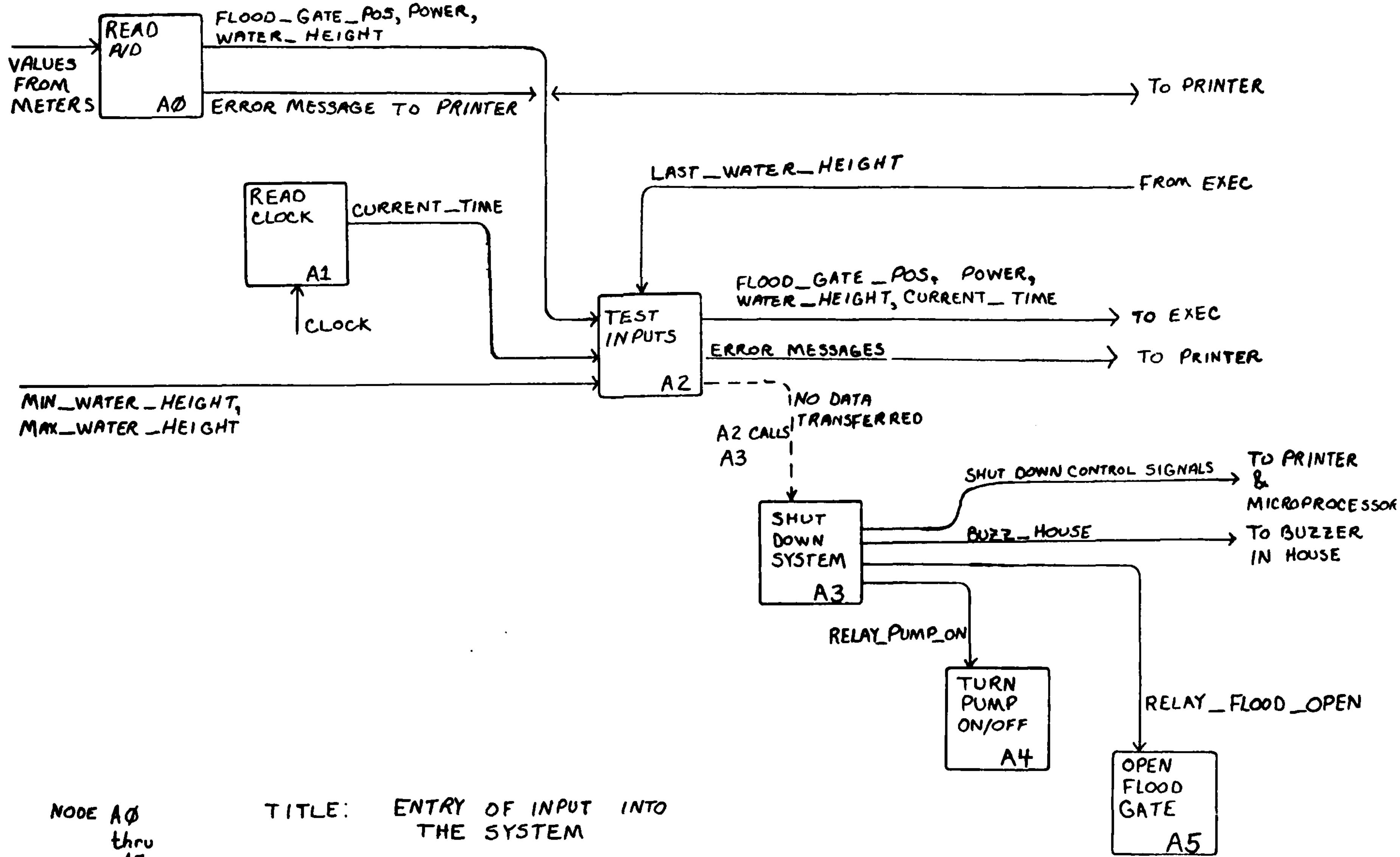
```
If (CON_SURFACE = UPPER_TABLE) Then
   LIMIT = UT_LIMIT
   Return to calling module
End If
```

```
If (CON_SURFACE = UI#1 or CON_SURFACE = ALL3_UIS) Then
   LIMIT = UI#1_LIMIT
   If (LIMIT = TRUE) Then
      Return to calling module
   End IF
End If
If (CON_SURFACE = UI#2 or CON_SURFACE = ALL3_UIS) Then
   LIMIT = UI#2_LIMIT
   If (LIMIT = TRUE) Then
      Return to calling module
   End If
End If
If (CON_SURFACE = UI#3 or CON_SURFACE = ALL3 UIS) Then
   LIMIT = UI#3_LIMIT
   If (LIMIT = TRUE) Then
      Return to calling module
   End If
End If
End
```

Appendix J

This appendix contains the controller software developed by Lt. Mark Walker (10). The software presented includes SADT's, psuedo-code and a data dictionary. The software for the control cycle mode of the controller is presented in Chapter 6.

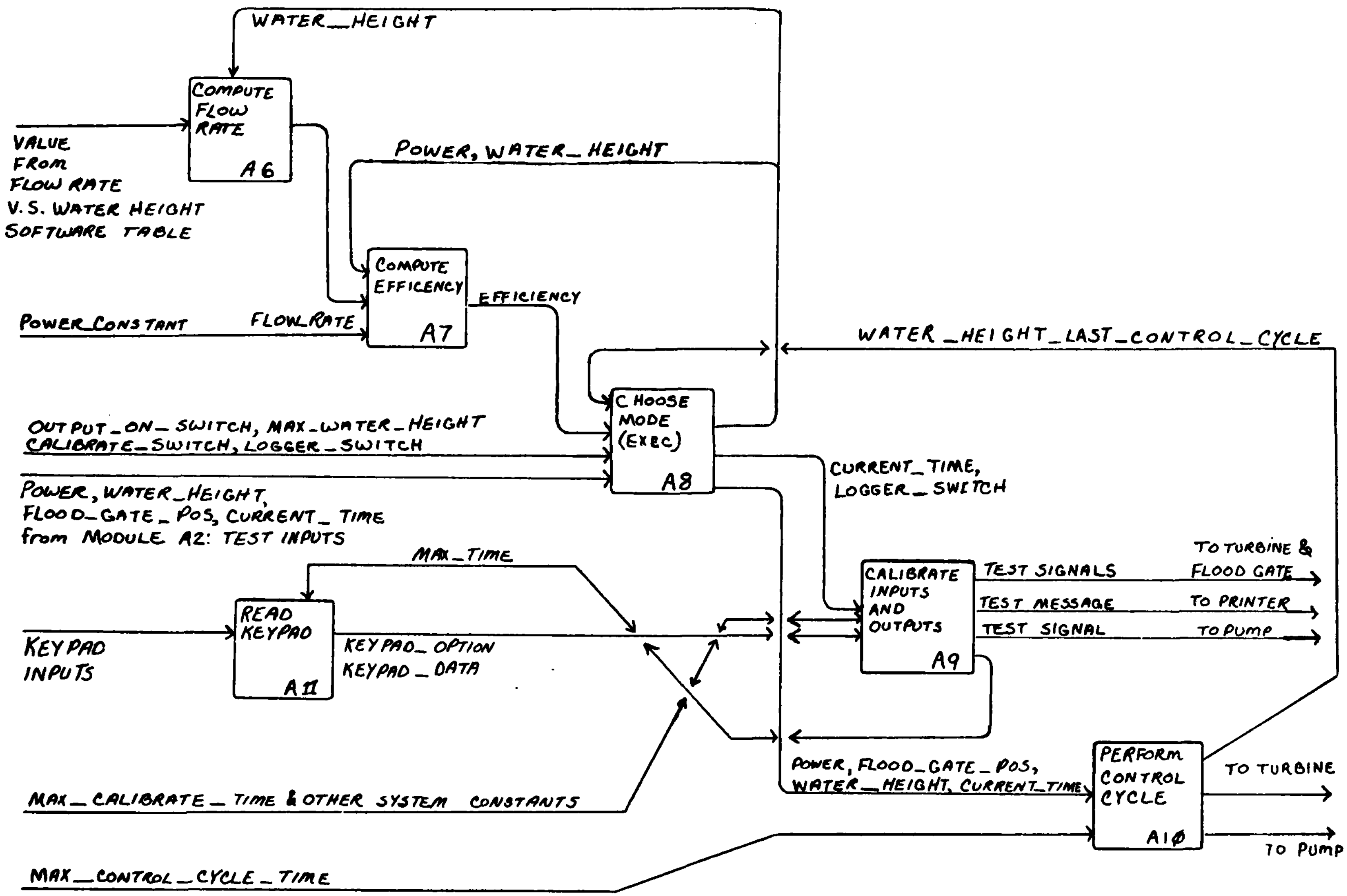
Node Index		SADT #
A0	Read Analog/Digital	1
A1	Read Clock	1
A2	Test Inputs	1
A3	Shut System Down	1
A4	Turn Pump On/Off	1
A5	Open Flood Gate	1
A6	Compute Flow Rate	2
A7	Compute Efficiency	2
A8	Exec or "Choose Mode"	2
A9	Calibrate Mode	2
A10	Control Cycle Mode	2
A10.1	Same as A4	2
A10.2	Same as A2	3
A10.3	Compute Lower Inlet Guide	3
A10.4	Open Turbine Actuators	3
A10.5	Gradient Search	3
A10.6	Check the Power Output	3
A11	Read Keypad	2



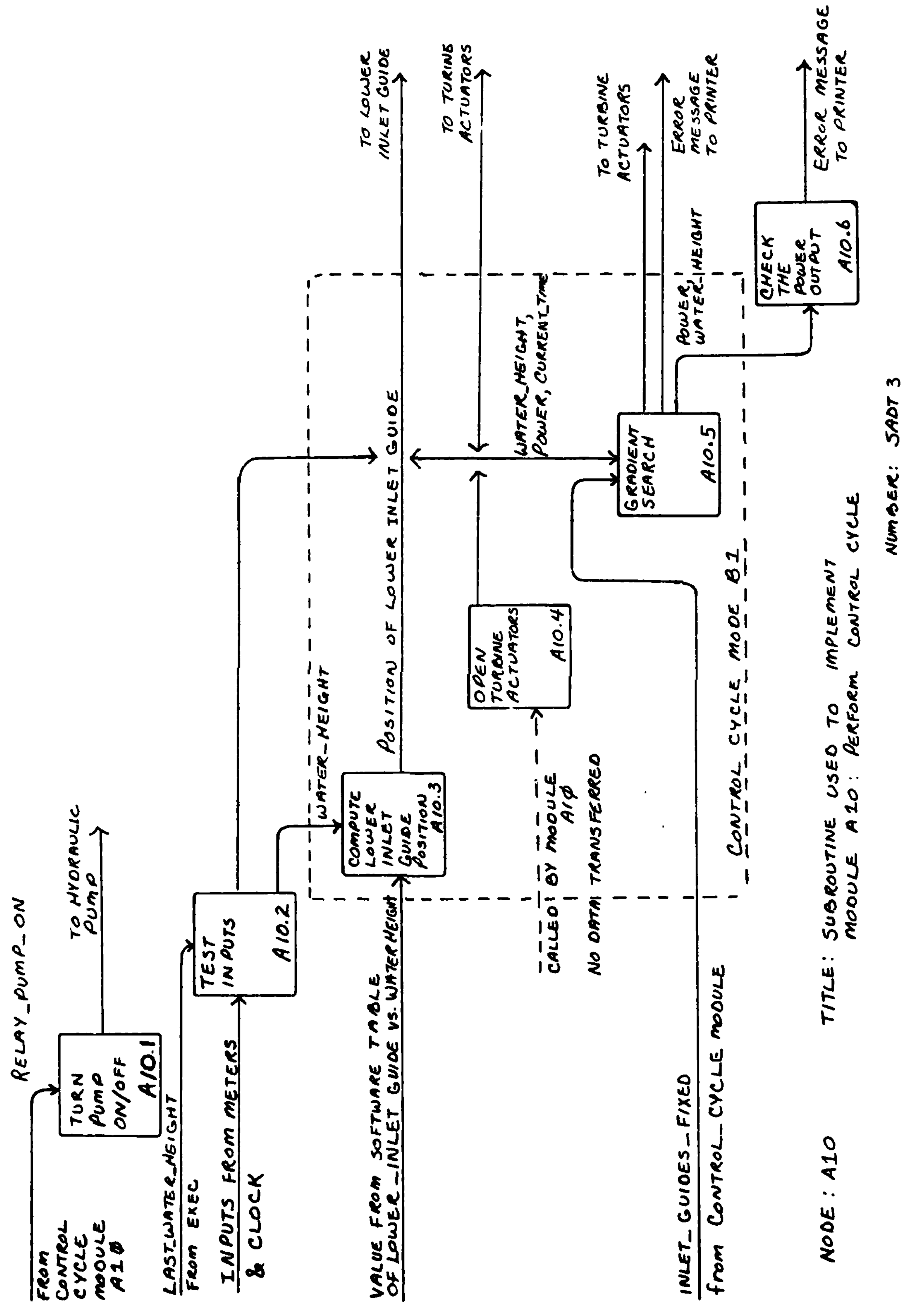
NODE A∅ thru A5

TITLE: ENTRY OF INPUT INTO THE SYSTEM

NUMBER: SADT 1



NODE: A6 thru A11 | TITLE: DECISON AS TO WHICH MODE TO GO INTO | NUMBER: SADT 2


RELAY_PUMP_ON
FROM CONTROL CYCLE MODULE A1Ø
TURN PUMP ON/OFF A10.1
TO HYDRAULIC PUMP
LAST_WATER_HEIGHT
FROM EXEC
INPUTS FROM METERS & CLOCK
TEST INPUTS A10.2
VALUE FROM SOFTWARE TABLE OF LOWER_INLET GUIDE VS. WATER HEIGHT
WATER_HEIGHT
COMPUTE LOWER INLET GUIDE POSITION A10.3
POSITION OF LOWER INLET GUIDE
TO LOWER INLET GUIDE
CALLED BY MODULE A1Ø
NO DATA TRANSFERRED
OPEN TURBINE ACTUATORS A10.4
TO TURING ACTUATORS
WATER_HEIGHT, POWER, CURRENT_TIME
GRADIENT SEARCH A10.5
TO TURBINE ACTUATORS
ERROR MESSAGE TO PRINTER
POWER, WATER_HEIGHT
CHECK THE POWER OUTPUT A10.6
ERROR MESSAGE TO PRINTER
CONTROL CYCLE MODE B1
INLET_GUIDES_FIXED
from CONTROL_CYCLE MODULE
NODE: A10
TITLE: SUBROUTINE USED TO IMPLEMENT MODULE A10: PERFORM CONTROL CYCLE
NUMBER: SADT 3

Psuedo Code

```
MODULE NAME:  Read A/D  (AO)
Read the A/D's I/O address to obtain POWER, WATER_HEIGHT,
  and FLOOD_GATE_POS
IF (any of the 3 inputs are negative) Then
    Writer "A/D Broken" to printer
End IF
END


MODULE NAME:  Read Clock Module  (A1)
Read clock I/O to obtain CURRENT_TIME
End


MODULE NAME:  Turn Pump On/Off  (A4)
If (RELAY_PUMP_ON is true) Then
  Set pump input signal high
  Ten second delay loof
Else
  Set pump input signal low
End if
End


MODULE NAME:  Open Flood Gate  (A5)
This module open closes the flood gate.  The control
algorithm for the flood gate has not been developed.


MODULE NAME:  Shut Down System  (A3)
Call Turn Pump On/Off (RELAY_PUMP_ON=True)
Call Open Flood Gate
Set House Buzzer signal High
Turn off Printer
Delay Until Flood Gate is Completely Open
Call Turn Pump On-Off (RELAY_PUMP_ON=False)
Loop in Idle Mode
End


MODULE NAME:  Test_Inputs  (A2)
Call Read A/D  (AO)
Call Read Clock  (A1)
If (WATER_HEIGHT>MIN_WATER_HEIGHT Then
  System is okay
Else If(WATER_HEIGHT=0 and LAST_WATER_HEIGHT>MIN_WATER_
  HEIGHT) Then
  Write "Water height meter is broken" to printer
  Call Shut Down System  (A3)
```

```
ELse
  Write "Water height is too low" to printer
End If
If (POWER=0) Then
  Write "no power output" to printer
  Call Shut Down System  (A3)
End If
If (FLOOD_GATE_POS=0) THEN
  IF (WATER_HEIGHT<MAX_WATER_HEIGHT) Then
    Write "flood gate broken" to printer
    Call Shut Down System (A3)
  End If
End If
End
```

```
MODULE NAME:  Compute Efficiency  (A7)
Call Compute Flow Rate (WATER_HEIGHT,FLOW_RA.E)
THEORETICAL_POWER=FLOW_RATE*WATER_HEIGHT/POWER_CONSTANT
EFFICIENCY=THEORETICAL_POWER-POWERO
             THEORETICAL_POWER
END
```

```
MODULE NAME:  Compute Flow Rate
Table look up of flow rate given WATER_HEIGHT from software
  table of FLOW_RATE vs WATER_HEIGHT
```

```
MODULE NAME:  Executive or "Choose Mode" (A8)  [Figure J-1]
Loop Forever
  Call Test Inputs (A2)
  Call Compute Efficiency (A7)
  If (CALIBRATE_SWITCH is on) Then
    Call Calibrate Mode  (A9)
  Else If [ABS(WATER_HEIGHT-WATER_HEIGHT_LAST_CONTROL_CYCLE
            > MAX_WH_CHANGE)  Then
    Call Control Cycle Mode  (A10)
  Else If (WATER_HEIGHT > MAX_WATER_HEIGHT) Then
    Call Turn Pump On/Off
    Call Open Flood Gate (RELAY_FLOOD_OPEN)  (A5)
    If (LOGGER_SWITCH is on) Then
      write "avoid flood"
    End If
    Else If (EFFICIENCY<MIN_EFFICIENCY) Then
    If (LOGGER_SWITCH is on) Then
      write "low efficiency"
    Call Control Cycle Mode  (A10)
  Else If (CURRENT_TIME-TIME_SINCE_LAST_CONTROL_CYCLE>1 hr)
    If (LOGGER_SWITCH is on) Then
      write "1 hr since last control"
    Call Control Cycle Mode  (A10)
```

```
    End If
    LAST WATER HEIGHT = WATER HEIGHT
End of Loop
End of Exec Module
```

```
MODULE NAME:  Calibrate Mode  (A9)
Time Since Last User Input=Current Time
Relay Pump On=True
Call Turn Pump On (RELAY_PUMP_ON)
Loop While (CALIBRATE_SWITCH is on)
  MAX_TIME=TIME_SINCE _LAST_USER_INPUT+MAX_CALIBRATE_TIME
  Call Read KeyPad  (A11)
  Select Keypad Option
  If (LOGGER_SWITCH is on) Then
    Write KEYPAD_OPTION and KEYPAD_DATA to printer
  End If
  Call Read Clock
  TIME_SINCE_LAST_USER_INPUT=CURRENT_TIME
End Loop
RELAY_PUMP_ON=FALSE
Call Turn Pump On/Off (RELAY_PUMP_ON)
End
```

```
MODULE NAME:  Read Keypad  (A11)
Read KEYPAD_OPTION and KEYPAD_DATA from Keypad I/O
End
```

```
MODULE NAME:  Control Cycle Module  (A10)
See Module B1 in Chapter VI.
```

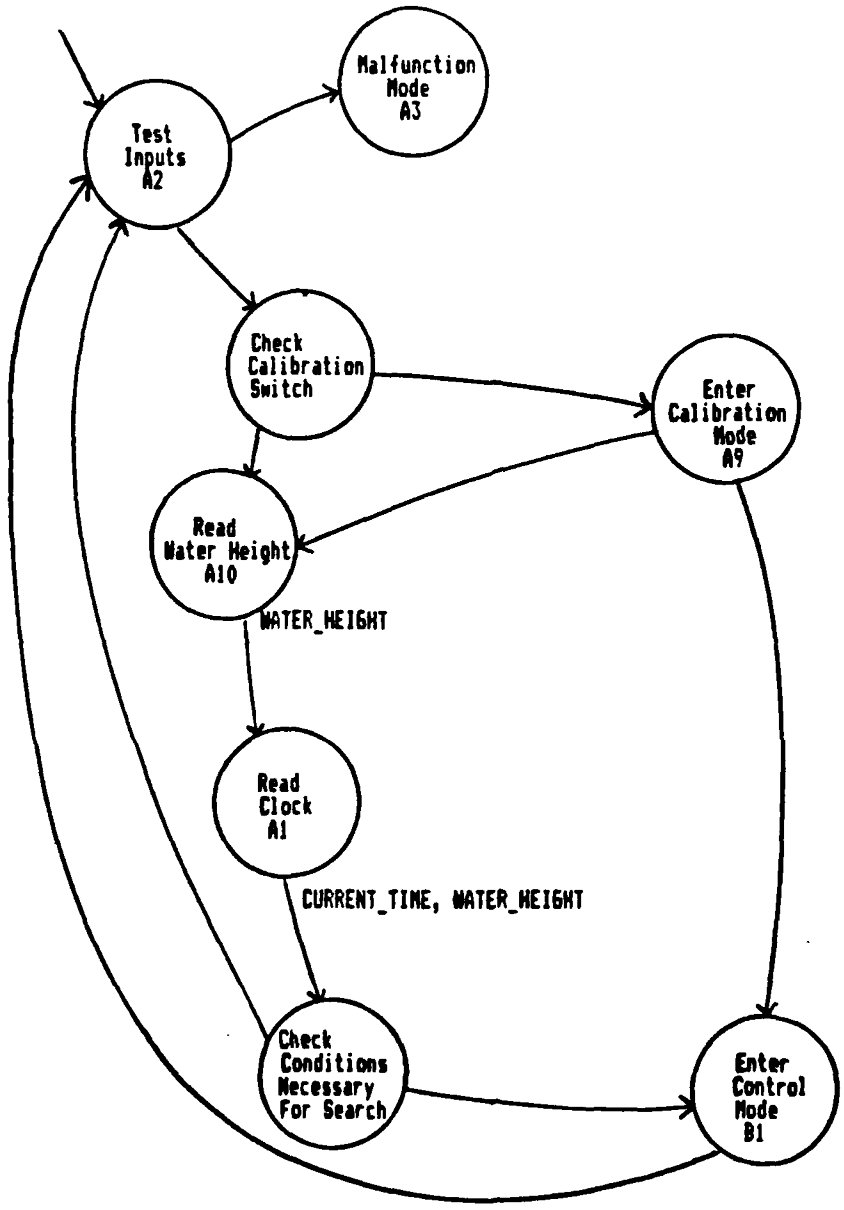


Fig. J-1 Executive or "Monitor" Module A8

<u>Data Dictionary</u>

NAME: CALIBRATE_SWITCH
DESCRIPTION: CALIBRATE_SWITCH is a boolean that sends the control system into the calibrate mode when it is set true.
COMPOSITION: Boolean value
ASSOCIATED PROCESSES: A8
SOURCE: CALIBRATE switch on Operator's Console

NAME: CURRENT_TIME
DESCRIPTION: CURRENT_TIME is the most current time in the software. It is set by module READ_CLOCK which is accessed by Test Inputs Module. CURRENT_TIME is mainly used in comparing time limits.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A1,A2,A8,A9,A10
SOURCE: Clock

NAME: EFFICIENCY
DESCRIPTION: Efficiency is the percentage efficiency as compared to the formula

EFFICIENCY = 100(THEORETICAL_POWER-POWER)/THEORETICAL_POWER

COMPOSITION: Real Value
ASSOCIATED PROCESSES: A7,A8,A10
SOURCE: Compute Efficiency

NAME: FLOOD_GATE_POSition
DESCRIPTION: FLOOD_GATE_POS tells if the flood gate is open or closed. A value of zero means the gate is fully open. A positive value means the gate is fully closed.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A0,A2,A8,A10
SOURCE: Read A/D

NAME: FLOW_RATE
DESCRIPTION: Flow rate is the software table value corresponding to the current water height. It represents the flow rate or the river (ie. cubic feet per minute)
COMPOSITION: Boolean
ASSOCIATED PROCESSES: A6,A7
SOURCE: Compute Flow Rate

NAME: KEYPAD_DATA
DESCRIPTION: Date entered via the keyboard. This does not

include option selections.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A11,A9
SOURCE: Read Keypad

NAME: KEYPAD_OPTION
DESCRIPTION: This is the selector variable for the options in the calibrate mode. The value must be between 1 and MAX_KEYPAD_OPTION. It is entered via the keypad.
COMPOSITION: Integer
ASSOCIATED PROCESSES: A11,A9
SOURCE: Read Keypad

NAME: LAST_WATER_HEIGHT
DESCRIPTION: This is the water height during the last computer cycle (not control cycle). This is always set by the EXEC module and used in Test Inputs
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A10,A2
SOURCE: EXEC

NAME: LOGGER_SWITCH
DESCRIPTION: This boolean is used to control printing (if a printer is installed). When this boolean is set false no control cycle information nor changes during the calibration mode will be printed. When LOGGER_SWITCH is true all information is printed. Note, the system shutdown error messages will be printed regardless of the value of LOGGER_SWITCH.
COMPOSITION: Boolean
ASSOCIATED PROCESSES: A8,A9
SOURCE: PRINT ON switch on operator' console

NAME: MAX_CALIBRATE_TIME
DESCRIPTION: Maximum time you remain in calibrate mode without user inputs via the keypad. This system constant can be changed in the calibrate mode. All system constants (global parameters) can be changed.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A9,A11
SOURCE: System constant in memory (RAM)

NAME: MAX_CONTROL_CYCLE_TIME
DESCRIPTION: Maximum time allowed in the control cycle mode.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A10

SOURCE: System constant in memory.

NAME: MAX_KEYPAD_DATA
DESCRIPTION: Maximum correct data that can be input for KEYPAD data. The system may be able to represent a larger number however.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A11
SOURCE: System constant in memory.

NAME: MAX_KEYPAD_OPTIONS
DESCRIPTION: Maximum number of calibration options.
COMPOSITION: Integer
ASSOCIATED PROCESSES: A11
SOURCE: System constant.

NAME: MAX_TIME
DESCRIPTION: Temporary variable used to impose an upper time limit on a process.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A9,A11,A10
SOURCE: System constant.

NAME: MAX_WATER_HEIGHT
DESCRIPTION: The maximum water height before the system tries to prevent flooding.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A2,A8
SOURCE: System constant.

NAME: MIN_EFFICIENCY
DESCRIPTION: The minimum efficiency before a control cycle is started.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A10
SOURCE: System constant.

NAME: MIN_KEYPAD_DATA
DESCRIPTION: Smallest correct data number that need be entered in via the keypad. The system may be able to represent numbers that are more negative. This value will most likely be negative or zero.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A11
SOURCE: System constant.

NAME: MIN_WATER_HEIGHT
DESCRIPTION: Lowest water height that will produce more power than the control system consumes. This constant is used to determine if the water level meter input is good.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A2
SOURCE: Systme Constant

NAME: OUTPUT_ON_SWITCH
DESCRIPTION: This boolean makes the executive skip the control cycle while the boolean is off. When it is on the control cycle conditions are teste in order to see if a control cycle is necessary.
COMPOSITION: Boolean
ASSOCIATED PROCESSES: A10
SOURCE: Output On/Off switch on the operator's console.

NAME: POWER
DESCRIPTION: The power produced by the turbine measured by a power meter.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A0,A2,A7,A10
SOURCE: Power Meter

NAME: POWER_CONSTANT
DESCRIPTION: Constant used in theoreticaly power calculation.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A7
SOURCE: System constant.

NAME: RELAY_FLOOD_OPEN
DESCRIPTION: This boolean opens the flood gate completely if it is true. If it is false the flood gate closes completely.
COMPOSITION: Boolean
ASSOCIATED PROCESSES: A5,A3,A8
SOURCE: All except A5.

NAME: RELAY_PUMP_ON
DESCRIPTION: This boolean turns the pump on when it is true. The pump turns off when it is false.
COMPOSITION: Boolean
ASSOCIATED PROCESSES: A3,A4,A8,A9,A10
SOURCE: A11

NAME: THEORETICAL_POWER
DESCRIPTION: Maximum theoretical available water power.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A7,A10
SOURCE: Both processes.

NAME: TIME_SINCE_LAST_CONTROL_CYCLE
DESCRIPTION: This is the time elapsed since last control cycle. This value will never exceed the MAX_TIME_BETWEEN_CONTROL_CYCLE time if the controller is in the normal monitor mode.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A8,A10
SOURCE: Control Cycle Mode.

NAME: TIME_SINCE_LAST_USER_INPUT
DESCRIPTION: Time since last user input on the keypad.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A9
SOURCE: Calibrate mode.

NAME: WATER_HEIGHT
DESCRIPTION: The water height of the river as input to the A/D through an electrical water height measuring device. This is the most important variable in the software.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A0,A2,A6,A7,A8,A10
SOURCE: Water height measuring device.

NAME: WATER_HEIGHT_SINCE_LAST_CONTROL_CYCLE
DESCRIPTION: The water height during the last control. This variable is used to determine if the water height has changed more than is allowable.
COMPOSITION: Real Value
ASSOCIATED PROCESSES: A8,A10
SOURCE: A10

Appendix K.

Simulation Program - Search

```
***********************************************************
*
*     NAME:  PROGRAM SEARCH
*     DATE:  18 OCT 84
*     MODULE NUMBER:  1
*     FUNCTION:  Main program to gradient search test.  The
*                file DINFO must be accessible and the
*                IPOWER subroutines must be attached in
*                order to run this program.
*     INPUTS:        H - Water Height
*                 DELX - Smallest Control Surface Movement
*                        (optional)
*               MAXSTP - Maximum Search Step (optional)
*               RDUSTP - Step Reduction Facts (optional)
*                 TPOS - Upper Table Position (optional)
*               UI1POS - UI #1 Position (optional)
*               UI2POS - UI #2 Position (optional)
*               UI3POS - UI #3 Position (optional)
*     OUTPUTS:       H - Water Height
*                 TPOS - Optimum Upper Table Position
*               UI1POS - Optimum UI#1 Position
*               UI2POS - Optimum UI#2 Position
*               UI3POS - Optimum UI#3 Position
*                 TCNT - Upper Table Movements
*               UI1CNT - UI#1 Movements
*               UI2CNT - UI#2 Movements
*               UI3CNT - UI#3 Movements
*               UI4CNT - All There UI's Movements
*                    P - Maximum Power
*
*     GLOBAL PARAMETERS: DELX, MAXSTP, RDUST,
*                        TPS - Table Position Data Array
*                         UI - Upper Inlet Data Arrary
*                          H - Water Height
*
*     GLOBAL VARIABLES:  TPOS
*                        UI1POS
*                        UI
*     MODULES CALLED:  LDATA, ALGNUI, GRASCH, READAD
*     CALLING MODULES: None
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
***********************************************************
      PROGRAM SEARCH
      REAL TPS(4,8),UI(4,8,135)
      REAL H,TPOS,UI1POS,UI2POS,UI3POS,P
      REAL DELX,MAXSTP,RDUSTP
      INTEGER CODE,TCNT,UI1CNT,UI2CNT,UI3CNT,UI4CNT
      COMMON/BLOCK1/TPOS,UI1POS,UI2POS,UI3POS
      COMMON/BLOCK2/DELX,MAXSTP,RDUSTP
      COMMON/BLOCK3/H,TPS,UI
```

```
      COMMON/BLOCK4/TCNT,UI1CNT,UI2CNT,UI3CNT,UI4CNT
      DATA TPOS,UI1POS,UI2POS,UI3POS/0.,0.,0.,0./
      DATA DELX,MAXSTP,RDUSTP/.03125,.125,.25/

      CALL LDATA(TPS,UI)
10    TCNT=0
      UI1CNT=0
      UI2CNT=0
      UI3CNT=0
      UI4CNT=0
      PRINT *,'INPUT WATER HEIGHT, INPUT 0.0 TO QUIT'
      READ *,H
      IF (H.EQ.0.0) GOTO 20
      PRINT *,'DO YOU WISH TO CHANGE PARAMETERS ?'
      PRINT *,'1=YES  2=NO'
      READ *,CODE
      IF (CODE.EQ.1) THEN
         PRINT *,'OLD DELTA_X= ',DELX
         PRINT *,'INPUT NEW DELTA_X'
         READ *,DELX
         PRINT *,'OLD MAX_STEP= ',MAXSTP
         PRINT *,'INPUT NEW MAX_STEP'
         READ *,MAXSTP
         PRINT *,'OLD REDUCE_STEP= ',RDUSTP
         PRINT *,'INPUT NEW REDUCE_STEP'
         READ *,RDUSTP
      END IF
      PRINT *,'DO YOU WISH TO CHANGE C.S. POSITIONS ?'
      PRINT *,'1=YES   2=NO'
      READ *,CODE
      IF (CODE.EQ.1) THEN
         PRINT *,'UPPER TABLE POSITION= ',TPOS
         PRINT *,'INPUT NEW UT POSITION'
         READ *,TPOS
         PRINT *,'UI#1 POSITION= ',UI1POS
         PRINT *,'INPUT NEW UI#1 POSITION'
         READ *,UI1POS
         PRINT *,'UI#2 POSITION= ',UI2POS
         PRINT *,'INPUT NEW UI#2 POSITION'
         READ *,UI2POS
         PRINT *,'UI#3 POSITION= ',UI3POS
         PRINT *,'INPUT NEW UI#3 POSITION'
         READ *,UI3POS
      END IF
      CALL ALGNUI
      CALL GRASCH
      CALL READAD(P)
      PRINT *,'  '
      PRINT *,'  '
      PRINT *,'H       = ',H
      PRINT *,'TPOS    = ',TPOS
      PRINT *,'UI1POS  = ',UI1POS
```

```
      PRINT *,'UI2POS  = ',UI2POS
      PRINT *,'UI3POS  = ',UI3POS
      PRINT *,'TCNT    = ',TCNT
      PRINT *,'UI1CNT  = ',UI1CNT
      PRINT *,'UI2CNT  = ',UI2CNT
      PRINT *,'UI3CNT  = ',UI3CNT
      PRINT *,'UI4CNT  = ',UI4CNT
      PRINT *,'POWER   = ',P
      PRINT *,'  '
      PRINT *,'  '
      PRINT *,'  '
      PRINT *,'  '
      GOTO 10
 20   CONTINUE
      END

************************************************************
*
*     NAME:  SUBROUTINE ALGNUI
*     DATE:  18 OCT 84
*     MODULE NUMBER: 2
*     FUNCTION:  Align Upper Inlets Module.  This subroutine
*                aligns the upper inlets prior to the
*                gradient search
*     INPUTS:  None
*     OUTPUTS: None
*     GLOBAL PARAMETERS:   DELX - Smallest Control Surface
*                                 Movement
*                        MAXSTP - Maximum Search Increment
*                        RDUSTP - Step Reduction Factor
*     GLOBAL VARIABLES:  None
*     MODULES CALLED:  READAD, FDARTC, MOVCS
*     CALLING MODULES: SEARCH
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE ALGNUI
      REAL P0,P1,STEP,DELX,MAXSTP,RDUSTP,PARTL
      INTEGER CS
      COMMON/BLOCK2/DELX,MAXSTP,RDUSTP
      CS=2
 10   CALL READAD(P0)
      CALL FPARTL(CS,PARTL)
      IF (PARTL.GT.0.0)THEN
         STEP=DELX
      ELSE IF (PARTL.LT.0.0) THEN
         STEP=-DELX
      ELSE
         GOTO 30
      END IF
 20   CALL MOVCS(CS,STEP)
```

```
      CALL READAD(P1)
      IF (P1.GT.PO) THEN
         PO=P1
         GOTO 20
      END IF
      CALL MOVCS(CS,-STEP)
 30   CS=CS+1
      IF (CS.LT.5) GOTO 10
      END

************************************************************
*
*     NAME:  SUBROUTINE GRASCH
*     DATE:  18 OCT 84
*     MODULE NUMBER: 3
*     FUNCTION:  Optimize control surface positions to
*                maximize power.  This subroutine performs
*                The Gradient Search #2 procedure.
*     INPUTS:  None
*     OUTPUTS: None
*     GLOBAL PARAMETERS:    DELX - Smallest Control Surface
*                                  Movement
*                         MAXSTP - Maximum Search Increment
*                         RDUSTP - Step Reduction Factor
*     GLOBAL VARIABLES:  None
*
*
*     MODULES CALLED:  FDARTL, READAD, MOVCS, RLIMIT
*     CALLING MODULES:
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE GRASCH
      REAL DELX,PARTL,STEP,MAXSTP,RDUSTP,PO,P1
      INTEGER I,LIMIT,CS
      COMMON/BLOCK2/DELX,MAXSTP,RDUSTP

      CS=1
 10   CALL FPARTL(CS,PARTL)
      IF (PARTL.EQ.0.0) THEN
         IF (CS.EQ.5) THEN
            GOTO 30
         ELSE
            CS=5
            GOTO 10
         END IF
      END IF
      IF (PARTL.GT.0.0) THEN
         STEP=MAXSTP
      ELSE
         STEP=-MAXSTP
```

```
      END IF
 15   I=0
      CALL READAD(PO)
 20   CALL MOVCS(CS,STEP)
      CALL RLIMIT(CS,LIMIT)
      IF (LIMIT.EQ.1) GOTO 10
      CALL READAD(P1)
      I=I+1
      IF (P1.GT.PO) THEN
         PO=P1
         GOTO 20
      END IF
      CALL MOVCS(CS,-STEP)
      IF (I.GT.1) GOTO 10
      STEP=STEP*RDUSTP
      IF (STEP.GT.DELX) THEN
         GOTO 15
      ELSE IF (CS.EQ.1) THEN
         CS=5
         GOTO 10
      END IF
 30   CONTINUE
      END

************************************************************
*
*     NAME:  SUBROUTINE FPARTL
*     DATE:  18 OCT 84
*     MODULE NUMBER: 4
*     FUNCTION:  Find Partial Module.  This subroutine finds
*                the approximate partial derivative of the
*                input control surface.
*     INPUTS:  CS - Control Surface
*     OUTPUTS: PARTL - Approximate Partial Derivative
*     GLOBAL PARAMETERS:    DELX - Smallest Control Surface
*                                  Movement
*                         MAXSTP - Maximum Search Increment
*                         RDUSTP - Step Reduction Factor
*     GLOBAL VARIABLES:  None
*     MODULES CALLED:  READAD, RLIMIT, MOVCS,
*     CALLING MODULES: ALGNUI, GRASCH
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE FPARTL(CS,PARTL)
      REAL PARTL,PO,P1,P2,DELX,MAXSTP,RDUSTP
      INTEGER CS,LIMIT
      COMMON/BLOCK2/DELX,MAXSTP,RDUSTP

      CALL READAD(PO)
      CALL RLIMIT(CS,LIMIT)
```

```
 10   IF (LIMIT.EQ.1) THEN
         CALL MOVCS(CS,DELX)
         CALL READAD(P1)
         IF (P1.GT.PO) THEN
            PARTL=(P1-PO)/DELX
         ELSE
            PARTL=0
         END IF
         CALL MOVCS(CS,-DELX)
         GOTO 20
      END IF
      CALL MOVCS(CS,-DELX)
      CALL RLIMIT(CS,LIMIT)
      IF (LIMIT.EQ.1) GOTO 10
      CALL READAD(P1)
      CALL MOVCS(CS,2*DELX)
      CALL READAD(P2)
      CALL MOVCS(CS,-DELX)
      IF (P1.LE.PO.AND.P2.LE.PO) THEN
         PARTL=0
      ELSE
         PARTL=(P2-P1)/(2*DELX)
      END IF
 20   CONTINUE
      END

************************************************************
*
*     NAME:  SUBROUTINE READAD
*     DATE:  18 OCT 84
*     MODULE NUMBER: 5
*     FUNCTION:  Simulates the Read AID Module.  Determines
*                the power based upon the control surface
*                positions and water height.
*     INPUTS: None
*     OUTPUTS:  P - Linear Interpolated Output Power
*     GLOBAL PARAMETERS:    H - Water Height
*                         TPS - Upper Table Position Data
*                               Array
*     GLOBAL VARIABLES:     TPOS - Upper Table Position
*                         UI1POS - UI#1 Position
*                         UI2POS - UI#2 Position
                          UI3POS - UI#3 Position
*     MODULES CALLED:  IPower
*     CALLING MODULES: SEARCH, GRASDCH, ALGNUI, FPARTL
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE READAD(P)
      REAL P,TPOS,UI1POS,UI2POS,UI3POS
      REAL H,TPS(4,8),UI(4,8,135)
```

```
      COMMON/BLOCK1/TPOS,UI1POS,UI2POS,UI3POS
      COMMON/BLOCK3/H,TPS,UI
      CALL IPOWER(H,TPOS,UI1POS,UI2POS,UI3POS,TPS,UI,P)
      END

****************************************************************
*
*     NAME:  SUBROUTINE RLIMIT
*     DATE:  18 OCT 84
*     MODULE NUMBER: 6
*     FUNCTION:  Simulate the Read Limit Module.  Determines
*                if a control surface is at the full open
*                physical limit:  LTOL determines the switch
*                tolerance.
*     INPUTS:  CS - Control Surface
*     OUTPUTS: LIMIT - One for Yes
*                      Zero for No
*     GLOBAL PARAMETERS:  None
*     GLOBAL VARIABLES:      TPOS - Upper Table Position
*                          UI1POS - UI#1 Position
*                          UI2POS - UI#2 Position
*                          UI3POS - UI#3 Position
*     MODULES CALLED:  None
*     CALLING MODULES: GRASCH, FPARTL
*     AUTHOR:  CAPT DAVE RAMSEY
*
****************************************************************
      SUBROUTINE RLIMIT(CS,LIMIT)
      REAL TPOS,UI1POS,UI2POS,UI3POS,LTOL
      INTEGER CS,LIMIT
      COMMON/BLOCK1/TPOS,UI1POS,UI2POS,UI3POS
      DATA LTOL/.01563/
      IF (CS.EQ.1) THEN
         IF (TPOS.LT.LTOL) THEN
            LIMIT=1
         ELSE
            LIMIT=2
         END IF
      END IF
      IF (CS.EQ.2) THEN
         IF (UI1POS.LT.LTOL) THEN
            LIMIT=1
         ELSE
            LIMIT=2
         END IF
      END IF
      IF (CS.EQ.3) THEN
         IF (UI2POS.LT.LTOL) THEN
            LIMIT=1
         ELSE
            LIMIT=2
         END IF
```

```
      END IF
      IF (CS.EQ.4) THEN
         IF (UI3POS.LT.LTOL) THEN
            LIMIT=1
         ELSE
            LIMIT=2
         END IF
      END IF
      END

************************************************************
*
*     NAME:  SUBROUTINE MOVCS
*     DATE:  18 OCT 84
*     MODULE NUMBER: 7
*     FUNCTION:  Simulate the Move Control Surface Module.
*                Moves the specified control surface the
*                designated distance.
*     INPUTS:   CS - Control Surface
*             DIST - Distance to Move Control Surface
*     OUTPUTS:  None
*     GLOBAL PARAMETERS:  None
*     GLOBAL VARIABLES:   TPOS - Upper Table Position
*                       UI1POS - UI#1 Position
*                       UI2POS - UI#2 Position
*                       UI3POS - UI#3 Position
*                         TCNT - Upper Table Movements
*                       UI1CNT - UI#1 Movements
*                       UI2CNT - UI#2 Movements
*                       UI3CNT - UI#3 Movements
*                       UI4CNT - UI#4 Movements
*     MODULES CALLED:  None
*     CALLING MODULES: ALGNUI, GRASCH, FPARTL
*
*     AUTHOR:  CAPT DAVE RAMSEY
*
************************************************************
      SUBROUTINE MOVCS(CS,DIST)
      REAL DIST,TPOS,UI1POS,UI2POS,UI3POS
      INTEGER CS,TCNT,UI1CNT,UI2CNT,UI3CNT,UI4CNT
      COMMON/BLOCK1/TPOS,UI1POS,UI2POS,UI3POS
      COMMON/BLOCK4/TCNT,UI1CNT,UI2CNT,UI3CNT,UI4CNT
      IF (CS.EQ.1) THEN
         TPOS=TPOS+DIST
         IF (TPOS.LT.0.0) TPOS=0.0
         TCNT=TCNT+1
      END IF
      IF (CS.EQ.2 .OR. CS.EQ.5) THEN
         UI1POS=UI1POS+DIST
         IF (UI1POS.LT.0.0) UI1POS=0.0
         IF (CS.EQ.5) THEN
            UI4CNT=UI4CNT+1
```

```
      ELSE
        UI1CNT=UI1CNT+1
      END IF
   END IF
   IF (CS.EQ.3 .OR. CS.EQ.5) THEN
      UI2POS=UI2POS+DIST
      IF (UI2POS.LT.0.0) UI2POS=0.0
      IF (CS.NE.5) UI2CNT=UI2CNT+1
   END IF
   IF (CS.EQ.4 .OR. CS.EQ.5) THEN
      UI3POS=UI3POS+DIST
      IF (UI3POS.LT.0.0) UI3POS=0.0
      IF (CS.NE.5) UI3CNT=UI3CNT+1
   END IF
   END
```

Appendix L

Turbine Modification Description

Figure L-1 shows the proposed modified crossflow turbine. The modification incorporates many of the design specifications illustrated in Dr. Banki's paper on the crossflow turbine (7). Based upon the Banki Design the number of adjustable control surfaces are reduced from six to two. The three upper inlets are replaced by one upper inlet. Consequently, the upper inlet and the upper table are the only two adjustable control surfaces. The lower inlet and turbine blade pitch will remain fixed in a optimum position.

The upper table will be modified with a new drive mechanism, however the function of the upper table will remain the same. The upper table's function is to optimize the water inlet area opening s_o (shown in Figure L-1). Since the lower inlet is to remain fixed, s_o is function of only the upper table position. Theoretically, the water inlet area should conform to the water velocity as the water enters the turbine (7). Therefore, if the water velocity entering the turbine can be determined, then an optimum s_o can also be calculated.

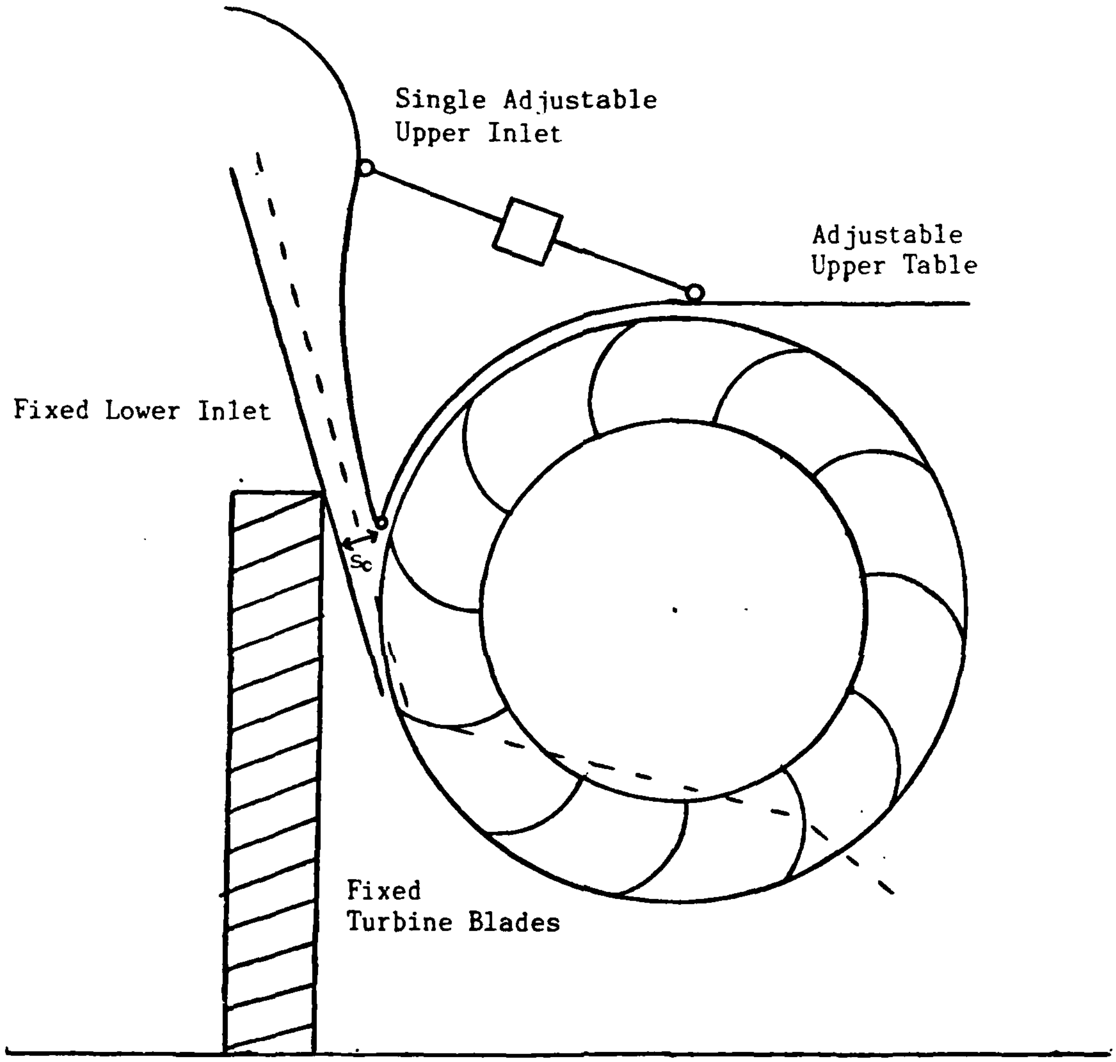


Fig. L-1 Profile of Modified Turbine

The water velocity entering the turbine can be estimated using the following equation

$$V = C(2gH)^{\frac{1}{2}}$$

where g is the gravitational acceleration constant, H is the head height, and C is a correction coefficient (C=.98 is the values used in the Banki turbine design) which depends on the efficiency of the water inlet guides. Dividing the water velocity by the rivers flow rate (ie. the cubic feet per minute) will yield the water inlet area (A) which conforms to the water' velocity. s_o can then be calculated by dividing the optimum inlet area by the fixed length (L) of the turbine.

$$A = Q/V$$

$$s_o = A/L$$

Based upon the modified turbine's dimensions the equation for$_o$ is

$$s_o = Q/4.83H^{\frac{1}{2}}$$

Under steady state conditions, the river flow rate (Q) is a function of the rivers water height (H). Once the turbine is installed, an expression for Q in terms of H can be found experimentally. The experimentally found Q is then substituted into the above equation yielding a solution for s_o in terms of the water height. This equation will be used by the controller algorithm to place the upper table at the approximate optimum position. The gradient search algorithm is then performed to 'fine tune' the upper table's optimum position.

The upper inlet is all three of the original upper inlets made into one control surface. The shape and size of the upper inlet has been changed so as to conform to the velocity of the water as the water enters the turbine (Figure L-1). The upper inlet performs the function of the three upper inlets described in the original turbine. The upper inlet's function is to provide a smooth transition for the water flowing from the river into the turbine. Controlling the upper inlet will be performed the same as controlling all three upper inlets of the original turbine.

The turbine blades and lower inlet will be fixed at positions determined from the specifications in Dr Banki's design. Therefore, these former control surfaces are excluded from the controller.

VITA

David Clyde Ramsey was born September 27, 1954 in Paramount California. He graduated from Paramount Senior High School and attended United States Air Force Academy where he received the degree of Bachelor of Science in Physics in June 1976. Upon graduation, he was commissioned a second lieutenant in the USAF. From September 1976 to September 1977 he attended undergraduate Pilot Training at Reese AFB, Texas. He then flew C-141 aircraft from December 1977 until May 1980 at Norton AFB, California. In June 1982 he entered the Air Force Institute of Technology to pursue a graduate degree in Electrical Engineering. He is a member of Eta Kappa Nu.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFIT/GE/ENG/85M-2

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: School of Engineering

6b. OFFICE SYMBOL (If applicable): AFIT/ENG

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State and ZIP Code): Air Force Institute of Technology, Wright-Patterson AFB, Ohio 45433

7b. ADDRESS (City, State and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State and ZIP Code):

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE (Include Security Classification): See box 19

12. PERSONAL AUTHOR(S): David C. Ramsey, B.S., Captain, USAF

13a. TYPE OF REPORT: MS Thesis

13b. TIME COVERED: FROM ________ TO ________

14. DATE OF REPORT (Yr., Mo., Day): 1985 March

15. PAGE COUNT:

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Microprocessor Controller; Gradient Search; Low-head Turbines

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: MICROPROCESSOR CONTROL DESIGN FOR A LOW-HEAD CROSSFLOW TURBINE

Thesis Chairman: Constantine H. Houpis

Approved for public release: IAW AFR 190-17.
LYNN E. WOLAVER 1 May 85
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr Constantine H. Houpis

22b. TELEPHONE NUMBER (Include Area Code): 513-255-2024

22c. OFFICE SYMBOL: AFIT/ENG

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

A microprocessor based controller is designed for use on a low-head crossflow turbine. The design contains a model of the turbine, an algorithm for maximizing output power, software design, and software testing. Modelling of the turbine is performed using tabular data in order to avoid the complexity of deriving an equation model. Linear interpolation of the tabular data is used to obtain a continuous model of the turbine.

Based upon turbine hardware, turbine characteristics, and economic feasibility, a search design is selected as most appropriate for the crossflow turbine. Specifically, a gradient search algorithm is chosen to maximize the turbine's output power. Software is designed for the gradient search and other modes of the controller. The software design contains flow diagrams, psuedo-code, and a data dictionary. Testing the software with the linear interpolation model, shows the gradient search adequately maximizes the output power of the modelled crossflow turbine.

END

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